DIGITAL CODE MODULATION (DCM) RADAR FOR AUTOMOTIVE APPLICATION

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ABSTRACT

This paper is intended as a tutorial to motivate the transition of automotive radar to Digitally Modulated Radar (DMR). It compares the characteristics of digital modulated radar – in particular, DMRs using Digital Code Modulation (DCM) – to traditional analog modulated radars used today, such as Frequency Modulated Continuous Wave (FMCW) radars. It explains how these radar systems operate, including the transmission, reception, and the associated signal processing employed to determine the distance, velocity, and angle of objects in the environment. By comparing these two radar systems, familiarity with digital radar is enhanced and the potential advantages of digital radar are better appreciated. This paper also introduces two new benchmarks of merit: 1) High Contrast Resolution (HCR), which is critical to resolving small objects next to large objects (e.g., a child in front of a truck), and 2) Interference Susceptibility Factor (ISF), which characterizes a radar's resilience to self-interference and cross-interference. These benchmarks are essential to understanding the value of radar in use cases that are crucial to achieving increased automation and autonomy.

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Executive Summary

The most common radar technology for automotive use to date has been Frequency Modulated Continuous Wave (FMCW) radar. Another type of radar, which has been used for military applications, but until recently was too expensive for high volume use cases like automotive, is Digital Code Modulation (DCM). Due to the advancements of CMOS technology and advanced signal processing, we are now at a tipping point where it is feasible to provide a cost-effective DCM radar system that meets the increasing performance demands of the automotive industry.

A comparison of the traditional FMCW versus DCM radar is enumerated here:

	FMCW / FCM	***DCM***
Analog Processing	*Complex – larger analog for increased number of Virtual Receivers (VRx's).*	*Simpler – smaller analog for increased number of VRx's.*
Signal Processing	*Partially done in analog circuitry.*	*Mostly done in digital which allows the use of advanced signal processing algorithms.*
Range Response	*Broad range response that may hide small objects in close proximity of a large object. Low High Contrast Resolution (HCR).*	*Sharp thumbtack-like range response due to near ideal auto-correlation function of long spreading codes providing much greater HCR.*
MIMO Support/ Angular Resolution	*Multiple VRx has been challenging for FMCW. Low HCR.*	*Native support for a large number VRx. High HCR.*
Interference	*Interference is highly dependent on the chirp parameters used by the interfering and victim radars and may result in a high Interference Susceptibility Factor (ISF).*	*Robust against interference from other DCM radars. Always low ISF.*

Introduction

There has been an increased demand for improved automotive radar systems to further the automation features in Advanced Driver Assistance Systems (ADAS) and to enable the path to higher levels of autonomous driving. The Society of Automotive Engineers (SAE) has defined six levels of driving automation, as shown in Figure 1, from no automation (Level 0 or L0) to full automation (Level 5 or L5) [1]. ADAS and autonomous driving could reduce accidents by 90% and significantly reduce the number of people killed in automotive accidents, which is significant considering that globally, 1.25M people die yearly from these accidents [2][3]. Since radars can operate at night and in major vision impairing weather conditions such as fog, snow, and heavy rain, they are an essential sensor to enable vehicle automation. Compared to vision-based systems, radars also have the advantage of being able to inherently detect doppler, which allows for very accurate speed estimation of moving objects.

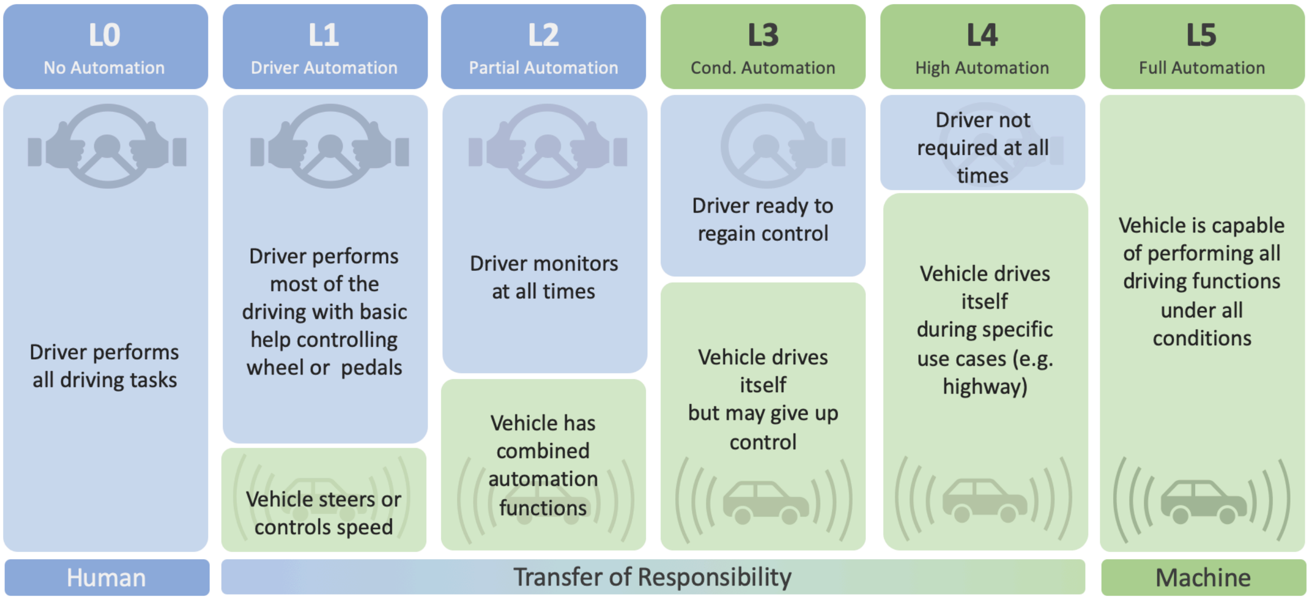

Figure 1: Vehicle Automation Levels

Today, an increasing number of automobiles contain various radar systems, such as long-range radar (LRR), mid-range radar (MRR), or short-range radar (SRR). The LRR is typically used for detection of objects at large distances (e.g., up to 300 m) over a fairly narrow angular region to help in emergency braking, collision warning, and adaptive cruise control. The MRR has a wider field of view and can typically detect objects up to 150 m and can detect objects approaching on crossroads (laterally); it may be used for cross traffic alert functions. In contrast, the SRR can detect objects over a wide angular region at a short distance and is usually used for park assistance, cross-traffic alert, pedestrian/cyclist detection, rear-collision warning, and lane change assistance. To ensure safer driving as well as autonomous driving, a car may contain multiple LRRs, MRRs, and SRRs as shown in Figure 2. In general, the higher the level of driving automation, the greater the number of sensors that are required.

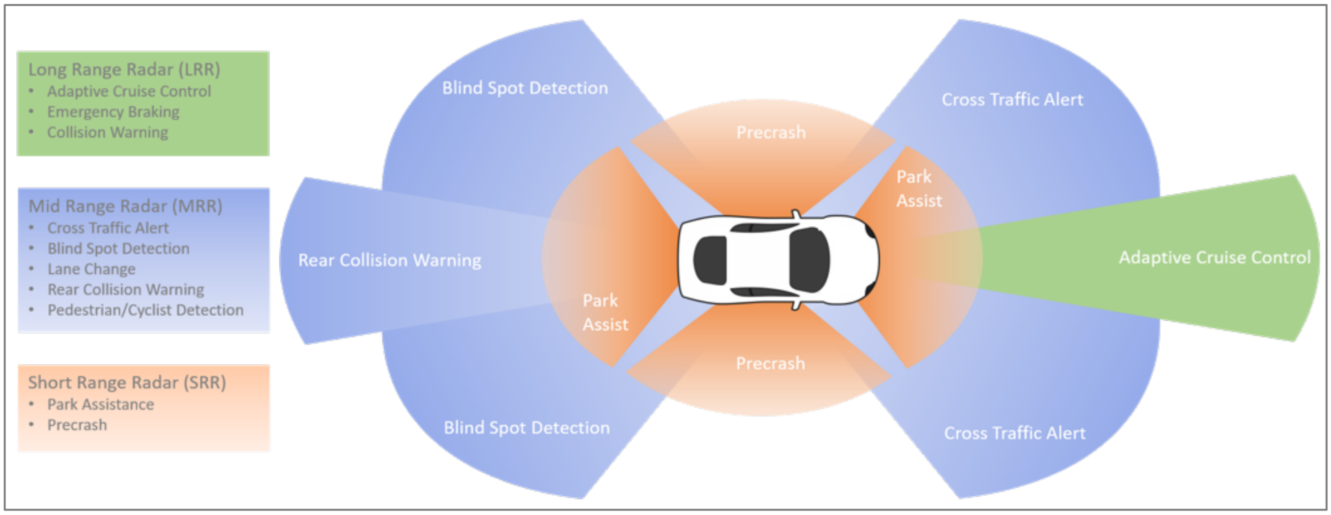

Figure 2: Automobiles can have Multiple Long-Range, Mid-Range, and Short-Range Radars

To improve the capability and reliability of ADAS in current cars, as well as overcome the challenges to advance to fully automated driving (L5), automotive radar systems need to provide a much higher resolution in azimuth and elevation, as well as provide better accuracy and discrimination. These advanced radar capabilities are required to address use cases such as those shown in Figure 3, which are challenging for traditional radars. Without higher resolution, better accuracy, and improved discrimination, a radar system can have difficulty identifying an open lane in traffic on a highway, a stalled car at the entrance of a tunnel or under a bridge, small debris on the road, or a bicyclist beside a car.

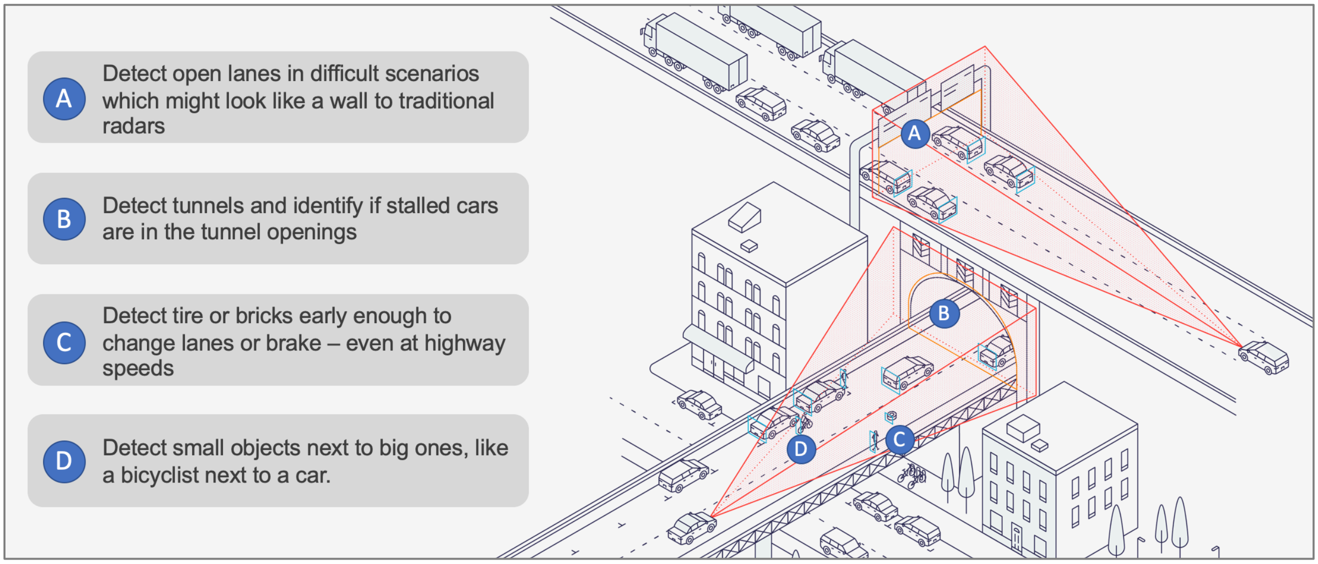

Figure 3: Important Radar Use Cases

In addition, radars must provide more robust interference mechanisms towards other radars on the road, especially with increasing deployment of higher levels of automation, i.e., cars with multiple radars. Radar is a technology which is particularly susceptible to self-interference (interference from other radars on the same car) or cross interference (interference from radars in other cars). This interference susceptibility is a significant limitation to the wide deployment of radars.

The most common radar technology for automotive use to date has been Frequency Modulated Continuous Wave (FMCW) radar, the most recent version of which is called fast chirp modulation (FCM). Another type of radar, which has been used for military applications, but until recently was too expensive for high volume use cases like automotive, is Digital Code Modulation (DCM), an instance of a Digitally Modulated Radar (DMR). However, advances driven by the communication and computing industry, such as advanced signal processing, state of the art CMOS technology, and low-power high speed analog-to-digital converters, are now making it possible to design cost effective DCM radar systems that meet the increasing demands of the automotive industry.

This paper will briefly describe FMCW/FCM radar and provide an overview of DMRs using DCM, as well as an introduction on how these radar systems operate, including the transmission, reception, and associated signal processing employed to determine the distance, velocity, and angle of objects in the environment and issues related to interference mitigation. A comparison of these two radar systems is provided, which describes the advantages and disadvantages of each approach.

Basics of Radar

A radar system transmits a signal and receives a reflected version of that signal after it reflects off objects or targets in the environment. The radar system compares the properties of the reflected signal to the transmitted signal as shown in Figure 4. A radar system with a single transmitter and single receiver (also known as single-input, single-output, or SISO) can estimate the range and velocity of an object in the environment.

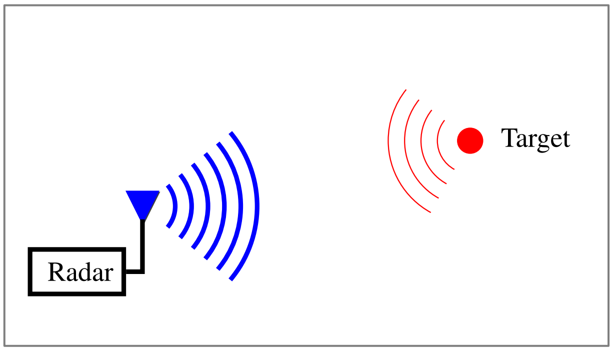

Figure 4: A Single Antenna Radar System

A radar system with a single transmitter and a single receiver can also estimate the angle of an object (azimuth, elevation, or both) but must employ mechanical or electronic scanning. Due to the additional required scanning, the angular estimation is not very accurate for fast moving objects.

A radar system with multiple transmit and receive antennas is referred to as a multiple-input, multiple-output (MIMO) radar system. In the example shown in Figure 5, the MIMO radar system includes two transmitting and three receiving antennas. Each receiving antenna receives both Tx1 and Tx2 waveforms; therefore, the signal received at receiver antenna 1 (Rx1) can be compared to both the transmitted signal from antenna 1 (Tx1) and the signal from the transmitted signal from antenna 2 (Tx2). Each receiver needs to be aware of the timing of the signal from Tx1 and Tx2. Thus, the radar system creates a 6 virtual receiver system (i.e., 2(Tx) x 3(Rx) = 6 virtual receivers).

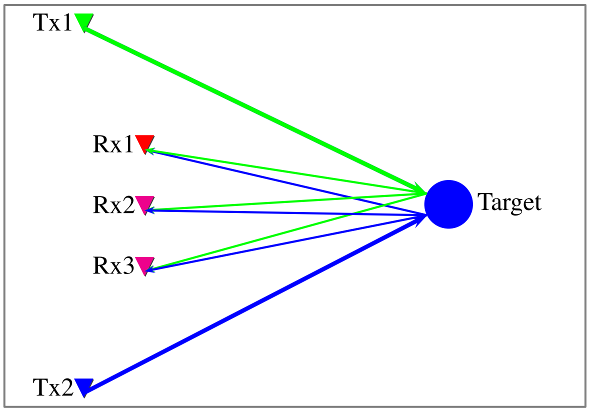

Figure 5: Radar System with Multiple Transmit and Receive Antennas

A MIMO radar system inherently allows for estimates of the angles (azimuth, elevation, or both) of an object in the environment. In general, a larger number of antennas (virtual receivers) allows radar systems to be designed with wider aperture, and thereby, higher angular resolution.

Performance Measures of Radar

Radar systems provide direct measurements of the range, the radial velocity, and the direction of the object being measured. The direction can be in terms of the azimuth angle, elevation angle, or both. Radars can be designed to achieve different performance objectives among any of these measurement dimensions. The parameters to optimize, as shown in Table 1, include coverage, accuracy, resolution, and scan time [4].

Parameter	Description
Coverage	Minimum and maximum value of the specified dimension within which an object can be detected
Accuracy	Error in estimating the specific measurement of the object
Resolution	Smallest offset of two objects that can be separately detected (resolved) in the specified dimension
Scan Time	The time needed to generate an image (location, velocity) of the objects in the environment

Table 1: Common Performance Parameters of Radar

Range Estimation

A radar generally determines the radial range of an object by comparing the timing of the transmitted signal and received signal. Detection range refers to the range at which the signal reflected from a specified object is strong enough to be detected by the radar receiver, and the received signal level is sufficiently larger than the background noise.

The smallest range offset of two objects that can be separately detected by a radar is the range resolution of the radar. The range resolution is inversely proportional to the bandwidth of the transmitted signal.

Sometimes, a radar will not be able to uniquely determine the range of an object. This is dependent on the type of transmit signal and receive processing used. The maximum unambiguous range is the maximum distance of an object such that the distance can be correctly (uniquely) determined without ambiguity from the received signal.

Velocity Estimation

A radar can determine the velocity of an object by using the Doppler frequency effect for which it does comparisons between the timing of the transmitted signal and the received signal. The smallest velocity difference that can be separately detected is the velocity resolution of the radar, which depends on the time duration of the signal.

There is also a maximum Doppler shift (or velocity) that a radar can determine without ambiguity. This is known as the maximum unambiguous velocity.

Angular Estimation

A radar system using mechanical scanning, electronic scanning, or MIMO can determine the angle of a target relative to some reference in either the horizontal plane or the vertical plane. The angle relative to the vertical plane, that is north-south, is called the azimuth angle or the bearing angle, and the angle relative to the horizontal plane, that is the ground, is called the elevation angle. A set of angles for which a radar can detect an object is called the field of view (FOV), as illustrated in Figure 6. Depending on the antenna scanning direction and/or antenna configuration, the azimuth angle, elevation angle, or both azimuth and elevation angles can be determined. The number of angles that can be determined depends on the number of transmit and receive antennas. Thus, for a given number of antennas, a large FOV results in less angular accuracy and coarser resolution, while a narrow FOV provides better angular accuracy and finer resolution.

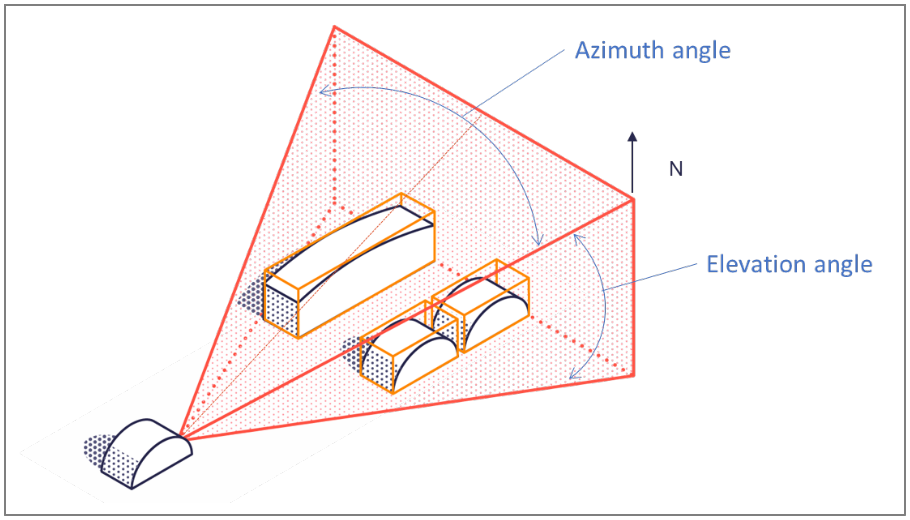

Figure 6: Maximum Azimuth and Elevation Angles define the Field of View

High Contrast Resolution

Traditionally, radar performance on resolution as defined above, in any measurement dimension (range, velocity, and angle), is based on targets of the same reflectivity, or Radar Cross Section (RCS). However, in automotive applications, this definition, though very important, is not sufficient. In such applications, it is also important to measure the radar's ability to discriminate small targets in close proximity to large targets, especially in range (e.g., a small child in front of a truck) and in angle (e.g., pedestrian beside a guard rail). We, therefore, introduce a new measure called 'High Contrast Resolution (HCR)' which we believe to be critical in determining how well radars support high levels of automation in driving. HCR represents how closely the radar can resolve two targets with a given difference in RCS in any of the measurement dimensions.

High Contrast Resolution
Radar's ability to discriminate between small targets in close proximity to large targets in range and angle.

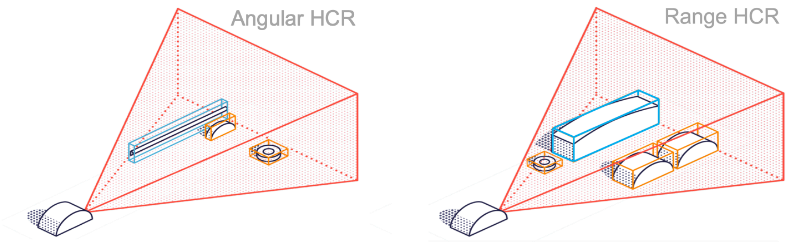

Figure 7: HCR Helps Discriminate Between Small Targets in Close Proximity to Large Targets

Interference Robustness

As previously mentioned, robustness to interfering signals from other radars is an important aspect for radar operation in automotive applications. In this paper, we introduce the concept of an Interference Susceptibility Factor (ISF) that is a measure of how resistant a radar is to self-interference or cross interference. This measure is impacted by the modulation scheme used by the potentially interfering radars.

Radar Signals

Typical radar systems either pulse the transmitted signal or transmit continuously. In a pulsed radar system, the signal is transmitted only during a certain, short time interval, and then the transmitter is silent. This process then repeats. The receiver senses the relative time of arrival of a reflected signal to estimate various parameters of the target (e.g., distance, velocity). In a continuous wave radar system, the signal is continuously transmitted.

As noted above, FMCW/FCM radars are predominantly deployed today in automotive vehicles. In FMCW radar, the transmitted signal is a sinusoidal signal with varying *frequency*. FMCW/FCM radars vary the frequency linearly over time, aka, linear FMCW/FCM. By measuring the frequency difference between the transmitted signal and the received signal, the range to an object can be determined.

DCM radars transmit a sinusoidal signal where the phase of the sinusoidal signal varies in a digital fashion. The received signal can be processed using a matched filter or can be correlated to various time delays of the transmitted signal so that important parameters of the target can be estimated.

Basics of FMCW/FCM Radar

A typical block diagram of an FMCW/FCM transmitter and receiver is shown in Figure 8. A waveform generator determines a sequence of linear frequency ramps that are generated by the voltage-controlled oscillator (VCO). The signal is amplified by a power amplifier (PA) and transmitted. The received signal is processed by a low noise amplifier (LNA) and then down converted in frequency using the same VCO signal before being filtered.

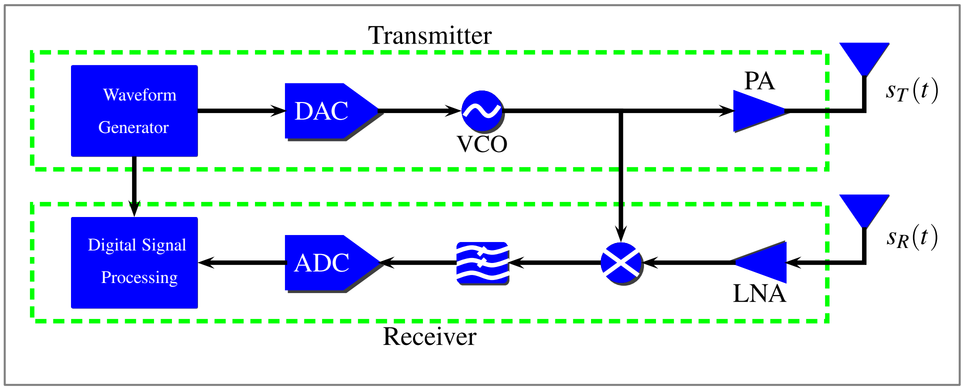

Figure 8: Block Diagram of an FMCW/FCM System

In FMCW/FCM radar, the transmitted signal is a sinusoidal signal in which the frequency of the signal varies with time. The transmitted signal is

$$s_T(t) = \sqrt{2P}\cos\left(2\pi\left(f_c + f_m(t)\right)t\right)$$

where f_c is the center frequency, P is the transmitted power, and $f_m(t)$ is the time varying frequency. The frequency of the transmitted signal is $f_T(t) = f_c + f_m(t)$.

There are different ways in which the frequency of an FMCW/FCM waveform varies. One way is via a ramp or sawtooth signal in which the frequency ramps from a minimum frequency to a maximum and then repeats. Alternatively, a signal that sweeps up in frequency (up-chirp) and then down in frequency (down-chirp) could be employed.

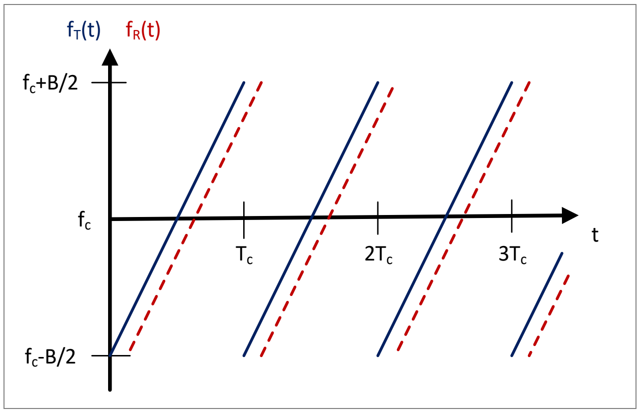

Figure 9: FMCW/FCM Frequency of Signals (Transmitted and Received)

Figure 9 portrays the case of FCM used by many radars, where either an up-chirp or a down-chirp is transmitted repeatedly, creating a saw-tooth signal (the signal in the figure represents an up-chirp). The parameter T_c is the time it takes for the up-chirp signal of the receiver to sweep over a bandwidth B Hz in frequency. At the receiver, the received signal is mixed with (multiplied by) the transmitted signal and filtered with a low pass filter of bandwidth B_r in order to remove the double frequency components in addition to some of the noise and interference.

Range Processing of FMCW Signals

The transmitted FMCW signal is reflected off a target and received. The received signal, in the case of a stationary target, is an attenuated and time-shifted version of the transmitted signal. The frequency-time relation for the transmitted signal is shown as the blue line in Figure 9, while the frequency of the received signal is shown as the red dashed line.

Based on propagation of signals at the speed of light, the delay τ is related to the range by

$$R = \frac{\tau c}{2} \text{ or } \tau = \frac{2R}{c}$$

where c is the speed of light, and the factor of 2 is due to the round-trip time from the transmitter to the receiver. This is true for any type of radar signal, not just FMCW/FCM signals.

The beat frequency of the signal after mixing and filtering is proportional to the delay between the transmitter and receiver and thus proportional to the range of the target. Suppose R_m is the maximum range of a target to be detected. The maximum delay is $\tau_m = 2\,R_m/c$. The maximum frequency shift is then $f_m = 2BR_m/(cT_c)$. The minimum frequency shift is 0 corresponding to a target at distance 0. The filter must have a bandwidth at least as large as this maximum beat frequency. Equivalently, with receive low pass filter bandwidth of B_r, the largest range that can be detected is

$$R_m = cT_cB_r/(2B).$$

This equation provides a fundamental trade-off in FMCW radars among chirp duration, transmit signal bandwidth, receive filter bandwidth, and maximum range. For example, if the chirp duration is 30 μs, the sweep bandwidth is 300 MHz, and the filter bandwidth is $B_r = 15$ MHz, then the maximum range is 225 m. For automotive applications, this might be considered an LRR. If the sweep bandwidth is 750 MHz, the sweep time is 50 μs, and the filter bandwidth is $B_r = 4.5$ MHz, then the maximum range is 45 m and would be considered an SRR.

The signal after mixing and filtering is then digitized using a sampling rate f_s and then processed using fast Fourier transform (FFT) to analyze the frequency contents of the received signal. The frequencies present in the signal correspond to the ranges of the targets. Due to the digitization of the signal, any frequency above the Nyquist rate of the sampling frequency will alias into lower frequencies, and thus, the corresponding range will fold over to lower ranges. There is then a limit based on the sampling rate, f_s, where the ranges can be estimated unambiguously. This limit is given by

$$R_u = cT_c f_s/(2B).$$

By carefully choosing the receive filter bandwidth, the sampling frequency, and the filter order, the signal energy of objects beyond the unambiguous range in the receive signal can be reduced.

When two objects are separated by a distance Δ_d, the difference in the corresponding frequencies in the receive signal is

$$\Delta_f = \frac{2B\Delta_d}{cT_c}.$$

The minimum frequency delta that can be detected using Fourier processing is equal to the inverse of the chirp (observation) time, i.e.,

$$\Delta_f > \frac{1}{T_c}.$$

This leads to the range resolution of

$$R_r = \frac{c}{2B}.$$

Basics of DMR/DCM Radar

In DMR/DCM radar systems [5], the phase during a given time period (called a chip period or chip duration) is typically one of a finite number of possible phases. A spreading code consisting of a sequence of chips, (e.g., +1, +1, -1, +1, -1, …) is mapped (e.g., +1 → 0, -1 → π) into a sequence of phases (e.g., 0, 0, π, 0,π, …) that is used to modulate the phase of the RF sinusoidal signal. The spreading code could be a periodic sequence, or it could be a pseudo-random sequence with a very large period that makes it appear to be a nearly random sequence. The resulting signal has a bandwidth that is proportional to the rate at which the phases change, called the chip rate, which is the inverse of the chip duration. By comparing the return signal with the transmitted signal, the receiver can determine the range and the velocity of reflected objects. This can be done using a matched filter or a bank of correlators.

As mentioned above, phase modulated continuous wave radar transmits a phase modulated signal. The signal is of the form

$$s(t) = \sqrt{2P}\cos\big(2\pi f_c t + \phi(t)\big)$$

where P is the power of the signal, f_c is the carrier frequency, and $\phi(t)$ is the phase of the transmitted signal. While the phase can vary continuously to minimize bandwidth, here we consider the phase function to be a sequence of phases that stay constant for T_c seconds and are called chips. T_c is known as the chip duration. That is, $\phi(t) = \phi_l$ for $l\,T_c < t \le (l+1)T_c, l = 0,1,\ldots$.

In the case of *binary* phase modulation, the phase is either 0 or π radians (180 degrees). The signal can then be written as $s(t) = \sqrt{2P}a(t)\cos(2\,\pi f_c t)$ where $a(t)$ is either +1 or -1 depending on if $\phi(t)$ is 0 or π respectively. Figure 10 shows an example of the signal $a(t)$. Such a sequence of chips causes the spectrum of the signal to spread the energy over a bandwidth proportional to $1/T_c$. The signal $a(t)$ is a baseband signal, which is modulated up to a carrier frequency by a mixer before being transmitted. This signal is also sometimes called a direct-sequence spread spectrum signal.

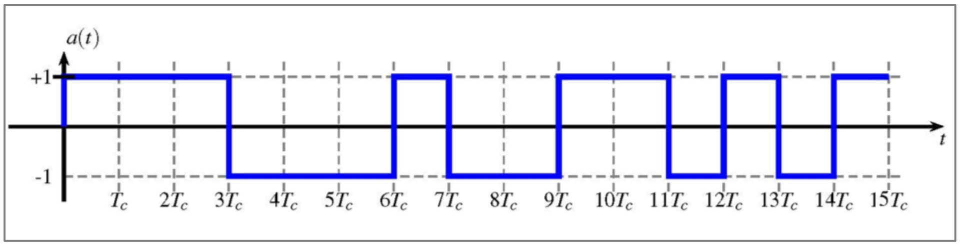

Figure 10: Binary Modulation Signal

The transmitter, conceptually, is portrayed by the simple block diagram shown in Figure 11. The spreading waveform $a(t)$ modulates the signal from an oscillator to generate a phase modulated continuous waveform signal $s(t)$.

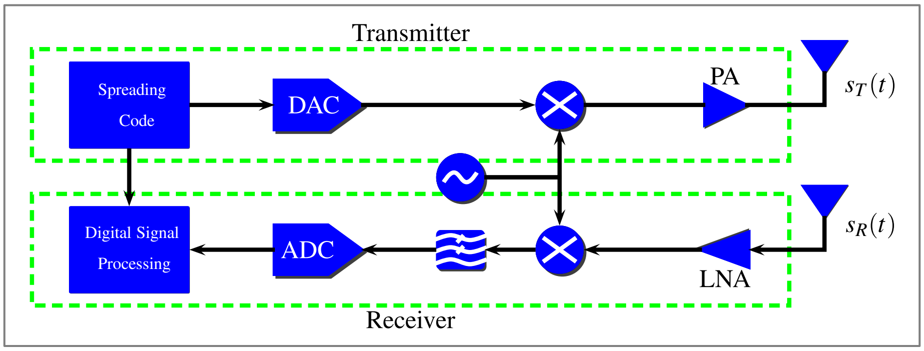

Figure 11: Block Diagram of a DMR/DCM System

The transmitted signal from a single antenna is reflected off of objects in the environment. The reflected signals are then received at the receiving antenna and processed. A simple model for the received signal in the absence of noise and other interfering signals is

$$r(t) = \sum_{l=1}^{L} \alpha_l s(t - \tau_l).$$

Here, there are L objects that reflect the transmitted signal that are stationary relative to the transmitter. An object that reflects the transmitted signal $s(t)$ is attenuated by the factor α_l and delayed by τ_l between the transmitter, object, and receiver. The delay between the transmitted signal and the received signal is related to the distance by $R_l = c\,\tau_l/2$ where c is the speed of light and the factor of 2 is due to the round-trip time from the transmitter to the receiver. In this paper, it is assumed that the transmitter and receiver are essentially co-located.

At a receiver, the received signal is amplified with a low noise amplifier (LNA), mixed down to baseband using the same oscillator signal at the transmitter. The signal is then converted from an analog signal to a digital signal with an analog-to-digital converter (ADC).

Range Processing of DCM Signals

In DCM radars, range processing is performed using a matched filter to determine the correlations of the received signal with various delays of the transmitted signal. There are two types of such correlation functions that can be used based on how the transmitted signal is generated.

- Non-repeating code transmission: In this case, different codes are transmitted from one transmission time (pulse) to the next. The matched filter output is represented by the *aperiodic autocorrelation function of the code.*

- Periodic code transmission: Here, the same spreading code is transmitted periodically. The matched filter output is represented by the *periodic autocorrelation function of the code.*

We illustrate these concepts through an example where there are three targets at various distances with different reflectivity (e.g., different size (RCS) objects). The matched filter output of the non-repeating code transmission is shown in Figure 12. The example shown in this figure belongs to a class of codes known as maximum-length sequences (m-sequences) [6].

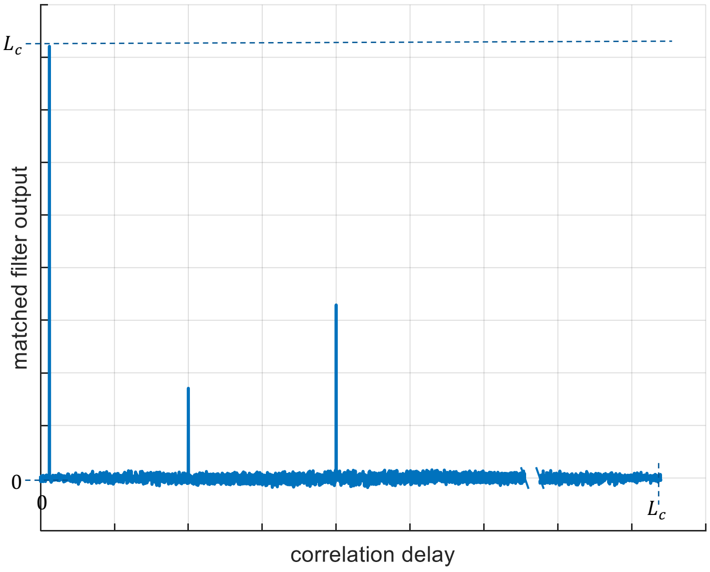

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Figure 12: Matched Filter Output for a Three Target Scenario

Using the same target scenario with three targets as in Figure 12, Figure 13 shows an example where multiple periods of the same spreading code (same code as the previous figure) are transmitted.

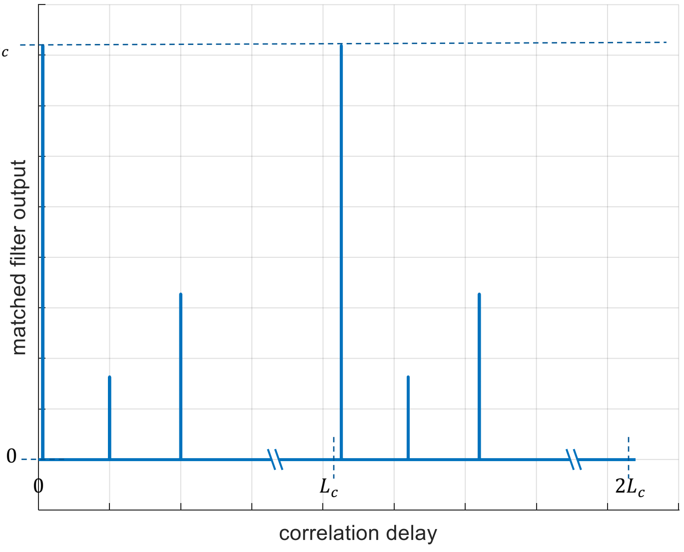


Figure 13: Matched Filter Output with Periodic Signal

In the latter case, the output repeats itself with a repetition period equal to the duration of the matched filter's impulse response corresponding to the length of the spreading code used. The fact that the output is a constant value in between target locations is a property of the m-sequence used as the spreading code.

There are many codes that can be used depending on the objective of the radar system and the desired performance. Some codes, like Barker codes, have good aperiodic autocorrelation functions, while others have excellent periodic autocorrelation functions. Codes with good aperiodic autocorrelation are desirable if the transmitted spreading code does not repeat. As shown in Figure 12 and Figure 13, when a single period of the code is transmitted, the output of the matched filter (Figure 12) for a maximum length sequence (known for good periodic autocorrelation) results in off-peak values higher than those when sent periodically (Figure 13). Increasing the length of the code improves the ratio of the off-peak autocorrelation function to the peak of the autocorrelation function.

The width of the spike in the matched filter output is proportional to the chip duration. That is, the width of the spike is inversely proportional to the chip rate or the signal bandwidth. Thus, larger bandwidths yield smaller width spikes and better range resolution. The horizontal axes of Figure 12 and Figure 13 represent correlation delay in chip scale, and thus, the width of the spike in terms of range will change proportionately to chip duration.

The range resolution R_r for a DCM system is the width of the spike in the matched filter output. Two targets that are closer than the corresponding time interval of the width of the spike will be indistinguishable. Thus, the range resolution is

$$R_r = (T_c/2)c$$

where T_c is the chip duration and c is the speed of light. Since chip duration is inversely proportional to the bandwidth of the signal B, i.e., $T_c = 1/B$, the above range resolution is equivalent to that in FMCW radars.

$$R_r = \frac{c}{2B}$$

For the case of periodic code as seen in Figure 13, if a target is at a distance larger than $c(L_c T_c)/2$, where L_c is the number of chips in the spreading code before repeating, the target will produce an output that will appear like a target at a distance between 0 and $c(L_c T_c)/2$. For objects at a distance smaller than $c(L_c T_c)/2$, the range will be correctly determined. This is the maximum unambiguous range R_u.

$$R_u = c\frac{T_c L_c}{2}$$

Two targets separated by the maximum unambiguous range will appear to the radar system as being at the same range. This is called range aliasing. If the chip duration, T_c, is decreased, then the range resolution would improve proportionally. As an example, if T_c is 1.33 nanoseconds corresponding to a chip rate of 750 Mchips/second, then the range resolution would be limited to 20 cm. For a periodic spreading code of length 1023, the maximum ambiguous range would be 204.6 m. For a periodic spreading code of length 4095, the maximum ambiguous range would be about 818 m. The unambiguous range for DCM can be increased by increasing the period of the code for a given chip duration. In the case of an aperiodic code, there is no range aliasing and thus ambiguity in range is non-existent.

One appealing feature of DCM radars is the sharpness of the peak (often referred to as thumbtack-like response). This is due to the use of the auto-correlation function as range response compared to using the FFT in FMCW radars. The FFT results in much slower drop in range response around a target. *This feature allows much better HCR performance in range for DCM radars.*

Velocity Processing

Another goal of an automotive radar system is to estimate the differential velocity between the radar system and a target. Because the targets in the environment, or the radar itself, are moving, the signal reflected from an object will not have the same frequency as the transmitted signal. This effect is known as the Doppler effect and can be used to estimate the relative velocity of targets in the environment. If the differential radial velocity (towards or away from the radar) of a target relative to a radar is Δ_v, and the carrier frequency is f_c, then the Doppler frequency shift of the signal reflected from the target is

$$f_d = 2\Delta_v \frac{f_c}{c}.$$

Or equivalently

$$\Delta_v = f_d \left(\frac{c}{2f_c}\right)$$

where the factor of 2 comes from the fact that there is a Doppler shift going both ways: radar to target and target to radar. A radar scan for DMR/DCM consists of N repetitions of the spreading code (same code for periodic code but different codes for aperiodic code) or NxL_c chips in a much longer spreading code. The received signal is filtered N times. The N samples of the matched filter output, when using both an in-phase and quadrature-phase down-conversion, produce complex numbers that will rotate around the circle at a rate proportional to the relative radial velocity. The technique is similar for FMCW/FCM radars. In these radars, the chirps (the frequency sweeps) are repeated N times.

A plot of the Q-component vs. the I-component for the first few samples of the matched filter output is shown in Figure 14. The rate that the samples rotate around the circle is related to the Doppler shift of the received signal, and thus the radial velocity of the target relative to the radar system. The direction of rotation around the circle is an indication of whether the target is moving toward the radar system or away from it.

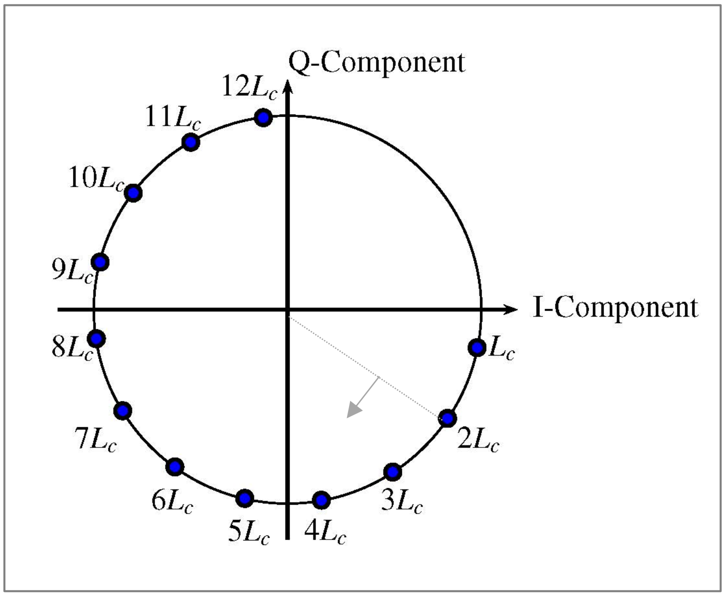


Figure 14: Samples of Matched Filter for Doppler

One approach to estimate the Doppler frequency, and thus the velocity, is to perform a fast Fourier transform (FFT) on the N complex samples. There is a maximum relative velocity that can be estimated without ambiguity. If the points in Figure 14 rotate completely around the circle in time, L_cT_c, then it would appear the object is not actually moving. A complete rotation represents a change of 2π in phase corresponding to a relative movement of the objects by one wavelength or $c/(2f_c)$ within a time period of

$L_c T_c$. As such, in a radar, the velocity can be estimated unambiguously only over a certain range. That is, two different objects separated sufficiently may appear to have the same velocity. The possible range of *unambiguous* velocities, v, that can thus be estimated, is given by

$$-\frac{c}{4\, f_c T_c L_c} < v < \frac{c}{4\, f_c T_c L_c}\,.$$

If there are N complex samples of the matched filter output, the velocity resolution possible, V_r, is then the unambiguous range of velocities above divided by the number of samples, i.e.,

$$V_r = \frac{c}{2 f_c N T_c L_c}\,.$$

Angle Processing

In modern automotive radar, the angles of arrivals from targets are estimated using multiple transmit antennas or multiple receive antennas or both. There are several ways that multiple transmit antennas can be employed. One approach is to use various phase shifts of a single signal for each transmit antenna. This is called a transmit-side phased-array or beam steering approach. The radar focuses the transmitted signal energy in a certain direction. Another approach, when multiple antennas are used in both transmit and receive, includes the use of the MIMO technique described earlier, increasing the virtual aperture, and hence, providing better angular resolution. Although the basic MIMO processing is similar for both FMCW and DCM radars, they differ on how signals are transmitted on the multiple transmit antennas.

In one approach, the radar can time multiplex the transmission on different antennas (TDM MIMO). In this approach, the radar transmits using a single antenna for some given time and then switches to another antenna. The interference between antennas is thus mitigated or eliminated. This is the most common implementation used in FMCW/FCM radars where the transmission is switched from antenna to antenna on a chirp by chirp basis. This approach has two major drawbacks. First, the maximum unambiguous velocity is reduced by a factor equal to the number of transmit antennas. Second, the scan time increases by the number of transmit antennas since each Tx must have enough time to transmit within its own window.

Type	Scan Time
TDM MIMO	Time Division Multiplexed MIMO: Only one Tx is active at a time; multiple Rx are active
CDM MIMO	Code Division Multiplexed MIMO: Multiple Tx are active at the same time within the same frequency band; multiple Rx are active
FDM MIMO	Frequency Division Multiplexed MIMO: Multiple Tx are active at the same time occupying different frequency bands; multiple Rx are active

Table 2: Multiplexing Options for MIMO Systems

The most advanced approach is for multiple transmitters to transmit simultaneously, which can be achieved by using code division multiplexing (CDM MIMO); basically, a special code for each Tx, which is then separated within the Rx path to achieve a true MIMO radar system. This approach requires additional digital processing but allows an improved unambiguous velocity window as well as shorter scan time, which means higher update rates are possible.

It is also feasible to use FDM or frequency division multiplexing. This method is typically not used since it increases the signal bandwidth at the transmitter and the receiver proportional to the number of transmitters.

A radar system with N_T transmitters and N_R receivers has $N_T \times N_R$ transmitter-receiver pairs or virtual receivers. Using these $N_T \times N_R$ virtual receivers and the estimated range to the targets from multiple transmitters/receivers, a radar system can use the receive side beamforming approach to determine the azimuth or elevation angle or both, depending on the geometry of the antennas.

DCM naturally uses CDM MIMO where unique spreading codes are employed for different transmitters. At each receiver antenna, a filter matched to each of the N_T transmitter signals can be used. Spreading codes that are orthogonal to each other can be used when transmitting to reduce the self-interference (interference from other transmitters in the same radar), but at the expense of larger auto correlation sidelobes. There is a tradeoff between the autocorrelation properties of spreading codes and the cross correlation of spreading codes. The cross-correlation indicates the amount of interference from different antennas using different spreading codes, while the autocorrelation indicates the self-interference from one spreading code. Generally, the better the cross-correlation properties, the worse the autocorrelation properties.

Figure 15 shows the case where eight transmitters are active at the same time but use different code sequences. We again use m-sequences with a three-target scenario for this illustration.

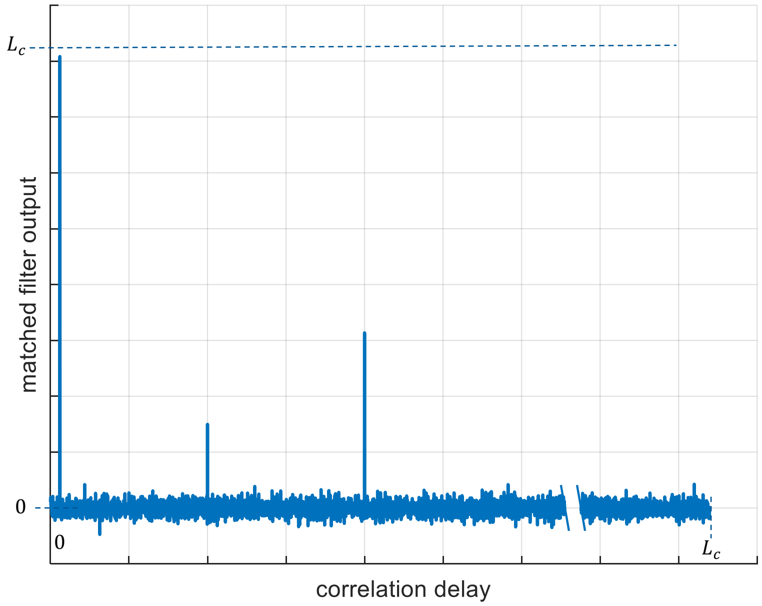


Figure 15: Averaged Matched Filter Output with Eight Transmitters Active

The filter output for a given receiver matched to a given transmitter spreading code now has contributions (due to cross-correlations between the codes) from the other transmitters. In this illustration, for a given receiver, we have a total of eight matched filter outputs corresponding to the eight transmitter codes. The MIMO processing for angle estimation performs a coherent summation in multiple directions (angles), and thus, effectively averages the multiple matched filter outputs. Figure 15 shows the averaged output of all the matched filters on one of the receivers.

If we compare Figure 15 with Figure 12, we see an increase in the off-peak signal energy in the MIMO case. This signal energy from the other transmitters spilling into the matched filter output for a given transmitter's code, known as *the channel isolation,* is a major metric for MIMO operations. This channel separation can only be improved by using longer spreading codes (larger L_c).

Some modern FMCW/FCM radars also use this idea to encode the transmitted chirps (sweeps) using spreading codes across multiple transmitters by adding a chirp-to-chirp pseudorandom binary sequence

(PRBS) phase code for each TX antenna. Channel isolation, as determined by the code length, is, however, much shorter than DCM (chirp rate being slower than the chip rate). For example, a scan time of 5 milliseconds with a chirp duration of 10 microseconds would provide use of 500 chirps. On the other hand, a DCM system with a scan time of 5 milliseconds and a chip duration of 1 nanosecond (for 1 GHz bandwidth) would have 5,000,000 chips in a scan, allowing many more transmit antennas to operate at the same time compared to phase coded FMCW/FCM. *The ability to use many more antennas, along with very high channel separation, allows DCM radars to have very high HCR performance in angle.*

Interference Considerations

The growing deployment of radars in vehicles brings the focus to one of the main challenges for all radars in the future – interference, specifically, interference from other radars [7][8]. Generally, automotive radar is inherently susceptible to interference from nearby interferers since the interferer's transmission has an "R^2" advantage at the victim over received signals from targets. In case of direct line of sight interference, the interference power in the victim radar has one-way propagation loss. On the other hand, the desired signal, which are reflections from targets being measured, goes through two-way propagation loss. With the potential proliferation of multiple radars operating simultaneously in "close proximity" and direct line-of-sight, as illustrated in Figure 16 below, mutual interference will increase as more radars are deployed. As seen in Figure 16, a "victim" radar is attempting to determine targets in the FOV, but an interfering radar is essentially jamming the victim radar.

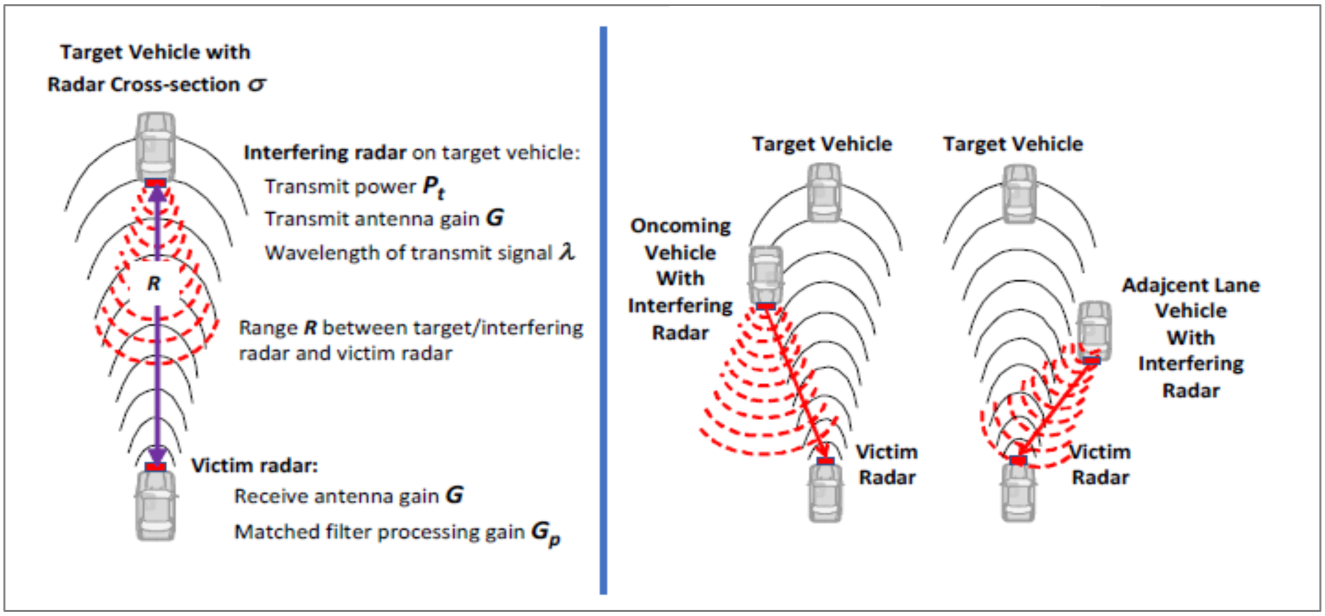


Figure 16: Example Interference Scenarios

The automotive radar waveforms and processing described here typically result in a broadband noise-like spectrum for interfering signals, which may potentially increase the overall noise floor. The impact of interference can be measured using interference-to-noise ratio (INR). The INR is defined as the ratio of the power spectral density of interference, PSD_{int}, as seen by the victim radar, to the power spectral density of noise, PSD_{noise}, in the victim radar, in the absence of any external interfering radars.

$$INR = \frac{\mathrm{PSD}_{int}}{\mathrm{PSD}_{noise}}$$

The power spectral density of interference seen by the victim radar depends on the transmitted power from the interferer, and the distance of the interferer from the victim. It also depends on the processing done in analog and digital. In the analog domain, the bandwidth of the interference at baseband following down-conversion and demodulation determines its characteristics. In the digital domain, the processing tends to spread the interference while concentrating the signals from targets in range and Doppler.

If the interfering radar has bandwidth B, then the power spectral density PSD_{int} of the interference at the victim radar is given by

$$PSD_{int} = \left[\frac{PG_T\lambda\, L_{TX}\, N_{TX}}{B(4\,\pi R^2)}\right]\left[\frac{G_R\lambda L_{RX} L_f N_{RX}}{4\,\pi}\right](D_F)(K)$$

where $G_T(G_R)$ is the antenna gain for the interfering (victim) radar, λ is the wavelength of the radar signal, P is the transmitted power of the interfering radar, $N_{TX}, (N_{RX})$ is the number of transmitting (receiving) antennas for the interfering (victim) radar, L_{TX} (L_{RX}) is the transmit (receive) loss for the interfering (victim) radar, and L_F is the loss due to the fascia (e.g., auto bumper) of both radars. The duty factor parameter D_F accounts for the fraction of time the interfering radar operates within the dwell time and band of the victim radar; hence, the value of D_F varies from 0 to 1.

Because the Interference Susceptibility Factor (ISF) (denoted in this paper as the constant K) depends on which kind of modulation the interferer and victim both have, we will describe the various interference characteristics for the different types of interfering and victim radars.

FMCW/FCM-FMCW/FCM

Consider a victim radar and interfering radar both using FMCW/FCM modulation. Figure 17 illustrates the mechanism of interference and the resulting time domain and frequency domain responses. For down-conversion in the receiver, FMCW/FCM radar uses a replica (coupled version) of the transmitted FMCW/FCM signal. For the situation where the interfering FMCW/FCM signal crosses the victim FMCW/FCM signal, the interference appears as a linear chirp signal after down-conversion in the victim radar receiver, which, assuming “dissimilar fast crossing" slopes, covers a wide bandwidth as it sweeps through the victim radar passband. After bandpass filtering in the victim radar, the interference signal resembles an impulse-like signal in the time domain. The resulting frequency spectrum is broadband, and often well above the background noise floor, as illustrated in the simulated example using a representative automotive radar.

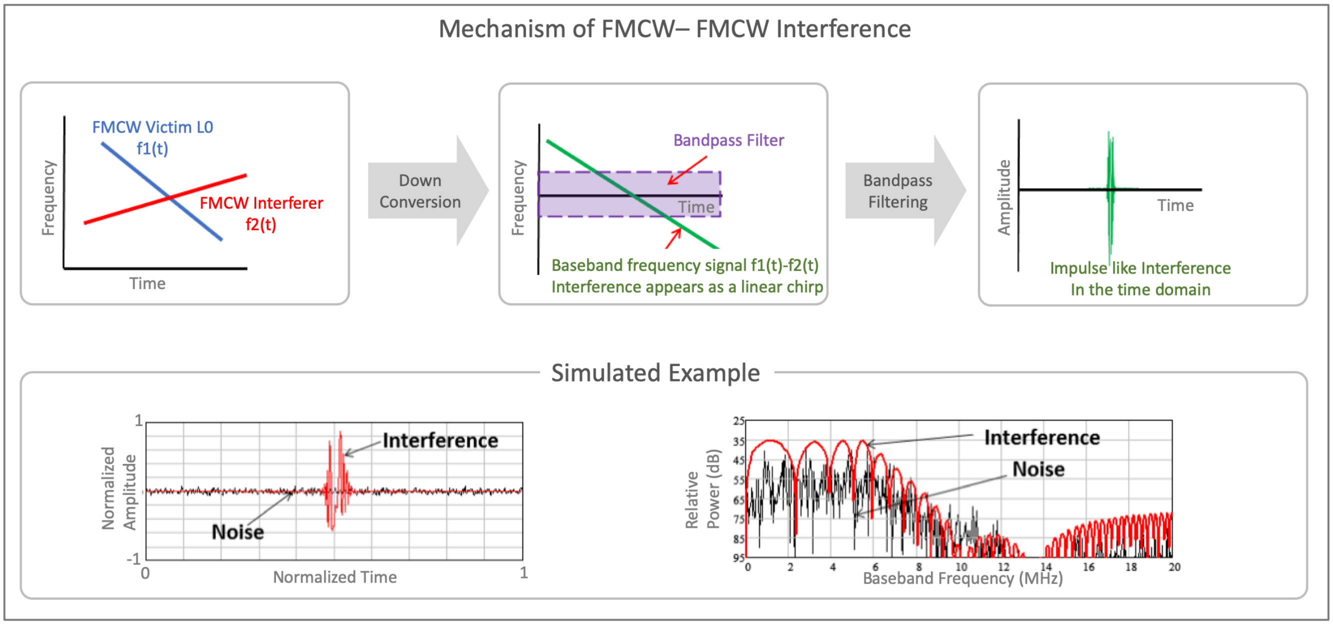


Figure 17: An FMCW-to-FMCW Interference Mechanism and its Simulated Time-Frequency Domain Characteristics

The position and width of the impulse-like interference signal in the time domain, following down-conversion and bandpass filtering in the victim radar, depends on the relative timing and FM slopes (frequency modulation rate) of the interfering and victim radars. The resulting frequency spectrum characteristics of the interference in the victim radar, including the power spectral density (PSD), depends on the relative timing and FM slopes as well. For example, with slower FM rates and/or similar FM slopes for the victim and interfering radars (“slow crossing" slopes), the time extent of interference in the victim radar passband, and the associated power spectral density, can increase significantly.

The factor K generally applies to the case of FMCW modulation for both the victim and interfering radars, and is given by the ratio of the interference power spectral density at baseband (after down-conversion) in the victim radar, to the interference power spectral density in the victim radar receiver at RF (prior to down-conversion). That is,

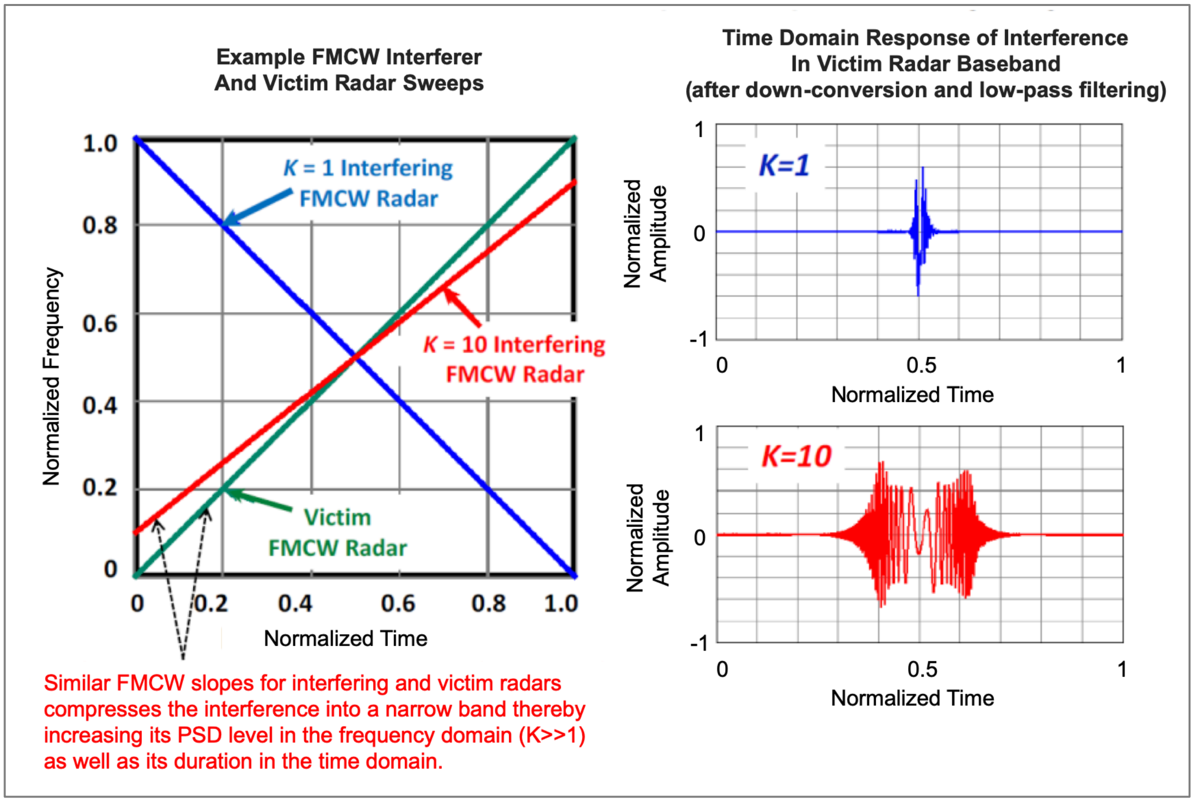
$$K = \frac{PSD_I^{BB}}{PSD_I^{RF}} = \frac{\Delta F_I^{RF}}{\Delta F_I^{BB}}$$

where PSD_I^{RF} is the power spectral density of interference at RF prior to down-conversion in the victim radar receiver, PSD_I^{BB} is the power spectral density of interference after down-conversion in the victim radar receiver, ΔF_I^{RF} is the RF sweep bandwidth of the FMCW interfering radar, and ΔF_I^{BB} is the interference bandwidth in the FMCW victim radar receiver after down-conversion to baseband.

In the equation for interference-to-noise ratio (INR), K for FMCW/FCM-to-FMCW/FCM interference is fundamentally the ratio of the chirp bandwidth transmitted by the interfering radar to the bandwidth of the interference chirp after down-conversion in the victim radar. For FMCW/FCM, the bandwidth after down-conversion in the victim radar depends on the difference in FM sweep (modulation) rate between the interfering and victim radars. Assuming the FM modulation rates of the interfering and victim radars produce “broadband" interference following down-conversion in the victim radar, that is, interference spread over no less than the baseband bandwidth of the victim radar, K generally ranges from a minimum value of 0.5 to a maximum value equal to the sweep bandwidth of the interfering radar divided by the baseband bandwidth of the victim radar.

The factor K for FMCW/FCM interference depends on the FMCW/FCM sweep rates of the interfering and victim radars, as well as their time and frequency alignment.

Figure 18 illustrates K and the corresponding interference in the time domain after down-conversion and bandpass filtering in the victim radar, for a situation where the FM sweeps of the victim and interfering radar are aligned in time and have the same center frequency. Two examples are shown in the Figure; the FM sweep of the victim radar is shown in green. One example corresponds to K =1 (FM sweep of interfering radar (blue) with sweep rate S_I equal in magnitude but opposite in sign to the sweep rate of the victim radar S_V); a second example corresponds to K =10 (FM sweep of interfering radar (red) with sweep rate similar to the sweep rate of the victim radar). Compared to a “fast" (high) crossing rate for “dissimilar" FM sweeps (e.g., K =1), as the FM sweeps become more similar (e.g., K =10), the crossing rate decreases, resulting in interference with longer time duration and higher power spectral density after down-conversion and bandpass filtering in the victim radar. All else being equal, the K =10 example results in interference with 10 times the power spectral density (and correspondingly, 10 times the INR) compared to the K =1 example.



Similar FMCW slopes for interfering and victim radars compresses the interference into a narrow band thereby increasing its PSD level in the frequency domain (K>>1) as well as its duration in the time domain.

Figure 18: The Influence of Victim and Interfering Radar FMCW Sweeps on Interference in the Victim Radar Passband

DCM-DCM

For situations where DCM is used by either the victim or interfering radar, K is generally equal to unity. Consider a victim radar and interfering radar both utilizing DCM modulation. Figure 19 illustrates the resulting time domain and frequency domain responses. DCM interference with random, noise-like bi-phase coding using chip rate $\Delta f_i = 1/T_c$ is assumed and appears as a spread spectrum, noise-like signal with bandwidth $\Delta f_i = 1/T_c$ centered at carrier frequency f_c.

In this example, the DCM victim radar is assumed to transmit a DCM bi-phase coded, noise-like signal with the same chip rate, bandwidth, and carrier (center) frequency as the interfering DCM radar, but with an independent, uncorrelated spreading code. The victim DCM radar down converts the received signal with a constant local oscillator frequency at the common carrier frequency (shown as $f_1 = f_c$) and demodulates the received signal with a delayed copy of the DCM bi-phase code (with chip rate $\Delta f_i = 1/T_c$ and bandwidth of $\Delta f_v = 1/T_c$, assumed to be the same as the corresponding parameters of the DCM interfering radar in the example shown). Following down-conversion, demodulation, and bandpass filtering in the victim radar, the interference appears as a noise-like signal in both time and frequency domains. The resulting frequency spectrum is broadband and often well above the background noise floor as illustrated in the example using representative parameters for an automotive radar.

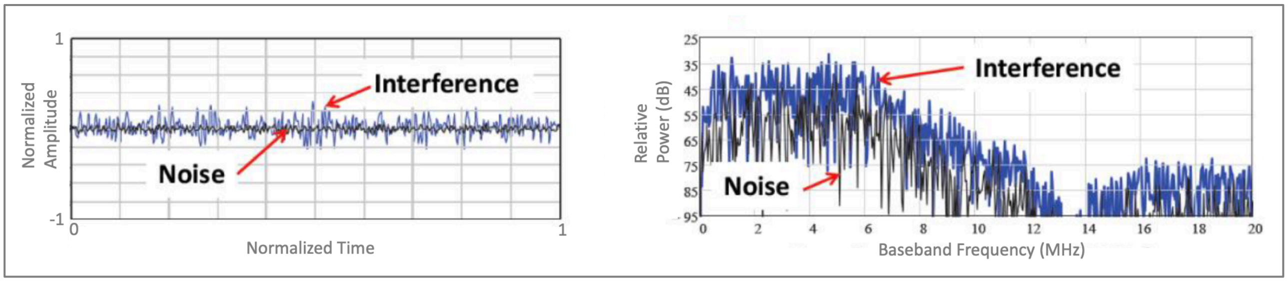


Figure 19: Time-Frequency Domain Characteristics of DCM-to-DCM Interference

DCM-FMCW/FCM (or FMCW/FCM-DCM)

Consider a victim radar with bi-phase DCM modulation, and an interfering radar with FMCW/FCM modulation, or vice-versa. Figure 20 illustrates the interference mechanism and the resulting time domain and frequency domain responses. In both situations (DCM victim-FMCW/FCM interferer or FMCW/FCM victim-DCM interferer) the interference is noise-like in the time and frequency domains and, all else being equal, the interference-to-noise ratio (INR) is the same.

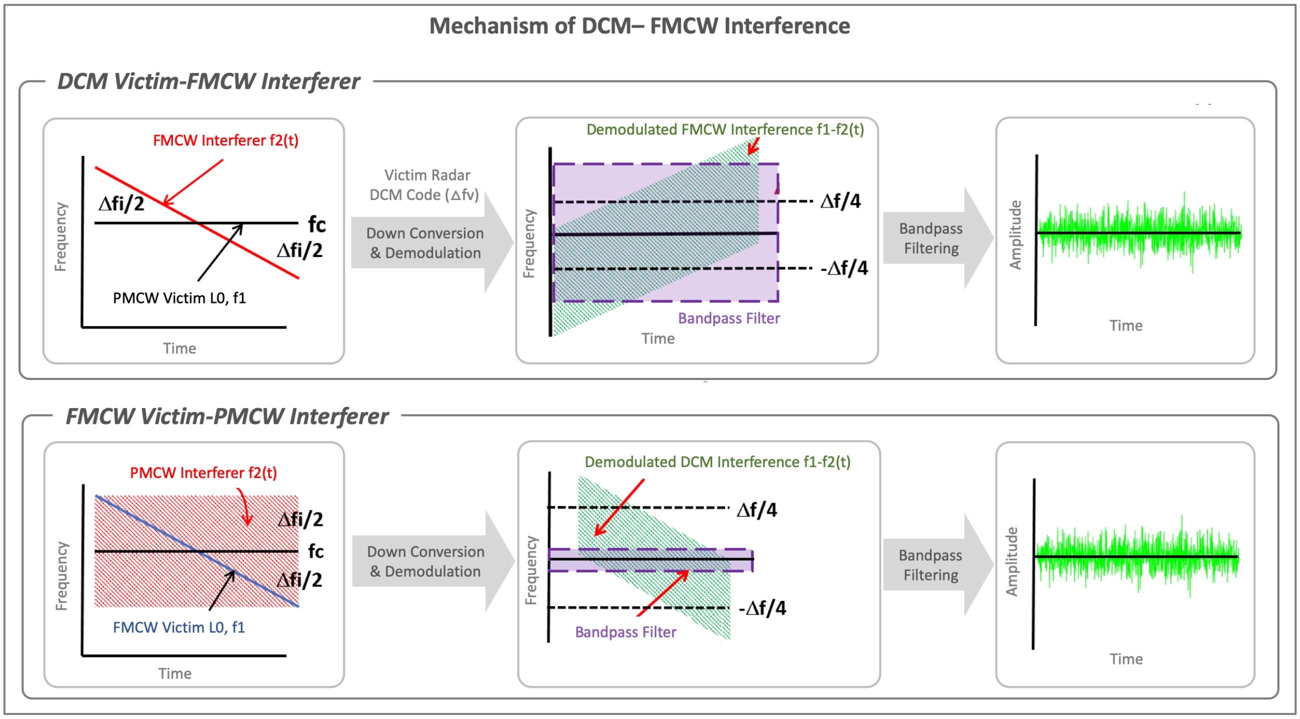


Figure 20: The Mechanism of Bi-Phase Noise DCM-to-FMCW Interference

Down-conversion/demodulation and subsequent signal processing in the victim radar generally results in spreading of the interference in a noise-like fashion over the passband and/or detection band. The resulting interference-to-noise ratio is then given by the power spectral density of interference divided by the power spectral density of noise in the victim radar. The power spectral density of interference in the victim radar depends on the bandwidth of the interferer, B_i (frequency spread of interference), and the interference power received by the victim radar, P_{iv}, which is based on one-way propagation loss.

However, in the case of FMCW/FCM to FMCW/FCM interference, the frequency spread of interference after down-conversion to baseband in the victim radar, and thereby its power spectral density at baseband, depends on the relative FM sweep rates (FM slopes) of victim and interfering radars (reflected in the parameter K). If the FMCW/FCM victim and interfering radar slopes are similar, the interference power is down converted into a narrow frequency band, increasing the power spectral density compared to that of dissimilar slopes ($K > 1$). *Hence, all else being equal, situations with phase modulation (DCM) for either the victim or interfering radar, generally results in lower interference-to-noise levels.*

Technology is Ripe for DCM

Automotive radar systems have traditionally employed FMCW/FCM types of radar signals. With FMCW/FCM, some of the signal processing is done in analog circuitry (mixers, filters). In DCM, the analog circuitry is used only to recover a bandlimited baseband version of the received signal, and the signal processing (e.g., matched filtering, etc.) is performed primarily digitally. The DCM radars thus trade-off the simpler analog processing of FMCW/FCM for much more advanced digital processing. This trade-off necessitates that DCM radars implement analog-to-digital conversion at a much higher rate (in the range of GHz) than is needed for FMCW/FCM (few tens of MHz rate). This has been one of the main impediments for bringing DCM technology, in a cost-effective way, to automotive applications.

Traditionally, FMCW/FCM radars use Silicon-Germanium (SiGe) technology for implementing the RF circuitry and analog-to-digital converters, whereas the digital processing is done in separate processors or micro-controllers. Advances in CMOS technology now allows the implementation of RF circuitry and consequent integration of digital processing, along with RF/analog processing, on a single chip. Some manufacturers have developed CMOS based FMCW/FCM solutions for automotive radar applications.

However, these solutions do not use the full capabilities that state-of-the-art CMOS technologies provide. RF design with CMOS has already been demonstrated [9][10], and a low-power high speed (2+ Gsamples/sec) analog-to-digital converter, as needed by DCM radars, is feasible in CMOS technology [10][11]. These capabilities, coupled with a cost and power efficient digital design with intelligent hardware-software partition, makes DCM radars (Figure 21) a reality for automotive applications [10]. Flexible special hardware accelerators can be used to process high rate digital baseband signals and reduce the rate of relevant data extracted from the raw baseband data. General purpose processors can then operate on the extracted data to perform application specific operations.

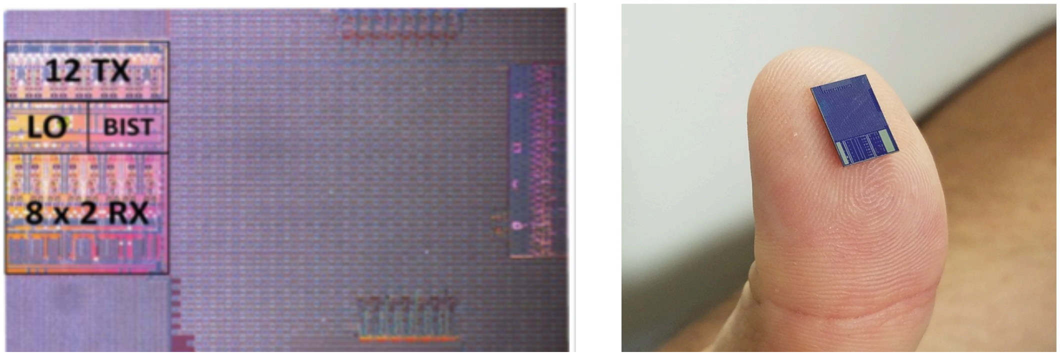


Figure 21: Example of CMOS-Based DCM Radar-on-Chip

The digital hardware can also simplify the analog processing challenges. As such, a joint design of the digital and analog circuitry can achieve better performance than separate analog and digital designs typical in the automotive semiconductor industry. This integrated, flexible chip design allows for software to modify the radar performance to meet customer and application requirements, as opposed to the long and costly approach of designing custom chips.

Summary

The growing interest in radars to address the new use cases for ADAS and autonomy, the increased focus on interference, and the significant advances in signal processing and CMOS technologies, is creating more visibility regarding the advantages of digitally modulated radar systems such as DCM, versus traditional FMCW/FCM radar systems. As discussed in this paper, below we enumerate some of the advantages that DCM radars offer over FMCW/FCM technology:

	FMCW / FCM	DCM
Analog Processing	Complex – larger analog for increased number of VRx's.	Simpler – smaller analog for increased number of VRx's.
Signal Processing	Partially done in analog circuitry.	Mostly done in digital which allows the use of advanced signal processing algorithms.
Range Response	Broad range response that may hide small objects in close proximity of a large object. Low HCR.	Sharp thumbtack-like range response due to near ideal auto-correlation function of long spreading codes providing much greater HCR.
MIMO Support/ Angular Resolution	Multiple VRx has been challenging for FMCW. Low HCR.	Native support for a large number VRx. High HCR.
Interference	Interference is highly dependent on the chirp parameters used by the interfering and victim radars and may result in a high ISF.	Robust against interference from other DCM radars. Always low ISF.

Introducing a fundamental shift from analog to digital has transformed several applications and industries such as radio, TV, video and cellular communication. Digital processing provides multiple advantages since data can be easily stored and replayed, enabling advanced signal processing algorithms and therefore providing:

- repeatability with fidelity,
- predictability,
- improved dynamic range, as well as,
- corrections of analog impairments which further simplifies the analog design and thus enables a wider dynamic range.

In the past, higher amounts of digital processing resulted in more power consumption, but that changed with improved processing in low geometry nodes. Therefore, this advanced digital processing can be performed easily within the required power constraints of automotive applications.

The DCM waveforms utilized are similar, in many respects, to CDMA that has been used in cellular systems for the last 20 years and in military systems for more than 40 years. This digital radar technology is now accessible to automotive radar designers to transform the automotive industry, making vehicles safer and able to address the challenges of enhanced autonomy.

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