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APPLICATION NOTE

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RF Power Calibration Improves Performance of Wireless Transmitters

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INTRODUCTION

Measurement and control of radio frequency (RF) power is a critical consideration when designing a wireless transmitter. High power RF power amplifiers (PAs) rarely operate in open-loop mode (that is, when the power to the antenna is not in some way monitored). External factors such as regulatory requirements on the amount of power transmitted, network robustness, and the need to co-exist with other wireless networks require strong control of transmitted power. In addition to these external requirements, precise RF power control may result in improved spectral performance and may make the power amplifier of the transmitter more energy and cost efficient.

To regulate the transmitted power of the PA, some form of factory calibration of the PA output power may be necessary. Calibration algorithms vary vastly in terms of their complexity and effectiveness. This application note describes how to implement a typical RF power control scheme and compares the effectiveness and efficiency of various factory calibration algorithms for RF detectors with a linear-in-dB transfer function.

TYPICAL WIRELESS TRANSMITTER WITH INTEGRATED POWER CONTROL

Figure 1 shows a block diagram of a typical wireless transmitter that incorporates measurement and control of transmitted power. Using a directional coupler, a small portion of the signal from the PA is coupled off and fed to an RF detector. In this case, the coupler is located close to the antenna, but after the duplexer and isolator. The power loss associated with the duplexer and isolator is thus factored in during calibration.

Directional couplers typically have a coupling factor of 20 dB to 30 dB. Therefore, the signal coming from the coupler is 20 dB to 30 dB lower than the signal going to the antenna. Coupling off power in this manner results in some power loss in the transmit path. This directional coupler insertion loss is usually a few tenths of a decibel.

In wireless infrastructure applications where the maximum transmitted power typically ranges from 30 dBm to 50 dBm (1 W to 100 W), the signal coming from the directional coupler is still too strong for the RF detector that measures the signal. As a result, some additional attenuation is required between the coupler and the RF detector.

Modern rms and log RF detectors have a power detection range of anywhere from 30 dB to 100 dB and provide a temperature and frequency stable output. In most applications, the detector output is applied to an analog-to-digital converter (ADC) to be digitized. Calibration coefficients stored in nonvolatile memory (EEPROM) convert the code from the ADC into a transmitted power reading. Compare this power reading to a setpoint power level. If there is a discrepancy between the setpoint and the measured power, make a power adjustment. Make this power adjustment at any one of a number of points in the signal chain. The amplitude of the baseband data driving the radio can be adjusted, a variable gain amplifier (at IF or RF) can be adjusted, or the gain of the PA can be changed. In this way, the gain control loop regulates itself and keeps the transmitted power within desired limits. It is important to note that the gain control transfer functions of voltage variable attenuators (VVAs) and PAs are often quite nonlinear. As a result, the actual gain change resulting from a given gain adjustment is uncertain. This uncertainty reinforces the need for a control loop that provides feedback on changes made and further guidance for subsequent iterations.

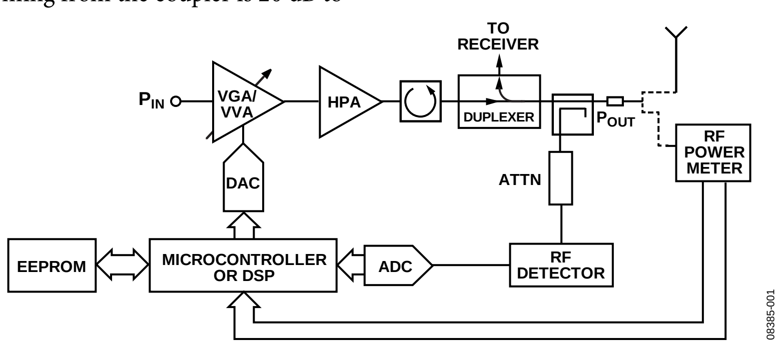

Figure 1. Typical RF Power Amplifier with Integrated Transmit Power Control (An integrated RF power detector provides continuous feedback on the current level of power being transmitted. Use an external RF power meter along with the RF power detector to calibrate the transmitter.)

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REVISION HISTORY

5/2018—Rev. 0 to Rev. A

Changes to Typical Wireless Transmitter with Integrated Power Control Section 1
Changes to RF Detector Transfer Function Section 3
Changes to Table 1 4
Changes to Postcalibration Errors Section 7

12/2009—Revision 0: Initial Version

THE NEED FOR FACTORY CALIBRATION

In the typical wireless transmitter system previously described, almost none of the components provide precise absolute gain accuracy specifications. Consider the case of a transmit power error target of ±1 dB. The absolute gain of devices such as PAs, VVAs, RF gain blocks, and other components in the signal chain can vary from device to device to such an extent that the resulting output power uncertainty is significantly greater than ±1 dB. In addition, signal chain gain varies further as the temperature and frequency change. As a result, it is necessary to continually monitor and control the power being transmitted.

Output power calibration can be defined as the transfer of the precision of an external reference into the system being calibrated. A calibration procedure involves disconnecting the antenna and replacing it with an external measurement reference such as an RF power meter, as shown in Figure 1. In this way, the accuracy of a precise external power meter is transferred into the integrated power detector of the transmitter. The calibration procedure involves setting one or more power levels, taking the reading from the power meter and the voltage from the RF detector, and storing all of this information in EEPROM. Then, with the power meter removed and the antenna reconnected, the transmitter is able to precisely regulate its own power. As parameters such as amplifier gain vs. temperature, transmit frequency, and desired output power level change, the calibrated on-board RF detector acts like a built-in power meter with an absolute accuracy that ensures that the transmitter is always emitting the desired power within a defined tolerance.

The Calibrating an RF Power Control Loop section describes a factory calibration procedure. First, the characteristics of a typical RF power detector must be examined. The linearity and stability over temperature and frequency of the RF detector of the system strongly influence the complexity of the calibration routine and the achievable postcalibration accuracy.

RF DETECTOR TRANSFER FUNCTION

Figure 2 shows the transfer function of a log-responding RF detector (log amp) with temperature drift exaggerated for illustrative purposes. The log amp transfer function is linear-in-dB and can be modeled using a simple first-order equation within its linear operating range. Three curves are shown: output voltage vs. input power at +25°C, +85°C, and −40°C. At +25°C, the output voltage of the detector ranges from around 1.8 V at −60 dBm input power to 0.4 V at 0 dBm. The transfer function closely follows an imaginary straight line, which is laid over the trace. Although the transfer function deviates from this straight line at the extremities, note that there are also signs of nonlinearity at power levels between −10 dBm and −5 dBm.

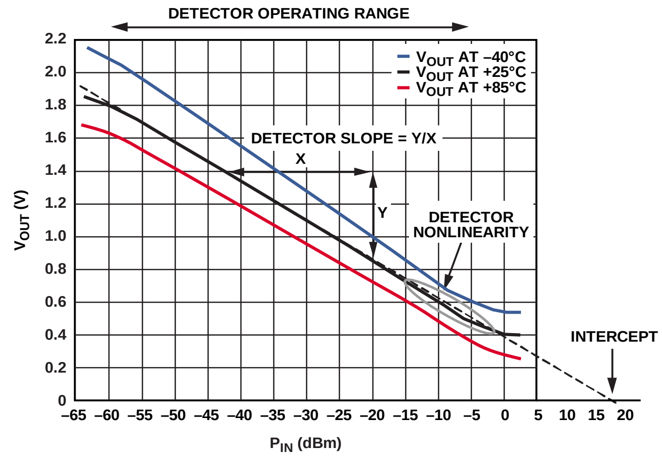

Figure 2. Transfer Function (V_{OUT} vs. P_{IN}) of a Log-Responding RF Power Detector with Temperature Drift Exaggerated for Illustrative Purposes

A quick calculation suggests that this detector has a slope of approximately −25 mV/dB (that is, a 1 dB change in input power results in a 25 mV change in output voltage). This slope is constant over the linear portion of the dynamic range. Thus, notwithstanding the slightly degraded nonlinearity that was identified at around −10 dBm, model the behavior of the transfer function at 25°C by using the following equation:

$$V_{OUT} = Slope \times (P_{IN} - Intercept)$$

where *Intercept* is the point at which the extrapolated straight line crosses the x-axis of the plot (see Figure 2).

When slope and intercept are known and the output voltage from the detector is measured, calculate the unknown RF input by rewriting the preceding equation as follows:

$$P_{IN} = (V_{OUT}/Slope) + Intercept$$

Therefore, model the transfer function of the detector by using this simple first-order equation. From a calibration perspective, this equation is useful because the equation allows the transfer function of the detector to be established by applying and measuring as few as two different power levels during the calibration procedure.

Next, consider the behavior of this imaginary detector over temperature. At an input power of –10 dBm, note that the output voltage changes by approximately 100 mV from ambient temperature to either −40°C or +85°C. From the previous calculation of the slope (−25 mV/dB), this equates to a deviation in measured power of ±4 dB, unacceptable in most practical systems. In practice, a detector whose transfer function has minimal drift vs. temperature is needed. To ensure that a calibration procedure performed at ambient temperature is also valid over temperature, allow the transmitter to be factory calibrated at ambient temperature to avoid expensive and time-consuming calibration cycles at hot and cold temperatures.

If the transmitter is frequency agile and must transmit at multiple frequencies within a defined frequency band, pay attention to the behavior of the detector vs. frequency. Ideally, an RF detector whose response does not change significantly within a defined frequency band must be used. The use of a detector with a flat frequency response allows calibration of the transmitter at a single frequency (generally at midband) and ensures that there is little to no loss of accuracy as the frequency changes.

Table 1 shows the detection ranges and temperature stability of various rms and log RF power detectors from Analog Devices, Inc.

Table 1. RMS and Log RF Power Detectors

Device	Description	Input Frequency (GHz)	Input Range (dB)	Temperature Drift (dB)	Supply Voltage, V_S (V)	Supply Current, I_{SY} (mA)
HMC1020	Linear-in-dB rms detector	0 to 3.9	72	±0.75	5	55
LT5581	Linear-in-dB rms detector	0.01 to 6	40	±1	2.7 to 5	1.4
LTC5583	Dual channel linear-in-dB rms detector	0.04 to 6	60	±0.5	3.3	80.5
ADL5902	Linear-in-dB rms detector	0.05 to 9	65	±0.5	5	73
ADL5904	Linear-in-dB rms detector	0 to 6	45	±0.5	3.3	3.5
LTC5582	Linear-in-dB rms detector	0.04 to 10	57	±0.5	3.3	41.6
LTC5596	Linear-in-dB rms detector	0.1 to 40	35	±1.5	3.3	30
AD8310	Log detector	0 to 0.44	95	±1	3 to 5	8
HMC602	Log detector/controller	0.001 to 8	70	±1	5	113
AD8317	Log detector/controller	0.001 to 10	55	±0.5	3.3 to 5	22
HMC611	Log detector/controller	0.001 to 10	70	±1	5	103
ADL5519	Dual log detector/controller	0.001 to 10	62	±0.5	3.3 to 5	60
AD8309	Log amplifier with limiter output	0.005 to 0.5	100	±1	3 to 5	16
LT5537	Log detector	<0.01 to 1	83	±1	2.7 to 5	13.5
ADL5506	Log detector	0.03 to 4.5	45	±1	3 to 5	3.8
LT5538	Log detector	0.04 to 3.8	75	±1	3 to 5	29
HMC600	Log detector/controller	0.05 to 4	70	±0.5	3 to 5	29
HMC713LP3E	Log detector/controller	0.05 to 8	54	±0.5	3.3 to 5	17
HMC1094	Millimeter wave log detector	1 to 23	50	±0.5	3.3	85
HMC948	Millimeter wave log detector	1 to 23	54	±0.5	3.3	91
HMC662	Millimeter wave log detector	8 to 30	54	±0.5	3.3	88

CALIBRATING AN RF POWER CONTROL LOOP

Figure 3 shows the flowchart used to calibrate a transmitter similar to the one shown in Figure 1. This simple and quick two-point calibration is useful where power levels must only be set approximately (but must be measured precisely). For this calibration to be effective, the integrated RF detector must be stable across temperature and frequency, and it must have a predictable response that can be modeled using a simple equation.

Ensure that the operating power range of the transmitter is aligned with the linear operating range of the RF detector. To begin, remove the antenna and connect the power meter to the antenna connector. Next, set the output power level close to the maximum power. The power meter measures the power at the antenna connector and sends the reading to the on-board microcontroller or digital signal processor (DSP) of the transmitter. At the same time, the RF detector ADC is sampled, and the processor of the transmitter reads the sample.

Next, reduce the output power of the transmitter to a level that is close to the minimum power and repeat the procedure (measure the power at the antenna connector and the sample RF detector ADC).

With these four readings (low power level, high power level, low ADC code, and high ADC code), the slope and intercept can be calculated (see Figure 3) and stored in nonvolatile memory.

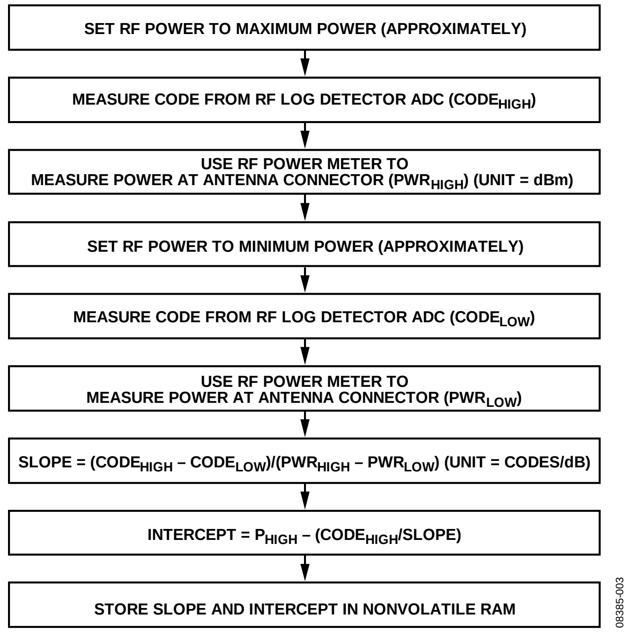

Figure 3. Simple Two-Point Calibration Procedure to Calibrate a Transmitter with an Integrated Log Detector

FIELD OPERATION OF AN RF POWER CONTROL LOOP

Figure 4 shows the flowchart used to precisely set power in a transmitter after calibration. In this example, the goal is to have a transmit power error that is less than or equal to ±0.5 dB. Initially, set the output power level based on a best first guess. Next, sample the detector ADC. Retrieve the slope and intercept from memory and calculate the transmitted output power level.

If the output power is not within ±0.5 dB of P_{SET}, increase or decrease the output power by approximately 0.5 dB using a VVA. The term approximately is used because the VVA may have a nonlinear transfer function. Measure the transmitted power again and apply further power increments until the transmitted power error is less than ±0.5 dB.

When the power level is within tolerance, continually monitor and adjust if necessary. For example, if the gain of a component in the signal chain drifts with changing temperature, activate the loop when the measured power goes outside its ±0.5 dB setpoint range.

Other variations of this algorithm exist. For example, if it is desirable to keep the output power as low as possible but still no more than 0.5 dB from the setpoint, take a different approach. In this case, the first power setting is at a level that is less than the desired power level (and outside the tolerance). The loop then measures the power but setpoint increments are much smaller (for example, 0.1 dB). In this way, the output power always approaches the setpoint from a value that is less than the setpoint. As soon as the output power enters the −0.5 dB band, power increments stop, ensuring that the actual level is always below the setpoint level while still being within tolerance.

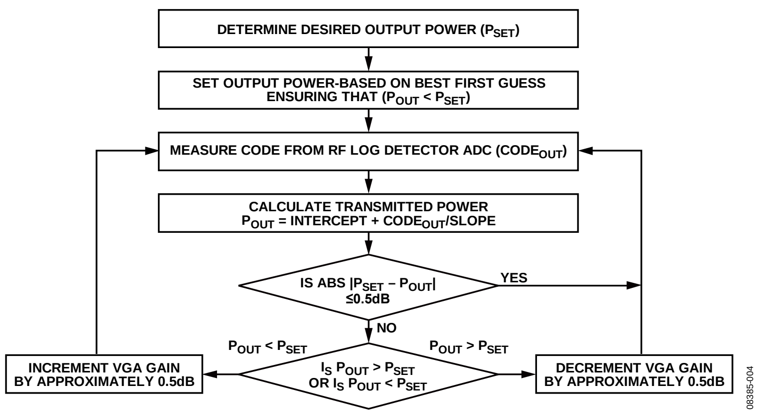

Figure 4. Operation of Transmitter After Calibration

POSTCALIBRATION ERRORS

Figure 5 to Figure 8 show data from the same RF detector but use a different selection and number of calibration points. Figure 5 shows the detector transfer function at 2.2 GHz for the AD8318, a wide dynamic range RF log detector that operates up to 8 GHz. In this case, the detector was calibrated using a two-point calibration (at −12 dBm and −52 dBm). When calibration is complete, plot the residual measurement error. Note that the error is not zero even at the ambient temperature at which calibration was performed because the log amp does not perfectly follow the ideal V_{OUT} vs. P_{IN} equation (V_{OUT} = Slope × (P_{IN} − Intercept)), even within its operating region. The error at the −12 dBm and −52 dBm calibration points is, however, equal to zero by definition.

Figure 5 also includes error plots for the output voltage at −40°C and +85°C. These error plots are calculated using the 25°C slope and intercept calibration coefficients. Unless a temperature-based calibration routine is implemented, the 25°C calibration coefficients with slight residual temperature drift must be used.

In many applications, it is desirable to have higher accuracy when the PA is transmitting at its maximum power. This desire makes sense from a number of perspectives. First, there may be regulatory requirements that demand this higher level of accuracy at full or rated power. However, from a system design perspective, there is also value in increased accuracy at rated power. Consider a transmitter designed to transmit 45 dBm (approximately 30 W). If calibration can at best provide accuracy of ±2 dB, the PA circuitry (power transistors and heat sinks) must be designed to safely transmit as much as 47 dBm or 50 W. Instead, a system where the postcalibration accuracy is ±0.5 dB can be designed so that the PA must be designed to transmit more RF power than the application calls for to safely transmit 45.5 dBm or approximately 36 W.

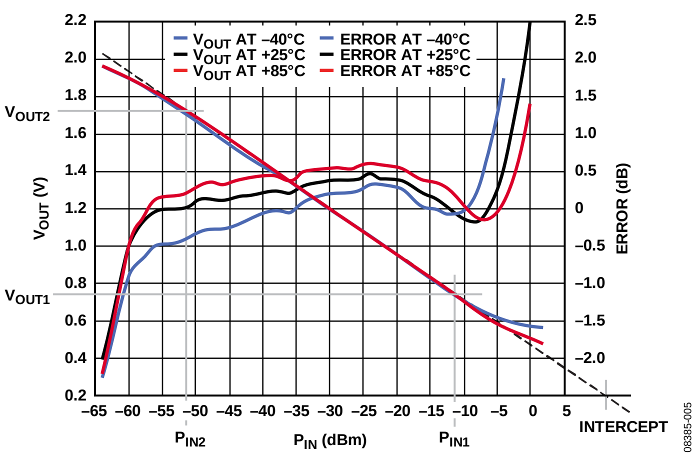

Figure 5. Two-Point Calibration with Calibration Points in Linear Operating Range of Detector Provides Good Overall Performance

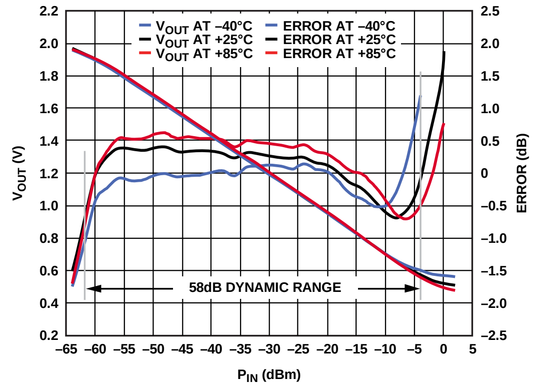

Figure 6. Moving Calibration Points Apart and into a Less Linear Operating Range Extends the Operating Range but at the Cost of Degraded Accuracy

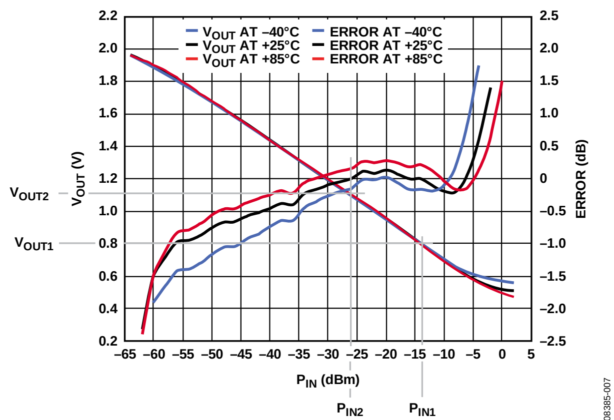

Figure 7. Two-Point Calibration with Calibration Points Close Together Provides Improved Accuracy over a Narrow Range

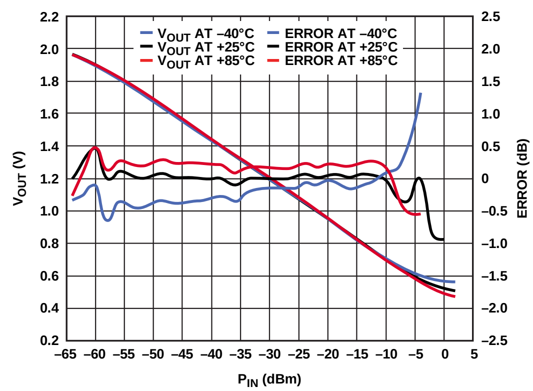

Figure 8. Multipoint Calibration Extends Detector Range and Can Improve Linearity but at the Cost of a More Complex Calibration Procedure

By changing the points at which calibration is performed, the achievable accuracy can in some cases be greatly influenced. Figure 7 shows the same measured data as Figure 5 but uses different calibration points. Notice how the accuracy is very high (about ±0.25 dB) from −10 dBm to −30 dBm in Figure 7. However, accuracy decreases at lower power levels that are further away from the calibration points.

Figure 6 shows how moving calibration points increases dynamic range at the expense of linearity. In this case, the calibration points are −4 dBm and −60 dBm. These points are at the end of the linear range of the device. Once again, an error of 0 dB at the calibration points at 25°C can be seen, and the range over which the AD8318 maintains an error of <±1 dB is extended to 60 dB at 25°C and 58 dB over temperature. The disadvantage of this approach is that the overall measurement error increases, especially in this case at the top end of the range of the detector.

Figure 8 shows the postcalibration error using a more elaborate multipoint algorithm. In this case, multiple output power levels (separated by 6 dB in this example) are applied to the transmitter, and the output voltage of the detector at each power level is measured. These measurements are used to break the transfer function down into segments, with each segment having its own slope and intercept. This algorithm tends to greatly reduce errors due to detector nonlinearity and leaves temperature drift as the main source of errors. The disadvantage of this approach is that the calibration procedure takes longer, and more memory is required to store the multiple slope and intercept calibration coefficients.

Figure 8 illustrates the difference between the behavior of the power detector at the low and high ends of its dynamic range. Although multipoint calibration extends the high end dynamic range, this range extension is not useful because of the increased temperature drift. Notice how the ambient, hot, and cold traces diverge at power levels greater than −10 dBm. At low power levels, the result is more useful. Again, the multipoint calibration helps to extend the low end dynamic range. However, in this case, the hot and cold traces closely track the ambient trace, even as it becomes nonlinear. Thus, when this nonlinearity is removed using multipoint calibration, excellent accuracy is maintained over temperature, which usefully extends the transfer function of the AD8318 down to −65 dBm.

CONCLUSIONS

In applications where accurate RF power transmission is required, some form of system calibration is necessary. Modern IC-based RF power detectors have linear responses and are temperature and frequency stable. A linear response coupled with stability across temperature and frequency can significantly simplify system calibration and can provide a system accuracy of ±0.5 dB or better. The placement and number of calibration points can have a significant effect on the achievable postcalibration accuracy.

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