Circuits from the Lab® Reference Designs

Circuits from the Lab® reference designs 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/CN0521.

Devices Connected/Referenced	
HMC639	400 MHz to 4000 MHz Low Noise Amplifier
ADG901	0 Hz to 4.5 GHz, 40 dB Off Isolation at 1 GHz, 17 dBm P1dB at 1 GHz SPST Switches
ADL5904	DC to 6 GHz, 45 dB TruPower Detector with Envelope Threshold Detection
LT8330	Low I_Q Boost/SEPIC/Inverting Converter with 1 A, 60 V Switch
ADP150	Ultralow Noise, 150 mA CMOS Linear Regulator
ADM7150	800 mA, Ultra Low Noise/High PSRR LDO
ADM7170	6.5 V, 500 mA, Ultralow Noise, High PSRR, Fast Transient Response CMOS LDO
LTC6991	TimerBlox: Resettable, Low Frequency Oscillator

USB-Powered, 2.4 GHz RF Low Noise Amplifier Receiver with Overpower Protection Circuit

EVALUATION AND DESIGN SUPPORT

▶ Circuit Evaluation Boards
  ▶ CN0521 Circuit Evaluation Board (EVAL-CN0521-EBZ)
▶ Design and Integration Files
  ▶ Schematics, Layout Files, Bill of Materials

CIRCUIT FUNCTIONS AND BENEFITS

The International Telecommunication Union allocates the 2.4 GHz industrial, scientific, and medical (ISM) radio band for use worldwide. The 2.4 GHz ISM band finds popular application in Bluetooth devices, cordless phones, baby monitors, microwave ovens, and some amateur radio equipment.

The Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards, including the 802.11b and 802.11g amendments, also provide basis for use of the 2.4 GHz frequency band for wireless networking systems such as Wi-Fi and Zigbee.

The circuit shown in Figure 1 is a two-stage RF low noise amplifier (LNA) optimized for receiver signal chains in the 2.4 GHz ISM band. At the center frequency, the circuit achieves a forward gain of 22 dB and an input return loss of more than 10 dB. The RF input and output ports are designed with a 50 Ω impedance match, enabling a direct connection between the circuit and a standard 50 Ω system.

The board includes a high speed overpower cutoff that protects sensitive downstream equipment connected to the receiver system. The receiver system also automatically returns to normal operation when the RF power level drops within the acceptable range. The RF inputs and outputs are standard subminiature version A (SMA) connectors, and the entire design is powered by a single micro-USB connector.
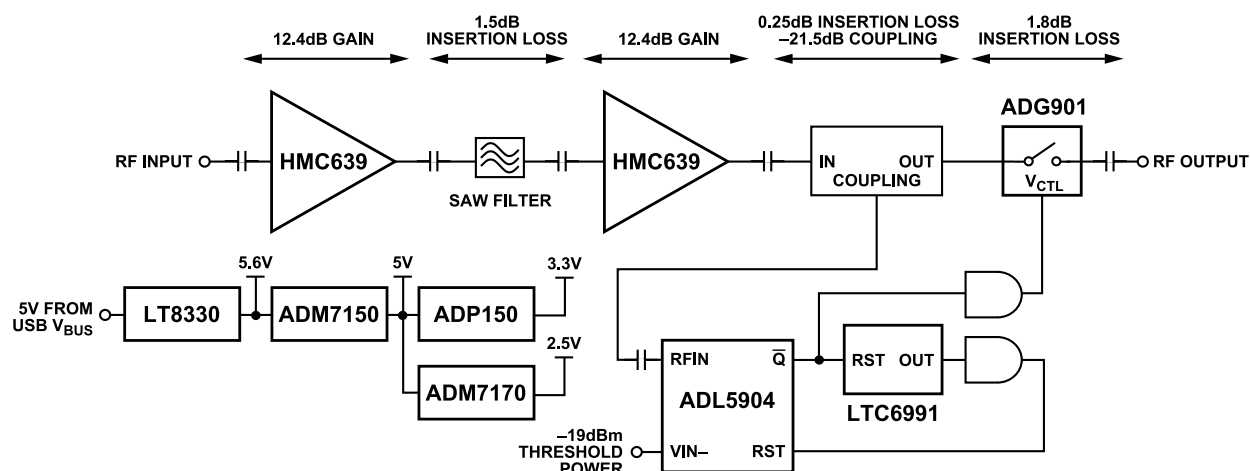

Figure 1. CN0521 Simplified Block Diagram

CIRCUIT DESCRIPTION

RF LOW NOISE AMPLIFIER

The CN0521 uses cascaded HMC639 low noise amplifiers for its RF signal path, achieving an overall gain of approximately 22 dB. The HMC639 is a gallium arsenide (GaAs), pseudomorphic high electron mobility transistor (pHEMT), high linearity, low noise, wideband gain block amplifier that operates from 0.2 GHz to 4 GHz.

Figure 2 shows the typical S-Parameter performance, with a typical gain of 13 dB and return losses of more than 10 dB throughout the entire frequency range. The HMC639 has a typical noise figure of 2.3 dB, a 1 dB compression point (P1dB) of 21 dBm, and a third-order intercept point (OIP3) of 38 dBm.
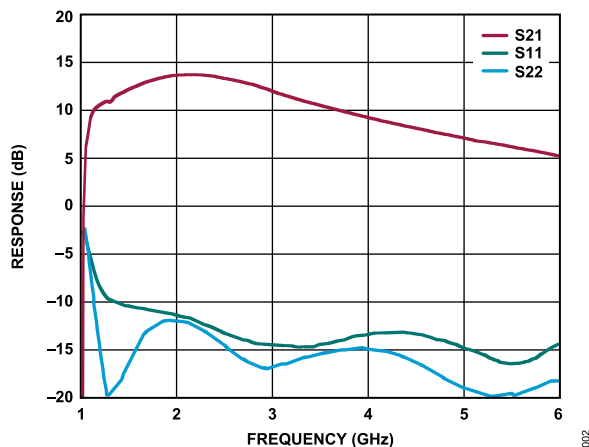

Figure 2. HMC639 Typical S-Parameters

Impedance Matching Network

The HMC639 RF input and output ports are internally matched for a single-ended 50 Ω impedance. This internally matched topology allows the HMC639 to be readily ported between any printed circuit board material regardless of its dielectric constant, thickness, or composition. The only requirement needed is to have DC-blocking capacitors with a value of 100 pF on both RF input and output.

Figure 3 shows the basic configuration and implementation of two cascaded HMC639 amplifiers.
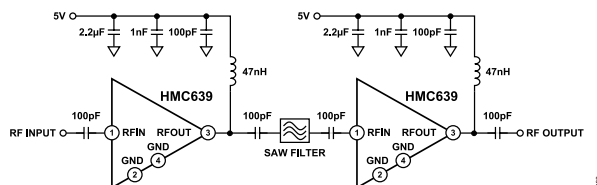

Figure 3. Basic Connections for Cascading HMC639 Amplifiers

RF SAW FILTER

The first stage amplifier output of the CN0521 is filtered by a surface wave acoustic (SAW) filter, which eliminates unwanted out-of-band amplification. When selecting a filter, a balance must be struck between the band flatness and the out-of-band rejection.

SAW filters are also a source of insertion loss, which reduces the overall gain of the signal chain and needs to be considered during selection.

The filter used has a pass band of 2.4 GHz to 2.5 GHz, with a return loss of 21 dB, and an insertion loss of 1.5 dB at 2.4 GHz.

RF DIRECTIONAL COUPLER

The CN0521 includes a high directivity hybrid RF directional coupler. This device has an operating frequency of 2.4 GHz to 2.484 GHz, with a coupling factor of 21.5 at 2.4 GHz. It has an input and output port impedance of 50 Ω and a typical insertion loss of 0.25 dB.

RF SWITCH

The ADG901 is a wideband RF switch that uses a CMOS process to provide high isolation and low insertion loss. It is an absorptive (matched) switch with 50 Ω terminated shunt legs. The switch enables the user to pass DC signals up to 0.5 V without the use of a DC-blocking capacitor.

The ADG901 operates at DC to 4.5 GHz at -3 dB frequency. At 2.4 GHz, this device has a typical insertion loss of approximately 1.8 dB at "ON state" as shown in Figure 4; and a typical isolation loss of approximately 30 dB at "OFF state" as shown in Figure 5.
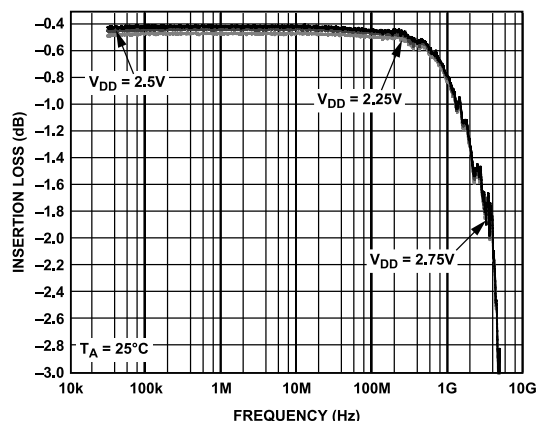

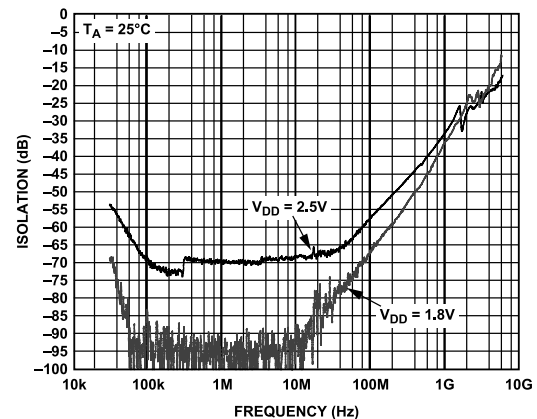*Figure 4. ADG901 Insertion Loss Performance at ON State*

Figure 5. ADG901 Isolation Loss Performance at OFF State

Combining the insertion loss from the filter, coupler, and the RF switch results in a total insertion loss of approximately 3.5 dB at the output of the RF switch in normal operating conditions.

RF PERFORMANCE

The resulting S-Parameters, phase noise measurements, spurious-free dynamic range (SFDR), noise figure, and stability measure of the CN0521 are shown in figures below.

At 2.4 GHz operating frequency, the CN0521 achieves a gain of 22 dB with input and output return losses of greater than 10 dB. Figure 6 shows the S-Parameters across the operating frequency range.
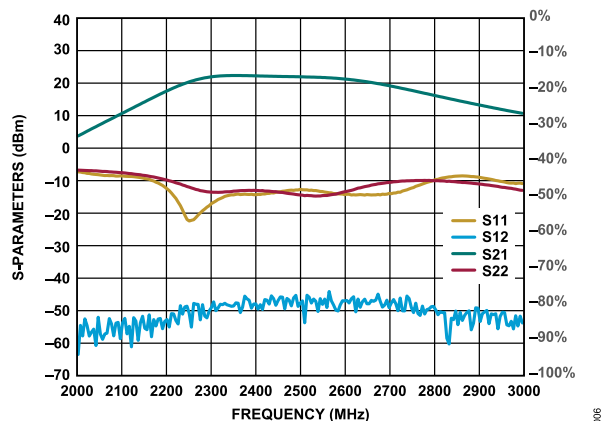
Figure 6. CN0521 S-Parameters vs. Frequency

Figure 7 shows the single sideband phase noise at 2.4 GHz, with a spot noise of approximately -125 dBc/Hz, -131 dBc/Hz, -133 dBc/Hz, and -139 dBc/Hz at frequency offsets of 1 kHz, 10 kHz, 100 kHz, and 1 MHz, respectively.
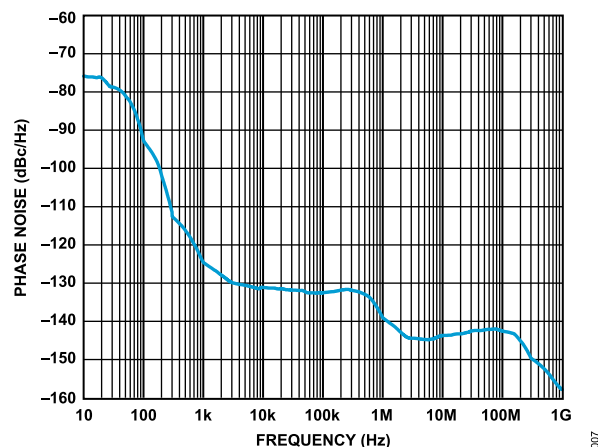

Figure 7. CN0521 Single Sideband Phase Noise at 2.4 GHz

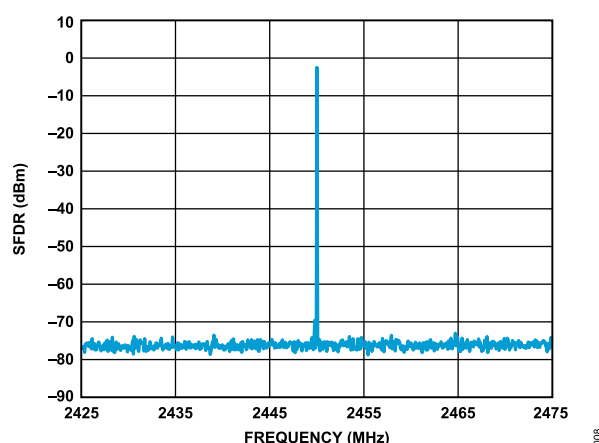Figure 8 shows the narrow-band single-tone RF output with an average SFDR of 67 dBFS.

Figure 8. CN0521 Narrow-Band Single Tone RF Output

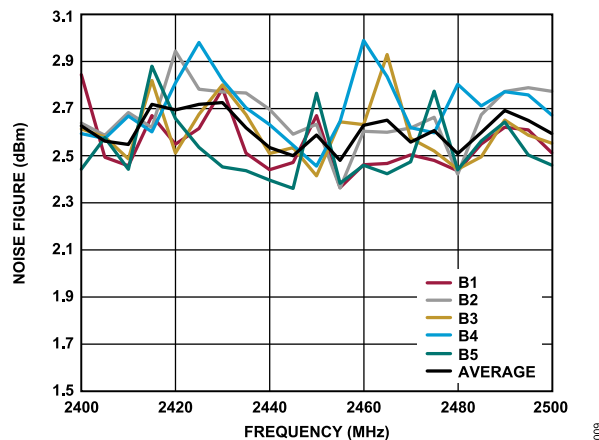Figure 9 shows the corresponding noise figure of approximately 2.5 dB over the entire frequency range.

Figure 9. CN0521 Noise Figure vs. Frequency

The system is stable across the entire 2.4 GHz ISM frequency bandwidth with the Rollet's stability factor (k) being above 1 and the supplementary stability measure (B1) being above 0, as shown in Figure 10. This makes the CN0521 unconditionally stable for any combination of source and load impedance.
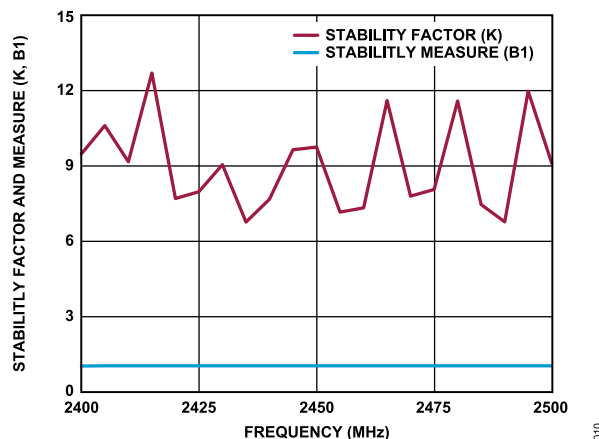

Figure 10. CN0521 Stability Factor and Measure vs. Frequency

OVERPOWER PROTECTION

An overpower management feature is implemented in CN0521 wherein the RF path of the board is automatically isolated when the output power reaches the preset threshold of 0 dBm. This feature is performed using an ADL5904 RF power detector.

The ADL5904 provides a resistor-programmable detection threshold, which compares the voltage from an internal envelope detector with a user-defined input voltage. When the voltage from the envelope detector exceeds the user-defined threshold voltage at the V_{IN-} pin, an internal comparator captures and latches the event to a set/reset (SR) flip-flop. Figure 11 shows the overpower protection circuitry for the CN0521.
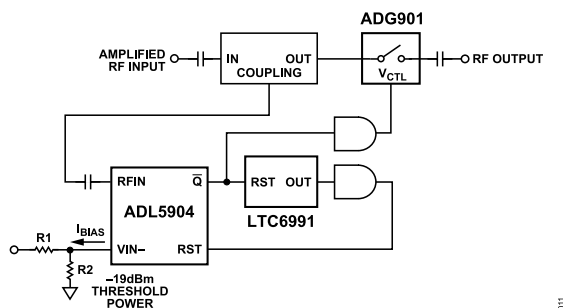

Figure 11. CN0521 Overpower Protection Circuit

The amplified RF input is sampled by a 21.5 dB RF coupler. This power is forwarded to the RFIN pin of the ADL5904, which is then sampled by the internal envelope detector. The ADL5904 threshold voltage level on V_{IN-} pin is set by a resistor divider network, which value can be computed using Equation 1:

$$V_{IN-} = \left[\frac{3.3 \times R_2}{(R_2 + R_1)}\right] + \left[\frac{(R_1 \times R_2)}{(R_1 + R_2)} \times I_{BIAS}\right] \quad (1)$$

where:
V_{IN-} is the voltage level at the V_{IN-} pin of the ADL5904.
R_1 is the user-defined resistance value.
R_2 is the user-defined resistance value.
I_{BIAS} is the input bias current.

The CN0521 was set at -19 dBm input threshold power, which is equivalent to 0 dBm RF output to protect any sensitive downstream equipment connected to the receiver system. Table 1 can be found in the ADL5904 data sheet, and shows the -19 dBm threshold power corresponds to a V_{IN-} voltage level of 29 mV when operating at 2600 MHz.

Table 1. Recommended Typical Values for Threshold Voltage (V_{IN-}) When Operating Uncalibrated

Input Threshold Power (dBm)	Threshold Voltage (mV)		
	1900 MHz	2600 MHz	3500 MHz
-21	23	24	17
-20	26	26	19
-19	29	29	21
-18	32	32	23
-17	36	35	25

The threshold level on V_{IN-} is set by a resistor divider. The value of R_1 is primarily chosen to minimize loading on the 3.3 V rail, and R_2 is chosen for an output impedance that is insensitive to leakage and bias currents. Setting R_1 to 80.6 kΩ and using the power threshold value of 29 mV, the R_2 value is calculated using Equation 1.

V_{IN-} = 29 mV
I_{BIAS} = 20 μA
R_1 = 80.6 kΩ

$$29\text{ mV} = \left[\frac{3.3 \times R_2}{(R_2 + 80.6\text{ k}\Omega)}\right] + \left[\frac{(80.6\text{ k}\Omega \times R_2)}{(80.6\text{ k}\Omega + R_2)} \times 20\text{ μA}\right]$$

R_2 = 479 Ω or 499 Ω (using standard resistor value)

Solving Equation 1 using the closest standard resistor value sets the V_{IN-} voltage level at approximately 29 mV. When the power exceeds the threshold value, an overpowering event occurs which isolates the RF path. The series combination of R_1 and R_2 results in a negligible divider current of 41 μA.

The ADL5904 introduces an error level of up to +2.5 dBm on its RF threshold power and can vary from device-to-device. If an accurate threshold power is required, a simple calibration routine must be performed to compensate for the device-to-device variation. Refer to the ADL5904 data sheet for more information on the calibration routine.

Automatic Reset Feature

The CN0521 also includes an automatic reset circuitry that activates when the power level returns within the acceptable range. This feature is done through the LTC6991, a programmable low frequency timer.

As shown in Figure 12, the $\overline{Q}$ output of the ADL5904 holds the LTC6991 in reset mode during normal operation. When an overpowering event occurs, the LTC6991 is enabled and a 4 ms delay begins. The ADL5904 resets after 4 ms, effectively resampling the power level. If the overpowering condition persists, the ADL5904 trips again and the control signal of the RF switch enters the low state. This shift in signal isolates the RF input and output of the ADG901 switch. Once the overpower event subsides, the ADL5904 starts to resample the power level and then returns to its normal operation.
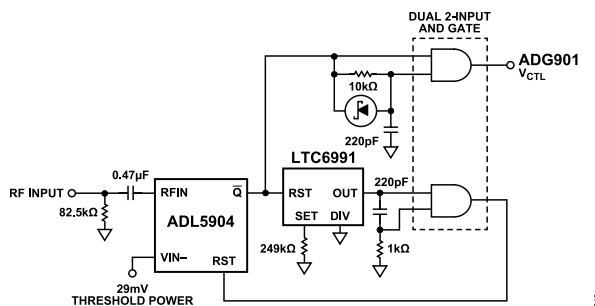

Figure 12. CN0521 Automatic Reset Circuitry

Overpower Protection Test

Figure 13 presents the setup used to test the overpower protection functionality of the CN0521. In this test, the RF signal generator is set to 2.4 GHz center frequency and the power to the input is ramped up from -25 dBm to -15 dBm. The CN0521 output power is monitored using a high speed oscilloscope, which shows the response time from the overpowering event to the output power being attenuated.
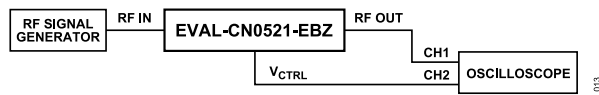

Figure 13. RF Overpower Response Test Setup

Figure 14 shows the overpower cutoff response time. Based on the figure, the output of the CN0521 has a response time of approximately 8 ns from its normal operation to the RF output power being attenuated.

CH1	1.00V/div, 0mV	−5.2ns	CH1 ⌐⌐ 1.00V
CH2	60mV/div, 0.0mV	5.00ns/div	
		1kS, 20GS/s	
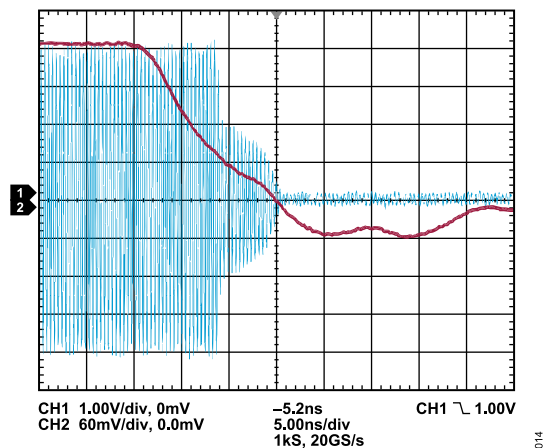
Figure 14. Typical Cutoff Response Time

Figure 15 shows the recovery time from when the overpowering condition subsides, and the power level returns to its acceptable range. The data demonstrate a 4 ns delay from the attenuated RF output to its normal operation.
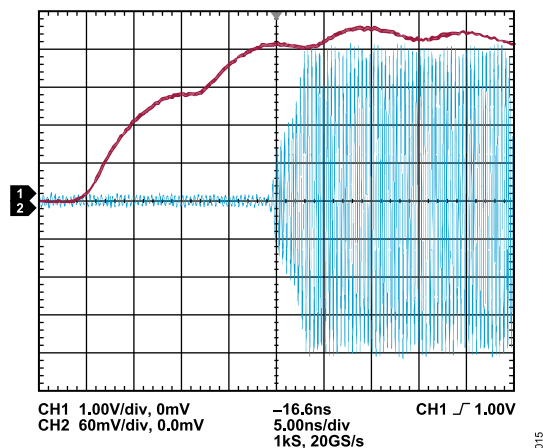

CH1	1.00V/div, 0mV	−16.6ns	CH1 ⌐⌐ 1.00V
CH2	60mV/div, 0.0mV	5.00ns/div	
		1kS, 20GS/s	

Figure 15. Typical Recovery Time after an Overpower Event

USB POWER MANAGEMENT

The CN0521 sources its power through a micro-USB adapter, which typically provides a 5 V, 1 A supply via the micro-USB port. The nominal 4.75 V to 5.25 V input from the USB port is boosted to 5.6 V, then post-regulated to 5.0 V, 3.3 V, and 2.5 V. The circuit requires an overall current of approximately 390 mA from the USB supply during normal operation.

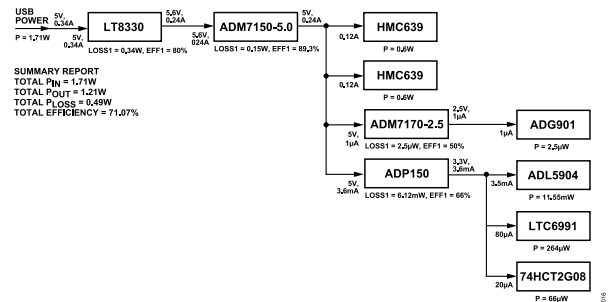Figure 16 shows the complete CN0521 power tree.

Figure 16. CN0521 Power Supply Architecture

SEPIC Converter

The LT8330 is a current-mode DC/DC converter capable of generating either positive or negative output voltages. It can be configured as boost, SEPIC, or inverting converter, consuming as low as 6 μA quiescent current. Figure 17 shows the basic configuration needed to set the LT8330 for a 5.6 V output.
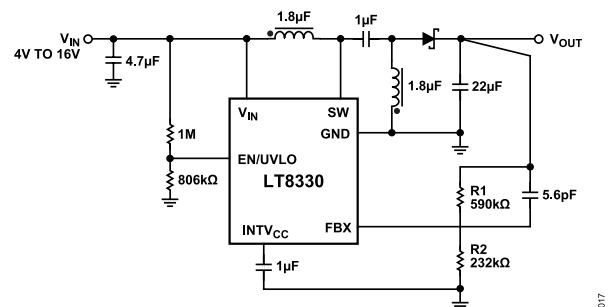

Figure 17. LT8330 Configuration for a 5.6 V Output

The output voltage is programmed with resistor divider from the output to the FBX pin of the LT8330. Equation 2 shows how to calculate a desired output voltage with the user-defined resistor values:

$$R_1 = R_2 \ \left(\frac{V_{OUT}}{1.60} - 1 \right) \tag{2}$$

where:
V_{OUT} is the desired output voltage in Volts.
R_1, R_2 are the user-defined resistor values.

For the required output voltage of 5.6 V, the equation results with R_1 = 590 kΩ and R_2 = 232 kΩ.

Ultralow Noise Linear Regulator

The 5 V output from the ADM7150 is used to power the two HMC639 LNAs. The ADM7150 is a low dropout linear regulator with a typical noise of 1 μV_{RMS} from 100 Hz to 100 kHz for fixed output voltage options and <1.7 nV/√Hz noise spectral density above 10 kHz.

The ADP150 is used to generate 3.3 V for powering the RF detector and auto retry circuit. It is a high performance low dropout linear regulator featuring an ultralow noise and ultra high PSSR architecture for powering noise sensitive RF applications.

An ADM7170-2.5 LDO regulator is used to generate the supply voltage required by the ADG901 RF switch. This device has an input voltage range of 2.3 V to 6.5 V and a fixed output voltage of 2.5 V. The ADM7170-2.5 only requires capacitors for proper operation. Particularly, the ADM7170-2.5 is compatible to use small decoupling capacitors of 4.7 µF on its input and output pins.

COMMON VARIATIONS

The ADL5523 can be used as an alternative low noise amplifier for applications using the 2.4 GHz ISM band. This device offers a slightly higher gain (S21) and a low noise figure at a cost of having lower return losses (S11, S22), output third-order intercept, and 1 dB compression point.

The ADG902 can also be used as the RF switch, this device is pin-compatible and shares the same specifications as the ADG901; but it is a reflective switch and offers lower isolation loss.

Analog Devices, Inc. offers a similar reference design for receiver amplifiers operating in the 433.92 MHz and 5.8 GHz ISM bands. For more information, refer to the CN0555 and CN0534 circuit notes respectfully.

If you are working in the 2.4 GHz ISM band and in need for a transmit signal chain solution, refer to the CN0417 reference design.

CIRCUIT EVALUATION AND TEST

This section describes the setup and procedure for the CN0521 circuit evaluation. For complete details, refer to the EVAL-CN0521-EBZ User Guide.

EQUIPMENT NEEDED

- ▶ EVAL-CN0521-EBZ circuit evaluation board
- ▶ Signal generator (Rohde & Schwarz® SMA100B)
- ▶ Signal analyzer (Keysight® E5052B)
- ▶ Vector network analyzer (Keysight N5242A PNA-X)
- ▶ 5 V, ≥0.5 A AC/DC power adapter with micro-USB cable
- ▶ SMA cables

SETUP AND TEST

Figure 18 shows the functional block diagram for the S-Parameter and noise figure test setup.
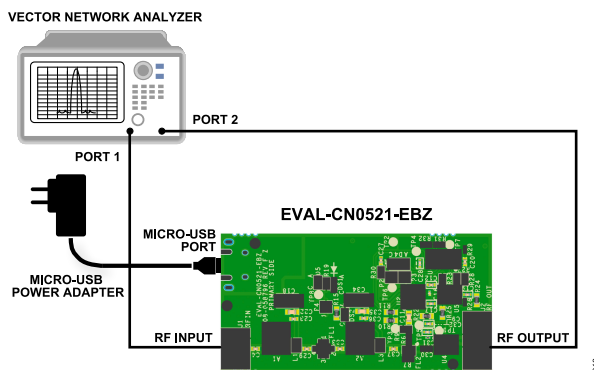

Figure 18. S-Parameter and Noise Figure Test Setup

The procedure for measuring S-Parameters and noise figure are as follows:

1. Set the measurement conditions of the vector network analyzer as follows:
   a. Set the frequency span from 2400 MHz to 2500 MHz.
   b. Set the frequency step size to 10 kHz.
   c. The power level must be less than or equal to -30 dBm.
2. Perform a full 2-port calibration of the vector network analyzer using a calibration kit. Note that the RF output of the EVAL-CN0521-EBZ can be connected directly to a test port, so that only one measurement cable is needed for the test setup.
3. Connect the EVAL-CN0521-EBZ across the test ports of the vector network analyzer using the calibrated test setup.
4. Power up the EVAL-CN0521-EBZ using the 5 V power adapter.
5. Set the vector network analyzer to display the traces of the individual S-Parameters and the noise figure.
6. Compare the measurements to the expected values. At 2.4 GHz center frequency, the values for input and output return losses are approximately 13 dB and 14 dB, respectively. For the gain and noise figure readings, values should be approximately 22 dB and 2.5 dB, respectively.

Figure 19 shows the functional block diagram for the phase noise and SFDR test setup.
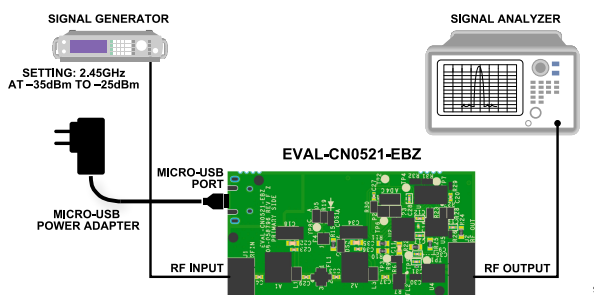

Figure 19. Phase Noise and SFDR Test Setup

To perform the phase noise and SFDR tests, follow the steps below:

1. Set the measurement configuration of the signal analyzer as follows:

   a. For SFDR measurement, set the center frequency to 2.4 GHz, the frequency span to 2400 MHz to 2500 MHz, and the RF amplitude to -30 dBm.

   b. For phase noise measurement, set the center frequency to 2.4 GHz and the offset frequency range to 10 Hz to 30 MHz.

2. Set the power level of the signal generator between -30 dBm to -20 dBm with a center frequency set at 2.4 GHz.

3. Connect the signal generator output to the RF input of the EVAL-CN0521-EBZ.

4. Connect the RF output of the EVAL-CN0521-EBZ to the signal analyzer.

5. Power up the EVAL-CN0521-EBZ using the 5 V power adapter.

6. Execute a measurement run on the signal analyzer.

7. Using the signal analyzer, get the phase noise value and verify if it is approximately -133 dBc/Hz at 100 kHz offset.

8. Run the SFDR test and compare the readings; expected value is approximately 67 dBc.

LEARN MORE

DATA SHEETS AND EVALUATION BOARDS

REVISION HISTORY

05/2023—Revision 0: Initial Version