Robust traffic and intersection monitoring using millimeter wave sensors

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Abstract

Numerous sensing technologies tackle the challenging problems of traffic-monitoring infrastructure, including intersection control, speed tracking, vehicle counting and collision prevention. TI's 77-GHz millimeter-wave (mmWave) radio-frequency complementary metal-oxide semiconductor (RF-CMOS) technology and resulting mmWave sensors have inherent advantages with respect to environmental insensitivity/robustness, range and velocity accuracy and system integration. TI's simplified hardware and software offerings—including evaluation module (EVM) references, reference designs in the TI Designs reference design library, software libraries and code examples—make mmWave sensing technology truly accessible and enable you to quickly evaluate and demonstrate its capability in an application.

Introduction

Transportation systems are an important component of the infrastructure necessary to move individuals and freight quickly, efficiently and safely around the world. These pieces of infrastructure focus on sensing conditions around trafficked areas and collecting data that can help the infrastructure react to changes. Traffic engineers use the data to build statistics and help target future infrastructure investments, while drivers use the data to help manage their routes. The value of this information is obvious, since the intelligent transportation systems market is forecasted to reach more than US $63.6 billion by 2022.

mmWave sensing technology detects vehicles such as cars, motorcycles and bicycles, at extended ranges regardless of environmental conditions such as rain, fog or dust. TI's mmWave-sensing devices integrate a 76–81 GHz mmWave radar front end with ARM® microcontroller (MCU) and TI digital signal processor (DSP) cores for single-chip systems. These integrated devices enable a system to measure the range, velocity and angle of objects while incorporating advanced algorithms for object tracking, classification or application-specific functions.

Traffic-monitoring applications

Traffic congestion is generally focused around choke points or high-volume areas, and so a large portion of traffic-monitoring systems are dedicated to monitoring vehicle behavior and traffic flow around intersections and highways.

Around intersections, traffic engineers look to understand specific information and telemetry about vehicles in order to react to intersection conditions and collect traffic statistics. Vehicle information can include its range from an intersection stop bar, speed, occupied lane and type (size). A variety of applications can use this vehicle information,including:

- **Dynamic green-light control**—real-time adjustment of green-light timing to enable more traffic to flow in certain directions across the intersection, depending on traffic density.
- **Statistics collection**—constant monitoring of traffic flow rate and traffic type over time. When

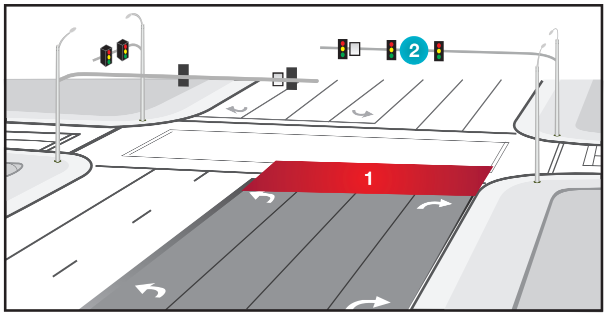

Figure 1. Example intersection where traffic sensors can be positioned at the stop bar (1) or on the traffic pole (2). Sensors mounted on the traffic pole are advantageous in that they do not require installation in the road surface.

collected over many intersections, statistics can help unveil the need for improvements or changes to an infrastructure.

- **Yellow-light timing (dilemma zone prevention)**—real-time adjustment of yellow-light timing based on traffic speed and type.

Figure 1 shows a typical mounting of an intersection sensing system so that it has maximum visibility to oncoming traffic. For close-range sensors such as inductive loop, this usually means installation embedded in the roadway. For noncontact sensors like vision and mmWave sensors, the sensors are typically located on a traffic pole or near the center of the intersection, and elevated several meters above the road for a clear line of sight. Mounting sensors on a pole has the advantage of not requiring installation in the road surface or impacting the sensors during road maintenance.

Around highways, traffic engineers seek to understand the average rate of travel in order to identify incidents. Vehicle tracking and pedestrian detection recognize congestion points or potential areas of concern for motorists.

Traffic-monitoring systems are supposed to improve transportation efficiency and safety in a variety of conditions, yet designers face a myriad of sensing challenges that include:

- **Measurement of position and velocity.** Useful traffic data requires knowledge of both traffic location and flow. Key factors around an intersection include measuring the range from the stop bar and the approaching vehicle speed. To maximize useful data collection, a sensing system should be able to measure both the position and velocity of traffic on the road.
- **Operation in all weather conditions.** A traffic infrastructure sensor is naturally located outdoors, and must be able to work across all environmental variations. This variation can include day/night lighting and inclement weather like rain, snow, fog and dust.
- **Detection of high-speed objects over extended ranges.** Maximizing a sensor's ability to anticipate traffic behaviors drives system efficiency. Sensors must be able to detect and measure faster-moving traffic at longer distances. Being able to sense vehicles farther away from an intersection enables lights to better control green and yellow durations to preempt incoming traffic.
- **Accuracy and performance of measurement.** Without accuracy of measurement – vehicle position and velocity – traffic data is useless. Accurately understanding vehicle lane location, vehicle distance from the sensor and vehicle speed is critical for the effective operation of traffic-monitoring infrastructure.

Today's traffic-monitoring technology

Let's review several sensing technologies in use today in traffic-monitoring applications, beginning with the role of these technologies in the market, as well as pros and cons of their implementation. **Table 1** on the following page summarizes this sensing technology information.

Type	Inductive loop sensors	Cameras and vision-based sensors	24-GHz radar
			
Description	• Use of insulated wire inside cuts in roadway • Changes in wire induction measured when vehicle passes over	• Video image processor takes in camera sensor data and analyzes imagery to determine traffic behavior	• Discrete components assembled to create a 24-GHz radar for traffic positioning and speed
Pros	• Well understood use and application	• Powerful algorithms for a variety of applications • Video for recording and monitoring	• Insensitive to weather, changing environments • Radar has extended range over camera (60 m+) • Inherent ability to measure speed
Cons	• Disruption of traffic for installation/repair • Short maintenance cycles • Detection only around intersection • No measurement of velocity/speed • Poor detection of two-wheel vehicles	• Complex signal processing needed to disregard shadows, occlusion, day/night cycles • No measurement of velocity/speed • Vulnerability to changing environments	• Lower angular resolution than camera • Limited integration—design complexity • Lower range/velocity performance vs. higher frequency ranges

Table 1. *Existing technologies in traffic monitoring including their pros and cons.*

Inductive loop sensors

Inductive loop sensors use insulated, electrically conductive wire passed through cuts in the roadway. Electrical pulses are sent through the wire, and when a metal vehicle passes over the loop, the vehicle body causes Eddy currents to form that change the inductance of the loop. An electronic sensing system can measure this change in inductance, and indicate when a vehicle occupies a space or passes by.

Inductive loop sensing is a simple technology that has been used for many years in traffic infrastructure. It is very well understood, but has several shortcomings. Detection is limited to a "presence" around wherever the loop is installed, and the scale of the system requires that each zone and lane have its own loop at an intersection. Perhaps the biggest negative is the fact that installing or repairing these systems requires digging up the road surface. This maintenance requires special personnel and equipment, and can close down roads. Combine that with the often-short maintenance cycles of inductive loop systems (one to two years), and the overall cost of an inductive loop system compounds quickly.

Cameras and vision-based sensors

Cameras and vision-based sensors use a video image processor to capture image data from a complementary metal-oxide semiconductor (CMOS) camera sensor and analyze the imagery in order to determine traffic behavior. These systems can be powerful tools to not only measure traffic behavior at intersections and highways, but also to transmit live video to operators.

Despite the power and flexibility of vision-based systems, the technology can be challenging to work with. Vision systems are prone to false detection as changing environmental conditions—day/night cycles, shadows and weather—directly impact the ability of these systems to "see." These vision challenges require advanced signal processing and algorithms.

24-GHz radar

One technology that's getting traction in the traffic-monitoring market is 24-GHz radar. Radar has unique advantages in the sensing space that play well into traffic-monitoring applications. Radar has the ability to inherently measure the position and velocity of objects in its view, which opens up new applications in traffic monitoring such as speed sensing and vehicle positioning. As a noncontact technology, radar has an extended range over vision-based systems, 50 m or more. Radar is also insensitive to lighting and changing weather conditions, making it suitable for outdoor sensing and detection.

There are certain challenges to implementing a radar solution, however. Today's radar solutions require multiple discrete components to create a complete solution. This lack of integration increases design complexity and comes at the expense of system size, cost and power consumption.

76 GHz–81 GHz mmWave radar

Texas Instruments has created a portfolio of innovative sensors based on millimeter-wave (mmWave) radar operating in the 76 GHz–81 GHz frequency band. These sensors integrate radio-frequency (RF) radar technology with powerful ARM MCUs and TI DSPs on to a single monolithic CMOS die, and wrapped in a 10.4-mm-by-10.4-mm package. This enables small form-factor applications to accurately measure the range, velocity and angle of objects in view as well as to integrate real-time intelligence through advanced algorithms that can detect, track and classify objects. These capabilities scale through the mmWave sensor portfolio to fit different system architectures and use cases, as shown in **Figure 2**.

The unique features and capabilities of TI's mmWave sensors make them an exceptional fit for traffic-monitoring applications.

Measurement of position and velocity

TI's mmWave sensors can accurately measure the range, velocity and angle of objects in view. These three data sets, as shown in **Figure 3** on the following page, can give sensing systems the ability to gain new intelligence about the world around them. For intersection monitoring, this can include the distance, speed and lane position of vehicles and pedestrians.

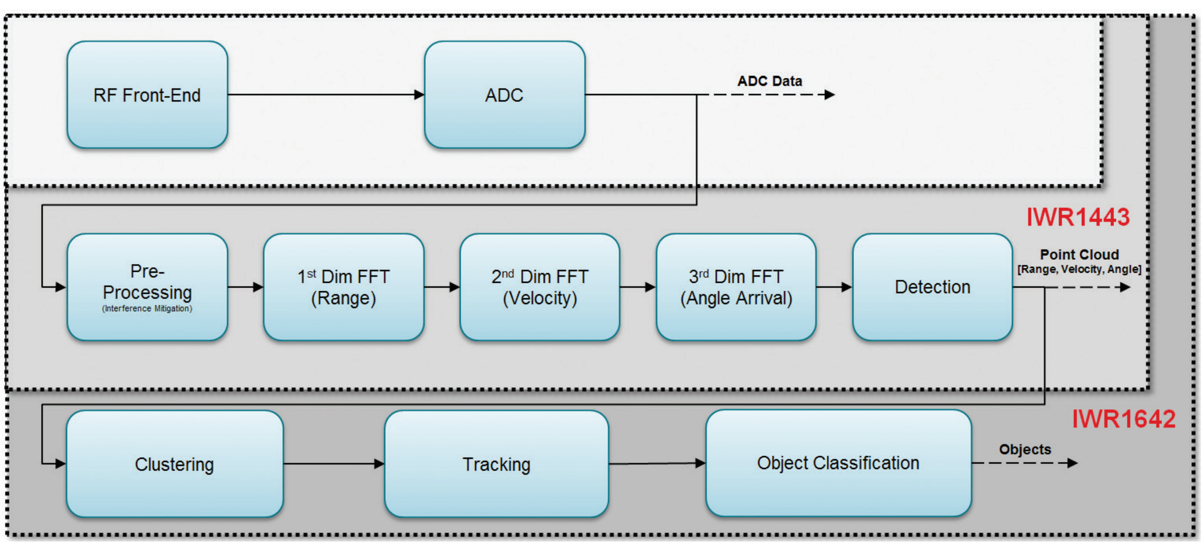

***Figure 2**. mmWave signal processing chain.*

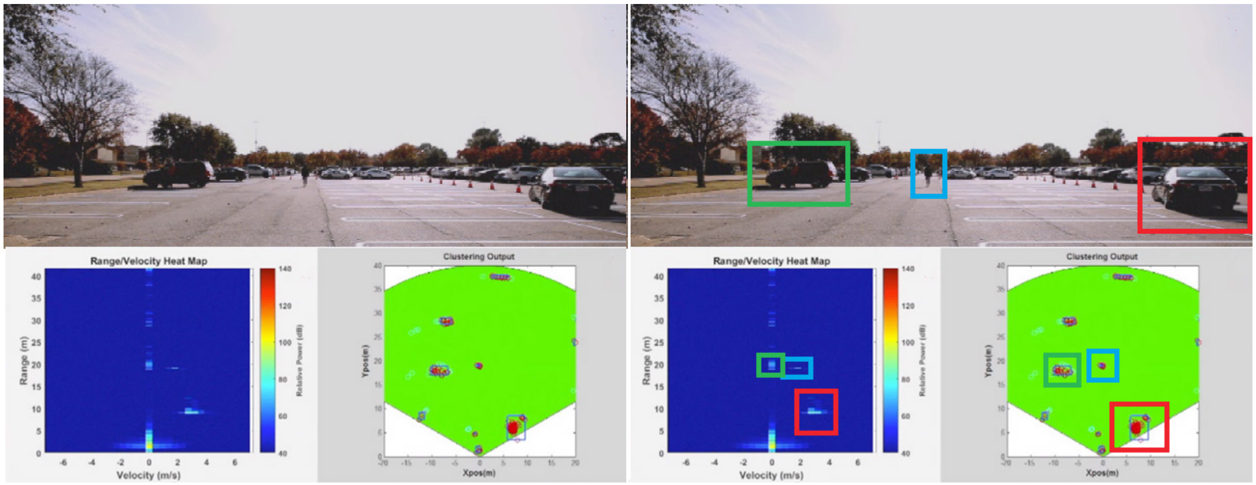

Figure 3*. Range, velocity and angle information from mmWave sensors in an example parking lot scene. The graph with the blue background is a range/velocity heat map, where moving and nonmoving objects and their velocities are identifiable; the graph with the green background is a range/angle visualization. Colored boxes highlight the moving and nonmoving vehicles and pedestrians in the scene.*

Operation in all types of weather

For those of you familiar with radar applications and RF signal propagation, you likely already know that mmWave has the ability to **penetrate and sense through adverse weather conditions such as smoke, fog and rain**. This capability enables mmWave sensors to be a solution for robust and consistent outdoor sensing in uncontrolled and variable environments.

Detection of high-speed objects over extended ranges

TI's mmWave sensors use fast frequency-modulated continuous wave radar (fast FMCW) in the 77-GHz range, the combination of which has several advantages over legacy radar systems.

Fast FMCW radar involves a transmit chirp design where the radar signal sweeps from a start frequency to a stop frequency for each chirp. In the example shown in **Figure 4**, the sweep is from low

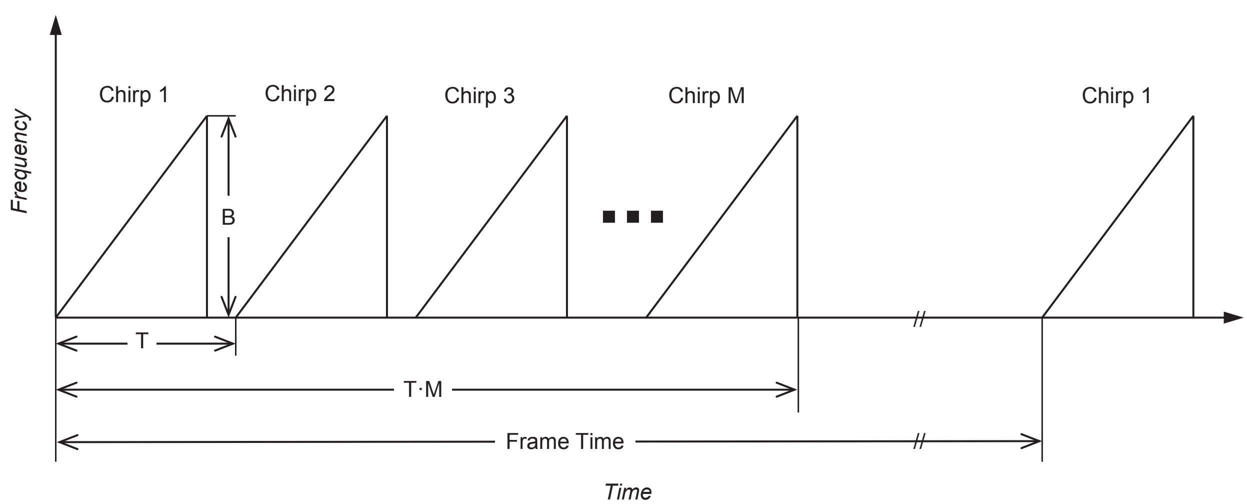

Figure 4*. Frequency vs. time graph depicting a fast FMCW frame where B is the chirp bandwidth, T is the chirp repetition time (which could be a few tens of microseconds) and T·M is the total active chirping time in one frame. The frame time includes an idle time that may be a few tens of milliseconds.*

frequency to high frequency. In the simplest design, a frame consists of several chirps with the same profile repeated a number of times, followed by an idle period before the frame repeats.

The transmitted signal radiates from the transmit antenna(s) and reflects off various objects. The received signal is collected on a receive antenna array and mixed with the transmitted signal to form a de-chirped signal that is filtered, sampled and further processed to detect objects in the scene.

The IWR1642 sensor has a fast ramp slope that enables fast chirp repetitions leading to high maximum velocity measurements. A typical ramp slope configuration of 11 MHz/µs enables chirp repetition times in the tens of microseconds. This enables direct target velocity measurements beyond 100 kph. Additional DSP processing can extend the maximum velocity by another 3× to 4× so that maximum target velocities in excess of 300 kph are trackable, making the IWR1642 sensor a suitable sensor for fast-moving traffic scenes such as those around highways and on-ramps.

Through the combination of antenna design and RF chirp configuration, the 77-GHz radar system can easily detect targets such as vehicles at ranges of 150 m or more. By combining many chirp repetitions to increase the processing gain, even the IWR1642 evaluation module (EVM) with a 120-degree field of view can achieve vehicle detection up to 135m in the center of the field of view where the antenna gain is highest. This turns out to be practical for centrally mounted traffic sensors, since the angular spread of vehicles across several lanes at that distance is quite small. Other antenna designs specifically intended to increase antenna array directivity can trade off field of view for additional range.

In a traffic-monitoring use case, both wide field-of-view antenna designs with a ~100-degree field of view, as well as narrower field-of-view designs as low as 20 to 40 degrees, are potentially useful depending on the specific geometry of the intersection or roadway and the specifics of the application.

Accuracy and performance of measurement

Fast FMCW radar with integrated processing is capable of measuring the range, radial velocity and angle of many target reflectors in a scene, many times per second. This facilitates higher-level processing for scene interpretation, including the identification and tracking of many vehicles.

For traffic-monitoring applications, the frequency band offers up to a 1-GHz sweep bandwidth compared to only 200 MHz in the 24-GHz band. This enables increased range resolution as fine as 15 cm – that's a 5 times greater range resolution than what's available in 24 GHz.

Velocity resolution is a function of active chirping time and carrier frequency. Therefore, 77 GHz provides 3× finer velocity resolution than 24 GHz for the same active chirping time. Velocity resolution of 1 kph or finer is achievable within the processing and memory resource boundaries of the IWR1642 sensor.

Example usage/architecture with the IWR1642 sensor

The IWR1642 sensor is a radar-based sensor that integrates a fast FMCW radar front end with both an integrated Arm R4F MCU and a TI C674x DSP for advanced signal processing. The configuration of the IWR1642 radar front end depends on the configuration of the transmit signal as well as the configuration and performance of the RF transceiver, the design of the antenna array, and the available memory and processing power. This configuration influences key performance parameters of the system, such as resolution in range and velocity, maximum range and velocity, and angular resolution.

When designing a chirp configuration for a traffic monitoring use case, start by considering the geometry of the scene, the field of view in both azimuth and elevation, and the ranges of interest. Let's use as an example a four-lane intersection with a radar sensor mounted overhead. Making some assumptions about the sizes and positioning of lanes, medians, crosswalks, stop bars and overhead sensor mountings, an azimuth field of view of at least 25 degrees will cover the stop bar and approaching +60 m of roadway. **Figure 5** illustrates this example traffic-monitoring geometry.

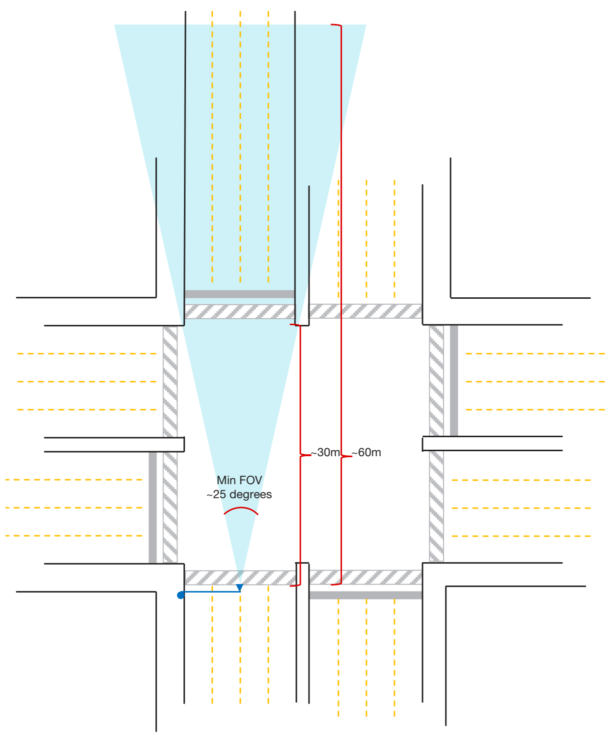

Figure 5. Example intersection with overhead radar sensor mount and azimuth field of view of 25 degrees covering a four-lane stop bar at a distance of approximately 30 m and an approach of approximately 60 m.

For this example, assume that the antenna pattern enables this azimuth field of view with two transmit and four receive antennas for azimuth angle estimation, while in the elevation axis the field of view is a narrow 15 degrees with no elevation angle processing. **Figure 6** shows the example elevation geometry.

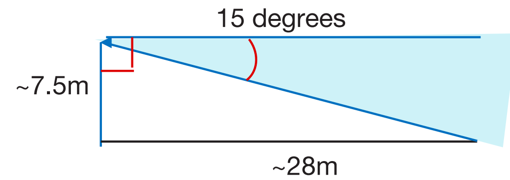

Figure 6. Example traffic-monitoring sensor mount at a height of 7.5 m with a 15-degree elevation field of view and a 7.5-degree downtilt.

The IWR1642 EVM has a much wider azimuth field of view of 120 degrees and a somewhat wider elevation field of view of 22 degrees, but it has sufficient antenna gain to achieve a +60-m range for vehicle detection. So let's use the IWR1642 EVM as a basis for a medium-range example chirp configuration.

The configurability of the IWR1642 sensor allows for flexibility of design to fit different use cases within traffic monitoring. After fixing the basic geometry of the intersection and the antenna pattern, the chirp design is carried out considering some target performance parameters and balancing the trade-offs among those parameters in the context of the IWR1642 sensor's device transceiver capabilities.

In particular, consider the maximum range as a starting point. Let's outline two examples. One is for a medium range of 70 m and includes transmit multiple-input-multiple-output (MIMO) processing to increase the angular resolution. The other is a longer-range 185-m design without the MIMO processing. In both cases, after setting the maximum range, the range resolution and maximum velocity are balanced in a trade-off to achieve the best range resolution while meeting the maximum

Key input parameters		
Performance paramters	**Medium-range MIMO example**	**Long-range non-MIMO example**
Performance parameters	Medium-range MIMO example	Long-range non-MIMO example
Antenna pattern	Two Tx, four Rx in azimuth plane	One Tx, four Rx in azimuth plane
Maximum range	70 m	185 m
Range resolution	0.25 m	0.8 m
Maximum chirp velocity[1]	27 kmph[1]	65 kmph[1]
Velocity resolution	1.7 kmph	1.1 kmph
Frame duration	50 ms	50 ms
ADC sampling rate	5.5 MSPS	5.5 MSPS
Derived chirp design parameters		
Chirp valid sweep bandwidth	600 MHz	186 MHz
Chirp time	56.64 µs	46.6 µs
Chirp repetition time	129.7 µs	54.6 µs
Number of samples per chirp	312	256
Nfft_range	512	256
Number of chirps per frame	32	118
Nfft_doppler	32	128
Radar cube size	512 KB	480 KB

*1Additional processing can extend the maximum trackable velocity by four or more times the chirp maximum velocity.

***Table 2**. Performance parameters of two example chirp designs on the IWR1642 sensor.*

velocity requirements. Increasing the velocity resolution to the practical limit of the internal radar cube memory also increases the effective range of the transceiver. It's possible to further extend the maximum chirp velocity with additional processing to an effective velocity estimation four or more times the maximum chirp velocity. This additional processing enables tracking and velocity estimation well above vehicular highway speeds.

The example chirp design starts with the input parameters shown in **Table 2**

Using the IWR1642 EVM antenna pattern for the medium-range example, you would expect to see small car-sized vehicles out to the chirp-limit range of 70 m. For the long-range example, you would expect to see car-sized vehicles up to 185 m, depending on the size of the vehicle.

The medium-range example chirp and frame design includes the use of time-division multiplexed MIMO. In this case, the two transmit antennas are separated by two times the carrier wavelength, and the chirp transmission alternates between the two antennas during the frame. Therefore, the transmitted signal from each antenna has double the chirp repetition period, and half as many chirps

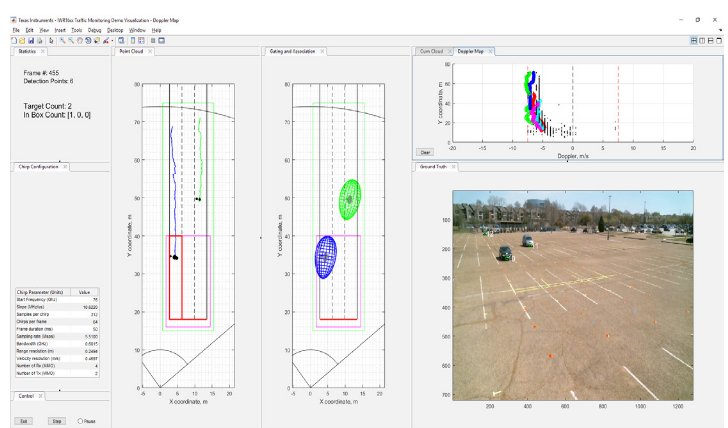

***Figure 7**. Two moving vehicles as detected by the example medium-range MIMO configuration. The graph on the right shows the detection of two vehicles around 40 m and 60 m, separated in angle for lane detection. The color of the points indicate the different Doppler measurements of the vehicles around 6 m per second (22 kph) and 8 m per second (29 kph).*

as in a non-MIMO case. This effectively doubles the angular resolution of the detector at the expense of halving the directly measurable maximum velocity. As mentioned before, the maximum velocity is extendable through additional signal processing.

Figure 7 shows a data snapshot for the medium-range example configuration where two vehicles approach the sensor at just over 40 m and just over 60 m, respectively. The two vehicles are easily detected.

The IWR1642 EVM implements an example processing chain for traffic monitoring using this chirp and frame design.

As described in **Figure 8**, the traffic-monitoring example implementation signal-processing chain consists of the following blocks implemented as DSP code executing on the C674x DSP core in the IWR1642 sensor:

- **Range processing**: for each antenna, 1-D windowing and 1-D fast Fourier transform (FFT). Range processing is interleaved with the active chirp time of the frame.
- **Doppler processing**: for each antenna, 2-D windowing and 2-D FFT, then noncoherent combining of received power across antennas in floating-point precision.
- **Range-Doppler detection algorithm**: cell averaging smallest of constant false-alarm rate (CASO-CFAR) plus CFAR-cell averaging (CFARCA) detection algorithms run on the range-Doppler power mapping to find detection points in range and Doppler space.
- **Angle estimation**: For each detected point in range and Doppler space, reconstruct the 2-D FFT output with Doppler compensation. A beamforming algorithm returns one angle based on the angle correction for Vmax extension.

After the DSP finishes frame processing, the results consisting of range, Doppler, angle and detection signal-to-noise range (SNR) are formatted and written in shared memory (L3RAM) for the R4F to perform high-level processing.

Input from the low-level processing layer (point-cloud data) is copied from the shared memory and adapted to the tracker interface. The group tracker is implemented with two sublayers: module layer and unit layer. One instance module manages multiple units. At the module layer, you should first attempt to associate each point from the input cloud with a tracking unit. Nonassociated points will undergo an allocation procedure. At the unit level, each track uses extended Kalman filter (EKF) process to predict and estimate the properties of the group. The R4F then sends all the results to the host through a universal asynchronous receiver transmitter (UART) for visualization.

Table 3 lists the results of DSP benchmark data measuring the overall million-instructions-per-second (MIPS) consumption of the processing chain, up to and including the angle estimation and shared memory writing on the DSP.

	Available time	Used time	Loading
Active chirp time	46 µs	20 µs	45%
Frame time	33 ms	22.73 ms	69%

***Table 3**. MIPS usage summary.*

The low-level processing chain implemented in the C674x DSP has two hard deadlines:

- The chirp-processing deadline, which is defined as the latest time that the acquisition and range processing for the given chirp shall complete. This is a hard deadline, and the available margin is used to estimate DSP loading during the acquisition period.
- The frame-processing deadline, which is defined as the latest time that the frame processing (Doppler, Constant False Alarm Rate (CFAR) and Direction of Arrival (DoA)) shall complete for a given frame. This is also a hard deadline, and DSP loading during frame processing can be estimated.

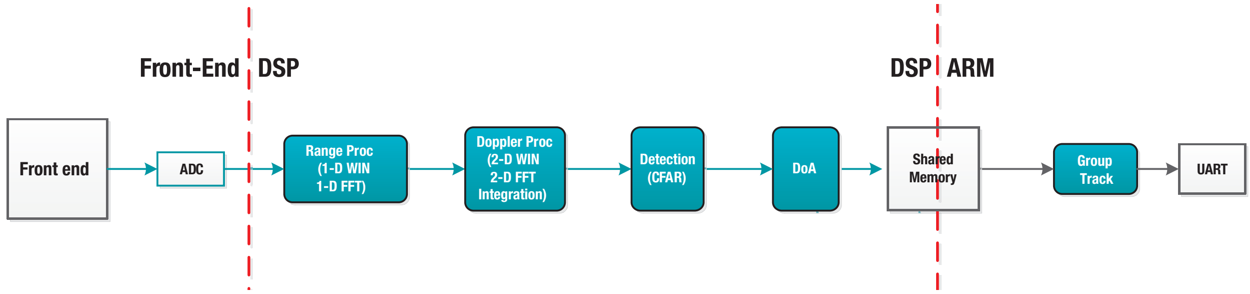

Figure 8. Processing chain flow for object detection, tracking and visualization for traffic-monitoring example.

Table 4 outlines specific physical memories available to the DSP and their usage after loading the mmWave software development kit (SDK) platform software and example application code.

	Available size (KB)	Used size (KB)	Spare (KB)
L1D	32	16	16 (for L1D cache)
L1P	32	24	8 (for L1P cache)
LL2	256	254	2
L3	768	352	416
HSRAM	32	3	29

Table 4. Memory usage summary.

The amount of time needed by the Arm R4F to process the input point cloud and deliver target information is a function of the number of targets currently tracked and number of measurements (points in the input point cloud) received. The processing time increases linearly with the number of tracking objects. With a fixed number of tracking objects, complexity increases linearly with the number of input points. Taking the worst-case number of points per frame of 250, you can derive up to ≈200 µs per tracking object. With a frame time of 50 ms, tracking 20 targets is complete in 4 ms, which will consume <10% of the central processing unit (CPU).

The R4F uses tightly coupled memories (256 KB of TCMA and 192 KB of TCMB). TCMA is used for program and constants (PROG), while TCMB is used for RW data (DATA). Table 5 summarizes memory usage at the R4F, which gives the total memory footprint, available member and memory utilization.

Memory	Available	Used	Utilization
PROG	261,888	103,170	39%
DATA	196,608	171,370	87%

Table 5. Memory usage summary.

Conclusion

TI's innovative mmWave sensors give system designers access to new levels of data and performance that were previously unavailable with other sensing technologies. mmWave sensors offer superior performance that works in adverse weather conditions and detects vehicles moving at high rates of speed and at large distances from the sensors. With powerful integrated processing cores, TI's mmWave sensors can be used by designers of traffic-monitoring infrastructure to collect and process the information and intelligence needed to facilitate robust, quality and high-efficiency operation.

TI has introduced a complete development environment for engineers working on industrial mmWave sensor products that includes:

- Hardware EVMs for IWR1443 and IWR1642 mmWave devices.
- An mmWave SDK that includes a real-time operating system (RTOS), drivers, signal-processing libraries, an mmWave application programming interface (API), mmWaveLink and security (available separately).
- mmWave Studio offline tools for algorithm development and analysis that includes data capture, a visualizer and a system estimator.

To learn more about mmWave products, tools and software, please see www.ti.com/mmwave.