Design of FMCW Radars for Active Safety Applications

Marco Roggero
Application Engineer
MathWorks GmbH
Aachen, Germany
marco.roggero@mathworks.de

John Zhao
Product Manager
MathWorks
Natick, MA, United States
john.zhao@mathworks.com

Giorgia Zucchelli
Technical Marketing
MathWorks
Eindhoven, Netherlands
giorgia.zucchelli@mathworks.nl

***Abstract*—With 28.000 road fatalities in 2012 in Europe, car manufacturers, automotive electronics suppliers, and universities are working to develop new electronic systems for accident prevention and collision mitigation. In the near future, vehicle-to-vehicle and vehicle-to-infrastructure networks based on dedicated short-range communication (DSRC) technology will warn drivers when dangerous conditions are detected. Information collected by radars, cameras, and other sensors integrated in vehicles and road infrastructure will be used to determine the driving situation and warn drivers of potentially dangerous events.**

Since radar systems are an essential source of information, it is necessary to equip vehicles and infrastructural elements with multiple radar modules. Frequency modulated continuous waveform (FMCW) radars fit the requirements of automotive active safety systems because of their accurate short-range measurements, low sensitivity to clutter, and easy integration. To assess the feasibility of high-volume production, it is necessary to evaluate the reliability and the cost of the individual RF components used for the radar implementation and their impact on the overall performance.

In this paper we show a unique tool chain for modeling and simulating a complete 77 GHz FMCW radar system, including waveform generation, antenna characterization, channel interference and noise, and digital signal processing algorithms for range and speed determination. Simulation and modeling of RF impairments such as noise, nonlinearity, and frequency dependencies enable us to test the behavior of "off the shelf" components described with datasheet parameters and provide information about the performance achievable with a specific component configuration and related costs.

***Keywords*—FMCW radar; MATLAB; Simulink; Automotive; Active Safety**

I. INTRODUCTION

Frequency modulated continuous waveform radars are becoming increasingly popular, especially in automotive applications such as adaptive cruise control (ACC). The transmitter of an FMCW system sends a chirp signal with high frequency and large bandwidth (Figure 1). The transmitted signal hits the target and is reflected back toward the receivers with a time delay and a frequency shift that depends on the target distance and relative speed.

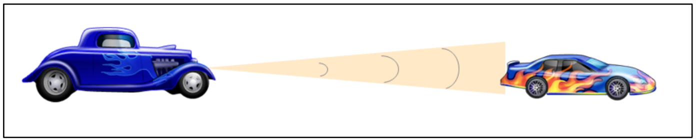


Figure 1. Example of radar for automotive application.

By mixing the transmitted and the received signal, the time delay corresponds to a frequency difference that generates a beat frequency. This allows a very accurate and reliable estimation of the target distance [1]. Often multiple antennas are used for spatial processing and beamforming to make the detection more reliable or to have a directional system (Figure 2).

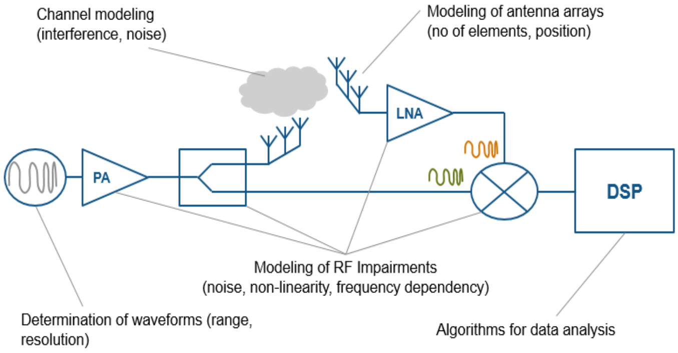


Figure 2. Structure of an FMCW radar system.

In the design, modeling, and simulation of an FMCW radar, the designer must take into account more than just the nominal behavior. After using the radar equation to determine the fundamental design parameters, the designer must analyze the impact of imperfections introduced by the RF front-end. Nonlinearity, noise, frequency selectivity, and mismatches between components operating over ultra-large bandwidth reduce the actual dynamic range of the detectable signal.

By accurately modeling the RF front-end, designers can make complexity tradeoffs between the hardware architecture and the digital signal processing algorithms. Moreover, they can assess whether previous implementations can be reused to retarget the radar for augmented specifications, or whether off-the-shelf components can be directly used for the front-end implementation.

In the following sections, we propose a MATLAB based tool chain supporting the simulation of all the relevant aspects of such a radar system including waveform determination, algorithms for data analysis, modeling of antenna arrays, communication channels, and RF impairments. In the last section, we introduce an ACC example in which the radar system is simulated taking into account the vehicle dynamics.

II. DETERMINATION OF FMCW WAVEFORM

The first problem we have to cope with when designing a new radar system is to determine the parameters of the triangular chirp waveform in order to achieve desired resolution with the specified range. We consider an automotive long-range radar used for automatic cruise control, which usually occupies the band around 77 GHz [2] [3].

As shown in Figure 3, the received signal is an attenuated and time-delayed copy of the transmitted signal where the delay, Δt is related to the distance of the target. Because the signal is always sweeping through a frequency band, at any moment during the sweep, the frequency difference f_b, usually called *beat frequency*, between the transmitted signal and the received signal is constant. Because the sweep is linear, one can derive the time delay from the beat frequency and then the distance of the target from the time delay.

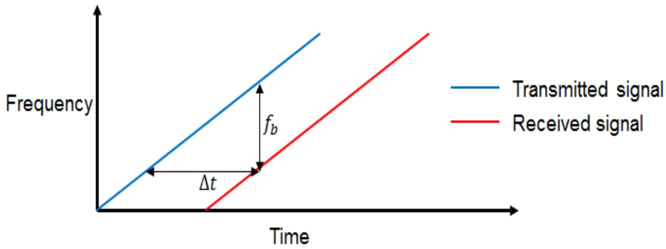


Figure 3. Waveforms of transmitted and received signals.

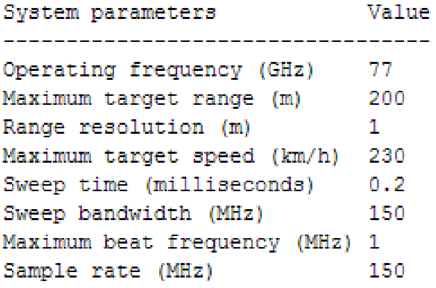
We can easily determine the fundamental waveform parameters for a radar working at 77 GHz in the MATLAB environment using Phased Array System Toolbox functionality. In the case shown in Figure 4, we assume the maximum speed of a travelling car of 230 km/h and we impose the requirement of distinguishing between two targets that are 1 meter apart at a range of 200 meters.

```
fc = 77e9;
c = 3e8;
lambda = c/fc;
range_res = 1; %resolution = 1 meter
v_max = 230*1000/3600; % Maximum speed 230 km/h

bw = range2bw(range_res,c); % sweep bandwidth
range_max = 200;
sweep_time = 2e-4;
sweep_slope = bw/sweep_time; % sweep slope

fr_max = range2beat(range_max,sweep_slope,c);
fd_max = speed2dop(2*v_max,lambda); % Doppler shift
fb_max = fr_max+fd_max; % maximum beat frequency

fs = max(2*fb_max,bw); % sample frequency
tstep = 1/fs; % sample rate
```

Figure 4. Determining the parameters of the FMCW chirp waveform.

III. MODELING TARGET, NOISE, AND NONLINEARITY

Once the chirp parameters have been determined as shown in Figure 5, we can proceed with modeling the transceiver of the radar system.

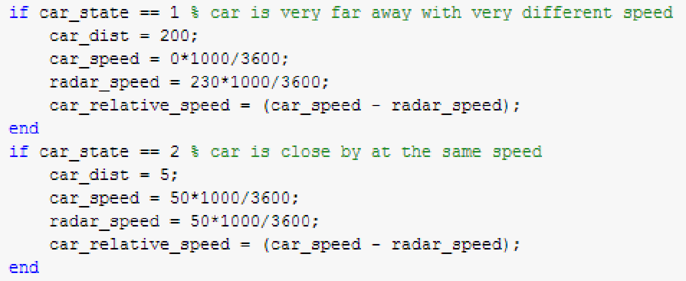


```
System parameters               Value
-----------------------------------
Operating frequency (GHz)       77
Maximum target range (m)        200
Range resolution (m)            1
Maximum target speed (km/h)     230
Sweep time (milliseconds)       0.2
Sweep bandwidth (MHz)           150
Maximum beat frequency (MHz)    1
Sample rate (MHz)               150
```

Figure 5. FMCW radar system parameters.

The script used in our example allows us to examine different configurations in which the parameters for the description of target vehicle, transceiver nonlinearity, and noise are changed to analyze different scenarios.

For example, the set of configurations for `car_state = 1` describes a car that is very far away and stationary, while the vehicle on which the radar is mounted is moving at extremely high speed (Figure 6). The set of configurations for `car_state = 2` describes a car that is very close to the vehicle on which the radar is mounted (5m) and moving at approximately the same speed (50km/h).

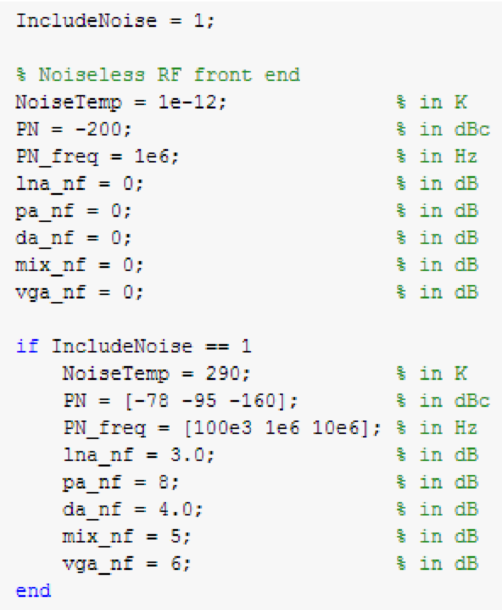


```
if car_state == 1 % car is very far away with very different speed
    car_dist = 200;
    car_speed = 0*1000/3600;
    radar_speed = 230*1000/3600;
    car_relative_speed = (car_speed - radar_speed);
end
if car_state == 2 % car is close by at the same speed
    car_dist = 5;
    car_speed = 50*1000/3600;
    radar_speed = 50*1000/3600;
    car_relative_speed = (car_speed - radar_speed);
end
```

Figure 6. Setting target parameters.

The front-end of the radar system includes the transmitter, the receiver, and the antenna. We can assign desired values for all the parameters describing these system components as part of the MATLAB script that we use to set up the simulation. We have created variables to describe the parameters of each constituent of the RF front-end.

For noise and nonlinearity models, we can switch between ideal and nonideal conditions. For example, as shown in Figure 7, we can isolate the impact of noise and include phase noise, thermal noise, and noise figure of the different components.



```
IncludeNoise = 1;

% Noiseless RF front end
NoiseTemp = 1e-12;            % in K
PN = -200;                    % in dBc
PN_freq = 1e6;                % in Hz
lna_nf = 0;                   % in dB
pa_nf = 0;                    % in dB
da_nf = 0;                    % in dB
mix_nf = 0;                   % in dB
vga_nf = 0;                   % in dB

if IncludeNoise == 1
    NoiseTemp = 290;          % in K
    PN = [-78 -95 -160];      % in dBc
    PN_freq = [100e3 1e6 10e6]; % in Hz
    lna_nf = 3.0;             % in dB
    pa_nf = 8;                % in dB
    da_nf = 4.0;              % in dB
    mix_nf = 5;               % in dB
    vga_nf = 6;               % in dB
end
```

Figure 7. Definition of ideal and nonideal noise conditions.

IV. COMPLETE SYSTEM SIMULATION

After defining a set of variables for all the parameters needed to describe our automotive FMCW radar system, we can proceed with a complete PC simulation to test whether the system will work properly under different test conditions. To do that we use a Simulink model with blocks that have as parameters the variables from the MATLAB workspace that have been set with the script described in the previous section. Figure 8 shows how we have modeled the RF front-end using SimRF blocks. This library provides a circuit envelope solver for the rapid simulation of RF systems and components such as amplifiers, mixers, and S-parameter blocks.

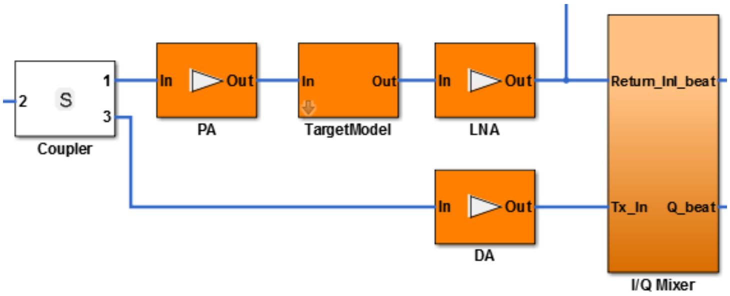


Figure 8. RF elements modeled in Simulink using SimRF circuit envelope blocks.

We can describe in detail the architecture of the transceiver and use datasheet parameters for each front-end element. Taking as an example the direct conversion I/Q mixer, we have modeled it as illustrated in Figure 9. This element demodulates the received signal, multiplying it with the originally transmitted waveform.

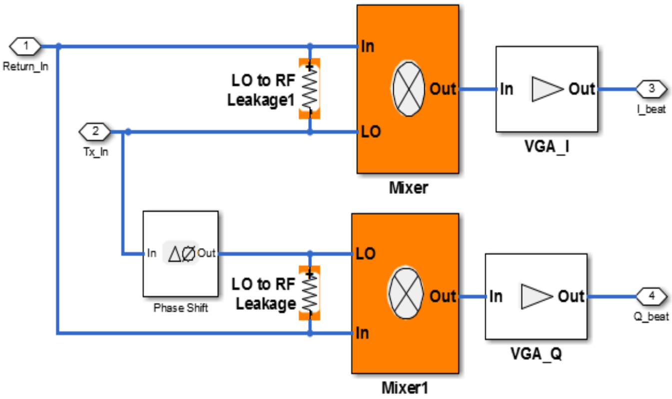
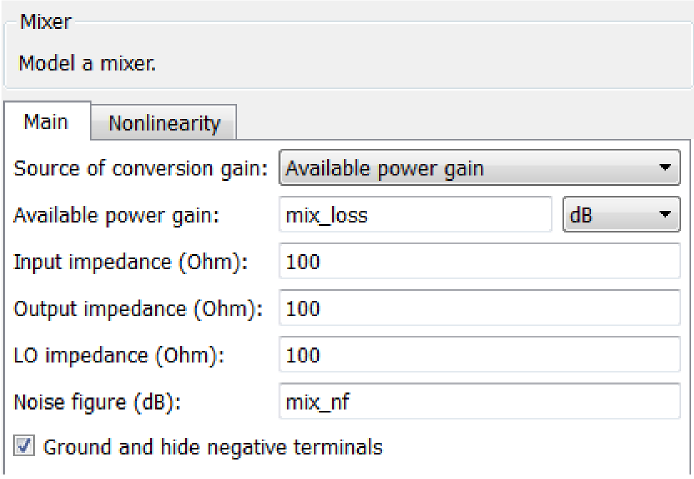


Figure 9. Structure of the I/Q direct conversion mixer.

Parameters of the two multipliers used in the I/Q mixer have been inserted directly or using workspace variable names in the block parameter window (Figures 10a and 10b): Finite mixer isolations and nonlinearity (IP2) result in a DC offset and cause dynamic range limitations.



Mixer

Model a mixer.

Source of conversion gain: Available power gain

Available power gain: mix_loss dB

Input impedance (Ohm): 100

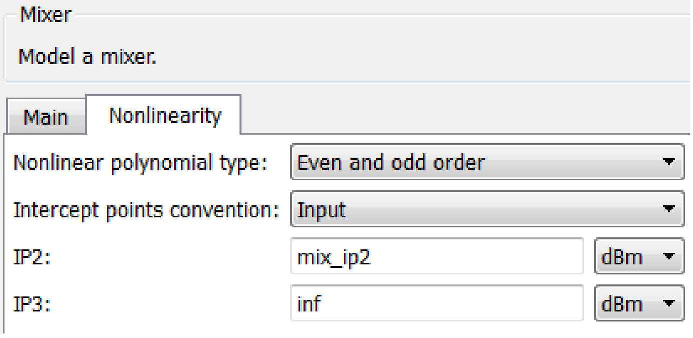
Output impedance (Ohm): 100

LO impedance (Ohm): 100

Noise figure (dB): mix_nf

☑ Ground and hide negative terminals

Figure 10a. Mixer parameters.



Mixer

Model a mixer.

Nonlinear polynomial type: Even and odd order

Intercept points convention: Input

IP2: mix_ip2 dBm

IP3: inf dBm

Figure 10b. Mixer parameters describing introducing nonlinearity.

With this configuration, it is easy to try different setups and explore design spaces, using different datasheet parameters for simulating off-the-shelf components.

For the ADC and the Receiver Signal Processing blocks we have used functionality provided with DSP System Toolbox. When running this simulation, the model not only provides the estimated values of relative speed and object distance but also visualizes the spectrum of transmitted and received signals, as shown in Figures 11 and 12.

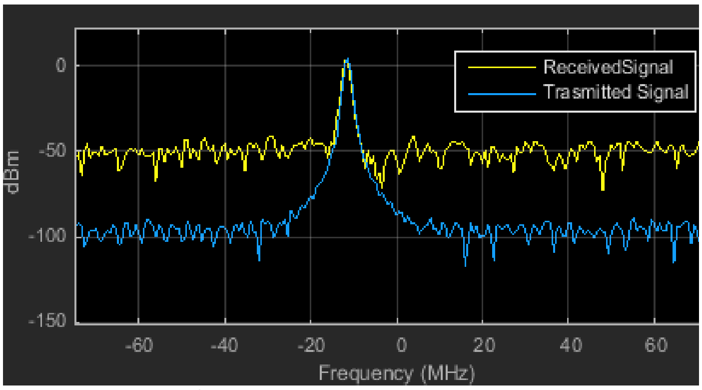


Figure 11. Spectrum of the transmitted and received signals.

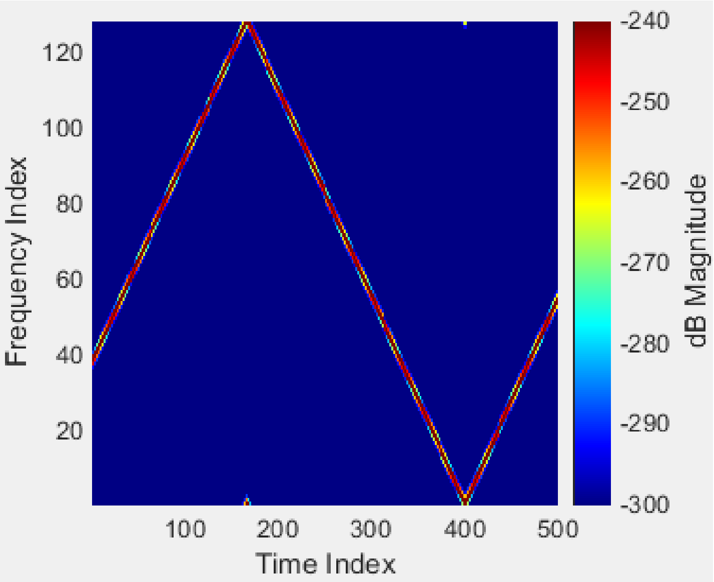
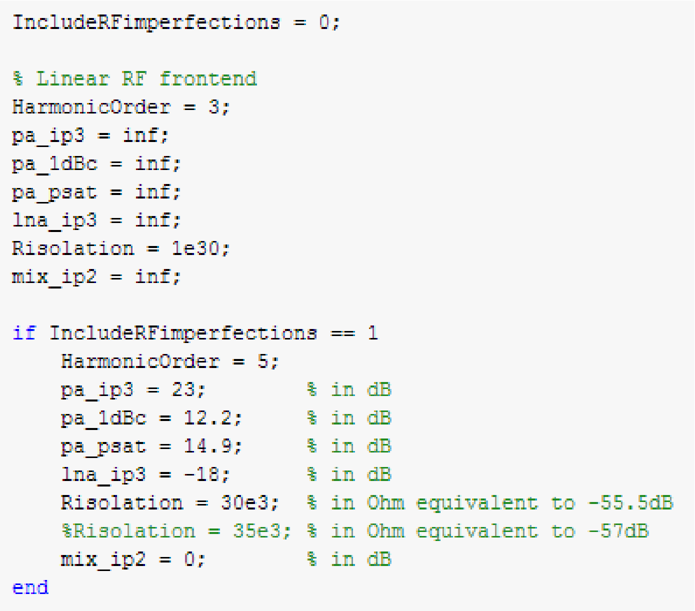


Figure 12. Spectrogram of the received signal.

A first simulation running under ideal conditions (absence of noise and distortion) shows that speed and position can be detected correctly for all targets in use. This simulation validates the testbench and the digital signal processing algorithms. When including transceiver nonlinearity (Figure 13) and adding noise, the radar deviates from the ideal behavior and cannot detect cars when they are far away.



```
IncludeRFimperfections = 0;

% Linear RF frontend
HarmonicOrder = 3;
pa_ip3 = inf;
pa_1dBc = inf;
pa_psat = inf;
lna_ip3 = inf;
Risolation = 1e30;
mix_ip2 = inf;

if IncludeRFimperfections == 1
    HarmonicOrder = 5;
    pa_ip3 = 23;        % in dB
    pa_1dBc = 12.2;     % in dB
    pa_psat = 14.9;     % in dB
    lna_ip3 = -18;      % in dB
    Risolation = 30e3;  % in Ohm equivalent to -55.5dB
    %Risolation = 35e3; % in Ohm equivalent to -57dB
    mix_ip2 = 0;        % in dB
end
```

Figure 13. Setting RF nonlinearity parameters.

By increasing the isolation of the mixer and the gain of the power amplifier, we can extend the radar range and correctly estimate the target speed. It is necessary to carefully trade off the gain of the different stages in order to avoid having the receiver operating in saturation. This analysis allowed us to select the suitable components for the radar implementation and to verify their impact on the radar performance.

The radar system we have described in this paper can be also integrated in a complete ACC model in which we use the Simulink environment to simulate the speed controller and the vehicle dynamics and to visualize the results using a 3D animation, as shown in Figure 14.

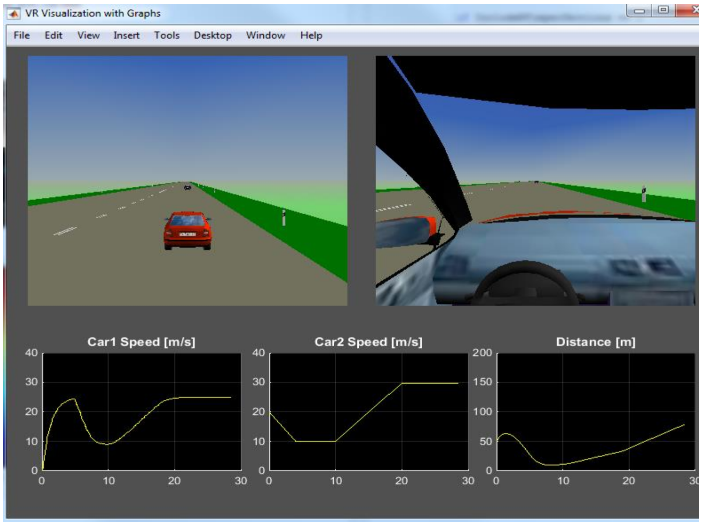


Figure 14. 3D animation for complete ACC system.

IV. CONCLUSION

This article has covered the modeling and simulation of a complete FMCW radar system for automotive active safety applications using a MATLAB and Simulink based tool chain. The proposed workflow allows us to simulate RF components within a complete system-level model, including digital signal processing algorithms. This approach reduces both the time needed for radar development and the complexity of system tests, making the development cycle less costly.

REFERENCES

[1] Design and Verify RF Transceivers for Radar Systems. Giorgia Zucchelli, MathWorks. http://www.mathworks.com/videos/design-and-verify-rf-transceivers-for-radar-systems-81990.html

[2] Automotive Adaptive Cruise Control Using FMCW Technology. http://www.mathworks.com/help/phased/examples/automotive-adaptive-cruise-control-using-fmcw-technology.html

[3] Karnfelt, C. et al. *77 GHz ACC Radar Simulation Platform*, IEEE International Conferences on Intelligent Transport Systems Telecommunications (ITST), 2009.