Behavioral Simulation of 60 GHz FMCW Radar using CppSim Simulator

Dušan Krčum, Dušan Grujić, Milan Savić, and Lazar Saranovac

Abstract - 60 GHz FMCW radar system modelling using CppSim is presented in this paper. Modelling methodology of fundamental radar blocks is discussed. Models are validated in several real scenarios. Simulation results can be used as guideline in design and usage of modern radars in millimeter frequency band.

Keywords - Behavioral simulation, CppSim, Radars.

I. INTRODUCTION

Radar systems now days are becoming widely used in automotive, healthcare and security applications, [1,2,3,4]. Like communication systems, radar systems are very sensitive to noise, intermodulation distortion and other non-linearities, whose influence on the system performance can't be fully determined analytically. System blocks have to be analysed separately in order to get deep insight in their impact on system performance. Particular attention should be paid on the non-linear characteristic of voltage controlled oscillator (VCO), its phase noise, distortion coming from amplifiers, quadrature signals mismatch in phase and amplitude, and Tx - Rx leakage. One of the major challenges in modern radar design is to provide inexpensive fast and reliable system level simulation, [5, 6, 7, 8]. The aim of this paper is to present usage of free general-purpose time domain simulator, CppSim, for simulation of FMCW radar. CppSim simulations were done in order to discover the possibilities and limitations in design and usage of modern radar systems. CppSim is not adapted to the simulation of system like radars, so it was necessary to develop suitable models of building blocks, radar channel, stationary and moving targets. The simulator works in the time domain, and supports transient noise. Exact system analysis requires insight in the time and frequency domain, and needs to pay attention to the digital signal processing using CppSim or external tools such as Octave and Python.

II. FMCW Radar

Block diagram of FMCW radar is presented on Fig. 1. Fundamental blocks of FMCW radar are voltage controlled oscillator, power amplifier, LNA, mixer, and low pass filter. FMCW radar uses time variable transmit frequency in order to determine the range and velocity of targets.

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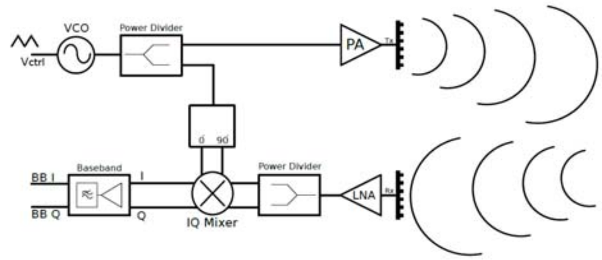

Fig. 1. Block diagram of standard FMCW radar front end.

VCO frequency is swept linearly in time by amount of frequency change:

$$f_{VCO}(t) = f_0 + \frac{\Delta f}{T_{ch}} t, \tag{1}$$

where f_0 is carrier frequency, Δf is frequency deviation, and T_{ch} is duration of frequency change. In reality, VCO frequency change is realized using triangular modulation signal, as shown on Fig. 2.

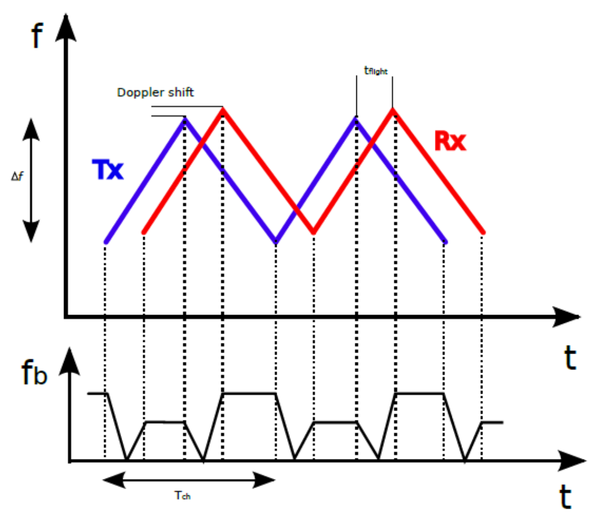

Fig. 2. Triangular modulation pattern.

This signal is amplified using power amplifier (PA) and transmitted. Received reflected signal from target is attenuated and time delayed transmitted signal. Received signal is amplified by LNA, and mixed with transmitted signal. Frequency difference between instantaneous VCO and received frequencies, called beat frequency - f_b, is proportional to time of flight (t_{flight}):

$$f_b = \frac{\Delta f}{T_{ch}} t_{flight} . \quad (2)$$

Target range is R and it's given with equation:

$$R = \frac{T_{ch} c}{2\Delta f} f_b . \quad (3)$$

III. CppSim Simulator

CppSim is a free, general behavioral simulator developed at MIT for behavioral simulation of PLLs [9]. Over time the scope of the tool has been expanded, and has been used for behavioral modeling of other circuits as well. System blocks are described using C++, and there are many built-in models for typical blocks in communication systems. Tool allows generation of models for new blocks, modification of existing and very detailed modeling of complex circuits. Digital circuits can be described using Verilog and simulated directly in CppSim. Synthesizable Verilog code is translated to C++ code using external tool called Verilator [9], then simulations are running as standard C++ program. Tool is running time-domain simulation which is important for transient noise analysis. Using C++, simulations are fast and modeling pretty flexible. Simulator has also integrated schematic environment that facilitates system overview.

IV. 60 GHZ FMCW RADAR MODELING USING CPPSIM

CppSim does not offer suitable models for accurate simulation of systems such as FMCW radar. In order to provide compatible models, FMCW radar blocks are modeled in C++:

- Low Noise Amplifier (LNA)
- Power Amplifier (PA)
- Voltage Controlled Oscillator VCO
- Band pass and Low pass Filters (BPF/LPF)
- Radar propagation channel
- Stationary and moving targets

Detailed modeling procedure for these blocks is presented in the following.

A. Nonlinear LNA with noise.

Nonlinear LNA model is described with the following parameters:

- Gain [dB] - linear gain
- P1dBin [dBm] - input referred 1dB compression Power
- NF [dB] - noise figure

Most common model used model for LNA nonlinearity is described by third order polynomial expression, [10]:

$$y(t) = a_1 t - a_2 t^3 , \quad (4)$$

Coefficient a_1 is actually the linear gain, and it can be calculated as:

$$a_1 = 10^{\frac{Gain}{20}} , \quad (5)$$

Coefficient a_3 gives information about 1dB compression point and third order inter modulation products. This coefficient is determined from following equations:

$$IIP_3 = P_{1dB_{in}} + 9.6[dB] , \quad (6)$$

$$V^2_{IIP_3} = 2R_{REF} 10^{\frac{IIP_3}{10}} 10^{-3} [V^2] \cdot \quad (7)$$

Combining equations 6 and 7 we get final expression for coefficient a_3:

$$a_3 = \frac{4a_1}{3V^2_{IIP_3}} . \quad (8)$$

Noise characterization of LNA was implemented as following. Using input and output signal to noise ratio (SNR) noise factor can be determined as:

$$F = \frac{SNR_{IN}}{SNR_{OUT}} . \quad (9)$$

Input noise comes from source resistance thermal noise, which has spectral density of:

$$\overline{v_n{}^2} = 4kTR_{noise} . \quad (10)$$

Thermal spectral noise power density is given with:

$$P_n = \frac{\overline{v_n{}^2}}{R} = 4kT , \quad (11)$$

while available noise power at matched load is:

$$P_{n,match} = \frac{\overline{\left(\frac{v_n}{2}\right)^2}}{R} = kT , \quad (12)$$

On the other hand, noise factor is defined as:

$$F = 1 + \frac{R_{noise}}{R_{ref}} , \quad (13)$$

where R_{ref} is referent resistivity, 50 in our case.

From equation 13 resistor which generates equivalent amount of noise as LNA is:

$$R_{noise} = R_{ref} \left(F - 1 \right) . \quad (14)$$

CppSim has built in function called *randg.inp()*, which generates random noise. This function needs input noise spectral density as input parameter.

Using these equations, nonlinear model of LNA has been developed. Beside single ended LNA, differential one was also introduced.

B. Power amplifier

Nonlinear model of PA is same as model of LNA, with only difference in compression point definition. PA compression point is specified at output. Parameters that describe PA are:

- *Gain* [dB] - linear gain
- P_{1dBout} [dBm] - output referred 1dB compression power
- *NF* [dB] - noise figure

C. Voltage Controlled Oscillator

VCO is an essential building block for radar systems, and it's parameters have significant impact on overall system performance. Simplified model of phase noise profile was used in first iteration. Modeled phase noise profile has two regions - $\frac{1}{f}$ and constant spectral density.

Noise samples are calculated by the provided model for $\frac{1}{f}$ noise and added to the VCO control voltage. More accurate model of VCO phase noise should be developed according to [11].

In real radar system, IQ signals can be generated using quadrature VCO or using VCO with quadrature generator. In both ways amplitude and phase mismatches are present. These imbalances degrade system performance. Phase and amplitude imbalances are incorporated in existing models, so it is possible to evaluate their impact on performance. Our model assumes quadrature VCO, with the following parameters:

- f_0 [Hz] - Center frequency
- *kv* [$\frac{Hz}{V}$] – VCO characteristics
- f_{corner} [Hz] – Corner frequency between $\frac{1}{f}$ and constant spectral density
- *noise at offset* [$\frac{dBc}{Hz}$] – Noise spectral density at f_{offset} from carier
- f_{offset} [Hz] – Offset frequency at which the noise floor is specified
- *phase imb* [$^\circ$] – phase imbalance
- *amp imb* [dB] – amplitude imbalance

Beside these parameters, proposed VCO model has also logical parameter noise enable. Value 0 switch off noise generator in VCO block. Default state is with noisy VCO.

In reality, VCO frequency is not linear function of control voltage. This nonlinearity leads to time-varying beat frequency, which can be interpreted as a moving target. This scenario can be modeled with higher order polynomial characteristics of VCO, instead of linear one, described with only *kv* parameter. Nonlinear characteristics of VCO is modeled with 14th order polynomial, and simulation of proposed model will be presented in section V.

D. Filters

Filters are implemented using 7th order Butterworth approximation. Several filters were used: Bandpass with cutoff frequencies of 54 GHz and 64 GHz, and low pass for beat frequencies with cutoff frequency of 200 kHz. CppSim has built-in Butherworth approximation class for filters, but filter order is fixed and equal to 1. This class was modified, and model parameter for bandpass filters are:

- Gain [dB] - linear gain
- BW

E. Radar Propagation Channel

Propagation of electromagnetic waves through radar channel is described by time delay due to finite velocity of propagation, and propagation loss. Time delay can easily be derived from target distance, and propagation loss is given with radar equation:

$$P_r = \frac{G_t G_r \left(\frac{c}{f}\right)^2 \sigma}{(4\pi)^3 R^4} Pt \quad (15)$$

Using same model, Tx to Rx leakage was modeled. This leakage is important because short path from Tx and Rx due to vicinity of antennas is presented in frequency domain as target at distance equal to distance between the antennas.

F. Stationary and Moving Targets

Stationary and moving targets implement free path loss, target radar cross section, while the moving target implements Doppler shift. They are characterized by the following parameters:

- *range* [m] – Distance to target
- *rcs* [m^2] – Radar Cross Section
- *velocity* [m/s] – Target velocity for moving targets

Static targets can be simulated as particular static block, or as moving target block with velocity parameter equal to 0.

V. Results

Test system has been made by using the designed behavioral models, as shown on Fig.3. Chirp signal is generated using triangle modulation pattern. System block specifications are given in Table I. First test was performed

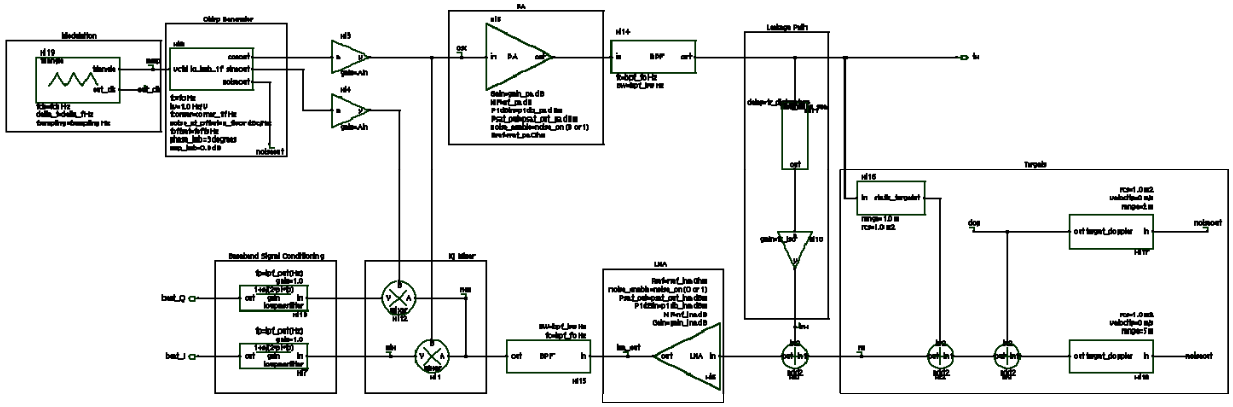

Fig. 3. FMCW Radar in CppSim.

TABLE I.

MODEL PARAMETERS FOR DESIGNED FMCW RADAR

Model Parameter	Label	Value
Chirp frequency	f_{ch}	500 Hz
Carier frequency	f_0	60 GHz
Frequency deviation	Δf	2 GHz
Phase noise offset	f_{offset}	1 kHz
Noise floor relative to carier at 1 MHz	/	-90 dBc/Hz
Amplitude of generated signal	A_{in}	117 mV
PA gain	G_{PA}	15 dB
PA 1dB Compression	P_{1dBPA}	1 dBm
PA output saturation power	$P_{satoutPA}$	20 dBm
LNA gain	G_{LNA}	10 dB
LNA noise factor	NF_{LNA}	6 dB
LNA 1dB Compression	P_{1dBLNA}	1 dBm
LNA output saturation power	$P_{satoutLNA}$	20 dBm

with three static targets at distances 1 m, 2 m, and 5 m. All noise generators and other nonidealities are included in simulation. Theoretically, expected peaks in spectrum of I or Q signals are located at 13.33 kHz, 26.67 kHz and 66.67 kHz for above targets. Peaks at exact frequencies are visible on Fig.4

Moving targets are also considered. Due to Doppler frequency shift, expected peaks in output spectrum are at frequencies equal to $f_b - f_{Doppler}$ and $f_b + f_{Doppler}$. Doppler shift is proportional to instantaneous velocity of target. As an example, single moving target was checked. On Fig.5 output spectrum is presented, where two peaks are visible. Chosen velocity was $v = 5m/s$ which correspond to Doppler shift of $f_{Doppler} = \frac{2vf}{c} 2.4kHz$.

In order to demonstrate nonlinear characteristic of VCO and Tx to RX leakage, test bench with single static target was chosen. On Fig.6 time domain output signal is presented. In ideal scenario, signal would be pure sinusoidal, with frequency f_b. On Fig.6 low frequency sine wave from leakage is visible, on which the beat frequency sine wave is riding. Nonlinear VCO is recognized by time varying beat frequency.

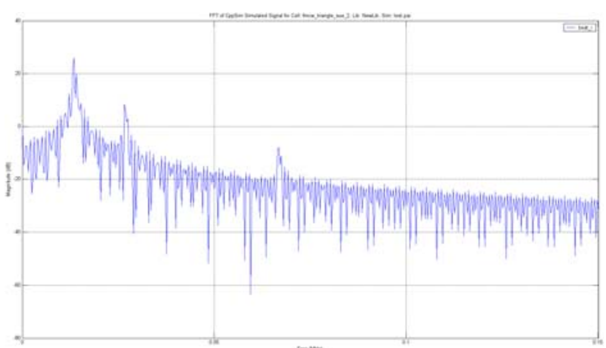

Fig. 4. Spectrum of I branch for 3 static targets.

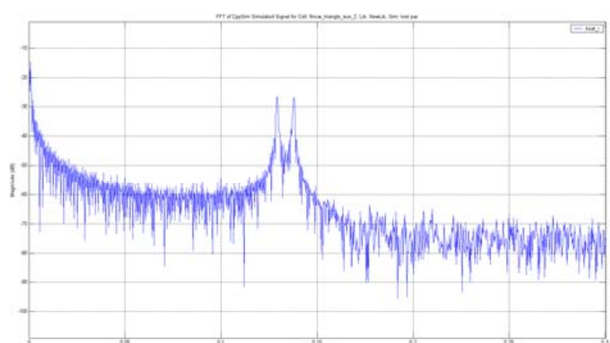

Fig. 5. Spectrum of I branch for one moving target.