

MIMO Radar

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ABSTRACT

MIMO radar is a key technology in improving the angle resolution (spatial resolution) of mmwave-radars. This article introduces the basic principles of the MIMO-radar and the different design possibilities. The application report also briefly discusses ways to implement MIMO-radar on the TI mmwave product line.

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1 Introduction

The term single-input-multiple-output (SIMO) radar refers to a radar device with a single transmit (TX) and multiple receive (RX) antennas. The angle resolution of a SIMO radar depends on the number of RX antennas. For example, a device with four RX antennas has an angle resolution of about 30°, while a device with eight RX antennas has an angle resolution of about 15°. Therefore, a direct approach to improving the angle resolution requires increasing the number of RX antennas. This approach has its limits because each additional RX antenna requires a separate RX processing chain on the device (each with an LNA, mixer, IF filter, and ADC).

Multiple-input-multiple-output (MIMO) refers to a radar with multiple TX and multiple RX antennas. As discussed later, the angle resolution of a MIMO radar with N_{TX} TX antennas and N_{RX} RX antennas can be made equivalent to that of a SIMO radar with $N_{TX} \times N_{RX}$ RX antennas. The MIMO radar therefore provides a cost-effective way to improve the angle resolution of the radar.

This application note serves as an introduction to the MIMO radar and equips engineers with sufficient information to design a MIMO radar application using the mmWave product line from TI. [Section 2](#) is a quick overview of the basics of angle estimation. [Section 3](#) lays out the foundational principles of the MIMO radar. This section explains how multiplexing transmissions across TX antennas can improve angle resolution. [Section 4](#) discusses different strategies for multiplexing the TX antennas. [Section 5](#) includes a discussion on implementing the MIMO radar, using the TI radar product line.

2 Angle Estimation Basics

Estimating the angle of arrival of an object requires at least two RX antennas. [Figure 1](#) shows a radar that has one TX antenna and two RX antennas separated by a distance, d .

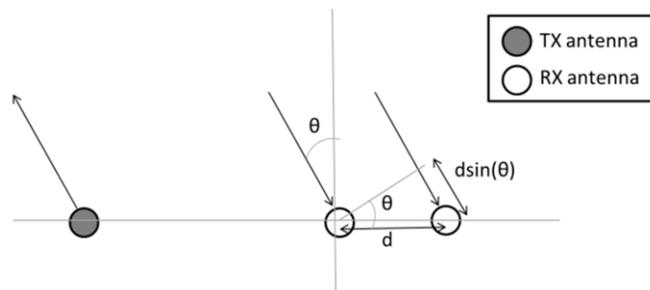


Figure 1. Angle Estimation Using Two RX Antennas

The signal from the TX antenna is reflected from an object (at an angle θ with regard to the radar) and is received at both RX antennas. The signal from the object must travel an additional distance of $d\sin(\theta)$ to reach the second RX antenna. This corresponds to a phase difference of $\omega = (2\pi / \lambda)d\sin(\theta)$ between the signals received at the two RX antennas. Therefore, when the phase difference, ω , is estimated, the angle of arrival, θ , can be computed using [Equation 1](#).

$$\theta = \sin^{-1}\left(\frac{\omega\lambda}{2\pi d}\right) \tag{1}$$

Because the phase difference, ω , can be uniquely estimated only in the range $(-\pi, \pi)$, it follows by substituting $\omega = \pi$ in [Equation 1](#), that the unambiguous field of view (FOV) of the radar is as follows in [Equation 2](#).

$$\theta_{FOV} = \pm \sin^{-1}\left(\frac{\lambda}{2d}\right) \tag{2}$$

Thus, the maximum FOV of [Equation 3](#) is achieved with an interantenna distance, $d = \lambda/2$.

$$\theta_{FOV} = \pm 90^\circ \tag{3}$$

In general, a radar has $N_{RX} > two$ RX antennas, as shown in [Figure 2](#) for the case of $N_{RX}= 4$. The signal at each subsequent antenna has an additional phase-shift of ω with respect to the preceding antenna. Therefore, a linear progression in the phase of the signal (with reference to the first RX antenna) across the N antennas (for example, $[0 \ \omega \ 2\omega \ 3\omega]$ in [Figure 2](#)) occurs. Thus, ω can be reliably estimated by sampling the signal across the N_{RX} antennas, and performing an FFT (often referred to as the angle-FFT) on this signal sequence.

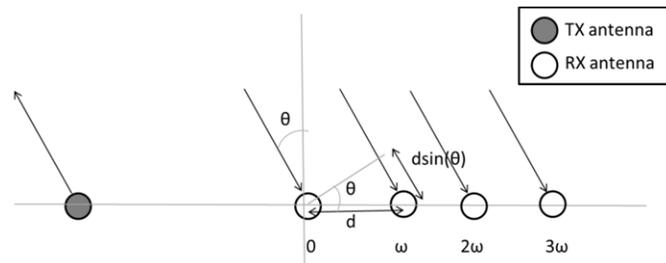


Figure 2. Angle Estimation Using Four RX Antennas

NOTE: A typical FMCW radar signal processing chain also includes a range-FFT and a Doppler-FFT that are performed before the angle-FFT. These resolve objects in the range and Doppler dimensions. For more information, see [Section 6](#).

Increasing the number of antennas results in an FFT with a sharper peak, thus, improving the accuracy of angle estimation and enhancing the angle resolution. [Figure 3](#) shows the angle-FFT from a radar device with four and eight antennas (interantenna distance of $\lambda / 2$), and two point objects at $\theta = -10^\circ$ and $\theta = +10^\circ$. The radar device with four antennas cannot resolve the two objects; however, the radar device with eight antennas can.

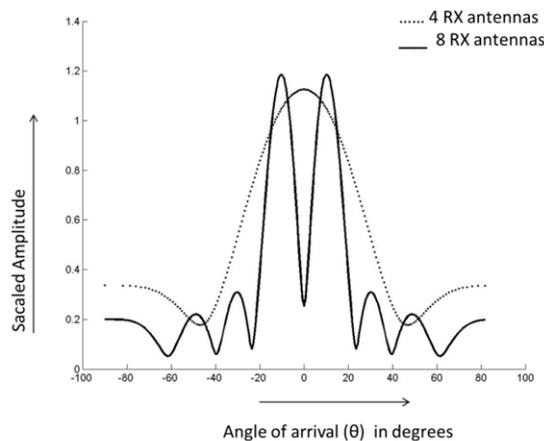


Figure 3. Angle Resolution Improves With Increasing Number of RX Antennas

[Appendix A](#) discusses that for an RX antenna array with N equispaced antennas (separated by $\lambda / 2$), the angle resolution is given by [Equation 4](#).

$$\theta_{RES} = 2 / N \tag{4}$$

3 Principle of the MIMO Radar

Building on the discussion of Section 2, let us say we want to double the angle resolution (half θ_{res}) capability of the radar in Figure 2. One way to double the angle resolution is to double the number of RX antennas (from four to eight), as shown in Figure 4.

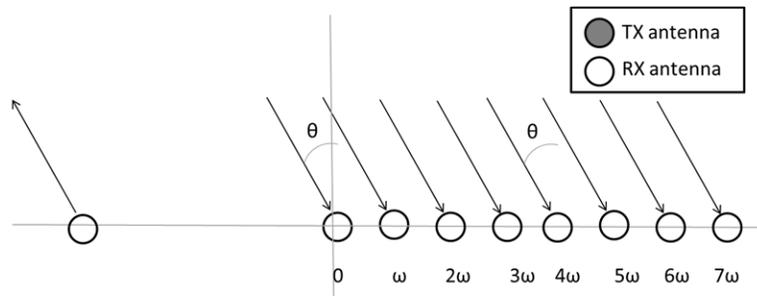


Figure 4. Radar With 1 TX and 8 RX Antennas

Using MIMO concepts, the same result can be achieved with just one additional TX antenna, discussed as follows in reference to Figure 5.

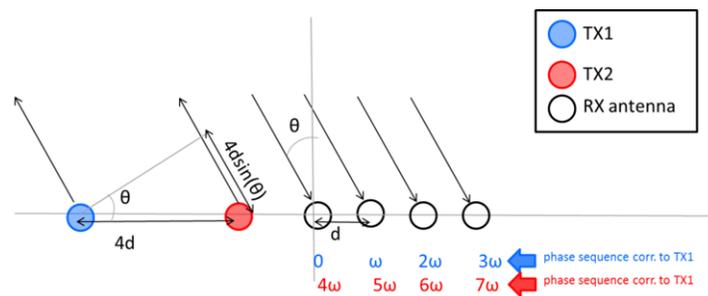


Figure 5. Principle of MIMO Radar

The radar in Figure 5 has two transmit antennas, TX1 and TX2. A transmission from TX1 results in a phase of $[0 \ \omega \ 2\omega \ 3\omega]$ at the four RX antennas (with the first RX antenna as a reference). Because the second TX antenna (TX2) is placed a distance of $4d$ from TX1, any signal emanating from TX2 traverses an additional path of length $4d\sin(\theta)$ compared to TX1. Correspondingly, the signal at each RX antenna sees an additional phase-shift of 4ω (with regard to transmission from TX1). The phase of the signal at the four RX antennas, due to a transmission from TX2, is $[4\omega \ 5\omega \ 6\omega \ 7\omega]$. Concatenating the phase sequences at the four RX antennas, due to transmissions from TX1 and TX2, gets the sequence $[0 \ \omega \ 2\omega \ 3\omega \ 4\omega \ 5\omega \ 6\omega \ 7\omega]$, which is the same sequence seen in Figure 4 with one TX and eight RX antennas. It can be said that the 2TX – 4RX antenna configuration of Figure 4 synthesizes a virtual array of eight RX antennas (with one TX antenna being implied).

To generalize the previous discussion, with N_{TX} and N_{RX} antennas, users can generate (with proper antenna placement) a virtual antenna array of $N_{TX} \times N_{RX}$. Thus, employing MIMO radar techniques, results in a multiplicative increase in the number of (virtual) antennas, and corresponds to improvement in the angle resolution.

If p_m denotes the coordinates of the m^{th} TX antenna ($m = 0, 1, \dots, N_{TX}$), and q_n denotes the coordinates of the n^{th} RX antenna ($n = 0, 1, 2, \dots, N_{RX}$), then the location of the virtual antennas can be computed as $p_m + q_n$, for all possible values of m and n . For example in Figure 5, $p_1 = 0$ and $p_2 = 4$, and $q_1 = 0$, $q_2 = 1$, $q_3 = 2$, and $q_4 = 3$ (where the coordinates are expressed in units of d , and the TX1 (respectively RX1) is assumed to be the origin for the TX (respectively, RX) antennas).

Figure 6 shows the principle of MIMO radar can also be extended to multidimensional arrays.

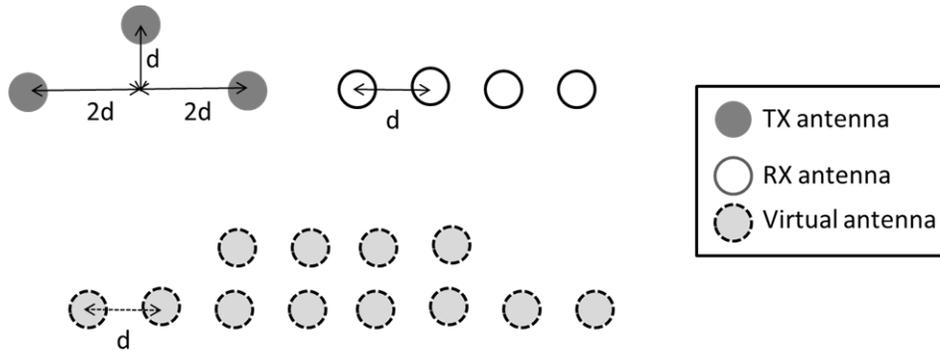


Figure 6. A 2-Dimensional MIMO Array (With Azimuth and Elevation Estimation Capability)

Different physical antenna configurations can be used to realize the same virtual antenna array. Figure 7 shows these configurations, where the physical arrays in Fig. (a) and Fig. (b) both synthesize the same virtual array of Fig. (c). In such cases, ease of onboard placement and routing may dictate the final choice.

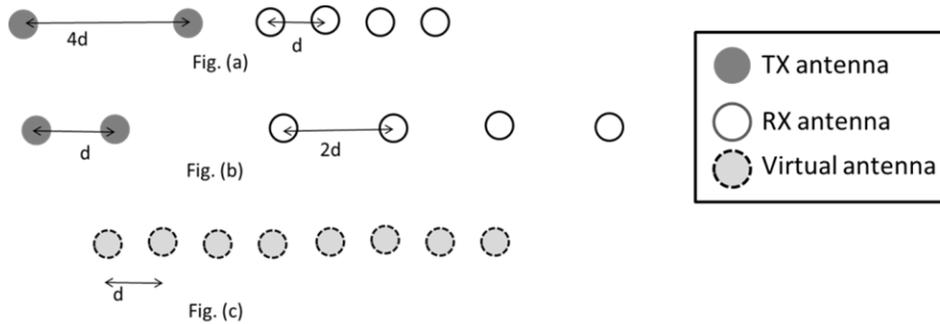


Figure 7. Different Configurations That Realize the Same Virtual Antenna Array

4 Multiplexing Strategies for the MIMO Radar

Section 3 detailed how the MIMO radar works by having the same set of RX antennas process signals from transmissions by multiple TX antennas. It is important to note that the RX antennas must be able to separate the signals corresponding to different TX antennas (for example, by having different TX antennas transmit on orthogonal channels). There are different ways to achieve this separation[3], and two such techniques are discussed here: time division multiplexing (TDM) and binary phase modulation (BPM). These techniques are described as follows, in the context of frequency-modulated continuous-wave (FMCW) radars, though the techniques have much wider applicability. For an introduction to FMCW radar technology, see [5].

4.1 Time Division Multiplexing (TDM-MIMO)

In TDM-MIMO [1], the orthogonality is in time. Each frame consists of several blocks, with each block consisting of N_{TX} time slots each corresponding to transmission by one of the N_{TX} TX antennas. In Figure 8, for an FMCW radar with $N_{TX} = 2$, alternate time slots are dedicated to TX1 and TX2. TDM-MIMO is the most simple way to separate signals from the multiple TX antennas and is therefore widely used.

In a typical processing scheme for TDM-MIMO FMCW radar, the 2D-FFT (range-Doppler FFT[5]) is performed for each TX-RX pair. Each 2D-FFT corresponds to one virtual antenna. A radar with $N_{TX} = 2$ and $N_{RX} = 4$, would compute $4 \times 2 = 8$, and such range-Doppler matrices as shown in Figure 9. The 2D-FFT matrices are then noncoherently summed to create a predetection matrix, and then a detection algorithm identifies peaks in this matrix that correspond to valid objects. For each valid object, an angle-FFT is performed on the corresponding peaks across these multiple 2D-FFTs, to identify the angle of arrival of that object. Prior to applying angle-FFT, a Doppler correction step must be performed in order to correct for any velocity induced phase change.

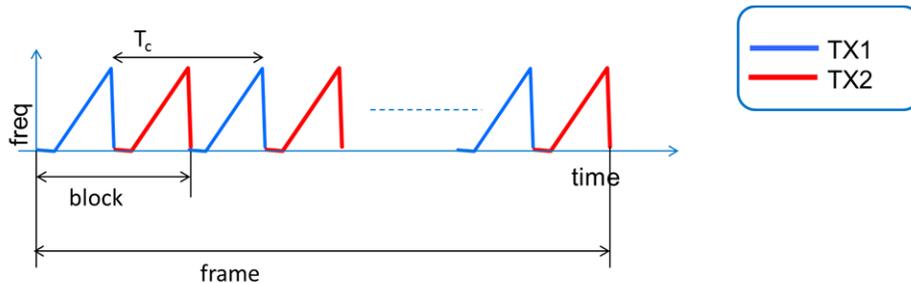


Figure 8. TDM-MIMO

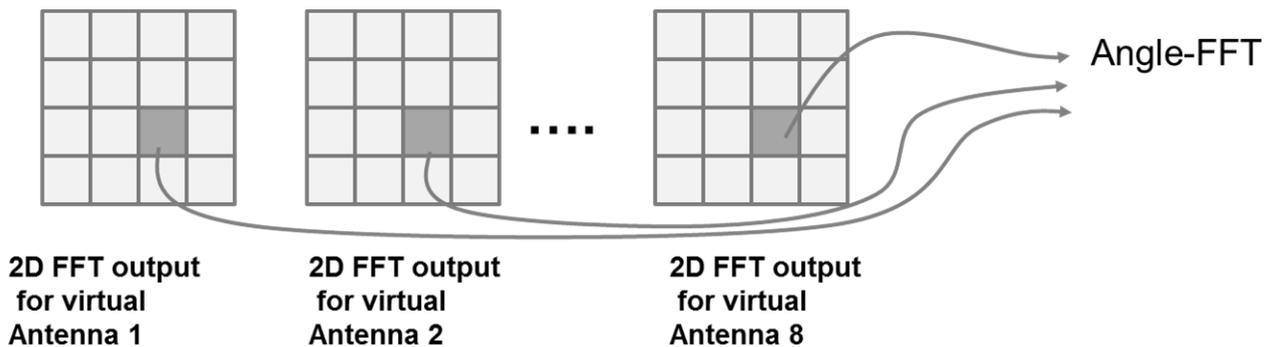


Figure 9. Angle Estimation in MIMO Radar

4.2 BPM-MIMO

The TDM-MIMO scheme previously described is simple to implement, however, it does not use the complete transmission capabilities of the device (because only one transmitter is active at any time). Techniques exist which are centered on modulating the initial phase of chirps in a frame, which allow simultaneous transmission across multiple TX antennas while still ensuring separation of these signals. In BPM-MIMO, these phases are either 0° or 180° (equivalent to multiplying each chirp by $+1$ or -1). One such variant of BPM-MIMO is described as follows.

Similar to TDM-MIMO, a frame consists of multiple blocks, each block consisting of N_{TX} consecutive transmissions. However, unlike TDM-MIMO (where only one TX antenna is active per time slot), all the N_{TX} antennas are active in each of the N_{TX} time slots of every block. For each block, the transmissions from multiple TX antennas are encoded with a spatial code (using BPM), which allows the received data to be subsequently sorted by each transmitter. In TDM-MIMO, the power that can be transmitted in each time slot is limited by the maximum power that can be radiated by one TX antenna. Allowing simultaneous transmission on all the N_{TX} transmitters (while still ensuring perfect separation by use of suitable spatial code) lets users increase the total transmitted power per time slot. This translates to an SNR benefit of $10\log_{10}(N_{TX})$.

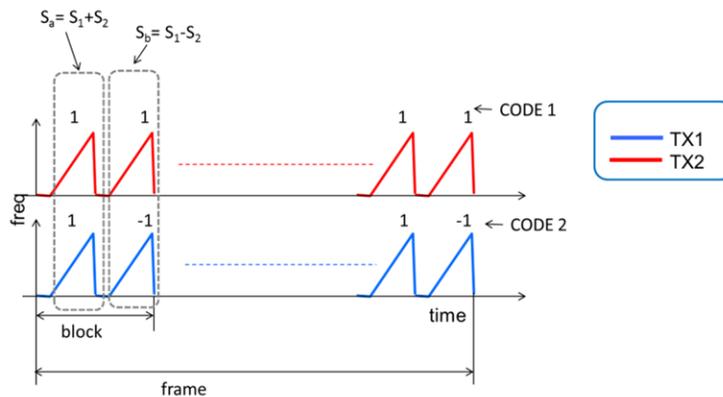


Figure 10. Spatially Encoded BPM-MIMO

Figure 10 shows the technique, for the case of $N_{TX} = 2$. Assume S_1 and S_2 represent chirps from the two transmitters. The first slot in a block transmits a combined signal of $S_a = S_1 + S_2$. Similarly the second slot in a block transmits a combined signal of $S_b = S_1 - S_2$. Using the corresponding received signals (S_a and S_b) at a specific received RX antenna, the components from the individual transmitters can be separated out using $S_1 = (S_a + S_b) / 2$ and $S_2 = (S_a - S_b) / 2$. For an example of $N_{TX} = 4$, where separation is achieved using a 4×4 Hadamard code, see [3].

The processing chain is almost identical to the flow as described earlier in the context of TDM-MIMO, with the exception of a decoding block which enables the signal contributions from the individual TX antennas to be separated in the received data. This decoding must be performed before the angle-FFT (and ideally after the Doppler-FFT, in order to enable phase corrections due to non-zero velocity to be applied prior to decoding).

5 Implementing MIMO Radar on mmWave Sensors

The TI product line of mmwave sensors has the analog front end closely coupled with digital logic. This coupling allows considerable flexibility in designing the TX signal. Further, the state machine within the digital logic allows multiple chirp types and various kinds of frame sequences to be programmed up front, relieving the processor from the burden of controlling the front end on a real-time basis. APIs^[4] which abstract out all the registers in the digital logic and present a simple and intuitive interface to the programmer are also provided. All this content amounts to a programming model that is easy to learn and easy on the processor.

Remember three concepts in mind when programming a TX signal: profile, chirp, and frame. Each of these concepts is briefly described as follows.

- **Profile:** A profile is a template for a chirp and consists of various parameters that are associated with the transmission and reception of the chirp. This includes TX parameters such as the start frequency, slope, duration, and idle time, and RX parameters such as ADC sampling rate. Up to four different profiles can be defined and stored.
- **Chirp:** Each chirp type is associated with a profile and inherits all the properties of the profile. Additional properties that can be associated with each chirp include the TX antennas on which the chirp should be transmitted and any binary phase modulation that should be applied. Up to 512 different chirps types can be defined (each associated with one of the four predefined profiles).
- **Frame:** Frame is constructed by defining a sequence of chirps using the previously defined chirp types. It also possible to sequence multiple frames, each consisting of a different sequence of chirps.

Thus, programming the device for a specific MIMO use case amounts to suitably configuring the profile, chirp, and frame.

Figure 11 shows the steps to configure a device for TDM-MIMO operation and Figure 12 shows the steps to configure a device for BPM-MIMO operation. For the message description corresponding to the profile, chirp, and frame configurations, see [4].

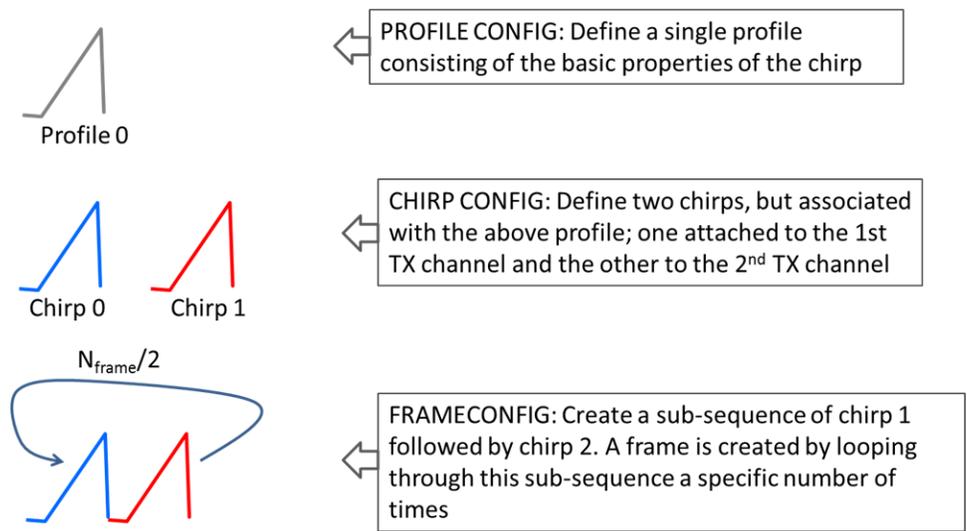


Figure 11. Steps to Configure Device for TDM-MIMO Mode Operation

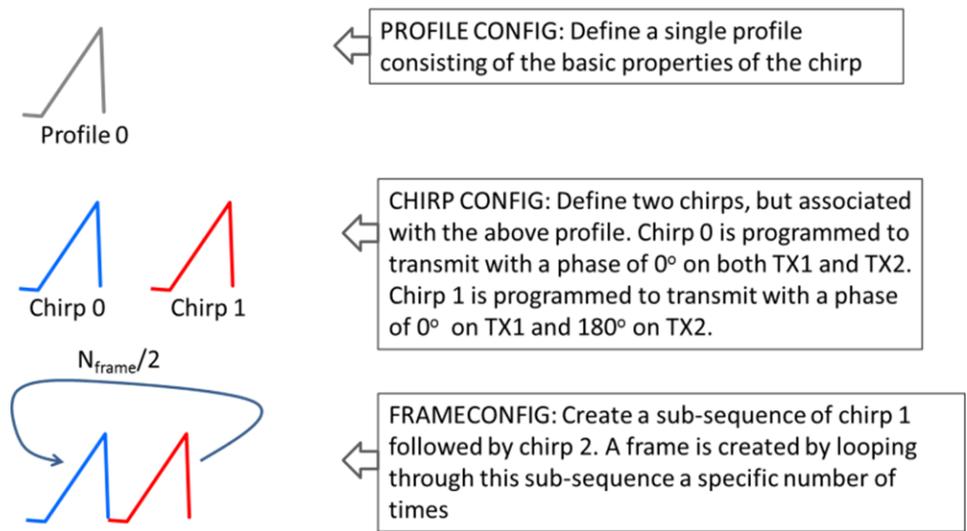


Figure 12. Steps to Configure Device for BPM-MIMO Mode Operation

6 References

1. FC Robey et al., *MIMO Radar Theory and Experimental Results*, 38th Asimolar Conference on Signal, Systems, and Computers
2. RY Chiao et al., *Sparse Array Imaging with spatially-encoded transmits*, IEEE Ultrasonics Symposium
3. H.Sun et al., *Analysis and Comparison of MIMO Radar Waveforms*, 2014 International Radar Conference.
4. *mmWave SDK User's Guide* that is included in <http://www.ti.com/tool/mmwave-SDK>
5. *Introduction to mmWave Sensing: FMCW Radars*

A.1

Consider an object with an angle of arrival θ with respect to the radar. The signal reflected from the object and arriving at the RX antenna array has a spatial frequency of $\omega_1 = \frac{2\pi}{\lambda} d \sin(\theta)$.

Likewise, an object with an angle of arrival of $\theta + \Delta\theta$ has a spatial frequency of $\omega_2 = \frac{2\pi}{\lambda} d \sin(\theta + \Delta\theta)$. Here the term *spatial frequency* refers to the phase-shift across consecutive antennas in the RX array. Equation 5 gives the difference in the spatial frequency corresponding to these two objects.

$$\Delta\omega = \omega_2 - \omega_1 = \frac{2\pi d}{\lambda} (\sin(\theta + \Delta\theta) - \sin(\theta)) \quad (5)$$

Noting that the derivative of $\sin(\theta)$ is $\cos(\theta)$, the expression $\sin(\theta + \Delta\theta) - \sin(\theta)$ can be approximated as $\cos(\theta)\Delta\theta$. Equation 5 now becomes Equation 6.

$$\Delta\omega = \frac{2\pi d}{\lambda} (\cos(\theta)\Delta\theta) \quad (6)$$

We assume that two spatial frequencies separated by $\Delta\omega$ will have distinct peaks in an N-point FFT, as long as their peaks are more than $2\pi / N$ away (corresponding to the size of an FFT bin). Thus, Equation 7 shows the condition for resolving the two objects in the angle-FFT.

$$\begin{aligned} \Delta\omega &> \frac{2\pi}{N} \\ \Rightarrow \frac{2\pi d}{\lambda} (\cos(\theta)\Delta\theta) &> \frac{2\pi}{N} \\ \Rightarrow \Delta\theta &> \frac{\lambda}{Nd \cos(\theta)} \end{aligned} \quad (7)$$

The resolution capability, θ_{res} , is usually quoted for an interantenna spacing of $d = \lambda / 2$ and for a bore-sight view ($\theta=0$), yielding Equation 8.

$$\theta_{RES} = \frac{2}{N} \quad (8)$$

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (May 2017) to A Revision	Page
• Update was made in Section 4.1	6
• Update was made in Section 4.2	7

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