Multimode RF transceiver advances WEDGE radio system

Wireless communications are evolving at an ever-increasing rate. Systems such as GSM, EDGE and CDMA are being augmented with 3G and Wi-Fi capabilities, making an efficient and cost-effective multimode solution essential. The RF transceiver is a key ingredient of any multimode solution. Its design presents several challenges that are magnified when distinctly different modes such as GSM and WCDMA must both be hosted. This article examines some of the challenges related to multimode transceiver design, and presents a highly integrated, multimode RF transceiver solution that addresses the needs of GSM, EDGE and WCDMA.

By James A. Crawford

Wireless standards necessarily pursue a dual path of consolidation and expansion, as if this were a law of nature. Market forces demand this. Wi-Fi solution providers were quick to integrate 802.11a/g with their 802.11b solutions. GSM solutions necessarily integrated EDGE. In the same manner, combined GSM-EDGE-WCDMA solutions are also unavoidable.

These same market forces drive the multimode aspect of transceiver design as well as the multiband perspective. Solutions that were acceptable for single- or dual-band applications may not be acceptable for triple- and quad-band service where external component cost and size become unacceptable. Transceiver designers must be increasingly forward-looking in anticipation of these factors, while at the same time employ measured restraint so that present customer demands are well served in the near-term. The discussion that follows focuses on attaining some of the more demanding requirements that are commensurate with a highly integrated GSM-EDGE-WCDMA transceiver solution, and the role these requirements play in transceiver architecture selection.

Receiver considerations

Industry-favored solutions for GSM-EDGE have converged to primarily one of two choices for the receive architecture: a) direct-conversion or b) low-IF. Aside from complexity and low-cost features that these architectures provide, several technical issues have warranted these choices.

GSM-EDGE requires IP2 performance on the order of 50 dBm or more when referred to the antenna input. This requirement amplifies the already challenging issues pertaining to dc offsets in the receiver. Direct-conversion receivers struggle with this problem more than low-IF receivers since the dc component falls directly within the receive bandwidth. The dc offset is also time varying because it is driven by dynamic adjacent-channel interferers. It also is affected by local oscillator (LO) leakage, low-noise amplifier (LNA) gain, and temperature.

CMOS designs must also contend with fairly severe 1/f noise in the sensitive IQ gain stages that immediately follow the down-conversion mixer. Detailed 1/f noise parameters depend significantly on oxide thickness and channel length. RF CMOS technologies in the 130 nm to 180 nm realm generally exhibit 1/f corner frequencies on the order of several hundred kHz, thereby making the low-IF architecture attractive for this reason. Issues of dc offset are not eliminated entirely with the low-IF architecture, but the severity is reduced.

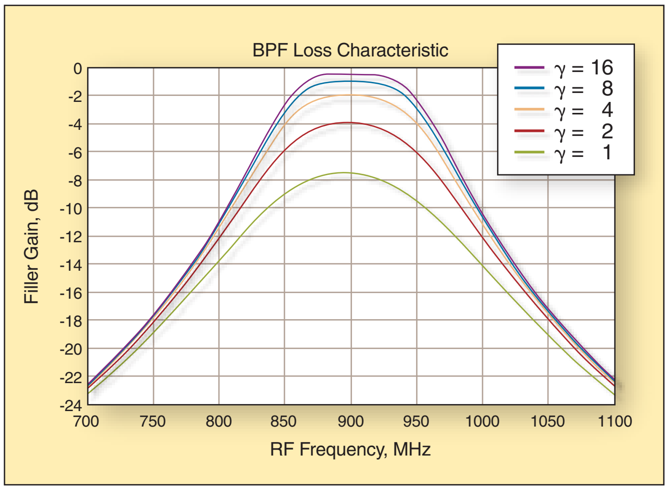

Figure 1. Example filter responses for a second-order bandpass filter with a filter-Q of 12 ($\gamma = Q_L / Q_{Fil}$).

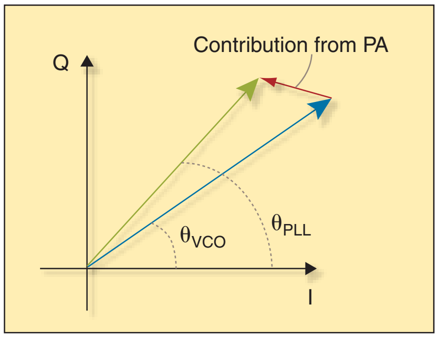

Figure 2. Re-modulation contributions from the PA to the VCO cause the desired VCO phase θ_{VCO} to appear as θ_{PLL} for on-channel designs.

Most WCDMA receivers have adopted the zero-IF architecture. Owing to WCDMA's much wider modulation bandwidth, dc offset issues are more easily addressed than for GSM-EDGE. The bandwidth argument also reduces the 1/f noise issue because (i) its impact on the overall receive signal-to-noise ratio (SNR) is considerably less, and (ii) this noise is spread across multiple chips of the WCDMA waveform where it can be effectively tracked out by the baseband signal processing if desired.

One of the major problems facing WCDMA receiver design pertains to transmitter leakage that falls through the duplexer filtering into

Harmonic / subharmonic	Q=5 dB	Q=10 dB	Q=20 dB
2	17.6	23.5	29.5
3	22.5	28.5	34.5
4	25.5	31.5	37.5
1/2	17.6	23.5	29.5
1/3	22.5	28.5	34.5
1/4	25.5	31.5	37.5

Table 1. VCO LC resonator suppression of harmonic and subharmonic contaminations.

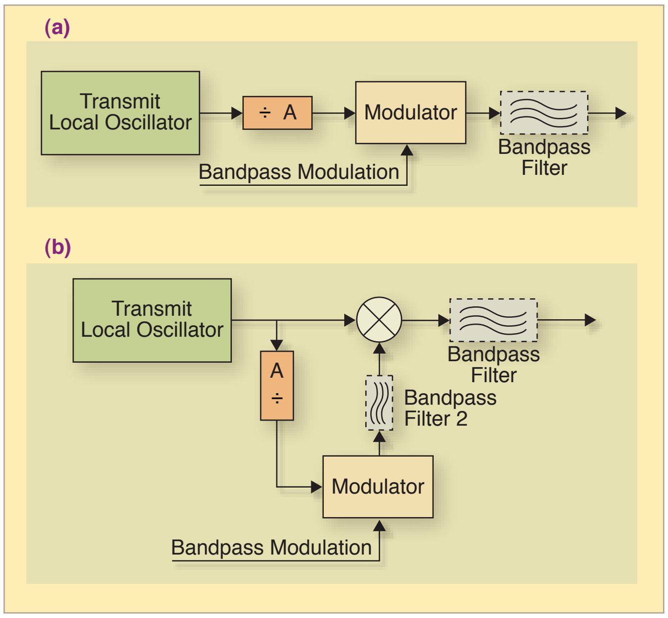

Figure 3. Off-frequency alternatives for transmit chain (a) using a digital divider or (b) frequency-offset.

the LNA input. This leakage adversely impacts attaining receiver IP2 and IP3 requirements, and normally requires band-specific SAW filters to be used between the LNA outputs and the mixer input. In WCDMA low-band, the transmit signal is offset from the receive signal by a scant 45 MHz whereas the offset is increased to 190 MHz for the IMT band near 2 GHz. These offsets combined with the required filter attenuation that is needed make the on-chip filtering option quite challenging. Since the filter follows immediately after the LNA, its insertion loss must be reasonable or else additional constraints are imposed on the LNA gain. As shown in Figure 1, the ratio of inductor-Q to filter-Q must be at least a factor of four in order to have a reasonably small insertion loss.

Transmitter considerations

One of the first questions that must be addressed in architecting the transmitter is whether the frequency synthesizer will operate on- or off-frequency relative to the PA output. On-frequency operation demands serious attention to oscillator pushing and pulling[1], and signal dynamic range can also be quite challenging particularly for WCDMA mode. Fully differential designs are almost mandatory for on-frequency architectures, particularly as die size continues to shrink and on-chip isolation is more difficult to obtain.

Oscillator re-modulation due to the PA is a particularly serious issue for on-frequency GSM-EDGE designs because a major portion of the modulation spectrum can fall within the frequency synthesizer's closed-loop bandwidth. Since the PA contributions coherently add with the oscillator's own sinusoidal waveform, the net phase error as seen by the phase-locked loop (PLL) cannot be nulled and near-chaotic behavior can result. The PLL believes that it is always behind or ahead in phase as suggested by the phasor diagram in Figure 2 and the PLL action exacerbates the problem further.

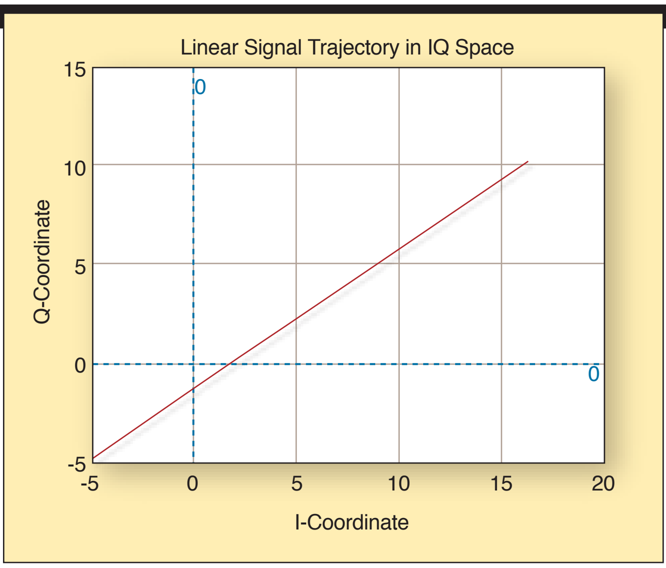

Figure 4. Example of straight-line signal trajectory in IQ space that comes near to the (0,0) origin.

Off-frequency designs can choose between (i) a divided-down synthesizer output and (ii) an offset-mix configuration as shown in Figure 3. The voltage transfer function of the oscillator's LC resonator falls off quickly with respect to harmonics and subharmonics thereby providing immediate relief from PA-related re-modulation. Several results are tabulated versus resonator loaded-Q in Table 1.

The bandpass filter shown in Figure 3(a) and BPF2 in Figure 3(b) should be considered optional depending on other detailed design considerations. Phase noise performance of the divider in Figure 3(a) is challenging for GSM-EDGE at frequency offsets greater than 20 MHz (on the order of -165 dBc/Hz). As far as traditional digital dividers are concerned, this normally requires rail-to-rail CMOS voltage swings along with careful design, but as CMOS technology migrates into the 90 nm realm, these performance levels are more attainable. Because of noise considerations, dividers must use a minimum number of active devices in circuit structures like differential cascade voltage switch logic (DCVSL)[5].

CMOS frequency dividers are ideally memoryless from one RF cycle to the next because they operate rail-to-rail. In contrast, a high-Q LC oscillator extracts only a small portion of the total stored reactive energy each cycle, and this is an important factor in achieving low-noise performance. Greater insight into the underlying differences is captured in Razavi's expanded definition of resonator Q based on phase-slope rather than energy storage[3]. These concepts make injection-locked dividers worthy of consideration, particularly for older process nodes where phase noise performance margins are slim.

The frequency-offset method shown in Figure 3(b) avoids most of the divider noise issues associated with Figure 3(a) in exchange for noise and linearity issues associated with the offset mixer. A single-sideband mixer is normally used to reduce the requirements for BPF1, which is present to reduce the unwanted sideband and LO feed-through from the mixer.

Challenging requirements

Few requirements for 3G transceivers are easy to achieve, but some requirements are certainly more difficult to achieve than others. The GSM-EDGE specification poses severe spectral requirements at 400 kHz and 20 MHz frequency offsets. Receive band noise is also a demanding requirement. Output spurious-tone performance often separates first-silicon from production-level silicon; spurs are always a serious challenge.

For WCDMA, dynamic range and error vector magnitude (EVM)

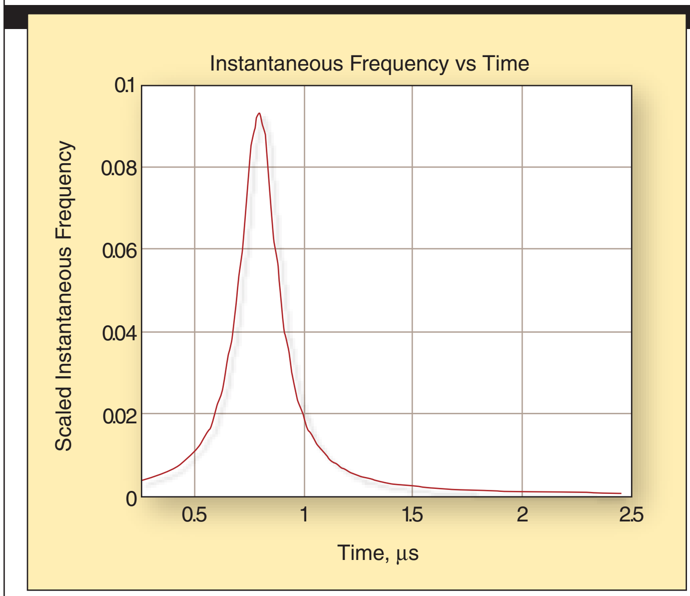

Figure 5. Instantaneous FM that results from the straight-line signal trajectory in Figure 4.

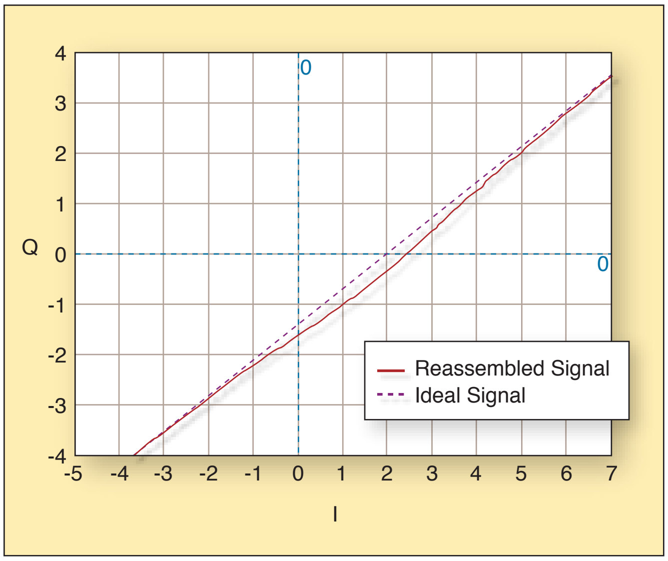

Figure 6. Reconstructed straight-line signal trajectory with first-order low-pass filtering of the instantaneous frequency deviation to accentuate signal error.

are frequently the pacing transmitter requirements that must be contended with. Modulation accuracy is increasingly difficult as more advanced signals like HSDPA and HSUPA come on the scene.

When it comes to design challenges, power consumption and die area cannot be left out of the discussion. Too frequently, these important product attributes are not accurately known until well into a design cycle where it is difficult to make mid-course corrections. Mid-course corrections are rarely localized to one or two small blocks in the design.

Polar transmitters

Polar transmitters exploit the one-to-one mapping that exists between the traditional signal description in (I,Q) rectangular coordinates and the equivalent description in polar coordinates (r,θ) where $r = (I^2 + Q^2)^{1/2}$ and $\theta = \tan^{-1}(Q,I)$. The major attractions to polar modulation are that (i) it is the preferred method for GSM and EDGE owing to its extremely low power spectral density at frequency offsets ≥ 20 MHz and attainable PA efficiency, (ii) its inherent ability to offer a unified means to extend the same architecture to more advanced waveforms like WCDMA, and (iii) its plausibility for extending these benefits through the entire transmit chain including the PA while also addressing the severe peak-to-average power ratio that accompanies more advanced transmission waveforms like orthogonal frequency-division multiplexing (OFDM). Even so, polar solutions are not without their own set of design challenges.

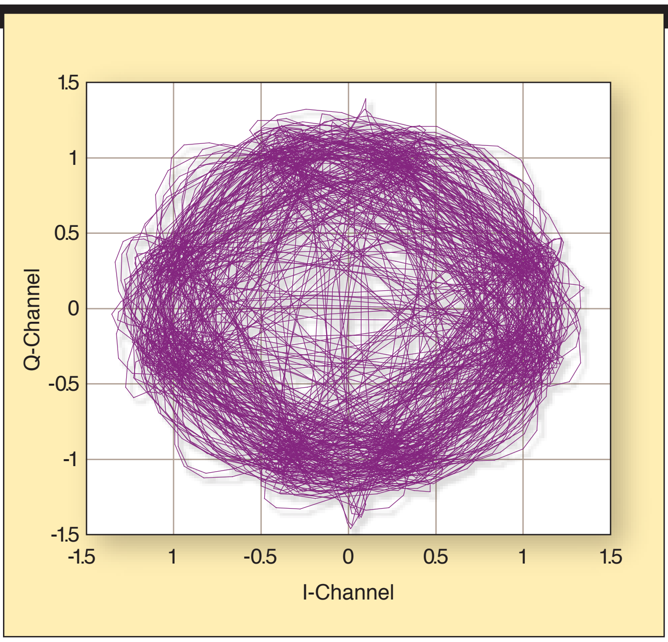

Figure 7. Example signal constellation for WCDMA.

When the original baseband modulation signal is described in terms of (I,Q) components, it is straightforward to show that the required instantaneous frequency deviation that is required in the equivalent polar-coordinate system is given exactly by

$$\frac{d\theta}{dt} = \frac{IQ' - QI'}{I^2 + Q^2} \tag{1}$$

where the apostrophes denote differentiation with respect to time. The lefthand side of the equation is equivalent to the instantaneous frequency required in rad/s and this result makes it possible to explore the peak-frequency deviation that is required in a polar implementation. It turns out that the most demanding signal trajectories in terms of peak-frequency deviation are those that pass near the origin of the (I,Q) signal space like the straight-line trajectory shown in Figure 4. The instantaneous FM that results from this straight-line trajectory is shown in Figure 5 and it becomes more δ-function-like as the path's minimum distance from the origin decreases.

Near-origin signal trajectories occur in the standard WCDMA signal constellation like those shown in Figure 7. Failure to properly handle signal trajectories that traverse near the origin normally have negligible effect on EVM (because the signal amplitude is low), but the impact on adjacent-channel noise can be substantial.

The δ-function-like instantaneous frequency behavior shown in Figure 5 is primarily responsible for the bandwidth expansion that is frequently attributed to polar modulation techniques. Although this expansion is fairly benign for GSM-EDGE because of its relatively low symbol rate and limited dynamic range (≈ 17 dB for EDGE), the demands imposed by WCDMA waveforms are considerably more severe in both regards.

Unless innovative measures are taken, most systems are unable to deliver the high peak-frequency deviations that occur for signal trajectories that come close to the origin. Normally, the magnitude and or the fidelity of the frequency deviations are compromised leading to poor out-of-band spectral performance as well as EVM degradation. In order to illustrate this point, the instantaneous frequency deviation (Figure 5) was strongly filtered with a first-or-

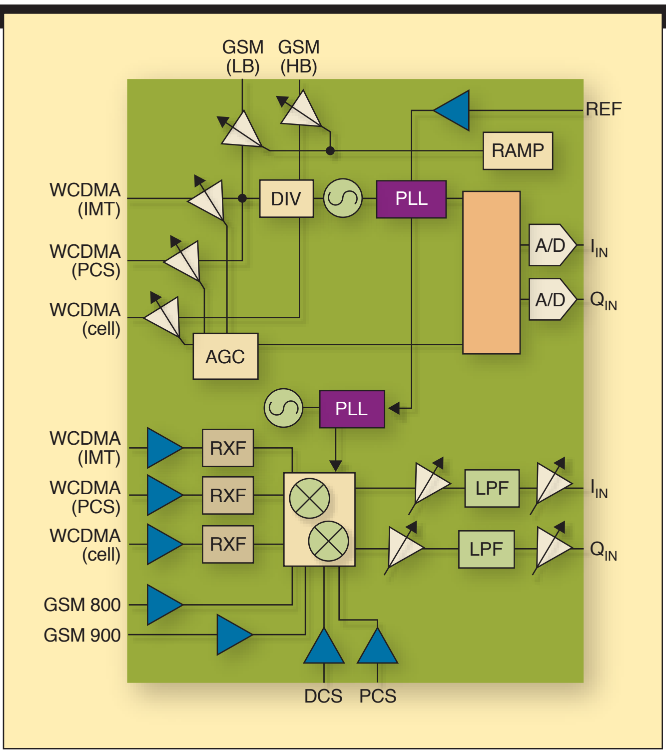

Figure 8. High-level block diagram of Sequoia's SEQ7400 GSM-EDGE-WCDMA tri-band solution.

der low-pass filter prior to AM-FM polar reconstruction. The strong filtering accentuates the pulse-like signal error behavior as shown in Figure 6. If allowed to occur, these signal errors degrade the out-of-band spectral performance substantially.

FM linearity is a second important performance requirement for any polar transmit scheme that directly modulates a voltage-controlled oscillator (VCO). If the instantaneous frequency versus applied control voltage is assumed to be modeled by a memoryless polynomial, it is easy to show that (i) accuracy of the first-order term is vital for achieving good EVM performance whereas (ii) accuracy of the other polynomial terms is necessary for good out-of-band spectral performance. These requirements are fairly reasonable to achieve for GSM-EDGE, but they require a substantially better solution to address the demands imposed by WCDMA waveforms.

Polar modulation entails breaking the (I,Q) baseband modulation signal into two paths (r and θ) that have distinctly different characteristics. Re-assembly of these signals at RF demands exacting time-alignment between the AM and FM signal paths. GSM-EDGE typically requires a time-precision on the order of 15 ns or better whereas the more extensive characteristics of WCDMA dictate more demanding requirements.

Integrated GSM-EDGE-WCDMA solution

A high-level block diagram of Sequoia's SEQ7400 GSM-EDGE-WCDMA tri-band solution is shown in Figure 8. It uses direct-conversion for receive with integrated filtering at RF thereby easing board-level integration issues substantially. No SAW filters between the LNA and mixer are required, and all GSM-EDGE-WCDMA LNAs are fully integrated on chip. The transmitter is based on Sequoia's patented FullSpectra common architecture that addresses all of the key issues discussed earlier. It eliminates many of the redundancies commonly found in other transceiver solutions that use separate transmit paths for WCDMA and GSM-EDGE. The high level of integration eases PCB integration with its concomitant low parts count while also reducing the cost of the overall solution.

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