APPLICATION NOTE

Increasing the Maximum Transmit Power Rating of a Power Amplifier Using a Power Combining Technique

Introduction

Today’s broadband communications use high order modulation transmission links with a high crest factor. As a result, a linear Power Amplifier (PA) in the transmit chain operates at a significantly backed-off power from compression to meet the linearity performance of Error Vector Magnitude (EVM) and Adjacent Channel Power Ratio (ACPR).

The PA circuit is usually designed and optimized for a given rated transmit power to minimize current consumption. Portable electronics such as laptops and cell phones that integrate a broadband interface like WLAN need to be efficient. In these cases, the headroom, or margin to the maximum operating power of a PA that guarantees EVM and ACPR performance may be in the order of a single decibel. Therefore, usage of the device is limited to a fairly narrow power range.

This Application Note describes a method to extend the headroom of a PA by the use of a power combining technique. Power combiners and splitters are popular RF components that can be used to combine power from different sources, or to split RF receive signals for processing through different receive chains.

The first section of this Application Note presents the theory of power combining. It is demonstrated that combining the output of two identical PAs can increase the transmitter output power by a factor of 3 dB while maintaining the same level of linearity performance.

The second section provides an example that illustrates and verifies the theory of operation. It shows the results of combining two Skyworks SKY65152-11 PAs using a WLAN 802.11g test bench.

Transmit Power Extension

Power Combiners/Splitters

A power combiner is a passive, three-port device that performs the linear function of adding incoming signals to a single output. As a passive device, the power combiner is reversible and can be used as a power splitter when using the combined output as the input.

There are various types of power combiner circuits depending on the number of signals combined together, and whether they combine power in phase, in quadrature or even out of phase. Note that this Application Note does not discuss power combiner design.

A two-way power combiner circuit that adds two incoming signals in phase is shown in Figure 1. Insertion loss from an ideal circuit (3 dB) is diagrammed in Figure 2.

![Figure 1. Ideal In-Phase Power Combiner S-Parameter Circuit](image-url)
A 3 dB Output Power Increase

Figure 3 shows a power combiner excited by two in-phase sources, V1 and V2. The in-phase sources are plotted against time along with the output of the combiner, V3.

The V3 peak voltage is $\sqrt{2}$ times V2, which corresponds to a 3 dB power increase. Note that the V1 and V2 signals are actually attenuated by 3 dB when passing through the combiner ($S31 = S32 = -3$ dB), which means their peak voltage is reduced by a factor of $\sqrt{2}$. When combined, they are multiplied by two.

The ideal combiner output voltage, V3, shown in Figure 4, can be defined as:

$$V3 = \frac{2}{\sqrt{2}} \times V1 = \sqrt{2} \times V1 = \sqrt{2} \times V2$$

Figure 5 shows the results when one of the inputs is zero (V2 in this case). It is interesting to note that the output of the combiner, V3, is now 3 dB lower than the input, V1.

The Complete Output Power Extension Circuit

Combined and standalone amplifier circuits are diagrammed in Figure 6. The top circuit shows two amplifiers in a combined configuration. The RF source, V1, is split into two signals, each one equal in amplitude and phase. The two signals feed the input of two PAs, AMP1 and AMP2.

The outputs of the two amplifiers are combined together in the same way previously described. The bottom circuit shown in Figure 6 diagrams the corresponding standalone amplifier, AMP3, which has 32 dB of gain and a 1 dB Output Compression Point (OP1dB) of +33 dBm.

Figure 7 shows the results of a simulation of output power versus input power for both circuits. The saturated power ($P_{Sat}$) of the combined amplifier circuit (marker 2) is 3 dB higher than the $P_{Sat}$ of the standalone amplifier (marker 1).
Figure 4. Time Domain Waveforms at the Inputs and Output of an In-Phase Power Combiner

Figure 5. Time Domain Waveforms at the Inputs and Output of an In-Phase Power Combiner
When One of the Input Signals is Zero

Figure 6. Combined and Standalone Amplifier Circuits
Figure 7 shows the output power (Stand-alone and Combined PA) vs input power characteristic of both circuits. It is very interesting to notice that in the linear region, both circuits have the same 32 dB Small Signal Gain (SSG). However, the gain rolls off sooner for the stand-alone amplifier (solid line) and the OP1dB of the combined circuit is +36 dBm compared to only +33 dBm for the stand-alone amplifier.

A possible application of the combined amplifier may be to improve linearity. As a matter of fact, for a given output power, the gain compression of the combined amplifier circuit is less than the gain compression of the stand-alone amplifier. In practice, the combiner has some loss (S31 = S32 < -3 dB) that reduces the combined OP1dB in the order of 0.5 dB for a 2.5 GHz combiner.

Figure 8 shows the gain vs output power (POUT) characteristic of both circuits. Other parameters may also reduce OP1dB. In fact, the peak voltages of the two amplifiers add up only if they are in phase. Figure 9 shows that a 45 degree phase shift between the two legs of the circuit produces a 0.7 dB drop in gain. Because the input for the two amplifiers comes from the same RF source, the phase mismatch is only due to the power splitter, PA, combiner, and board layout.

A narrow band splitter/combiner can easily achieve less than a 5 degree phase imbalance while the PA contribution (such as with the Skyworks SKY65152-11) is fairly small since the input/output matching is integrated within the Multi Chip Module (MCM). Eventually, the RF designer should pay attention to the PCB layout design to make sure the traces that connect each side of the splitter and combiner to the PAs have the same length, which will help to minimize any phase difference.
Combining Two SKY65152-11 PAs Using a WLAN 802.11g Test Bench

A WLAN 802.11g test bench is diagrammed in Figure 10. The 802.11g output waveform of the signal generator feeds a power splitter. The outputs of the power splitter provide an input signal to both of the SKY65152-11 PAs.

A power combiner combines the output of the two PAs, which is analyzed for Error Vector Magnitude (EVM) using a vector demodulator.

The insertion loss of the power splitter is 3.3 dB (see Figure 11). The insertion loss of the power combiner is 3.5 dB (see Figure 12). The phase mismatch between the two paths was measured to be less than 5 degrees, which does not impact the output power as indicated in Figure 9.

In Figure 13, gain is plotted against output power for the three different circuits: two standalone circuits (PA1 and PA2) and one combined circuit (PA1/PA2).

The gain of standalone circuits PA1 and PA2 is 32.7 dB and 31.8 dB, respectively, at an output power of +3 dBm. The gain of the combined circuit (PA1/PA2) is 31.7 dB because of the insertion loss due to the splitter and combiner. However, the saturated output power plotted in Figure 14 is about 2 dB higher (+38 dBm) for the combined circuit compared to the standalone circuits (PA1 = +36 dBm and PA2 = +35.1 dBm).
Figure 11. Insertion Loss of The Power Splitter

Figure 12. Insertion Loss of The Power Combiner
WLAN 802.11g Modulated Measurements

The EVM performance of the combined PA circuit was compared to a standalone PA circuit for compliance with the WLAN 802.11 g standard. Figure 15 shows that a standalone WiFi PA can transmit up to +27.6 dBm and meet a 2.5 percent EVM. However, the combined WiFi PAs can transmit up to +30 dBm for the same 2.5 percent EVM level.

The impact on EVM of phase mismatch between the two paths is shown in Figure 16. EVM has no effect at a lower output power. The main affect of EVM, which was theoretically evaluated in the previous section of this document (refer to Figure 9), is to decrease the combining efficiency and reduce the maximum output power.

Theoretically, power drops by 0.7 dB and 3 dB for a 45 degree and 90 degree phase imbalance, respectively.

EVM follows the same trend: 2.5 percent EVM for an output power of +28 dBm and +25.5 dBm (45 degree and 90 degree phase imbalance, respectively) compared to +30 dBm when there is no mismatch.

Efficiency was also compared between the different PA circuits. For the 2.5 percent EVM threshold, Figure 17 shows that the standalone PA transmits +27 dBm and achieves 15 percent efficiency. For the same EVM performance, the combined PA circuit transmits +30 dBm and achieves a 14 percent efficiency.

Conclusion

Power combining techniques can significantly increase the transmit output power of a PA up to 3 dB. The example described in this Application Note shows the simplicity of the combined circuit. It also demonstrates that the output power of the SKY65152-11 PA can be extended to +30 dBm with good linearity and efficiency performance.
Figure 15. EVM vs Output Power (802.11g Signal)

Figure 16. Impact of Phase Imbalance on EVM

Figure 17. Efficiency vs Output Power