MODERN RADAR SYSTEMS AND SIGNAL DETECTION ALGORITHMS FOR CAR APPLICATIONS

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The present paper is devoted to analysis of modern radar sensor systems and signal detection algorithms used in car applications, namely, Closing Vehicle Detection (CVD) and Blind Spot Detection (BSD). We consider a possibility to use the radar systems in Intelligent Transportation System (ITS) with the purpose to drive safety. We compare the radar sensor systems with ultra sound, video camera, 3D camera, Infra Red (IR) sensor, and Laser Imaging and Radar Detection (LIDAR) systems. Comparative analysis shows that for CVD and BSD applications the radar sensor systems possess superiority over all other kinds of car safety driving systems under poor weather conditions – the rain, snow, fog, etc. Also, we compare two kinds of radar systems, namely, 24 GHz and 77 GHz. Analysis shows that 24 GHz radar sensor systems are preferable to use in CVD and BSD applications. Specific radar signal processing issues that need to be addressed within the evaluation framework of the signal detections algorithms are under discussion in order to make the final decision about the appropriate signal detection algorithm for CVD and BSD. We discuss the main principles of signal detection and signal processing algorithms used by the 24 GHz radar sensor systems employed in CVD and BSD applications: the frequency-modulated continuous wave (FMCW); pulse Doppler; stepped frequency pulse Doppler (SFPD); frequency shift keying (FSK); spread spectrum; and random noise radar sensor systems. Comparative analysis shows advantages to use the FMCW principles of signal processing in 24 GHz radar sensor systems in comparison with other signal detection and signal processing algorithms. A framework is proposed to evaluate the signal detection algorithms in radar sensor systems for vehicles safety and general steps to design the signal detection algorithms are introduced in this paper, too. Performance metrics and test cases are defined to allow an impartial comparison of different detectors. In this framework, the main approach for detector comparison is to collect all the useful and important information that can help us to evaluate the considered radar sensor systems to make the best choice. Available data suitable to the fair comparison of different algorithms are highlighted with results for a selection of algorithms. The proposed framework, performance metrics, and general steps for any signal processing algorithm design, as mentioned before, all are under discussion and analysis. Many investigations have been published on the development of effective signal detection algorithms. The present paper can be considered as a continuation of research for car applications even if it is carried out under specific assumptions for a predefined usage or application. Finally, we propose some recommendations to design the 24 GHz radar sensor systems in CVD and BSD applications.

Keywords: radar sensor systems, signal detection algorithms.

1. INTRODUCTION

One first traffic application of radar technology was invented by Christian Huelsmeyer, described in a well known German patent certificate dated April 30, 1904. Since this time many different radar systems have been developed for vehicle, vessel and air traffic control in several civil, transportation or defense applications. Henry Ford revolutionized the automotive industry more than 100 years ago with his new production ideas. We are now facing another major shift in automotive production, when an increasing part of the car value comes from electronic systems. The introduction of more automotive safety systems plays an important role in this shifty. For instance, one expert predicts that the software value will increase from 4% in 2003, to 13% in 2011. This, of course, affects the engineering community in many ways. The automotive industry has always been dominated by mechanical engineering, but today we see an increasing need for engineers specialized in signal processing, automatic control, electronics, communication, and computer hardware.

A key reason for this trend is the rapid development of safety systems. As the numbers of vehicles on our public roads increases, the requirement on safety is also increased. There has been a tremendous progress in this area over the last two decades as is evident from accident statistics. For instance, the number of fatalities in Sweden [1] suddenly started to drop around 1990. According to this report [1], the car fleet becomes safer for each year and the trend is that the fatality risk in a new car is reduced 5% each year. A research report by an insurance company [2], partly acknowledges on-board safety systems for this trend change, and, for instance, it ranks an electronic stability system (antiskid control) as important as safety belts to prevent severe injuries on skiddy roads. Every year the National Highway Traffic Safety Administration's (NHTSA's) National Automotive Sampling System (NASS), USA, conducts a sampling of police accident reports (PARS) for national estimates of the crash problem. The NASS selects about 48,000 PARS from across the nation to feed the General Estimates System (GES) of the NASS for crash count estimates. For example, in 2006, the GES estimated the total number of passenger cars and light trucks involved in crashes to be 11.6 million, while the total number of crashes was about 6.8 million, giving a light vehicle share of over 94% of all vehicles involved [4]. Accident data from the NHTSA shows that driving task errors caused 75.4% of all crashes in 2006. According to data from the GES and the Fatal Accident Reports (FARS) databases, rear end collisions are the second largest category of collisions. They represent 23% of all collisions [5]. Also 88% of all rear end collisions are caused by driver inattention and following too closely. NHTSA countermeasure effective modeling has found that headway detection systems can theoretically prevent approximately from 37% to 74% of all police reported rear end crashes [6].

A study conducted by NHTSA in conjunction with the Research and Special Programs Administration (RSPA) Volpe National Transportation Systems Centre (Volpe Centre) between 2001 and 2010 found the following distribution of primary causes of vehicular crashes [7]: *Driving Task Errors* – 75.4% of all crashes: driving recognition errors – 43.6% of all crashes; for instance, driver did not see the vehicle ahead due to inattention; obstructed vision due to intervening vehicles, road geometry, and road appurtenances; driver decision error – 23.3% of all crashes; for example, driver misjudged gap/speed to an approaching vehicle; tailgating/unsafe passing; excessive speeding; driver erratic action – 8.5% of all crashes; for example, driver intentionally ran the red light; failure to control vehicle; deliberate unsafe driving act; driving task errors – 75.4% of all crashes; *Driver Physiological State* – 14% of all crashes: drunk driver– 6% of all crashes; sleepy driver – 3.5% of all crashes; ill driver – 4.5% of all crashes; *Vehicle Defects* – 2.5% of all crashes; *Road Surface* – 8% due to surface being wet or due to snow, ice on the surface; *Reduced Visibility* – 0.1%, for instance, due to glare.

There are seven major crash types which were targeted for radar technology in car applications: Rear End (RE) – the front of the Subject Vehicle (SV) strikes the rear of a leading Principal Other Vehicle (POV), both traveling in the same lane; Backing (BK) – the SV strikes, or is struck by an obstacle while moving backwards, the obstacle can be another vehicle or an object, animal or pedestrian; Lane Change/Merge (LCM) – the SV driver attempts to change lanes and strikes or is struck by a vehicle in the adjacent lane; Single Vehicle Roadway Departure (SVRD) – the SV leaves the roadway as a first harmful event; this crash type does not include roadway departures resulting from a collision with another vehicle; Opposite Direction (OD) – the SV collides with a vehicle traveling in the opposite direction; this impact results in a frontal impact or sideswipe; Intersection Crossing Path (ICP) – three types of ICP crashes were identified: *Signalized Intersection, Straight Crossing Path* (*SI/SCP*) – the SV without a right of way strikes or is struck by a vehicle with right-of-way both traveling through a signalized intersection in straight paths perpendicular to each other; *Unsignalized Intersection, Straight Crossing Path (UI/SCP)* – the SV without a right-of-way strikes or is struck by a vehicle with right-of-way while both are trying to pass in perpendicular directions straight through an unsignalized intersection, generally controlled by stop signs; *Left Turn Across Path (LTAP)* – the SV attempts to turn left at an intersection and strikes or is struck by a vehicle traveling in the opposing traffic lanes; Reduced Visibility (RV) – this crash circumstance encompasses all crash types occurring in reduced visibility conditions that include non-day light (dark, dark but lighted, dawn or dusk) or bad weather (rain, sleet, snow, fog, or smog). Table 1 presents us the causal factors for each crash type.

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Causal Factors	RE	BK	LCM	SVRD	OD	SI/SCP	UI/SCP	LTAP
Inattention	56.7	0.0	3.8	15.4	17.8	36.2	22.6	1.6
Looked - did not See	0.0	60.8	61.2	0.0	0.0	0.0	36.7	23.2
Obstructed Vision	0.0	0.0	0.0	0.0	0.0	4.3	14.3	24.4
Tailgating/ Unsafe Passing	26.5	0.0	0.0	0.0	1.1	0.0	0.0	0.0
Misjudged Gap/ Velocity	0.4	0.0	29.9	0.0	5.9	0.0	12.2	30.0
Excessive Speed	0.0	26.6	2.2	17.8	0.0	0.0	0.0	0.0
Tried to Beat Signal/ Vehicle	0.0	0.0	0.0	0.0	0.0	16.2	0.0	11.2
Failure to Control Vehicle	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0
Evasive Maneuver	0.0	0.0	2.6	13.7	18.6	0.0	0.0	0.0
Violation of Signal/Sign	0.0	0.0	0.0	0.0	0.0	23.2	3.4	7.4
Deliberate Unsafe Driving Act	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0
Miscellane-ous	1.1	0.1	0.0	0.0	1.0	5.9	0.0	1.7
Drunk	2.1	3.0	0.0	10.1	31.7	12.6	2.7	0.4
Asleep	0.0	1.9	0.0	11.8	0.0	0.0	0.0	0.0
Ill	9.6	0.0	0.0	3.5	1.1	0.0	0.0	0.0
Vehicle Defects	1.2	5.7	0.3	5.3	4.5	1.6	00	0.0
Bad Roadway Surface Conditions	2.3	0.0	0.0	20.2	18.3	0.0	7.0	0.0
Reduced Visibility/ Glare	0.1	0.0	0.0	0.0	0.0	0.0	1.1	0.1
Total %	100	100	100	100	100	100	100	100

The requirements on the safety systems will continue to increase in the future motivating the continued development on improved versions of existing and new safety systems. The automotive executives share this view [3], since safety is a basic tenet to the industry now and will continue to be an ongoing major focus for consumers and manufacturers alike. New technology will be as important as new models in attracting customers. The research community also has to make contribution, The main purpose of this paper is to point out certain directions in signal detection and signal processing algorithms employed by radar systems for car applications where research is needed. The underlying theme is the radar sensor fusion for Closing Vehicle Detection (CVD) and Blind Spot Detection (BSD) systems, namely, to utilize existing and affordable radar sensors as efficiently as possible for as many purposes as possible.

2. MODERN RADAR SYSTEMS

2.1 CVD System

ITS: The Intelligent Transportation System (ITS) is the output of the integration between information and communications technologies with the transport infrastructure and vehicles to manage the traffic, improve the safety, reduce the transportation times, and, also, the fuel consumption. Various technologies in the ITS are applied by basic management systems, for example, car navigation, traffic control systems, container management systems, variable message signs, automatic number plate recognition or speed definition systems, cameras applications, such as security CCTV systems, integration of live data, and feedback from a number of other sources, such as parking guidance and information systems, weather information, predictive techniques that are being developed in order to allow advanced modeling and comparison with historical baseline data, and the usage of wireless communications (V2V-V2I-Mobile networks applications). There are the following ITS applications: electronic toll collection; high occupancy toll lanes; emergency vehicle notification systems; automatic road enforcement; variable speed limits; traffic management systems; road vehicle cooperative smart cruise systems; dynamic avoidance light sequence; safety driving in vehicle applications.

<u>*Safety Driving Applications*</u>: The theoretical, experimental, and operational aspects of electrical and electronics engineering and information technologies are applied to enrich the vehicle with required ability to safe driving and accident avoidance systems. Road traffic consists of three elements: the people (the drivers), the vehicles, and the roads. In order to improve a road traffic safety, all three elements must be elevated. It is necessary to prevent the occurrence of accidents by compensating the errors made by drivers, From this view point, to have ITS installed on vehicles is very important and essential. Among the systems emerging on the market there are systems that can detect the cruising environment including the distances between the vehicle and obstacles and, also, other vehicles (warning sound for the driver or automatic adjustment of the distance between vehicles), and systems that can detect the lane lines on the road serving as the lane markings, for example, the alarm sound when a vehicle crosses this lane line [8]. However, there are the limits to implement of ITS in vehicles. Some of these limits are associated with the road infrastructure and others are related to limitation of available technologies being in the market or under designing (detection systems based on radar sensors or laser sensors, video cameras, etc).

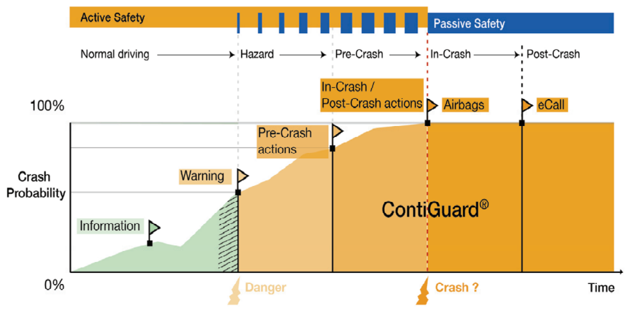


Fig. 1. Total safety approach.

<u>*Total Safety Approach*</u>: The total safety means the way that the vehicle must employ to avoid accidents and prevent injuries. This approach is achieved by integrating environmental sensors to build a network of active and passive vehicle safety systems. The main goal is to incorporate an active vehicle intervention technology to prevent accidents. Figure 1 shows the total (passive and active) safety approach.

<u>*Radar Systems*</u>: The term *radar* means two procedures: the detection and the distance measurement. The inherent high resolution and small antenna size made a radar as the first natural application in the millimeter-wave area. Automotive radar facilitates various functions that increase the driver safety and convenience. Exact measurement of distance and relative speed of vehicles in front, beside, and behind the car allows us to improve performance systems and the driver ability to perceive vehicles and objects where visibility is poor or vehicles and objects are hidden in the blind spot in the course of parking or changing lanes. Radar technology has proved its ability to vehicle applications for several years. Comparing with optical or video counterpart with image processing, the advantages of radar are obvious [9]: the direct distance and speed measurement; robustness against weather influences and pollution; unaffected by light; measurement of stationary and moving vehicles both on the road and in the vicinity of the road; invisible integration behind electromagnetically transparent materials (e.g. bumpers). Evolution of advanced radar from X-band to 24 GHz, 77 GHz, and, then, to 100 GHz or 220 GHz has meant that the submillimeter resolution is possible. Radar can be used now for car applications at short distances. Before going farther in the radar sensors applications, in brief about the radar principles that could be useful for better understanding.

<u>*Basic Radar Principles*</u>: Radar systems use the delay measured between the transmitted and target return signals to compute a target range. The target range is as a function of time causing the Doppler offset in the target return signal phase and frequency. Consequently, the closing velocity between the Target Vehicle (TV) and radar can be defined by measuring the Doppler offset of the target return signal. The closing velocity is also known as a radial velocity or line-of-sight velocity. The Doppler frequency is measured by the pulse Doppler radar as a linear phase shift over a set of radar pulses during some Coherent Processing Interval (CPI). Radars detecting and measuring a target velocity are known as the Moving-Target-Indicator (MTI) radars. Multiple MTI radar systems might be employed in concert, for example, each radial velocity can be measured in different spatial directions.

<u>*Standard Form of the Radar Equations*</u>: The basic radar range is given by the following equations [10], [11]:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 L_s L_{ATM} R^4}, \tag{1}$$

where P_r is the received power; P_t is the transmitted power; G is the antenna gain; λ is the wavelength; σ is the target effective scattering area; $L_s > 1.0$ means the system loss; $L_{ATM} > 1.0$ means the atmospheric loss; and R is the target range. The effective receive antenna area A is given by

$$A = \frac{G\lambda^2}{4\pi}. \quad (2)$$

The power density at target range R is defined by

$$P_d = \frac{P_t G}{4\pi R^2}, \quad (3)$$

and the isotropic power reflected from the target at the range R is given by

$$P_r = \frac{P_t G \sigma}{4\pi R^2}. \quad (4)$$

The propagation delay t is given by

$$t = \frac{2R}{c}, \quad (5)$$

where c is the velocity of light. To obtain the TV range we must define the difference in frequency between the transmitted and target return signals. The difference in frequency is detected by various ways based on the radar sensor system type. In the case of moving TVs, a shift in the Doppler frequency is given by

$$f_D = \frac{2Vf}{c}, \quad (6)$$

where f is the nominal radar frequency and V is the TV velocity. The Doppler effect or Doppler shift is the wave frequency change when an observer moves relative to the wave source. Definitions of other important parameters such as the range resolution, velocity resolution, and the accuracy of both range and velocity can be defined only for individual kind of radar sensors. For example, a simple relation between the range resolution ΔR and pulse width T_p, in the case of pulse radar system, is given by:

$$\Delta R = \frac{cT_p}{2}. \quad (7)$$

In a general case, the velocity resolution ΔV defines the required Doppler frequency resolution

$$\Delta f_D = \frac{2\Delta V f}{c} = \frac{2\Delta V}{\lambda}. \quad (8)$$

The basic types of radars for car applications are: the bistatic and multistatic continuous wave (CW) [12]; the Frequency Modulation Continuous Wave (FMCW) and the Linear FMCW (LFMCW); the Frequency Shift Keying (FSK); the Frequency-Stepped Continuous Wave (FSCW); the Pulse Doppler (PD); the Stepped Frequency Pulsed Doppler (SFPD); the combination of LFMCW and FSK Radar; the noise radar; the Spread Spectrum Radar (SSR). All the above mentioned radar sensor systems present differed advantages for vehicle applications: the target range measurement can be accomplished with high precision; the sensors are capable to measure relative velocities; the sensors are capable to detect multiple targets; the measurements with high update rates (i.e. low cycle time) are typical; the sensors are robust against many different weather conditions and dirt or dust; the detection performance is not affected by light conditions changes; the sensors can be installed behind a plastic vehicle bumper with low reduction of sensitivity if it is needed for design aspects; the sensor front-ends show small physical dimensions; the low cost is finally one of important factors to employ the microwave radars on vehicles.

Automotive Radar and Vision System Applications: The shift of focus from passive to active vehicle safety has already moved beyond the safety community and into regulatory agencies. There is a grow of public awareness of such systems driven by combination of increased regulatory and insurance industry research, and, also, media interest. Figure 2 shows a progress in car applications.

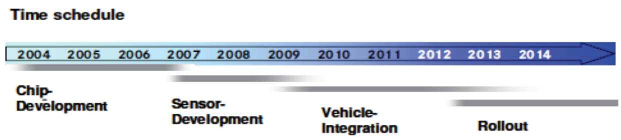


Fig. 2. Time schedule of vehicle development.

The general idea of radar network for automotive applications is to surround a vehicle completely by very small and cheap and quite powerful radar sensors to build a kind of safety shield around the vehicle, for example, 16 individual radar sensors are required to develop a 360° protection for each individual car (see Fig. 3).

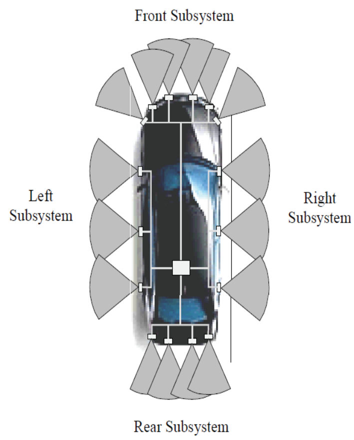


Fig. 3. Radar sensors around a vehicle.

Set of functions are presented below with a short description [13].

Sensor and Display (Comfort): Parking aid – invisibly mounted distributed sensors behind the bumpers (the ultrasonic technology is also widely used for this application); BSD – the zones beside a vehicle are covered by radar sensors; a warning is displayed when the driver is about to change the lane but the radar system field of view is occupied by any TV.

Vehicle Control Related (Comfort + Control): Adaptive Cruise Control (ACC) – longitudinal vehicle control at the constant speed with additional distance control loop; ACC Plus – to improve the handling of cutin situations with a wider field of view at medium range; ACC Plus Stop & Go – to improve/allow the vehicle control function in urban environment; complete coverage of the full vehicle width; it is possible due to the fact that the short range sensors have a higher beam width in comparison with the forward looking long range sensor.

Collision Related (Safety + Control): Collision Mitigation – similar to restraint systems of related functions; the sensor system detects unavoidable collisions and applies a total brake power by overruling the driver; Collision Avoidance – future function; the vehicle would automatically take maneuvers to avoid a collision and determine an alternative path by overruling the driver's steering commands. Figure 4 shows the safety systems using radar sensors around the vehicle.

Fig. 4. Safety system using radar sensors around a vehicle.

Restraint Systems Related (Safety): Closing Velocity Sensing – the main technical problem in this application is to decide whether a crash will be happened and to define the impact position and speed before it can be happened to adjust adaptively the thresholds/performance of restraint systems that are not fired by the radar system; Pre-Crash Firing for Reversible Restraints – in this case, reversible restraint systems, as electrical belt tensioners or pedestrian protection systems, as bonnet lifters are excited by the radar system; Pre-Crash Firing for Non-Reversible Restraints – non-reversible restraint systems, for example, airbags, are directly excited by the sensor system, that can be done even before the crash happens; this function is of most importance for side crashes to gain a few life-saving milliseconds to excide before the crash is happened. Many other applications are under design, for example, the lane keeping support, drowsy driver detection, and blind spot monitoring (see Fig. 5).

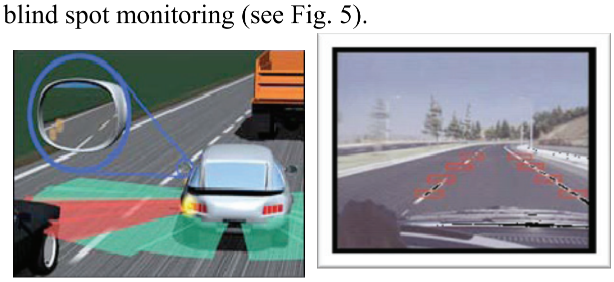


Fig. 5. Safety systems

Automotive Radar System Requirements and Standards : For all above mentioned applications the implementation process has the specific requirements that should be satisfied. The following aspects give an overview to understand the main requirements for the specific applications and may give an idea about technical challenges. All applications evolve different system dynamics and situations and, therefore, various requirements. In each case of application, the system specifications are divided into the *range, velocity,* and *azimuth angle* estimation accuracy and resolution. Additionally, we can use the cycle time as an important requirement. The accuracy and resolution for the TV range, velocity, and a azimuth angle are defined as follows: the TV range accuracy is the absolute accuracy of TV range measurement; the TV range resolution is the ability to distinguish two targets by range measurement in the case if there are only two targets; the velocity accuracy is the absolute accuracy of relative velocity measurement; the velocity resolution is the ability to distinguish two targets by velocity measurement in the case if there are only two targets; the azimuth angular accuracy is the absolute precision of an azimuth angle measurement; the azimuth angular resolution is the ability to distinguish two targets by azimuth angle measurement in the case if there are only two targets.

In Table 2, in the case of Short Range Radar (SRR), the numbers for each kind of applications indelicate to the differences in the requirements. For example, a parking aid needs the low update rates due to very slow movements. In this case, the velocity is unimportant, but a wide angular range in azimuth has to be covered by limited accuracy. BSD as a mere presence detection with the limited range measurement performance does not require the velocity and azimuth angle measurement [14].

Table 2.

Requirements for the main parameters.

	Parking Aid	Stop & Go / ACC Support	Pre-Crash	Blind Spot Surveillance
Cycle Time [ms]	100	10 – 20	5	100
Distance:				
Range [m]	0.05 - 5	0.5 - 20	0.5 - 20	0.2 – 5
Accuracy [m]	0.05	0.5	0.5	0.5
Resolution [m]	n. r.[1]	1	1	n. r.
Velocity:				
Range [km/h]	n. r.	-360 … +180	-360 … 0	n. r.
Accuracy [km/h]	n. r.	1	1	n. r.
Resolution [km/h]	n. r.	5	5	n. r.
Azimuth Angle:				
Range [°]	-90 … +90	-60 … +60	-60 … +60	n. r.
Accuracy [°]	5	2	2	n. r.
Resolution [°]	n. r.	5	5	n. r.

1) n.r. : Not Required

Other important practical issues should be taken into consideration and can be summarized as follows: 1) the sensor network time synchronization is an important aspect for target state estimation; in many cases, the asynchronous data and data transmission have to be handled; the delay is especially important when the SRR system cycle is required; 2) the sensors distributed in a network need communication interfaces; 3) to minimize the data transmission rate there is a need to define a minimum of the data transmission rate without serious performance degradation; 4) the alignment and recognition of misalignment can be important depending on the used sensor; 5) the positions of sensors, for example, on a vehicle bumper, effect the performance and must be defined very accurately to guarantee a determination of the azimuth angle estimation with high precision; 6) the possible crosstalk and undesired microwave propagation behind a vehicle bumper must be avoided; 7) the computation complexity is increased in the case of sensor network; all sensor signals have to be evaluated and the data association and fusion has to be performed; the optimal allocation of processing resources within the network is an important problem; 8) the structural complexity should be as low as possible owing to reducing the average time between failures and in automotive applications and the price constraints have to be also met; 9) integration space in modern vehicle bumpers is very small; the number and size of components have to be small, too; 10) the sensors must have the same quality that assumes very precise reproducibility in large volumes; otherwise, a difference in quality has to be considered in the course of signal processing. More information and details concerning the sensors network design can be found in [15].

Table 3.

Automotive radar operation frequencies in Europe, US and Japan.

Automotive radar operation frequencies [power density @ 3 meters/cm^2]		
Europe	US	Japan
	10.5-10.55 GHz (allocated) [1.66 μW]	
24-24.25 GHz (ISM-band)	24-24.25 GHz (ISM-band) [16.6 nW]	24-24.25 GHz (ISM-band)
	46.7-46.9 GHz (allocated) [60 μW]	
		60-61 GHz (allocated)
76-77GHz (allocated)	76-77 GHz (allocated) [60 μW]	76-77 GHz (allocated)
	94.7-95.7 GHz (considered) [30 μW]	
140 GHz (considered)	139-140 GHz (considered) [30 μW]	

Automotive Radar Sensor Applications Frequency Range: The millimeter wave region is generally considered with the purpose to cover the frequency range from 30 to 300 GHz that corresponds to the wavelengths from 10 mm to 1 mm respectively. The IEEE established bandwidths for radar [16] are designated the 33-36 GHz band as the Ka-band, from 46 to 56 GHz region as V-band, and from 56 to 110 GHz as the W-band. Table 3 presents the formal automotive radar operation frequencies in some countries.

Table 4.

Applications for 24GHz and 77GHz radar sensors.

Function	Requirements Range/Velocity Field of view	Sensors, Category	Proposed Radar Principle	Pro-posed Carrier Freq.	Alterna-tive Sensors	Remarks
Parking Aid	- 0.2...5m - 0...±30km/h - full vehicle width	2-4xSRR per bumper	UWB Pulsed	24GHz	Ultra-sonic	- 100ms cycle time
Blind Spot Surveillance	- 0.5...10m/0.5...40m - reasonable velocity interval - two lanes beside vehicle	1-2xSRR or 1-2xMRR per side	FMCW/ FSK/ Pulsed	24GHz	Video/ Laser	- 50ms cycle time
ACC	- 1m...150m - reasonable velocity interval - three lanes in front of vehicle in 65m	1xLRR	FMCW/ FSK/ Pulsed	77GHz	Laser	- 50ms cycle time
ACC plus	- 1m...150m/0.5...40m - reasonable velocity interval - three lanes in front of vehicle in 20m	1xLRR/ 1xMRR	FMCW/ FSK/ Pulsed	77GHz/ 24GHz	Laser	- 50ms cycle time - Laser/Video sensor fusion rea-sonable
ACC plus Stop&Go	- 0.5m...150m/0.5...40m - reasonable velocity interval - three lanes in front of vehicle in 10m - full vehicle width in 0.5m	1xLRR/ 2xMRR	FMCW/ FSK/ Pulsed	77GHz/ 24GHz	Laser	- 50ms cycle time - Laser/Video sensor fusion rea-sonable
Closing Velocity Sensing	- 0.5m...10m/0.5...30m - any velocity - about 45°	1xSRR/ 1xMRR	FMCW/ FSK	24GHz	None	- 10ms cycle time
Pre-Crash Reversible Restraints	- 0.5m...10m/0.5...30m - any velocity - full vehicle width in 0.5m	2xSRR/ 2xMRR	FMCW/ FSK	24GHz	None	- 10ms cycle time - function is add-on to line above, - very low false alarm rate
Pre-Crash Non-Rev. Restraints	- 0.5m...10m/0.5...30m - any velocity - full vehicle width in 0.5m	2xSRR/ 2xMRR	FMCW/ FSK	24GHz	None	- 10ms cycle time - function is add-on to line above, - ultra low false alarm rate, - laser/video sensor fusion requ.
Collision Mitigation	- 0.5m...150m/0.5...40m - any velocity - three lanes in front of vehicle in 10m - full vehicle width in 0.5m	1xLRR/ 2xMRR	FMCW/ FSK	77GHz/ 24GHz	None	- 10ms cycle time - function is Add-on to ACC plus S&G, - ultra low false alarm rate, - laser/video sensor fusion requ.
Collision Avoidance	- 0.5m...150m/0.5...40m - any velocity - three lanes in front of vehicle in 10m - full vehicle width in 0.5m	1xLRR/ 2xMRR	FMCW/ FSK	77GHz/ 24GHz	None	- 10ms cycle time - function is Add-on to line above, - ultra low false alarm rate, - laser/video sensor fusion requ.

Sensor Categories: There are two widely used classification categories for radar sensors. The first category is based on a simple and suitable parameter that is the *maximum range*. According to this parameter, we can recognize three main types of radar sensors, namely: a) Long Range Radar (LRR) with a maximum range of 150 m (up to 200m); b) Middle Range Radar (MRR) with a maximum range of 40m (up to 60m); c) SRR with a maximum range of 15m (up to 20m). The second category is based on the *operation frequency*. The most popular sensors according to the operation frequency are based on 24 GHz and 77 GHz owing to many aspects both for technical and for regulation background.

24 GHz Sensors: This technology [17] seems to be the best tradeoff between today cost of production and the sensor size. Typically, the SRR sensors do not measure the detected TV azimuth angle and they have a very broad lateral coverage. Therefore, single antenna elements are sufficient. The beams are directed only vertically to increase the antenna gain and to minimize the clutter effects from road surface. These sensors are typically operate in the pulsed mode (the pulse, Doppler pulse) or in the CW mode, namely CW, FMCW, FSK, FMCW & FSK. Additionally, the coded radar with spread spectrum techniques i.e. pulsed, CW, pseudo-noise, is a common technique.

77 GHz Sensors: The 76–77 GHz band [18] is widely recognized by overseas regulatory bodies, international and regional standards bodies for automotive radar applications. The range of typical vehicle equipped by this kind of radar sensors is for about 150 m or 300 m round-trip. This is generally for LRR and these sensors are applicable in the pulsed, FMCW, and FSK radars. Table 4 represents a large variety of applications for two kinds of radar sensors, namely 24 and 77 GHz.

CVD: This technology is one of the most recent applications in the driving systems safety and is under development and widely attractive according to importance and its ability to be integrated with different other safety driving systems.

System Definition: CVD is a vehicle detection in one or several rear zones. There is a need to define two terms: *Rear Zone* is the zone located behind and from one side of SV. The rear zone is intended to cover the lane lines adjacent to SV. However, the position and size of the rear zone are defined with respect to SV and are independent of any lane line markings. *Closing Speed* of TV is defined as the difference between TV and SV speeds. This definition applies to TV only in the rear zone. A positive closing speed indicates that TV is coming near SV at the rear. Some safety driving applications are classified in Table 5 and it is evident that the CVD system is also essential for any lane change assistant system. Moreover, this system provides additional information before the crash to improve the behavior of current restraint systems [19]. Figure 6 shows the definition of the directions around the car.

Table 5.
Coverage zone of each safety driving applications.

Type	Left Adjacent Zone Coverage	Right Adjacent Zone Coverage	Left Rear Zone Coverage	Right Rear Zone Coverage	Function
I	☻	☻			Blind Spot Warning
II			◙	◙	Closing Vehicle Warning
III	☻	☻	◙	◙	Lane Change Warning

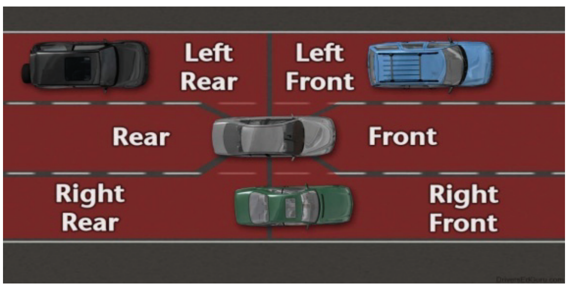


Fig. 6. Definition of the directions.

CVD System Functional Requirements: The warning function must provide a coverage on the left and right rear zones of SV. On the left and right side, the warning function should be active according to the maximum TV closing speed and the estimated time to collision. Visual information pertaining to one or more TV, e.g. the TV location, closing speed, etc. may be delivered to the SV driver at any time provided that this information is distinguishable from a warning indication [20]. Table 6. presents a classification of the closing vehicle warning time to collision by TV closing speed. The CVD system should be subjected to the requirements with respect to the distance and time measurement accuracy as follows: d*istance measurement accuracy* – the distance is less than 2 m, the accuracy should be 0.1m or better; the distance is from 2 m to 10 m, the accuracy should be 5% or better; the distance is greater than 10 m, the accuracy should be 0.5 m or better; *time measurement accuracy* – the time is less than 200 ms, the accuracy should be 20 ms or better; the time is between 200 ms and 1 s, the accuracy should be 10% or better; the time is greater than 1 s, the accuracy should be 100 ms or better.

Table 6.
Classification of the Closing Vehicle Warning time to collision.

Type	Maximum Target Vehicle Closing Speed	Time to Collision
A	10 m/s	2.5 s
B	15 m/s	3.0 s
C	20 m/s	3.5 s

2.2 BSD Principles

A vehicle blind spot is the area around the vehicle that cannot be directly observed (see Fig. 7). Various kinds of vehicles have the blind spot, namely, cars, trucks, motorboats, aircrafts and so on. The blind spot is the viewing angle area on the rear left and right sides of a vehicle that is not covered by the internal and external regular mirrors [21]. The biggest blind spot is located over a driver right shoulder between the edge, where the peripheral vision ends, and the area up to the back of the car that is not seen in the side mirror. The left side blind spot is smaller and should be checked, too.

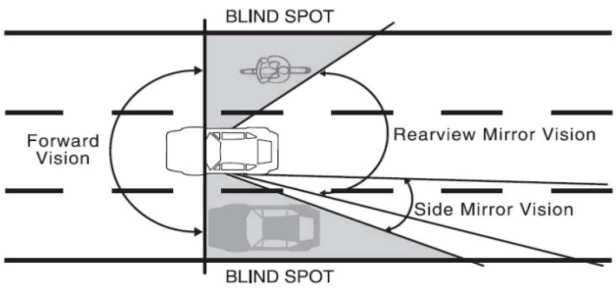


Fig. 7. Blind Spot definition.

The blind spot can be extremely dangerous and every driver needs to learn his vehicle location and how and when he should check it. The purpose of safety applications is to avoid a classical reason for accidents.

The driver cannot oversee an obstacle being within the blind spot of his car or TV that is approaching at high speed by a neighboring lane line while the driver is maneuvering in the appropriate direction. Accident can simply be prevented if, for example, an acoustical or optical signal in the side rear mirrors informs the driver about the TV presence within the blind spot area of SV. The blind spot surveillance system requires a small detection area with maximum range of 5m at the location of the car's blind spot [22].

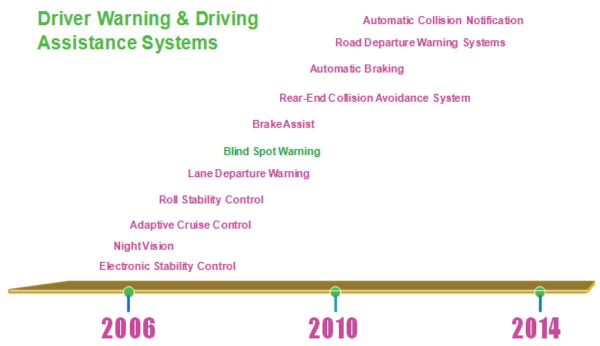


Fig. 8. Automotive Technologies Timeline.

At this point, the driver is informed whether TV will be located on the right or left lane relatively to SV in the next moments. If the driver wants to change lanes under such a situation a warning signal will be appeared. The representation of automotive technologies timeline for driver warning and driving assistance systems are shown in Fig. 8.

Sensors: The Sensor is any electronic device that produces electrical, optical or digital data. Sensor data are transformed to make a decision by the user. Many kinds of sensors are used in automotive applications. Table 7 presents a comparison of sensors that are considered as good facilities for the range measurement and TV detection.

Table 7.

Comparison between the sensors produced by different technologies [24] and [25].

	Short Range Radar	**Long Range Radar**	**Lidar**	**Ultra sound**	**Video Camera**	**3D Camera**	**Far IR camera**
Range Measure-ment < 2m	o	o	o	++	-	++	-
Range Measure-ment 2...30m	+	++	++	-	-	o	-
Range Measure-ment 30…150m	n.a.	++	+	--	-	-	-
Angle Measure-ment< 10^0	+	+	++	-	++	+	++
Angle Measure-ment > 30^0	o	-	++	o	++	+	++
Angular Resolut-ion	o	o	++	-	++	+	++
Direct Velocity Inform-ation	++	++	--	o	--	--	--
Operati-on in Rain	++	+	o	o	o	o	o
Operati-on in Fog or Snow	++	++	-	+	-	-	o
Operati-on if Dirt on Sensor	++	++	o	++	--	--	--
Night vision	n.a.	n.a.	n.a.	n.a.	-	o	++

++ - Ideally suited; + - Good performance; o- Possible, but drawbacks to be expected; - Only possible with large additional effort;-- Impossible / n.a.- Not applicable

RADAR: Radar sensors are widely used for Adaptive Cruise Control (ACC) systems. Implementation of radar sensor system is restricted to luxury cars owing to the cost of this technology. Two frequencies are mainly used in automotive applications: 24 GHz and 76-77 GHz. The first is used for SRR up to 30 m. The second is used for LRR and speeds up to 150 km/h. The radar has a good performance under poor weather conditions.

IR Sensors: InfraRed (IR) laser is used for LRR. The IR light beam is reflected by TV and the target return light is received by sensors. The target return signal is processed in order to define the TV range. These sensors are typically used by the automation systems produced by industry.

LIDAR: Laser imaging and detection radar is also referenced sometimes as LIDAR. Since RADAR uses microwaves to detect targets, the LIDAR uses a laser light beam to detect ones. These sensors are used by automation systems for detection and navigation purposes. LIDAR is widely used by numerous systems owing to its ability to provide the same performance as radar systems under specific conditions [24]. From Table 7 we can see that the overall performance of RADAR sensor is better in comparison with other sensors technology. Thus, the employment of RADAR systems is a robust solution with respect to other technologies. Table 8 introduces many kinds of collision avoidance systems that are covered by ultrasonic and RADAR sensors and also the main benefits for each application. The Table 9 presents the frequency allocation for car applications in different countries. Table 10 represents the recently reported RADAR sensors with technical features implemented by different companies. Table 11 represents the assigned frequencies and bandwidth for car applications due to the range. Table 12 represents the summary of typical SRR sensor system requirements for a variety of different applications [29]. Table 13 introduces LLR specifications using 76.5 GHz frequency and SSR specifications using 79 GHz frequency.

Table 8.
Collision avoidance is covered by many types of systems.

Application	Range (m)	Rate (m/s)	Zone Width (m)	Benefit	Technology
Parking Aid	2	2	2	Reduced accident risk	Ultrasoni c
Autonomous Intelligent Cruise Control(AICC)	12 0	50	10	Reduced driver workload and added convenience	77GHz Radar
Backup Aid (Hybrid Ultrasonic/Radar)	5	5	2-3	Reduced accident risk	17GHz Radar
Lane departure	50	35	10	Reduced accident risk	Vision
Blind Spot Aid	5	15	3.5	Reduced accident risk	24GHz radar
Rear Approach System	25	25	3.5	Reduced accident risk	24GHz radar
Pre-Crash System	25	70	10	Increased Warning time and additional information regarding Impact	77GHz radar 24GHz radar
Stop-Go/Urban Cruise Control	25	15	10	Reduced driver workload	24GHz radar
Side Impact Pre-Crash	5	35	10	Increased warning time	24GHz radar

Table 9.
Allocated frequency band.

Country	24GHz NB(ISM)	24GHz UWB SRR	26GHz UWB SRR	77GHz LRR	79GHz SRR
Europe	200MHz 20dBm Restr. in UK/F available	5GHz 41.3dBm /MHz until 2013	4GHz 41.3dBm /MHz proposed	1GHz 23.5dBm available	4GHz 9dBm /MHz available
USA	100/250 MHz 32.7/12.7dBm available	7GHz 41.3dBm /MHz available	4GHz 41.3dBm /MHz available	1GHz 23dBm available	No activity
Japan	76MHz 10dBm @antenna port available	Study underway	proposed	0.5GHz 10dBm @antenna port available	In discussi-on

Table 10.
Summary of recently reported millimeter-wave automotive radar sensors [26]-[28].

Company, Institute	Frequency [GHz]	Radar Type
GEC-Plessey	77	FMCW
Fujitsu/Fujitsu Ten	60	FMCW
TEMIC&DASA	77	Pulsed
LUCAS Ltd.	77	FMCW
Millitech	77	Pulsed of FMCW
Technical Univ.Munich/ Germany	61	PN-code modulate, FSK
VORAD Safety Systems	24.725	FMCW
DASA	77	FMCW
Hino	60	FMCW
Celsius Tech	77	FMCW
HIT	77	FMCW
Philips	77	FMCW
Lucas & Jaguar	77	FMCW
Isuzu	60	FMCW
Toyota & Fujitsu/ Fujitsu-Ten	60	FMCW
TRW	94	FMCW
TU-Braunschweig/ Germany	77	FMCW
National Academy of Sciences of Ukraine	40	noise radar
Nissan	60	Pulsed FMCW
Raytheon	77	FMCW
Delco	77	FMCW
Furukawa Electric	60	spread-spectrum
ADC&M/A-Com	77	Pulsed
Siemens	77	FMCW
Thomson-CSF	77	FMCW
VORAD Safety Systems	77 (24,47,60)	FMCW,FSK-modulated

Table 11.
Car applications frequencies and the bandwidth for different ranges.

Frequency	Application	Center Frequency	Band Width
24 GHz, NB	ACC Lane change	~24.2 GHz	0.2 GHz ΔD=1.5m
24 GHz, UWB	SRR	24.5 GHz (21.6 ~ 25.6)	5 GHz
26 GHz	SRR	26.5 GHz	4 GHz
77 GHz	ACC/LRR	76.5 GHz	1 GHz
79 GHz	MRR/SRR	79.0 GHz	4 GHz

1) SRR(short range radar); MRR(middle range radar); LRR (long range radar); NB(narrow band); UWB(ultra wide band).

Table 12.
SRR system requirements for differing applications areas.

	Blind Spot	Parking Aid	Stop & GO	Simple Pre-Crash
Max. Detection Range (m)	4-8	2-5	20	7-10
Required Range Resolution (m)	0.1-0.2	0.05-0.2	0.2-0.5	0.1-0.2
Max. Relative Velocity (m/s)	15-25	3-5	8-12	40-60
Acquisition Time (ms)	200	500	300	50
Update Rate (ms)	50	50	40	20
Minimum Object Size	Bicycle	3' PVC Pole	Bicycle	Metal post

Table 13.
Specifications of LRR (76.5 GHz) and SRR (79 GHz).

LRR		SRR	
Centre frequency	76.5 GHz	Centre frequency	79 GHz
Bandwidth	1 GHz	Bandwidth	4 GHz
Maximum field of view	±10°	Maximum field of view	±80°
Azimuth beam width	1°	Range	30 m
Elevation beam width	5°	Range accuracy	±5 cm
Range resolution	1 m	Bearing accuracy	±5°
Velocity resolution	1 km/h		

Figure 9 represents some applications using SRR sensor systems and Fig. 10 represents the Synergies within higher frequency bands.

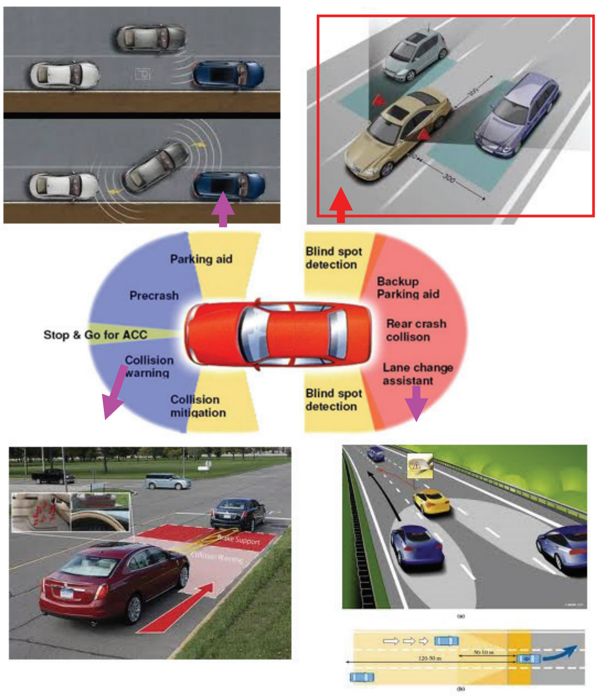


Fig. 9. Applications using short-range radar sensor.

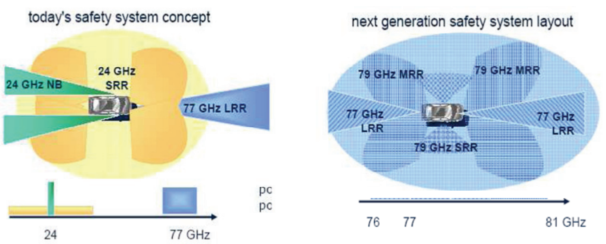


Fig. 10. Synergies within higher frequency bands.

Tables from 14 to 20 present the BSD application in terms of general functions, specifications, classifications, limitations, subsystems, sensor technologies, and system output.

Table 14.
General data on BSD.

General data on Blind Spot Detection	
Name of the system	Blind Spot Detection
General function	Stand alone driver assistance system that helps to avoid side swipe collisions in lane change situations. The system issues a warning to the driver when an object is detected in the blind spot area. Normally the warning signal consists of a red warning light close to the left and right hand rear-view mirrors.
Type of vehicles	Passenger cars
	Trucks
	Buses

Table 15.
Functional specifications of BSD

Functional specifications of Blind Spot Detection	
Main use cases	The driver receives a visual warning when an object is in the subject vehicles blind spot.
Major technology	Perception: Current solutions are using 24 GHz radars or vision sensors to detect objects in the blind spot zone. Prototype systems which monitor vehicles that are rapidly closing in on the blind spot in the adjacent lanes have been demonstrated by the use of radar sensors.
Intended benefits with function	Avoid sideswipe collisions during lane change maneuver
Intended driver behavior	Upon receiving the warning the driver is assumed to avoid lane changes target to a collision.
Time schedule	The warning should be issued as soon as another vehicle is in the defined blind spot zone.

Table 16.
Function classification of BSD

Function classification		
Type of target object for detection	No sophisticated object recognition is currently used for blind spot detection systems. Any object may be detected by the sensors currently used.	
Road types	Urban	
	Rural roads	
	Highway	
Road section type	All	

Table 17.
Function limitations for BSD

Function limitations of Blind Spot Detection	
Weather that function should work well in	Adverse (Rain)
	Adverse (Snow)
	Adverse (Ice on road)
	Adverse (fog): depending on sensor technology
Function of Light condition the function should work well in	Dark
	Light

Table 18.
Technologies of BSD

Blind Spot Detection Technologies	
Sensor Input	TECHNOLOGIES (current / trends)
Subject vehicle lane change	Blinker active in vehicle sensor and/or steering angle sensor
Short range laterally oriented objects detection	SRR 24GHz, mounted in host's rear bumper Left/right sensing, 150-degree FOV, up to 40m. 2D CMOS camera, mounted in host's exterior rear-view mirror up to 130-degree FOV Radar and vision fusion: SRR (56º FOV, 65m DOV) and LRR (17º FOV, 200m DOV) with dual-CMOS (50º FOV, 150m with follow-through to 200m DOV)
Subject vehicle dynamics	Yaw rate sensor Steering angle sensor Acceleration sensor Other sensors depending on OEM

Table 19.
Subsystems for BSD

Description of subsystems for Blind Spot Detection	
Sensors	Radar or vision sensors
Actuators	Various warning displays
Human Machine Interface (HMI) design details	Visual displays may be hard to recognize when it is exposed to direct sunlight

Table 20.
Function output of BSD

Blind Spot Detection Output	
Function output	System Reaction
Warning: Hap tic	Vibration actuators in contact with driver (seat belt, seat, steering wheel)
Warning: Visual	Display mounted on cockpit
Warning: Acoustic	Gradual sound alert

BSD sensors will detect SRR laterally oriented vehicles on the SV blind spot and SV lateral movement. BSD actuators will warn the driver using visual, acoustic or hap tic warnings. Figure 11 represents the input/output system of the BSD.

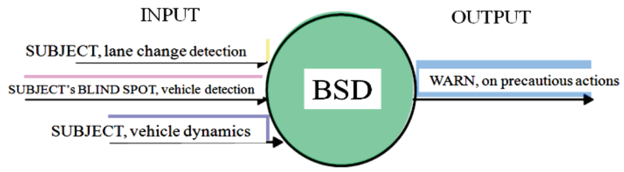


Fig. 11. Input/output system of the BSD.

<u>Specifications of 24 GHz Radar Sensors for Car Applications</u>: It is useful to present some products produced by various companies. The first product (see Fig. 12) is made by MANDO company and has the following two functions:

Fig. 12 . The Radar of MANDO Company.

BSD, lane line change assist – this function has the main following features: safety lane line changes supported by two 24 GHz radar sensors; detection of vehicles alongside and behind and warning the driver; objects located in the blind spot area are also detected. *Rear Pre Crash* (*RPC*) *System* – the main features of this function are: tracking TV that is approaching in the rear detection zone and automatic prediction about the collision with TV.

The second product (see Fig. 13) is made by Siemens Company and has also two functions:

Fig. 13. The Radar of Siemens Company

BSD – the features of this function can be summarized as follows: Ultra WideBand (UWB); pulse and frequency modulated; bandwidth is 500 MHz; range up to 16m; update rate < 20 ms. *Lane Line Change Assist (LLCC)* – this second function has the following features: narrow band; FMCW; bandwidth 200 MHz; range up to 90 m; update rate <20 ms.

2.3 Radar Sensor Systems Analysis and Performance Comparison

The radar system can be applied for detection of vehicle, the rear and lateral parking aid, BSD, and CVD. Because of this, the radar system must possess an accurate performance. In a general case, 77 GHz radar sensor system has the better resolution and performance in comparison with 24 GHz one. However, it is difficult to use 77 GHz radar sensor system to detect rear and lateral because the bandwidth is too narrow to carry out accurate measurements. For instance, to recognize 7.5 cm the bandwidth should be over than 4 GHz [30]. Table 21 presents the recommendations of International Telecommunications Union Radio communication Sector (ITU-R) for the radar system requirements and specifications.

Table 21.
International Telecommunications Union Radiocommunication Sector Recommendations for vehicle radar systems [31].

System Requirement	System Specification
Frequency	60 GHz band (60-71 GHz) 76 GHz band (76~77 GHz)
Modulation	FMCW Pulse 2-Frquency CW Spread Spectrum
Antenna Power	less than 10mW (Peak Power)
Antenna Gain	less than 40dB
Bandwidth	less than 1GHz

Table 22 introduces various radar products produced by some companies that satisfy all requirements of ITU-R recommendations and standards.

Table 22.
Vehicle radar systems produced by some companies [32].

Manufacturer	Fujitsu Ten	ADC	Delphi	Bosch	Honda elesys	Denso	Hitachi
Appearance							
External dimensions (mm)	89X107X86	136X133X68	137X67X100	91X124X79	123X98X79	77X107X53	80X108X64
Modulation method	FMCW	FM Pulse	FMCW	--	FMCW	FMCW	2-frequency CW
Detection range	4 m to 120 m or greater	Approx. 1 m to 150 m	Approx. 1 m to 150 m	2 m to 120 m or greater	4 m to 100 m or greater	Approx. 2 m to 150 m	Approx. 1 m to 150 m
Horizontal detection angle	±8°	Approx. ±5°	Approx. ±5°	±4°	±8°	±10°	±8°
Angle detection method	Mechanical Scan	Beam conversion	Mechanical scan	Beam conversion	Beam conversion	Phased array	Monopulse
EHF Device	MMIC	GUNN	GUNN	GUNN	MMIC	MMIC	MMIC

FMCW Radar: Using the linear modulated chirp signals, for example, the saw-tooth wave, triangular wave, and trapezoidal wave, it is possible to define and estimate the relative velocity and distance between SV and TV. The basic structure of FMCW radar system and signal wave is introduced in Figs. 14 and 15, respectively, [33] and [34].

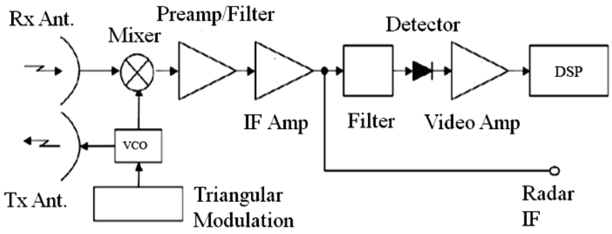


Fig. 14. Structure of FMCW radar system.

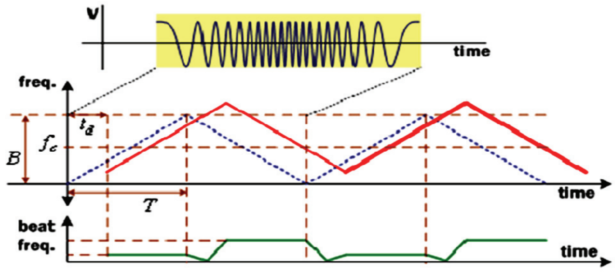


Fig. 15. Triangular wave of FMCW radar.

The frequency difference between the transmitted and target return signals is the beat frequency. In the case of a stationary TV, the beat frequency has the constant value. However, if the target is moving, there is the Doppler effect and the beat frequency is changed according to the target moving. The beat frequency can be divided into the up beat frequency f_{bu} and down beat frequency f_{bd}. The range beat frequency $f_r = 0.5|f_{bd} + f_{bu}|$ is caused by the TV range and the Doppler frequency $f_D = 0.5|f_{bd} - f_{bu}|$ is caused by difference in velocities between SV and TV. The range R and relative velocity V can be defined in the following form:

$$R = \frac{cTf_r}{2B}, \tag{9}$$

$$V = \frac{cf_D}{2f_c}, \tag{10}$$

where B is the bandwidth of FMCW radar; f_c is the center frequency; T is the period of up-chirp and down-chirp waveform. The estimation performance depends on measuring f_{bu} and f_{bd}. FMCW radar is usually used for all radar ranges because it can be easily employed and the requirements for antenna power are lower in comparison with other radar sensor systems when the accuracy of measurement is high. Recently, Bosch Inco introduced the 77 GHz FMCW radar that is the third generation for LRR based on SiGe. Radar coverage of the second generation FMCW radar is 2 ~ 200 m. The operating range of the third generation FMCW radar is for about 0.5 ~ 250 m and the beamwidth has been increased approximately in two times [35].

Pulse Doppler Radar: In the present time, the UWB pulse Doppler radar is most widely used for SRR. Table 23 represents a relationship between the radar and appropriate area around the vehicle for SRR, MRR, and

LRR sensor systems. The pulse radar sensor system basic structure and used waveform are shown in Figs. 16, 17, and 18, respectively.

Table 23.

Radar range.

	Range	Radar System
SRR	less than 5 m	detecting rear and lateral
MRR	5 m~40 m	detecting rear and lateral and forward
LRR	40 m~over than 200 m	detecting forward

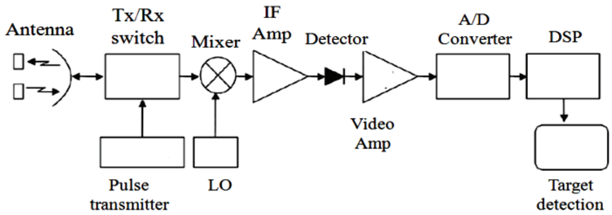


Fig. 16. General structure of pulse Doppler radar system.

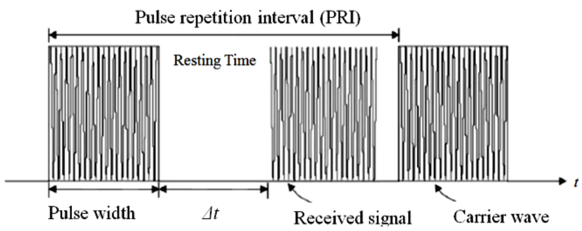


Fig. 17. Waveform used by the pulse radar system in time domain.

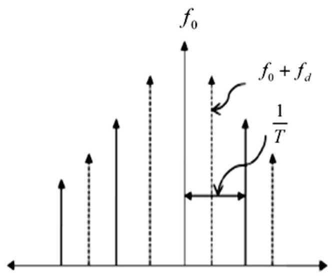


Fig. 18. Waveform used by the pulse radar system in frequency domain.

The pulse Doppler radar can define the relative velocity V and distance R' between the SV and TV using the time delay Δt of the target return signal and the Doppler frequency shift f_D

$$R' = \frac{c\Delta t}{2}, \tag{11}$$

$$V = \frac{cf_D}{\cos\theta \ f_c} \tag{12}$$

where f_c is the center frequency; θ is the angle between the measuring direction and moving direction of TV. In spite of the fact that the pulse radar has a high resolution performance, it is difficult to employ its hardware owing to the narrow pulse width. This disadvantage can be overcome using 79 GHz UWB radar system or SRR. Comparing the high frequency 79 GHz radar sensor system with the lower frequency 24 GHz one, we can see that the first has a better resolution sensitivity performance in comparison with the low frequency radar sensor system owing to the Doppler frequency shift that becomes considerable when the frequency is increased. Additionally, the pulse Doppler radar can be easily implemented in LRR. The weight and size of the pulse Doppler radar platform can be light and small. These are the main benefits of the pulse Doppler radar system.

SFPD Radar: SFPD radar sensor system [36] has a high resolution performance. SFPD radar system functioning is similar to the pulse Doppler radar system operation. SFPD radar system allows us to control a resolution performance by transmitting and receiving various arbitrary pulses at several stepped frequencies. The SFPD radar system flowchart and signal waveform are shown in Figs. 19 and 20, respectively.

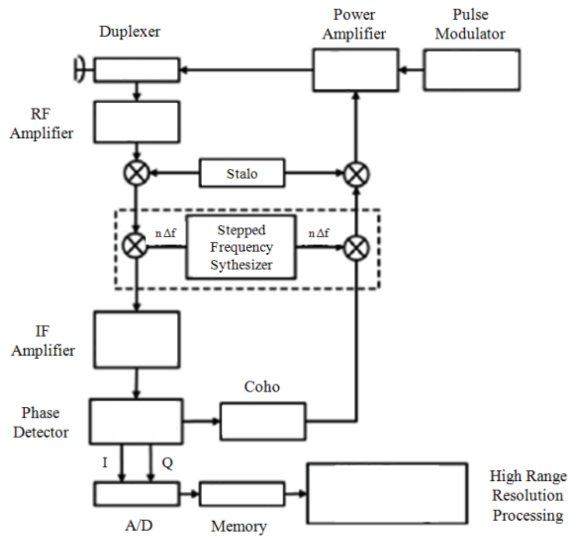


Fig. 19. Structure of SFPD radar system.

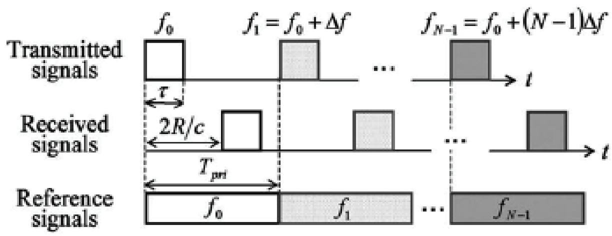


Fig. 20. SFPD radar system signal waveform

The received stepped frequency signal is given by

$$A_1 \cos 2\pi (f_c + n\Delta f)\left(t - \frac{2R}{c}\right) =$$

$$= A_1 \cos\left[\{2\pi (f_c + n\Delta f)t\} - 2\pi (f_c + n\Delta f)\frac{2R}{c}\right]. \tag{13}$$

The process at the in-phase (I) and quadrature (Q) channel outputs can be presented in the following form:

$$I = A\cos\left[-2\pi f_n \frac{2R_{NM}}{c}\right] = A\cos\left[2\pi f_n \frac{2R_{NM}}{c}\right], \tag{14}$$

$$Q = A\sin\left[-2\pi f_n \frac{2R_{NM}}{c}\right] = -A\sin\left[2\pi f_n \frac{2R_{NM}}{c}\right], \quad (15)$$

$$f_n = f_c + (N-1)\Delta f\ , \quad (16)$$

$$R_{NM} = R_0 + V_r t_{NM}\ , \quad (17)$$

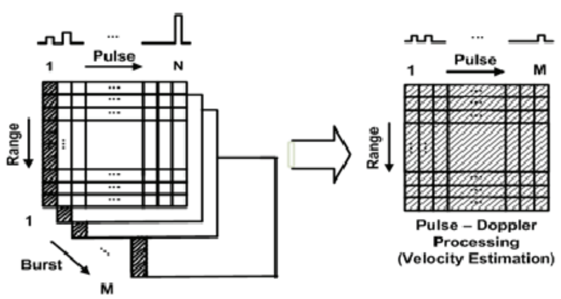
$$t_{NM} = (NM-1)PRI + \frac{2R_0}{c} + \frac{T_P}{2}\ , \quad (18)$$

where n is the number of pulses, N is the order of received pulses, M is the order of pulse burst, T_p is pulse duration, f_c is the carrier frequency of radar system, Δf is the stepped frequency, V_r is the relative target velocity, and t_{NM} is the sampling period. Equation (18) is the received stepped frequency model. To define the velocity and range with high accuracy, the following algorithm is represented by Figs. 21 and 22. Figures 21a and 22a illustrate the signal processing algorithm to define the relative velocity estimation. Defining the Doppler frequency, we are able to measure the TV relative velocity applying the Fast Fourier Transform (FFT) after extracting the frequency of 16 pulse bursts. Figures 21b and 22b illustrate the signal processing algorithm to define the TV range. After integrating 16 stepped-pulses and comparing a compensating measurement of the SV velocity and the relative velocity between SV and TV that is estimated in advance we can measure the TV range after applying the Inverse Fast Fourier Transform (IFFT).

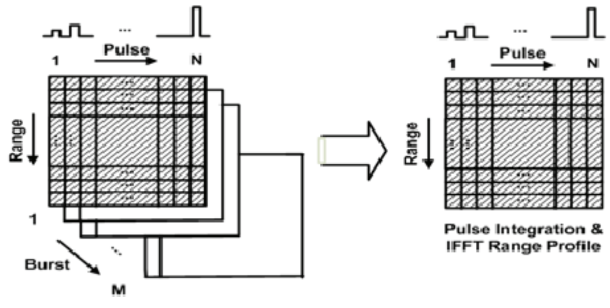
The main benefit of the SFPD radar system is a high resolution performance in the case of large pulse duration in comparison with the pulse Doppler radar sensor system. The SFPD radar system has a disadvantage in accuracy to measure the TV range and relative velocity owing to the range-Doppler effect, i.e. the radial velocity may cause the shifted TV range estimate and both the TV range position and radial velocity cannot be correctly retrieved using the inverse discrete Fourier transform (IDFT) [87-89]. This disadvantage can be overcome using the high pulse repetition frequency. Table 24 represents a set of parameter for the FMCW, Pulse Doppler, and SFPD radar sensor systems when the TV range is for about 150 m.

Table 24.
The main parameter of FMCW, pulse Doppler, and SFPD radar sensor systems.

Parameter	FMCW	PD	SFPD
Detection Range	150 m	150 m	150 m
Range Resolution	1 m	1 m	0.625 m
Bandwidth	0.15Ghz	0.15GHz	0.24 GHz
Dwell time	7.2 ms	7.2 ms	0.72 ms
Pulse width	-	6.7 ns	50 ns
PRF	-	71 kHz	355 kHz

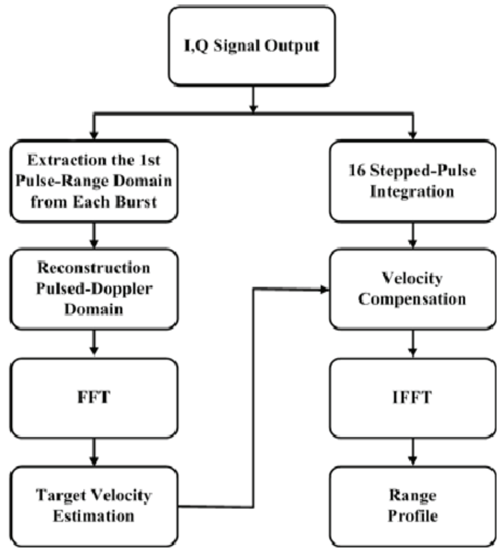


a)



b)

Fig. 21. Stepped-frequency pulsed-Doppler signal processing algorithm: a – signal processing algorithm to define the TV velocity; b – signal processing algorithm to define the range of target vehicle.



a) b)

Fig.22. Stepped-frequency pulsed-Doppler signal processing algorithm block diagram: a – signal processing algorithm to define the relative velocity; b – signal processing algorithm to define the range.

<u>FSK Radar:</u> The functional principle of FSK radar sensor system is similar with the FMCW one. This radar sensor system uses the FSK modulation technique instead of FM chirp [37]. The FSK signal waveform is shown in the Fig. 23. FSK radar system parameters are also the same as the FMCW radar one under measuring the TV range and relative velocity. In the case of FSK radar system, it is possible to use the phase $\Delta\varphi$ of the target return signals. The TV range can be defined in the following form:

$$R = \frac{c\Delta\varphi}{4\pi\ f_{STEP}}\ . \quad (19)$$

Under comparison of the phase $\Delta\varphi$ at different frequencies, the FSK radar system can directly extract the phase information. This is a great advantage of FSK radar system. If there are several TVs, the performance of resolution and accuracy is decreased. This is the main disadvantage of FSK radar system. Table 25 represents a comparison between the pulse Doppler, FSK, and FMCW radar sensor systems.

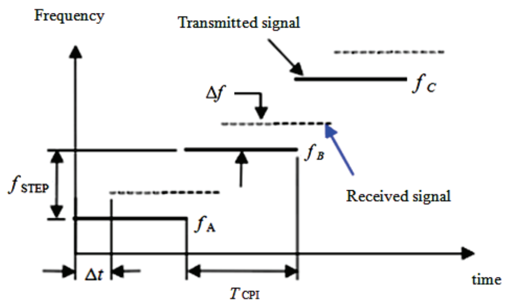


Fig. 23. FSK signal waveform.

Table 25.
Comparison of the pulse Doppler, FSK and FMCW radar systems.

Criteria	PD	FSK	FMCW
Range resolution Quality of velocity	Good	Average	Good
Measurement	Average	Good	Average
Fixed obstacle detection	Good	Poor	Good
Robustness to jamming	Poor	Good	Good

<u>*Spread Spectrum Radar for Intelligent Cruise Control*</u>: This radar sensor system ensures the TV range for about 100 meters and 3-beam switched antennas for detection of TV directions. There are some kinds of radar systems based on the MMW radars using the spread spectrum (SS) modulation. These systems have superior performance compared with others in the following: accuracy of ranging, sensitivity, target separation (multivehicle detection), accuracy of power estimation, interference suppression. The detection performance of TV direction and velocity depends on the power estimation accuracy.

In the case of direct sequence SS (DS/SS) modulation with a bandwidth of 480 MHz, the only antenna is used for transmission and three antennas are used for receiving. The receive antennas have different tilts to sector or divide the observation area. The detectable relative velocity between the SV and TV lies between (-200) km/h and (+200) Km/h. Data update is carried out every 50 msec.

<u>*Signal Processing features*</u>: The radar system employs three signal processing algorithms: detection algorithm; tracking algorithm; TV direction and range estimation algorithm. The TV range and directions are detected using the algorithm of the TV range and direction estimation algorithm employing the multibeam antennas. The algorithm of estimation of the TV range and direction power uses the same TV target return signal in each beam.

<u>*Random Noise Radar:*</u> Random noise radar system uses the noise waveform as a signal source. The random noise radar system can measure the relative velocity and distance between the SV and TV [38], [39]. The transmitted signal is delayed and correlated with the target return signal. Flowchart of random noise radar system is presented in Fig. 24.

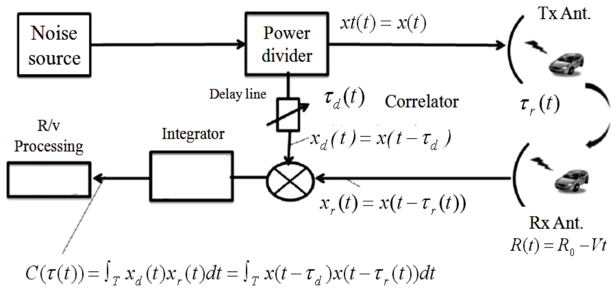


Fig. 24. Simple flowchart of random noise radar system.

Consider the noise radar system with the correlated target return signals. The CW noise generated by the noise generator is radiated using the transmit antenna. Part of this signal is taken via directional coupler and serves as a reference signal. Both the radar return and reference signals are converted coherently down into the intermediate frequency band (IF-band) using the coherent two-channel converter that is formed by a local oscillator and two radio frequency (RF) mixers. The IF reference signal is delayed and multiplied by the IF radar return signal. The low pass filter is used to define a cross-correlation between the reference and target return signals multiplied by each other before. Mathematically these operations can be presented in the following form. The cross-correlation function between the reference $X(t-\tau^*)$ (the transmit noise waveform delayed by the noise radar delay line), and the target return signal $X(t-\tau)$ is given by:

$$R(\tau_0) = \lim_{T\to\infty} \frac{1}{T} \int_{-0.5T}^{+0.5T} X^*(t) X(t-t_0) dt, \qquad (20)$$

where $\tau_0 = \tau^* - \tau$ and $\tau = \dfrac{2R}{c}$ is the time of signal propagation; R is the distance between the SV and the TV. In the case of random stationary signal, we can apply the Wiener-Khintchin formula:

$$R(\tau_0) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} |F(f)|^2 e^{-i2\pi f \tau_0} df\ , \qquad (21)$$

where $F(f)$ is the noise waveform Fourier spectrum.

Random stationary signal has the frequency spectrum in the form of Gaussian pulse with 3dB bandwidth B and is centered about the frequency f_c . Thus, we can write:

$$|F(f)|^2 = \exp\left[-\frac{(f-f_c)^2}{B^2}\right]. \qquad (22)$$

Substituting (22) into (21), we obtain:

$$R(t_0) = B\sqrt{\pi} \exp\left[-(\pi\tau_0 B)^2 - i2\pi f_c \tau_0\right] = \frac{\sqrt{\pi}}{\tau_c} \exp\left[-\left(\frac{\pi\tau_0}{\tau_c}\right)^2 - i2\pi f_c \tau_0\right], \qquad (23)$$

where $\tau_c = \dfrac{1}{B}$ is the correlation decay time of random signal. As we can see from (20) to (22), the wide power spectrum of the random signal bandwidth B provides the fast decay of correlation and, thereby, independent regulation between three important radar characteristics: the probe signal compression rate (20), the optimal signal processing of radar returns (21), and the minimization of radar ambiguity function side-lobe (22). The random noise radar system is robust with respect to interference caused by other neighboring vehicles that can be processed with high resolution performance and can measure the relative velocity and target range of various TVs simultaneously. The random noise radar system can be appropriate for SRR owing to good ElectroMagnetic Compatibility (EMC) property and high Low Probability of Intercept (LPI) with the performance. However, it is difficult to use the noise waveform radar system to require the bandwidth within the MMW band.

3. RADAR SIGNAL PROCESSING ALGORITHMS

The waveform design is an innovative topic and new research results for special applications as automotive radars are available. The TV range and velocity have to be measured simultaneously with high resolution and accuracy even in multitarget situations and are important parameters for any car applications. Automotive radar systems must have the ability to measure the range, velocity, and azimuth angle at the same time for all TVs inside the radar coverage. The short measurement time, even in dense TV situations, high range resolution, and accuracy are required for all car applications. The radar signal processing philosophy adapted for MMW radars is to maximize the TV information processed by MMW radar sensor system. Signal processing algorithms have to be associated with MMW radars in addition to TV detection and ranging and include the coherent and non-coherent Doppler processing techniques to achieve the moving target identification, Stationary Target Identification (STI) technique, for example, CFAR, clutter decorrelation, high range resolution, and polar metric techniques to extract target geometrical features to achieve STI.

In a general case, any kind of radar sensor system for car applications has one or more output parameters, namely: the TV range, velocity, and azimuth angle, the target acceleration, and the target height. This kind of radar sensors are classified as the type of collected data radars, namely, the range (delay of target return signal), azimuth (beam pointing of antenna beam, amplitude of target return signal), elevation (only for 3D radar, multifunctional tracking), height (derived by range and elevation), intensity (the target return signal power), Radar Cross Section (RCS) derived by the target return signal intensity and range, the radial velocity (measurement of differential phase along the remaining time of radar beam on a target owing to the Doppler effect; it requires a coherent radar), the polarimetry (the target return signal phase and amplitude in the polarization channels: HH–horizontally transmitted, horizontally received - HV, VH, VV), the RCS profiles along the range and azimuth (the high resolution along the radar range, the imaging radar).

Radar Signal Processing can be defined as extracting a desired information from the target return signal. By other words, any radar system makes a decision about the presence or absence of targets cancelling interferences caused by various sources. Whatever the radar system, the basic operations performed by the signal and data processors are the detection of targets and extraction of information from the received waveform to determine a wealth of relevant parameters of the targets, such as the position, velocity, shape, etc. The first step of radar sensor system design can be recognized as a formulation of mathematical models more adherent to the real environment, in which the radar sensor system operates. Several major areas of research and development can be singled out in connection with radar detection: the theory of optimum detection, the adaptive detection theory, and the detection of signals processing the non-Gaussian probability density function (pdf), the multidimensional signal processing, and the super resolution algorithms. The main concept of *Data Processing* is the tracking system for specific targets. The tracking filter processes the target radar measurements, e.g. the range, azimuth, elevation, and range rate, in order to achieve the following purposes, namely, to reduce the measurement errors by means of a suitable time average, to estimate the TV velocity and acceleration, and to predict a TV future position.

3.1 Linear FMCW Radar

Radars using the LFM technique [37] modulate the transmit frequency by a triangular waveform (see Fig. 25) The f_{sweep} value of the oscillator defines the range resolution by the following equation:

$$\Delta R = \frac{c}{2 f_{sweep}} . \tag{24}$$

A typical value f_{sweep} =150 MHz for the bandwidth is to achieve a range resolution of ΔR = 1 m.

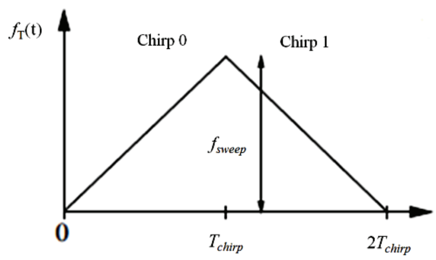


Fig. 25. FMCW radar waveform.

A single sweep of LFM waveform gives the measured values of the TV range and relative velocity. The target return signal is sampled and the Fourier transform is applied within the limits of a single CPI. Thus, if a spectrum peak is detected at index k in the Fourier spectrum, the normalized integer frequency, the TV range and velocity can be defined by the following equation

$$K = \frac{V}{\Delta V} - \frac{R}{\Delta R} \underset{so}{\Leftrightarrow} \frac{V}{\Delta V} = \frac{R}{\Delta R} + K , \tag{25}$$

where ΔV is the velocity resolution resulting from the CPI duration by

$$\Delta V = \frac{\lambda}{2T_{chirp}} . \tag{26}$$

Many measurements with different chirp gradients in the waveform are necessary to achieve the required range and velocity measurement values. The LFM waveform can be used even in multitarget environments, but the extended measurement time is an important drawback of this LFM technique.

The Angular Position is a characteristic of radar sensor network signal processing algorithms. The angular position of each TV is defined by means of multilateral techniques based on the specific measured TV range within the limits of radar sensor network. This technique is to derive the desired TV position by calculating the intersection point of all TV range measures using different radar sensor positions.

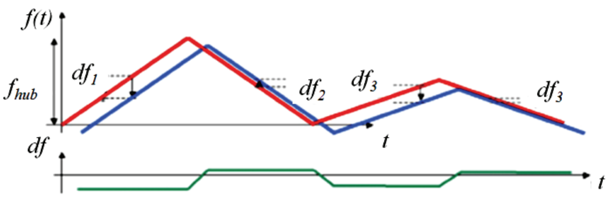


Fig. 26. FMCW radar waveform (red) and the corresponding target return signal (blue) for a single target.

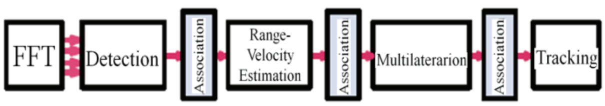


Fig. 27. FMCW radar signal processing.

Single Sensor Signal Processing: The linear FMCW waveform consists of four individual chirp signals (see Fig. 26). This waveform combines the high accuracy measures in the TV range and velocity and reliable TV detection in multitarget situations. Four individual chirps provide sufficient redundancy in multitarget or extended TV situations to suppress ghost TVs under the range and velocity processing. For each individual chirp signal the beat frequencies df_1, df_2, df_3, df_4 are estimated by FFT. The FMCW radar signal processing system is structured into the following different independent blocks (see Fig. 27): the beat frequency estimation based on FFT; the target detection Constant False Alarm Rate (CFAR); the TV range and velocity processing; the multilateral technique to define the TV azimuth angle, and for the tracking purposes. After CFAR detection, each signal processing block contains an independent association procedure to combine measurements from different chirps and radar sensors for one or multitarget vehicles. The detection process is based on four detected beat frequencies ($f_{c,s}$) per one TV and the FMCW waveform with four individual chirp signals. Thus, a single TV that is detected by radar sensor network will have $4 \times N$ beat frequencies, where N is the number of sensors in the network. In the case of $N = 4$, the radar sensor network will lead to 16 beat frequencies at the FFT device output and these beat frequencies could be combined into the vector describing all available information for every TV. This vector can be defined in the following form:

$$\boldsymbol{m}^f = \left[f_{1,1}, f_{2,1}, f_{3,1}, f_{4,1}, \ldots, f_{1,4}, f_{2,4}, f_{3,4}, f_{4,4}\right]^T . \tag{27}$$

Range and Velocity Calculation: Each beat frequency contains a definite information about the TV range and velocity, and, also, each TV with the range R_s and velocity V_s leads us to have a special beat frequency for every chirp signal of the waveform. The following linear equation relates the beat frequency and the TV range and velocity:

$$f_{c,s} = a_c R_s + b_c V_s , \tag{28}$$

where the parameters a_c and b_c depend on chirp characteristics such as the chirp duration, bandwidth, and carrier frequency [40]. Applying the intersection process, the TV range and velocity can be derived from four beat frequencies measured by a single sensor. In this network, each sensor has a position and determines individual values for the TV range and velocity based on four measured beat frequencies. Thus, all the measurements can be defined using the following parameter vector:

$$\boldsymbol{m}^t = \left[\underbrace{R_1, V_1}_{sensor1}, \ldots, \underbrace{R_4, V_4}_{sensor4}\right]^T . \tag{29}$$

A set of linear equations can be derived to describe a relation between the beat frequencies and all sensor specific TV range and velocity parameters:

$$\boldsymbol{m}^f = \boldsymbol{C}\boldsymbol{m}^t . \tag{30}$$

Signal Processing by Radar Network: The main purpose to use the radar sensor network is to define the azimuth angle, i.e. the target position in the Cartesian coordinates, for every TV based on the range measures by each radar sensor of the network, and, also, to implement a tracking procedure that is a part of signal processing algorithm employed by the radar sensor network. To obtain the TV position and velocity we should apply the *multilateral procedure*. In this case, the TV state vector in the Cartesian coordinate system takes the following form:

$$\vec{t} = \left(t_x, t_y, V_x, V_y\right)^T . \tag{31}$$

Based on the sensor specific range and velocity measurements for every TV, this state vector can be estimated if the position of selected sensor in the SV radar network is known

$$\vec{s} = (s_x, s_y)^T . \tag{32}$$

Assuming that the TV and radar sensor positions in the Cartesian coordinate system are known, the TV range can be determined by

$$R_s = \sqrt{\left(t_x - s_x\right)^2 + \left(t_y - s_y\right)^2} . \tag{33}$$

The TV velocity can be determined in the following form:

$$V_s = \frac{t_x - s_x}{R_s} V_x + \frac{t_y - s_y}{R_s} V_y . \tag{34}$$

The combination of all previous equations leads us to the following nonlinear equation

$$\boldsymbol{m^t} = \boldsymbol{h}(\boldsymbol{t}) . \tag{35}$$

The Jacobian matrix can be defined as:

$$H_{t_0} = \left. \frac{\partial h(t)}{\partial t} \right|_{t=t_0} . \tag{36}$$

This matrix is used by the iterative Gauss-Newton algorithm to estimate the TV position in the Cartesian coordinate system.

Linear FMCW Parameters Direct Calculation: Now, we discuss the measure procedure of the TV range in the case of CW radar sensor systems that can be accomplished by the frequency modulation (FM) of transmitted waveform [10]. The FMCW technique operates by changing continuously the transmitted signal frequency in some predetermined special form (see Fig. 28).

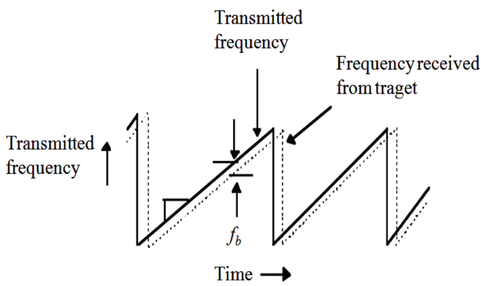


Fig. 28. FMCW saw-tooth waveform.

For the linear FMCW (LFMCW) radar sensor systems, the transmitted signal frequency is ramped by a linear waveform, for example, the saw-tooth between values f_1 and f_2. At any instant, the target return signal has a different frequency in comparison with the transmitted signal by value related to the TV range and frequency of deviation (the ramp frequency). The target return signal has the same shape (replica) as the transmitted signal but it is delayed by two propagation ways and has different frequency because the transmitter has changed the frequency and the transmitted signal needs to travel to the TV and come back to the receiver. The propagation delay t is given by $t = \frac{2R}{c}$. To obtain the TV range we must determine the frequency difference between the transmitted and target return signals. The beat frequency can be introduced in the following form:

$$f_b = \frac{2\Delta F R}{T_m c} , \tag{37}$$

where ΔF is the frequency deviation or the swept bandwidth, and T_m is the modulation period. These two values are ordinary held constants. The TV range can be determined in the following form:

$$R = \frac{T_m c}{2\Delta F} f_b . \tag{38}$$

For any radar waveform the ideal range resolution ΔR_0 is linearly proportional to the time resolution Δt and inversely proportional to the bandwidth ΔF of the transmit waveform

$$\Delta R_0 = \frac{c\Delta t}{2} = \frac{c}{2\Delta F} , \tag{39}$$

where Δt is the time resolution and ΔF is the bandwidth of the transmit waveform. Note that the range resolution depends only on the frequency deviation (sweep bandwidth).

In practice, the range resolution can be defined by the following formula

$$\Delta R = \frac{T_m c}{2\Delta F} \Delta f_b , \tag{40}$$

where Δf_b is the beat frequency resolution produced by the receiver. The beat frequency resolution is inversely proportional to the modulation period that is less than the round trip propagation time t

$$\Delta f_b = \frac{1}{T_m - 1} . \tag{41}$$

Range Doppler Coupling (*Moving Target*): For any moving TV the beat frequency depends on the TV range and velocity and can be presented as

$$f_b = -\frac{2\Delta F R}{T_m c} + \frac{2Vf}{c} . \tag{42}$$

The second term in (42) is the Doppler frequency shift, V is the TV velocity, and f is the nominal radar frequency (operation frequency). To determine the TV range we should introduce the beat frequency f_{b1} during the upsweep part of the ranging cycle as given by

$$R = \frac{T_m c}{2\Delta F} f_{b1} , \tag{43}$$

where $\frac{T_m c}{2\Delta F}$ is called the FM linear sweep rate in Hz/sec. In the case of moving TV, the Doppler shift makes a great contribution to define the TV range. However, under determination of the TV range we face difficulties caused by errors. To solve this problem the waveform should be modified in such a way that the radar sensor system would have two frequency slopes. In other words, the equal up-slope and down-slope linear sweeps must be used by the triangle waveform (see Fig. 29). For this waveform the beat frequency can be defined as

$$f_{b_{triangle}} = \frac{4\Delta F f_m R}{c} = \frac{4\Delta F R}{T_m c} , \tag{44}$$

where f_m is the modulation frequency and T_m is the modulation period. Note that there is an additional factor 2 in the numerator, since the period of the triangle wave consists of up-sweep and down-sweep components. For the triangle waveform, the TV range is linearly proportional to the up-sweep and down-sweep beat frequencies and the TV velocity is also proportional to the sum of these frequencies. As to moving TV case, the target return signal contains the Doppler shift and the frequency shift owing to delay. This frequency shift should be subtracted from the Doppler frequency in the case of positive slope if TV approached to SV and should be added in the case of negative slope (down-sweep). Thus, we can separate the beat frequencies on f_{d+} in the case of the positive (up-sweep) slope and f_{d-} in the case of the negative (down-sweep) slope portions of the ranging cycle:

$$f_{b+} = -\frac{4\Delta FR}{T_m c} + \frac{2Vf}{c} \quad \text{and} \quad f_{b-} = \frac{4\Delta FR}{T_m c} + \frac{2Vf}{c}. \quad (45)$$

The TV range is given by

$$R = \frac{T_m c}{8\Delta F}(f_{b-} - f_{b+}). \quad (46)$$

The TV velocity can be defined in the following form:

$$V = \frac{c}{4F}(f_{b-} + f_{b+}). \quad (47)$$

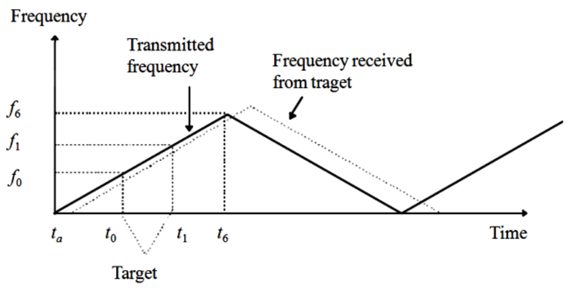


Fig. 29. Triangular waveform FMCW radar system.

<u>*Linear FMCW Signal Analysis*</u>: To estimate the TV range and velocity there is a need to use the saw-tooth modulation. In this case, the target return signal is delayed and we have the Doppler shift copy of transmitted signal. After mixing these two signals, the beat frequency (the beat signal) is filtered and processed. Assume that the signal is transmitted by the FMCW radar sensor system within the limits of the time interval $[0, T_s]$. Then the linear frequency modulation takes the form [12]:

$$s(t) = e^{j\varphi(t)}, \quad (48)$$

where $\varphi(t)$ is the signal phase described by the second order time polynomial

$$\varphi(t) = a_0 + a_1 t + a_2 t^2. \quad (49)$$

The signal frequency is given by

$$f(t) = \frac{a_1 + a_2 t}{2\pi}. \quad (50)$$

We can see that

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt}, \quad (51)$$

where $\frac{a_1}{2\pi}$ is the starting carrier frequency f_c, $\frac{2a_2}{2\pi}$ is the slope of the frequency modulation, and the signal bandwidth is defined as

$$BW = \frac{2a_2 T_s}{2\pi}. \quad (52)$$

The signal processed by the radar sensor system can be presented in the following form:

$$y(t) = s(t)s^*(t-\tau) = Y_0 e^{j(b_0 + b_1 t)}, \quad (53)$$

where the delay τ is defined before, Y_0 is the return signal amplitude, and the parameters b_0 and b_1 are defined in the following form:

$$b_0 = a_1\tau - a_2\tau^2, \quad (54)$$

$$b_1 = 2a_2\tau^{-1}. \quad (55)$$

To detect various TV ranges we use FFT taking into consideration that the beat frequency is harmonic. When the TV is moving the TV range and the delay are changed as a function of time that causes a change in the starting phase of the beat signal for each saw-tooth modulation and, also, shifts the beat frequency. The TV range and velocity can be computed by 2D-FFT. The first dimension is related to the fast time, the time within each saw-tooth modulation, and gives a pseudo range. The second dimension is related to the slow time, the saw-tooth count and gives the target velocity. The true range is computed by correction of the pseudo range using the velocity information. The FMCW radar sensor system can also be used to detect and estimate the TV acceleration [41]. The constant acceleration for any TV produces the second order time polynomial for the starting phase of each saw-tooth beat signal. Using the generalized chip transform (GCT) or polynomial phase transform (PPT), it is possible to estimate the TV range and velocity in addition to the TV acceleration.

Another analysis and presentation for the FMCW radar sensor system could be helpful to understand the way to apply 2D-FFT or any other kind of algorithms based on a special shape for the transmitted waveform (the ramp with different slopes) [42]. The basic idea is to generate a linear frequency ramp with bandwidth B (for a single ramp) and duration T within the limits of the interval $[-0.5T,\ 0.5T]$. In this case, the frequency can be defined as

$$f_T(t) = f_c + \frac{B}{T}t. \quad (56)$$

The transmitted signal phase cos $\varphi_T(t)$ can be determined in the following form:

$$\varphi_T(t) = 2\pi\int_{-0.5T}^{t} f_T(t)dt = 2\pi\left(f_c t + \frac{1}{2}\frac{B}{T}t^2\right) - \varphi_{T_0}. \quad (57)$$

The phase of the down converted signal is given by:

$$\Delta\varphi(t) = \varphi_T(t) - \varphi_T(t-\tau) = 2\pi\left(f_c\tau + \frac{B}{T}t\tau - \frac{B}{2T}\tau^2\right). \quad (58)$$

Based on the condition $\tau/T << 1$, the last term is (58) can be neglected. The delay τ can be defined as

$$\tau = \frac{2(R+Vt)}{c}. \quad (59)$$

We can rewrite the last equation in the following form:

$$\Delta\varphi(t) = 2\pi\left[\frac{2f_cR}{c} + \left(\frac{2f_cV}{c} + \frac{2BR}{Tc}\right)t + \frac{2BV}{Tc}t^2\right]. \quad (60)$$

The last term in (60) is called the range-Doppler coupling and can be neglected. Thus,

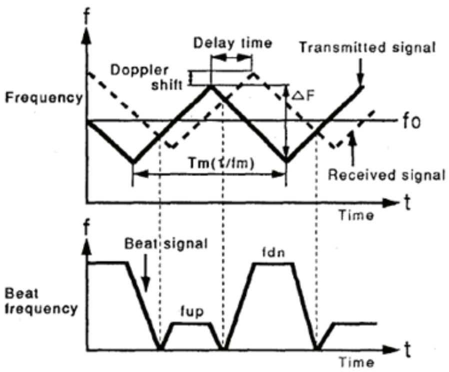
$$\Delta\varphi(t) = 2\pi\left[\frac{2f_cR}{c} + \left(\frac{2f_cV}{c} + \frac{2BR}{Tc}\right)t\right]. \quad (61)$$

The generated frequency can be determined as

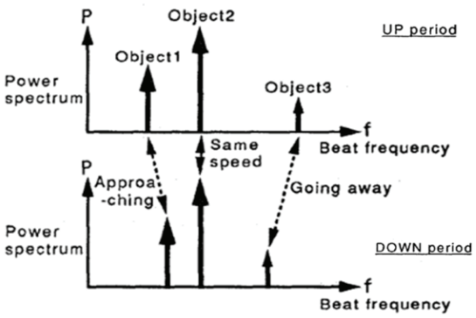
$$f_{IF} = \frac{2f_cV}{c} + \frac{2BR}{Tc}. \quad (62)$$

The received signal $S_{IF} = \cos\Delta\varphi(t)$ is sampled within the limits of the interval T_A and the samples are multiplied by the window function before the FFT is done. In signal processing, the window function is a mathematical function that is zero valued outside of some chosen interval and can be used for spectral analysis.

The above mentioned discussion is summarized by Figs. 30a and b. Figure 30a shows a general concept and Fig. 30b presents the obtained beat signal spectrum [43].



a)



b)

Fig. 30. a – functioning principle of FMCW radar; b – principle of beat signal spectrum.

Target Angle Detection: The monopulse principle [44] can be described by two antennas having the complex receive patterns $G_1(\alpha)$ and $G_2(\alpha)$. The distance between the antennas is *d*, as shown in the Fig. 31. The phase difference $\Delta\varphi$ for an incident plane wave takes the form:

$$\Delta\varphi = d\sin\alpha\frac{2\pi}{\lambda}, \quad (63)$$

where $\lambda = \frac{c}{f_c}$ is the wavelength caused by the carrier frequency f_c. In the case of monopulse angle detection, we can introduce the following ratio:

$$R_{mono} = \frac{\Delta(\alpha)}{\Sigma(\alpha)}, \quad (64)$$

where

$$\Delta(\alpha) = G_1(\alpha) - e^{-i\Delta\varphi}G_2(\alpha), \quad (65)$$

$$\Sigma(\alpha) = G_1(\alpha) + e^{-i\Delta\varphi}G_2(\alpha). \quad (66)$$

If the detection is based only to define the amplitude, R_{mono} is called the amplitude comparison monopulse. This approach uses two overlapping antenna beams. By this reason, the radiation patterns have slightly different searching directions. Based on the ratio R_{mono}, we can define the TV azimuth angle. If the antenna patterns G_1 and G_2 are identical, only the phase difference can be used for angle detection. This procedure is referred as the phase comparison monopulse or as the phase interferometry. In this case, the ratio R_{mono} takes the form:

$$R_{mono} = \frac{\Delta(\alpha)}{\Sigma(\alpha)} = \frac{1-e^{i\Delta\varphi}}{1+e^{i\Delta\varphi}}. \quad (67)$$

Under the use of phase monopulse technique, the phase difference $\Delta\varphi$ is evaluated in order to avoid the amplitude calibration required the amplitude monopulse technique. The angle of arrival or Direction of Arrival (DOA) is easily obtained by rearranging (63), i.e. using the following equality

$$\alpha = \sin^{-1}\left(\frac{\lambda\Delta\varphi}{2\pi d}\right). \quad (68)$$

The phase monopulse technique is preferred for 24 GHz systems because the antennas are implemented as patch antennas oriented in the same searching direction. The unambiguous angular range depends on the distance *d* between two receive elements:

$$\Delta\alpha = 2\sin^{-1}\left(\frac{\lambda}{2d}\right). \quad (69)$$

In the case of SRR, the unambiguous angular range should be very close to $\pm 90^\circ$. Therefore, the spatial sampling theorem has to be fulfilled and the antennas separation must be half of wavelength. For MRR and LRR radar sensor systems the spacing has to be chosen according to the transmit antenna beamwidth. An increased spacing between the receive antennas allows us to increase the size of the antennas and, consequently, the gain. Furthermore, this action results in a direct improvement of the angle measurement accuracy. However, in this case, we obtain an increased radar module size.

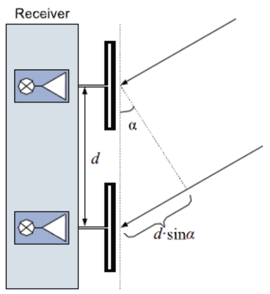


Fig. 31. Antenna array in receive mode.

3.2 FSK Radar

CW radar sensor system transmits continuously the signal with the known stable frequency and then receives the target return signal from any TV. The TV return frequencies are shifted relative to the transmitted frequency based on the Doppler effect if the SV and TV are moving with respect to each other. The main advantage of CW radar sensor systems is that the transmitted and target return signals are not pulsed and simple to produce. However, the transmitted and target return signals have also the disadvantage, namely, an ability to detect only the moving TVs, because the stationary TV is not a Doppler frequency shift case and the TV return signals are filtered out [23]. The CW waveform has to be modulated to measure the TV range. Two classes of CW waveform are well known: LFM and FSKCW waveform.

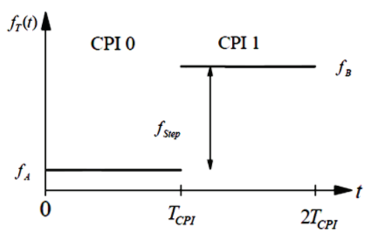


Fig. 32. FSK modulation principle.

Pure FSK Modulation Principle shown in Fig. 32 uses two discrete frequencies f_A and f_B, so called two measured frequencies, under transmission of the signal. Each frequency is transmitted within the limits CPI of the length T_{CPI}. The frequency step f_{Step} is small by value and can be considered as a function of the maximum unambiguous target range. In this case, the frequency step can be represented by the following form [45]:

$$f_{Step} = f_A - f_B , \qquad (70)$$

where f_A and f_B are two discrete frequencies. The phase shift in the receiver defined as $\Delta\varphi = \varphi_A - \varphi_B$ depends on two frequencies f_A and f_B and the TV range R can be presented in the following form [46]:

$$\Delta\varphi = e^{4\pi R(f_B - f_A)/c} = \varphi_A - \varphi_A . \qquad (71)$$

The TV range is given by

$$R = -\frac{c\Delta\varphi}{4\pi\ f_{Step}} . \qquad (72)$$

Pure LFM Principle: Radars sensor systems employing the pure LFM technique use the transmit frequency modulated by triangular waveform. The well known up- and down-chirp principle is shown in Fig. 25. The LFM waveform may be used in multitarget environment, too. In this case, the expanded measure time is an important drawback of the LFM technique [36]. The TV range resolution ΔR can be defined in the following form:

$$\Delta R = -\frac{c}{2 f_{Step}} . \qquad (73)$$

The TV velocity resolution ΔV is given by

$$\Delta V = -\frac{\lambda}{2T_{Chirp}} . \qquad (74)$$

Normalized integer frequency can be determined based on Eq. (25). The combination of FSK and LFM waveform design principles offers a possibility to measure the unambiguous TV range and velocity simultaneously. In this case, the transmit waveform consists of two linear frequency modulated up-chirp signals (the intertwined signal sequences are called A and B). Two chirp signals will be transmitted in an intertwined sequence ABABAB..., where the stepwise frequency modulated sequence A is used as a reference signal and the second up-chirp signal is a reference signal version shifted in frequency on the value f_{Shift}. The target return signal is down converted into the base band and directly sampled at the end of each frequency step. The combined and intertwined waveform concept is shown in Fig. 33. Each signal sequence A or B will be processed separately using the Fourier transform and conventional CFAR target detection techniques. Single TV with the specific TV range and velocity will be detected in both sequences at the same integer index $k = k_A + k_B$ in the FFT-output signal for two processed spectra. In each signal sequence A or B the same TV range and velocity ambiguities will occur as given by (74).

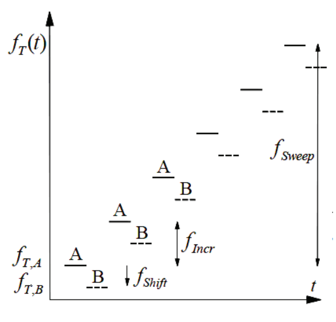


Fig. 33. Combined FSK-LFMCW waveform principles.

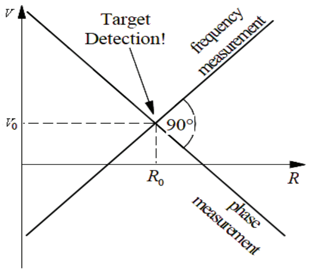


Fig. 34. Graphical resolution principle of ambiguous frequency and phase measurements.

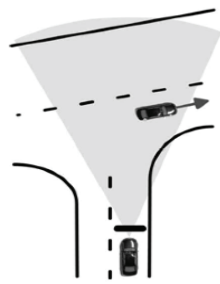


Fig. 35. Sketch of a crossroad-scenario.

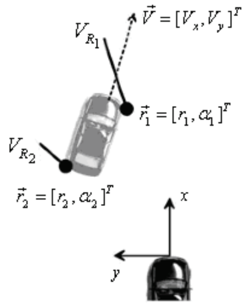


Fig. 36. Example for an extended target with several reflections.

The measured phases of two complex spectral peaks are different and include the fine target range and velocity information used for ambiguity resolution. Due to the coherent measurement technique in the sequences A and B, the phase difference $\Delta\varphi$ can be evaluated for the TV range and velocity estimation. The graphical resolution principle of ambiguous frequency and phase measurement technique is shown in Fig. 34. The measured phase difference $\Delta\varphi$ can be defined analytically in the following form:

$$\Delta\varphi = \frac{\pi}{N-1}\frac{V}{\Delta V} - 4\pi R\frac{f_{Shift}}{c}, \tag{75}$$

where N is the number of frequency steps or samples of the target return signal in each transmitted signal sequence A and B. The intersection point of two measurements shown in Fig. 34 gives us the unambiguous TV range R_0 and relative velocity V_0. Using (73) and (75), we can define the TV range R_0 and relative velocity V_0 in the following form:

$$R_0 = \frac{c\Delta R}{\pi} \times \frac{(N-1)\Delta\varphi - k\pi}{c - 4(N-1)f_{Shift}\Delta R}, \tag{76}$$

$$V_0 = \frac{(N-1)\Delta V}{\pi} \times \frac{c\Delta\varphi - 4k\pi \; f_{Shift}\Delta R}{c - 4(N-1)f_{Shift}\Delta R}. \tag{77}$$

<u>Lateral Velocity Estimation:</u> In typical city traffic situations, the radar measurement is also important. In this case, a lateral velocity component of each detected vehicle represents a great interest. Figure 35 shows an example of a typical city road situation when a car travels almost in lateral direction along a crossroad. The most common TV parameters that should be measured by any radar sensor system are the TV range and azimuth angle. Additionally, the radial velocity of each TV can be measured based on the Doppler effect. According to the direction of motion, the different reflection points generate various azimuth angles and radial velocities that can be resolved by high resolution spectral measurement. Figure 36 represents the considered geometrical situation when different reflection points on a single TV can generate various radial velocities. It is assumed that these TV reflections can be resolved by Doppler frequency measurement. The related azimuth angle can be measured by the classical monopulse technique.

Radar sensors are capable to measure the TV range and azimuth angle. They are also capable to measure the radial component for the TV velocity vector V based on the Doppler frequency shift f_D defined as

$$f_D = -\frac{2V_R f_c}{c}, \tag{78}$$

where V_R is the radial component of the TV velocity vector, defining the positive values with increasing in the TV range, f_c is the carrier frequency of the transmitted signal. The respective velocity resolution ΔV of a radar sensor is mainly affected by the time on target T and the radar wavelength λ [47]

$$\Delta V = \frac{\lambda}{2T}. \tag{79}$$

The radial velocity component V_R is a function of the velocity absolute value $|V|$, ϕ_i is the angle between the direction of movement and position of the TV radar (see Fig. 37).

$$V_{R_i} = |V|\cos(\phi_i) = \frac{<V, R_i>}{|R_i|}. \tag{80}$$

In a general case, the angle ϕ_i is unknown. The radial velocity components V_{R_i} can be presented as a function of the velocity components V_x and V_y, as well as the azimuth angle α_i, in the following form:

$$V_{R_i} = V_x\cos(\alpha_i) + V_y\sin(\alpha_i). \tag{81}$$

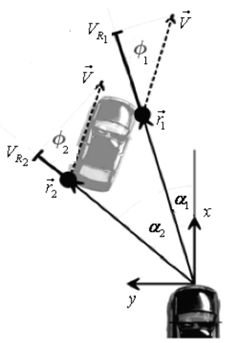


Fig. 37. Graphical representation of TV ranges and angles.

If the TV range and/or velocity resolution capability of the radar sensor system is high, the radar sensor will detect multiple reflection points positioned because a single vehicle changes its relative position (new TV position). Based on TV geometry and corresponding to the TV position without limits in the observation area, the new azimuth angle A_α of the observed TV can be evaluated based on a difference between the maximal $\alpha_{\max}$ and minimal $\alpha_{\min}$ target azimuth angles:

$$A_a(x,y) = \alpha_{\max}(x,y) - \alpha_{\min}(x,y) \,. \tag{82}$$

Combining (81) and (82), the position A_V defining a new velocity, i.e. the changed velocity A_V of the pointed out TV, can be presented in the following form:

$$A_V(x,y) = V_{R_i}^{\max}(x,y) - V_{R_i}^{\min}(x,y) \,. \tag{83}$$

New velocity is defined by a difference between the maximal and minimal radial velocities of TV traveling with the constant linear velocity vector within the limits of radar sensor coverage. In the case of simulation, the new TV velocity can be normalized by a length of actual TV velocity vector. This leads us to the normalized velocity $A_{V,\%}$:

$$A_{V,\%}(x,y) = \frac{A_{V,\%}(x,y)}{|V|} \,. \tag{84}$$

The measured target parameters of radial velocity and related target azimuth angle α_i for a single reflection point define an ambiguity line in the $V_x \times V_y$ area if (80), (81), (82), (83), and (84) are solved with respect to V_x, for example:

$$V_x(V_y, V_{R_i,\alpha_i}) = \frac{V_{R_i} - V_y \sin(\alpha_i)}{\cos(\alpha_i)} \,. \tag{85}$$

In the mathematical form, a set of equations can be given based on (81). If the vector $\mathbf{V}_\mathrm{M}$ contains the radial velocity measurements of N reflection points and the matrix $\mathbf{M}$ represents the measured TV azimuth angles, the objective function can be given in matrix notation as follows:

$$\mathbf{V}_M = \mathbf{MV} \tag{86}$$

or

$$\begin{bmatrix} V_{R_1} \\ V_{R_2} \\ \vdots \\ V_{R_N} \end{bmatrix} = \begin{bmatrix} \cos(\alpha_1) & \sin(\alpha_1) \\ \cos(\alpha_2) & \sin(\alpha_2) \\ \vdots & \vdots \\ \cos(\alpha_n) & \sin(\alpha_n) \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{87}$$

The solution of (87) gives us the desired TV vector including the radial and lateral components, at the least, for two detected reflection points per single TV.

3.3 Pulse Doppler Radar Systems

The main characteristics of the pulse Doppler radar system can be summarized in the following way: the pulse Doppler radar is the most widely used for SRR and the pulse Doppler radar has a high resolution performance. The pulse Doppler radar system can measure the TV range and velocity using the target return signal delay and Doppler frequency [31]. Based on the pulse parameter knowledge (see Fig. 17), we can define the resting time that is the time between the transmitted and target return pulses and the Pulse Repetition Interval (PRI) that is the time between two transmitted pulses. The basic signal processing algorithm in pulse radar sensor system is simple, but it requires to use the Fourier transforms many times to measure the Doppler frequency in each range gate. Usually, a complex signal processing is preferred using the in-phase and quadrature sampling. The coherent target return pulse train is received by the receiver and converted by the cosine and sine signals of the local oscillator. The target return signal is converted by the cosine and sine functions at the quadrature demodulator mixer. After low-pass filtering and sampling with the pulse repetition frequency f_{PRF}, the in-phase and quadrature signals take the following form [36]:

$$\text{In-phase:} \quad I(t_n) = 0.5p(t_n)\cos[2\pi f_d t_n], \tag{88}$$

$$\text{Quadrature:} \quad Q(t_n) = 0.5p(t_n)\sin[2\pi f_d t_n], \tag{89}$$

where

$$\begin{cases} p(t_n) = 2\sqrt{I^2(t_n) + Q^2(t_n)}, \\ \varphi(t_n) = \arctan\left[\dfrac{Q(t_n)}{I(t_n)}\right] . \end{cases} \tag{90}$$

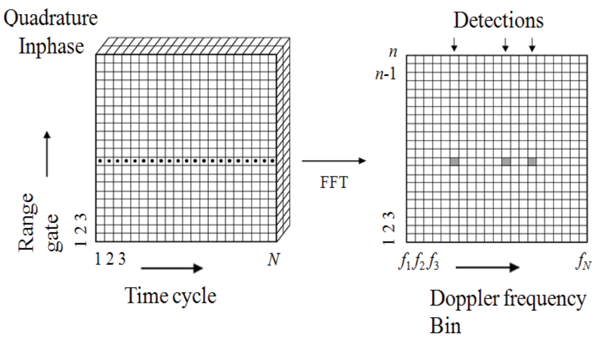


Fig. 38. Signal processing by pulse radar system.

Figure 38 shows the standard signal processing procedure for the pulsed radar sensor systems. Depending on the type of radar sensor systems and their pulse repetition frequency, the sampling frequency is set and all range gates are sampled using the in-phase and quadrature channels in the course of one scan. For a single range gate, the DFT is calculated using an implementation of the FFT [11] and [36]. The pulse number frequency f_N can be presented in the following form:

$$f_N = f_r + (N-1)\Delta f \ , \tag{91}$$

where f_r is the radar operation frequency; N is pulse number; and Δf is the stepped frequency. The sampling range R_{NM} can be presented in the following form:

$$R_{NM} = R_0 - V_r t_{NM} \ , \tag{92}$$

where R_0 is the ideal range, V_r is relative velocity, and t_{NM} is sampling time given by

$$t_{NM} = (NM-1)T_{PRI} + \frac{2R_0}{c} + \frac{T_p}{2} \ , \tag{93}$$

where M is the burst number, T_{PRI} is the pulse repetition interval, T_p is the pulse width, $T_p\Delta f < 1$. The difference in phase φ_n between the transmitted and target return pulses is presented in the following from:

$$\varphi_N = -4\pi f_N \frac{R_{NM}}{c} \ . \tag{94}$$

The TV range R and velocity V are defined as

$$R = \frac{c\Delta t}{2} \ , \tag{95}$$

$$V = \frac{\lambda \ f_D}{\cos\theta} \ , \tag{96}$$

where Δt is the target return signal delay, θ is the angle between the SV direction and TV moving direction, f_D is the Doppler frequency, and λ is the wavelength. The Doppler frequency f_D for the pulse Doppler radar system is given in the following form:

$$f_D = \frac{2V_r}{\lambda} = \frac{V}{\lambda}\cos\theta \ . \tag{97}$$

The relative velocity V_r between the SV and TV can be presented in the following form:

$$V_r = f_D \frac{2}{\lambda} = \frac{V}{2}\cos\theta \ . \tag{98}$$

Finally, the range resolution ΔR of the pulse Doppler radar system can be presented in the following form:

$$\Delta R = \frac{c}{2N\Delta f} \ . \tag{99}$$

4. EVALUATION AND DESIGN OF RADAR SIGNAL PROCESSING ALGORITHMS

4.1 The Design Steps

The process of signal detection algorithm design is an essential element to develop the digital signal processing (DSP) for car applications. To a large degree, the signal detection algorithm design has a significant impact on the performance and functionality of the radar sensor system. Radar engineers must define the mathematical function that is able to meet the application or the product requirements to ensure the signal detection algorithm compatibility. In the previous discussion and based on the extended analysis for the signal processing algorithm of different kinds of radar sensor systems, we could divide the signal detection process into three levels: *the first level* (the basic level) – the same for any radar sensor system; *the second level* – the waveform and the predefined parameter formulas; *the third level* – the signal defection and signal processing algorithms, the error correction and noise cancellation, and the radio frequency interference cancellation and so on. The main signal detection algorithm design stages are: the initial selection of prototypical algorithm; the manipulation and analysis of the selected algorithm; the exploration of input/output parameters; and the performance improvement description as a final result. The following design steps that can be presented in detail based on the baseline detector definition includes: the baseline detector proposed for initial selection framework of the signal processing algorithm and the symbolic and numeric description of the selected signal detection algorithm. Theoretical investigation includes the theoretical analysis of detection performance and improvement of signal processing algorithm for radar sensor systems. The signal detection algorithm design includes: the waveform design of the radar sensor system for CVD and BSD; the modification of the signal processing algorithm for required application; the false alarm management (adjust the threshold of the radar return signal power); the target detection – the probability of detection P_D of the target with a threshold given by the fixed probability of false alarm P_F; algorithms and any practical operations needed to eliminate the errors and cancel the interference and noise – for this purpose, there is a need to have a complete radar sensor system; the alternative signal detection algorithm description that means to find all the identity transformations applicable to the signal detection and processing; the computer costs under the use of signal detection and signal processing algorithms in radar sensor systems.

Performance Comparison: The final step in the process to design the signal detection algorithm is to confirm the performance improvement of radar sensor system in comparison with modern radar sensor systems for CVD and BSD.

Empirical Performance: The emphasis on signal detection and signal processing perspectives enables us to better understand the advantages and disadvantages of each signal detection and signal processing algorithm, avoid unrealistic performance expectations, and apply the system detection algorithm properly and sensibly.

4.2 Evaluation Framework

The radar sensor system specifications reflect a required level of operational performance, based on which several design concepts are generated. To compare the feasibility of the design concepts, it is necessary to derive the metrics of BSD and CVD to solve the practical problems and the weak points of the suggested radar sensor system and to catch or reach the acceptable performance level and considerable improvement. A significant trade-off among these signal detection and signal processing algorithms should be considered in order to evaluate the radar sensor system performance. A common evaluation framework allows us to compare different classes of signal detection algorithms in similar scenarios. The proposed evaluation framework can be summarized by the following key steps: the output parameters of every radar sensor system; the required input parameters for BSD and CVD; the signal detection and signal processing algorithms should provide the BSD and CVD with the required set of input variables related to the TV; the same operational frequency can be used for different radar sensor systems and for BSD and CVD; the possibility to meet the required performance level, namely, the TV range accuracy and resolution, the TV velocity accuracy and resolution, etc; the availability and the cost of the chosen radar sensor system based on the suggested signal detection and signal processing algorithms in the case of industry production; the flexibility of the chosen signal detection and signal processing algorithms to be designed and to overcome all the related problems to achieve the desired level of performance; the computational complexity and the measure time of the signal detection and signal processing algorithms; the radar sensor system ability to be integrated with other systems, in the case of idea to add more functions or to use more safety driving applications; the balancing between the gained benefits that are obtained from using the combined signal detection and signal processing algorithms and their related complexity, simplicity, and low cost; the system ability to be implementable avoiding the unrealistic performance estimation and accept any reasonable limitations. Application of these evaluation criteria to the signal detection algorithms employed by the radar sensor systems leads us to the final selection of the most suitable signal detection algorithm satisfying the requirements and specifications in BSD and CVD.

4.3 Technical Considerations

Radar is a robust technology in terms of its object detection capabilities in the sense of virtually unaffectability by lighting or weather conditions that can make worse the performance of other technologies such as LIDAR and laser systems. Unlike LIDAR collision mitigation systems that are primarily SRR city traffic systems, 24 GHz radar sensor system can detect vehicles at a range of 150m and can be effective at highway speeds. SRR units operating at 24 GHz require an operating range up to 30 meters and are used for a number of applications to enhance the active and passive safety for all kind of road users. Applications that enhance the passive safety include the obstacle avoidance, collision warning, lane line departure warning, lane line change aid, BSD, parking aid, and airbag arming. SRR applications which enhance the active safety include the stop and follow, stop and go, autonomous braking, firing of restraint systems, and pedestrian protection. The combination of these functions is also referred to as a "safety belt" for cars [22]. The SRR functions are intended to allow for a significant increase in safety, the saving of lives and avoiding damage of goods.

Myriad Possibilities: 24 GHz radar sensor systems create a foundation for full range of safety systems that provides a spectrum to support the driver abilities under combination with other technologies such as advanced electronic braking systems.

Forward Collision Warning: Technology has been identified by governments and automakers as an important opportunity to support drivers and reduce or mitigate accidents. It provides a visual, audible or haptic warning when a TV is determined to be close too fast to SV. The system reacts on moving vehicles, braking vehicles or stopped vehicles and larger objects, but it does not react to stationary objects below 10 km/h. It can be overridden if a driver uses the turn signal to indicate that they avoid the object or have initiated braking.

Forward Distance Warning: This is a higher speed function that is active over 20 km/h and is primarily used to warn drivers when they are too close to a vehicle (tailgating) and will warn them in two steps: once when the following time gap is determined to be below 0.9 seconds with relative vehicle speeds that are negative and the driver is not braking, and again at 0.54 seconds if the same conditions apply and braking has still not been activated.

Collision Mitigation Braking: Owing to the fact that 24 GHz radar sensor system offers a wider field of view than traditional 77 GHz radar, it is well suited to detect TV and relative distances between them under low speed city traffic and provide an assistance to help prevent rear end collisions. The collision mitigation braking system tracks both moving and stationary vehicles and objects and can automatically react to stationary vehicles when travelling is below 30 km/h. The system deceleration is limited to 0.5g with a maximum speed reduction of 15 km/h. The system can be overridden through driver action or can be cancelled if a danger is no longer considered to be critical.

Advanced Brake Assist: In this case, the 24 GHz radar sensor system data are used to determine potentially imminent collisions. If the driver's braking input is not sufficient to decelerate the vehicle and avoid a collision, the system will automatically provide break forces with high levels and deceleration. In emergency situations, the system can apply maximum brake force as quickly as possible when the driver initiates braking. Beyond the safety functions, 24 GHz radar sensor system can be used to enable convenience systems as well.

Adaptive Cruise Control (ACC): This system automatically adjusts the distance to TVs through a link to the engine throttle and braking systems to maintain a safety time gap (typically two seconds). When there are TVs the system acts as a standard cruise control holding the vehicle at a speed determined by the driver. This first generation system is active at 30 km/h and both above and below then the speed under which the driver must brake the vehicle to a stop.

Follow to Stop ACC: Further iterations of ACC include the follow-to-stop that will bring the vehicle to a full stop if the TV stops ahead. The driver must take action to initiate an acceleration and the system can be reactivated at the speed above 5 km/h.

Stop and Go ACC: This system enhances the ACC following to stop function with the capability to decelerate the SV down to a full stop and accelerate automatically again from standstill within a short period of time (typically three seconds). This system also checks an absence of impeding pedestrians or large objects behind the vehicle track before accelerating the SV following the TV.

The Road Ahead: The future for active safety and convenience systems should be a bright one as environmental sensing offers great possibilities that are not possible with indirect sensing alone. Since automakers, suppliers, and governments recognize a potential further, one of the challenges will make these systems both affordable and acceptable for consumers. The 24 GHz radar sensor system should be considered as a great step forward in bringing these systems to roadways around the globe. The 24 GHz SRR/MRR is a combination of two functions: the high resolution distance measurement to provide a speed information about the approaching object using the Doppler radar and wide-band radar to provide information about the position of TVs with a high resolution. The 24 GHz SRR/MRR technology allows a low-cost design and keeps the product size small enough to fit in the space available while providing the useful range resolution and object separation which is needed for object tracking in the Cartesian coordinate system. The data processing obtained by radar sensors provides the position of the TVs in the Cartesian coordinate system and can predict a possible crash impact point and the closing angle. Using this information the radar sensor system can alert the driver or can do counter measures to prevent collisions or to circumvent obstacles autonomously. At the present time, those SRR/MRR functions are not covered by other means or systems owing to installation, manufacturing and cost constraints.

Technical Considerations Based on Frequency: The car having sensing functions requires several individual SRR/MRR sensing units in the front, rear, and sideways with an approximate number of 16 units per vehicle but with limited overlapping beam characteristics. The 24 GHz band is considered as the best compromise for the functionality, performance, spectrum efficiency, cost, manufacturability, and integration in vehicle structures. The carrier of the SSR/MRR signal is allocated inside the 24 GHz within the limit of 24.050 GHz to 24.250 GHz. Selecting the 24 GHz band, manufacturers have taken the following factors into consideration, namely, the propagation loss at 24 GHz; the directed and narrowed beamwidth for elevation, as well as the very low power of the modulation sidebands. SRR/MRR sensors do not require a long range capability. Hence, the lower frequencies are preferred to enable the use of available microwave components used also in the telecommunication industry. At the present time, the 24 GHz technology seems to be the best trade-off between the component costs and sensor size. Typically, the SRR/MRR sensors do not measure the angle of detected objects but, as we mentioned before, it is possible by using many sensors. Therefore, the single antenna elements are sufficient. The beams are directed only vertically to increase the antenna gain and to minimize the clutter effects from road surface [17]. The SRR/MRR sensors operate using the pulsed mode or pulse Doppler, or using the CW mode, namely, CW, FMCW, FSK, FMCW & FSK as a rule. The coded radar sensor system with spread spectrum techniques i.e. the pulsed, CW, and pseudo-noise technique, is a common one. Under the use of SRR, the higher bandwidth is needed for the sufficient object radial TV range separation. The target range separation is inversely proportional to the occupied spectral bandwidth B_{occ}

$$\Delta r = \frac{kc}{B_{occ}}, \tag{100}$$

where Δr is the capability of a given radar sensor system to distinguish two objects with equally ideal reflective ability. The factor k can be set as $0.5 < k < 1$. The minimum target range separation Δr less then 0.05 m is needed if a definition of several TV positions in the Cartesian coordinate system using the sensor data fusion (2-D triangulation) needs a very precise target range information. This procedure requires a minimal bandwidth B_{occ} of 5 GHz.

Table 26.

Production of various companies.

No.	Company	Radar
1.	**Bosch**	FMCW
2.	**Continental TEMCI**	Pulse
3.	**Denso**	FMCW, Pulse
4.	**Hella**	FMCW
5.	**RodaEye**	FMCW
6.	**TRW Automotive**	FMCW
7.	**Valeo**	FMCW
8.	**Fujitsu TEN**	FMCW
9.	**ADC**	Pulse
10.	**Raytheon**	FMCW
11.	**Delphi**	FMCW
12.	**Honda elesys**	FMCW
13.	**Hitachi**	FSK
14.	**Hino**	FMCW
15.	**Philips**	FMCW
16.	**Lucas & Jaguar**	FMCW
17.	**Delco**	FMCW
18.	**Siemens**	FMCW, Pulse
19.	**TEMIC&DASA**	Pulse
20.	**Thomson-CSF**	FMCW

4.4 The Signal Detection Algorithms Comparison

Comparison of FMCW, Pulse, and FSK Radar Systems: We briefly summarize advantages and disadvantages for each radar sensor system. FMCW: *Advantages* are: the 100% duty cycle and the simple bandwidth implementation requirements. *Disadvantages* are: the high noise figure problem and the problem to isolate the transmit and receive antennas. PULSE: *Advantages* are: the signal detection and signal processing algorithms are simple. *Disadvantage* are: the TV detection problem for short distance blind range and the difficulties in implementation of narrow pulse width and the low duty cycle. FSK: *Advantages* are: the distance, velocity and angle information can be calculated directly. *Disadvantage* are: the high signal-to-noise ratio is needed at the receiver output, the problem to detect stationary objects, the problem to detect the moving object with the same velocities. In Table 26, we summarize the radar sensor system technologies employed by several companies [32], [48]. As we can see from Table 26, at the present time, most of companies employ the FMCW or Pulse radar sensor systems. Therefore, we consider the FMCW and Pulse radar systems as a favorable technology in details in order to decide what the radar sensor system is more suitable for BSD and CVD.

4.5 Comparison of FMCW and Pulse Radar Sensor Systems

Similarities: Each radar sensor system has to measure the TV range and azimuth angle and then present the final results to the user. Figure 39 illustrates a procedure of calculation by the FMCW and Pulse radar sensor systems [49]. The B Plane in Fig. 39 is a memory size addressed to the TV range and azimuth angle. There are several methods to measure the azimuth angle, namely, the beam steering by mechanical rotation and encoder or mechanical steering, the digital beam forming by transceiver array or electronics steering, the direction of arrival estimation by receive antenna array [50] and [51], the multimeasure by radar sensor array. Generally, the azimuth angle is determined based on knowledge where the antenna was pointed, when the target return signal had been received. Several radar sensor lobes are transmitted and analyzed. Then, the ratio of signal amplitudes or phases (this ratio is defined under the TV azimuth angle detection, Fig. 31) of the several radar sensor lobes provides the azimuth angular information. The TV range is determined by measuring the dwelling time between the transmitted and target return signals. Therefore, both radar systems, the FMCW and Pulse radar sensor systems, should measure the round trip delay.

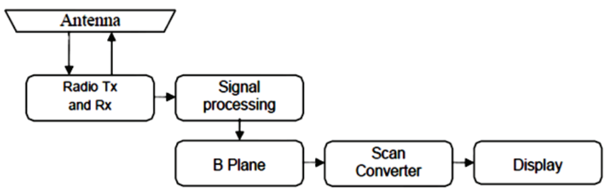


Fig. 39. Block diagram of typical radar sensor system.

Differences: The main difference between the FMCW and Pulse radar sensor systems is that in the last system the radar transmits the pulses (not continuous wave) and measures the delay. The FMCW radar transmits signal continuously but with the varied frequency. Once the signal has left the antenna, its frequency obviously does not change. As the target is further away, the difference in frequencies between the transmitted and target return signals is increased. Figure 40 shows two radar wave forms.

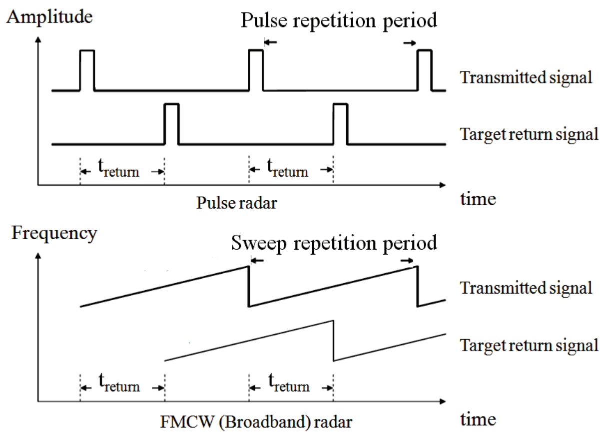


Fig. 40. Radar waveforms.

Target Detection: All radar sensor system receivers possess the thermal noise, and there is a need to detect the target return signal to use specific signal detection algorithms allowing us to get the required detection performances. The radar sensor receiver does not receive a single frequency, but a range of frequencies called the bandwidth. The noise power is proportional to the radar receiver bandwidth. Another obvious difference is the receiver bandwidth scale. The Pulse radar sensor system requires a bandwidth that is inversely proportional to the pulse duration. It requires a wide bandwidth for SRR in comparison with LRR. The FMCW radar sensor system has the opposite requirements, namely, the shorter radar range, the lower a difference between the transmitted and target return signal frequencies. Thus, the narrow bandwidth is required. The narrower the bandwidth, the lower the receiver thermal noise power in comparison with the target return signal power needed to be exceeded in the case of reliable detection. For example, it is easy to achieve the required signal-to-noise ratio in the receiver. FMCW radar sensor systems have difficulty in LRR because their performance tends to be determined by spectral purity of the transmitted signal rather than the receiver thermal noise. The FMCW radar sensor system is inherently capable to have the better target detection performance than the Pulse radar sensor systems in SRR and worse in LRR.

Target Resolution: The target resolution means how much two targets can be close to each other and still be resolved as two targets. The FMCW and Pulse radar sensor systems use similar antennas. Thus, their angular resolution will be almost the same but, in the case of the range resolution, the FMCW radar sensor systems have the better performance in comparison with the Pulse radar sensor systems. In the case of the FMCW radar sensor system, the target resolution has no low theoretical limits. The resolution is defined by application of the radar sensor system. In practice, the resolution in LRR by the FMCW radar sensor systems is less than 5 meter in range and 1 degree in azimuth [52]. However, the FMCW radar sensor system is easily overwhelmed by interference. Table 27 presents a comparison between the FMCW and Pulse radar sensor systems. There is another difference between the FMCW and Pulse radar sensor systems. The typical Pulse radar sensor system is half duplex, while the FMCW radar sensor system is full duplex. Hence, the Pulse radar sensor system provides a high isolation between the transmit and receive antennas. We cannot say the same with respect to the FMCW radar sensor system. However, a drawback of half duplex operation is a blind zone existence in the immediate radar sensor vicinity. Therefore, the Pulse Doppler radar sensor system is more suitable for LRR detection, while the FMCW radar sensor system is more appropriate for SRR and MRR detection. In the case of BSD and CVD, we should guarantee a high detection performance in SRR and MRR from 0.5 m to 55 m. Because of this, the FMCW radar sensor system is more suitable for BSD and CVD. The FMCW radar sensor systems have the following advantages in comparison with the Pulse radar sensor systems: the low complexity, the better performance in SRR and MRR detection, the better resolution in TV range and lower cost, the low CFAR, the small size beamwidth.

Table 27.
Inherent differences between the FMCW and Pulse radar sensor systems.

Characteristic	FMCW Radar Systems	Pulse Radar Systems
SSR detection	Better	Worse
LRR detection	Worse	Better
Visibility of close in targets	Better	Worse
Target resolution in azimuth	Same	Same
Target resolution in range	Better	Worse
Power requirements	Similar	Similar
Requires standby period	No	Yes
Vulnerability to interference from other radars	Difficult to solve	Easy to solve
Potential for future development	Relatively new technology	Relatively mature technology

5. CONCLUSIONS AND FUTURE WORK

The Recommended System: The main purpose of the present paper is to review the radar sensor systems in order to define the best solution for CVD and BSD. The output of this stage is to define the most appropriate radar sensor system and signal detection algorithms, functioning frequency, and other related parameters. As a result, we recommend to use the 24 GHz and FMCW radar sensor system for BSD and CVD. The recommended 24 GHz and FMCW radar sensor system has the following main characteristics.

24 GHz Operation Frequency: The analysis carried out in the present paper allows us to make a conclusion that the designed signal detection algorithm must operate in SRR and MRR at 24 GHz, i.e. in BSD and CVD areas, which are allocated at the rear part of the SV.

FMCW Radar Sensor System: FMCW radar sensor system promises us to cover all requirements and specifications under BSD and CVD.

Review of the radar sensor systems has been provided to facilitate an explanation of radar signal detection and signal processing principles for different kinds of radar sensor technologies related to the safety driving applications. Based on our analysis, we can divide the signal processing procedure for any radar sensor system on three main levels: *the first level* – the basic level and it is similar for any radar (the main principles); *the second level* – the waveform and predefined parameter formulas; *the third level* – the signal detection and signal processing algorithms used to cancel the errors, noise and radio frequency interference. The evaluation criterion of the acceptable signal detection and signal processing algorithms for BSD and CVD is presented to compare the radar sensor systems. Implementation of the evaluation criteria to the discussed modern signal detection and signal processing algorithms allows us to make a strong comparison in various aspects defining the final decision to define the appropriate signal detection and signal processing algorithms. According to the previous discussion of the recommended system for BSD and CVD, the next step is to carry out a complete and deep analysis for the chosen radar sensor system and to investigate the best ways to design and map all the possible methods to improve the detection performance.

An important part of this paper is to know the current limitations and the best existed performance of the recommended FMCW radar sensor system. It is very helpful to define where we have to start and how we can manage the design and development process of BSD and CVD in order to satisfy the required specifications. The design of signal detection and signal processing algorithms follows by the specified designing steps: *the baseline detector definition* – the proposed detector and the signal detection and signal processing algorithms including simulation; *the theoretical design* – the modified signal processing algorithm, the numerical analysis, the target detection, the method to define the target parameters, the costs definition; *the performance comparison* – the improvement of radar sensor system performance by comparison the modified signal detection and signal processing algorithms with the basic algorithms; *the empirical performance* – the complete analysis of advantages and disadvantages, the test simulation, and the definition of the proper vision for an applicable radar sensor system.

Thus, our recommendation is the following. All the research efforts must be focused on the 24 GHz FMCW radar sensor system employed in BSD and CVD applications.

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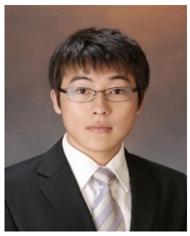

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