Tutorial: Millimeter Wave Frontend for Integrated Sensing and Communication System Transceiver on Edge

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1 Introduction

In this tutorial, we present our Millimeter Wave Frontend (MFE) design for an Integrated Sensing and Communication (ISAC) system. The design is implemented in Simulink, enabling simulation and performance testing of the ISAC waveform at millimeter-wave (mmWave) frequencies. Two Simulink models, "Radar Testbench" and "Comm Testbench", are integrated using MATLAB code referred to as "ISAC Code". Both the designs and the code are available through our GitHub repository. The link to the Github repository is provided at the end of the document. Additionally, the Simulink model is capable of simulating the impact of hardware impairments at mmWave frequencies. The impairment values have been configured in the code based on the parameters provided in Table 1, and these settings can be adjusted to accommodate different hardware devices.

2 Design Description

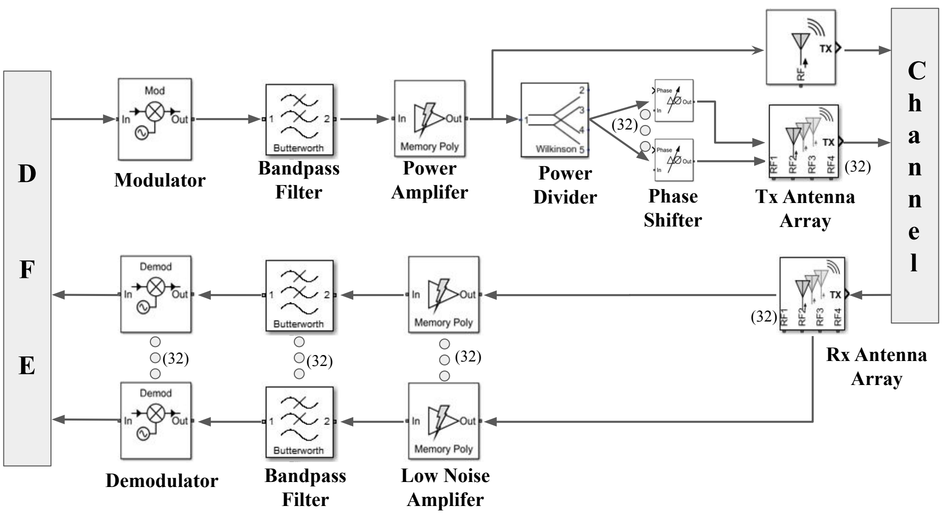

Figure 1: Simulink block level representation of MFE.

The Simulink model along with the signal flow and processing involved in a MFE system is presented in Fig. 1. Each block in the model performs a specific operation that transforms the signal mathematically, enabling modulation, amplification, phase shifting, transmission, reception, and demodulation. Below is a detailed explanation of each block along with its corresponding equations. The output signal from DAC ($x_{dac}(t)$) at intermediate frequency (f_{if}) is presented using equation 1. The process begins with

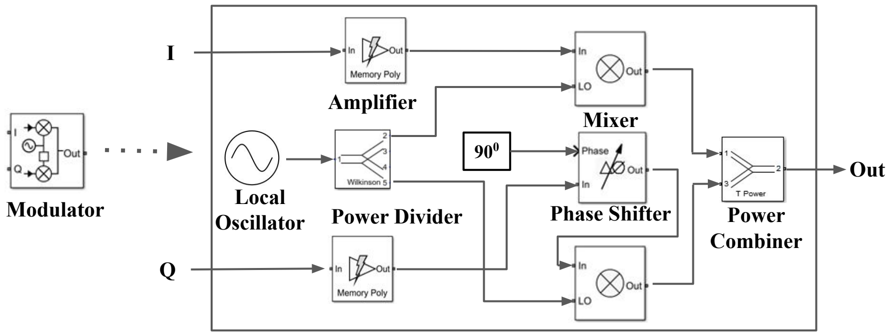

Figure 2: Simulink block level representation of internal architecture of modulator used in MFE.

the modulator, which takes the signal from DAC embedded in DFE and upconverts it to mmWave frequency (f_c) by multiplying it with a carrier signal at frequency (f_{lo}). This operation is mathematically represented as as given in equation 2. The output of this block ($x_{mod}(t)$) is a modulated signal containing both the baseband information and the carrier frequency component.

$$x_{dac}(t) = Ae^{(j2\pi f_{if}t+\phi)} \tag{1}$$

where A is the amplitude of the output signal from DAC.

$$x_{mod}(t) = x_{dac}(t)e^{(j2\pi f_{lo}t)} \tag{2}$$

Fig. 2 presents the simulink block level representation of internal architecture of modulator which is used as one of the component to design MFE. The implemented modulator is an IQ modulator which has a phase difference of 90°in each branch. The modulator has a local oscillator embedded inside it which provides the carrier frequency to modulate the input signal from IF frequency to mmWave frequency. The output from the local oscillator is fed into the power divider to split into two branches. For the I branch the output of the power amplifer is directly fed into the mixer, while for the Q branch a 90°phase shift is applied to the output of power divider and then fed into the mixer. The mixer then performs the modulation and provides us with the output modulated at mmWave frequency. The output from both the I mixer and the Q mixer is fed to power combiner. The output of the modulator is then fetched from the power combiner.

Next, the signal passes through a bandpass filter with filter coefficients $x_{txcoeff}(t)$, which is designed to remove unwanted frequency components and retain only the desired band. This ensures that the transmitted signal remains within the allocated frequency spectrum, reducing interference and improving signal quality. This operation is mathematically represented as as given in equation 3. ($x_{txf}(t)$) is the output of the bandpass filter at transmitter.

$$x_{txf}(t) = x_{txcoeff}(t)x_{mod}(t) \tag{3}$$

After filtering, the signal is fed into a power amplifier, which boosts the signal strength to ensure proper transmission over a wireless channel. The amplifier applies a gain G_{pa} to the input signal, producing an amplified output ($x_{pa}(t)$) given by equation 4. The power amplifier is crucial for compensating signal attenuation over long distances.

$$x_{pa}(t) = G_{pa}x_{txf}(t) \tag{4}$$

Following amplification, the amplified signal is splitted into multiple branches for the antenna array. The divided signals ($x_{pd,i}(t)$) remain the same in amplitude but are distributed to different antenna elements. This operation is mathematically represented as as given in equation 5. N represents the total number of power splitting lines which are 32 in our case.

$$x_{pd,i}(t) = \frac{1}{N}\sum_{i=1}^{n} x_{pa}(t) \tag{5}$$

Following power divider signal is processed by a phase shifter, which introduces a phase shift ϕ_k to control the direction of transmission in an antenna array. The output of the phase shifter ($x_{ps,i}(t)$) is given by equation 6. This phase adjustment is essential in beamforming, where multiple antennas transmit signals with controlled phase differences to steer the beam toward a desired direction.

$$x_{ps,i}(t) = x_{pd,i}(t)e^{(\phi_k)} \tag{6}$$

The transmit antenna array then radiates the processed signal. When multiple antennas are used, the signals from different elements combine, resulting in an effective transmitted signal ($x_{tx}(t)$) given by equation 7. The factor $\frac{1}{N}$ ensures proper normalization when summing over N antenna elements. The combined output is transmitted over the wireless channel.

$$x_{tx}(t) = \frac{1}{N}\sum_{k} x_{ps,k}(t) \tag{7}$$

At the receiver side, the receive antenna array captures the incoming signal, which may have undergone attenuation, phase shifts, and noise addition due to the propagation environment, resulting in an effective transmitted signal given by equation 8. Here ($h_i(t)$) represents impulse response of the channel, ($n(t)$) represents the noise and the received signal power at i_{th} antenna element is represented using ($x_{rx,i}(t)$).

$$x_{rx,i}(t) = \sum_{i} h_i(t)x_{tx,i}(t) + n(t) \tag{8}$$

The received signal is then passed through a LNA, which amplifies the weak signal while minimizing additional noise. The amplification process is represented by equation 9, where (G_{lna}) is the gain provided by the LNA and ($x_{lna,i}(t)$) is the amplified output . The LNA is a critical component in maintaining signal integrity before further processing.

$$x_{lna,i}(t) = G_{lna}x_{rx,i}(t) \tag{9}$$

After amplification, the signal undergoes filtering through another bandpass filter with filter coefficients $x_{rxcoeff}(t)$, which removes out-of-band noise and retains the relevant frequency components. The output of bandpass filter at receiver for i_th chain is represented by ($x_{rxf,i}(t)$) and is given by equation 10.

$$x_{rxf,i}(t) = x_{rxcoeff}(t) * x_{lna,i}(t) \tag{10}$$

Finally, the demodulator extracts the original baseband signal by removing the carrier frequency component. This is achieved through a frequency downconversion process, where the received amplified signal is multiplied by $exp(-j2\pi f_{lo}t)$, yielding equation 11. The resulting signal is the recovered baseband signal ($x_{demod,i}(t)$), which can then be processed further for data extraction.

$$x_{demod,i}(t) = x_{rxf,i}(t)e^{(-j2\pi f_{lo}t)} \tag{11}$$

Hardware Impairment Modeling and Performance Evaluation: A key focus of this Simulink design is to analyze and mitigate hardware impairments that arise in mmWave systems. Unlike conventional sub-6 GHz wireless systems, mmWave operation is highly susceptible to RF impairments. Simulink, combined with the Toolboxes, allowed us to model these impairments at the circuit level and evaluate their impact on system performance. By integrating these simulations into our system design, we ensured that our ISAC implementation remains robust under practical operating conditions, reducing the risk of performance degradation in real-world deployments. The hardware impairment has been performed on modulator and demodulator which includes:

1. **IQ Gain Imbalance:** We have specified gain difference between I and Q branches. The input to the I branch ($x_{dac,i}(t)$) is (Available Power + 0.5 × IQ gain imbalance) and the input to the Q branch ($x_{dac,q}(t)$) is (Available Power - 0.5 × IQ gain imbalance). The input to the modulator with IQ gain imbalance is given by equation 12 and 13.

$$x_{dac,i}(t) = (A + 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi) \tag{12}$$

$$x_{dac,q}(t) = (A - 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi) \tag{13}$$

2. **IQ Phase Imbalance:** We have specified phase difference between I and Q branches. For phase imbalance the signal at I branch will be $exp(j2\pi f_{if}t + \phi + 0.5(\phi_{iq}))$ and the signal at Q branch will be $exp(j2\pi f_{if}t + \phi - 0.5(\phi_{iq}))$. Here $(\phi_i q)$ is the specified IQ phase imbalance. The input to the modulator with IQ gain and IQ phase imbalance is given by equation 14 and 15.

$$x_{dac,i}(t) = (A + 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi + 0.5(\phi_{iq})) \tag{14}$$

$$x_{dac,q}(t) = (A - 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi - 0.5(\phi_{iq})) \tag{15}$$

3. **LO to RF Leakage:** The ratio of magnitude between LO voltage to leaked RF voltage, is specified in dB. Becuase of the leakage we get spurs in the other frequency bands of the spectrum.

4. **Carrier Frequency Offset:** We have defined phase noise of the local oscillator, becuase of which we get carrier frequency offset in modulator and demodulator. The output signal from the modulator and demodulator has a frequency offset of (f_{off}). The output from the modulator along with carrier frequency offset is given by equation 16.

$$x_{mod_{cfo}}(t) = A_{mod} \times exp(j2\pi(f_{if} + f_{lo} + f_{off})t + \phi) \tag{16}$$

   where A_{mod} is the amplitude of the output signal from the modulator.

Other hardware properties like noise, amplification and loss is specified for each and every model presented in Fig. 1. The tabel of components used in designing of the MFE is presented using Table 1. This tables contains all the parametric values of the components which we have used in Simulink to replicate the component in software simulation.

Table 1: Table of components along with parametric values used for designing the MFE of ISAC.

Component	Part No.	Gain	Noise Figure	Gain Offset	Phase Offset	Leakage	Phase Noise
Modulator [1]	ADMV1013	18 dB	25 dB	0 to 9 dB	0 to 30°	-12 dBm	-
Demodulator [2]	ADMV1014	17 dB	5.5 dB	1 to 9 dB	1 to 30°	-12 dBm	-
Local Oscillator [3]	ADF4372	-	-	-	-	-	-156 dBc/Hz
Power Amplifier [4]	ADPA7008	17 dB	8 dB	-	-	-	-
Low Noise Amplifier [5]	PE15A3260	40 dB	2.5	-	-	-	-

Link to the Github Repository: `https://github.com/Dr-Jai-Mangal/MMW_ISAC.git`

References

[1] A. Devices, "Admv1013 data sheet." https://www.analog.com/media/en/technical-documentation/data-sheets/admv1013.pdf. Accessed: February 13, 2025.

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[3] A. Devices, "Adf4372 datasheet." https://www.analog.com/media/en/technical-documentation/data-sheets/adf4372.pdf. Accessed: February 13, 2025.

[4] A. Devices, "Adpa7008 datasheet." https://www.mouser.in/datasheet/2/609/adpa7008-3121474.pdf. Accessed: February 13, 2025.

[5] Pasternack, "Pe15a3260 datasheet." https://www.pasternack.com/images/ProductPDF/PE15A3260.pdf. Accessed: February 13, 2025.