Chapter IX
Using Calibration and Temperature Compensation to improve RF Power Detector Accuracy

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Introduction
Accurate RF power management is a critical issue in modern wireless transmitters, offering a variety of benefits ranging from power amplifier protection in base-stations to battery conservation in mobile applications. RF power detectors, such as logarithmic amplifiers, allow RF power management systems to monitor and dynamically adjust the transmitted power over a wide range. Although the accuracy of power detection has significantly improved in recent years, applications such as those requiring high power transmission are dramatically affected even by fractions of a dB of power detection error. As a result, there is a continuous push for tighter detector performance.

Using a combination of a logarithmic amplifier and a temperature sensor it is possible to design a temperature compensation scheme to significantly reduce the contributions of the two major error factors in RF power management, temperature and process variations. In some cases, the temperature compensation hardware is integrated onto the power detector chip.

RF Power Management

- **RF Power Management is Critical in Modern Wireless Transmitters**
- **Preserves Battery Current in Terminals**
- **Protects High Power Amplifiers**
- **RF Detectors Enable Measurement and Control of RF Power**
- **High RF Power Measurement Precision Can Be Achieved Using Temperature Sensors and On-Board Temperature Compensation**

RF Power Management at a Glance
Accurate RF power management in base-stations is of high importance. Overdriving the transmitting power amplifier beyond the necessary output power level can be costly. Excessive current usage will result in higher expenses and also introduces thermal dissipation issues requiring more thermal relief. In the extreme case, overdriving the power amplifier can lead to reliability issues resulting from burn-out failures.

The added benefits of accurate RF power management in base-stations also transcend to mobile transmitters as they have similar demands. With the ability to accurately control the output power, the mobile device can minimize supply current expenditures. For instance, RF power management allows the transmitted power to be precisely limited to the minimum required power level reducing battery current Accurately controlling the power will extend talk time while still permitting the mobile transmitters to meet the cellular standard requirements.

A Typical Wireless Transmitter with RF Power Control
Figure 1 shows a block diagram of a typical RF transmitter with integrated power management. The transmit signal path consists three consecutive stages – base-band, radio, and power amplifier.

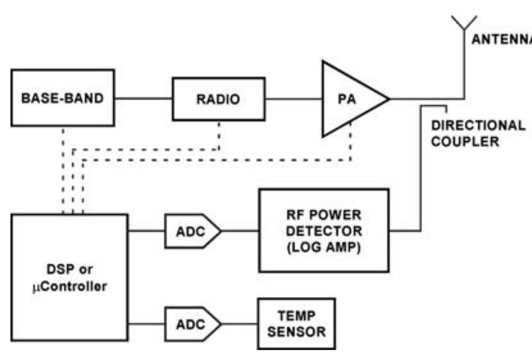

Figure 1. RF power management circuits use logarithmic amplifiers to take advantage of the their wide linear-in-dB detection range.

A portion of the transmitted signal is sampled by the directional coupler before it reaches the antenna. The sampled RF power is delivered to the power detector where it is converted to a DC voltage. The output voltage of the power detector is digitized and fed to the digital signal processor (DSP) or the microcontroller. Once the power measurement is available as a digital level, a decision is made based on the measured output power versus the desired output power. The microcontroller will adjust the output power using a digital to analog converter (DAC) and a variable gain amplifier (VGA) to drive the signal path power control – either at the base-band, radio, or power amplifier. The RF power management loop will reach steady-state once the measured output power and the desired output power are balanced. A temperature sensor can also be introduce as an input to the microcontroller to add temperature compensation capabilities. A similar RF power management loop can be implemented using only analog circuitry in transmitters.

Implementing RF Power Control

- **With Digital Control, Detector Output Is Sampled By An ADC**
- **DAC Adjusts Gain In Signal Chain To Achieve Desired Output Power**
- **External Temperature Sensor Helps Compensate For Drift of Detector**
- **Analog Control Loop Can Also Be Implemented**

Historically, diode detectors have been used in RF power management circuitry to regulate transmitted power. They offer good temperature stability at high input power levels, but have poor performance at low power levels. Even with temperature compensation circuitry, a diode detector can only offer a small detection range with worsening temperature performance at low input powers. A popular alternative to the diode detector is the demodulating logarithmic amplifier. The logarithmic amplifier offers an easy to use linear-in-dB RF power detection response with a wide dynamic range.

A 50 dB Log Amp With Operation Up To 3.5 GHz

Figure 2 shows the block diagram of a progressive compression logarithmic amplifier. This is a complete, low cost subsystem for the measurement of RF signals in the frequency range of 50 MHz to 3.5 GHz. It has a typical dynamic range of 45 dB and is intended for use in a wide variety of cellular handsets and other wireless devices. It provides a wider dynamic range and better accuracy than using discrete diode detectors. In particular, its temperature stability is excellent over the full operating range of −40°C to +85°C.

In the block diagram, there are four 10 dB cascaded limiting amplifiers that make up the progressive compression chain. Five full-wave rectifier detector cells convert the RF signal voltages to currents – one detector cell at the RF input and four at the outputs of the amplifier stages. The currents generated by the detector cells are proportional to the average of the voltage signal levels and are added together to approximate a logarithmic function. The sum of currents in converted to a voltage with a high-gain stage. The five detector cells across the four 10 dB amplifier stages allow the logarithmic amplifier to have a 50 dB detection range.

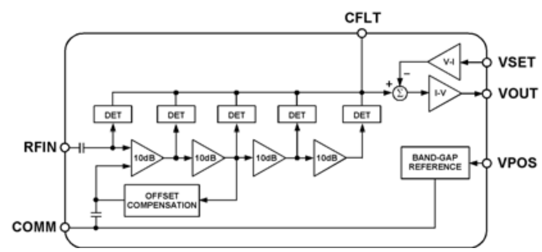

Figure 2. Five detector cells across four 10 dB amplifier stages allow the progressive compression logarithmic amplifier to have a 50 dB detection range.

Figure 3 shows the transfer function a 60 dB logarithmic amplifier. There is a linear relationship between the RF input power and the output voltage, that is, as the input power increases, the output voltage follows in a linear-in-dB fashion. The figure also includes a logarithmic conformance error curve. The conformance error curve serves to more closely examine the logarithmic amplifier's performance. The slope and x-axis intercept of the curve are calculated over the linear part of the detection range, highlighted in grey. This information provides a simple linear model to compare with the actual response of the logarithmic amplifier. The ideal linear reference model is represented by the dashed-line in the plot. The comparison of the ideal linear model to the transfer function yields the logarithmic conformance error curves scaled in dB.

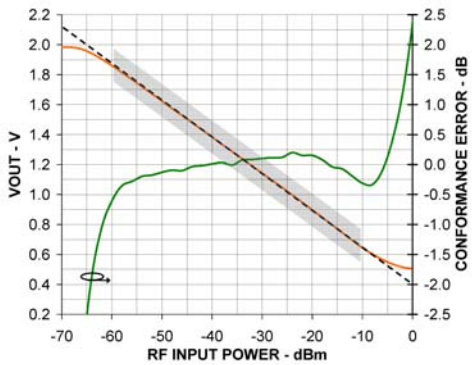

Figure 3. An ideal reference model calculated over the linear part of the detection range is used to compare with the actual response of the logarithmic amplifier. The comparison yields a logarithmic conformance error curve.

The method of calculating logarithmic conformance error is similar to the two-point calibration technique used in RF power management system calibration. During production testing, two known RF signal strengths are chosen in the linear range of the detector. Using the resulting voltage outputs, the slope and intercept characteristics of the response are calculated and stored in non-volatile memory to form a simple linear equation. The transmitted power in the field can then be easily calculated using the linear-in-dB function and the measured detector voltage. There are the considerable benefits of reduced cost and trimmed test time by using only two points at calibration. However, this calibration practice is only possible due to the log amp's linear performance.

Log Conformance Calculations

- **Conformance error curves serve to examine the log amp's performance**
- **The slope and intercept are calculated over the linear part of the detection range**
- **The comparison of the ideal linear model to the transfer function yields the logarithmic conformance error curves scaled in dB**
- **Error calculation method is similar to the two-point calibration technique used in system calibration**
- **Once ideal model is established, transmitted power can be calculated using the linear-in-dB function and the measured detector voltage**

Because calibration is generally done at a single temperature, the effects of temperature on the detector are important to quantify. The accuracy of a detector over temperature can be expressed in terms of conformance error. Figure 4 shows the transfer function at 900 MHz. The plot includes the transfer functions at -40ºC and +85ºC, as well as the logarithmic conformance error curves over temperature. As would be the case with two-point calibration, the same 25ºC linear reference is used to generate the three linear conformance error curves.

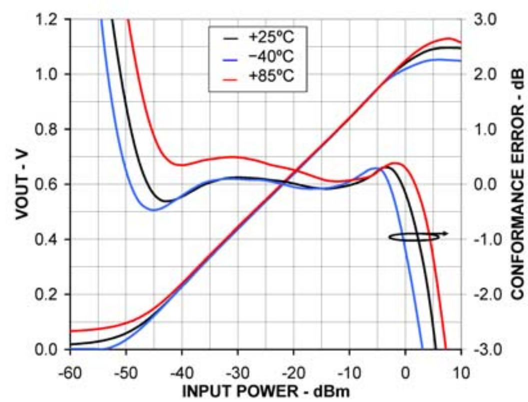

Figure 4. The logarithmic conformance error at 900 MHz of a single log detector device shows an accuracy of ±0.5 dB over temperature.

The transfer function of the logarithmic amplifier at 25ºC ambient temperature has a slope of 50.25 dB/V and a -51.6 dBm intercept (the point at which the extrapolated linear reference would intersect with the x-axis). The curve at 25ºC hovers around the 0 dB error line, while the temperate extremes have minor slope and intercept shifts. The logarithmic conformance error of this single device across temperature stays within ±0.5 dB across a 40 dB detection range. The temperature drift at +85ºC is the limitation to the dynamic range. Individual devices may have excellent accuracy over temperature, however, minor part-to-part variations inherent in semiconductor processing can prove to be an obstacle to precise RF power management.

Figure 5 shows the distribution of logarithmic conformance error curves of 70 multiple devices. The sampling of devices spans across various lots to demonstrate process variations. Each device has three temperature curves calibrated to its 25ºC linear reference. Although there is a clear variation from part-to-part, the distribution is very tight. The population of device over temperature has an accuracy of ±1 dB over more than 40 dB of detection range. Temperature compensation can be introduced due to the repeatable drift from part-to-part.

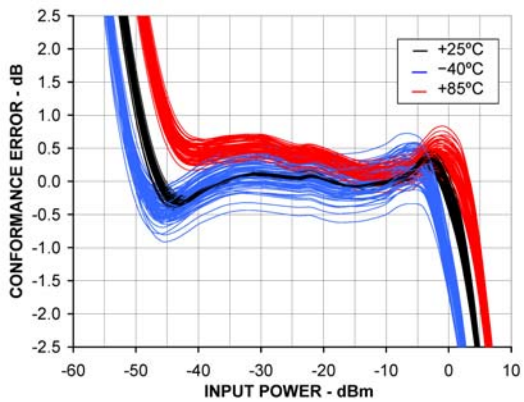

Figure 5. There is a clear variation in logarithmic conformance error curves from part-to-part, however, the distribution is very tight. Temperature compensation can be introduced due to the repeatable temperature drift.

Typically wireless communication standards require ±1 dB and ±2 dB accuracy from transmit power detection schemes with relaxed limits at extreme temperatures. The raw accuracy of the logarithmic amplifier is sufficient to meet most standards without any fine tuning. Still, there are clear advantages associated with exceeding the RF power management requirements set by the different standards.

Digital Compensation Of Errors

As previously discussed, the microcontroller can actively adjust the transmitted power by biasing the transmit signal path. By adding a temperature sensor, the microcontroller can further increase the accuracy of a RF power management system. As long as the detector has repeatable temperature drift, some level of error compensation is possible. Compensation routines taking into account environmental changes can be integrated in the microcontroller's decision making to significantly reduce or eliminate process and temperature variations. For example, if a power detector repeatedly drifts with temperature, a compensation algorithm can be implement to remove the expected error at the known temperature.

Figure 6 shows the logarithmic conformance error curves for a large number devices. At 3.5 GHz, the temperature drift is spread out from +1 dB to -4 dB. The population at -40ºC follows the 25ºC curves closely. In contrast, the distribution at +85ºC is shifted by 2.5 dB and is no longer parallel to the 25ºC distribution. Although the temperature drift at this frequency is sizeable, the distribution at each particular temperature remains very tight. Because of this drift repeatability, a compensation scheme can be implemented to dramatically improve the accuracy.

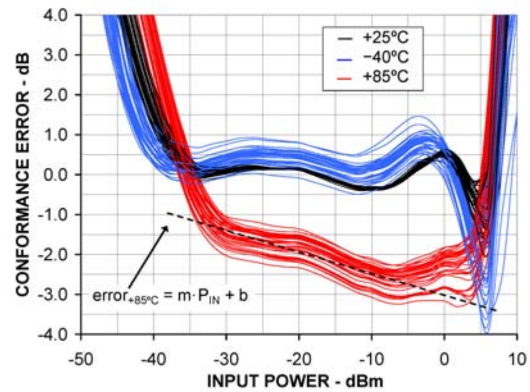

Figure 6. At 3.5 GHz, the temperature drift distribution at +85ºC is shifted and no longer parallel to the 25ºC distribution. A trend line through the linear region of the +85ºC logarithmic conformance curves represents the error model at that temperature.

Over temperature there are slope and intercept variations that lead to temperature drift. With this in mind, an error model can be derived by analyzing the population of devices. An error function expressing the movement of the population over temperature can be created, as shown in Figure 6. A trend line is drawn through the linear region of the +85ºC log conformance curves to represent the error model at +85ºC, $error_{+85\,ºC}$. Using the slope and intercept characteristics of the error line, a complimentary function can be used to cancel out the temperature variation. Still, the model only represents the error introduced by the +85ºC temperature drift.

The majority of the temperature drift occurs linearly between 25ºC and +85ºC. A generalized error function for all temperatures in that range can be created using a scaling factor, k(T), which is a function of temperature. The combination of the complimentary error function and the temperature scaling function are combined as shown in Figure 7. As the temperature increases, the scaling factor will track and eliminate the error caused by the rising temperature drift.

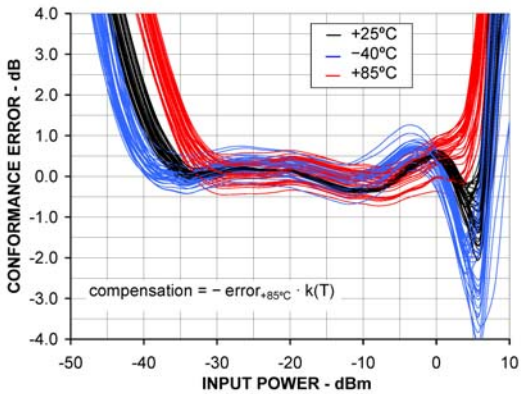

Figure 7. A complimentary error function is used to cancel out temperature variation. The logarithmic conformance error over the full temperature range is improved with error compensation.

Figure 7 shows the distribution of logarithmic conformance using the error compensation scheme described. Before compensation, the logarithmic conformance error spanned 5 dB. With the incorporation of error compensation, the logarithmic conformance error over the full temperature range is improved to approximately ±0.5 dB from -30 dBm to 0 dBm. The achievable accuracy of a RF power management system is determined by the distribution of the population of devices. Similar results are also possible at lower temperatures and lower frequencies where temperature drift is not as significant.

Error Compensation Method

- **Over temperature, slope and intercept variations lead to temperature drift.**
- **An error function can be created to express the movement of the distribution over temperature**
- **A function complimentary to the error is used to cancel out the temperature variation**

A 60 dB Log Amp with Analog Temperature Compensation

Figure 8 shows the block diagram of the AD8318, a demodulating logarithmic amplifier capable of accurately converting an RF input signal to a corresponding decibel-scaled output voltage. It also employs a progressive compression technique over a cascaded amplifier chain, each stage of which is equipped with a detector cell. The device can be used in measurement or controller mode. The AD8318 maintains accurate log conformance for signals of 1 MHz to 6 GHz and provides useful operation to 8 GHz. The input range is typically 60 dB (re: 50 Ω) with error less than ±1 dB. The AD8318 has a 10 ns response time that enables RF burst detection to beyond 60 MHz. The device provides unprecedented logarithmic intercept stability versus ambient temperature conditions. A 2 mV/K slope temperature sensor output is also provided for additional system monitoring.

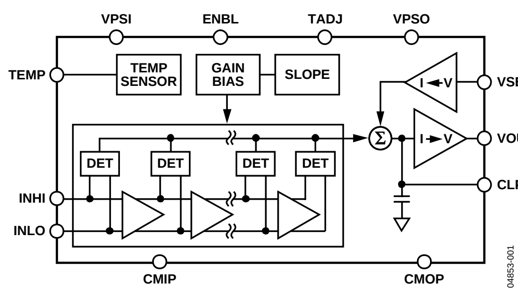

Figure 8. Block diagram of the AD8318 progressive compression logarithmic amplifier with 60 dB log conformance for signals of 1 MHz to 8 GHz

Through the life span of a semiconductor process there are variations in its parameters, such as sheet resistance, capacitance, and beta. All of these variants influence the slope, intercept, and temperature performance of the detectors. A method to mitigate the influence of process variation is to use a laser-trimmed logarithmic amplifier. Figure 9 shows a distribution of logarithmic conformance of the AD8318, a trimmed 60 dB logarithmic amplifier, at 1.9 GHz. Instead of digital compensation, the device uses on-board temperature circuitry and an external resistor to optimize temperature performance. The value of the resistor is dependant on the required magnitude of the correction coefficient. The analog compensation circuit alone achieves a tight distribution with ±0.5 dB in the central detection range.

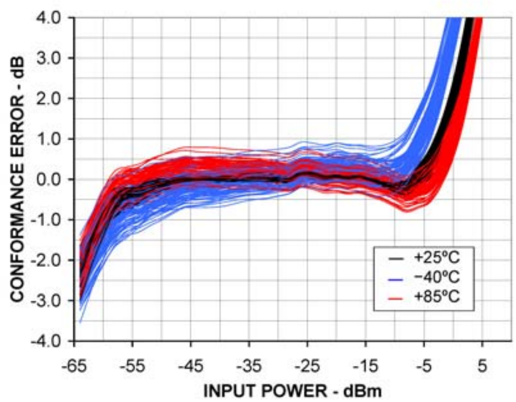

Figure 9. Instead of digital compensation, a laser-trimmed logarithmic amplifier using analog compensation circuitry can achieve accurate RF power management.

Summary

With accurate RF power management, base-stations and mobile transmitters can benefit from power amplifier protection and reduced power consumption while dramatically surpassing cellular standard requirements. Using a stable logarithmic amplifier and a temperature sensor, microcontrollers can compensate for temperature drift errors to improve the overall accuracy of a RF power management system. Logarithmic amplifiers with tight temperature distributions allow for simple error compensation. Two point calibration with a moderate amount of temperature drift characterization can set the stage for accurate RF power management of ±0.5 dB over temperature.