Technical White Paper

Improving Your RF Signal Chain With an RF Fully Differential Amplifier (FDA)

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Linear Amplifiers, RF Amplifiers

ABSTRACT

Many high-performance RF analog-to-digital converters (ADCs) use differential inputs to reject common-mode noise and interference, increase dynamic range by a theoretical factor of two, and improve overall performance due to balanced signaling. Though ADCs with differential inputs can accept single-ended input signals, optimal ADC performance is achieved when the input signal is a differential. Most RF signal chains are single-ended at the antenna, making single-ended to differential conversion for ADC interfacing an important design element to maximize signal chain performance. Converting from a single-ended signal to a differential can be accomplished through varying transitions, but is commonly achieved with an RF passive balun, active balun, or a fully differential amplifier (FDA).

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1 Understanding the Benefits Differential Signaling

Single-ended signaling is a simple and common way of transmitting an electrical signal from a transmitter to a receiver and vice versa. The single-ended electrical signal is transmitted by a voltage, which often varies and is referenced to a fixed potential, typically a 0-V node or *ground*; differential signaling employs two complementary inverted voltage signals referenced to a common-mode voltage to carry the information. Figure 1-1 demonstrates the conversion from a single-ended to differential conversion, where the differential signals are equal in magnitude, but opposite in polarity.

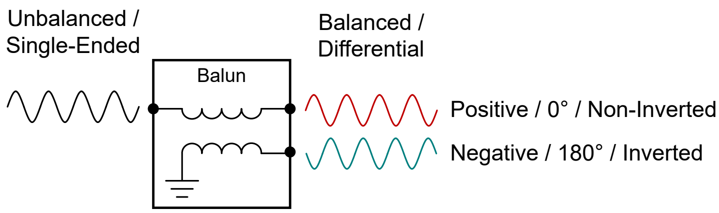

Figure 1-1. Unbalanced-to-Balanced Signal Through a Theoretical Passive Balun

Differential configuration allows the common-mode noise or crosstalk to come in as a common-mode signal that is equal in both lines and subtracted at the receiver. This allows differential signals to be much more robust due to a differential topology having inherent common-mode noise immunity. A differential receiver extracts information by detecting the difference between the inverted and non-inverted signals. The two voltage signals are *balanced*, meaning that they have equal amplitude and opposite polarity relative to a common-mode voltage. The return currents associated with these voltages are also balanced and thus cancel each other out.

Common-mode rejection ratio (CMRR) is often specified for fully differential ADC inputs and describes the ADCs ability to reject a common-mode (typically DC) voltage. A DC common-mode voltage appearing across the ADC inputs has the same effect as a DC input offset. Normally, if the signal and ground are in close proximity physically and will couple in common-mode noise. CMRR is defined as the ratio of differential voltage gain and the common-mode voltage gain:

$$CMRR = \frac{Differential\ Voltage\ Gain}{Common - Mode\ Voltage\ Gain} \quad (1)$$

Note that CMRR is a frequency-dependent parameter. As the frequency of the common-mode voltage increases, the phase matching between the non-inverted and inverted signal for optimal common-mode rejection becomes more difficult to sustain. As a result, good common-mode rejection is harder to obtain at higher frequencies.

One of the key advantages of differential signals is the increased dynamic range. With power supplies dropping to 3.3 V and lower for high-speed and RF data converters, design engineers are looking for ways to achieve greater input dynamic range. In theory, given the same voltage range for single-ended and fully differential inputs, the fully differential inputs will have twice the dynamic range. This is because the two differential inputs can be 180° out of phase, as shown in Figure 1-1. Another way to think about this advantage is the relationship to signal-to-noise ratio (SNR). The SNR is defined in terms of the full-scale input level and the minimum detectable signal of the ADC:

$$MAX\quad SNR = 20\log\left(\frac{Full\ Scale\ Voltage\ Level}{Minimum\ Detectable\ Signal}\right) \quad (2)$$

Typically, the minimum detectable signal is limited by the noise floor. Since fully differential inputs have twice the full-scale input voltage level with approximately the same level of noise as its single-ended configuration, while having superior DC and AC common-mode rejection, SNR increases. However, many single-ended signals must maintain a relatively high voltage to ensure adequate SNR. Common single-ended interface voltages are 5 V or higher. Because of the improved immunity to noise, the differential approach in lower voltage systems is advantageous to maintain adequate SNR.

2 Why are Baluns Commonly Used?

The term *balun* is a portmanteau of *bal*anced and *un*balanced, indicating that a balun will transition between a balanced (also called *differential*) transmission line (where opposite signals both travel in transmission lines) and an unbalanced (also called *single ended*) transmission line (where the return current travels in the ground). However, this description obscures the simplicity of the balun. A balun has equal power outputs just like a Wilkinson power divider, resistive power divider, or quadrature hybrid coupler. However, it has a 180° phase difference between outputs. This is in contrast to the power dividers, which have 0° phase difference, and quad hybrids, which have 90° phase difference. Also, baluns are passive elements that do not require a supply voltage and more than likely do not add much noise. Baluns are considered by some designers to be the standard component of choice when converting between single-ended and differential signals for narrowband applications.

An ideal balun is a device that has a single-ended port and a differential port. A differential port may be considered as two separate ports or a combined port. The following S-parameter equations describe an ideal balun which has port 1 as input and port 2 and 3 are output ports.

$$|S12| = |S13| = |S21| = |S31| \tag{3}$$

$$S11 = -\infty \tag{4}$$

Note what is implied by this:

- A balun is a three-port power splitter
- The two outputs will be equal and opposite
- The unbalanced input is matched to the input transmission line impedance (usually 50 Ω)
- Unlike an isolator or circulator, a balun is a reciprocal device that can be used bidirectionally

Also note what is not implied by this:

- The two outputs are not necessarily matched
- The outputs of the balun may or may not be the same impedance as the input
- There is no constraint on S23, so the outputs may or may not have isolation
- Therefore there may be a different return loss on the outputs for differential and common-mode signals

2.1 Downfall of Baluns at Low Frequencies

At low frequencies, the terms balun and transformer are often used interchangeably because low-frequency baluns are almost always implemented using *flux coupled transformers*. For this reason it is often said that a balun is a type of transformer, but it is more accurate to say that a transformer can sometimes be used to implement a balun. Many other structures can also be used to implement balun functionality. Key specs for a balun are gain and phase balance, CMRR, insertion loss, isolation and delay flatness.

The single-ended to differential conversion is typically performed using passive magnetic baluns that are generally narrowband and increase in size with lower operating frequencies, wider range support also makes the baluns bulkier and costlier. Wideband passive baluns can be expensive with compromised phase and amplitude balance and insertion loss. Passive baluns offer the advantage of high linearity; however, their insertion loss directly hits the Output 3rd Order Intercept Point (OIP3) of the preceding amplifier while impacting the overall noise figure. Poor phase and amplitude imbalance directly impacts the ADC's 2nd order non-linearity. As with all RF and microwave circuits, each performance metric is only valid across some specified bandwidth. Increasing the bandwidth from octave, to decade, to multi-decade without sacrificing performance is a major challenge. In general baluns can be divided into two types. Those with magnetic coupling perform below 10 MHz, while those with only capacitive coupling have low-end performance limited to about 1 GHz, but can operate up to millimeter wave frequencies.

For wideband applications, baluns may not be able to mitigate 2nd order harmonics that cause ripples throughout the desired pass band. At higher frequencies, the output impedance of the amplifier into a balun can change, and may result in a more pronounced imbalance across the entire frequency range. Conversely, baluns that have their frequency range extend to 10 MHz and lower will become significantly larger in size and consume more board space. Even though baluns can convert single-ended signals to differentials and provide the benefits of differential signaling, high-performance wideband passive baluns can be costly, large, and potentially unreliable, if mechanically constructed. Figure 2-1 shows a generic use-case of a balun being used to interface with an ADC.

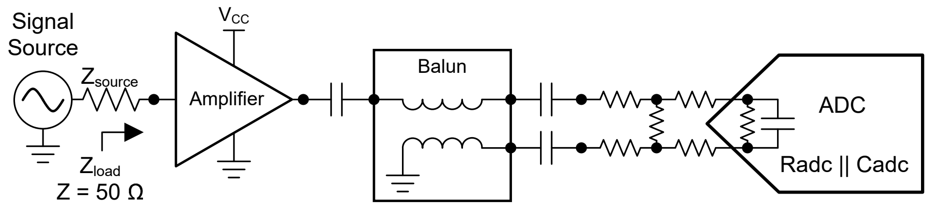

Figure 2-1. Simplified Schematic of an Amplifier and Balun Solution Interacting With an ADC

For performance-demanding applications, a solution that combines the preceding amplifier and the passive balun becomes very attractive provided that the overall specifications of the active balun can beat those of the two cascaded parts. The ultimate test; however, is when cascaded with the ADC, the active balun must have negligible impact on the native ADC performance. It is preferred that the active balun does not reside on the same die as the ADC; otherwise, common-mode spur injection can limit ADC performance.

There are two general architectures used for active baluns – closed loop or open loop. For high-frequency applications, open loop structures are preferred for their stability advantages. While open-loop structures offer noise figure advantages, they tend to be AC coupled with a high-pass pole. A closed-loop implementation not only addresses this, but also yields an OIP3 or OIP2 that tracks the linearity profile of the ADC – high at low frequencies while gracefully degrading with higher frequencies. This is critical because across frequency, the active balun must always outperform the ADC by at least 6 dB to 8 dB to have minimal impact on the ADC.

3 Why use a Fully Differential Amplifier?

A fully differential amplifier (FDA) provides an active gain component while providing the same benefits as a balun, potentially reducing the overall BOM count and the board space for the RF signal chain. However, an FDA does require a power supply and adds noise to the passing signal, and may cause the phase imbalance to become more pronounced.

Figure 3-1 shows an FDA configured in three different typologies, a differential-to-differential, a single-ended-to-differential, and a differential-to-single-ended setup, allowing engineers to accommodate multiple RF configuration needs with a single device.

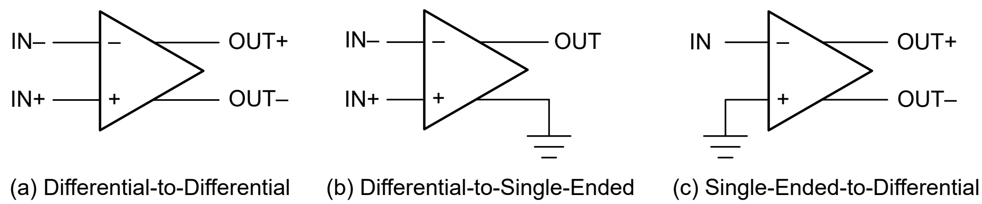

Figure 3-1. Different Configurations With an FDA

In Figure 3-2, an FDA is configured as a single-ended-to-differential amplifier and can be used to replace a single-ended gain amplifier and a passive balun to interface with the ADC as shown in Figure 2-1.

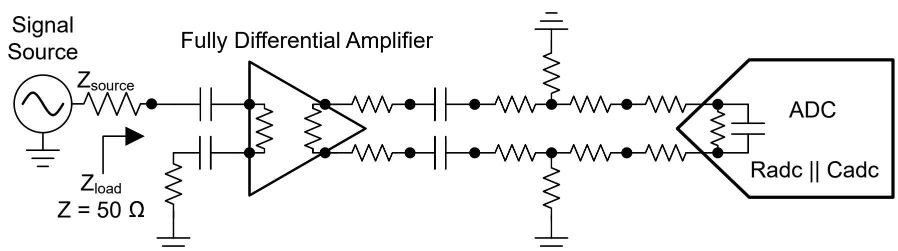

Figure 3-2. Simplified Schematic of a Fully Differential Amplifier Interacting With an ADC

Inherently, amplifiers and gain blocks are single-ended and will provide poor phase imbalance and higher even-order distortion. For example, analog inputs of ADCs are typically a differential interface, the two inputs are ideally required to be equal in amplitude and 180-degrees out of phase. However, maintaining this balanced signal can be quite challenging. As these two input signals slip away from ideal 180-degrees, this produces a phase shift, which generates a common-mode signal, causing even-order distortion (HD2) to become more pronounced.

Specifically, for wideband applications, the TRF1208 (a single-channel, 10-MHz to 11-GHz, 3-dB bandwidth, single-ended to differential RF amplifier in a small 4-mm^2 QFN package) provides superior gain and phase imbalance of ±0.3 dB and ±3 degrees, which is competitive with the best passive wideband baluns on the market. In Figure 3-1, the TRF1208 combined with the ADC12DJ5200RF provides a 2nd order harmonic distortion lower than –60 dBFS up to 8 GHz. With a discrete wideband low-noise amplifier (LNA) and passive balun solution, the amplifier can be the limiting factor for linearity and ultimately cause unwanted higher HD2 performance as seen in Figure 3-3. The TRF1208 provides up to –30 dBFS better in HD2 performance than a competitor LNA and balun solution.

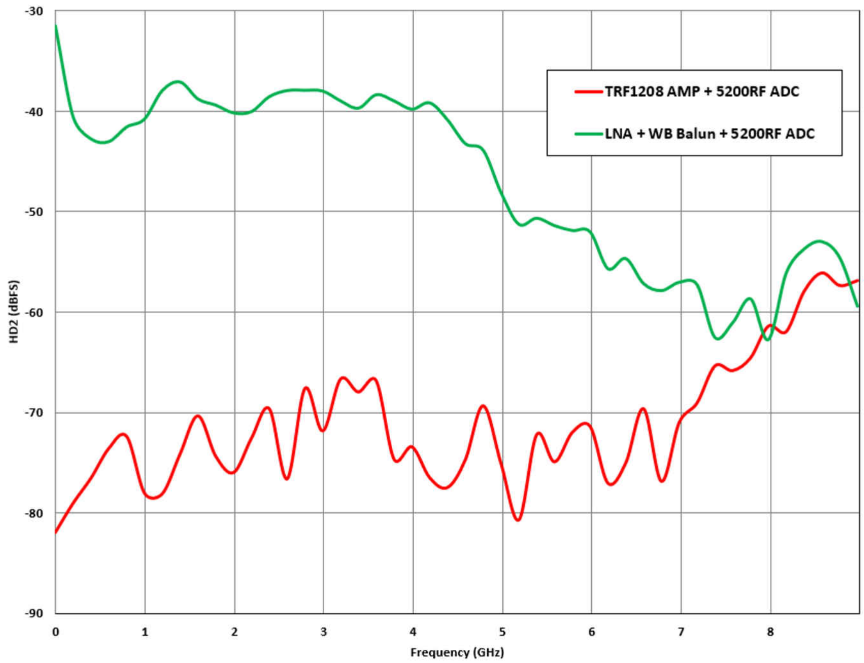

Figure 3-3. Second Order Harmonic Distortion (HD2) Performance of TRF1208 (FDA) and ADC12DJ5200RF (ADC) vs a Wideband LNA and Balun Solution

Matching a wideband ADC to a single-ended source can be a difficult challenge, especially at frequencies above the fundamental Nyquist zone. The input impedance of an ADC is typically much higher than 50 Ω, generally 100 Ω or in the kΩ range. This means that a higher output impedance balun will typically match better to an ADC input than a 1:1 balun. Due to the band-limiting nature of the ADC, it is often necessary to use a balun that is much wider band in a pure 50-Ω system than the required system bandwidth. However, passive baluns can become larger in size, the lower frequency the system goes, causing the single-ended amplifier and balun solution to increase the total system size.

Figure 3-4, shows that a balun and gain block solution that covers a frequency range up to 12 GHz is a significantly larger solution size than an FDA, such as the TRF1208. The TRF1208 is housed in a 4-mm^2 QFN package with an overall board solution size of 120 mm^2 versus mechanically built baluns that can reach package sizes greater than 64 mm^2 and the board space usage can average around 171 mm^2. With the addition of a gain block to the balun solution, the board space can approach 200 mm^2 of PCB area.

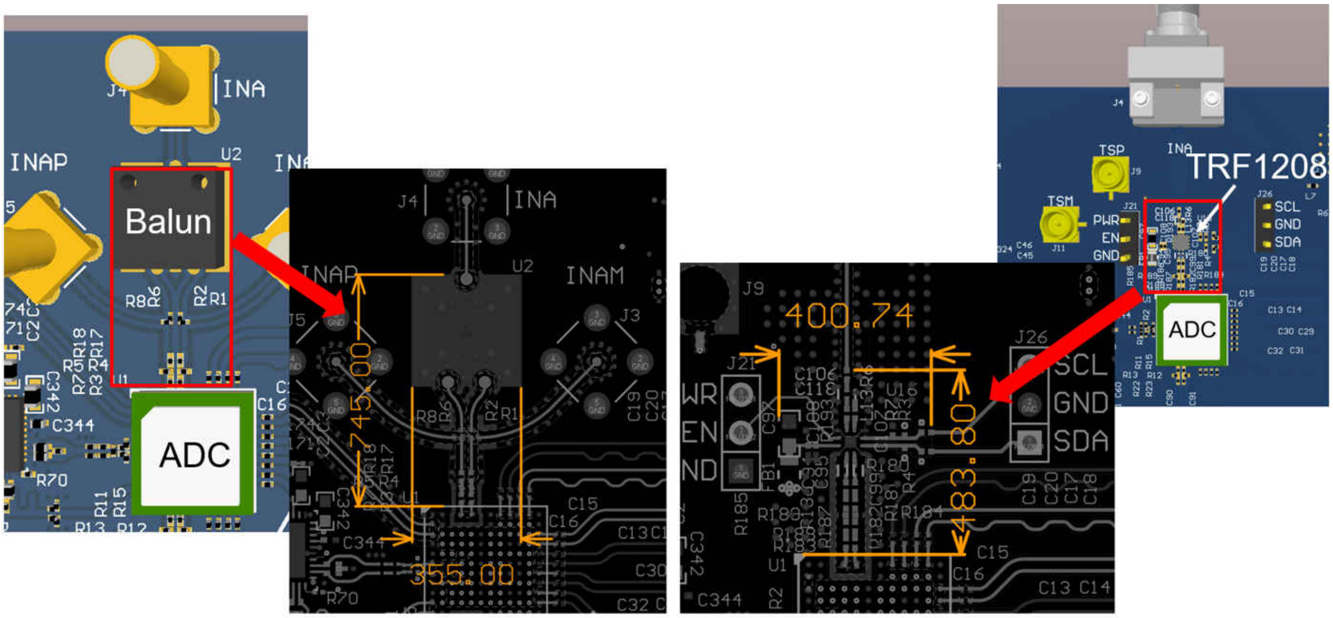

Figure 3-4. Solution Size Comparison Of Surface-Mount Broadband Balun and TRF1208

4 Summary

Baluns can be beneficial by allowing for differential signaling, eliminating common-mode noise without filtering, isolating the ports, providing decent SNR performance and suppressing even-order harmonic distortion products (HD2). A TI differential amplifier such as the TRF1208 can provide the same competitive performance as a balun, and often better performance than a combined gain block paired with a balun solution. In addition, it provides a gain component and a reduction in IC BOM count in the RF signal chain.

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