Small Cell Amplifier and System Design Considerations

By Jean-Christophe Nanan and Barry Stern

Understanding small cell base station systems requires an understanding of how they differ from their larger counterparts.

Now that the wireless industry has delivered on its promise of truly high-speed data service in the form of LTE along with the tablets and smartphones to exploit it, the challenge for wireless carriers lies in ensuring that the requisite high data rates are available seamlessly within a geographic area. So-called "small cells" are the most broad-based solutions for this task and unlike their massive macrocell predecessors are small, light, inexpensive, and can easily be sited. They also provide a way to offload network and backhaul traffic.

The Small Cell Defined

Like so many "high-tech" terms, these base stations in a box began their lives as femtocells, which were (and increasingly are) used in residences to boost coverage. However, with the introduction of high-end third- and fourth-generation standards such as HSPA+, CDFMA 2000 Rev. A, and LTE, carriers have realized that small cells could also be the answer for handling, in the uplink, downlink, and backhaul paths, the massive amounts of data traffic generated by these high-speed networks. This resurgence of interest spawned new terms, including metrocells, metro femtocells, public access femtocells, enterprise femtocells, super femtocells, Class 3 femtocells, picocells, and microcells.

Figuratively speaking, the most prudent approach is to lump all these cells together under the term "small cells" because, regardless of their size or coverage area, they are all designed to accomplish more or less the same thing: To increase signal strength to acceptable levels in areas where it is low, such as "urban canyons" in cities where buildings obscure the signal path, to residences and businesses in which signals are impeded by walls, ceilings, and many other areas. A comparison of these various base station constructs with a macrocell is shown in Table 1.

Their small size and comparative ease of installation allow small cells to be placed on

Cell type	Installation	Subscribers	Maximum cell radius	Maximum RF output power	Signal Bandwidth (MHz)	Wireless standard	Maximum sectors	MIMO support
Femto	Indoor	4 to 16	10 m	100 mW	10	3G/4G/ Wi-Fi	1	2x2
Pico	Indoor Outdoor	32 to 100	200 m	250 mW	20	3G/4G	1	2x2
Micro/ metro	Outdoor	200	2 km	6.3 W	20, 40	2G to 4G	2	4x4
Macro	Outdoor	200 to 1000	10 km	100 W	60 to 75	2G to 4G	3	4x4

Table 1 • Characteristics of Various Small Cell Types and Macrocell.

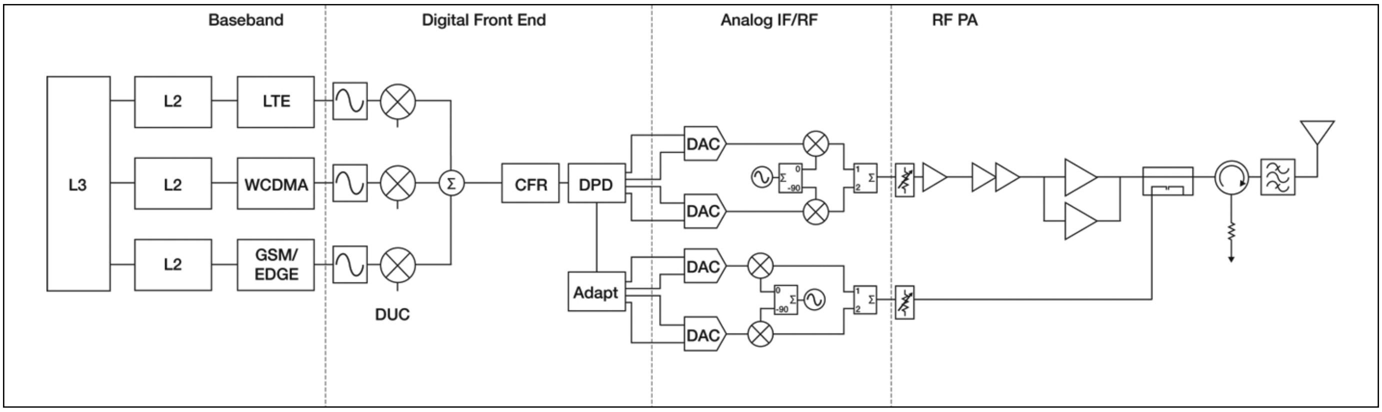

Figure 1 • A typical single-sector transmission link.

lamp posts, utility poles, rooftops -- basically anywhere they have access to a power source and a high-speed communications path back into the wired infrastructure. They can be used to provide good reception and transmission quality throughout office buildings, airports, convention centers, and dozens of other places where people need to communicate but are hampered by low signal strength. As small cells send their traffic into the wired network via hybrid fiber coax or all-fiber networks, they can also offload network traffic as a backhaul solution.

While small cells may be a fraction of the size of macrocells, they are nevertheless high-performance base stations that perform the same functions and often others such as managing inter-cell interference that macrocells themselves do not encounter. Small cells include signal capture, baseband digital signal processing, general-purpose processing, and RF and microwave receive and transmit capabilities (and other functions) in a densely-packed enclosure and operate in hostile environmental conditions. They may also need to accommodate second-generation legacy standards as well as CDMA 2000 Rev. A and R, TD-SCDMA, W-CDMA, WiMAX, HSPA+, and LTE in up to 15 different frequency bands.

Design Considerations

A major goal of small cell design is to efficiently integrate all functions from baseband through RF and microwave transceivers as tightly as possible while maintaining the ability to differentiate and scale products as technologies evolve. In addition to the small form factor of these base stations, they are often powered by a low-voltage source or even batteries, which makes high-level integration and efficiency essential tasks for the designer. A typical single-sector transmission link is illustrated in Figure 1 with its important interfaces identified.

Using LTE as the primary example, the baseband functions of the physical layer (Layer 1) in an LTE base station are implemented with DSP cores and baseband accelerators and radio front end logic in an ASIC or FPGA. Digital baseband processing for Layers 2 and 3 consists of medium access control (MAC), radio link control (RLC), and packet data convergence protocol (PDCP), all of which are typically implemented by a general-purpose processor.

In Layer 1, the 3GPP standards for third-generation W-CDMA and LTE, for example, employ different approaches for modulating and mapping data to the physical medium. W-CDMA requires that processing resources efficiently perform the spreading and despreading, scrambling and descrambling, and combining operations. In contrast, LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) modulation for the downlink path and Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation for the uplink path.

The primary operations in an OFDMA/SC-FDMA environment are Discrete Fourier Transforms (DFT) in the form of Fast Fourier Transforms (FFT) or DFT and multiply-accumulate operations. The data organization and subframe structure in LTE allow Layer 1 processing steps to be scheduled sequentially according to subframe user and allocation information. Latency has a major influence on both voice and data performance and it requires adherence to the tight latency requirements of physical layer processing so that time can be made available for MAC layer scheduler tasks. The LTE standard defines end-user round-trip latency as less than 5 ms, so latency in the base station must be significantly less (0.5 ms in the downlink and less than 1 ms in the uplink). MIMO equalization and detection and forward error correction are heavily used in LTE and MIMO equalizer and turbo coding error correction algorithms have a significant impact on base station throughput and latency. Freescale implements Layer 1 using StarCore® SC3850 or SC3900 DSP cores and its MAPLE baseband accelerator platform that efficiently implements standardized building blocks for each air inter-

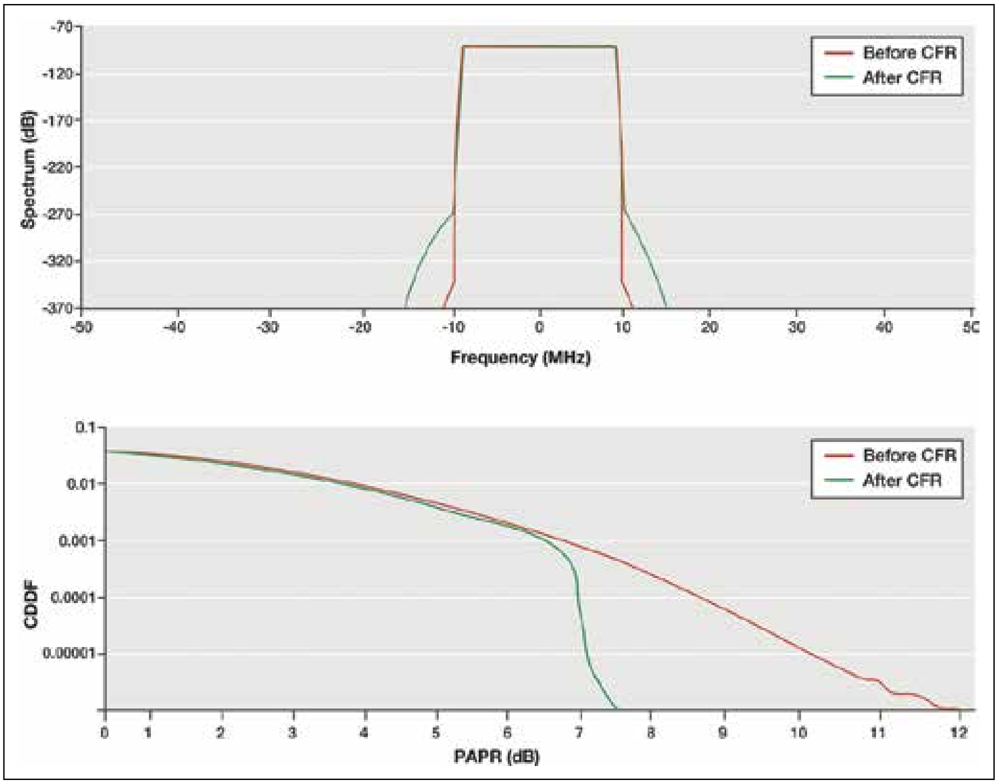

Figure 2 • The positive effects of CFR (a). PAPR extraction via the CCDF (b) can be used to size the RF power amplifier.

face standard in single- and multimode operation. Programmable DSP cores provide upgrade paths for each supported wireless standard while also supporting legacy standards.

The MAPLE hardware block enables multimode operation such as turbo and Viterbi decoding and turbo encoding. Algorithms for Layers 2 and 3 are performed by Freescale Power Architecture® general-purpose cores to efficiently implement any standard along with multimode operation. In macro base stations, the baseband channel card employs a single general-purpose processor and multiple DSPs to handle transmit and receive sectors, which vary depending with the number of users and required throughput. Femtocells and picocell base stations usually have only a single sector and a specific number of users and data rates, and unified system-on-chip (SoC) solutions are now available that integrate the general-purpose processor and DSP.

Signal Optimization

The digital front end prepares and multiplexes the signals created by the baseband processing subsystem and sends them to the RF power amplifier for transmission. A digital upconverter receives the carriers created by Layer 1 and then pulse-shapes and sums them according to the carrier's specified pattern using oversampling and filtering. The digital front end can employ crest factor reduction (CFR) for limiting peak-to-average power ratio (PAPR) and signal linearization using digital predistortion (DPD), both of which can increase amplifier efficiency.

Crest factor reduction has proven to be very effective tool for reducing the PAPR of complex modulated signals. When characterized in the frequency domain by their power spectrum, signal amplitude can be characterized in the time domain through the signal's statistical distribution (Figure 2). This exercise extracts the PAPR, which can be used to size the RF power amplifier and its devices. If average trans-

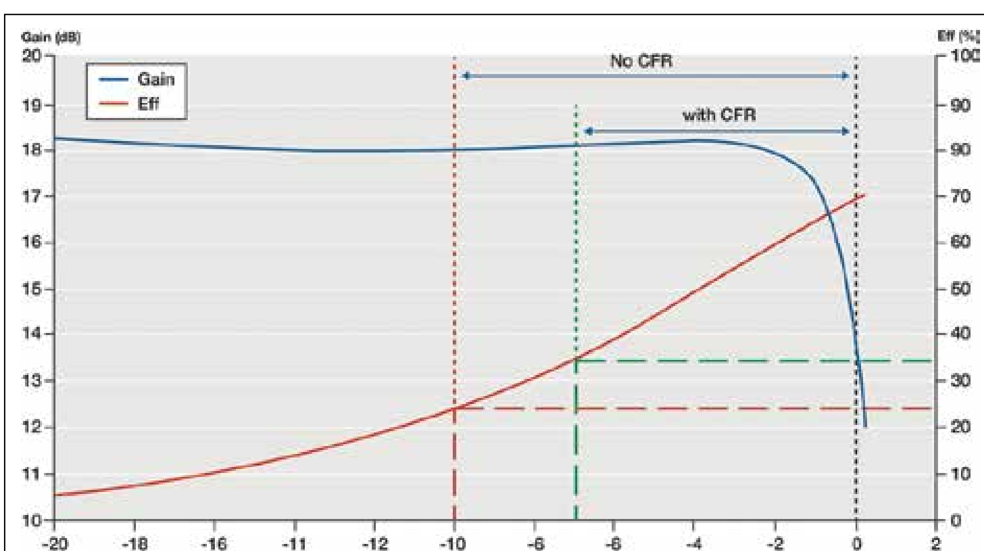

Figure 3 • The PAPR directly impacts amplifier efficiency as it decreases as OBO increases.

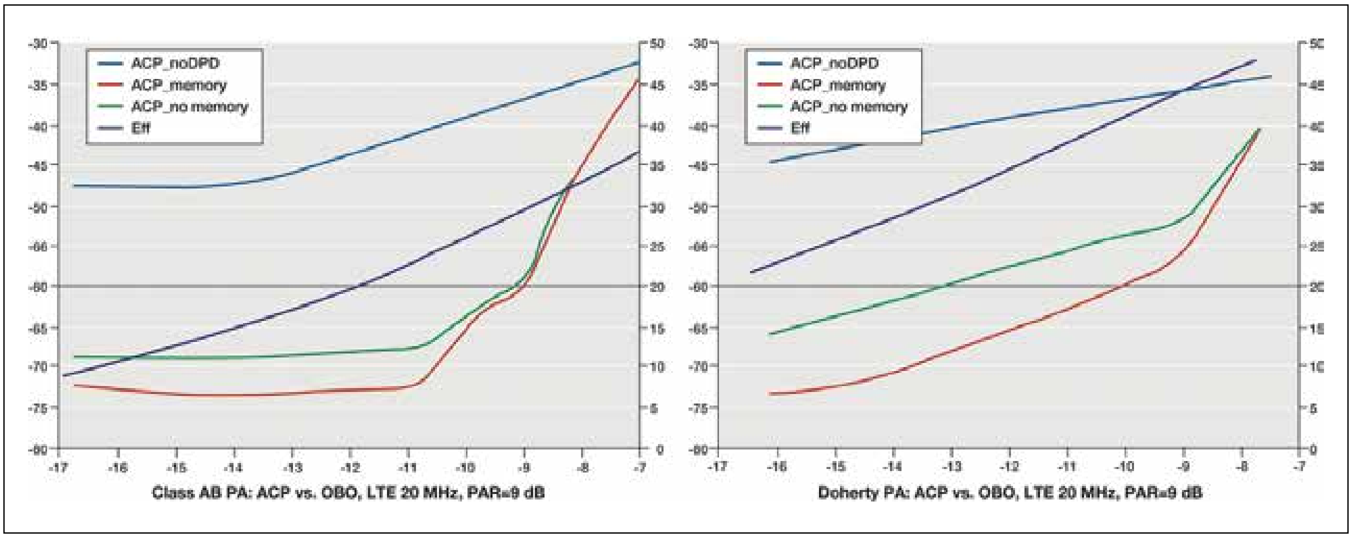

Figure 4 • Adjacent Channel Power (ACP) with and without the use of DPD in simulated Class AB (a) and Doherty (b) amplifiers fed with 20-MHz-wide LTE signals that have a PAR of 9 dB.

mit power must be +30 dBm with a PAPR of 10 dB, the amplifier's saturated power (Psat) should be greater than 40 dBm (30+10=40 dBm).

The PAPR dictates the minimum output back-off (OBO) from saturated power at which the amplifier usually operates and directly impacts amplifier efficiency because PAPR decreases as OBO increases (Figure 3). Consequently, reducing the PAPR helps to reduce both the size (and thus cost) of the devices used in the RF power amplifier and the amplifier's power consumption. This is obviously of major interest in small cell design.

Amplitude-modulated signals pose challenges for the amplifier as its non-linear behavior creates in-band distortion that increases Error Vector Magnitude (EVM) and out-of-band distortion (spectral regrowth). To meet increasingly stringent linearity and efficiency requirements, the power amplifier must be linearized using DPD. This consists of approximating amplifier characteristics using a behavioral model with the required level of correction depending on the accuracy of the model and its ability to follow the amplifier's behavior over temperature and with changes in carrier frequency and RF output power. These "memory effects" are changes in the amplitude or phase (or both) of distortion components as a function of input signal frequency and tend to be extremely difficult to model using standard steady-state characterization techniques. The less the contribution of memory effects, the easier linearization will be.

The simplest DPD scheme is open-loop correction without memory effect compensation and is based on static AM/AM and AM/PM power amplifier behavior. Closed-loop DPD includes memory effect correction and requires a demodulation path to sample the output signal and compare it with the desired transmitted signal. Figure 4 shows adjacent channel power (ACP) versus OBO for simulated final-stage Class AB and Doherty power amplifiers.

To demonstrate the effects of CFR and DPD and estimate RF power amplifier DC power budget for various types of small cells, an analysis was performed using 5-VDC GaAs and 28-VDC LDMOS RF power transistors in Class AB and Doherty power amplifier architectures. The amplifier line-up provided more than 50 dB of gain and had signals with a PAR of 10 dB without CFR and a PAR of 7 dB with CFR (at 0.01% CCDF probability). Depending on the power amplifier architecture and DPD scheme, margin for linearity varies from 1 to 4 dB including 3 dB of loss incurred by the isolator and filters between the amplifier output and the antenna.

From Figure 5 it can be assumed that low-power transmitters (less than 15 dBm), do not require CFR or DPD and as power increases (15 to 24 dBm), CFR pro-

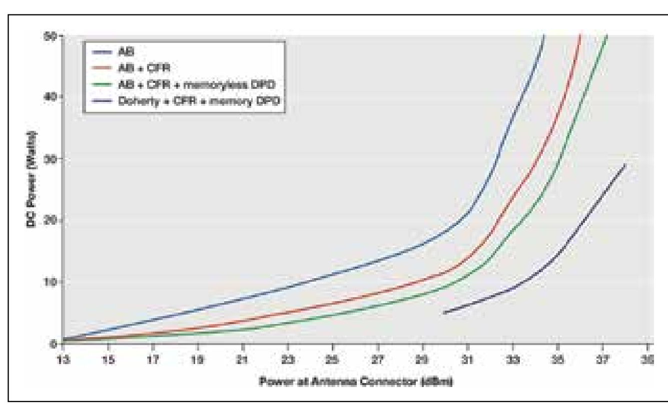

Figure 5 • The results of the amplifier DC power budget analysis provide insight as to the need for CFR or DPD under specific conditions.

Figure 6 • The femtocell reference platform based on Freescale's baseband architecture and RF devices, built by Benetel, and available to designers.

vides a modest improvement (with greater system complexity and cost). For power levels greater than 24 dBm, DPD helps keep transmitter power consumption in check and at power levels greater than +31 dBm the Doherty architecture is desirable. It is important to remember however, that performance can be improved with CFR and DPD together with an optimized RF amplifier architecture.

However, analyses of DC power consumption and estimates of the cost associated with processing features implemented by the digital front end is required to achieve optimum system definition. The results in Figure 5 are based on a single transmitter although equipment usually includes at least two and sometimes four RF power amplifiers to implement MIMO.

The modulation schemes and wireless access methods that the small cell is required to process, amplify, transmit, and receive impact the required resolution and dynamic range of the analog-to-digital and digital-to-analog converters. Conversion speed depends on signal bandwidth and the presence or absence of DPD, as the predistorted signal should include intermodulation products up to the fifth order. DPD also requires an additional return path to sample the output signal and send it to the front end for adapting the pre-distorted signal. This added complexity has a cost, which should be justified or offset depending on the small cell's performance improvements.

An Integrated Approach

As noted earlier, Freescale's baseband architecture is based on its StarCore data processing engines and Power Architecture technology, which scale from femtocells to macrocells. The company offers processors dedicated to small cells within its QorIQ Qonverge™ BSC913x series. For example the BSC9131 incorporates a Power Architecture processor, StarCore DSP engine, MAPLE baseband accelerator with LTE, W-CDMA, and CDMA2000 support, trusted-boot security, and an 800-MHz DDR3 memory interface and flash memory controller. The RF interface includes an antenna controller, two pulse-width modulators to control external components, and three JESD207/MaxPHY serial baseband interfaces. Controllers include two Gigabit Ethernet and one for USB 3.0, DMA, GPIO, UART, SPI, eSDHC, and two for PCs.

The BSC9131 targets applications with up to 16 users and integrates one e500 Power Architecture core and one SC3850 DSP core. The BSC9132 is optimized for picocell base stations serving up to 100 users and employs two of Freescale's e500 cores containing Power Architecture technology and two SC3850 DSP cores. The QorIQ Qonverge B4420 baseband processor is designed for microcells and the B4860 processor for macrocells.

In collaboration with Benetel, Freescale has created a BSC913x-based reference design platform (Figure 6) that can implement most major frequency bands throughout the world as well as LTE-FDD/TDD and WCDMA (HSPA+) access methods, allowing manufacturers to speed development of 3G Home Node B femtocells. The RF module in the platform delivers RF output power of 13 dBm and covers low-band (700 MHz to 1 GHz) and high-band (1.5 to 2.7 GHz) transmit/receive configurations, including 2x2 MIMO (Figure 7).

The RF module has JESD207 (JEDEC) and MaxPHY serial interfaces to the BSC913X and supports software-selectable dual-band operation, which allows the platform to support most wireless allocation throughout the world. There are two transmit and two receiver inputs for each frequency band to support 2x2 LTE and 3GPP W-CDMA (HSPA+) transmission and reception.

Freescale's linear, efficient MMZ09312B and MMZ25332B GaAs HBT power amplifiers and GaAs E-pHEMT low-noise amplifiers complete the transmit/receive path. The onboard MML09211H and MML20211H low-noise amplifiers have high sensitivity and cover UMTS frequency bands from 1 to 14. The MMZ25332 MMIC drives the final amplifier stage with 25 dB of gain and 33 dBm P1dB RF output power from 1.8 to 2.7 GHz and can also be used as the final stage in a picocell, providing an embedded RF power detector for monitoring and providing alarm information. The MMZ09312B covers 400 to 1000 MHz with P1dB RF output power of 29.6 dBm, gain of 31.7 dB, and an OIP3 of 42 dBm (all at 900 MHz). Both devices have externally-adjustable active bias control and RF power detection for monitoring and alarm, and operate from a single 3 to 5 VDC supply.

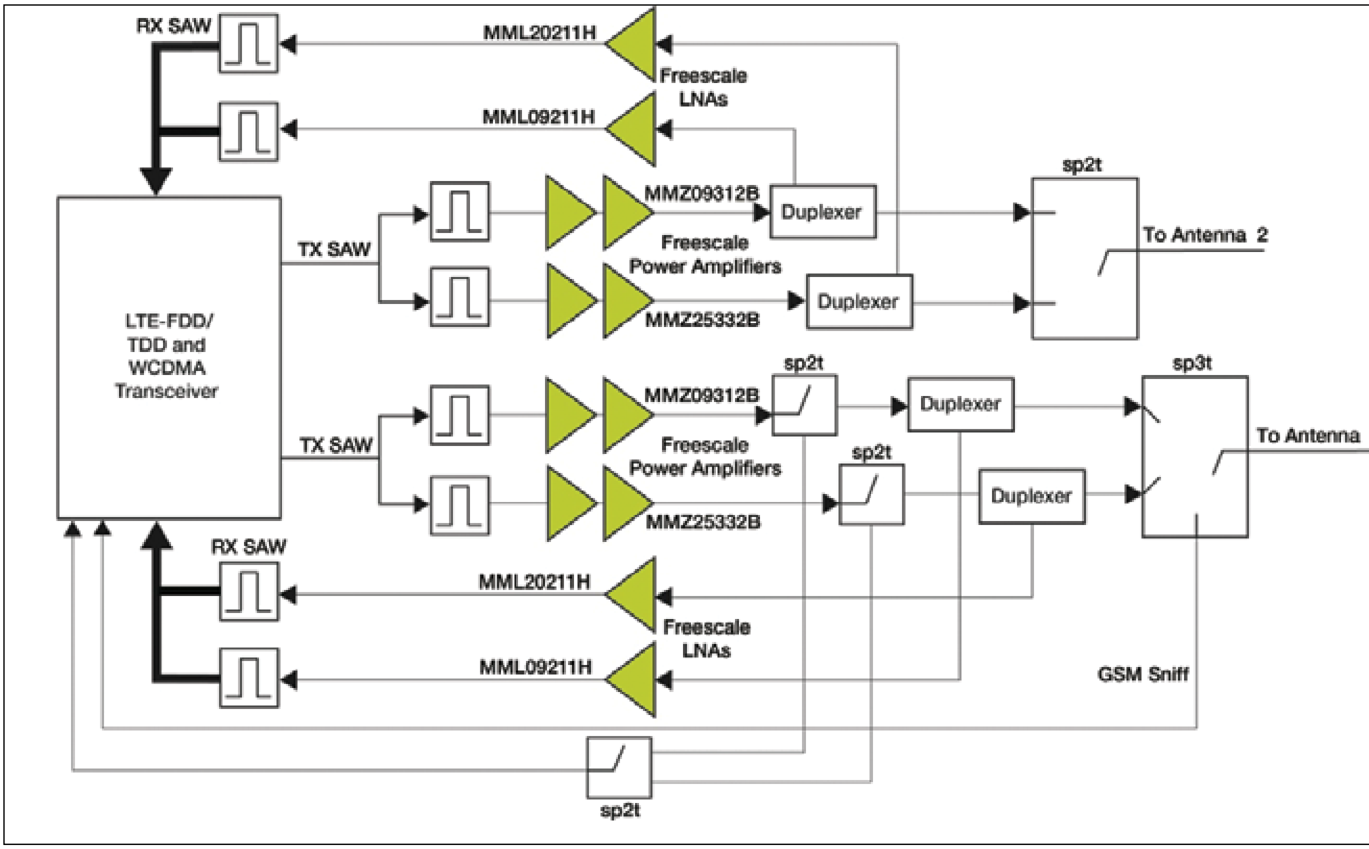

Figure 7 •The reference platform's dual-band RF front end showing Freescale's driver and final-stage amplifiers and low-noise amplifiers.

Summary

Although they perform similar function, small cell base stations differ from macrocells in ways that place significant demands on the designer. However, the ability to start from a reference design that addresses every system element from baseband through RF and microwave transmit and receive circuits, then adding differentiating features, reduces the time, cost -- and frustration inherent in building such a complex product in such a small enclosure. Additional small cell resources are available from Freescale at www.freescale.com/RFMMIC and www.freescale.com/BSC9131RDB.

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