

Circuits from the Lab™
Reference Circuits

Circuits from the Lab™ reference circuits are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit www.analog.com/CN0248.

Devices Connected/Referenced	
ADRF6510	30 MHz Dual Programmable Filters and Variable Gain Amplifiers
ADL5387	50 MHz to 2 GHz Quadrature Demodulator
ADL5336	LF to 1 GHz VGA with 48 dB Gain Control Range and Programmable RMS Detectors

An IQ Demodulator-Based IF-to-Baseband Receiver with IF and Baseband Variable Gain and Programmable Baseband Filtering

EVALUATION AND DESIGN SUPPORT

Circuit Evaluation Boards

- [ADRF6510 Evaluation Board \(ADRF6510-EVALZ\)](#)
- [ADL5387 Evaluation Board \(ADL5387-EVALZ\)](#)
- [ADL5336 Evaluation Board \(ADL5336-EVALZ\)](#)
- [AD8130 Evaluation Board \(AD8130-EBZ\) two required](#)

Design and Integration Files

- [Schematics, Layout Files, Bill of Materials](#)

CIRCUIT FUNCTION AND BENEFITS

This circuit is a flexible, frequency agile IF-to-baseband receiver. Variable gain at both IF and baseband is used to adjust the signal level. The [ADRF6510](#) baseband ADC driver also includes a programmable low-pass filter that eliminates out-of-channel blockers and noise.

The bandwidth of this filter can be dynamically adjusted as the bandwidth of the input signal changes. This ensures that the available dynamic range of the ADC that this circuit drives is fully used.

The core of the circuit is an IQ demodulator. The $2\times$ LO based phase-splitting architecture of the [ADL5387](#) allows for operation over a wide frequency range. Precise quadrature balance and low output dc offsets ensure that there is minimal degradation of the error vector magnitude (EVM).

The interfaces between all of the components in this circuit are fully differential. Where dc coupling is required between stages, the bias levels of the adjacent stages are compatible with each other.

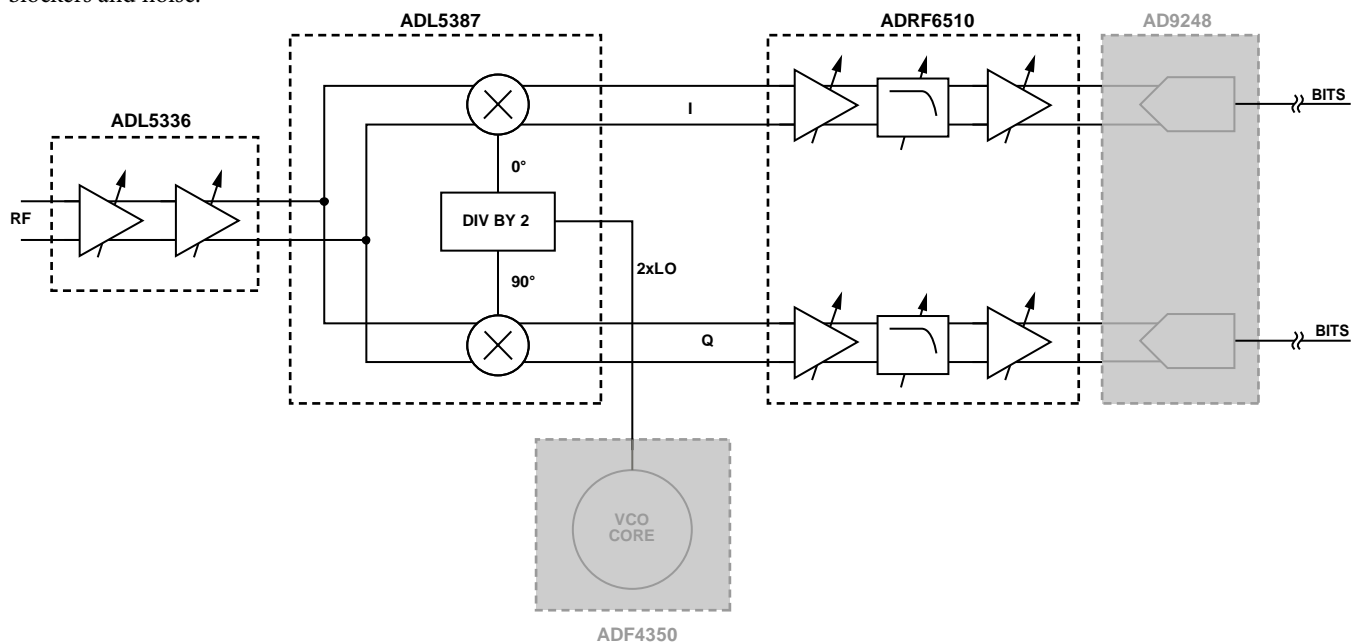


Figure 1. Direct Conversion Receiver Simplified Schematic (All Connections and Decoupling Not Shown)

Rev. 0

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CIRCUIT DESCRIPTION

Receiver Architecture

A direct conversion (also known as a homodyne or zero IF) architecture for a receiver is presented in this circuit note. Direct conversion radios perform just one frequency translation compared to a superheterodyne receiver that can perform several frequency translations. One frequency translation is advantageous because it

- Reduces receiver complexity and the number of stages needed; increasing performance and reducing power consumption
- Avoids image rejection issues and unwanted mixing products; one LPF at baseband is all that is needed
- Has high selectivity (adjacent-channel rejection ratio [ACRR])

Figure 1 shows the basic simplified schematic of the system that consists of cascaded IF variable gain amplifiers (VGAs) with integrated automatic gain control (AGC) loops, followed by a quadrature demodulator and by programmable low-pass filters with variable baseband gain. The grayed out components shown in Figure 1 ([ADF4350](#) and [AD9248](#)) are included for clarity but were not included during system-level measurements (see the Common Variations section for more information on these devices).

Ideally, the input of the first stage and the output of the last stage should set the dynamic range (signal-to-noise ratio) of the system. Practically, this may not be the case. Having a cascaded VGA before the quadrature demodulator not only adds more gain to the system, but it also helps with overall system noise performance if the noise figure of the VGA is less than that of the quadrature demodulator, and if the VGA still has gain, and it is not attenuating. The noise figures of the subsequent stages are divided by the gain of the initial VGA. Another benefit of having a VGA (vs. just having a fixed gain amplifier) is that an AGC loop can be designed to level the incoming signal to the quadrature demodulator. It is important to have this ability to limit the signal levels applied to the quadrature demodulator and any subsequent stages.

IF VGAs and AGC Loops

The IF VGA and AGC loop functions are accomplished with the [ADL5336](#). It has two cascadable VGAs, each with 24 dB of analog dynamic range and the ability to digitally change the maximum gain on each VGA via a SPI port.

To achieve the signal leveling AGC function, each [ADL5336](#) VGA has a square law detector connected to its output through a programmable attenuator. The detector compares the output of the attenuator to an internal reference of 63 mV rms. If there is a difference between the output of the attenuator and the 63 mV rms reference, an error current is produced and is integrated onto a C_{AGC} capacitor. The AGC loop is closed by connecting the DTO1/DTO2 pin to the GAIN1/GAIN2 pin. For the AGC loop to function properly, pull the MODE pin low, causing a negative VGA gain slope.

Each [ADL5336](#) VGA has an allowable range of input power over which the AGC will level to a particular setpoint. Outside that range, the VGA output either increases or decreases dB-for-dB with the input (assuming the VGA is not in compression or that the signal is not in the noise floor).

IQ Demodulator

From the [ADL5336](#), the signal is routed to the [ADL5387](#), where it is demodulated and the frequency is translated to a zero IF. The [ADF4350](#) synthesizer can provide the required $2\times$ LO signal to the [ADL5387](#) (see the Common Variations section); however, a signal generator was used instead of the [ADF4350](#) for actual testing.

The [ADL5387](#) uses two double-balanced mixers, one for the I channel and one for the Q channel. The LO provided to the mixers is generated using a divide-by-two quadrature phase splitter. This provides the 0° and 90° signals for the I and Q channels. There is about 4.5 dB of conversion gain provided by the [ADL5387](#) from the RF input to the baseband I and Q outputs.

Low-Pass Filter, Baseband VGA, and ADC Driver

The low-pass filtering, baseband gain, and ADC driver functions are all achieved using the [ADRF6510](#). The signal, now in its separate I and Q paths, is applied to the [ADRF6510](#) where the signal is first amplified by the preamplifier, then low-pass filtered to suppress any unwanted out-of-band signals and/or noise, and finally amplified by the VGA.

Each channel of the [ADRF6510](#) can be broken up into three stages:

- Preamplifier
- Programmable low-pass filter
- VGA and output driver

The preamplifier has a user-selectable gain, via the GNSW pin, of either 6 dB or 12 dB. The low-pass filter can be programmed for a corner frequency of 1 MHz to 30 MHz in 1 MHz steps via the SPI port. The VGA has a 50 dB gain range with a gain slope of 30 mV/dB. The gain of the VGA is controlled via the GAIN pin, and it can range from -5 dB to $+45$ dB when the GNSW pin is pulled low to $+1$ dB to $+51$ dB when the GNSW pin is pulled high. The output driver has the ability to drive 1.5 V p-p differential into a 1 k Ω load while maintaining a HD2 and a HD3 of better than 60 dBc.

The maximum CW signal that can be applied to the low-pass filters, while still maintaining acceptable HD levels in the [ADRF6510](#), is 2 V p-p. In applications where a large out-of-band interferer is present that could overload the input of either the [ADL5387](#) and/or the [ADRF6510](#), the out-of-band interferer (and the in-band desired signal) can be attenuated by the [ADL5336](#) VGA. Once the out-of-band interferer is rejected by the low-pass filter of the [ADRF6510](#), the wanted signal can then be amplified with the X-AMP VGAs that follow the filters of the [ADRF6510](#).

From the [ADRF6510](#), the IQ signal can be applied to an appropriate analog-to-digital converter (ADC), such as the [AD9248](#).

Measurement Results

A 4-QAM, 5 MSPS modulated signal was applied to the input of the [ADL5336](#). For more information on the test setup, see the Circuit Evaluation and Test section.

EVM is a measure of the quality of the performance of a digital transmitter or receiver and is a measure of the deviation of the actual constellation points from their ideal locations, due to both magnitude and phase errors. This is shown in Figure 2.

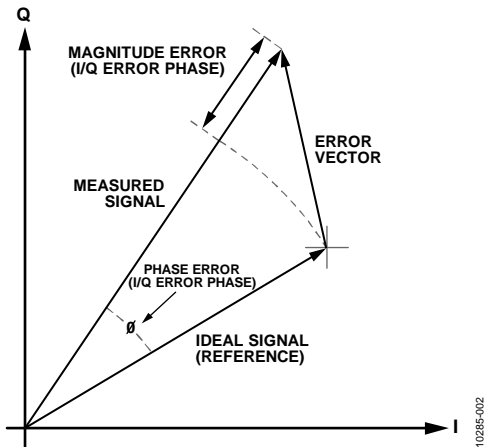


Figure 2. EVM Plot

Figure 3 shows the system EVM vs. the input power to the [ADL5336](#) while the maximum gains on the VGAs are set to 15.2 dB and 19.5 dB for VGA1 and VGA2, respectively. Several AGC setpoint combinations were tested. Figure 4 is also system EVM vs. the input power to the [ADL5336](#); however, the gain of the VGAs was set 9.7 dB and 13.4 dB, respectively. The same AGC setpoint combinations were tested.

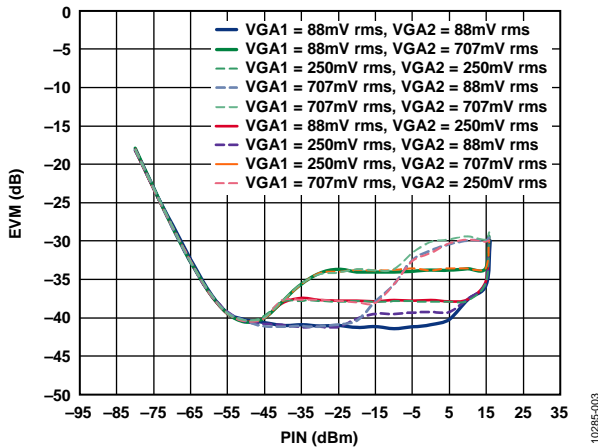


Figure 3. System EVM, Digital VGA Gains = 11

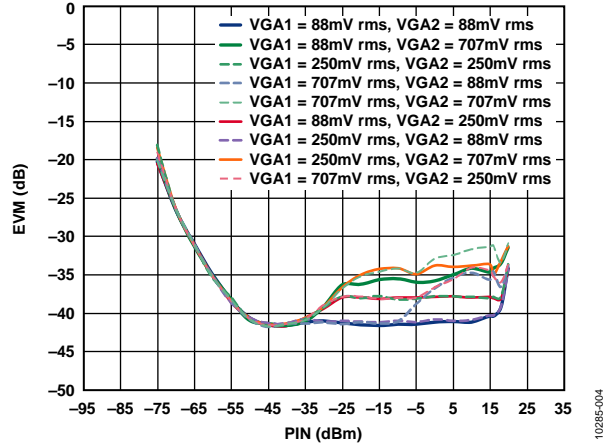


Figure 4. System EVM, Digital VGA Gains = 00

Figure 3 and Figure 4 illustrate the importance of keeping the signal levels applied to the [ADRF6510](#) low enough not to compress the input stage and/or filter. At the highest of AGC setpoints (500 mV rms and 707 mV rms), the input of the [ADL5387](#) IQ demodulator is starting to compress and adds additional degradation to the EVM. The best EVM is achieved when the AGC setpoints are at their lowest (88 mV rms). EVM is already beginning to degrade when the setpoints are 250 mV rms.

Figure 5 compares the EVM between the minimum and the maximum digital gain settings (both VGAs were set to either a gain code of 11 or a gain code of 00) on the [ADL5336](#) VGAs when VGA1 and VGA2 setpoints are 250 mV rms and 88 mV rms, respectively.

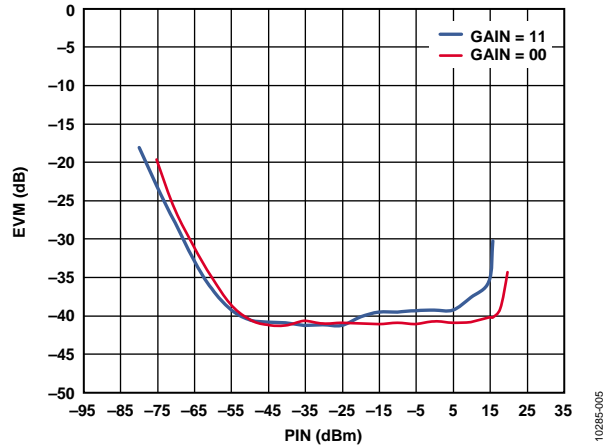


Figure 5. System EVM with VGA1 Setpoint = 250 mV rms and VGA2 Setpoint = 88 mV rms

For the given AGC setpoints, when the maximum gain code was 11, the handoff from VGA2 to VGA1 occurs after VGA2 runs out of the gain range; therefore, the signal level being applied to the [ADRF6510](#) continues to increase (and degrade EVM) until VGA1 reaches its setpoint. Once VGA1 reaches its own setpoint, the EVM levels off again; therefore, the signal level being applied to the [ADRF6510](#) does not change until VGA1 runs out of the gain range at about 5 dBm of input power. When the maximum gain code was set to 00, both VGAs have more attenuation available, thus allowing VGA2 to shift its dynamic range such that it does not

reach its setpoint at as low an input power as when the maximum gain code was 11. This allows VGA2 to keep its setpoint at higher input powers, thus allowing the handoff from VGA2 to VGA1 to take place before VGA2 runs out of gain. This ensures that the signal level applied to the [ADRF6510](#) is maintained at a constant level until the uppermost of the input power range.

Figure 6 compares the EVM between the minimum and the maximum digital gain settings (both VGAs were set to either a gain code of 11 or a gain code of 00) on the [ADL5336](#) VGAs; however, the VGA1 and VGA2 setpoints were 707 mV rms and 88 mV rms, respectively.

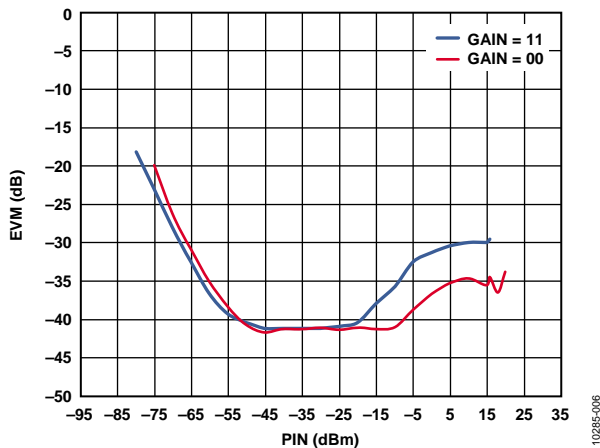


Figure 6. System EVM with VGA1 Setpoint = 707 mV rms and VGA2 Setpoint = 88 mV rms

The same dynamics are occurring in Figure 6 as they were in Figure 5, only they are much more exaggerated. When the maximum gain code is 00, VGA2 reaches its setpoint at around -40 dBm input power. It maintains its setpoint until about -10 dBm, at which point, VGA1 has not reached its setpoint of 707 mV rms. VGA1 does not reach its setpoint until about 0 dBm, and the EVM starts to level off somewhat. When the maximum gain is set to 11, this same behavior happens again; however, VGA2 maintains its setpoint only to about -20 dBm because there is more gain available to attain the prescribed setpoints.

COMMON VARIATIONS

System and Synthesizer

The signal generator that provides the 2×LO for the [ADL5387](#) can be replaced by a wideband synthesizer, such as the [ADF4350](#), which has an integrated VCO. The [ADF4350](#) belongs to a family of synthesizers that operate over a wide frequency range, from 135 MHz to 4350 MHz, and that has varying phase noise and output power metrics, making it easy to find the device to match the required specifications of the application.

System and ADC

Adding an ADC to the system to sample the I and Q signals of the [ADRF6510](#) is a natural progression to complete the analog signal chain. A dual ADC, such as the [AD9248](#), provides 14 bits of resolution and is offered in 20 MSPS, 40 MSPS, or 65 MSPS sampling rates. An antialiasing filter is recommended between the output of the [ADRF6510](#) and the [AD9248](#). Refer to the [ADRF6510](#) data sheet for the antialiasing filter design example.

ADRF6510 Output Common-Mode Voltage Considerations

The [ADRF6510](#) output common-mode voltage is adjustable from 1.5 V to 3.0 V without loss of drive capability. Many modern ADCs have input common-mode voltages of less than 1.5 V. Driving the VO_{CM} pin to an output common-mode voltage less than 1.5 V starts to degrade the distortion performance of the [ADRF6510](#); however, it is still functional for less than 1.5 V common-mode voltage levels. To maintain distortion performance, a dc level shifting circuit may be required, or an integrated filter and VGA device with a lower common-mode voltage, such as the [ADRF6516](#), can be used.

CIRCUIT EVALUATION AND TEST

Equipment Needed/Used

Signal generators include the following:

- Agilent E4438C vector signal generator
- Agilent E4438C signal generator

The baseband signal capture device is the

- Agilent DSO90604A oscilloscope

The EVM computation device(s) include the following:

- Agilent 89600 VSA software
- PC running Windows XP connected to oscilloscope via a USB cable

The power supply includes the following:

- ±5 V supply. All boards require +5 V with the exception of the [AD8130](#) boards that require ±5 V

The evaluation boards include the following:

- [ADL5336-EVALZ](#) (one required)
- [ADL5387-EVALZ](#) (one required)
- [ADRF6510-EVALZ](#) (one required)
- [AD8130-EBZ](#) (two required)

Getting Started

To use the [ADL5336](#) and [ADRF6510](#), the evaluation software is needed to control various aspects of each part. This software can be found on the respective product web pages under the **Tools, Software, & Simulations Models** link.

Once the software is downloaded and installed, plug in the USB cables from the computer to the evaluation boards and then run the software for the part that needs to be controlled.

Functional Block Diagram

Figure 7 shows the functional block diagram of the test setup that was used for testing the receive chain. The [ADL5336](#) evaluation board only allows for single-ended input and output. The same is true for the RF input on the [ADL5387](#) board. The RF output port on the vector signal generator is only single ended; therefore, a balun between the generator and the input of the [ADL5336](#) is necessary. As shown in Figure 7, the rest of the signal path is differential until the [AD8130](#) difference amplifiers. The differential-to-single-ended conversion was needed because the oscilloscope only allows for sampling of single-ended signals while being controlled by the VSA software.

Setup and Test

The first step of the setup of the receiver test is to turn on all test equipment. While the test equipment is warming up, the boards must be configured correctly for proper use in this signal chain.

On the [ADL5336](#), ensure that the 0 Ω jumper resistors that connect the VGA1 output to the VGA2 input are populated

On the [ADL5387](#) board, bypass the output baluns for full differential, dc-coupled signal paths between the [ADL5387](#) and the [ADRF6510](#).

On the [ADRF6510](#) board, do the following:

- Bypass the input and output baluns
- Place 1 k Ω differential output loads on the output signal lines (two 500 Ω resistors to ground will suffice on each output path)
- Replace the stock C_{OF5} capacitors with 1 μ F capacitors

Collect the evaluation boards and connect all the signal paths together, as shown in Figure 7. Connect all boards to +5 V and the two [AD8130](#) boards to -5 V as well. Ensure that the power supply current is consistent with what is expected.

As shown in Figure 7, make the following connections:

- Connect the single-ended, 50 Ω output of the vector signal generator to INPUT1 of the [ADL5336](#) evaluation board.
- Connect the I signal path output of the [AD8130](#) to Input 1 on the oscilloscope, and connect the Q signal path output of the [AD8130](#) to Input 3 of the oscilloscope.
- Connect the USB cable from the PC to the oscilloscope.
- Connect the RF port of the signal generator to the LO input of the [ADL5387](#) evaluation board.

On the Agilent E4438C signal generator, do the following:

- Set the frequency to 400 MHz
- Set the amplitude to 0 dBm
- Turn the RF port on

On the Agilent E4438C vector signal generator, do the following:

- Set the RF carrier frequency to 200 MHz
- Set the amplitude to -30 dBm
- Turn the RF port on
- Turn on the custom ARB inside the vector signal generator
- Set the signal to 4-QAM, symbol rate to 5 MSPS, and pulse shaping filter alpha to 0.35

On the PC, start the Agilent 89600 VSA software. In the VSA software, do the following:

- Turn the digital demodulator on
- Set the input to the I+ jQ option
- Set the frequency to 0 Hz, symbol rate to 5 MSPS, and alpha to 0.35

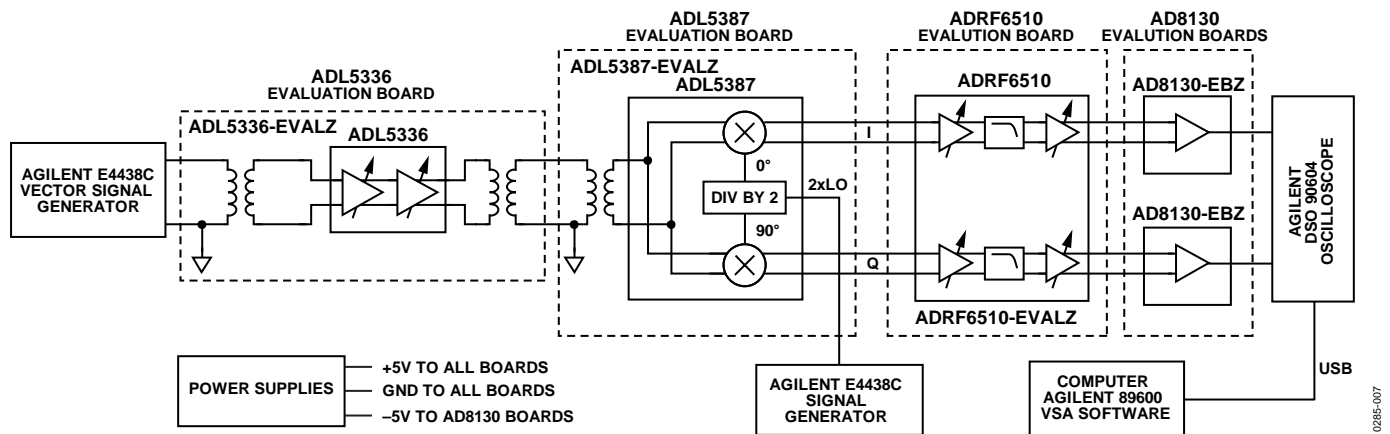


Figure 7. Functional Block Diagram for Testing Direct Conversion Receiver

The signal metrics on the vector signal generator must match the metrics on the VSA software. When the software starts up, it should display the **IQ Constellation** pane and the **Spectrum** pane. Add the information window on the VSA software by taking the following steps:

1. Click **Display**
2. Click **Layout**
3. Select **Grid 2x2**

By default, the other two panes that have appeared should be an **Error Vector vs. Time** and the information window, **Syms/Errs**. If this is not the case, do the following:

1. Double-click the title of any pane
2. Select **Syms/Errs** in the window that appears

The **Syms/Errs** pane presents a number of results, including EVM. The software should be locked onto the signal and reporting an EVM number.

The AGC setpoint, maximum gain, and filter bandwidth can all be set with the respective control software of the individual devices. Power control at the input of the [ADL5336](#) can be done via a power sweep on the vector signal analyzer. A -80 dBm to almost $+16$ dBm sweep was performed to test the receiver in this test setup. The gain on the [ADRF6510](#) was always set to achieve a 1.5 V p-p differential output level, assuming there was sufficient gain to achieve this. In some cases, for very small signal levels, the [ADRF6510](#) did not have enough gain to reach the 1.5 V p-p differential level.

LEARN MORE

CN-0248 Design Support Package:

<http://www.analog.com/CN0248-DesignSupport>

Arducci, John. *A Practical Guide to High-Speed Printed-Circuit-Board Layout*, *Analog Dialogue* 39-09, September 2005.

MT-031 Tutorial, *Grounding Data Converters and Solving the Mystery of "AGND" and "DGND."* Analog Devices.

MT-073 Tutorial, *High Speed Variable Gain Amplifiers (VGAs)*. Analog Devices.

MT-101 Tutorial, *Decoupling Techniques*, Analog Devices.

ADIsimPLL Design Tool

ADIsimRF Design Tool

AN-0996 Application Note. *The Advantages of Using a Quadrature Digital Upconverter (QDUC) in Point-to-Point Microwave Transmit Systems*. Analog Devices.

AN-1039 Application Note. *Correcting Imperfections in IQ Modulators to Improve RF Signal Fidelity*. Analog Devices.

CN-0134 Circuit Note, *Broadband Low Error Vector Magnitude (EVM) Direct Conversion Transmitter*, Analog Devices

Data Sheets and Evaluation Boards

[ADRF6510 Data Sheet and Evaluation Board](#)

[ADL5387 Data Sheet and Evaluation Board](#)

[ADL5336 Data Sheet and Evaluation Board](#)

[ADF4350 Data Sheet and Evaluation Board](#)

[AD9248 Data Sheet and Evaluation Board](#)

[ADRF6516 Data Sheet and Evaluation Board](#)

[AD8130 Data Sheet and Evaluation Board](#)

REVISION HISTORY

4/12—Revision 0: Initial Version

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