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

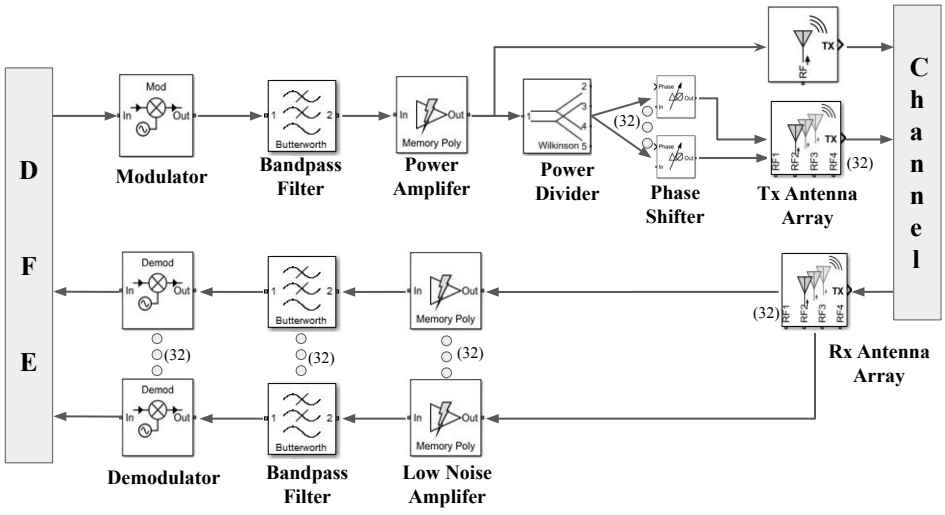

Figure 1: Simulink block level representation of MFE.

The Simulink model, along with the signal flow and processing involved in the MFE system, is presented in Fig. 1. The modulator upconverts the output signal from DAC of DFE to mmWave frequency. The output from both the I mixer and the Q mixer is fed to power combiner. Next, the signal passes through a bandpass filter to remove unwanted frequency components and retain only the desired band in the modulated signal. After filtering, the signal is fed into a power amplifier, which boosts the signal

strength to ensure proper transmission over a wireless channel for compensating signal attenuation over long distances. For radar operation, the output signal is fed into a dipole antenna and transmitted omnidirectionally. The signal is then passes through the channel and strikes to the MU. The signal is then reflected from the MU. However for the communication operation the analog beamforming is performed. The output from the power amplifier is fed into the phase shifters. The signal is then fed into the 16 element uniform linear dipolar antenna array and transmitted directionally over the air.

At the receiver side, the receive antenna array captures the incoming signal from MU. The received signal is then passed through an LNA, which amplifies the weak signal. Then the signal undergoes filtering through another bandpass filter, which removes out-of-band noise and retains the relevant frequency components. Finally, the demodulator extracts the original baseband signal by removing the carrier frequency component. The resulting signal is the recovered baseband signal, which can then be processed further for data extraction.

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).

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 1 and 2.

$$x_{dac,i}(t) = (A + 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi + 0.5(\phi_{iq})) \tag{1}$$

$$x_{dac,q}(t) = (A - 0.5 * G_{IQ}) \times exp(j2\pi f_{if}t + \phi - 0.5(\phi_{iq})) \tag{2}$$

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.

2.1 Modulator

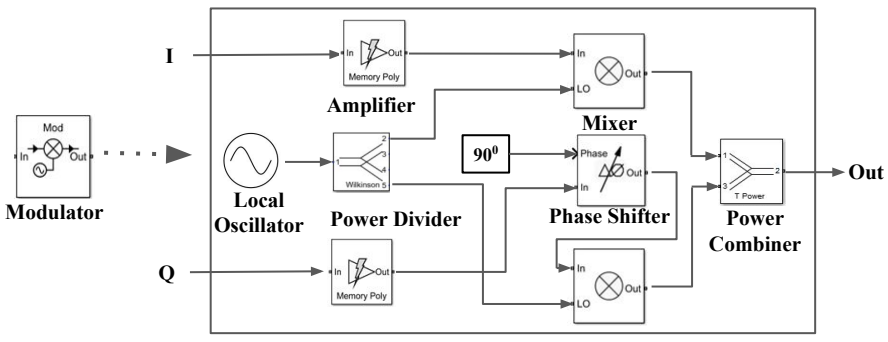

Figure 2: Simulink block level representation of internal architecture of modulator used in MFE.

Figure 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.

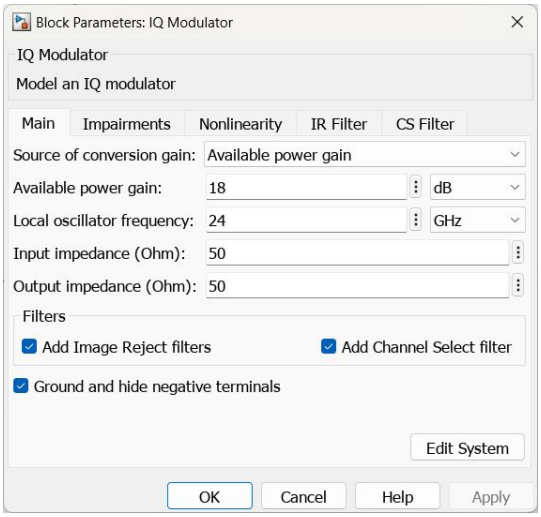

Figure 3: Block parameters of IQ modulator.

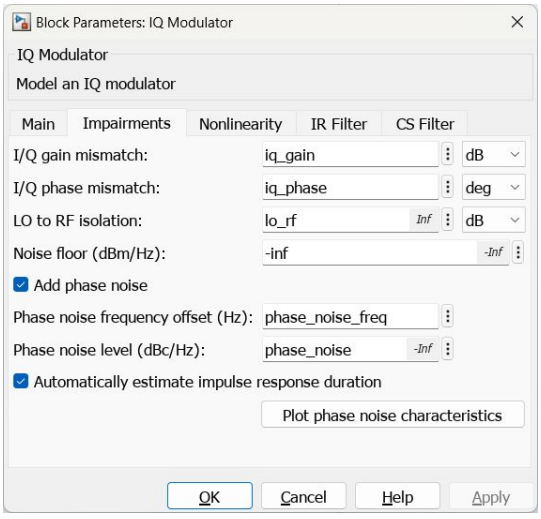

Figure 4: Hardware imapirment parameters of IQ modulator.

The parameters of the IQ modulator based on the hardware specification can be inserted into the Simulink block as presented in Figures 3 and 4. Multiple parameters can be tuned like the gain from the amplifier inside the modulator and the frequency of the local oscillator. In terms of hardware imapairment parameter we have explored IQ gain imabalance, IQ phase imbalance, LO to RF leakage and phase noise which results in carrier frequency offset. These parameters can be tuned for other hardware specifications

as well. The Simulink blocks act a GUI and take these parameters. It will then put it into the equations explained above and provide the results based on input hardware parameters.

2.2 Demodulator

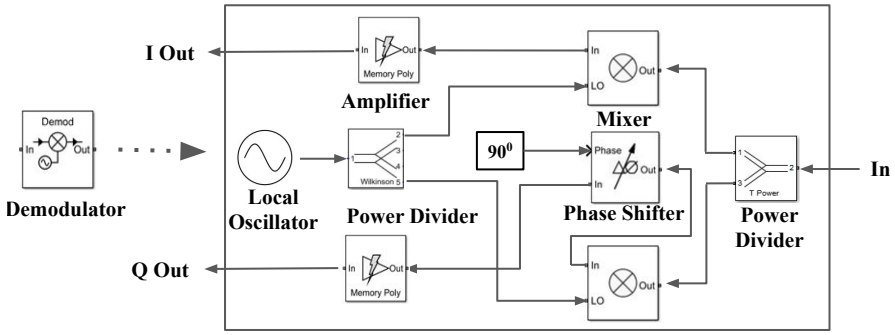

Figure 5: Simulink block level representation of internal architecture of demodulator used in MFE.

Figure 5 presents the simulink block level representation of internal architecture of demodulator which is used as one of the component to design MFE. The implemented demodulator is an IQ demodulator which has a phase difference of 90°in each branch. The demodulator has a local oscillator embedded inside it which provides the carrier frequency to demodulate the input signal from mmWave frequency to IF 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 demodulation and provides us with the output demodulated at IF frequency. The output from both the I mixer and the Q mixer is fed to amplifier. The output of the amplifier is then fetched from the respective I and Q branches of the demodulator.

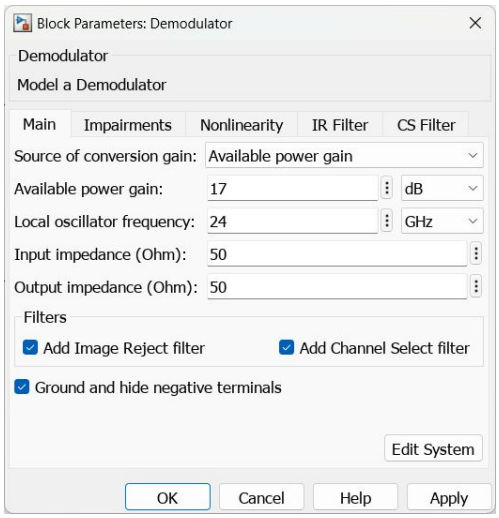

Figure 6: Block parameter of IQ demodulator.

The parameters of the IQ demodulator based on the hardware specification can be inserted into the Simulink block as presented in Fig. 6. It has the same interface as IQ 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.

Ref.	Component	Part No.	Gain	Noise Figure	Gain Offset	Phase Offset	Leakage	Phase Noise
[1]	**Modulator**	ADMV1013	18 dB	25 dB	0 to 9 dB	0 to 30°	-12 dBm	-
[2]	**Demodulator**	ADMV1014	17 dB	5.5 dB	1 to 9 dB	1 to 30°	-12 dBm	-
[3]	**Local Oscillator**	ADF4372	-	-	-	-	-	-156 dBc/Hz
[4]	**Power Amplifier**	ADPA7008	17 dB	8 dB	-	-	-	-
[5]	**Low Noise Amplifier**	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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[4] A. Devices, "Adpa7008 datasheet." `https://www.mouser.in/datasheet/2/609/adpa7008-3121474.pdf`. Accessed: February 13, 2025.

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