 By David Marsh, Contributing Technical Editor

Direct conversion receivers battle superhets for GSM design wins

WITH TODAY'S EXPLOSIVE GROWTH IN MOBILE COMMUNICATIONS, HANDSET DESIGNERS ARE UNDER IMMENSE PRESSURE TO ACCOMMODATE NEW DATA-CENTRIC TECHNOLOGIES WHILE REDUCING MANUFACTURING COSTS. SUPERHETERODYNE RECEIVERS HAVE A LONG-ESTABLISHED REPUTATION FOR SELECTIVITY AND STABILITY BUT ARE NOT WELL-SUITED TO HIGH DEGREES OF INTEGRATION. CAN DIRECT CONVERSION RADIO RECEIVERS FULFIL THEIR PROMISE TO SIMPLIFY HANDSET ARCHITECTURES AND IMPROVE INTEGRATION POTENTIAL?

You can reach Contributing Editor David Marsh at forncett@compuserve.com.

Mobile telephony's meteoric rise looks set to continue with industry sources predicting a fourfold increase in users by 2010. Fuelling this growth, the underlying communications infrastructures are evolving from voice to data-centric systems to support new services such as mobile Internet access. Originally designed as a voice service, GSM (global system for mobile communications) is the world's most successful cellular technology by far - and still expanding fast, with 450million global consumers expected by the end of next year. Today, GSM is evolving to handle data services by adapting to packet switching with technologies such as GPRS (general-packet radio service) and EDGE (enhanced data for the GSM environment). Such "second generation-and-a-half" enhancements also pave the

way towards third-generation (3G) systems that are specifically designed for data handling, making the mobile data terminal a consumer-level reality (see reference 1).

With so much competition for consumer revenues, service providers routinely underwrite handset production costs against their expectation of a future revenue stream. Accordingly, handset designers must balance the service providers' demands for absolute lowest cost against consumer expectations. Consumers typically don't care how it works as long as it works, but are accustomed to their phones getting smaller, lighter, and lasting longer on a battery charge. Meanwhile, data-centric services demand ever more computational power, straining battery life. Against this background, handset designers are continually forced to re-evaluate key elements of their circuitry while also delivering products to market in tightening timescales.

Changing emphasis from voice to data transmission especially stresses the mobile's reception chain. Transmission is affected to a lesser degree because data exchanges are typically asymmetrical with higher reception rates than transmission. Asymmetrical data exchanges typify the Internet model, as you're far more likely to consume data than to generate it. It's also far harder to transmit than receive - especially within a mobile's power budget - so the asymmetrical model wins again. On the receiver side, data reception requires faster baseband circuits to handle decoding duties but standard submicron CMOS processes readily accommodate this requirement. But the radio receiver is an ultra high-frequency (UHF) linear circuit that's difficult to accommodate outside of exotic processes such as BiCMOS, gallium-arsenide (GaAs), or silicon-germanium (SiGe). Bulk CMOS still has problems at 2 GHz even in 0.18-μm technologies, principally due to noise and substrate coupling. These problems currently prevent the handset designer's dream of a single-chip 'phone from becoming a reality. But single-chip transceivers are becoming available that use varied receiver architectures and process technologies, reducing the phones' principal elements to two ICs.

SUPERHETS STILL HOT 80 YEARS ON

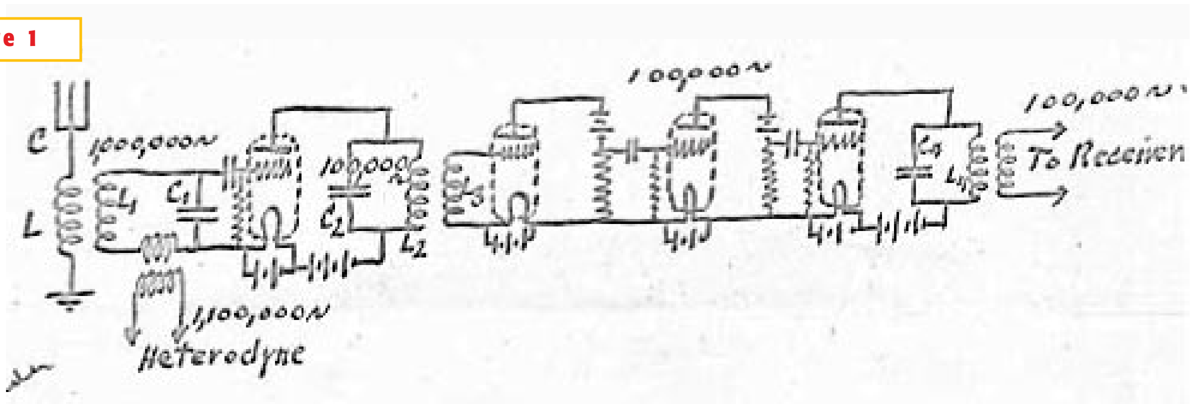
Designing a receiver for GSM is a complex task (see sidebar, Data sharpens GSM receiver specs). The classic radio receiver design is the superheterodyne (superhet) architecture that US Signals Corps officer Edwin Armstrong devised in 1918. In his design submission, Armstrong describes how to overcome signal reception difficulties with contemporary short-wave transmissions that were due to low signal strength and poor receiver selectivity. Before superhets, receivers followed the tuned-RF (TRF) model. A TRF receiver comprises a parallel tuned inductor/capacitor circuit that selects the broadcast frequency, followed by a diode and capacitor/resistor demodulator to recover the amplitude-modulated (AM) signal content. But when several transmissions occupy similar parts of the spectrum, selectivity is inadequate to reject adjacent stations. Also, the TRF circuit's gain changes with the frequency that it's trying to receive due to impedance changes when tuning the LC network. As the gain changes, selectivity can become so low that adjacent channels swamp the signal you're trying to recover.

AT A GLANCE

- ▷ Handset designers are under continual pressure to miniaturise and lower costs.
- ▷ Data services such as GPRS and EDGE stress the handset's receiver chain.
- ▷ Superhets are still highly competitive despite external filters.
- ▷ Direct conversion receivers are difficult to design but increasingly common.
- ▷ All receiver designs involve considerable compromise.

A superhet receiver translates transmission signal components to generate a new signal at a fixed intermediate frequency (IF). Shifting all incoming RF signals to one IF value lets you optimise receiver stage responses within a given bandwidth, so gain and selectivity become independent of broadcast frequency. To illustrate how his superhet design worked, Armstrong gave the example of downconverting a 1 MHz signal to a 100 kHz IF using a mixer. The mixer "heterodynes" a 1.1 MHz local oscillator frequency with the incoming 1 MHz signal to generate sum and difference frequency components, the output difference frequency being 100 kHz (see **Figure 1**). But superhets aren't problem free, and choosing an IF frequency plan is a compromise that routinely challenges RF engineers. The main design challenge involves image rejection. Harmonics of the local oscillator frequency combine to form "images" either side of the wanted signal, creating interference. Referred to as second-order input intercept point (IIP2) performance, the second harmonic dominates, but the third harmonic is also troublesome. A conventional mixer can't reject these images, so the standard solution filters image fre-

Figure 1



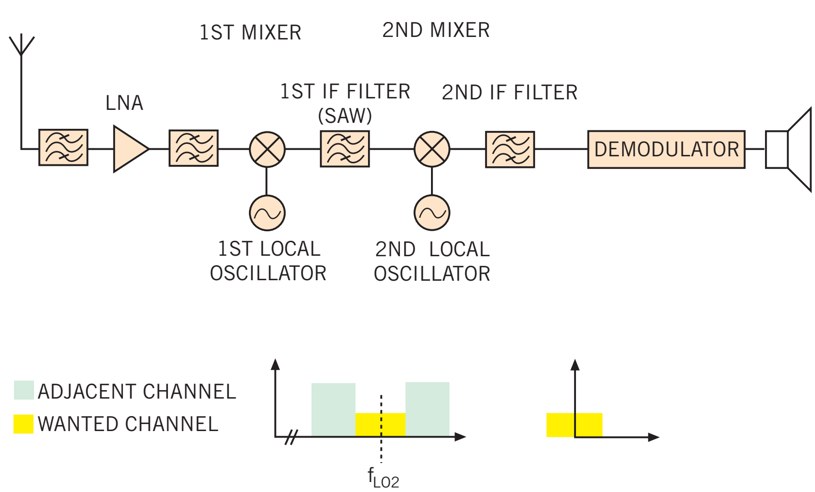
Edwin Armstrong's original drawing for his superhet design shows a 1.1 MHz local oscillator mixing 1 MHz RF down to a 100 kHz intermediate frequency (IF).

quencies at the RF amplifier stage. It's then desirable to have a high IF value to increase separation between images and wanted signals to make filtering easier. But choosing a very high first IF frequency stresses the power budget and complicates filter design at cellphone frequencies that already approach microwaves, so some compromise is always necessary.

Armstrong's superhet approach is so elegant that it appears in some form in virtually every receiver today. The receiver's ability to reject adjacent channels primarily depends on the IF amplifier's frequency response and gain. Multiple-conversion superhets ease filter responses by splitting downconversion from RF to baseband into two or more stages (see **Figure 2**). Dividing voltage gain among multiple stages also improves circuit stability. In a typical modern dual-conversion receiver, the first RF filter is a bandpass filter for the desired frequency range. A low-noise amplifier (LNA) provides RF voltage gain. The first local oscillator (a digitally controlled synthesiser) provides finer tuning by placing the wanted signal at the centre of the IF pass-band, potentially surrounded by adjacent channels. Both the LNA and the first mixer (a linear multiplier) must be highly linear to avoid intermodulation distortion due to multiple incoming signals that are separated by or near to IF frequency. The LNA also has to drive a filter with 50Ω input impedance, which can compromise the LNA's noise performance. The filter before the first mixer attenuates unwanted images, with optimum performance coming from balancing filter selectivity and the first local oscillator's frequency. The first IF filter is typically a surface acoustic wave (SAW) or ceramic device that provides most selectivity and rejects adjacent channel signals. The second frequency conversion stage shifts the signal down to a suitable frequency (typically centred on DC) and provides further filtering before demodulation recovers the signal information.

Superhets are justly popular in GSM applications and new designs continue to appear, such as National Semiconductor's LMX3411. The LMX3411 is a triple-band transceiver IC for worldwide use. The receiver part is a dual-conversion design that requires three sets of bandpass filters at the input to accommodate triple-band operation. But as William Keese, application manager at National explains, it's far less straightforward to devise a frequency plan that shares a single synthesiser between all three bands: "It's all about filtering and you still can't beat a SAW filter for quality. But you also want to use a common SAW for the IF to meet cost and space constraints." One approach is to choose an IF that supports low-side mixing for GSM-1800 and high-side mixing for GSM-1900, with a frequency divider accommodating GSM-900. This approach minimises the synthesiser's tuning range but results in an IF around 50 - 100 MHz. With a frequency band of 75 MHz for GSM-1800, the second harmonic image lies within the receive band for some reception frequencies. Another approach is to use an IF that's halfway between GSM-900 and GSM-1800/1900, resulting in an IF around 440 MHz. Here, the front end must provide very high isola-

Figure 2



Dual-conversion superhet receivers have excellent selectivity but require a costly and space consuming external SAW (surface acoustic wave) filter in the first IF stage (figure courtesy Philips).

tion between the GSM-900 and GSM1800/1900 bands. If a signal in the GSM-1800 band at the image frequency arrives at the mixer and couples into the GSM-900 path, the unwanted signal will convert to - and most likely dominate - the wanted signal. Also, SAW filters above about 300 MHz traditionally have poor temperature coefficient performance that limits selectivity, although recent advances address this problem.

National chose an IF around 250 MHz as the best compromise between filter selectivity and synthesiser tuning range. To provide accurate phase shifting and avoid in-phase/quadrature (I/Q) mismatches, the synthesiser runs at twice IF with a divide-by-two driving the mixer. The synthesiser's range is about 2050 - 2250 MHz providing high-side mixing for GSM1800/1900, and low-side mixing for GSM-900 via a divide-by-three circuit. To get sufficient isolation between bands, the LMX3411 uses two mixers, one each for GSM-900 and GSM1800/1900. Each mixer is a conventional Gilbert cell mixer followed by a multiplexer to share the same path to the SAW IF filter. For the second frequency conversion, there's a choice of going to another low IF and then sampling, or going directly to baseband as the LMX3411 does. Advantages of direct-to-baseband conversion include being able to use a cheaper IF SAW filter, because of the additional filtering at baseband before the major gain blocks. Gain and filtering are easier at baseband frequencies, and you need a lower sampling frequency for the baseband processor's ADCs. Also, baseband I/Q outputs are compatible with existing baseband ICs, so you don't need a custom IF sampling interface. Keese concludes, "The main disadvantage of direct-to-baseband conversion is handling DC offsets via compensation schemes. With a low-IF approach, you can employ AC coupling." Built in a 0.5 µm Bi-CMOS process, the LMX3411 is available now and costs $19.60 in 1k quantities.

Atmel is another company to recently announce a triple-band transceiver IC. The company's T0701 is designed to accommodate GPRS, as well as EDGE, in the receive path. Built in a bipolar process, the T0701 uses a 378 MHz IF centre frequency that requires an external synthesiser tuning range of about 8.5%. The device uses a three-wire serial bus for control and outputs standard I/Q baseband signals.

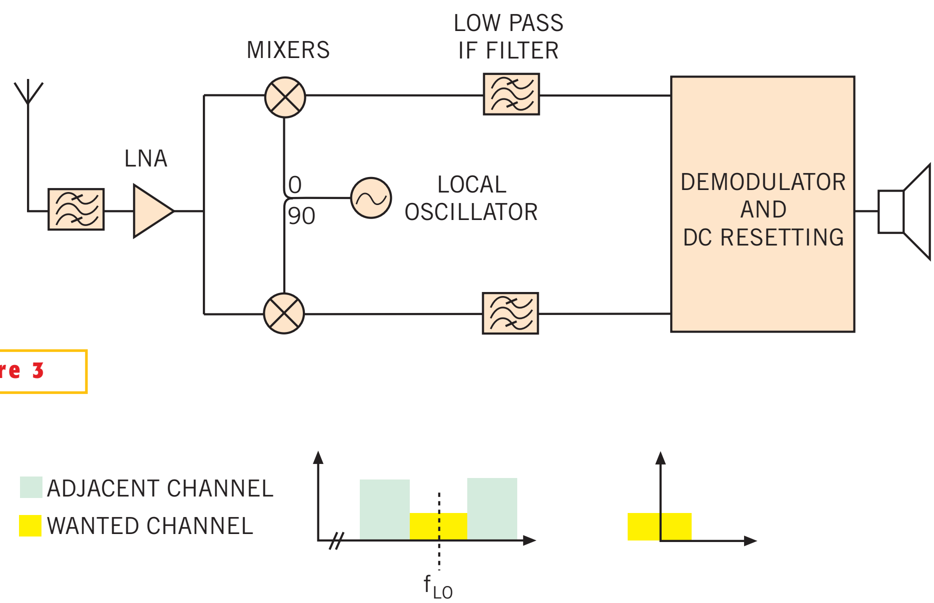
ZERO-IF KILLS IMAGES

Although the superhet offers excellent selectivity and stability, external filter stages are not well-suited to integration. Direct conversion receivers - also known as homodyne and zero-IF receivers - mix the incoming RF signal with an identical local oscillator frequency in a pair of I/Q mixers to generate a complex baseband signal (see **Figure 3**). Low-pass IF filters shape the baseband signal that's now at zero frequency (DC) before A/D conversion and demodulation in a digital signal processor (DSP). Mixing the signal down to DC folds the spectrum around zero frequency, producing positive and negative frequencies and dividing signal bandwidth in two. The I/Q mixer outputs preserve signal information by resolving the ambiguity in the received signal's instantaneous frequency. The frequency is positive if Q leads I; otherwise, the frequency is negative. Visually, the I and Q components represent the x/y co-ordinates of a vector in a transmission engineer's constellation diagram (see **Reference 2**). GPRS and EDGE data exchanges require especially accurate DC offset control because of the increase in the number of points on the constellation diagram and lesser distances between individual vectors.

Converting RF to baseband in one step avoids the superhet's image problems, dispensing with external IF filters and image filters. But this integration potential comes at a price and introduces problems that few vendors have overcome. Vendors including Analog Devices, Alcatel Microelectronics, Ericsson, Infineon, Maxim, Micro Linear, Nokia, Philips, STMicroelectronics, and Texas Instruments have, or soon will have, zero-IF technology. Of these vendors, Alcatel is a direct conversion pioneer and has produced some 30m zero-IF 'phones over the past nine years. Steve Beckers, Alcatel's wireless business unit director, notes that the company's MTC-70500 dual-band GSM transceiver reduces the VLSI chipset count, in the 'phone in which it was first used, from seven to just two - the transceiver and a baseband processor. Alcatel also uses direct conversion techniques in its ICs for Bluetooth and DECT (digitally enhanced cordless telephony) applications.

Key problems with direct conversion receivers include channel-select filter design and local oscillator frequency isolation. To keep noise low in an active low-pass filter, the resistor element needs

Figure 3



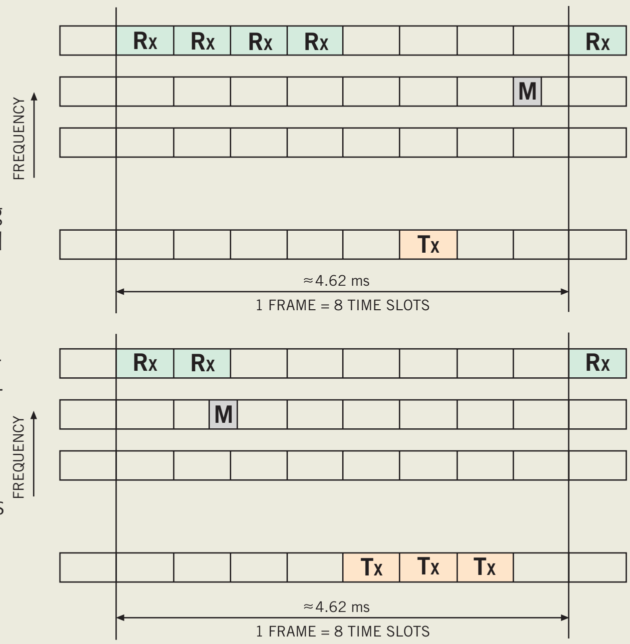
Direct conversion receivers eliminate the superhet's external SAW filter by down-converting the RF signal directly to zero frequency (figure courtesy Philips).

DATA SHARPENS GSM RECEIVER SPECS

The GSM standard specifies stringent receiver requirements that primarily relate to sensitivity, dynamic range, noise performance, linearity, and blocking signal performance. The minimum reference sensitivity is −102 dBm for the global frequency bands with 200 kHz channel separation, but most receivers offer better sensitivity for better reception range. But the receiver must also work with input signals up to −15 dBm, so you need about 90 dB of dynamic range. Digital signal processor performance largely determines noise performance requirements, with a 9 dB signal-to-noise ratio at the DSP input calling for a noise figure of around 11 dB for the whole front end. GSM specifies a two-tone test to evaluate receiver linearity with interfering tones of −49 dBm at 800 and 1600 kHz away from the wanted signal. In the presence of these tones, the receiver must correctly decode a wanted signal at −99 dBm. GSM also includes a set of blocking signal tests for receiver channel selectivity assessment. Two fading adjacent channel signals, 200 and 400 kHz away from the wanted signal, together with fixed-power blockers further away, stress channel selectivity and the receiver's ability to reject interfering signals as strong as 0 dBm.

As well as using 200-kHz channels for multiple access, GSM uses time-domain multiple-access (TDMA) modulation to divide each 4.615-msec transmission frame into eight 577-μsec timeslots. Potentially, up to eight users can share one frequency for a spectral efficiency bandwidth equivalent to 12.5 kHz/channel. The modulation method is Gaussian-filtered minimum-shift keying (GMSK). The GSM waveform is a succession of multi-frames, each containing 26 frames; 24 frames carry traffic and frames 13 and 26 provide control information. To encode speech, GSM quantises the audio waveform into a 13-kbps stream and arranges the data in 20-msec blocks, each containing 260 bits. The transmission encoder splits the 260 bits into the 182 most-significant bits and 78 least-significant bits before adding 196 forward-error correction bits to the MSB portion. The encoder than splits the resulting 456 bits into eight 57-bit sub-blocks that are interleaved and redistributed within the timeslots. Each block of 456 bits requires four timeslots but with redistribution, the 456 bits are spread across eight timeslots and eight frames. Adding forward-error correction and temporally redistributing the data guards against random and impulse noise errors.

GSM requires the receiver to monitor signal strength and report a received signal strength indication (RSSI) back to the basestation for transmission power management. The receiver can adjust itself to compensate for fading signals and request a handover to another frequency if signal strength is too low. This "frequency hopping" can occur once per frame for a worst-case hop rate of 217 Hz. To support handovers, GSM periodically resynchronises basestations in the cellular group by reading adjacent broadcast control channel information during the idle 26th frame. In the handset, therefore, the receiver is much more active than the transmitter as it has to continually monitor control information. The receiver must also equalise received signals to compensate for multi-path reflections that are a feature of working at GHz frequencies and that worsen if the mobile handset is, in fact, moving. GSM requires the receiver to equalise distortion that multi-path reflections cause for a time difference of 4 bit-periods, or about 15 μsec. A 26-bit training pattern is transmitted during each timeslot to permit active equalisation.



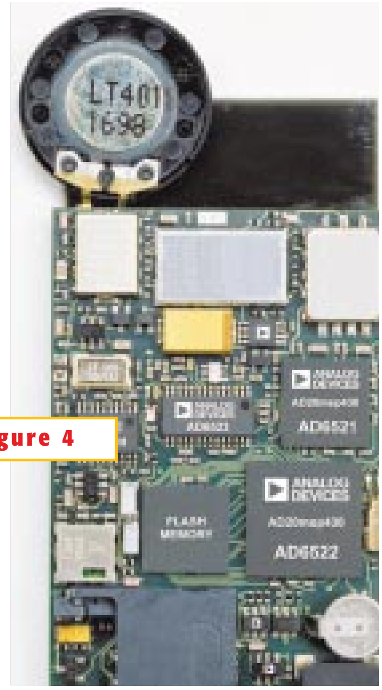
GPRS class-12 operation permits four transmit and four receive timeslots but system overheads limit data exchanges to five timeslots per frame.

Enhancements to GSM for data reception provide further design challenges. For voice use, the handset receives during one timeslot and transmits three timeslots later, so the handset never transmits and receives at the same time. With a maximum distance of 35 km between basestations, the handset's synthesiser has approximately 900 μsec to switch from one frequency to another and synchronise with a new cell. Data services such as GPRS enable multi-slot operation, where sequential timeslots combine to improve GSM's standard 9.6 kbps data rate. GPRS specifies some 29 operational classes that theoretically support data rates up to 384 kbps. These classes subdivide into type-1 and type-2, where type-2 mobiles are capable of simultaneous transmission and reception. Because type-2 mobiles require costly re-engineering, it's likely that type 1 mobiles will dominate, using class 8 (4-Rx/1-Tx timeslots), class 10 (4-Rx/2-Tx) or class 12 (4-Tx/4-Rx) operation. The timeslots need not be contiguous, but because of system overheads, any of these class options supports 5 timeslots per frame (see **Figure A**). GPRS reserves a free frame before synchronising to an adjacent cell and doesn't require adjacent cell signal level monitoring. Now, the handset's synthesiser has half a timeslot (288 μsec) in which to change frequencies. Fractional division and high comparison frequencies in the phase-lock loop (PLL) speed synthesiser tracking and reduce in-band PLL noise, reducing phase errors well below GSM's maximum of 5 degrees RMS. Fractional division synthesiser ICs such as Philips SA8026 switch in about 180 μsec, leaving some 100 μsec margin for other system elements.

to be as low a value as possible, which then requires a large capacitor. As IC capacitors are metal-to-metal devices, they occupy substantial and expensive die space. You also get less selectivity from an integrated active filter than from external passive devices so channel selectivity can be a problem. Power consumption can suffer too, because the active filter's extra noise requires compensation from a highly linear low-noise front-end that's relatively power hungry. But the direct conversion receiver's biggest problem relates to isolation. Any leakage in the local oscillator frequency that couples into the mixer is at the same frequency as the wanted signal, so the local oscillator component mixes down as a DC term that appears as a baseband blocking signal. Leakage can come from numerous sources, such as through the IC's bond wires and substrate, and can couple back into the receiver's front-end. The user can contribute to the leakage path as the HF radiation couples through the body and back to the receiver's antenna, creating a varying DC offset that's very difficult to compensate. This self-mixing interference can also worsen with movement due to varying reflections between the antenna and surrounding objects.

Tackling the direct conversion receiver's problems requires a mixture of approaches that currently demand mixed-process technology. Alcatel's BiCMOS technology combines analogue, digital and RF elements on a single chip using four-layer metal interconnections. Analogue components for building active filters include metal-to-metal capacitors with values around 1 $fF/\mu m^2$ and tolerances of $\pm$20%. Filters need accurately matched components and the process matches capacitors to 0.25% and polysilicon resistors to better than 0.5%. The optional fourth thick metalisation layer also permits 2-μm deep on-chip inductors. The bipolar element builds n-p-n transistors with polysilicon emitter and base components that provide transition frequencies above 20 GHz; lateral p-n-p transistors are also available. The CMOS part is similar to standard self-aligned 0.35-μm processes and offers a 30 - 35% speed improvement over 0.5-μm processes. To suit the RF environment, the CMOS elements are optimised for analogue performance with poly-buffered local silicon oxidisation to reduce leakage currents.

Figure 4



Analog Devices' direct conversion reference design packs about 90 components on a single side of a 35×57 mm pcb.

Alcatel's MTC-70500 includes separate mixer paths for each GSM band. A single voltage-controlled oscillator (VCO) running at around 1800 MHz generates the local oscillator frequency. The VCO is external but the chip integrates the synthesiser, which includes a divider for GSM-900. Variable-gain amplifiers and an automatic gain control (AGC) loop normalise the I/Q signals after mixing to a common level for subsequent processing. Francois Humbert, the company's GSM line manager, explains that the design includes a two-stage approach to controlling DC offsets: "The first stage is an analogue correction directly after downconversion that uses trim DACs to roughly subtract DC errors. After analogue-to-digital conversion, we employ an algorithm to remove the remaining offset errors in hardware." Continuous-time filters at the ADC inputs pre-filter useful signal content. Humbert observes that the toughest challenge is building an ADC with the dynamic range to support the digital correction. Each signal path has about 90 kHz bandwidth, which the MTC-70500 oversamples at 6.5 MHz using a 14-bit ADC: "Dramatic improvements in ADC dynamic range are the key to realising zero-IF's benefits. High-resolution ADCs allow us to handle the DC offset in the digital domain, which always beats analogue domain solutions."

With the announcement of its "Othello" chipset late last year, Analog Devices was first to openly market a direct conversion transceiver for GSM. The company's dual-band AD6523 integrates the LNA front-end and dispenses with the image-reject filter, saving at least 15 components compared with an equivalent superhet approach. The LNA is the major gain element so subsequent noise

FOR MORE INFORMATION...

For more information on receiver ICs for digital data services such as those discussed in this article, enter the appropriate numbers at www.edn-info.com. When you contact any of the following manufacturers directly, please let them know you read about their products in *EDN Europe*.

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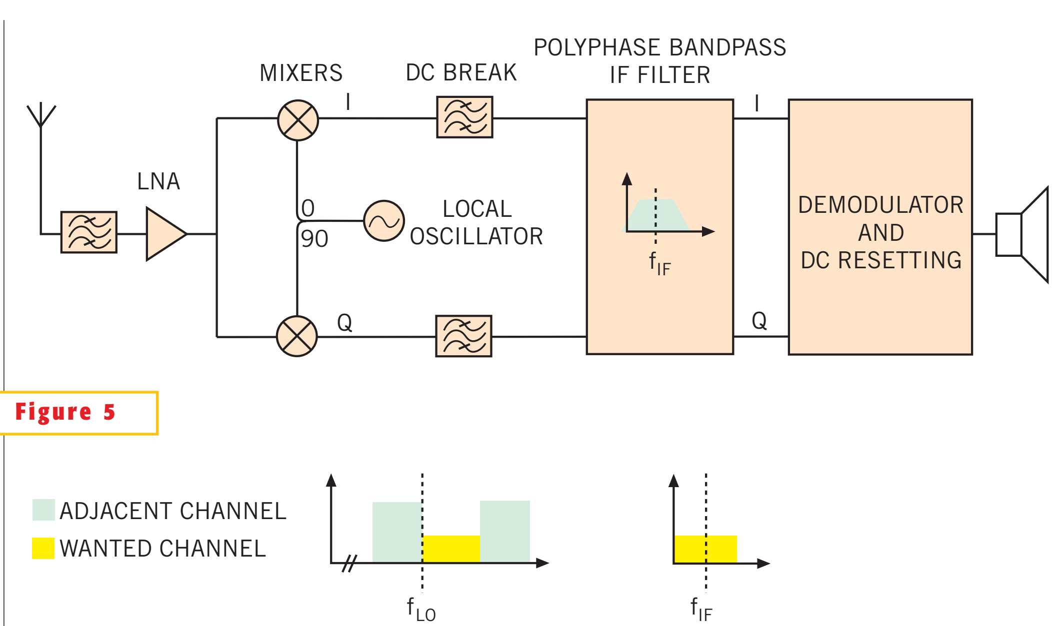

Figure 5

Philips' near-zero IF architecture eliminates the external IF filter and prevents DC errors with a DC break in the IF path (figure courtesy Philips).

contributions are essentially at system floor noise level. The I/Q mixer outputs feed variable gain baseband amplifiers that help filter adjacent channels and in-band blocking signals. The tricky local oscillator's centre frequency is about 1350 MHz to fall halfway between GSM-900 and GSM-1800. As the basic local oscillator frequency is distant from either band, front-end filters attenuate radiation to suppress DC offset errors. Doug Grant, business development director at Analog Devices, elaborates: "We tackle local oscillator RF leakage with an on-chip regenerative divider that's converted by 2/3 or 3/2 the VCO frequency to get to 900 or 1800 MHz. This approach minimises radiation to the RF port since there are no pcb tracks forming an antenna for the VCO to radiate. Other steps are also necessary to obtain adequate performance. For example, the signal path is differential wherever possible and we use precision analogue design and layout techniques throughout. This step helps attenuate the second-order intermodulation distortion that non-linearities create within typical direct conversion receivers. We also control mixer offsets with on-chip trim DACs controlled by the baseband controller and software, and our baseband processing algorithms gain a few extra dB of dynamic range." Analog's reference design uses about 90 components on one side of a 35×57 mm pcb, compared with an estimated 225 components for a comparable superhet design (see **Figure 4**). Built in BiCMOS, the AD6523 and its companion AD6524 synthesiser will reach full production late this year and will cost around $6 in 100k quantities.

LOW-IF PRESENTS ANOTHER OPTION

You might wonder if it's possible to combine the superhet's resistance to DC offsets with the direct conversion receiver's lower component count and image rejection capabilities. Such a receiver is called a low-IF design, where the RF is downconverted to a relatively low frequency. Philips uses its "near zero-IF" (N-ZIF) technology to tackle DC offset problems in its UAA3535 triple-band transceiver IC (see **Figure 5**). The UA3535 supports GPRS class 10 data exchanges, with four transmit and two receive timeslots. The IC's designers considered DC offset subtraction schemes but rejected this approach because of the level of complexity required to obtain adequate performance. Mike Barnard, wireless communications group leader at Philips Research, notes: "You're facing continuously changing DC offset levels, particularly in the presence of strong AM interferers. GSM itself can cause similar headaches because its bursty nature has much the same effect as AM blocking signals." The basic N-ZIF premise is to downconvert RF to a low frequency - in this case 100 kHz, or half GSM's channel spacing - to allow AC coupling to remove unwanted offsets. The major downside to the low-IF approach is that you now need an ADC with twice the bandwidth of a zero-IF design, together with additional baseband processing to cope with the low-IF frequency. The channel-select filter becomes a complex design task because its frequency response now centres on 100 kHz and is no longer symmetrical around zero. The low-IF signal also contains interference from adjacent channels and low-level image components. To restore adequate filtering, the UAA3535 employs integrated polyphase filters that obviate the need for external devices. These filters process the mixer's I/Q outputs as a complex pair to discriminate between the wanted signal and adjacent channel interferers. The filter design comprises a pair of identical ladder networks that cascade capacitors and gyrators. In between each network, another set of gyrators connects to opposite capacitor pairs to shift the filter's frequency response upward from zero. The filter's frequency response is shaped to be broadly Gaussian to suit GSM's modulation scheme, with adjustments to meet in-band and adjacent channel interference rejection. A further feature of the UAA3535 is the use of logarithmic compression after the polyphase filter. The compression stage dispenses with the need for AGC loops and increases the efficiency of the incoming frequency translation, reducing the ADC's dynamic range requirements. □

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2. Marsh, David: "GSM phones threaten professional radio", EDN Europe, May 1999.