77GHz single chip radar sensor enables automotive body and chassis applications

Texas Instruments

Sandeep Rao
Radar Systems Architect

Adeel Ahmad
Systems Engineer

Dr. June Chul Roh
Senior Systems Architect

Sachin Bharadwaj
Systems Engineer

Introduction

Well-established applications of frequency-modulated continuous-wave (FMCW) radar in automobiles range from safety to comfort functions – such as blind-spot detection, lane-change assist, automatic cruise control and park assist. These functions are based on the radar's ability to reliably and accurately detect and locate obstacles regardless of weather and ambient lighting conditions.

However, there are several other applications even within automotive that can benefit from a radar sensor's unique advantages. These include:

- Free-space sensing,
- Driver vital-sign monitoring,
- Gesture-based recognition,
- Occupancy detection.

FMCW radar resolves objects in range and velocity. Its performance is independent of ambient light, and it does not require investments in an additional signal source to illuminate the scene. Its high frequency of operation (77GHz) directly translates to a smaller overall solution size. FMCW radar signals can travel through plastic, which enables the sensor mounts behind a façade, such as a car bumper, dashboard or cladding, to enhance the aesthetics of the solution.

TI's line of single-chip millimeter-wave (mmWave) sensors bring the advantages of FMCW radar to a sensor that has a small form factor, low power, best-in-class bandwidth (4GHz bandwidth translates to 4cm resolution), and the on-chip computational and memory resources needed to accommodate the requirements of the applications in the list above. The AWR1443 has a radio-frequency (RF) front end that supports three transmit (TX) and four receive (RX) antennas [1]. This device has a programmable Arm® Cortex®-R4F running at 200MHz, 0.5MB of on-chip memory and a hardware accelerator to perform lower-level radar signal processing. The AWR1642 has an RF front end that supports two TX and four RX antennas. This device comes with a programmable Arm Cortex-R4F (200MHz); a C6748 digital signal processor (DSP) core (600MHz), which provides full flexibility in implementing signal-processing algorithms; and 1.5MB of on-chip memory [2].

Introduction to FMCW

Figure 1 is a block diagram of an FMCW radar showing a single representative TX chain and RX chain (although in practice, multiple chains are present to support multiple TX and RX antennas). The local oscillator (LO) generates a linear frequency ramp (also called a chirp) transmitted on the TX antenna. The received signal (reflected from the scene in front of the radar) on the RX antenna mixes with the transmit signal to create an intermediate frequency (IF) signal. An analog-to-digital converter (ADC) then digitizes the received IF signal for subsequent processing.

Fast Fourier transform (FFT) processing on the digitized samples resolves objects in range such that the frequency of the peaks in the range FFT directly corresponds to the ranges of various objects in the scene, as illustrated in the inset to the right of Figure 1.

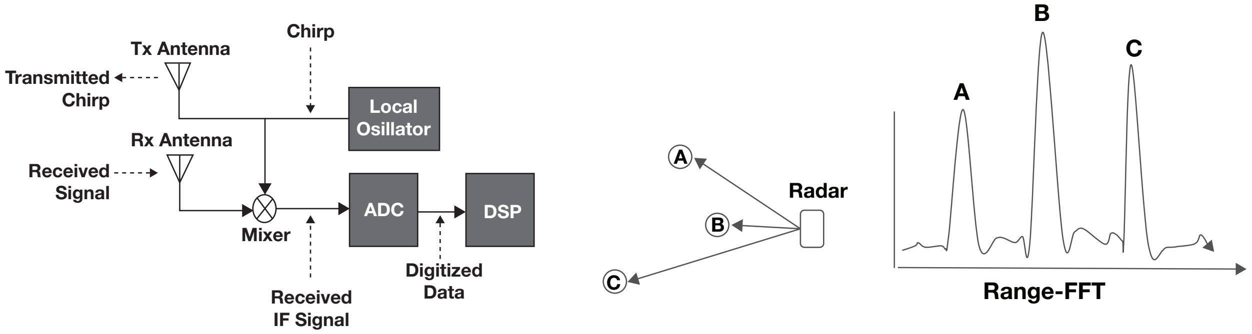

Figure 1. *Block diagram of an FMCW radar.*

While the frequency of a peak in the range FFT directly corresponds to the range of the object, the phase of this peak is extremely sensitive to small changes in the range of the object. For example, a change in the object's position by a quarter of a wavelength (≈1mm at 77GHz) translates to a complete phase reversal of 180 degrees. This phase sensitivity is the basis of radar's ability to estimate the frequency of a vibrating object. It also forms the basis for velocity estimation.

In order to resolve scenes in the velocity dimension, a radar typically sends out a sequence of chirps, equally spaced in time, in a unit called a frame (Figure 2). Exploiting the phase difference across chirps resolves and measures the velocity of objects in a scene.

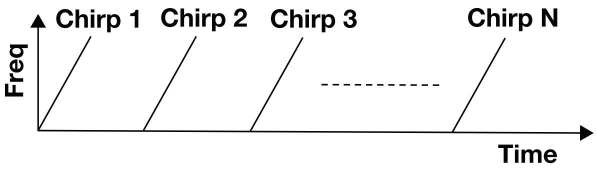

Figure 2. *A single frame with N equally spaced chirps.*

In a typical signal-processing chain, the device performs a range FFT on the digitized samples corresponding to each chirp, with the output stored as consecutive rows in a matrix (matrix A of Figure 3). Once the device receives and processes all of the individual chirps in a frame, it performs a second series of FFTs (Doppler FFT) across the chirps (across columns in matrix A). The combined operation of the range FFT (row-wise) followed by a

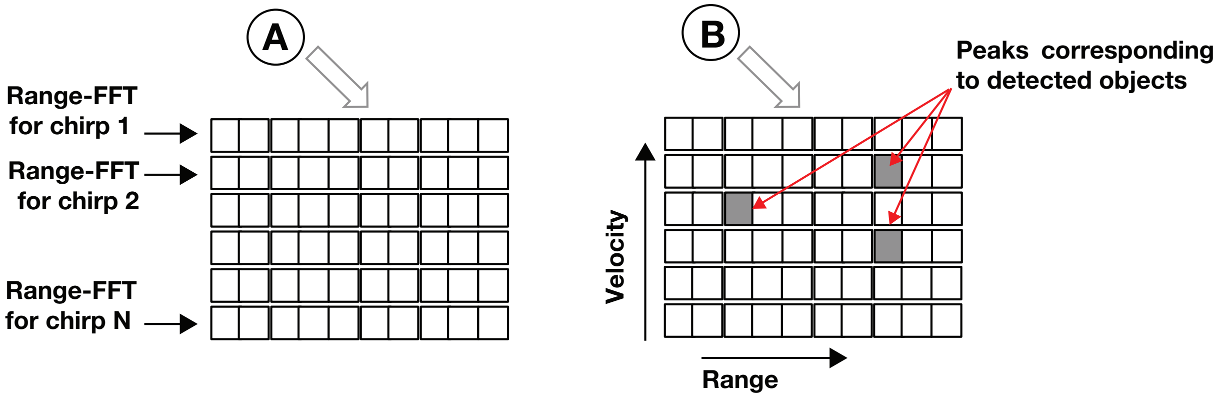

Figure 3. *Range and Doppler processing in FMCW radar.*

Doppler FFT (column-wise) is viewable as a 2-D FFT of the digitized samples corresponding to the frame. This 2-D FFT resolves objects in both range and velocity; that is, the location of peaks in the 2-D FFT directly corresponds to the range and velocity of objects in front of the radar (matrix B in Figure 3).

Resolving objects in the angle dimension requires multiple RX antennas. For this, the device first processes the signal received at each antenna to create a 2-D FFT, as described above with reference to Figure 3. Processing the 2-D FFT matrices obtained across multiple antennas then yields the angle of arrival of objects.

Thus, radar can resolve objects in the dimensions of range, velocity and angle. The performance metrics of a radar depend on the choice of transmit signal [3]. For example, range resolution improves as the bandwidth spanned by the chirp increases; velocity resolution improves as the frame duration increases. Likewise, the maximum measurable velocity is inversely proportional to the spacing between adjacent chirps. The number of TX/RX antennas limits the angle resolution. See [4] and [5] for a more in-depth discussion on FMCW radar operation.

Free-space sensing

A free-space sensor extends the natural ability of radar to detect obstacles for applications such as collision prevention while opening the door or trunk of a car. Such an application leverages the high-range resolution of radar and its ability to detect obstacles at close range (poles, parking barriers, walls, adjacent parked cars). See Figure 4. A free-space sensor can also act as a park-assist sensor.

Figure 5 depicts a typical processing chain for free-space sensor applications. The device processes the analog-to-digital converter (ADC) data across a frame by performing a 2-D FFT, which resolves objects in range and Doppler and separates moving objects in the vicinity from stationary obstacles. With a moving radar such as one mounted on a door, Doppler resolution also helps resolve objects, which though stationary, are at different relative velocities with respect to the radar. The noncoherent accumulation of 2-D FFT matrices across antennas creates a range-Doppler heat map which a detection algorithm then processes.

The detection algorithm can be a basic constant false-alarm rate – cell averaging (CFAR-CA) detector

Figure 4. *Applications for a free-space sensor application.*

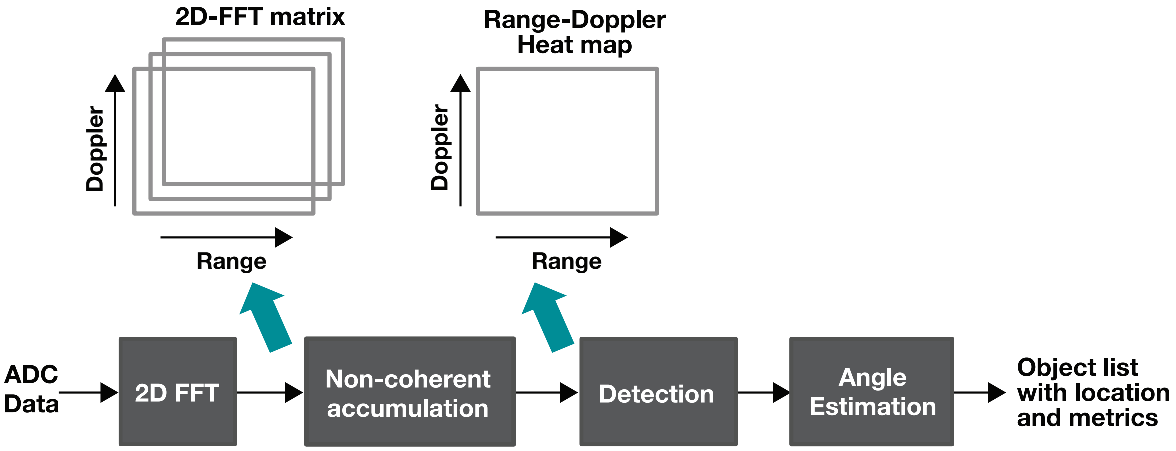

Figure 5. *A representative processing chain for a free-space sensor application.*

[6]. More sophisticated variants such as CFAR-ordered statistic (CFAR-OS) can also help improve detection in the presence of ground clutter.

Processing the corresponding bins across the 2-D FFT matrices is used to estimate the angle of arrival of detected objects. In order to make best use of the available TX/RX antennas, I recommend operating the system in multiple input/multiple output (MIMO) mode [7]. The angle-estimation block uses the 2D-FFT processed signals at the virtual antennas synthesized by the MIMO operation. The angle-estimation algorithm could be based on an FFT or beamforming algorithm. More sophisticated algorithms such as multiple signal classification (MUSIC) can provide higher angle resolution [8].

The choice of antenna configuration and the field of view (FOV) of antenna elements are important considerations in free-space sensor applications. In general, there is a trade-off between elevation FOV and ground-clutter suppression, as well as between elevation estimation capability and azimuth resolution. While many design possibilities exist, let's look at two approaches specifically. One option is to design antennas with a wide FOV in both azimuth and elevation. The placement of the antennas can then be such that operation in MIMO mode synthesizes a 2-D virtual array, thus enabling angle estimation in both elevation and azimuth. Figure 6 shows some examples. While a wide FOV in both azimuth and elevation provides true 3-D sensing, the placement of the radar needs to be well thought out to minimize ground clutter.

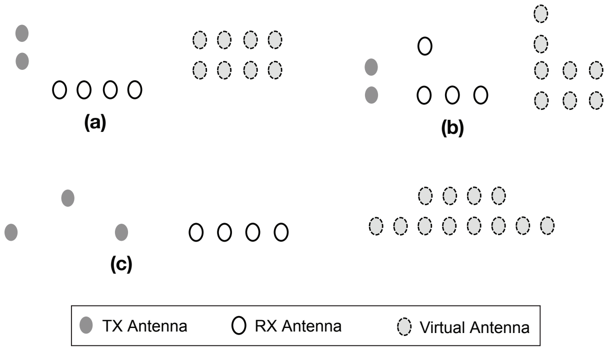

Figure 6. *2-D antenna configurations (a and b: TI's AWR1642; c: TI's AWR1443).*

Another option is to design antennas with a narrow FOV in the elevation while retaining a wide FOV in the azimuth, with placement of the antennas designed to ensure maximum resolution in the azimuth dimension (Figure 7).

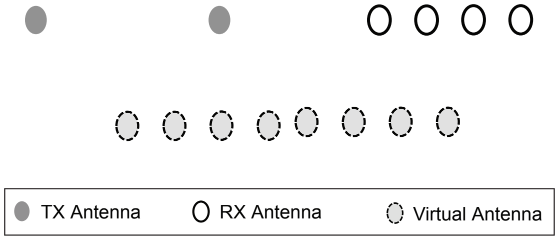

Figure 7. *1-D antenna configuration.*

Table 1 is an example chirp configuration for a free-space sensor application.

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	100µs
Number of chirps per frame	32 (interleaved between TX1 and TX2)
Maximum velocity	17kmph
Range resolution	~4cm
Maximum range	4m
Velocity resolution	1kmph
Memory requirement	~100KB

Table 1. *A representative chirp configuration for a free-space sensor application.*

Driver vital-sign monitoring

An important application that enhances road safety, FMCW radar technology can enable the continuous monitoring of a driver's vital signs by accurately monitoring their heart and breathing rates. This sensor's small size means a nonintrusive implementation; for example, the sensor can be embedded in the backrest of the driver's seat.

The phase of the received signal in an FMCW radar is extremely sensitive to small changes in object location. (Recall that the sensitivity of the phase of the range FFT processed data changes by 180 degrees for every 1mm movement in the object.) Exploiting this property can estimate the vibration frequencies of objects (such as vibrations induced by heartbeats and breaths). The device transmits a sequence of chirps, and a peak in the range FFT identifies a strong reflection coming from the driver's chest. The algorithm in the device tracks the phase of this peak across chirps and performs a spectral analysis on this sequence of phases in order to extract the driver's heart and breathing rates.

Figure 8 is a simplified block diagram of a representative signal-processing chain. First, the device performs a range FFT on ADC data corresponding to each transmitted chirp. After identifying the relevant peak, it records the phase of this peak across chirps. Note that the movement of the chest due to breathing can be on the order of 12mm, which is several times the radar's operating wavelength (~4mm at 77GHz). Thus, appropriate unwrapping of the phase is necessary in order to correctly interpret the results.

The algorithm in the device then band-pass filters the phase sequence to extract the spectrum of interest (0.1-0.5Hz for breaths, 0.8-2Hz for heartbeats). Spectral analysis on the output (using an FFT) can then identify the heart rate and breathing rate. Optionally, for improved robustness, you could use a motion-detection block to detect motion in the driver and either suitably compensate for this motion or discard the reading. In this particular application, there is no concept of a frame. Instead, the chirps are sent in a continuous stream and processing occurs over a running window.

Table 2 is a representative chirp configuration for this application. For best performance, choose chirps to maximize the range resolution. This

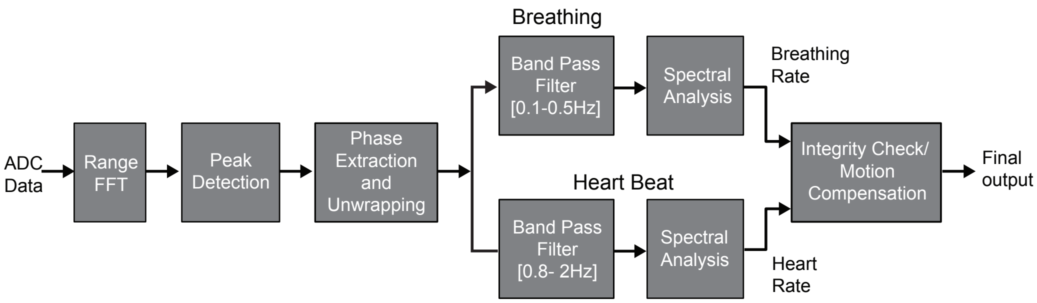

Figure 8. *A representative processing chain for a driver vital-sign monitoring application.*

helps in separating the reflection coming from the chest from other nearby clutter. Performing angle measurements using multiple RX antennas further separates the driver from surrounding clutter or can even measure the vital signs of multiple people simultaneously. Since both heartbeats and breaths have low frequencies, the chirps can be spaced quite far apart. A rate of 20 chirps per second is sufficient to ensure no phase rollover between sampling instants. Higher chirps per second would be beneficial for measuring heart-rate variability (instantaneous changes in heartbeat intervals), which studies have shown correlates with drowsiness.

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	50ms (20 chirps per second)
Number of chirps per frame	–
Maximum velocity	–
Velocity resolution	–
Memory requirement	~16KB

Table 2. *A representative chirp configuration for a driver vital-sign monitoring application.*

Gesture-based recognition

The high range and velocity (or Doppler) resolution possible using FMCW radars makes it a good fit for a gesture-based touchless interface. Automotive use cases include gesture-based door/trunk opening (Figure 9) and gesture-based control of an infotainment system (such as waving a hand to switch between screens or twirling a finger to control the volume).

Figure 9. *Applications for gesture-based door/trunk opening*

Figure 10 shows a recommended processing chain for a gesture-based recognition application. First, the device performs a 2-D FFT on the ADC data collected across chirps in a frame. This resolves the scene in range and Doppler. It then computes a 2-D FFT matrix for each RX antenna (or each virtual antenna if the radar is operating in MIMO mode). The non-coherent accumulation of the 2-D FFT matrix across antennas creates a range-Doppler heat map.

The next step involves extraction of multiple features from the range-Doppler heat map. Think of a feature (such as average Doppler or average range) as a single number extracted from the range-Doppler heat map whose value reflects the weighted average of a specific parameter. Feature extraction usually happens over the region of the range-Doppler heat map where the gesture is expected to happen (such as within half a meter in range, and ±2m per second in Doppler). This region can either be fixed a priori or adapted dynamically.

A single frame of the radar yields a single value for each feature. A sequence of frames generates a time series for each feature. Mining the time series corresponding to multiple extracted features identifies and classifies various gestures. Figure 10 depicts this action in the feature processing block.

Multiple approaches to feature processing exist. One approach involves sending the features extracted over a certain time window to a machine-learning algorithm, such as an artificial neural network, decision tree or support vector machine, which then performs the classification. Another approach involves hand-crafted logic to identify various signatures in the extracted features. Hybrid solutions are also possible.

The output of feature processing is the type of gesture detected. Feature processing can also output additional metrics related to the gesture (such as gesture speed), which you can then use to improve the user experience.

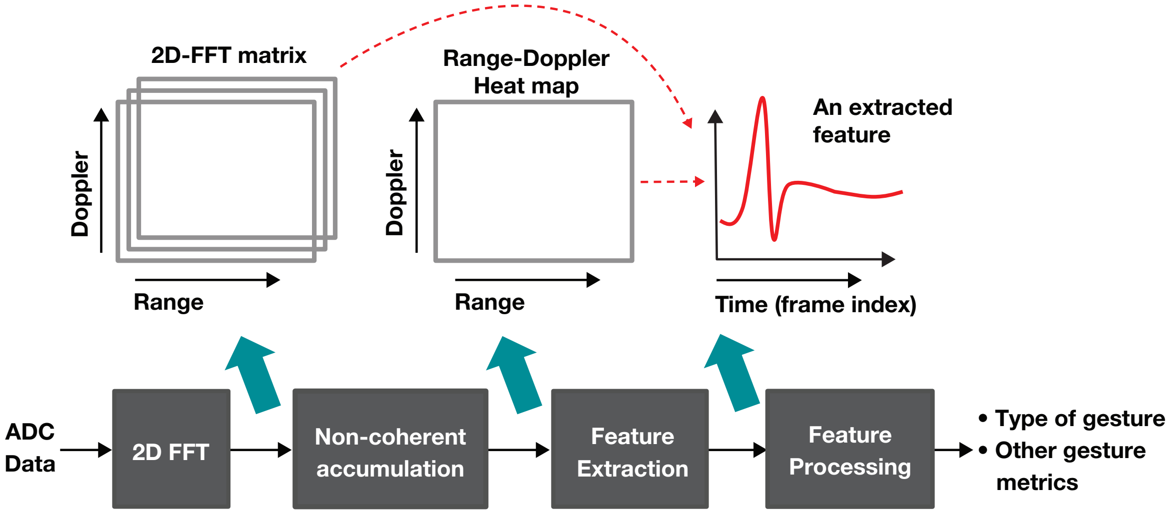

Figure 10. *A representative processing chain for a gesture-based recognition application.*

High range and velocity resolution are critical for good gesture recognition, so choose a chirp with a high bandwidth. The frame time should be large in order to improve velocity resolution. Since the maximum velocity requirements are not high, you can increase the spacing between chirps, which also helps keep the number of chirps (and hence required memory) to a minimum, while still ensuring a large frame time. Table 3 shows an example chirp configuration.

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	800µs
Number of chirps per frame	256
Range resolution	4cm
Maximum range	40cm
Maximum velocity	4kmph
Velocity resolution	0.034kmph
Memory requirement	40KB

Table 3. *Representative chirp configuration for a gesture-based recognition application.*

The AWR family of single-chip radars can be used for implementing cost-effective gesture-recognition solutions. For single-gesture applications such as gestures to open the door or trunk of a car, the AWR1443 may be an appropriate choice. For applications requiring classification across a wider gesture set, such as for an infotainment interface, the AWR1642, with its built-in C674x DSP, would be a good fit.

Occupancy detection

Children and animals left inside locked vehicles can die very quickly from the heat. An FMCW radar installed in the cabin can detect their presence in an otherwise unattended vehicle, thus enabling timely intervention.

This application hinges primarily on the radar's capability to achieve fine velocity resolution. The radar must separate objects making even the slightest movements (such as a sleeping child) from stationary clutter in the vehicle.

Figure 11 shows a representative processing chain. The frame consists of a series of equally spaced chirps in MIMO mode, alternating between TX1 (blue) and TX2 (red). The large gap between each pair of chirps serves to stretch the frame time and improve the velocity resolution. First, the device computes the range FFTs for all chirps in the frame. The output of the range FFT is sent to a clutter removal block, which removes the signal contribution corresponding to stationary clutter so that subsequent blocks can operate on signals of

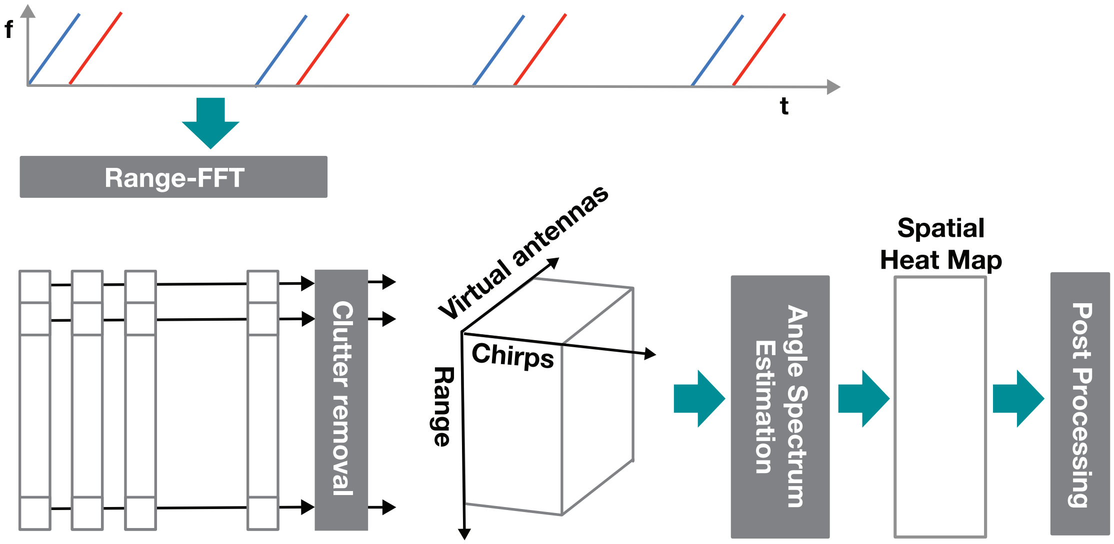

Figure 11. *A representative processing chain for an occupancy-detection application.*

interest (namely signals corresponding to slow/intermittently moving objects). This block operates by estimating the DC component for each range bin (the average of the range bin across chirps), and subtracting it from the corresponding range bin (across all range FFTs in the frame).

The range FFTs for all antennas pass to an angle spectral estimation block that calculates the angle spectrum for each range bin. Micromotions in the objects of interest serve to de-correlate the phases of the range FFT peaks computed across multiple chirps, which in turn helps improve angle resolution.

Once the range FFT has resolved signals in range and angle spectral estimation has resolved the angle, a spatial heat map plots the signal intensity in a 2-D x-y axis, or alternatively, a range-azimuth axis. Subsequent post-processing can then detect objects in this heat map based on detection algorithms (such as CFAR) or more sophisticated feature extraction and analysis techniques. The output of the post-processing can be a flag indicating either the presence or absence of objects of interest. Additionally, the post processing block can also output the spatial location of the object of interest.

Parameter	Value
Chirp bandwidth	4GHz
Chirp periodicity	340µs
Number of chirps	512 (256 each of TX1 and TX2)
Range resolution	~4cm
Maximum range	3m
Maximum velocity	2.28m per second (10kmph)
Velocity resolution	0.02m per second (0.08kmph)
Memory requirement	600KB

Table 4. *A representative chirp configuration for an occupancy-detection application.*

The AWR family of highly integrated radar devices can be used to develop compact ‘radar-on-a-chip’ solutions to enhance the automotive experience beyond ADAS, including free-space sensing, driver vital-sign monitoring, gesture-based recognition and occupancy detection.

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