

Developing a UHF RFID Reader RF Front End with an Analog Devices' Solution

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Introduction

Ultrahigh frequency radio frequency identification (UHF RFID) systems have been widely adopted for applications like asset management and apparel retail. Recently, they have gained attention for use in unmanned super-market applications and for the electronic identification of motor vehicles. This article describes two implementations of an Analog Devices' signal chain-based UHF RFID reader RF front end. One implementation is based on the [ADF9010](#) and [AD9963](#), while the other is based on the AD9361. This article focuses on a target application for the electronic identification of motor vehicles in China, which must be compliant with the Chinese standards GB/T 29768-2013 "Information Technology—Radio Frequency Identification—Air Interface Protocol at 800/900 MHz"¹ and GB/T 35786-2017 "General Specification for Read-Write Equipment of the Electronic Identification of Motor Vehicles."² In comparison to a discrete, two component implementation, this AD9361-based solution greatly decreases design complexity, component count, and board space, with a trade-off of receiver sensitivity degradation. Although the RF front end described in this article is application specific, both the analysis method and the front end itself are applicable for general UHF RFID reader solutions.

Table 1. Reader to Tag Physical MAC Layer Key Parameter Summary

Parameter	Description
Frequency Range	920 MHz to ~925 MHz
Occupied Bandwidth (OBW)	250 kHz
Channel Center Frequency	920.125 + 0.25 n (0 ≤ n ≤ 19) MHz
Adjacent Channel Leakage Ratio (ACLR)	Adjacent channel: <-40 dB Alternate channel: <-60 dB
Reader Maximum ERP	20 dBm at Channel 0 and Channel 19 33 dBm from Channel 1 to Channel 18
Reader Out of Band Emission	See Table 2
Modulation Type	DSB-ASK, SSB-ASK
Modulation Depth	30% to ~100%
Data Coding	Truncated pulse position (TPP)
Tari	6.25 μs or 12.5 μs

Table 2. Reader Out of Band Emission Requirement

	Frequency Range	Limit (dBm)	Measurement Bandwidth	Detector Mode
Maximum Output Power Mode	30 MHz to ~1 GHz	-36	100 kHz	rms
	1 GHz to ~12.75 GHz	-30	1 MHz	
	806 MHz to ~821 MHz 825 MHz to ~835 MHz 851 MHz to ~866 MHz 870 MHz to ~880 MHz 885 MHz to ~915 MHz 930 MHz to ~960 MHz	-52	100 kHz	
	1.7 GHz to ~2.2 GHz	-47	100 kHz	
	Standby Mode	30 MHz to ~1 GHz	-57	
	1 GHz to ~12.75 GHz	-47	100 kHz	

Table 3. Type 2 Reader Key Performance Requirement

Item	Limit
Receiver Sensitivity	≤-65 dBm
Read Distance in Static Mode	≥25 m
Write Distance in Static Mode	≥12 m
Dynamic Identification Performance	Car speed ≤ 150 km/h: Successfully read information in a chip identifier data bank and vehicle registration data bank 150 km/h < car speed ≤ 200 km/h: Successfully read information in a chip identifier data bank

Standards Summary

According to the GB/T 29768-2013 and GB/T 35786-2017 standards relating to the electronic identification of motor vehicles, the key air interface parameters and the performance requirements of high performance Type 2 readers for these applications are summarized in Table 1 through Table 3.

System Link Budget Analysis

Passive RFID systems have two fundamental link limits: The forward link normally limited by the minimum RF to dc power to supply the tag electronics and the reverse link limited by the reader receiver sensitivity. The forward and reverse link budget formulas^{3,4} are described in Equation 1 through Equation 3:

$$P_{rip} = \frac{P_{tx} \times G_{tx}}{FSPL} \tag{1}$$

$$P_{rx} = \frac{P_{tx} \times G_{tx} \times G_{rx} \times G_{tag}^2}{FSPL^2} \eta_{mod} \tag{2}$$

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{3}$$

- P_{rip}: tag receive isotropic power
- P_{tx}: reader transmit power
- G_{tx}: reader transmit antenna gain
- G_{tag}: tag antenna gain
- FSPL: free space pass loss
- P_{rx}: reader receive signal power
- G_{rx}: reader receive antenna gain
- η_{mod}: tag modulation efficiency
- d: distance between reader and tag
- λ: signal wavelength in free space

As defined in GB/T 35786-2017 section 6.2 and section 6.5.2.2, P_{tx} is 30 dBm and the feeder cable insertion loss is less than 1 dB, so the real P_{tx} is around 29 dBm. An antenna of 10 dBi to 12 dBi gain is used in the field test, so G_{tx} is assumed to be 12 dBi. As for G_{rx}, in an electronic identification of motor vehicles application, the reader normally uses the monostatic configuration, whereas a single antenna is used at the reader for both transmission and reception, so G_{rx} = G_{tx} = 12 dBi. A tag antenna is usually similar to a dipole and it is reasonable to assume G_{tag} = 2 dBi. η_{mod} represents the modulation efficiency of the tag, which depends on the tag antenna matching and the tag impedance shift that occurs during modulation and it is reasonable to assume that η_{mod} = -8 dB. The center frequency is 922.5 MHz, so λ = 0.33 m. The system link budget shown in Figure 1 is based on the previously described formulas and parameters.

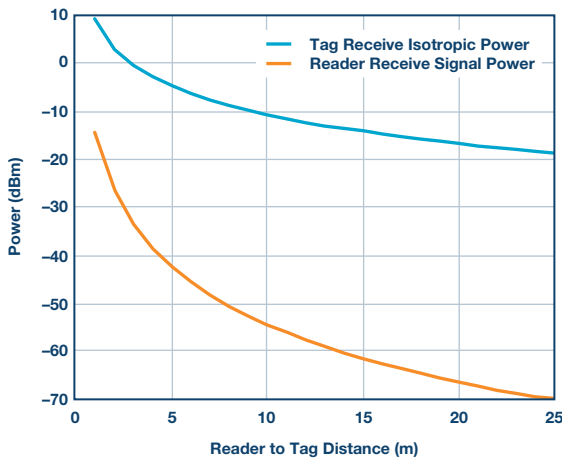


Figure 1. Forward and reverse link budget calculation.

To support the link range at 25 meters as defined in the standard, the tag sensitivity should be better than -18.7 dBm and the reader sensitivity should be better than -70.4 dBm. In the standard, the tag sensitivity requirement is defined as -18 dBm, which matches the analysis result quite well. However, the reader sensitivity requirement is defined as -65 dBm, which has considerable deviation when compared to the

analysis result. This deviation may come from the tag antenna gain value. In electronic identification of motor vehicles applications, it is not necessary to design the tag antenna to be omnidirectional. Adding a reflector will result in an additional 3 dB antenna gain. And since the tag antenna gain (G_{tag}) is squared in Equation 2, the reader sensitivity analysis result will increase by 6 dB to be at -64.4 dBm. In this case, the analysis result will match with the standard requirement.

Self Jammers in UHF RFID Readers

In a UHF RFID system, the reader transmits a continuous wave (CW) signal to power the passive tags while simultaneously receiving the backscattered signal from the tag at the same frequency. Due to the poor transmitter-to-receiver isolation, the strong CW signal, together with the related transmitter noise, will leak into the receiver. Usually this leakage signal is called a self jammer (SJ) signal and this self jammer signal will degrade the reader's sensitivity.

In an RFID reader for the electronic identification of motor vehicles, a directional coupler is normally used as the duplexer for the transmitter and receiver. The SJ signal occurs mainly because of the reflection of the antenna, the limited isolation of a directional coupler, and the reflection of the circuit connected to the coupler port.

To overcome this SJ signal issue, two methods could be used. The first one is to design a self jammer cancellation (SJC) circuit before the receiver LNA. The second method is to use direct conversion receiver architecture while using the same local oscillator (LO) that's used by the transmitter and the receiver. In this case, the self jammer signal will convert to dc at baseband, and then dc block capacitors will be used for the ac coupling of the signal. After this dc blocking point, the SJ signal is removed and the dynamic range requirement on the subsequent components is loosened. This means that enough gain could put on baseband to decrease the receiver noise figure (NF). These two methods could be used separately or combined. A typical SJC circuit is shown in Figure 2.⁵

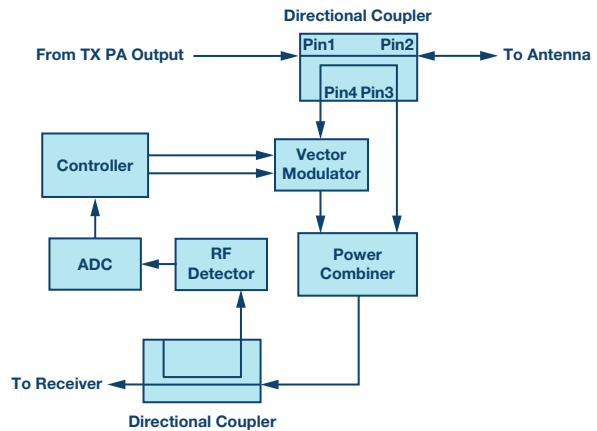


Figure 2. Typical self jammer cancellation circuit.

Reader Key RF Performance Analysis

An SJC circuit including a UHF RFID reader RF front-end block diagram is shown in Figure 3. Analog Devices' AD9963 integrates a dual-channel DAC and a dual-channel ADC. ADF9010 integrates a transmitter modulator, PLL/VCO, and receiver baseband filter and PGA. The demodulator ADL5382 is included on the ADF9010 evaluation board. The ADL5523 is used as an LNA as it provides low noise figures, high gain, and high linearity. The 75 dB high dynamic range RF detector LT5538 is suitable for the SJC RF power detector.

For the transmitter, in the digital domain, the signal should be low-pass filtered to meet both the frequency domain ACLR requirement and the time domain RF envelope requirement. And in the analog domain, both

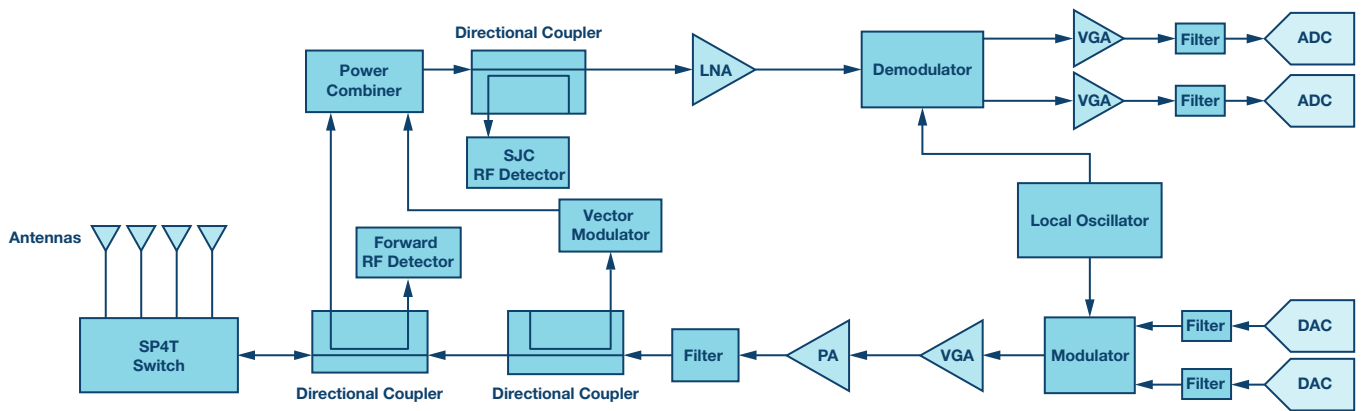


Figure 3. UHF RFID reader RF front-end block diagram.

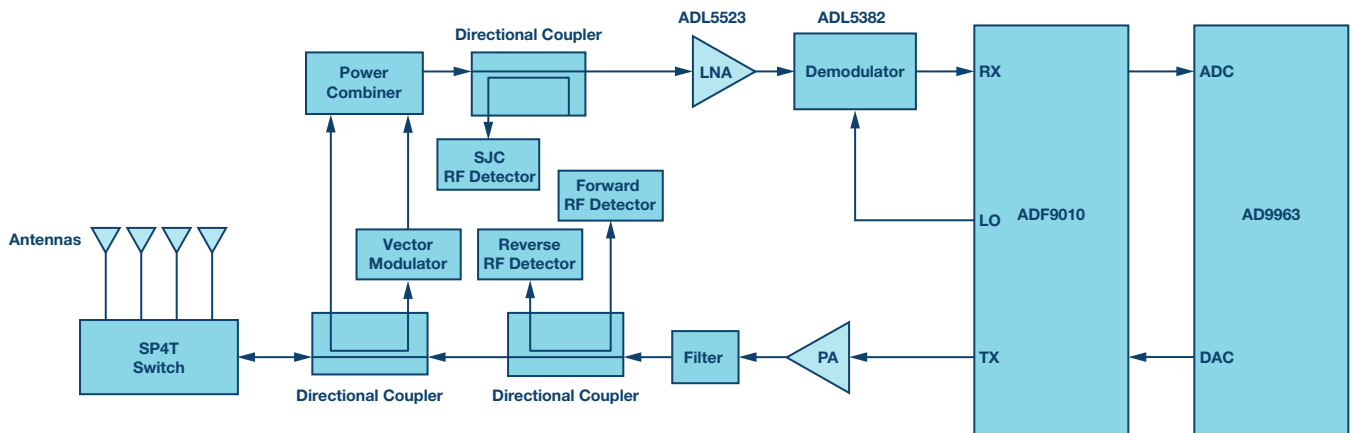


Figure 4. UHF RFID reader RF front end using the ADF9010 and AD9963.

PA linearity and LO phase noise will impact the ACLR performance. The low-pass filtered, TPP coded ASK signal has around a 2 dB peak-to-average ratio (PAR). The average PA output power is around 32 dBm, with a 1 dB margin, so a PA of more than 35 dBm P-1 dB should be chosen. As for the LO phase noise, the phase noise integration from 125 kHz to 375 kHz should be less than -40 dBc and the phase noise integration from 375 kHz to 625 kHz should be less than -60 dBc. As for the out of band emission requirement, an RF filter is needed to meet the requirement at the transmitter harmonics frequency. For the requirement close to working frequency such as the requirement of -52 dBm of 100 kHz measurement bandwidth at 915 MHz and 930 MHz, the RF filter normally has no attenuation yet, so the noise floor requirement for the modulator at 0 dBm output power is around $-52 - 10 \times \log_{10}(10^6) - 30 = -132$ dBm/Hz. And the phase noise requirement at a 5 MHz offset should be less than -132 dBc as well.

For the receiver, the receiver sensitivity is specified as -65 dBm in the GB/T 35786-2017 standard. It is assumed that the reader should meet this -65 dBm sensitivity at all possible data rates and that the back link frequency (BLF) of 640 kHz is the worst case. For an SJC that includes an RFID reader, the insertion loss from an antenna port to the SJC output is around 15 dB, so that the sensitivity requirement at the SJC output point is -80 dBm and assume the tag backscattered signal power not including dc is $-80 - 3 = -83$ dBm. The ASK modulation signal demodulation threshold is around 11 dB and the signal bandwidth of BLF 640 kHz uplink signal is 2.56 MHz. So the total NF requirement is $NF \leq -83 - (-174 + 10 \times \log_{10}(2.56 \times 10^6) + 11) = 15.9$ dB. This total NF requirement includes the impact of the noise of the receiver circuit after SJC, the SJC circuit induced noise, and the transmitter leakage noise. Assuming the delay is matched between the vector modulator signal branch and

self jammer branch, which means both the CW self jammer signal and the transmitter leakage noise are cancelled. The transmitter leakage noise includes three parts: the phase noise, the amplitude noise, and the white noise. Normally the amplitude noise and the white noise will be cancelled to the noise floor of -174 dBm/Hz. For the residual phase noise, since the transmitter and receiver use the same LO, it will convert to dc during down conversion because of the range correlation effect.⁶ In this case, the vector modulator branch noise will be the only extra induced noise. Assume the vector modulator branch noise floor is -162 dBm/Hz, so at the SJC circuit output, the effective NF is $-174 - (-162) = 12$ dB, then the NF requirement for the receiver circuit after SJC is $10 \times \log_{10}(10^{1.59} - 10^{1.2}) = 13.6$ dB.

ADF9010- and AD9963-Based Solution

The ADF9010 is a fully integrated RF transmitter modulator, local oscillator (LO), and receiver analog baseband front end that operates in the frequency range of 840 MHz to 960 MHz. The AD9963 is a 12-bit, low power MxFE[®] converter that provides two ADC channels with sample rates of 100 MSPS and two DAC channels with sample rates to 170 MSPS.

The block diagram using ADF9010 and AD9963 to implement the UHF RFID reader RF front end is shown in Figure 4. The NF of the ADL523 cascaded with the ADL5382 and ADF9010 receiver gain setting of 24 dB is less than 3 dB.

To implement the UHF RFID reader RF front end, both an SJC board including the adaptive SJC algorithm and the ADF9010 and AD9963 board are built. The ADF9010 and AD9963 board integrated the demodulator ADL5382 as well. The two boards are cascaded to test the transmit and receive system-level RF performance.

For the transmit test, a TPP coded, 50% modulation depth, DSB-ASK with Tari set to 12.5 μ s RFID downlink waveform is built in Python® and downloaded to the FPGA board. The spectrum domain ACLR and time domain RF envelope are tested at the antenna port with a PA output power of 32 dBm. The test result is shown in Figure 5. For the ACLR test result, the adjacent channel is around -42 dBc which has 2 dB margin and the alternate channel is -64 dBc which has a 4 dB margin. For the RF envelope, the ripple is less than 1%, which has enough margin when compared to the 5% limit and the rise time and fall time are in the range limit of 1 μ s and 8.25 μ s.

For the receive test, a Tag simulator is built using the Analog Devices SPDT RF switch HMC545A and it is controlled by a microcontroller unit. The control pattern is an RFID uplink FMO coded data list. An ASK decoding program is built by MATLAB.® By using this program to decode the IQ and comparing it to the original data in the data list, the BER and the receiver sensitivity can be calculated. Figure 6 shows the received IQ data and the FFT plot. The figure shows that a -74 dBm RFID uplink signal with 320 kHz BLF was successfully decoded by the program.

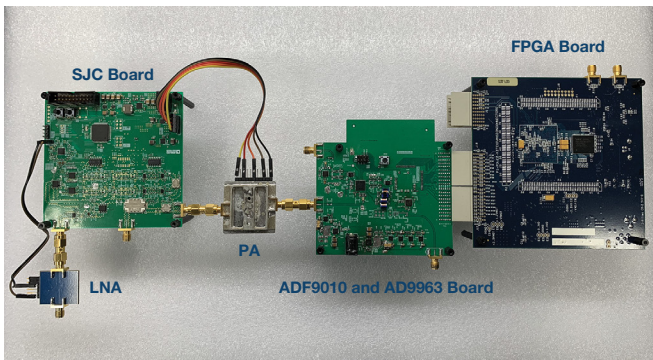


Figure 5. Test setup photo.

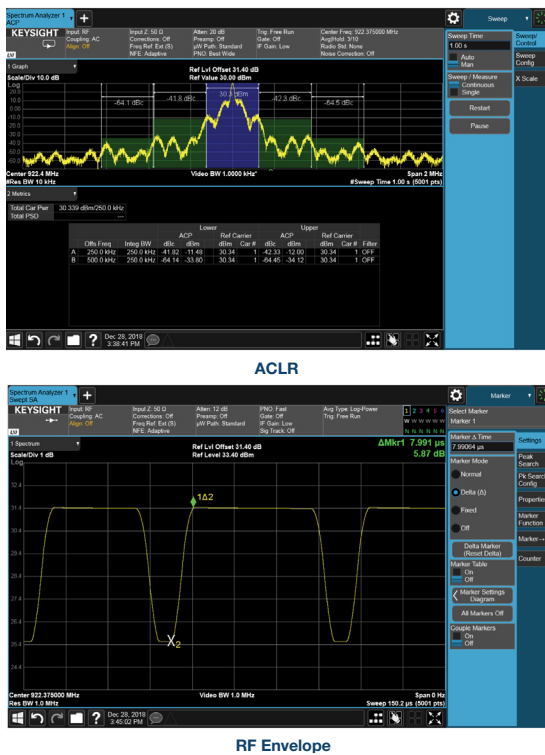


Figure 6. Transmitter test result.

Using AD9361 to Implement the Front End

The AD9361 is a highly integrated radio frequency (RF) transceiver capable of being configured for a wide range of applications. The device integrates all RF, mixed-signal, and digital blocks necessary to provide all transceiver functions in a single device. To implement a UHF RFID reader, the transmitter and receiver should use the same LO to take advantage of the range correlation effect, so the AD9361 transmitter monitor path, rather than the normal receiver path, will be used. The AD9361 transmitter monitor path bypasses the internal LNA, so an external LNA, such as the Analog Devices ADL5523, is added. The ADL5523 is a high performance GaAs pHEMT LNA with 0.8 dB NF and 21.5 dB gain. The block diagram in Figure 8 shows the AD9361 being used to implement the UHF RFID reader RF front end. Compared to the discrete component implementation, this AD9361-based solution is significantly simplified. The AD9361 baseband is dc coupling, rather than ac coupling. In this case, it is required that the SJC circuit can decrease the self jammer signal to a low enough level—for example, less than -35 dBm—that will not saturate the analog circuit. This allows the self jammer converted dc signal to be removed in the digital domain.

The AD9361 transmitter monitor path gain distribution is comprised of two gains: front-end gain (transmitter monitor gain) and receive low-pass filter gain (G_{BBF}). The transmitter monitor gain could be set to 0 dB, 6 dB, or 9.5 dB. G_{BBF} could be set from 0 dB to 24 dB with 1 dB step. With this flexible gain configuration, receiver AGC functionality could be implemented easily. For this UHF RFID reader application, a transmitter monitor gain setting of 3 dB and a G_{BBF} setting of 6 dB is chosen. When the AD9361 gain setting is 3 dB, then the cascaded NF of the ADL5523 and AD9361's transmitter monitor port is around 12.6 dB. This setting has a 1 dB margin compared to the analysis requirement of 13.6 dB, while the digital domain power is -7 dBfs if the residual self jammer is -35 dBm.

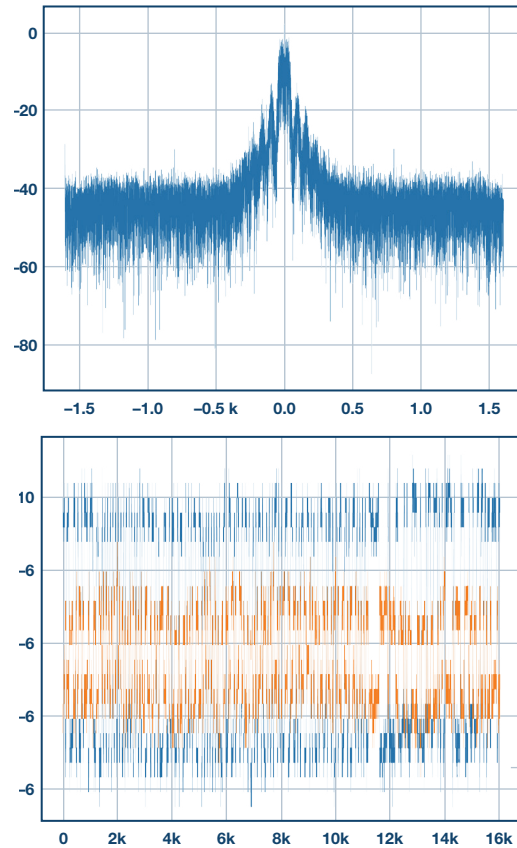


Figure 7. Received receiver data FFT plot and decoded data.

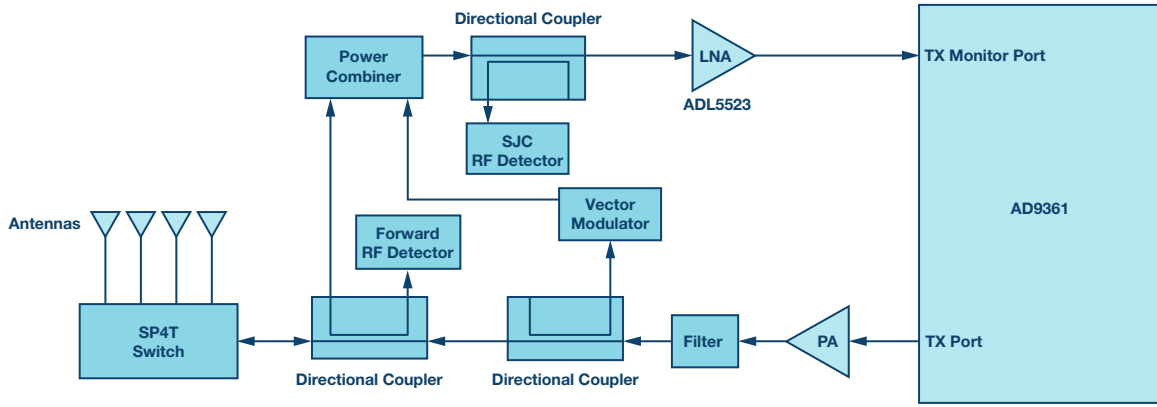


Figure 8. A UHF RFID reader RF front end using an AD9361 block diagram.

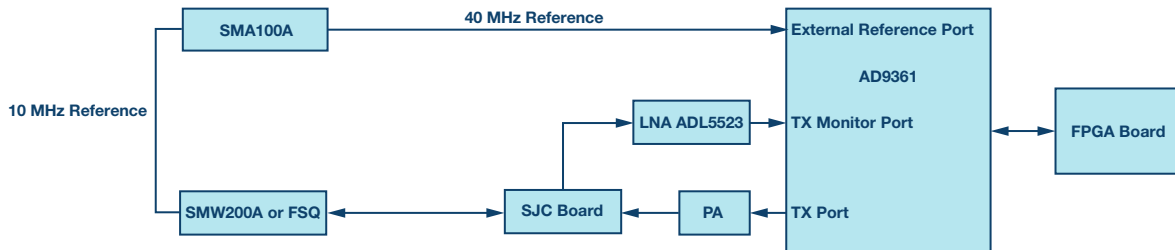


Figure 9. Test setup block diagram.

AD9361-Based Solution, Test Setup, and Results

To implement the UHF RFID reader RF front end, an SJC board including an adaptive SJC algorithm is built. This is cascaded with AD9361 to test transmitter and receiver system-level RF performance. The test setup block diagram and photo are shown in Figure 9 and Figure 10.

The test result is shown in Figure 11. For the ACLR test result, the adjacent channel is around -42 dBc, which has a 2 dB margin, and the alternate channel is -61 dBc, which has a 1 dB margin. For the RF envelope, the ripple is less than 1%, which meets the margin requirements for a 5% limit. The rise time and fall time are in the range limits of 1 μ s and 8.25 μ s.

For the receiver test, an RFID uplink FM0 coded data list is built and downloaded to the signal generator SMW200A and then configured for SMW200A to transmit a DSB ASK signal with this data list. The AD9361 received IQ data are stored in the FPGA board and fetched to a PC using an FTP tool. An ASK decoding program is built by MATLAB. Using this program, decoded data is compared to the original data in the data list, which then allows for the BER and receiver sensitivity to be calculated. Figure 12 shows the FFT plot and decoded data of the MATLAB program. It is tested that -65 dBm RFID uplink signal with a 640 kHz BLF is successfully decoded by the program.

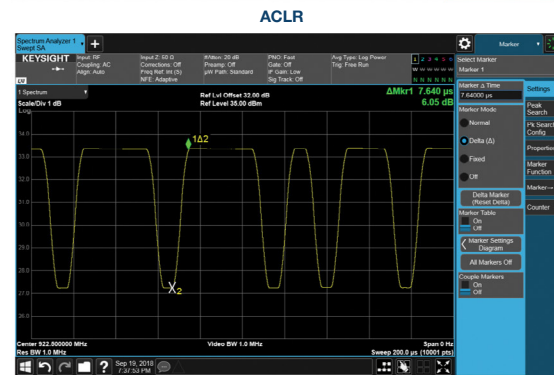


Figure 11. Transmitter test result.

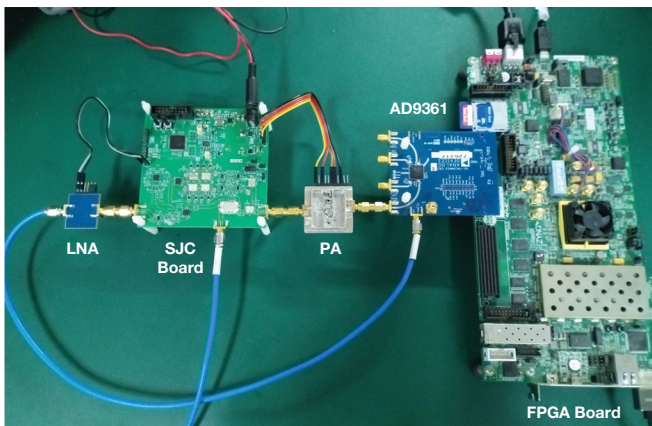


Figure 10. Test setup photo.

Conclusion

China's standards for electronically identifying motor vehicles are summarized firstly in this article. The UHF RFID system-level link budget, the key technique in RFID such as SJC, and the key RF performance requirement were then analyzed. Lastly, an ADF9010- and AD9963-based solution, as well as an AD9361-based UHF RFID reader RF front end, are set up to test system-level performance. The ADF9010- and AD9963-based solution has high performance and a great margin to meet the GB/T 29768-2013 and GB/T 35786-2017 requirements. The AD9361-based integrated solution also meets these requirements with the trade-off of receiver sensitivity degradation and it is significantly simplified when compared to the discrete, two component implementation. Although the RF front end described in this article is application specific, both the analysis method and this front end itself are applicable for general UHF RFID reader solution.

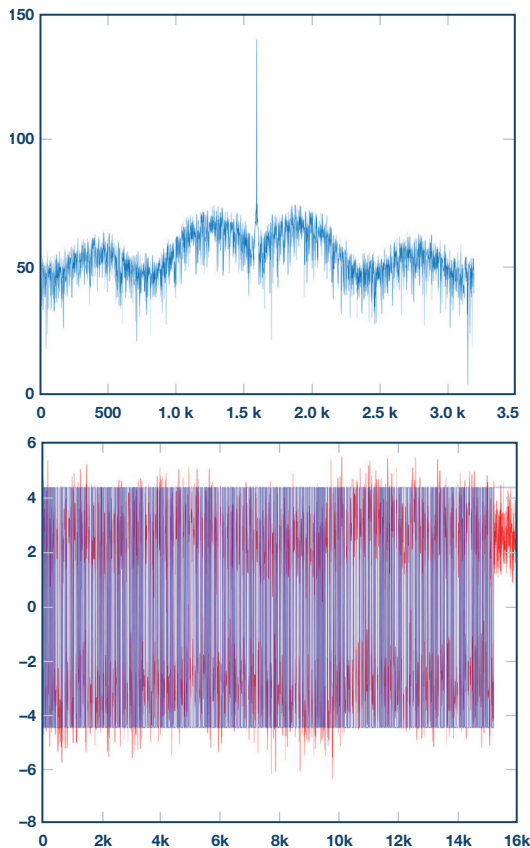


Figure 12. Received receiver data FFT plot and decoded data.

Reference

- ¹ GB/T 29768-2013 "Information Technology—Radio Frequency Identification—Air Interface Protocol at 800/900 MHz."
- ² GB/T 35786-2017 "General Specification for Read-Write Equipment of the Electronic Identification of Motor Vehicles."

³ Monza X Antenna Application Note. Impinj.

⁴ Gregor Lasser and Christoph F. Mecklenbrauker. "Self-Interference Noise Limitations of RFID Reader." *2015 IEEE International Conference on RFID (RFID)*, June 2015.

⁵ Alirio Boaventura, João Santos, Arnaldo Oliveira, and Nuno Borges Carvalho. "Perfect Isolation: Dealing with Self-Jamming in Passive RFID Systems." *IEEE Microwave Magazine*, Vol. 17, No. 11, November 2016.

⁶ Byung-Jun Jang and Hyun-Goo Yoon. "Range Correlation Effect on the Phase Noise of an UHF RFID Reader." *IEEE Microwave and Wireless Components Letters*, January 2009.

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