AWR1243 sensor: Highly integrated 76–81-GHz radar front-end for emerging ADAS applications

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Introduction

The use of millimeter wave (mmWave) technology in advanced driver assistance systems (ADAS) has grown tremendously in recent years. Applications have rapidly evolved, from comfort functions such as adaptive cruise control (ACC), to safety functions such as emergency braking, to newer applications such as pedestrian detection and 360-degree sensing. There is also a shift in the industry toward the use of the 76–81-GHz frequency band due to emerging regulatory requirements, larger bandwidth availability, smaller sensor size and performance advantages.

Traditionally, radar implementations used discrete components, but in today's market more integrated solutions are becoming available. A complementary metal-oxide semiconductor (CMOS) integrating radio-frequency (RF) and analog functionality, as well as digital control capability into a single chip reduces cost and form factor. In addition, such a highly integrated solution also makes it efficient to implement advanced techniques that improve system performance and enables developers to meet functional safety compliance using on-chip processor-based built-in self-test (BIST) capabilities.

FMCW radar concept

In an FMCW radar, the transmitted signal is a linear frequency-modulated continuous wave (L-FMCW) chirp sequence, whose frequency vs. time characteristic follows a saw tooth pattern, as shown in **Figure 1** (in red).
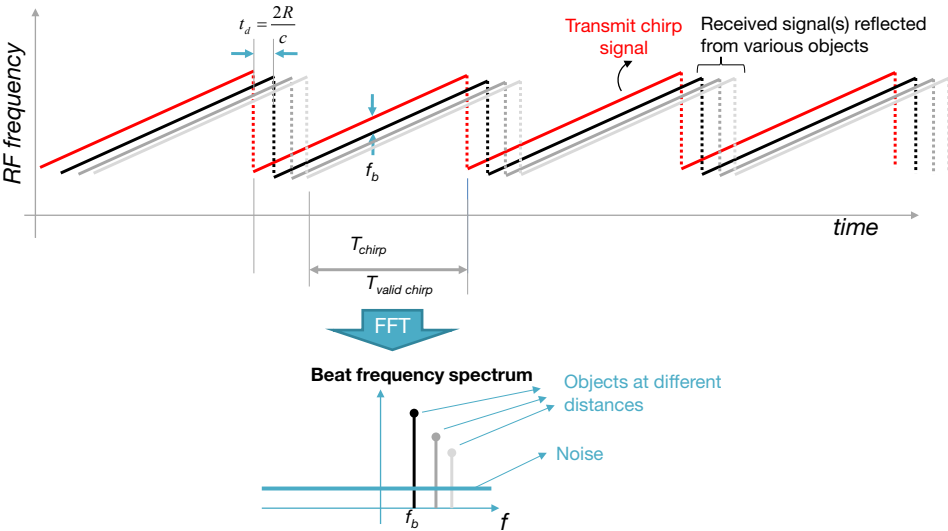
A local oscillator generates the L-FMCW signal, also known as the chirp signal, for amplification and transmission from the transmit antenna. Any object(s) present in the region of interest illuminated by the radar reflect the transmitted signal back. Mixing the reflected signal with the local oscillator signal

Figure 1. *Received FMCW radar signal and beat-frequency spectrum.*
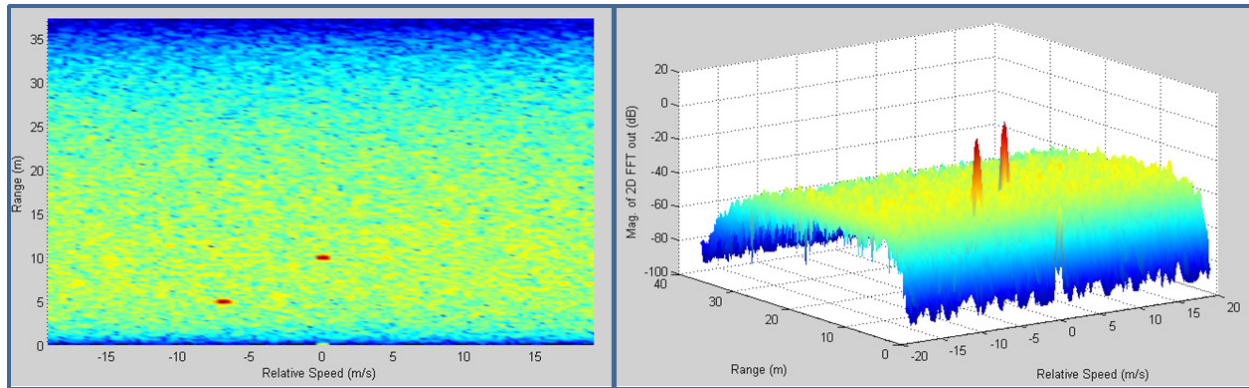
Figure 2. Radar 2-D FFT image showing range and velocity of two point objects.

produces a beat-frequency (intermediate frequency [IF] frequency) output, which is digitized and subsequently processed in a DSP.

Figure 1 shows the received FMCW signal, which comprises different delayed and attenuated copies of the transmitted signal corresponding to various objects. From **Figure 1**, you can see that the beat-frequency signal corresponding to each object is a tone (ignoring the edge effects at the start and end of the chirp), whose frequency (f_b) is proportional to the distance (R) of the object from the radar. The process of detecting objects (targets) and their distances from the radar involves taking a Fast Fourier Transform (FFT) of the beat-frequency signal and identifying peaks that stand out from the noise floor.

In the case of moving objects, the beat-frequency signal also has a Doppler component that depends on the relative velocity between the radar and the target. Looking at the phase shift of the beat signal from one chirp to the next provides an estimate of the Doppler and hence the relative velocity. This is typically accomplished by performing a second FFT across chirps[1].

The detection process involves performing a first-dimension FFT of the received samples corresponding to each chirp and then a second-dimension FFT of this output across chirps. The result of the 2-D FFT procedure is an image of the target(s) in the range-velocity grid, as shown in **Figure 2**. The detection process is often performed on this 2-D FFT output and involves detecting peaks amid the noise floor or surrounding clutter.

Additionally, for the detected objects, an angle estimation process is performed using digital beamforming with multiple TX/RX antennas. Thus, the FMCW radar can provide a 3-D image (range, relative velocity and angle of arrival) of the scene that it illuminates.

For a comprehensive description of FMCW, see the citations in the References section.

Advantages of fast FMCW modulation

The 2-D FFT processing procedure is applicable to radar implementations that use fast FMCW modulation. This is in contrast to other techniques, such as triangular FMCW waveform (slow FMCW modulation). In fast (saw tooth) FMCW modulation, the chirp durations are in the order of tens of microseconds, whereas in slow (triangular) FMCW modulation, the chirp durations are much longer, typically in milliseconds.

One of the key advantages of fast FMCW modulation is that the range and velocity of various objects are automatically resolved into a 2-D image.

The efficient 2-D FFT processing method enables an accurate estimation of the range and velocity of each object without ambiguity. This is particularly important when there are multiple objects present.

Other advantages of fast FMCW modulation include the fact that the beat-frequency signals from various objects are higher than the flicker-noise corner frequency, and enable better signal-to-noise ratio (SNR) for detection of weak objects. Also, implementing the low- and high-pass filters required in the analog baseband on-chip reduces the number of external components.

With slow FMCW modulation, the beat frequency signal of each chirp contains a combination of range and Doppler information. By using up-slope and down-slope chirps of the triangular waveform (**Figure 3**), it is possible to separate the range and Doppler information contained in the beat frequency. However, this procedure suffers from ambiguity problems when there are multiple objects and hence can be less robust.

As radar systems get deployed in denser target situations and as new use-cases emerge, the benefit of automatic unambiguous separation of range and Doppler that is achievable with fast FMCW modulation is a significant advantage.

mmWave front-end features for emerging ADAS applications

Table 1 captures some of the recent industry trends in automotive radars and their implications for mmWave front-end requirements.

Automotive radar industry trends	mmWave front-end requirements	TI automotive radar
24-GHz SRR → 77-GHz multimode LRR/MRR/SRR	76–81-GHz support, with flexible chirp configurations	• Support for 76–81-GHz RF frequency • Intelligent mmWave front-end with flexible and easy-to-use chirp config
Slow FMCW → Fast FMCW modulation	Wide IF bandwidth and sampling rate	• Up to 15-MHz IF bandwidth and 37.5-MSPS ADC sampling rate (AWR1243)
Discrete → Highly integrated	Integrated Radar-on-a-chip solution	• TX, RX, LO, ADC integrated in to single chip (AWR1xxx) • MCU, HW accelerator (AWR1443) • MCU, DSP integrated (AWR1642)
Digital beamforming, elevation and azimuth	Multiple TX/RX channels and cascading of multiple chips	• Up to 3 TX,4 RX (AWR1243, AWR1443) • Multichip cascading (AWR1243)
Newer applications (Pedestrian detection, 360° sensing)	Wide sweep bandwidth with fast ramp slope, precise chirp synthesis	• Up to 4-GHz sweep bandwidth • Fast ramp slopes up to 100 MHz/µs • Highly linear FMCW chirp generation using closed loop PLL
Comfort functions → Safety functions	Requires better functional safety and monitoring mechanisms	• Built-in safety monitoring mechanisms controlled by on-chip dedicated BIST processor.

AWR1243 (+TDA3x), AWR1443 and AWR1642 TI automotive radar solutions

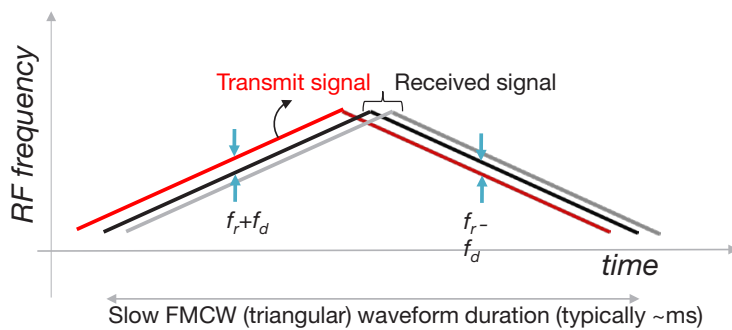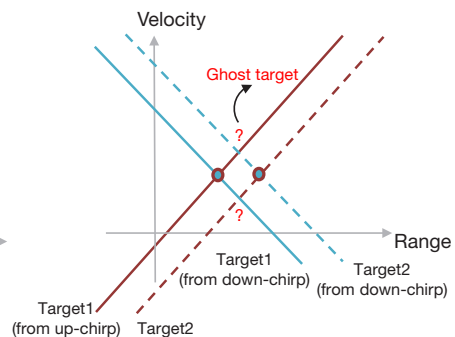*Table 1. Industry trends and mmWave front-end requirements.*

Figure 3. *Typical mmWave module design*

As noted in **Table 1**, industry trends pose increasing demands on the mmWave front end. There is a shift toward 76–81-GHz multimode mmWave sensor implementation due to spectral regulations, the availability of a wide bandwidth, a smaller sensor form factor and other performance advantages. This requires mmWave front-end integrated circuits (ICs) to support a 76–81-GHz RF frequency range, with the flexibility to configure a variety of chirp profiles depending on long-, medium- and short-range radar (LRR/MRR/SRR) applications. The use of mmWave for safety functions such as emergency braking brings additional functional safety and monitoring requirements.

In terms of RF specifications, newer radar applications can benefit significantly from features such as a wide RF sweep bandwidth, fast ramp slope, wide IF bandwidth and precise chirp synthesis. Let's briefly outline the benefits of these features on radar system performance.

Wide RF sweep bandwidth

FMCW radar system-level performance depends on the parameters of the chirp. **Table 2** summarizes how the range-, velocity- and angle-resolution performance of a typical radar system depends on the mmWave front-end configuration.

Parameter	Performance dependency	Comments
Range resolution	Inversely proportional to RF sweep bandwidth	A wide RF sweep bandwidth capability gives better range resolution
Velocity resolution	Proportional to wavelength and inversely proportional to frame duration	A smaller wavelength (77 GHz) and longer frame time give better velocity resolution
Angular resolution	Inversely proportional to aperture width	More TX/RX channels with digital beamforming give better angular resolution

Table 2. FMCW radar system performance.

There is an increasing need for higher-range resolution, velocity resolution and angular resolution arising from more demanding ADAS applications. Higher range, velocity and angle resolution provide a few benefits: better division of closely spaced targets and better information for object identification/classification. For example, a high spatial resolution (range and angle resolution) can help separate the gap between two vehicles or identify the presence of a child near a vehicle. Similarly, a high-resolution range profile and high-resolution velocity profile (Doppler spectrum) can help future systems specifically identify pedestrians.

One of the primary factors impacting range resolution is the RF sweep bandwidth of the chirp. As shown in **Table 2**, the range resolution is inversely proportional to the RF sweep bandwidth. For example, a sweep bandwidth of 300 MHz can provide a range resolution of 0.5 m, a sweep bandwidth of 1 GHz can provide a range resolution of 15 cm, and a sweep bandwidth as high as 4 GHz can provide a range resolution as low as 3.75 cm.

Fast ramp slope and wide IF bandwidth

While a wide RF sweep bandwidth improves range resolution, it can generally lead to a longer chirp duration. This can result in a limitation on the maximum unambiguous velocity detectable with the 2-D FFT processing method, because longer chirps lead to under sampling of the Doppler frequency shift.

Supporting fast ramp slopes is essential to achieving higher-range resolution without compromising the maximum velocity. For example, achieving the maximum unambiguous relative velocity of 170 kmph requires support for a chirp duration less than 20 μs. An mmWave sensor system that requires a 1-GHz sweep bandwidth swept within a 20-μs chirp duration requires a ramp slope as fast as 50 MHz/μs.

$$t_d = \frac{2R}{c}$$
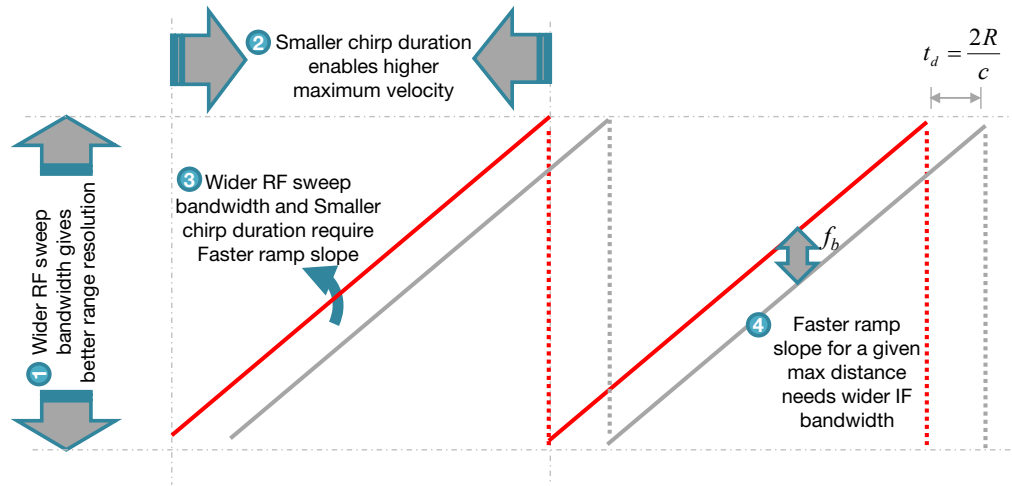
Figure 4. Radar system performance and mmWave front-end requirements.

While a faster ramp slope allows better range resolution and maximum velocity, it leads to a higher beat frequency for a given distance of an object. Thus, supporting a wider IF bandwidth would be useful to ensure that the maximum distance for which the radar can detect objects is not compromised due to a limited IF bandwidth in the analog baseband. **Figure 4** depicts the need for a fast ramp slope and wide IF bandwidth. Note that the DSP processing MIPS and memory requirements increase in proportion to the IF bandwidth.

Another advantage of a fast ramp slope and wide IF bandwidth is related to the fact that objects are separated more in the beat-frequency domain; thus, the noise skirt from a strong object produces less interference in the detection of a nearby weak object. Also, the effect of flicker noise in the analog baseband is reduced due to the use of a wider IF bandwidth.

Highly linear chirp generation, precise and repeatable

The linearity of the FMCW chirp is a key parameter impacting the accuracy of an object's estimated range. Traditional open-loop voltage-controlled oscillator (VCO)-based chirp generation can result in high nonlinearities within the chirp, which can lead to a smearing of the FFT peak and a resulting inaccuracy in the estimated range. This is particularly possible given the wide RF sweep bandwidth of up to 4 GHz, across which the linearity needs to be ensured.

The use of a closed-loop phase-locked loop (PLL) enables the generation of highly linear chirps, improving range accuracy and gaining the full benefit of high-range resolution. It also avoids the need for elaborate techniques to measure and compensate for nonlinearities in the VCO. **Figure 5** on the following page depicts a few examples of chirp nonlinearity (shown as instantaneous frequency error within the chirp) and the resulting impact on the FFT peak.

Since digital ramp-generator logic controls chirp generation in the closed-loop PLL producing high precision and repeatability, both in the RF frequency and in the timing across both chirps and frames. This repeatability across chirps is essential in order to take advantage of the high-velocity resolution available from 77 GHz, and to accurately measure the Doppler spectrum signature for future applications.
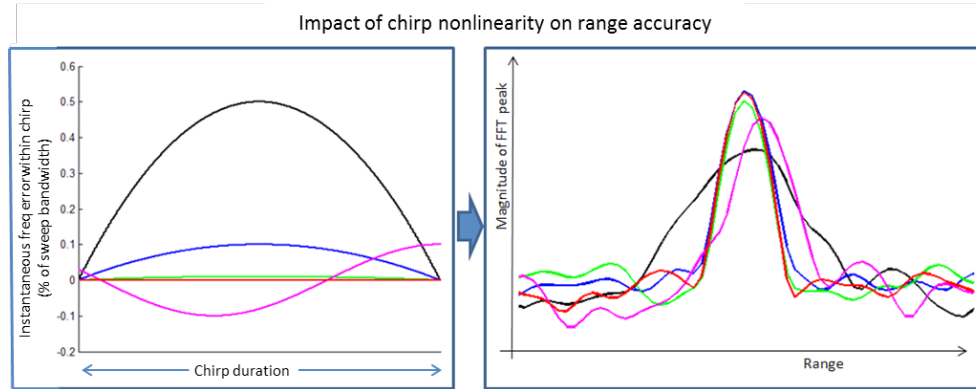
Figure 5. *Zoomed-in FFT peak showing how linear chirp reduces smearing and improves accuracy.*

TI's sensor portfolio

TI offers a family of devices for mmWave sensing— the AWR1243, AWR1443 and AWR1642 devices for automotive applications and the IWR1443 and IWR1642 devices for industrial applications. Let's look at some of the key features of the AWR1243 sensor.

AWR1243 sensor:
An Intelligent mmWave front-end

The AWR1243 mmWave sensor is a compact, high-performance front-end, supporting fast chirp FMCW modulations from a closed-loop frequency synthesizer and featuring a wide-IF bandwidth complex baseband. All mmWave, clock and analog baseband circuits are integrated in a single die in TI's mmWave CMOS technology, along with a digital sub-system for control, calibration and digital front-end.

Figure 6 shows the block diagram of the AWR1243 mmWave sensor. It includes three transmit (TX) chains, each of which includes an independent binary phase modulation and variable gain power amplifier with a simple single-ended output for direct interfacing to an antenna. Four receive (RX) chains include LNAs, mixers, and a complex baseband with a

15-MHz IF bandwidth. Continuous-time sigma-delta ADCs digitize the signals, and the digital front-end provides decimation and signal conditioning. The use of a complex-baseband architecture provides advantages for interference detection. See the white paper entitled "Using a complex-baseband architecture in FMCW radar systems".

The clock sub-system generates the fast-chirp FMCW waveform at one fourth of the RF frequency in a closed-loop fractional-N PLL. Synchronization
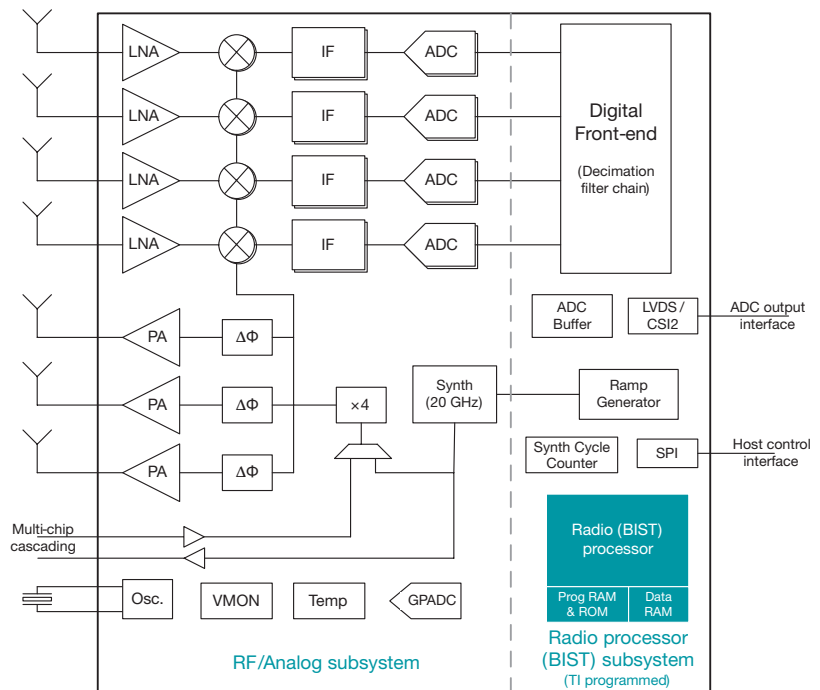

Figure 6. *AWR1243 mmWave intelligent front-end sensor.*

signals are provided to bypass this synthesizer in order to cascade multiple AWR1243 mmWave front-end sensors.

The radio processor sub-system includes an internal processor for control and calibration, a ramp generator for flexible real-time operation and associated peripherals and interfaces. The ramp generator provides flexible chirp generation with 512 unique chirps following 4 chirp profiles that can be pre-configured, eliminating any need for real-time control within the active radar operation period.

The primary data interface is over CSI-2, a common camera interface, to connect to an external DSP. A simple API interface provides control via SPI. LVDS is also provided as a debug interface for raw data capture and recording.

The intelligence advantage

The flexibility of various chirp configurations for multimode radar implementations, the ease of use of a mmWave front end, and advanced functional safety and monitoring are key priorities in emerging automotive radar applications. In this context, an intelligent mmWave front-end that has on-chip processor-based intelligence to control and monitor functionality is a big advantage.

The on-chip BIST processor shown in **Figure 6** controls chirp-generation parameters in real time so that the entire chirp configuration can be easily loaded via non-real-time messaging from the external host. The mmWave front end is fully self-contained and thereby offers significant ease of use from an external host perspective. The BIST processor provides automatic adaptation of the mmWave front-end over environmental changes, particularly temperature and aging. This enables better control and self-calibration of drift in key parameters such as output power and gain.

From a functional safety perspective, the intelligent mmWave front-end can autonomously monitor

its various RF/analog functional blocks for safety within each fault-tolerant time interval (a few tens of milliseconds). Important safety-monitoring features include TX output power, RX noise figure, synthesizer frequency error, and inter-RX gain and phase balance and ball break. The availability of a dedicated on-chip processor enables the handling of these numerous monitoring requirements and enhances safety while eliminating real-time control or processing constraints from the external host.

TI has a specific development process that was designed to meet the requirements of ISO 26262:2011. This development process has been certified by independent third party TÜV SUD. Those TI products that are developed in accordance with this certified process are developed as Safety Elements out of Context (SEooCs).

Cascading multiple AWR1243 mmWave devices

For objects at the same distance and velocity, sensors rely on angle to resolve multiple targets. Angle is estimated by measuring relative delays of the received signal across multiple received antennas[5]. Larger numbers of antennas are required to improve the angular resolution. For example, if two cars are separated by 2 m at 120 m distance, angular resolution of 1° is required. Further, it is beneficial to be able to separate out objects that are above the road, such as overpasses, and identify save drive-under and drive-over conditions. There is a tradeoff between horizontal and vertical resolutions. Given limited numbers of antennas available, today's radars typically offer only horizontal antenna arrays with limited resolutions.

AWR1243 sensors include synchronization features to enable cascading multiple devices on a single PCB to create large coherent arrays for high-resolution processing. As configured as a
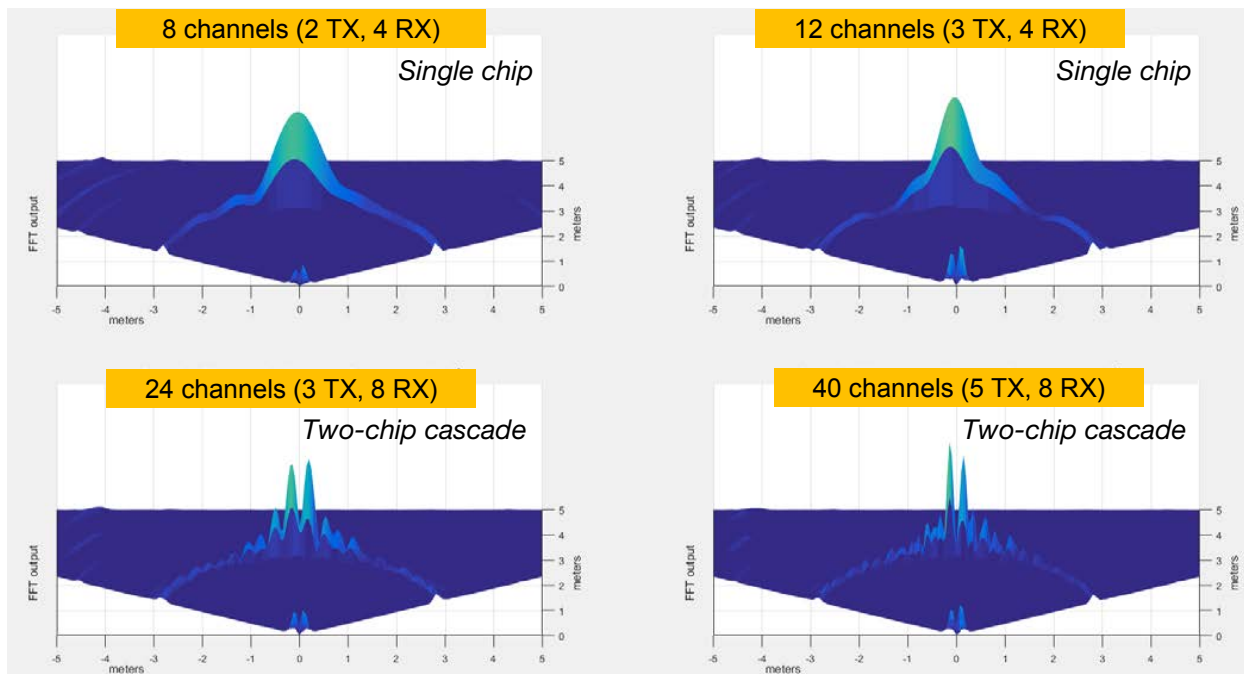
Figure 7. Measured radar responses of 2 corner reflectors with 4° angular separation with 1- (top) and 2-chip (bottom) configurations.

master device, the AWR1243 sensors can output a modulated 20-GHz signal that multiple AWR1243 sensor slaves can receive and use as their LO for radar signaling. With shared clocks and a baseband sync pulse also generated by the master, seamless cascaded operation is made possible. **Figure 7** shows that with two chips, sharp peaks in angle are evident, with clear separation of two closely spaced targets, which are indistinguishable for the single chip case.

Extending this further, a single master AWR1243 sensor driving three slaves, has up to 192 virtual antennas, capable of providing 1° angular resolution in azimuth (horizontal) and still providing coarse resolution for identifying safe tunnels, overhead road signs, and overpasses, a true imaging class of sensor.

Let's now discuss some use-case examples for the AWR1243 device.

AWR1243 sensor with TDA3x processor for high-performance MRR

For a high-performance medium range radar application, the **AWR1243** mmWave front-end can be connected to one of TI's **TDA3x** processors using CSI-2 for data and SPI for control, as shown in **Figure 8**. Including the C66x high-performance DSP and embedded vision engine (EVE) that can efficiently perform the low-level radar processing, the TDA3x processor is capable of handling the full bandwidth of the AWR1243 sensor.
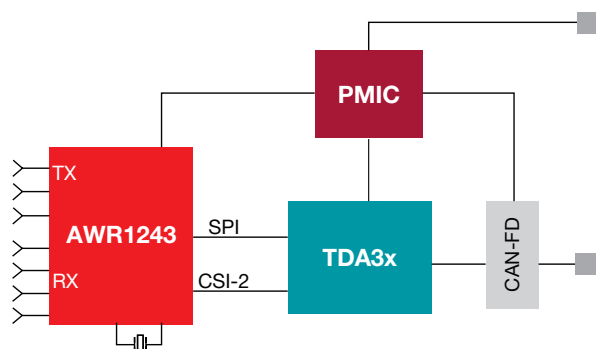
Figure 8. Medium-range radar using AWR1243 sensor and TDA3x processor

The high-IF bandwidth enables the AWR1243 sensor to maintain high range resolution out to longer distances. **Table 3** shows an example configuration where a range resolution of 33 cm is maintained out to 150 m while still supporting a raw maximum unambiguous velocity of 85 kmph.

AWR1243 sensor + TDA3x processor medium-range radar	
Sweep bandwidth	460 MHz
Range resolution	**33 cm**
Max unambiguous range	**150 m**
Ramp slope	15 MHz/µs
Chirp duration	30.7 µs valid (+ 7 µs inter-chirp)
Number of chirps	256
Max unambiguous rel. vel.	± 93 kmph
Max. beat frequency	15 MHz
ADC sampling rate (I, Q)	16.7 MSPS (complex)
Frame time	256 × 37.7 µs = 9.7 ms
Range FFT size	512 (complex)
Radar data memory	512 × 256 × 4 RX × 4 Bytes = **2 MB**

Table 3. *Example chirp configuration for MRR use case.*

For sensors limited to 5-MHz bandwidth, the range resolution or the maximum velocity would need to be degraded. As one example, 5-MHz IF bandwidth limits the maximum velocity to 60 kmph at a range resolution of 60 cm.

Imaging radar with AWR1243 mmWave sensors

As cars add more highly automated features, enhancing the performance of radar is needed. Four-chip cascaded AWR1243 sensor can achieve both superior angular and distance resolution at short ranges over a wide field of view while extending out to long distances. A multi-mode example is given in **Table 4** for the situation where a short period of the frame achieves very high resolution up to 40 m with extended view for detecting motorcycles up to 250 m, all while retaining 1° angular resolution.

Four AWR1243 cascaded 3D radar		
Sweep bandwidth	3333 MHz	275 MHz
Range resolution	**4.5 cm ← high resolution**	**55 cm**
Max unambiguous range	**40 m**	**250 m ← long range**
Azimuth angular resolution	**1°**	**1°**
Cross-range resolution @ max range	**70 cm**	**4.4 m**
Elevation angular resolution	**14°**	**14°**
Ramp slope	54 MHz/µs	9 MHz/µs
Chirp duration	61.3 µs valid (+ 13 µs inter-chirp)	30.7 µs valid (+ 7 µs inter-chirp)
Number of chirps	16	256
Max beat frequency	15 MHz	15 MHz
ADC sampling rate (I, Q)	16.7 MSPS (complex)	16.7 MSPS (complex)
Frame time	16 × 74.3 µs = 1.2 ms	256 × 37.7 µs = 9.7 ms
Range FFT size	1024 (complex)	512 (complex)
Radar data memory	1024 × 16 × 16 RX × 4 Bytes = **1 MB**	512 × 256 × 16 × 4 = **8 MB**

Table 4. *Full resolution radar with long-range mode for a four AWR1243 solution.*

These modes can be interleaved within each frame, as the operating time is much less than a typical total frame time of 40 ms. In addition, a third mode for medium-range radar with moderate resolution can also be inserted. The AWR1243 mmWave sensor has the flexibility of storing 512 unique chirps that map to four profiles. The short- and long-range modes typically would use two of the profiles and, as shown above, 272 chirps, allowing an additional mode to be added without any real-time overhead on the host microcontroller (MCU).

Summary

TI's mmWave family of devices includes 76–81-GHz intelligent front-end (AWR1243 sensor), as well as, devices that pair this front-end with on-chip processing for complete radar systems-on-chip (AWR1443 and AWR1642 sensors). The

AWR1443 and AWR1642 devices are covered in separate white papers. Designers are now able to hand select the best mmWave sensors for their needs. These sensors enable improved mmWave system performance and can better facilitate ADAS applications. The benefits for developers are endless.

- AWR1243, AWR1443 and AWR1642 mmWave sensors are designed to provide up to a 4-GHz sweep bandwidth.

- AWR1243 mmWave sensor supports ramp slopes up to 100 MHz/μs and an IF bandwidth up to 15 MHz.

- AWR1243, AWR1443 and AWR1642 sensors use a closed-loop PLL to generate highly linear chirps that are precise and repeatable.

- AWR1243, AWR1443 and AWR1642 sensors include an on-chip BIST processor for real-time control, self-calibration and functional safety monitoring, thus enabling ease of use, improved performance and enhanced safety.

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