

# Base Station Receiver Design Using a Direct-Conversion I/Q Demodulator

by James Wong, Min Zou, Doug Stuetzle and Sunny Hsiao  
Linear Technology Corporation

This new I/Q demodulator IC supports high dynamic range applications with performance that has previously required designs using discrete devices

Direct conversion (or low IF) receiver designs have been in existence for many years. They are widely used in cell phones and cordless telephones because of their simplicity and lower cost. Direct conversion receiver ICs have only recently met the level of performance required for base stations. However, the relentless drive to reduce the cost of next generation base stations compels attention to direct conversion architectures which offer a flexible approach to cover multiple RF standards and to simplify system design. Many benefits accrue from pushing channel selection into the baseband digital domain, particularly for multi-standard receivers. A problem with this approach, however, is its susceptibility to interfering signals that are in-band to the receiver. This necessitates that the I/Q demodulator used in the direct conversion receiver is able to handle demanding dynamic range requirements that can be as high as 80 dB. This article reviews the issues specific to direct conversion receivers for base station applications, and describes a new RF direct conversion IC that takes great strides in resolving these issues.

A new generation demodulator such as the LT5575 from Linear Technology makes it possible to exploit the advantages of the direct conversion receiver architecture. The LT5575 integrates the functionality of an LO precision quadrature phase splitter and two high linearity downconverting mixers. The integrated on-chip broadband transformers provide user-friendly 50 ohm single-ended interfaces at



Linear Technology's LT5575 I/Q demodulator provides the high dynamic range performance needed for direct-conversion base station receivers.

both the RF and LO ports while still maintaining excellent RF-to-LO isolation and minimum LO-to-RF leakage across a wide RF operating frequency range. A single-ended RF signal is applied to the primary side of the on-chip RF transformer and is converted into a differential signal at the inputs of the integrated RF signal splitter. The chip directly down-converts the RF signal to baseband, while separating the in-phase (I) and quadrature-phase (Q) signal components. The matched I and Q channels ensure precise gain and phase matching. The LT5575 operates over the input frequency range of 0.8 GHz to 2.7 GHz. The chip also integrates single-pole, low pass filters with 490 MHz bandwidth on each of the I and Q channels. The typical RF performance of the LT5575 is summarized in Table 1.

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RF Frequency Range	800-2700 MHz			
BB Frequency Range	DC-490 MHz			
Test Frequency (MHz)	900	1900	2100	2500
Conversion Gain (dB)	3.0	4.2	3.5	2.0
NF (dB)	12.8	12.7	13.6	15.7
IIP3 (dBm)	28.0	22.6	22.7	23.3
IIP2 (dBm)	54.1	60.0	56.0	52.3
I/Q Gain Mismatch (dB)	0.03	0.01	0.04	0.04
I/Q Phase Mismatch	0.5°	0.4°	0.6°	0.2°
LO Leakage at RF Input (dBm)	-60.8	-64.6	-60.2	-51.2
RF to LO isolation (dBc)	59.7	57.1	59.5	53.1
Output DC Offset Voltage	-	<9 mV	-	-
Offset Voltage vs. Temp.	-	39 $\mu\text{V}/^\circ\text{C}$	-	-

Table 1 · LT5575 performance highlights (@ P<sub>LO</sub> = 0 dBm).

The LT5575 is designed for applications where high receiver linearity is required. These include wireless base stations (for GSM, CDMA, WCDMA, etc.) and wireless infrastructure such as WiMAX and broadband microwave links, as well as RFID applications. The device is particularly suited for single-carrier micro- and pico-cell base stations where the cost benefit from its direct conversion architecture is even more pronounced. Direct conversion receiver ICs eliminate the need for additional intermediate frequency (IF) stages, and relax the demands on high frequency filters, especially by eliminating the IF channel-select filter. With its +22.6 dBm input 3rd-

order intercept (IIP3) and +60 dBm input 2nd-order intercept (IIP2) at 1900 MHz, this direct conversion receiver meets the strict dynamic range requirements of base station receivers.

**Direct Conversion Receivers Introduce a Different Set of Design Issues**

The block diagram of a direct conversion receiver, as it might be used in a W-CDMA base station application, is shown in Figure 1. There are several considerations with this design that distinguish it from multi-stage receiver designs. These can be summarized as: (1) DC offsets, (2) vulnerability to 2nd order distortion,

(3) increased sensitivity to port-to-port coupling, (4) I-Q mismatch, and (5) requirement for proper high frequency termination of the baseband outputs.

**DC Offsets**

DC offset voltage at the I or Q outputs of the I/Q demodulator (i.e., non-zero DC output voltage when there is no RF signal) can be a problem for DC-coupled receiver designs due to subsequent amplification by the baseband amplifiers. If the DC offset voltage is too large, then it can limit the baseband amplifier signal swing and degrade the dynamic range of the baseband A-D converters. DC offset can arise from mismatches in the I/Q demodulator itself. The LT5575 realizes a typical differential DC offset voltage of <9 mV at the I and Q outputs, which is low enough to allow up to 40 dB of baseband voltage gain in the architecture of Figure 1, without the need for AC coupling or DC offset cancellation.

DC offsets can also be generated from self-mixing of the LO signal due to LO-RF coupling, or from self-mixing of the RF signal due to RF-LO coupling. Particular attention must be paid to the PC board layout to preserve the isolation between the RF and LO inputs (more on this in the IC Layout Consideration section later in this article).

**Second Order Distortion**

For a conventional superheterodyne receiver, third order distortion is dominant, producing intermodulation terms of the form  $\cos[(2\omega_i - \omega_j)t]$ , which may be in-band, depending on the frequencies of the interfering signals. For direct conversion receivers, however, second order distortion can also play an important role in limiting performance. That's because 2nd order distortion contributes a baseband term of the form  $\cos[(\omega_i - \omega_j)t]$ . This term is out-of-band for a superheterodyne receiver, but is likely to be in-band for a direct conversion design.

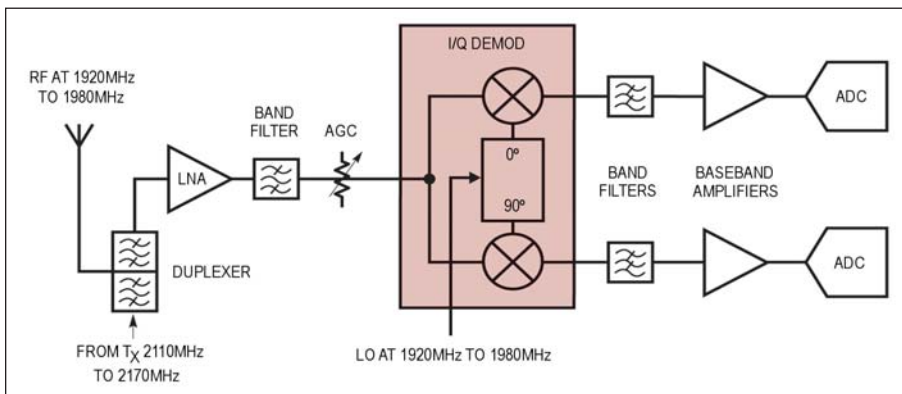


Figure 1 · Example direct-conversion receiver for a W-CDMA application.

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In an actual application, 2nd order distortion can become a problem in the presence of a single strong nearby interferer. Because channel selection is performed at baseband, and usually in the DSP, even those interferers which are not “on-channel” may still pass freely through the RF and baseband filters. These interferers are then more likely to produce unwanted products that fall directly on top of the desired baseband signal, at which point they cannot be filtered out. Second order distortion is most troublesome in this regard, because it can yield such products as a result of even a single interfering signal.

Specifically, 2nd order distortion due to a tone interferer will give rise to a DC offset at the mixer output. If the interferer is modulated, then a modulated signal due to 2nd order nonlinearity will appear at the baseband output. The second order intercept point (IP2) of a direct conversion receiver system is therefore a critical performance parameter. It is a measure of second order non-linearity and helps quantify the receiver's susceptibility to single and two tone interfering signals. The LT5575 minimizes the impact of 2nd order distortion due to its exceptionally high IIP2, 60 dBm at 1900 MHz and 54 dBm at 900 MHz.

#### Port-to-Port Coupling

In a superheterodyne receiver, careful selection of the LO and IF frequencies can usually minimize the resultant mixing products in the IF passband that arise from port-to-port coupling. No such protection is afforded with the direct conversion receiver architecture, where the RF and LO frequencies are nearly the same, and where their mixing products appear directly at the baseband I/Q outputs, as described previously. The LT5575 specifies LO-RF leakage of -60 dBm or better (to 2100 MHz), and RF-LO suppression of 57 dBc or better, which largely eliminates this concern.

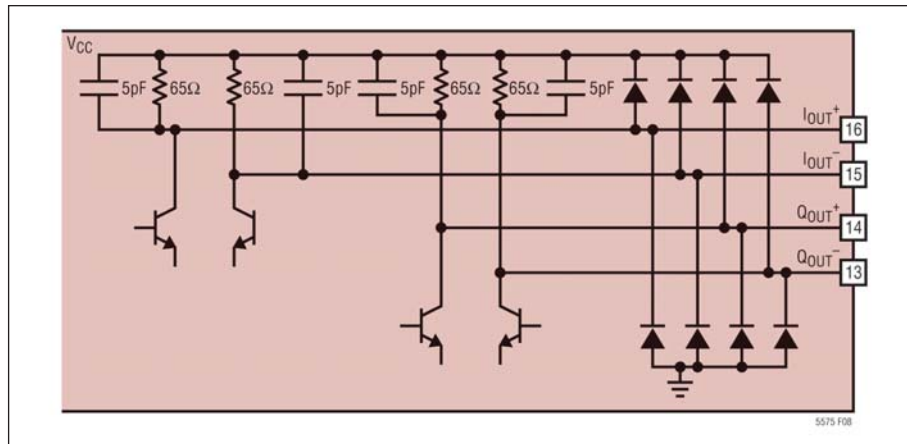


Figure 2 · LT5575 I/Q output equivalent circuit.

#### I-Q Mismatch

Ideally, the I and Q channels of a radio signal carry orthogonal, i.e., non-interfering, channels of information. However, mismatch in the gain or phase of the I and Q channels results in interference between the channels, which makes it more difficult to recover the information they contain. Modern digital communication systems specify a maximum Error Vector Magnitude (EVM), typically on the order of a few percent, which can be related to the gain and phase mismatch error of the I/Q channels. Phase mismatch error, which arises from unequal time delays in the I/Q signal paths, from inaccuracy in the LO quadrature generator, and from port-to-port coupling is particularly problematic. The higher the frequency, the more severe is the phase error problem. This is why I-Q mismatch is more of an issue for direct conversion receivers, which operate at the RF frequency. The LT5575 specifies a typical phase error of 0.5°, and a typical gain error of 0.04 dB, which results in an EVM penalty of about 1% for QPSK-type modulation formats.

#### High Frequency Termination of the Baseband I/Q Outputs

One key advantage of the direct conversion architecture is that it eliminates the classical image rejection

problem. This is because there is no longer an image frequency that will yield a mixer output signal at the desired baseband frequency. There is, however, still an unwanted product that will be generated by even a perfectly linear mixer. This signal is the sum of the RF and LO frequencies, and it will appear at the mixer output well above the baseband frequency. Consider for example a 1900 MHz RF application; the LO frequency will also be at 1900 MHz. The desired output at baseband will be accompanied also by a signal at 3800 MHz, which is the sum of the RF + LO frequencies. It may seem obvious that the baseband filters following the mixer will completely suppress this sum product—well, maybe not. Any integrated circuit uses internal wire bonds to connect the IC chip to the terminals of its package. These wire bonds act as small inductors which at high frequency tend to isolate the chip from any external filtering elements. If no on-chip filtering is used, then the sum frequency signal as well as high frequency distortion products will manifest themselves on-chip in unpredictable ways. Most importantly, any improperly terminated high frequency signals will consume the signal headroom of the chip, causing degradation of the chip's intrinsic linearity. Figure 2 shows the equivalent output circuit



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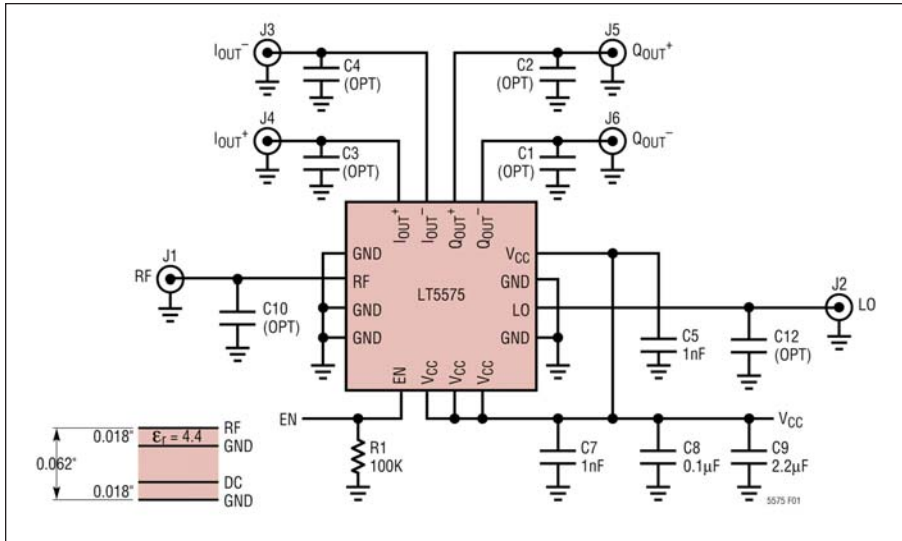


Figure 3 · Evaluation circuit schematic diagram.

of the LT5575, which contains on-chip 5 pF capacitors on each of the  $I_{OUT+}$ ,  $I_{OUT-}$ ,  $Q_{OUT+}$  and  $Q_{OUT-}$  outputs. These on-chip capacitors, augmented by off-chip termination capacitors as needed, serve to mitigate the Image problem and optimize linearity for any given application.

More detailed discussion of many of these factors and others can be found in [1].

IC Layout Considerations

Because of the aforementioned issues, the actual receiver implementation requires optimum placement of the direct conversion demodulator IC and its external components, as

well as careful RF layout of the printed circuit board (PCB). Special attention should be given to power supply decoupling, grounding, signal path routing, and high frequency termination of the baseband ports.

Linear Technology's Demonstration Circuit DC1048A (Figures 3, 4, and 5) illustrates proper implementation of the LT5575 direct conversion I/Q demodulator IC as it might be employed in a high performance receiver application. The evaluation board uses 4 layers of commonly available FR-4 PCB materials with a total thickness of 62 mils. Layers 1 and 2, and layers 3 and 4 are separated by 18 mils of dielectric material.

To ensure stability and maintain performance, all  $V_{CC}$  pins must be decoupled from the power supply using bypass capacitors placed as closely as possible to the designated  $V_{CC}$  pins. For the LT5575,  $V_{CC}$  pins 6, 7, and 8 are decoupled using one 1000 pF and one 0.1  $\mu$ F capacitor to ground, while  $V_{CC}$  pin 12 has its own 1000 pF decoupling capacitor. A 2.2  $\mu$ F bypass capacitor is optional.

As with all high frequency circuits, proper grounding is essential for optimum performance. Use conservative layout with solid, uninterrupted ground planes on the top and the second PCB layers. Apply plated through-hole vias liberally to connect ground planes on all PCB layers, especially along plane edges. Avoid "floating" copper fills as they can act as RF resonators and antennas. The exposed IC back side ground pad is the ground return for the chip and provides heat sinking, and it must be soldered directly to the PCB ground plane for optimum performance. Adding several plated through-hole vias directly under the ground pad will ensure a good electrical ground and promote thermal conduction.

As mentioned previously, RF and LO coupling can lead to "self-mixing," causing undesirable signals as well as DC offset errors to appear at the baseband outputs, and may degrade IP2 performance. Also, large in-band RF interference signals that leak to

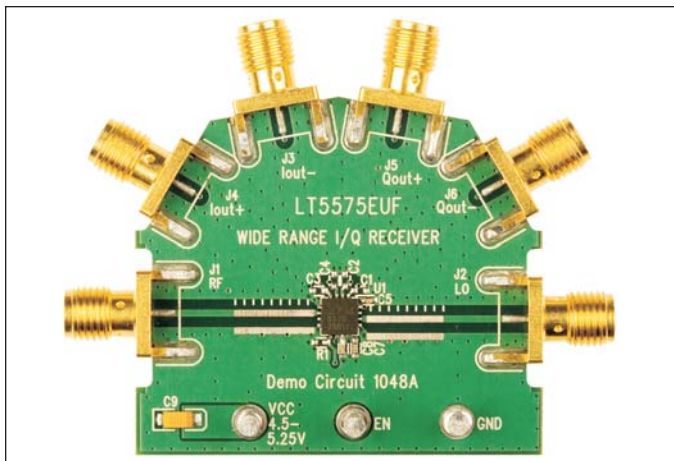


Figure 4 · Top side of the evaluation board.

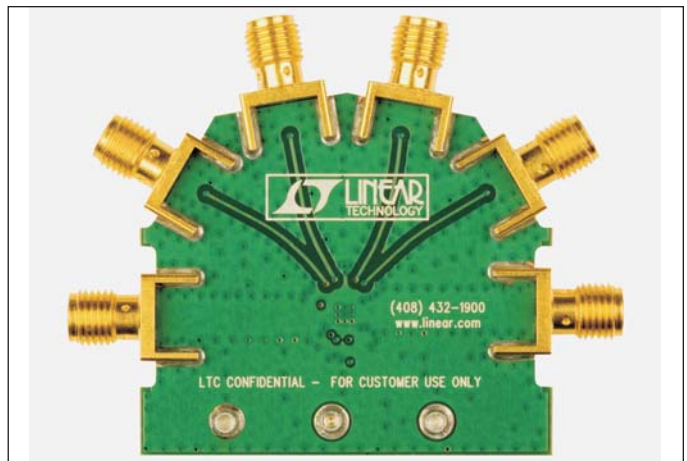


Figure 5 · Bottom side of the evaluation board.

the LO port can change the phase and/or pull the LO VCO off frequency, degrading the receiver performance. Moreover, the LO signal, along with its harmonics, leaking into the baseband outputs can degrade the phase balance of the baseband I/Q signals.

To avoid such signal coupling, all RF, LO and baseband signal traces should be routed in different layers separated by ground planes, whenever practical, keeping the traces as short as possible. The RF and the LO inputs may reside on the same layer if they are separated by adequate ground plane and ground vias to reduce coupling. However, best performance can be attained when the baseband traces are placed on a separate layer.

On the DC1048A demo board, the RF and LO input traces are routed on the top metal layer from opposite ends of the PCB. The four baseband outputs are routed on the bottom metal layer, thus separating them

from the RF and LO inputs by two internal ground layers. The baseband output traces are equal in length to preserve proper phase relations.

Proper filtering of unwanted high frequency mixing products at the baseband I and Q outputs is also important to maintain superior linearity. The most convenient method is to terminate each baseband output with a shunt capacitor to ground, placed as closely as possible to the IC's baseband output pins. The capacitor value should be selected to optimize IIP2 performance depending upon the signal bandwidth.

### Summary and Conclusions

The day of the direct conversion receiver for base station and other infrastructure applications has arrived, enabled by high performance I/Q demodulators such as the LT5575. With a good understanding of the issues of direct conversion receivers reflected in proper layout of

the printed circuit board, the dynamic range performance of even the most demanding applications can be realized using this intrinsically low cost radio architecture.

### Reference

1 Razavi, Behzad, *RF Microelectronics*, Prentice Hall, 1998, ISBN 0-13-887571-5, pp. 129-138.

### Author Information

James Wong is RF Product Marketing Manager, Min Zou is Design Manager, Doug Stuetzle is Senior Applications Engineer, and Sunny Hsiao is Applications Engineer at Linear Technology Corporation. Readers may contact the authors at: [jwong@linear.com](mailto:jwong@linear.com)

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