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Evolution of the Smartphone

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In less than 10 years, mobile phones have evolved from tools used mostly for talking and texting to highly complex, sophisticated devices that are central to almost every aspect of our lives. They have changed the way we communicate, letting us share experiences in real time by uploading and downloading live video. They guide us while driving, making paper maps almost obsolete. They have become universal controllers for Internet of Things (IoT) devices ranging from home thermostats to hotel room door locks. And they have enabled companies to create entire new cloud-based business models. Ride-sharing companies like Uber rely on the ubiquity of mobile devices that let users find and pay for rides that are automatically directed to their locations.

All of these applications mean that high speed, highly reliable data connections are essential to everyone's daily life. Demand for mobile data continues to grow rapidly: the November 2016 Ericsson Mobility Report predicts that global smartphone subscriptions will rise from 3.3 billion in 2015 to 6.8 billion in 2022, with the data used per smartphone expected to rise nearly 8x to 11 GB/month over the same period. Trends such as virtual reality and real-time video require high performance networks that provide low latency as well as higher data rates.

To handle the growth in mobile data, successive network generations—2G, 3G, 4G (LTE) and, in the future, 5G—have used a variety of methods to progressively increase network capacity and data rates. One way is allocating many more frequency bands. A flagship LTE smartphone designed for global use may support more than 30 bands today, compared with fewer than 10 in 2010. The trend is continuing, as regulators allocate new higher frequency bands at 3.5 GHz and above and refarm existing spectrum, such as the 600 MHz band previously used for TV broadcasting. Channel bandwidth has increased, from 200 kHz with 2G to 20 MHz with 4G, even more using carrier aggregation (CA) in LTE Advanced (see ***Figure 1***). This is being combined with techniques for producing higher data rates and capacity from a given bandwidth, such as MIMO, more complex modulation and network densification, including the use of small cells.

Today, key trends include LTE Advanced, which network operators are now deploying, and its successor LTE Advanced Pro (defined in 3GPP Release 13 and later releases). These LTE network enhancements ensure that 4G will continue to play an important role even after 5G begins to be deployed. LTE will operate in parallel with 5G and provide adequate performance for many applications. LTE Advanced introduced CA, which aggregates the bandwidth of up to five RF carriers,

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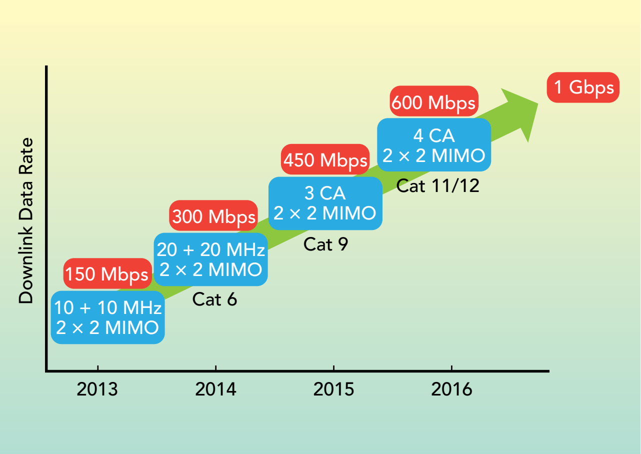


Fig. 1 Increasing downlink data rate enabled by carrier aggregation.

TABLE 1
COMMON CELLULAR BANDS

Band	Uplink (MHz)	Downlink (MHz)	Duplex Type
1	1920 to 1980	2110 to 2170	FDD
3	1710 to 1785	1805 to 1880	FDD
4	1710 to 1755	2110 to 2155	FDD
7	2500 to 2570	2620 to 2690	FDD
17	704 to 716	734 to 746	FDD
25	1850 to 1915	1930 to 1995	FDD
40	2300 to 2400	2300 to 2400	TDD
41	2496 to 2690	2496 to 2690	TDD
66	1710 to 1780	2110 to 2200	FDD

called component carriers (CC). LTE Advanced allows maximum network data rates up to 1 Gbps, and LTE Advanced Pro will increase the possible number of CCs to 32, allowing up to 3 Gbps. Wi-Fi is becoming more important with the introduction in LTE Advanced Pro of licensed assisted access (LAA), which uses CA to combine licensed LTE spectrum with unlicensed Wi-Fi spectrum at 5 GHz to achieve greater data rates.

SMARTPHONE TRENDS AND CHALLENGES

As smartphone data performance requirements continue to grow, so does the complexity of the RF front-end, creating a series of new challenges for the engineers working on smartphone designs. Today's requirements are creating design challenges that include maximizing linearity and isolation, managing power consumption and antenna tuning. Greater integration is required, since an increasing number of bands must squeeze into the limited space allocated to the RF front-end. Another important trend is the emergence of smartphone market tiers, each with differing RF requirements. This article discusses each of these and how the smartphone will evolve to handle 5G.

Isolation

The requirement to accommodate more LTE bands within the RF front-end creates challenges achieving the necessary isolation between different bands, between the transmit and receive frequencies of each frequency division duplex (FDD) LTE band and between LTE and other wireless services, such as Wi-Fi and public safety communications. High performance acoustic filters are needed to achieve the required isolation. Bulk acoustic wave (BAW) filters provide better performance (higher Q factors) than surface acoustic wave (SAW) filters, especially at higher frequencies, and are typically used for the most demanding applications.

The isolation challenges increase with CA, because the RF front-end must communicate simultaneously on multiple bands. This leads to new requirements for cross-isolation between bands, to avoid situations where the transmit signal of one aggregated band interferes with receive signals on another aggregated band, which will degrade the sensitivity of the receiver. There are various problem scenarios. When aggregating widely separated frequency bands, issues can arise with harmonic frequencies generated at multiples of the transmit frequency by non-linear components in the RF chain, including power amplifiers (PA), switches and even filters. With some band combinations, such as bands 17 and 4 (see ***Table 1***), the third harmonic of the lower frequency band (17) falls into the receive frequency range of the higher frequency band (4), as shown in ***Figure 2***. To prevent interference, the filters in the RF front-end must provide very high rejection of the problem harmonics without adding unacceptable insertion loss. High linearity is required in all the components—PAs, switches, filters—to minimize the generation of harmonics.

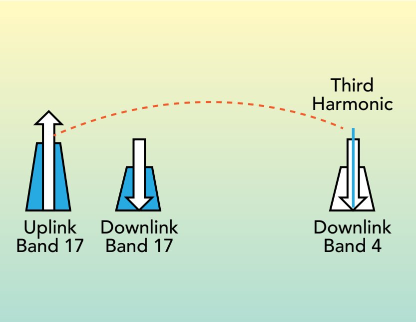
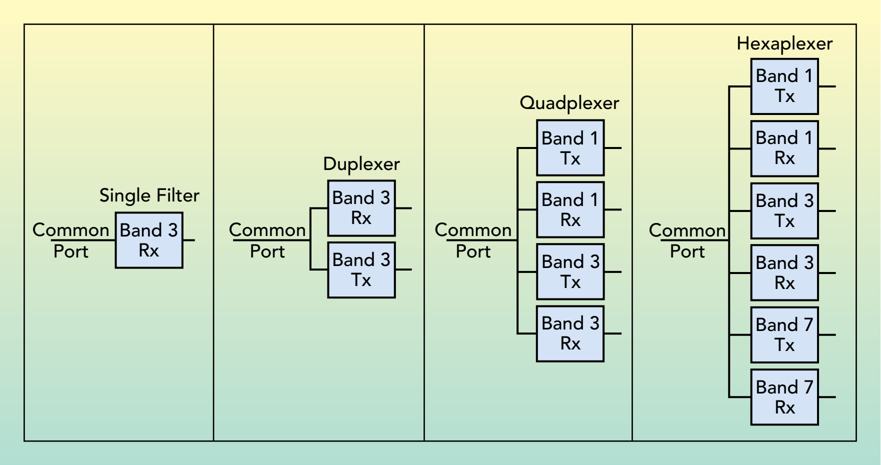


Fig. 2 With carrier aggregation, the third harmonic of the Band 17 uplink signal can interfere with the receive signal in Band 4.

A different cross-isolation issue occurs when aggregating closely spaced bands, which typically share the same RF pathway within the RF front-end. Examples include bands 1 and 3 and bands 25 and 66. In these cases, the problem is that the transmit frequency of one band is close to the receive frequency of the other aggregated band. Multiplexers, which combine all the transmit and receive filters for multiple aggregated bands into a single device, provide an efficient solution, allowing simultaneous use of the aggregated bands while providing isolation between them. Multiplexers will become increasingly important as network operators aggregate three or more bands (see ***Figure 3***), due to limits on the available space and number of antennas within the smartphone.



▲ **Fig. 3 Multiplexers become increasingly important as network operators aggregate bands to increase data rates.**

Power Management

Several trends require better power management to maximize smartphone battery life and avoid overheating. Greater transmission bandwidth, achieved with techniques such as uplink CA, will require more power. Also, intra-band uplink CA, which combines component carriers within a single band, involves higher peak-to-average power ratios than standard LTE signals, increasing the demand on PA linearity. For example, doubling the uplink bandwidth with CA to 20 + 20 MHz (200 resource blocks) more than doubles the probability that the peak-to-average power ratio of the modulated signal envelope will exceed 4.5 dB.

Another emerging requirement is Power Class 2, a new standard that doubles output power to 26 dBm to overcome the greater propagation losses of high frequency bands (e.g., Band 41). The greater output power enables operators to maintain cell coverage as higher frequency bands are used, to add spectrum and support higher data rates. Thermal performance becomes critical at this higher power; reliability depends on maintaining acceptable device operating temperatures by efficiently dissipating the additional heat.

Envelope tracking (ET), which continuously adjusts the PA supply voltage to track the RF envelope and maximize PA efficiency, is spreading from flagship phones to mainstream use because it can reduce power consumption and heat dissipation. The increased efficiency provided by ET facilitates the use of broadband PAs, which minimizes the number of PAs required in handsets. However, the use of ET is limited to 20 to 40 MHz channels and will need to evolve to handle the wider bandwidth for applications such as intra-band uplink CA. (Editor’s note: for further discussion of ET, read the article “Envelope Tracking in Handsets Solves a Network Problem” in this issue, page 102.)

Antennas

The number of antennas in smartphones has grown with the requirement to support faster data services as well as the growing range of RF frequencies and technologies. Today’s handsets may include as many as six or seven antennas, including primary cellular and diversity receive (DRx), Wi-Fi, near field communications (NFC) and other standards. It becomes an increasingly difficult engineering challenge to fit more antennas into the limited physical space available within a typical handset. MIMO adds to the challenge, because it requires simultaneous transmission on multiple antennas. The need for additional antennas has been minimized by sharing the same antenna among multiple services that use similar frequencies, such as Bluetooth and Wi-Fi. Antenna sharing is also used to support faster Wi-Fi performance, enabling 2x2 MIMO Wi-Fi by sharing the LTE DRx antenna between LTE and a second Wi-Fi RF chain.

Antenna tuning, which adjusts antenna impedance to optimize efficiency at specific frequencies, has become increasingly prominent as a method to support the growing range of LTE frequencies.

RF Integration

Even though smartphones have become larger, mostly due to users’ desire for larger screens, the space allocated to the RF front-end has not increased. In today’s flagship phones, typically only 10 to 15 percent of the internal area is dedicated to cellular, Wi-Fi and Bluetooth RF functionality. Smartphones are getting thinner, reducing the internal volume, and manufacturers need to use the available space for new functionality and to maximize battery size to respond to user demands for longer operating time. As a result, the RF front-end must accommodate the growing complexity, including support for a growing number of frequency bands, within roughly the same space. Higher levels of RF front-end integration are key to accommodating this growing RF complexity, particularly in flagship phones that support a large number of bands and CA combinations. Besides saving space, the integrated RF front-end modules simplify smartphone design, because many RF challenges are solved within the module rather than requiring the smartphone manufacturer to engineer solutions. This frees smartphone manufacturers to focus on other aspects of smartphone design, to attract consumers in an increasingly competitive market. By simplifying design, highly integrated modules also help smartphone makers accelerate time to market. Also, smartphone manufacturing yields are improved because there are fewer components that can fail.

An example of a highly integrated RF front-end architecture

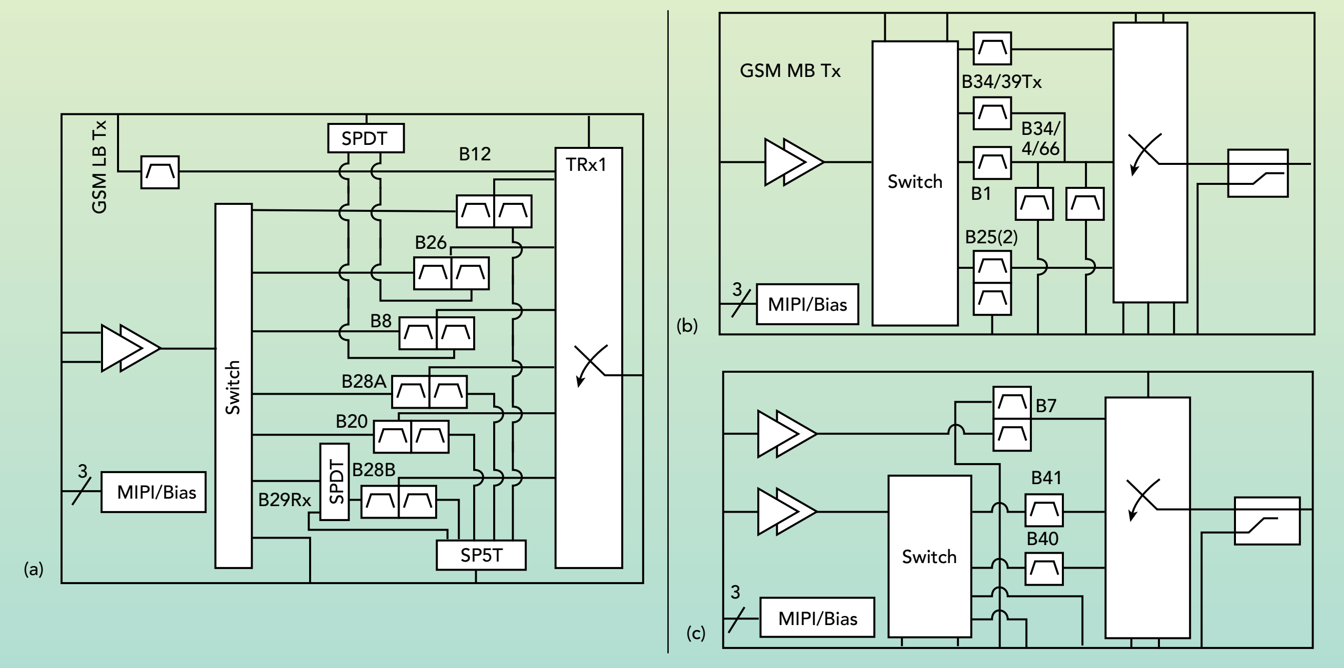


Fig. 4 To handle all major cellular frequencies, smartphones integrate the PAs, switches and filters into three front-end modules that cover the low (a) mid (b) and high (c) bands.

is Qorvo's RF Fusion, which includes support for all major LTE frequency bands in three compact placements: low, mid and high band (see ***Figure 4***). Each module includes PAs, switches and filters and uses advanced packaging to achieve space savings of 30 to 35 percent compared to the printed circuit board (PCB) area required for discrete components. Besides conserving valuable PCB real estate, this approach has several advantages: it improves performance by integrating components along each pathway, which eliminates the need for on-board matching, reduces losses by as much as 0.5 dB, reduces current consumption and the thermal load (see ***Figure 5***). Reducing losses makes it easier to meet handset manufacturers' performance targets. This integrated architecture also helps manage RF isolation, such as the interaction between bands aggregated for CA. For example, multiplexers supporting specific band combinations can be incorporated into each module. In the future, it may be possible to integrate an entire RF front-end into a single module, depending on whether the benefits to the manufacturer outweigh the additional cost of including bands that may not be used by the phone's owner.

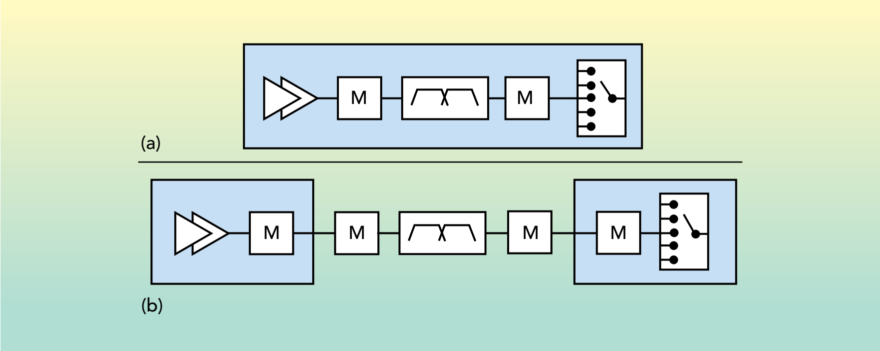


Fig. 5 Integrated front-end modules (a) can reduce losses by up to 0.5 dB compared to on-board matching (b).

SMARTPHONE TIERS

As smartphones continue to proliferate worldwide, the market has stratified into distinct tiers: flagship phones, which typically offer the highest performance and global band support, and mid-tier phones that deliver good performance and are designed primarily for domestic use, with only regional band support. Mid-tier phones have been popular in emerging markets such as Asia and Latin America, where consumers are price-sensitive. According to Strategy Analytics, smartphone tiers are here to stay; the company forecasts that mid-tier phones will account for 37 percent of handset volume by 2022, up from 32 percent in 2016. However, premium phones will continue to generate the bulk of global smartphone revenue because they sell for a much higher price.

This market stratification is reflected in RF front-end trends. Highly integrated RF front-end modules are typically seen only in premium handsets; mid-tier phones generally use a more discrete approach, such as Qorvo's RF Flex, giving handset manufacturers the flexibility to reduce component costs by including only the filters required for local frequency bands. As the RF environment becomes more complex, greater RF front-end integration will be seen in mid-tier phones. Market stratification has also spawned other trends, such as mid-tier phones that support dual SIMs. These enable users to minimize monthly costs, by using different services for voice and data or using local operators when traveling to different countries. Dual SIMs are supported with dual transceivers or techniques that use a single transceiver, such as time multiplexing.

THE FUTURE RF FRONT-END

The smartphone RF front-end will continue to evolve and grow in complexity over the next few years to meet changing requirements. In addition to supporting 5G, the smartphone will likely assume the role of a hub for communications among rapidly proliferating IoT devices and sensors, which will require the integration of new air interfaces into the RF front-end.

5G specifications development currently focuses on three high-level use cases, including IoT:

- Enhanced mobile broadband, to support consumers' use of video and other data-intensive mobile applications, which will require lower latency as well as faster data rates
- Massive machine type communications for IoT applications; and
- Ultra-reliable and low latency communication for applications where reliability and performance are critical, such as autonomous vehicles.

5G specifications are due in two main phases: Phase 1 (3GPP Release 15), due in late 2018, will support a subset of use cases, including enhanced mobile broadband, and will focus on frequencies below 6 GHz. Currently, bands between 3.8 and 4.99 GHz are under consideration. Since 4G LTE will continue to be widely used, an important goal is to maximize coexistence by designing the specifications for the 5G new radio (NR) to minimize interference with 4G bands. In general, the RF front-end technologies required for 5G Phase 1 may be similar to those used for 4G LTE, with improvements to support the new requirements.

The main challenges for Phase 1 include PA performance and increased linearity to support new uplink requirements designed to improve performance for data-intensive applications. These encompass more complex modulation (e.g., 256-QAM) and optional cyclic prefix orthogonal frequency division multiplexing (CP-OFDM). The adoption of 4x4 MIMO to further boost data throughput will require increased integration and more complex switching, as well as increasing the number of antennas. Enhancements to bulk acoustic wave (BAW) filter technology, which is widely used for higher-frequency LTE bands, are being developed to meet the filtering requirements for the sub-6 GHz frequencies for 5G.

5G Phase 2 (3GPP Release 16), expected by the end of 2019, will include the remaining use cases and focus on much higher frequencies (28 GHz and above). Though specifications are at an earlier stage than Phase 1, it is clear that communications at millimeter wave frequencies will require radical new antenna array architectures, beamforming techniques and sophisticated algorithms to compensate for the greater path losses at these frequencies. Coexistence between the millimeter wave frequencies and 4G LTE will pose other challenges.

Tunable analog filters are being explored to reduce the number of filters in the RF front-end. However, it is extremely challenging to create a broadband tunable analog filter that meets the power handling, insertion loss, isolation and coexistence needs of modern smartphones. The adoption of CA, which requires simultaneous operation on multiple bands, introduces complications that make broadband tunable filters even more difficult to achieve.

Silicon technologies such as CMOS, SOI and SiGe will continue to spread throughout the RF front-end for control, switching and amplification. Nonetheless, GaAs offers performance advantages for PAs and is likely to remain the dominant PA process technology. Digital signal processing is increasingly being employed to improve front-end performance through functions such as digital predistortion (DPD) and ET.

CONCLUSION

The growing complexity of the RF front-end and the ever-improving performance will require a mix of many different technologies combined in highly integrated modules. Suppliers with the ability to design using such a wide range of technologies, including advanced filtering and millimeter wave, will be best positioned to succeed as the smartphone enters its second decade.■