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Introduction to MIMO Radar Waveforms

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Introduction of MIMO Radar

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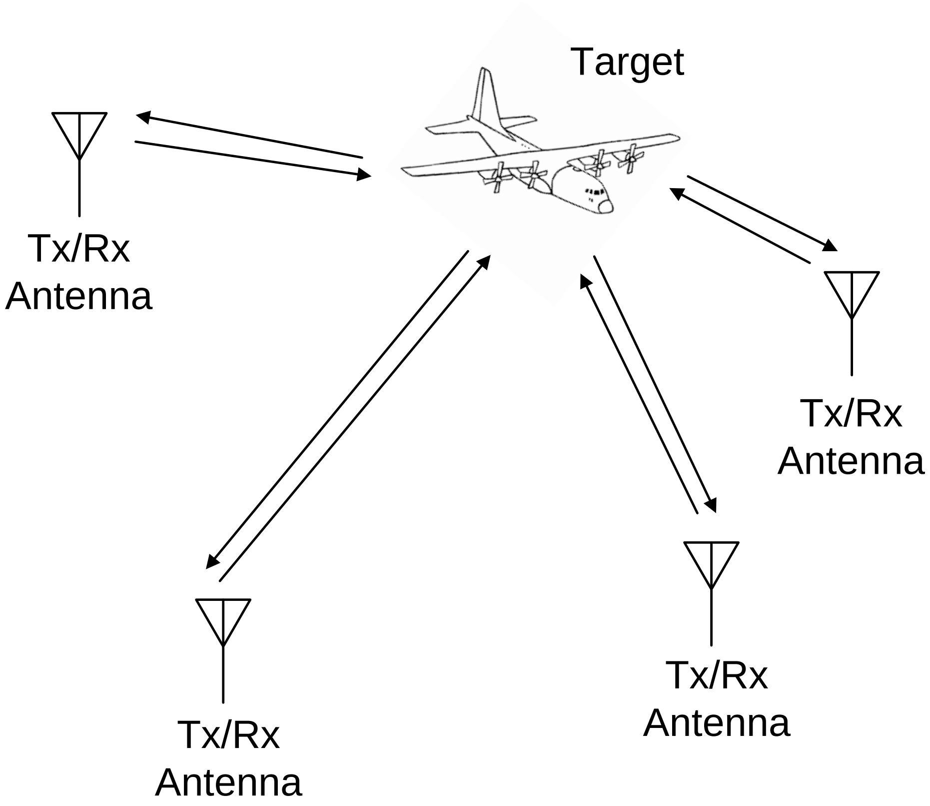
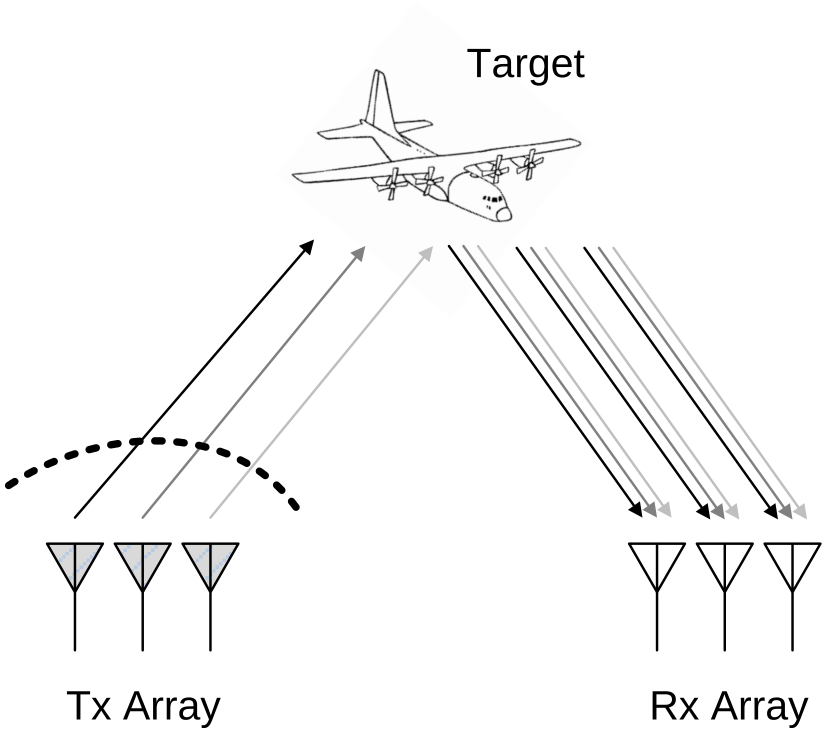
Statistical MIMO Radar v.s. Coherent MIMO Radar

MIMO radar with widely separated antennas
(Statistical MIMO radar)



- Diversity gain to overcome the RCS fading and achieve more robust detection performance

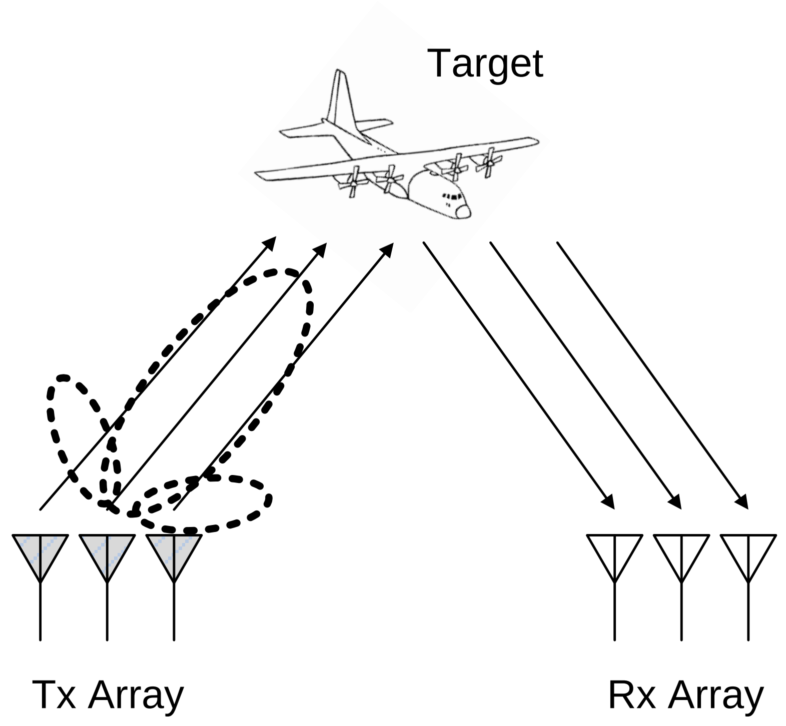
MIMO radar with co-located antennas
(Coherent MIMO Radar)



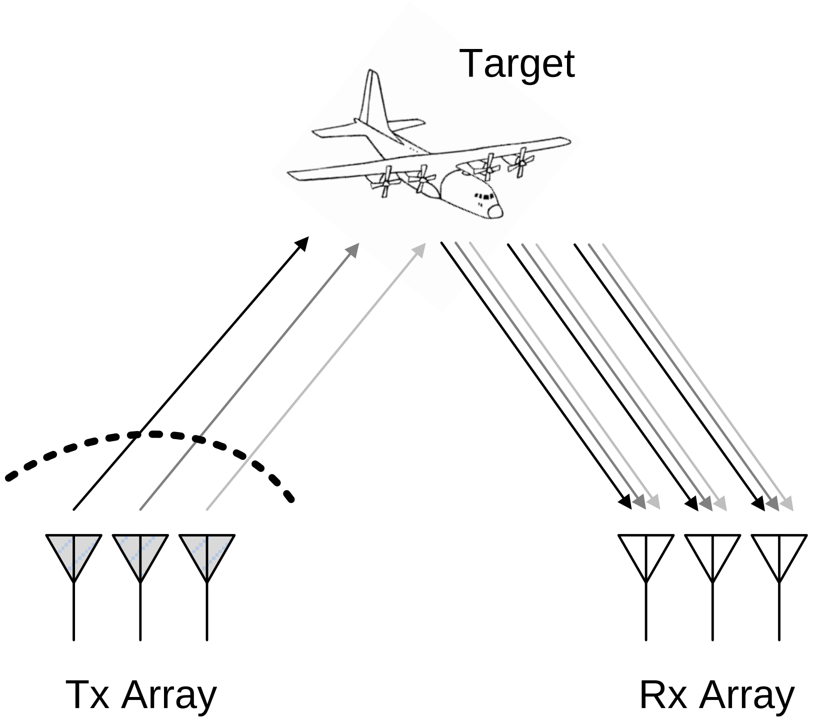
- Flexibility of extending array aperture (in 1D or 2D) with less number of Tx/Rx elements

Coherent MIMO Radar v.s. Phased Array Radar

Phased Array Radar

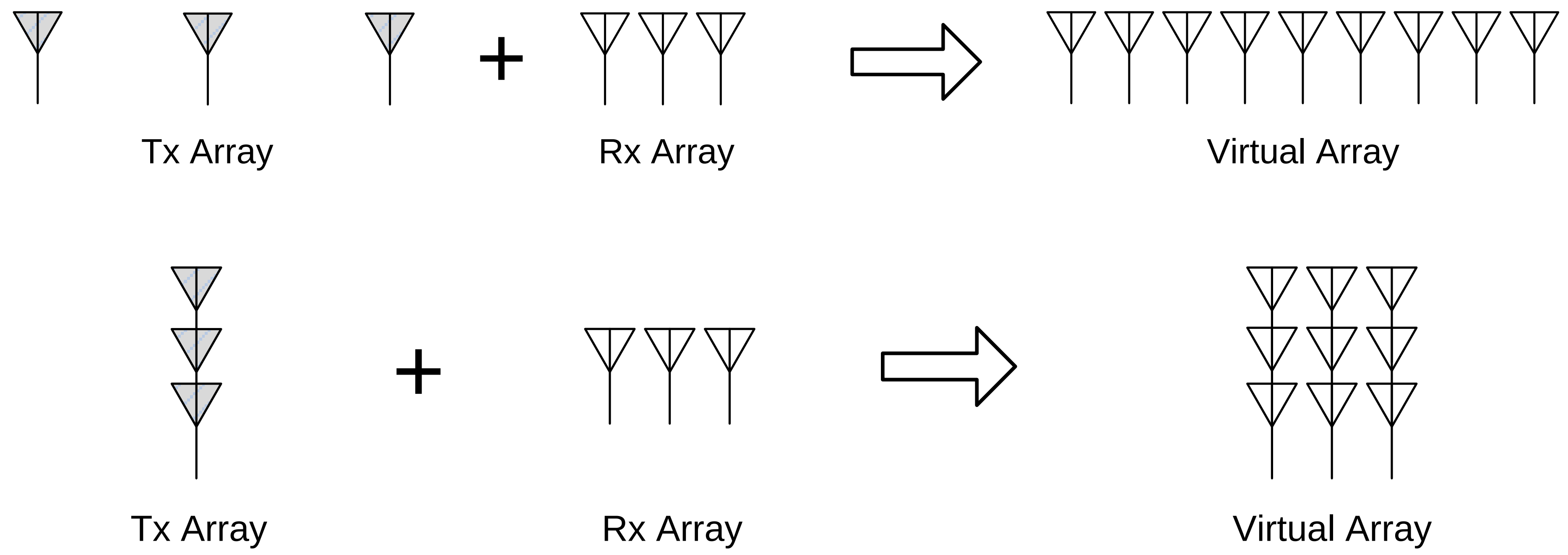


Coherent MIMO Radar



- Loss of transmit array gain
- Continuous illumination with longer coherent integration gain

Virtual Aperture of MIMO Radar



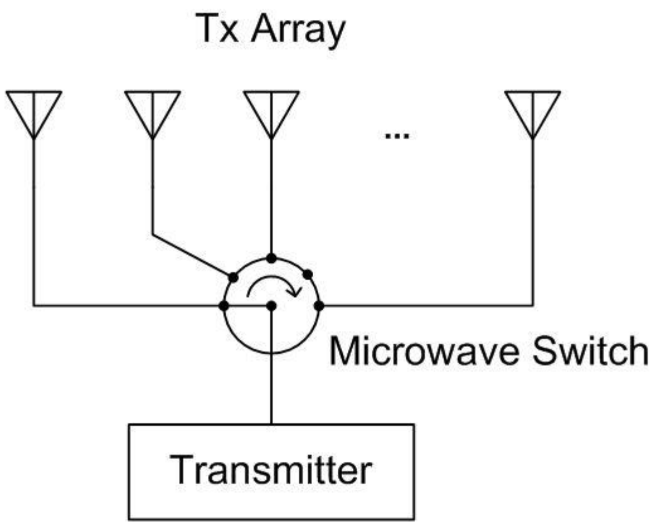
Virtual array formed by different MIMO configurations

Typical MIMO Radar Waveforms

(TDMA, DDMA, CDMA, FDMA, Hadamard coding, circulating waveforms)

Time Division Multiple Access (TDMA) Waveform – Alternative Transmission

- Easy to implement and with almost ideal orthogonality.
- Cannot make full use of Tx resource.



Example: MIMO-SAR imaging (FHR, Germany)

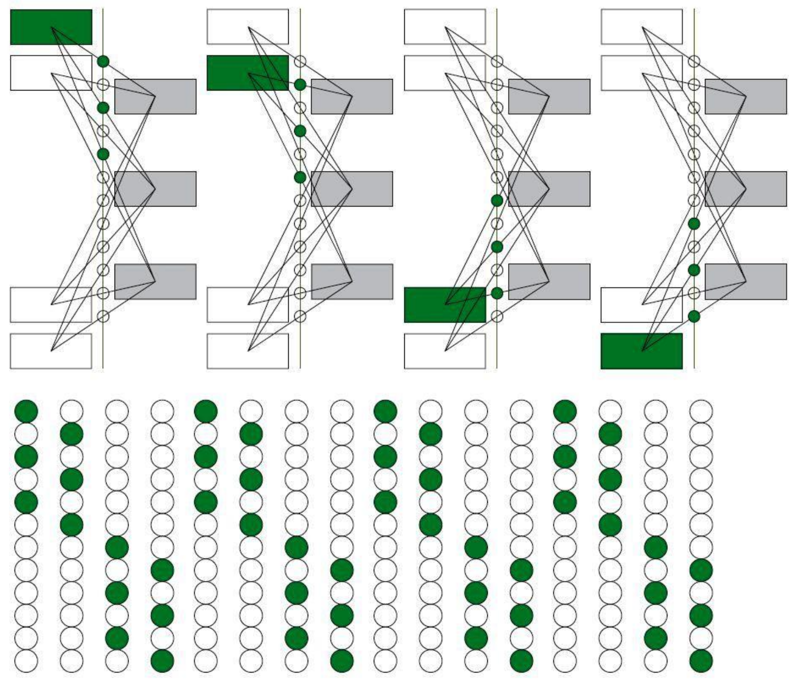
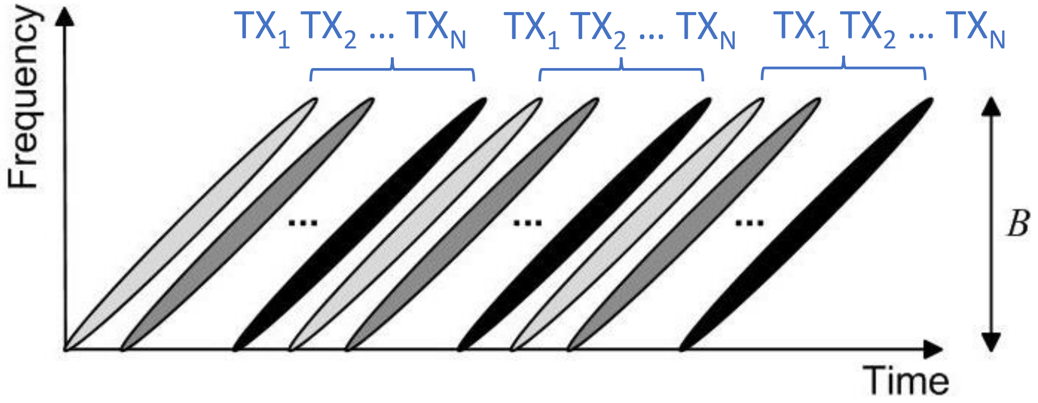


Fig. 3. Tx switching and the resulting synthetic array

[Ref] J.H.G. Ender, J. Klare, "System architectures and algorithms for radar imaging by MIMO-SAR", 2009 IEEE International Radar Conference, Pasadena, CA, USA, May 2009

Time Division Multiple Access (TDMA) Waveform – Time Staggered FMCW

- Almost ideal orthogonality.
- Only applicable to low frequency radar with enough PRF tolerance.



Example: HF over-the-horizon radar (DSTO, Australia)

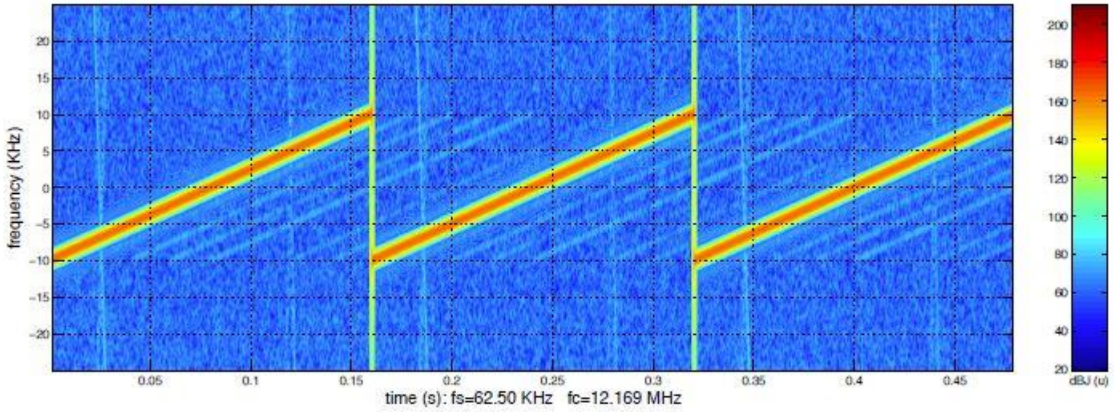


Fig. 3. Spectrogram of the output of one waveform generator and high power amplifier for the case of a staggered linear FMCW waveform set. The signal shown corresponds to one member of the waveform set and is the signal radiated from one transmit array element.

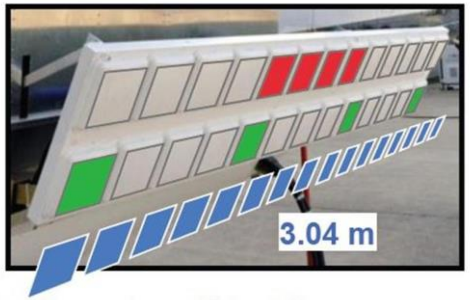
[Ref] G. J. Frazer, Y. I. Abramovich, B. A. Johnsonz, and F. C. Robeyx, "Recent Results in MIMO Over-the-Horizon Radar", 2008 IEEE Radar Conference, Rome, Italy, May 2008, pp.789-794

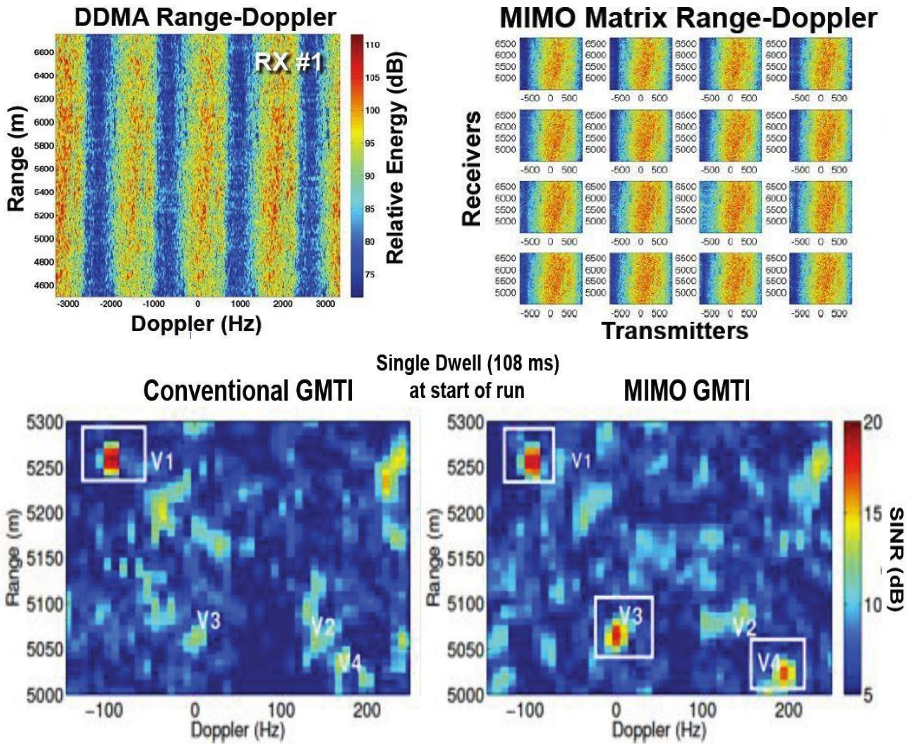
Doppler Division Multiple Access (DDMA) Waveform

- Linear phase ramps are applied to the pulse trains of different transmit antennas to produce different Doppler offsets.
- Almost ideal orthogonality.
- Only applicable to low frequency radar with enough PRF tolerance.

Example: Airborne GMTI radar (MIT Lincoln Laboratory)

MIMO Array Configuration





[Ref] J. Kantor, S.K. Davis, "Airborne GMTI using MIMO techniques", 2010 IEEE International Radar Conference, Washington D.C., US, pp.1344-1349, May 2010

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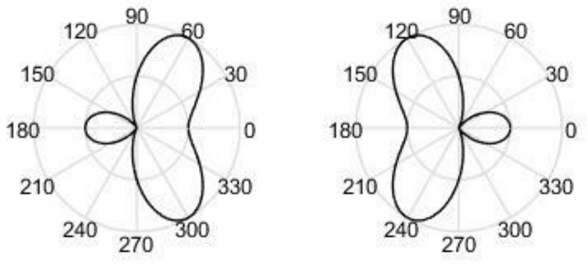
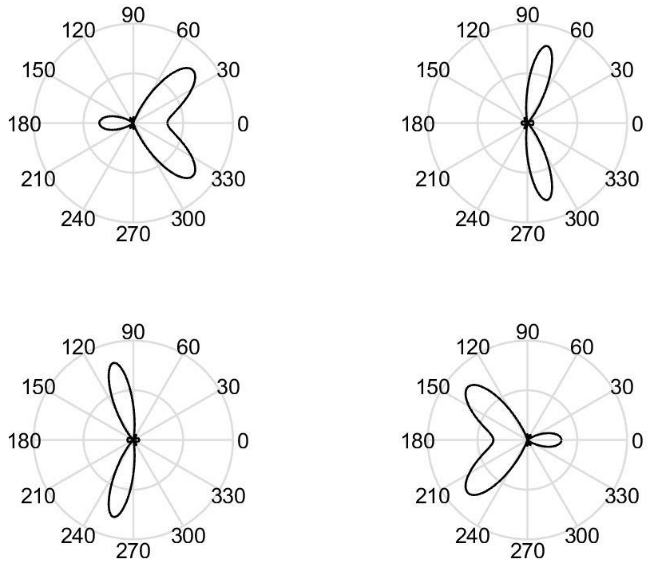
Doppler Division Multiple Access (DDMA) Waveform

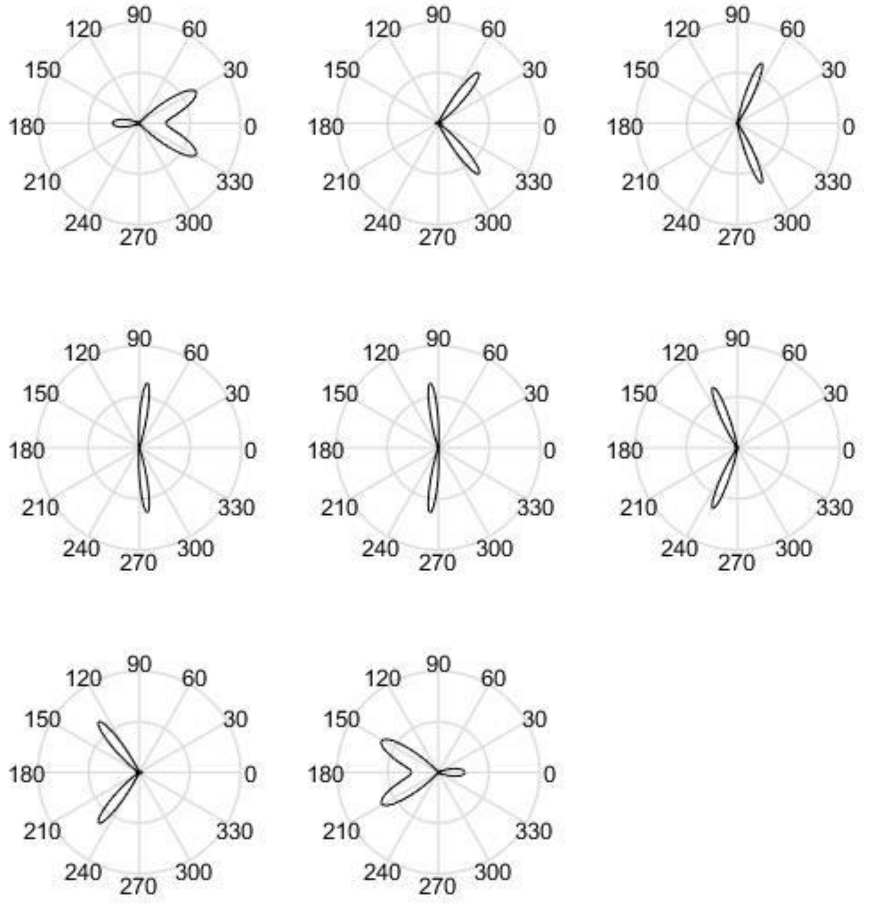
The instantaneous beam patterns of DDMA waveform



2 Tx with normalized Doppler offsets [-0.25, 0.25]



4 Tx with normalized Doppler offsets [-0.375, -0.125, 0.125, 0.375]



8 Tx with normalized Doppler offsets [-0.4375, -0.3125, -0.1875, -0.0625, 0.0625, 0.1875, 0.3125, 0.4375]

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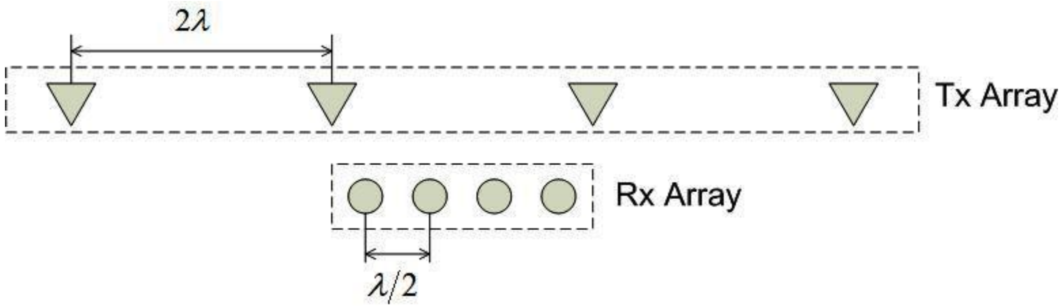
Simulation Parameters

4x4 MIMO Radar Configuration:



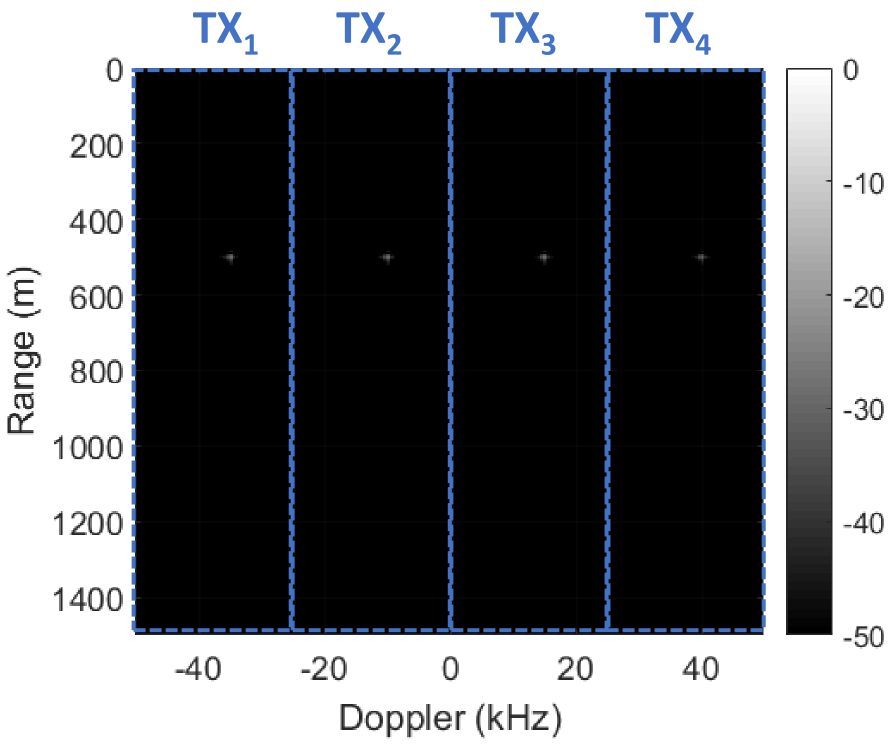
MIMO radar parameters in simulations

Carrier Frequency	35 GHz	**Pulse Width**	1 μs
No. of Transmitting Antennas	4 (two-wavelength interelement spacing)	**Pulse Repetition Interval (PRI)**	10 μs
No. of Receiving Antennas	4 (half-wavelength interelement spacing	**Pulse Repetition Frequency (PRF)**	100 kHz
Array Configuration	Co-linear	**Duty Cycle of Pulse**	10%
Total signal bandwidth	500 MHz	**Coherent Integration Time**	2 ms

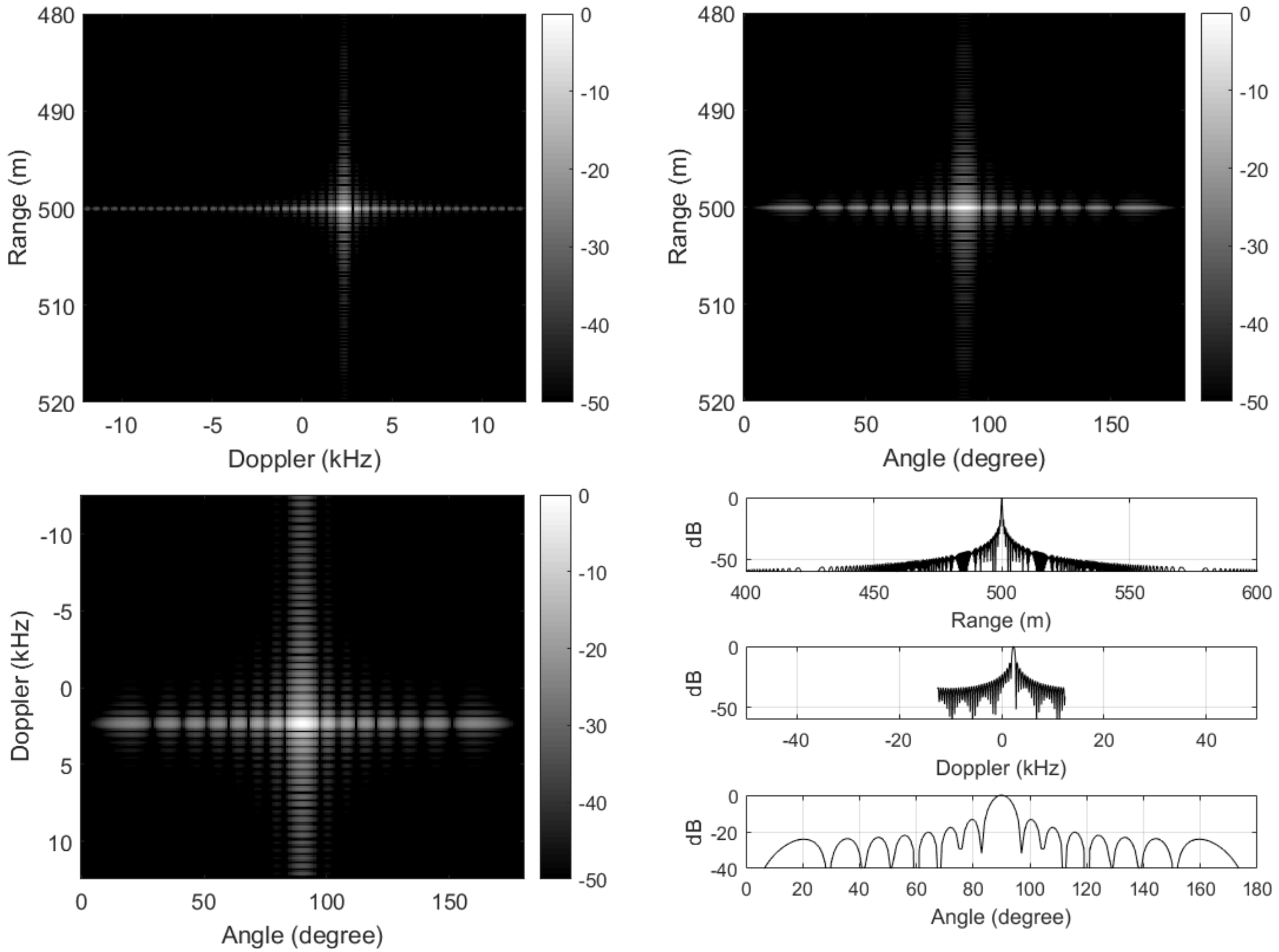
Target parameters in simulations

Range	500 m	**Angle**	90^{o} (array boresight)
Radium Velocity	10 m/s	**Doppler Frequency**	2.333 kHz

Doppler Division Multiple Access (DDMA) Waveform



Range-Doppler plot of DDMA data received by one antenna



Target PSF of DDMA waveform

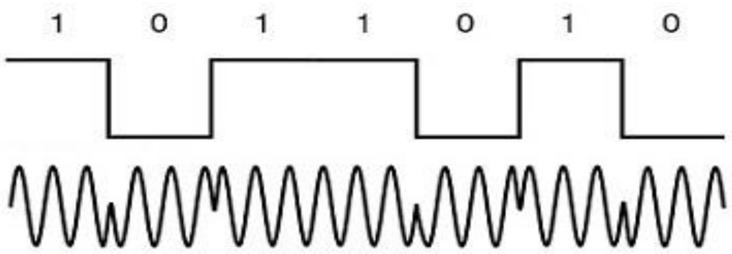
Code Division Multiple Access (CDMA) Waveform

- **Code Division Multiple Access (CDMA) MIMO waveform** means the signals transmitted by different antennas are modulated by different sets of orthogonal phase codes, either in fast-time (i.e., intrapulse modulation) or in slow-time (i.e., interpulse modulation), so that the transmitted signals can be decoded/separated in radar receiver.

- Strictly speaking, the CDMA MIMO waveforms can just approximately satisfy the orthogonality requirement, since the exact orthogonal code sequence with ideal auto- and cross-correlation properties does not exist.

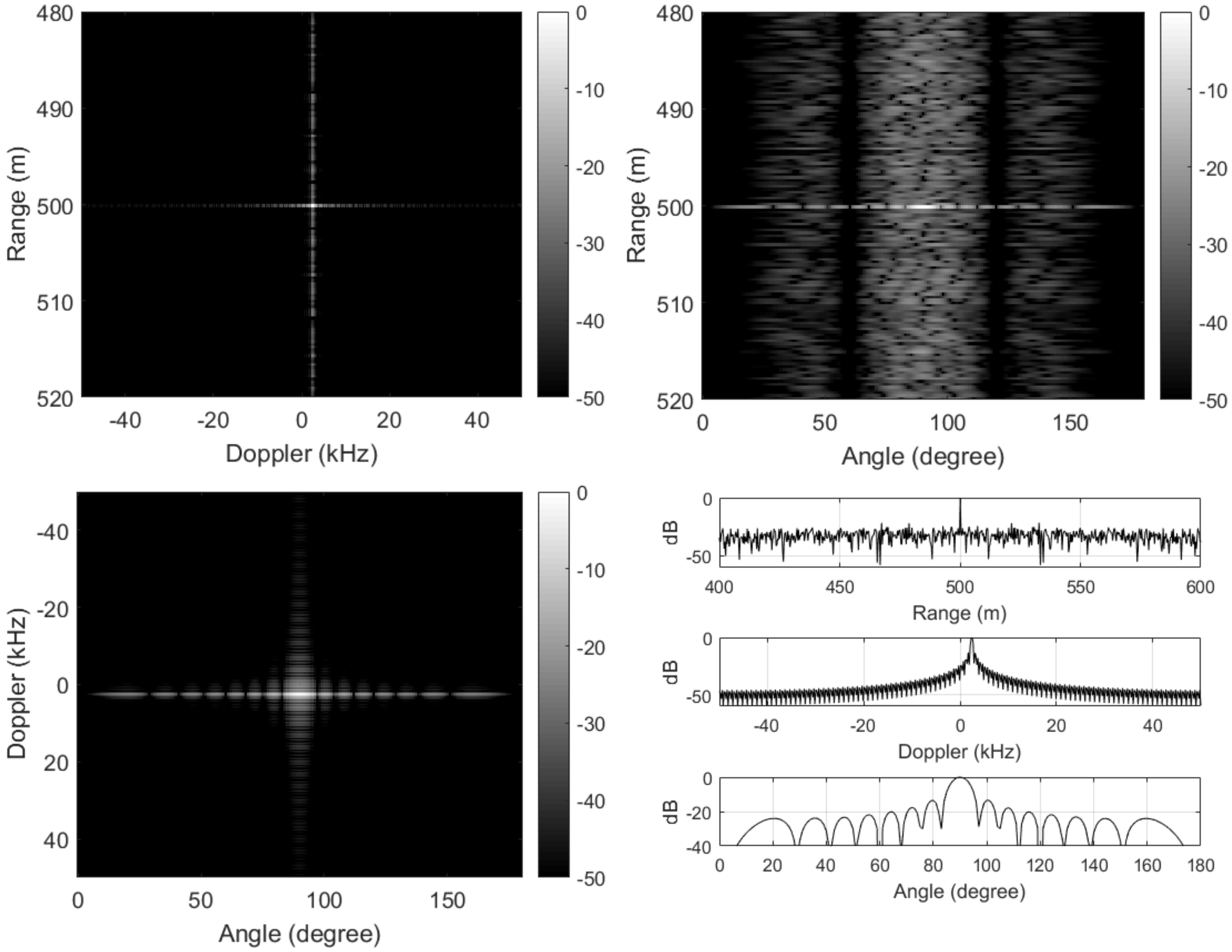
Fast-Time CDMA Waveform

Fast-time CDMA waveform: the phases of pulse signals transmitted by different antenna are modulated by a set of code sequences which are orthogonal to each other within each pulse (→ high range sidelobes), while the phase coding modulation from pulse to pulse remains the same.



Example: Cyclic Algorithm New (CAN)* MIMO code

$$N = B \cdot T_p = 500$$



Target PSF of fast-time CDMA waveform

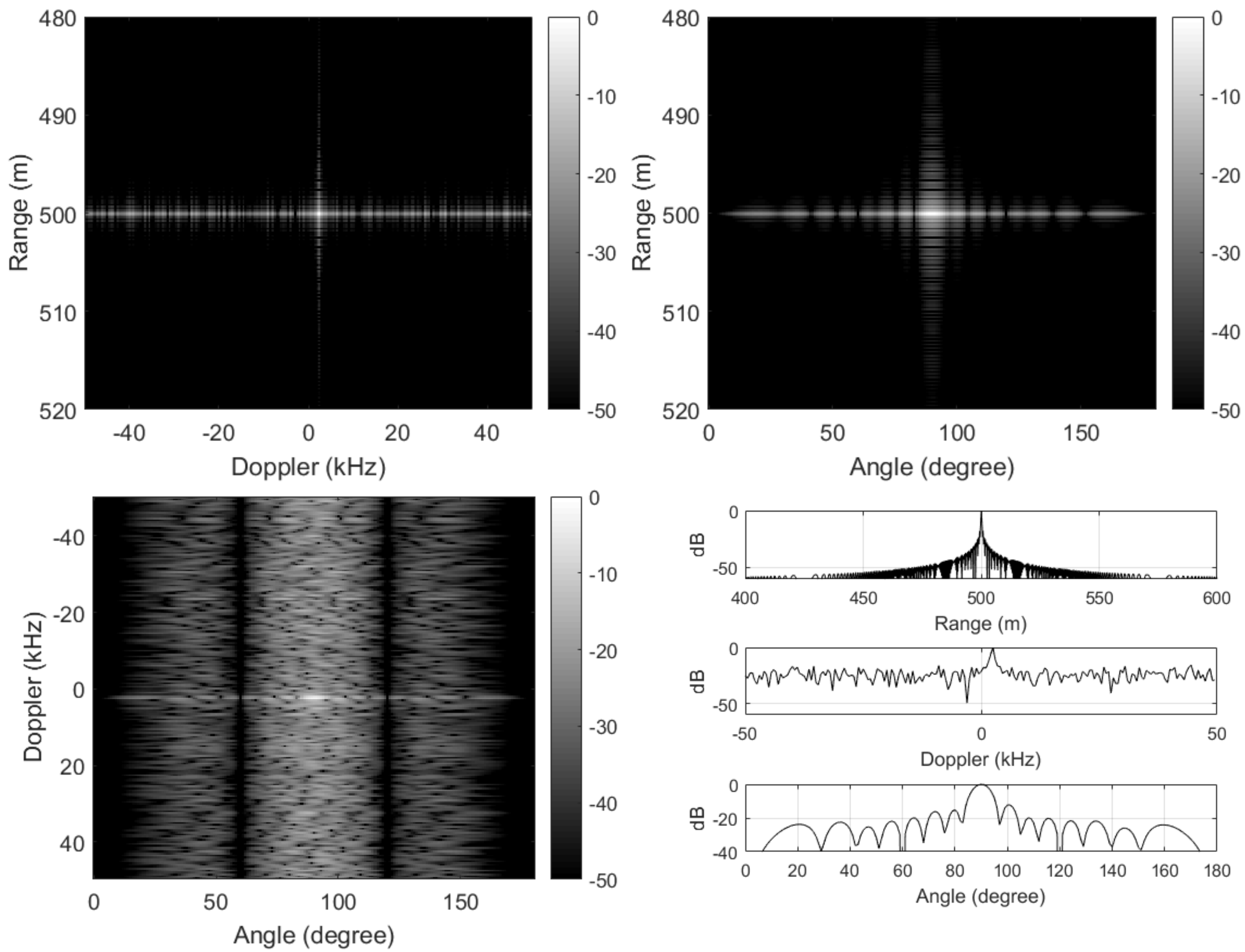
* H. He, P. Stoica, J. Li, "Designing unimodular sequence sets with good correlations – Including an application to MIMO radar", IEEE Transactions on Signal Processing, Vol.57, No.11, pp.4391-4405, Nov 2009

Slow-Time CDMA Waveform

Slow-time CDMA waveform: phase codes are used to modulate the initial phases of the signals from pulse to pulse, and the orthogonality of different transmitted signals are realized across the whole pulse train (→ high Doppler sidelobes, 2D joint processing for Doppler and beamforming is required).

Example: Cyclic Algorithm New (CAN)* MIMO code in 500 pulses.

** H. He, P. Stoica, J. Li, "Designing unimodular sequence sets with good correlations – Including an application to MIMO radar", IEEE Transactions on Signal Processing, Vol.57, No.11, pp.4391-4405, Nov 2009*



Target PSF of slow-time CDMA waveform

Hadamard Coding Waveform

- **Hadamard coding waveform**: the initial phases of N_e successive pulses of N_e transmit antennas are modulated by a N_e-by-N_e Hadamard matrix. At the receive side, the decoding is performed by multiplying the N_e-by-N_e Hadamard matrix to the received N_e successive pulse signals.
- Thus, effectively the unambiguous Doppler range are reduced by N_e times (exactly same as the DDMA waveform). It is only applicable to low frequency radar with enough PRF tolerance. The waveform orthogonality is sensitive to the Doppler frequency of fast moving targets.

Tx Process

The 1st pulse received by Rx

The 1st pulse of 4 Tx elements

Tx signal vector

$$\begin{bmatrix} \boxed{r_1} \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \underbrace{\begin{bmatrix} \boxed{1 \quad 1 \quad 1 \quad 1} \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}}_{\text{Hadamard Matrix}} \begin{bmatrix} \alpha_1 e^{j\theta_1} \\ \alpha_2 e^{j\theta_2} \\ \alpha_3 e^{j\theta_3} \\ \alpha_4 e^{j\theta_4} \end{bmatrix}$$

Rx Process

Reconstructed Tx signal vector

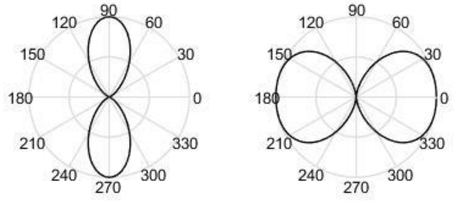
4 pulses received by Rx

$$\begin{bmatrix} \alpha_1 e^{j\theta_1} \\ \alpha_2 e^{j\theta_2} \\ \alpha_3 e^{j\theta_3} \\ \alpha_4 e^{j\theta_4} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}}_{\text{Hadamard Matrix}} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix}$$

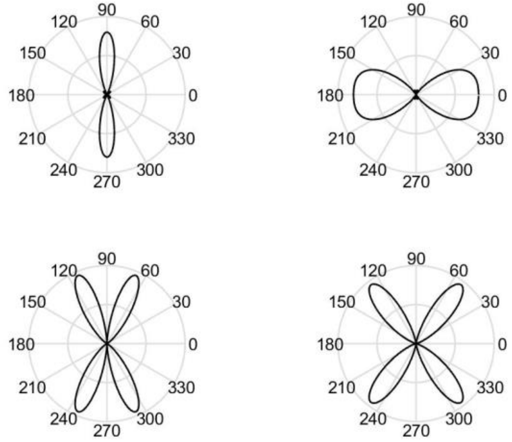
Hadamard Coding Waveform

The instantaneous beam patterns of Hadamard coding waveform for 2, 4 and 8 Tx

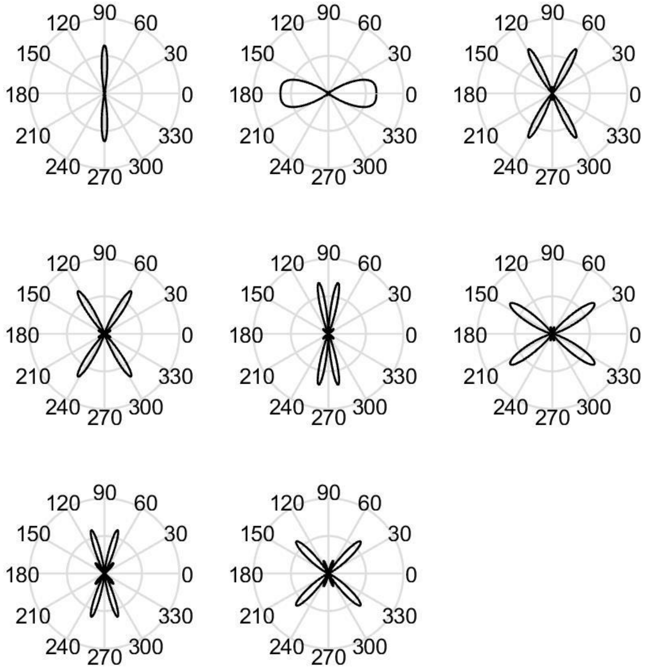
$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$



$$\mathbf{H}_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$



$$\mathbf{H}_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix}$$



Frequency Division Multiple Access (FDMA) Waveform

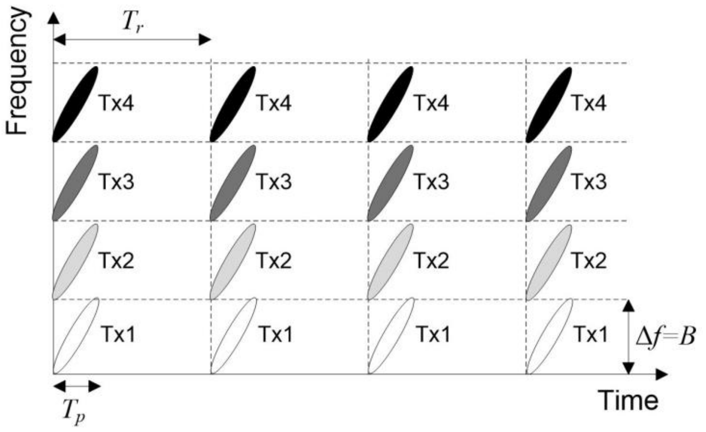
- **Frequency Division Multiple Access (FDMA) MIMO waveform means** the signals transmitted by different antennas are modulated by different carrier frequencies, which is also called “orthogonal spatial-frequency coding” in some literatures

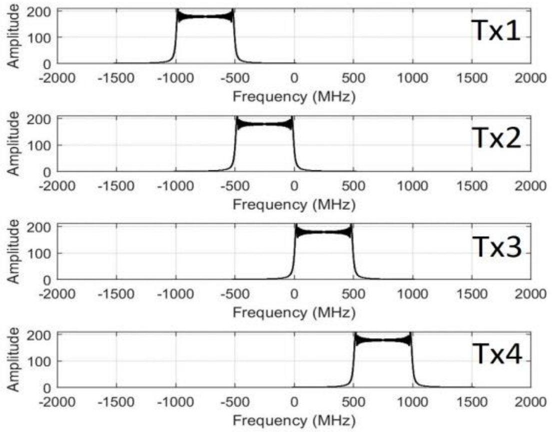
- Similar to the CDMA waveform, the FDMA waveform can also be implemented in either fast-time (i.e., intrapulse frequency modulation) or slow-time (i.e., interpulse frequency modulation).

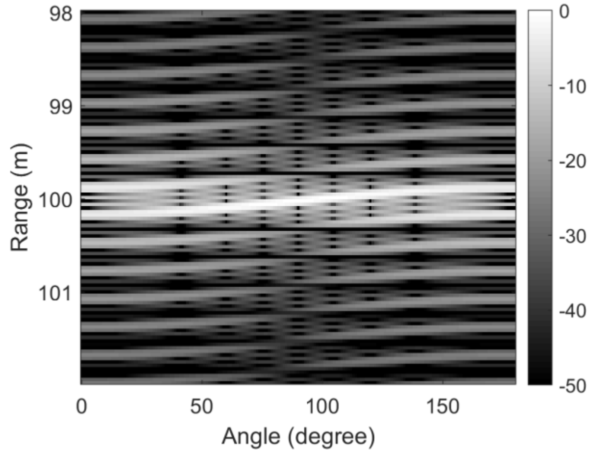
Fast-Time FDMA Waveform

Strong range-angle coupling!

Regular fast-time FDMA waveform (4 Tx)

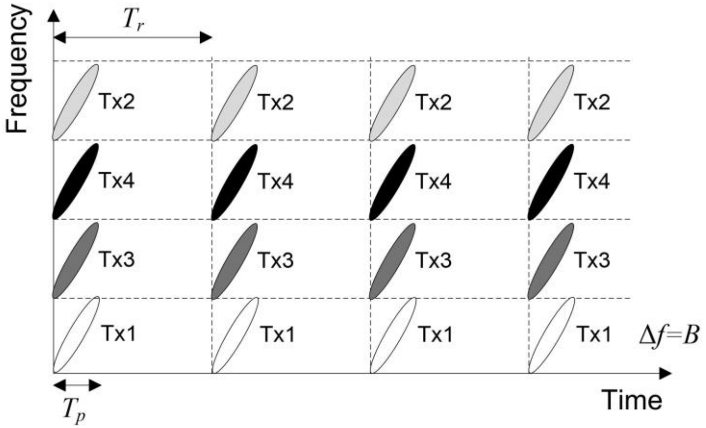


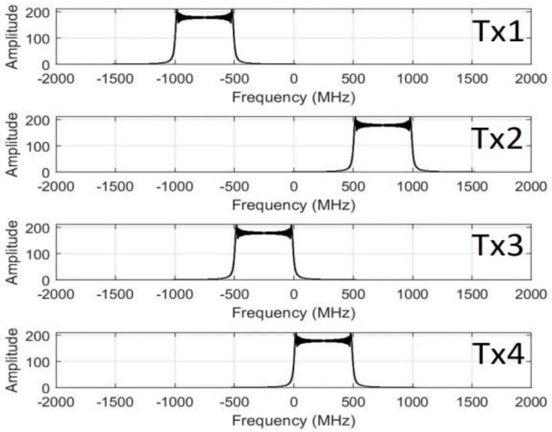


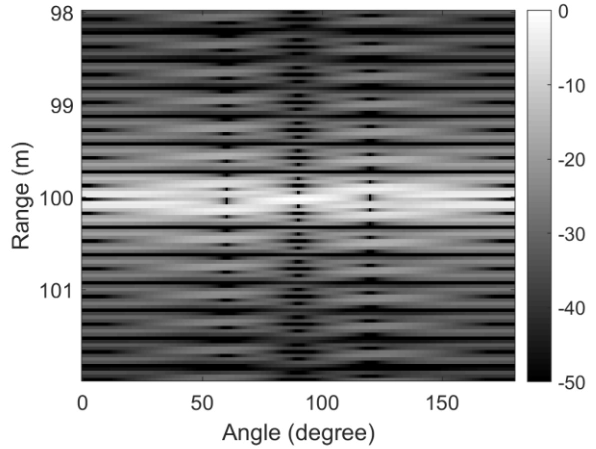


Range-angle coupling alleviated

Randomized fast-time FDMA waveform (4 Tx)





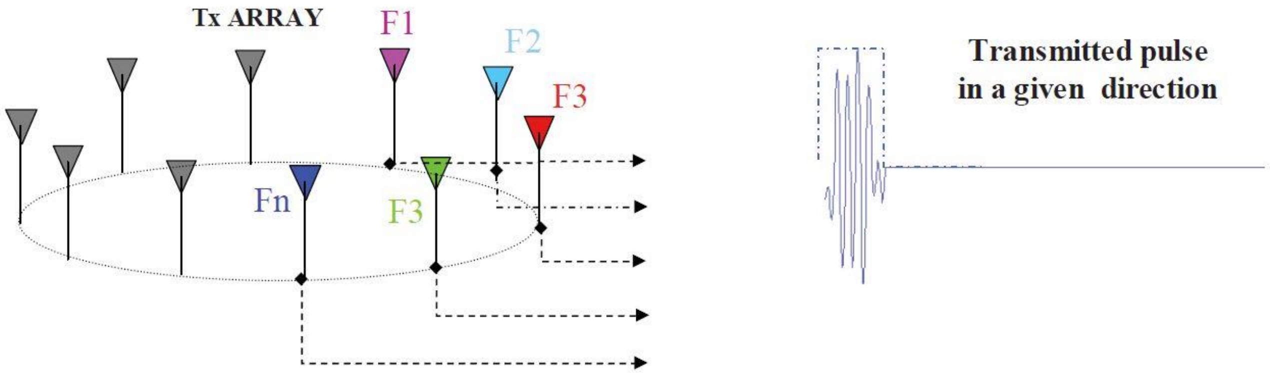


Fast-Time FDMA Waveform

Example: The first MIMO radar in the world - RIAS radar (ONERA, France)

ONERA mock up (1987)

Thales demonstrator (1990)



[Ref] J. Dorey, G. Gamier, G. Auvray, "RIAS - synthetic impulse and antenna radar", 1989 International Conference on Radar, Paris, pp.556-562, 1989

- Not applicable for GMTI radar (clutter de-correlates for different waveforms)
- Only applicable to large number of Tx antennas. Proper optimization is required to reduce the sidelobes

Fast-Time FDMA Waveform

Example: MIMO High Frequency Surface Wave Radar Using Sparse Frequency FMCW Signals

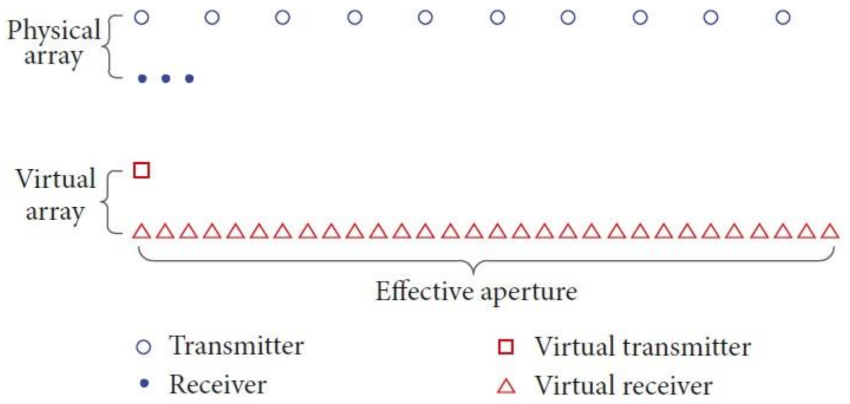
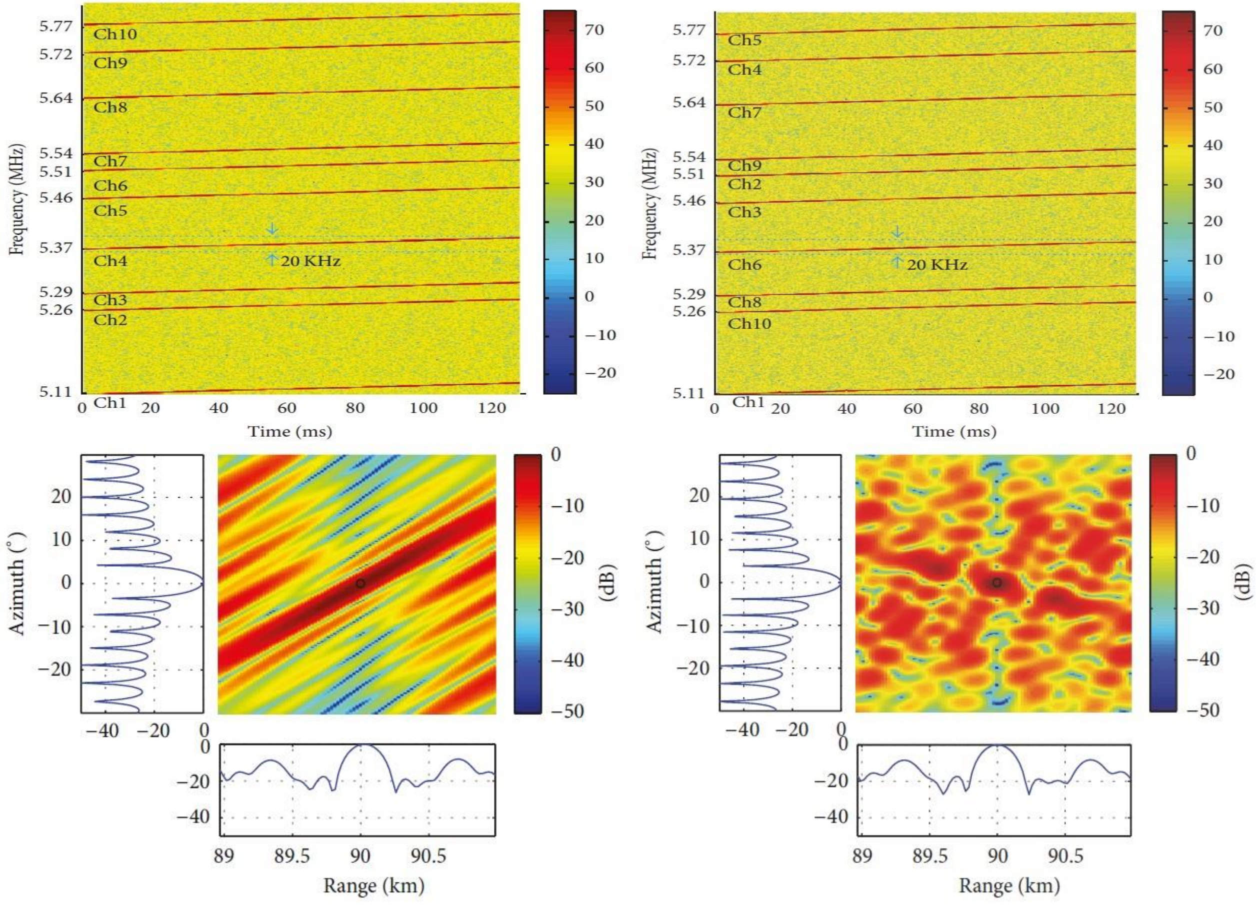


TABLE 1: Canada 1999 summer available spectrum [11].

Channel	Frequency range/MHz	Bandwidth/KHz
1	5.11~5.14	40
2	5.26~5.27	20
3	5.29~5.31	30
4	5.37~5.39	30
5	5.46~5.48	30
6	5.51~5.52	20
7	5.54~5.59	60
8	5.64~5.66	30
9	5.72~5.73	20
10	5.77~5.80	40



(a) Sequential distribution
(b) Optimized distribution

[Ref] Mengguan Pan, Baixiao Chen, "MIMO High Frequency Surface Wave Radar Using Sparse Frequency FMCW Signals", International Journal of Antennas and Propagation, 2017:1-16, August 2017

Slow-Time FDMA Waveform

Slow-time FDMA waveform extends the frequency coding across the pulse train, and each antenna transmits different carrier frequencies at different pulses. In this way the waveform DoF are greatly increased and low sidelobes are easier to achieve. Therefore, the slow-time FDMA waveform can be used for the MIMO radar with only a few antennas.

Discrete frequency coding LFM (DFC-LFM) waveform*

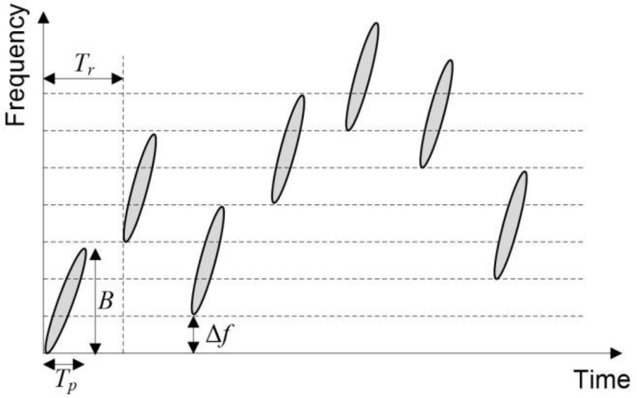
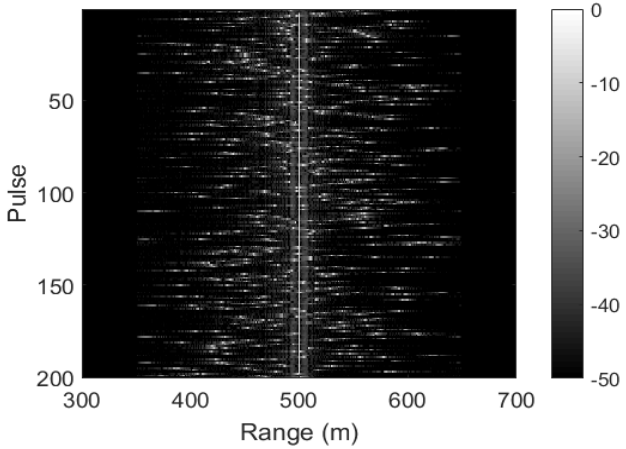


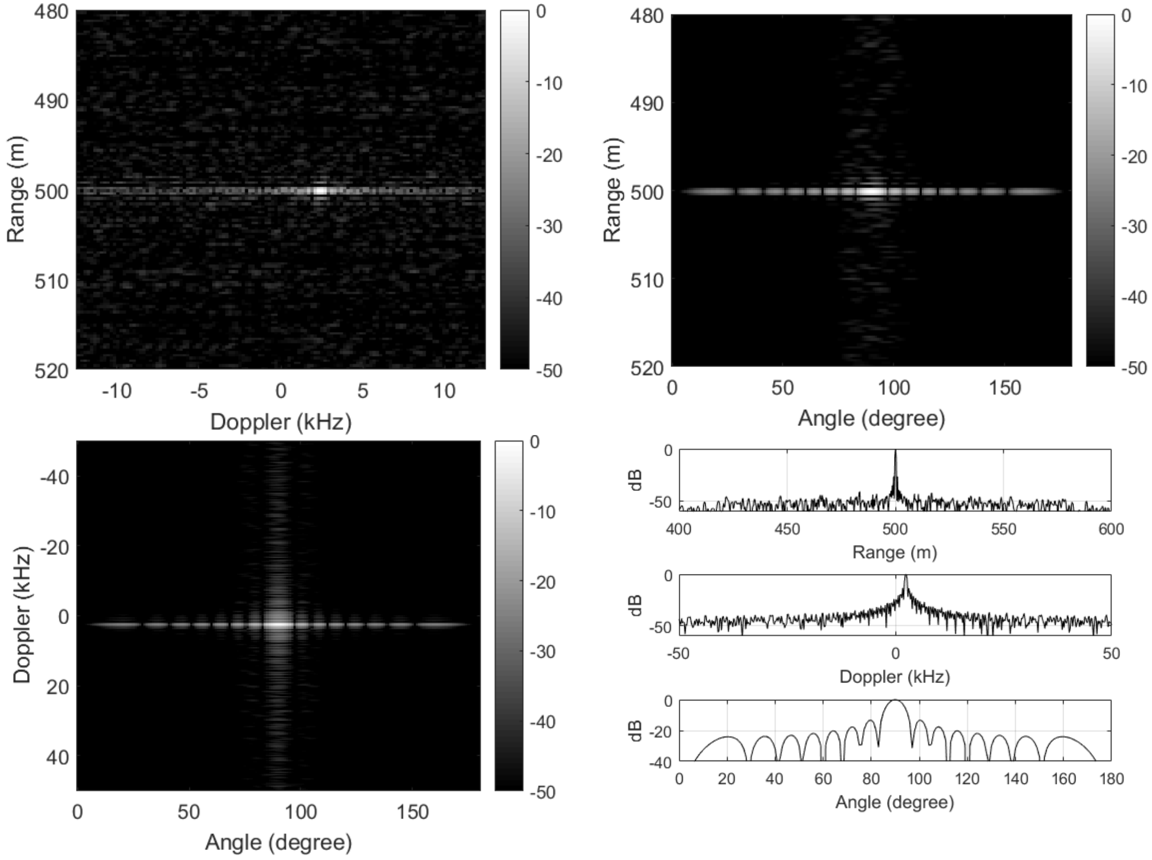
Illustration of slow-time FDMA waveform transmitted by one antenna



Range compressed signal received by one antenna

The range resolution of DFC-LFM waveform is determined by max[$N\Delta f$, B], which is smaller than the total occupied bandwidth $B+(N-1)\Delta f$.

* B. Liu, *"Orthogonal discrete frequency-coding waveform set design with minimized autocorrelation sidelobes", IEEE Trans. on Aerospace and Electronic Systems, Vol.45, No.4, pp.1650-1657, Oct. 2009*



Target PSF of slow-time CDMA waveform

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Circulating Waveform

Circulating MIMO waveform means the waveform (with any modulation) transmitted by each antenna is a time-circulating copy of the same signal, where the circulating step should be equal to $1/B$, B is the waveform bandwidth, to satisfy the orthogonality. The range resolution is degraded (N_e times poorer), but the range sidelobe level is greatly reduced.

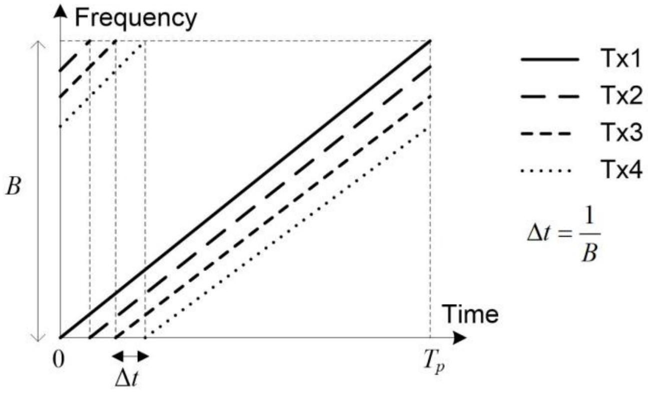
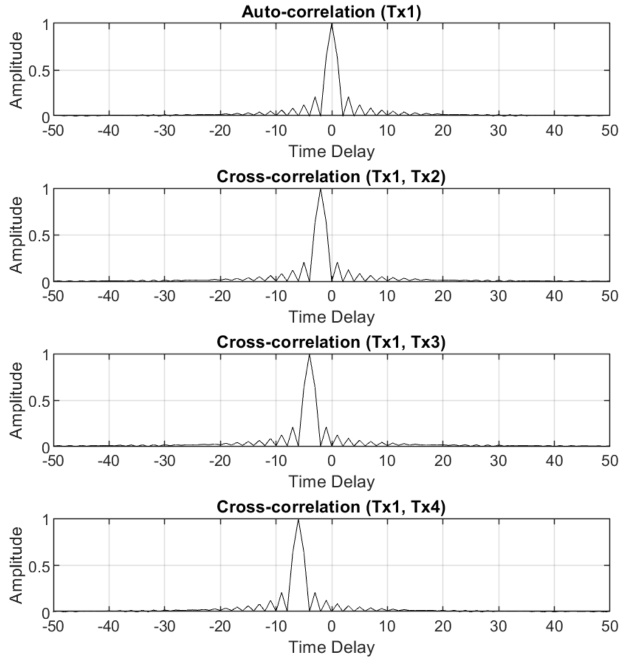
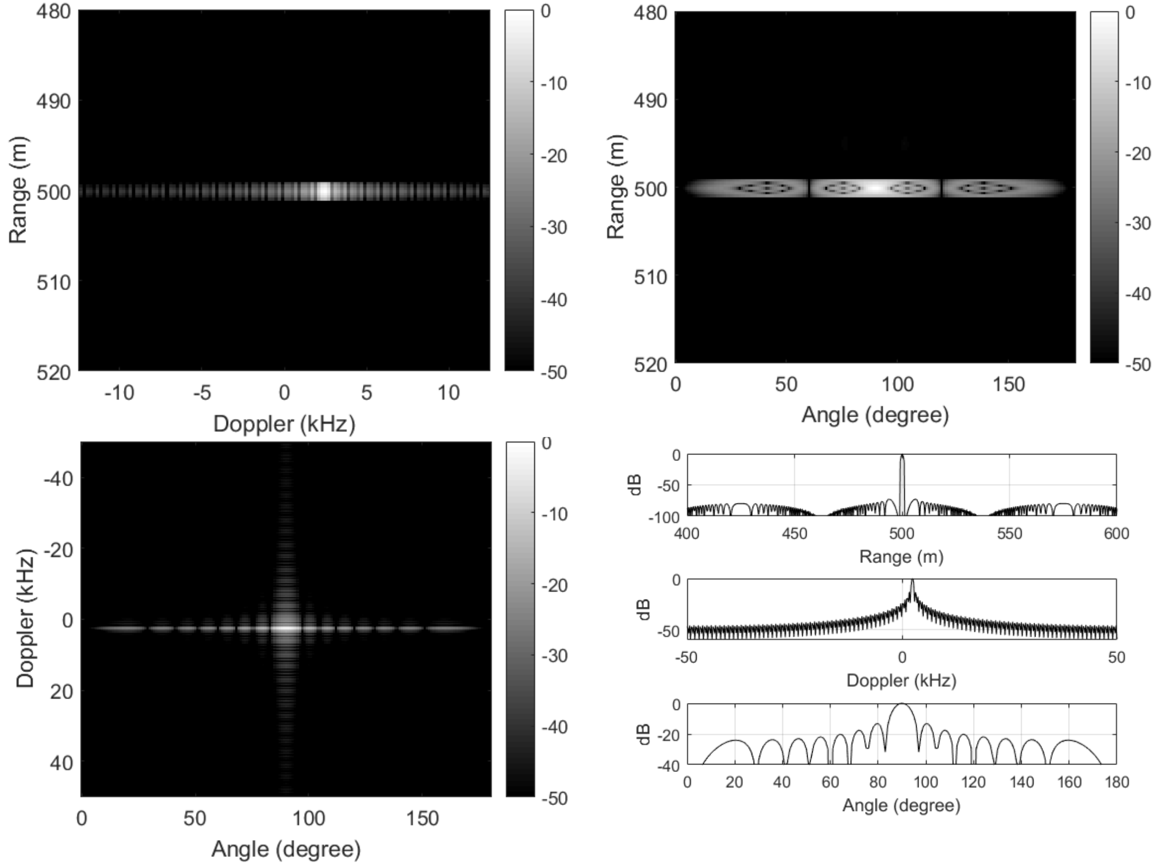


Illustration of circulating LFM MIMO waveform

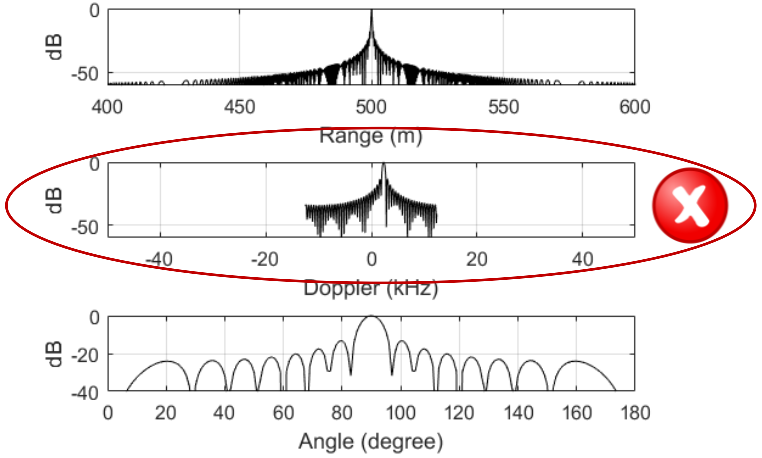


Auto/cross-correlations of the circulating LFM MIMO waveform

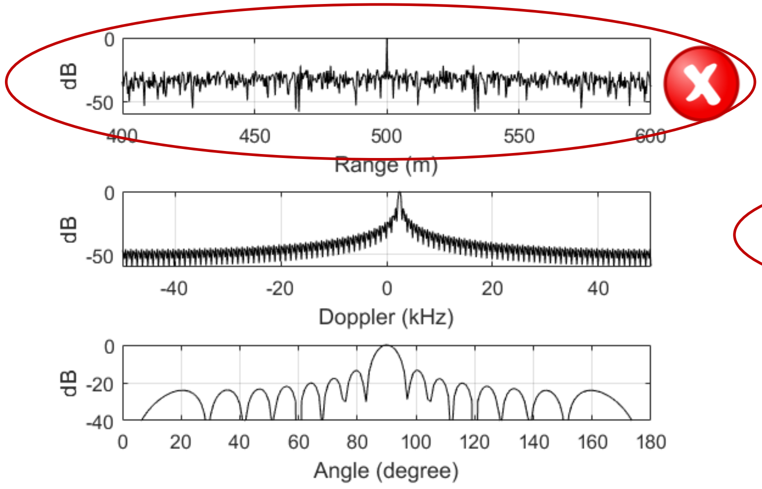


Target PSF of circulating waveform

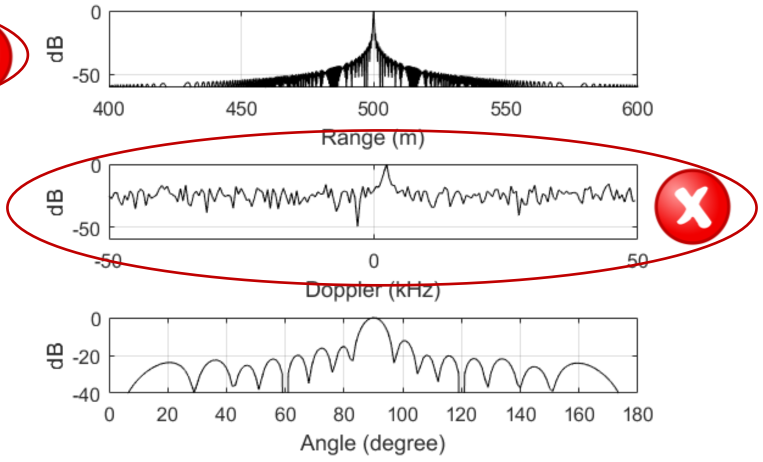
PSF Comparison for Various MIMO Radar Waveforms



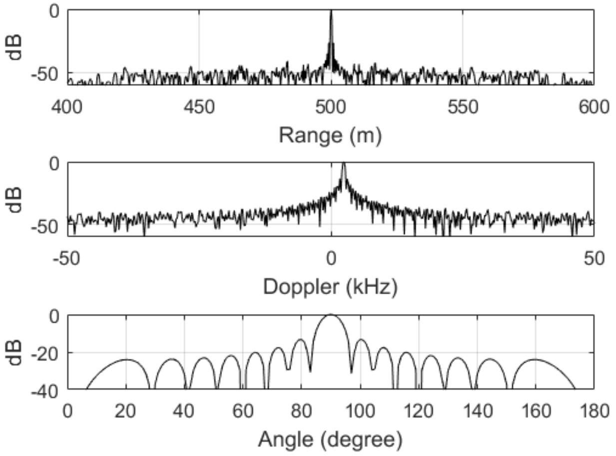
TDMA time-staggered / DDMA / Hadamard coding waveform



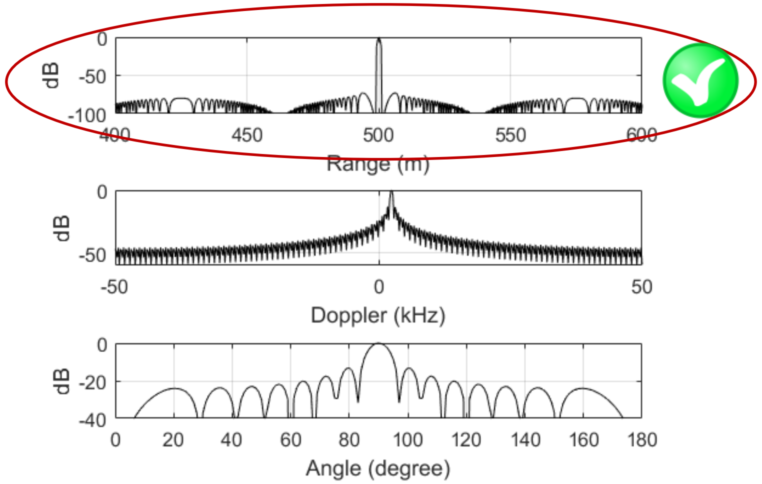
Fast-time CDMA waveform



Slow-time CDMA waveform



Slow-time FDMA waveform



Circulating waveform

Summary of MIMO Radar Waveforms

MIMO Waveforms	Advantages	Disadvantages	Suitable Applications
TDMA - Alternative Transmission	Good orthogonality Low range / Doppler sidelobes	Loss of transmitting efficiency	Short-range radar with low transmitting power
TDMA - Staggered LFMCW	Good orthogonality Low range / Doppler sidelobes	Reduced Doppler unambiguity range	Low-frequency radar (e.g., HF-OTHR), or microwave radar for short range detection
DDMA	Good orthogonality Low range / Doppler sidelobes	Reduced Doppler unambiguity range	Low-frequency radar (e.g., HF-OTHR), or short-range microwave radar
Fast-time CDMA	Approximate orthogonality Low Doppler sidelobes	High range sidelobes	All
Slow-time CDMA	Approximate orthogonality Low range sidelobes	High Doppler sidelobes	All
Hadamard Coding	Good orthogonality (only for slow moving targets); Low range / Doppler sidelobes	Reduced Doppler unambiguity range; Sensitive to very fast-moving targets	Low-frequency radar for slow moving target detection
Fast-time FDMA	Good orthogonality	High range sidelobes	Large MIMO radar with many transmitting antennas
Slow-time FDMA	Good orthogonality	Moderate range / Doppler sidelobes Reduced range resolution	All
Circulating LFM	Good orthogonality; Ultra-low range sidelobes; Low Doppler sidelobes	Reduced range resolution	All

Summary of MIMO Radar Waveforms

Ideal orthogonal MIMO waveform does not exist.

There is no free lunch!

<u>We have to sacrifice some performance when choosing a MIMO waveform.</u>

Examples of MIMO Radar Demonstrations

Radar System	Country	Year	MIMO Waveform	Reference
Synthetic impulse and antenna radar (RIAS) for air surveillance	France	1989	Fast-time FDMA	J. Dorey, G. Gamier, G. Auvray, “RIAS - synthetic impulse and antenna radar”, 1989 International Conference on Radar, Paris, pp.556-562, 1989
HF surface wave over-the-horizon radar	France	2015	Not mentioned	F. Jangal, M. Menelle, “French HFSWR contribution to the European integrated maritime surveillance system I2C”, 2015 IET Radar Conference, Hangzhou, China, pp.1566-1570, Oct 2015
HF surface wave over-the-horizon radar	Canada	2015	Slow-time CDMA	A. Ponsford, R. McKerracher, Z. Ding, P. Moo, D. Yee, “Towards a cognitive radar: Canada’s third-generation high frequency surface wave radar (HFSWR) for surveillance of the 200 nautical mile exclusive economic zone”, Sensors, 17(7), 1588, 2017
HF sky-wave radar	Australia	2008	TDMA (Time-staggered LFMCW)	G.J. Frazer, Y.I. Abramovich, B.A. Johnson, F.C. Robey, “Recent results in MIMO over-the-horizon radar”, 2008 IEEE Radar Conference, Rome, Italy, pp.789-794, May 2008. G.J. Frazer, Y.I. Abramovich, B.A. Johnson, “Multiple-input multiple-output over-the-horizon radar: Experimental results”, IET Radar, Sonar & Navigation Vol.3, No.4, pp.290-303, Sep 2009
Airborne GMTI radar	United States	2010	DDMA	J. Kantor, S.K. Davis, “Airborne GMTI using MIMO techniques”, 2010 IEEE International Radar Conference, Washington D.C., US, pp.1344-1349, May 2010
Atmospheric Radar	Japan	2023	DDMA	T. Matsuda, H. Hashiguchi, “DDMA-MIMO observations with the MU radar: validation by measuring a beam broadening effect”, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, pp.(99):1-9, January 2023
Ground-based imaging radar	Germany	2010	TDMA (Alternative transmission)	J. Klare, O. Saalmann, H. Wilden, A.R. Brenner, “First Experimental Results with the Imaging MIMO Radar MIRA-CLE X”, The 8th European Conference on Synthetic Aperture Radar, Aachen, Germany, pp.374-377, Jun 2010

Example – Implementing MIMO Waveform in mmWave Automotive Radar

Institute for Infocomm Research
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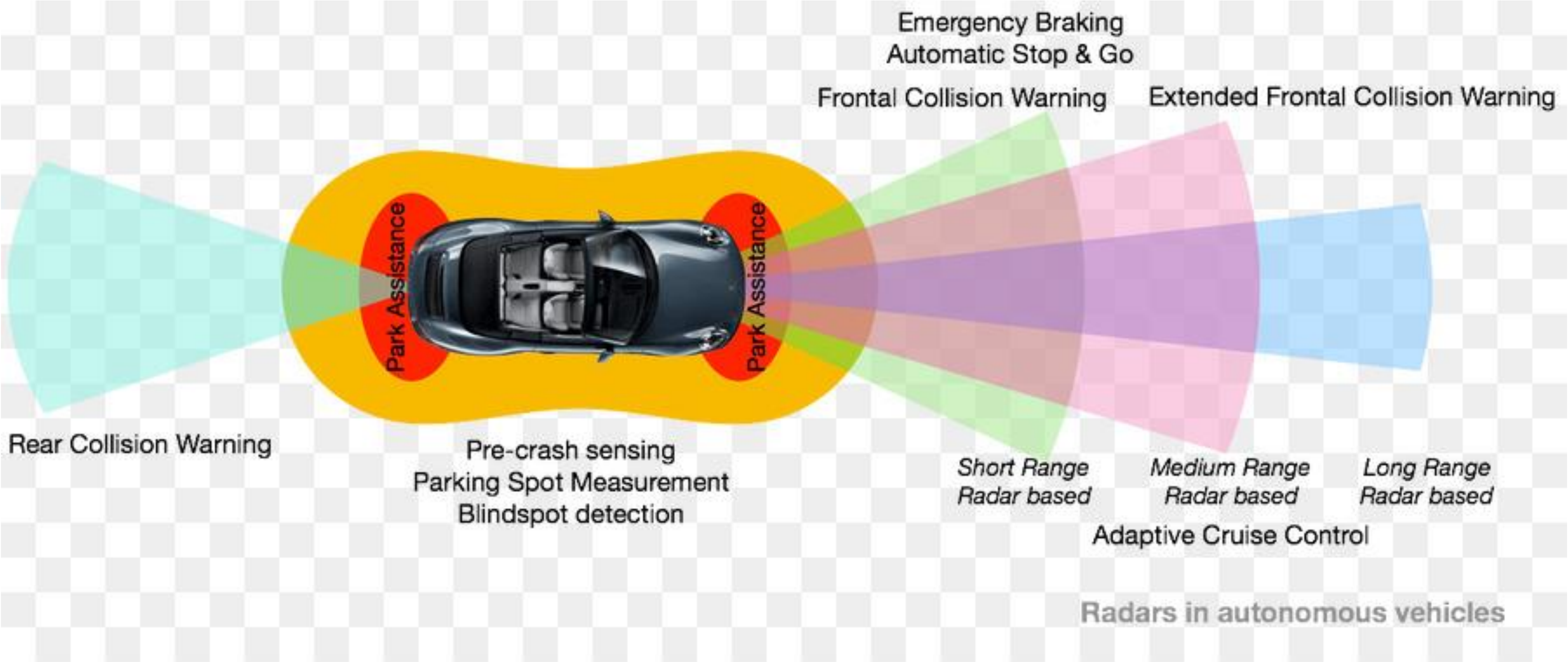
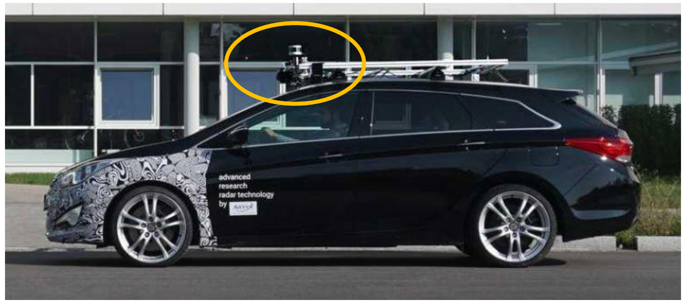
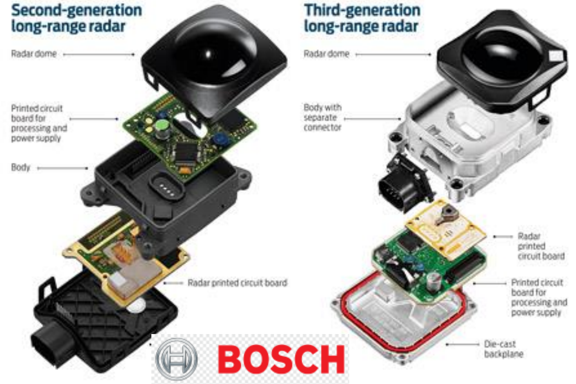
mmWave Automotive Radar

https://www.mwrf.com/technologies/systems/article/21848960/the-startups-trying-to-revamp-automotive-radar







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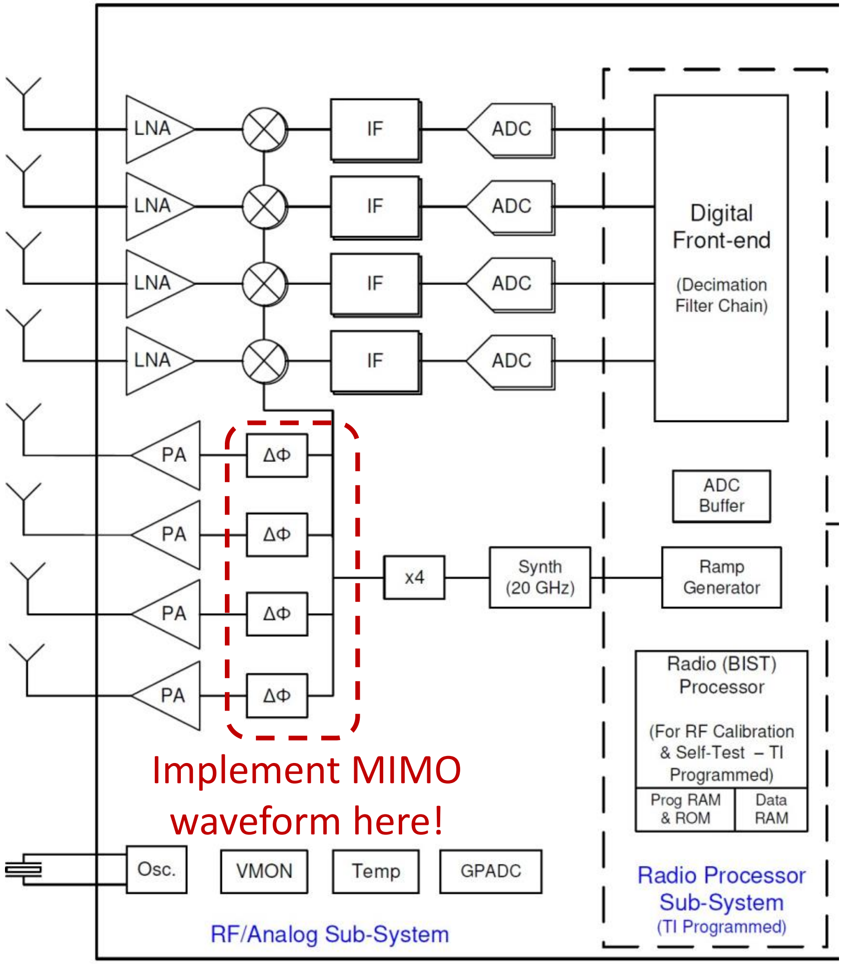
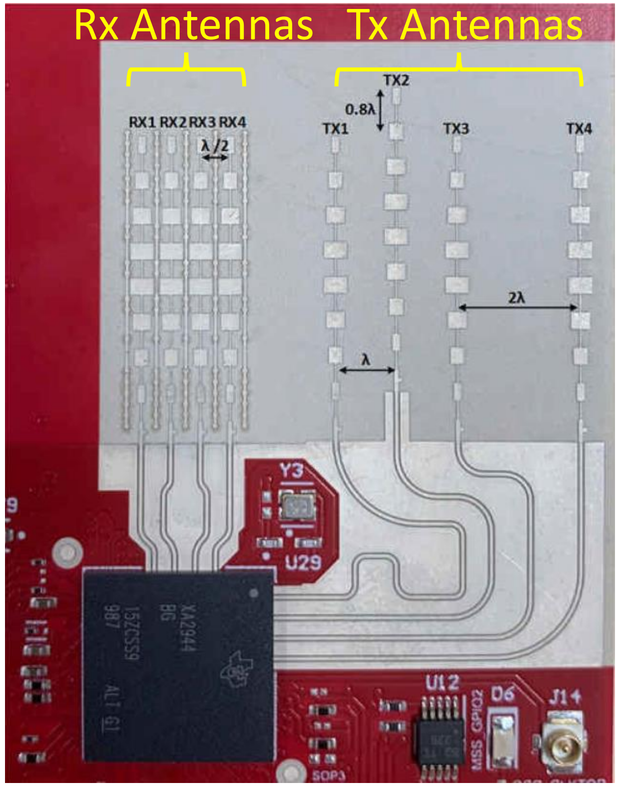
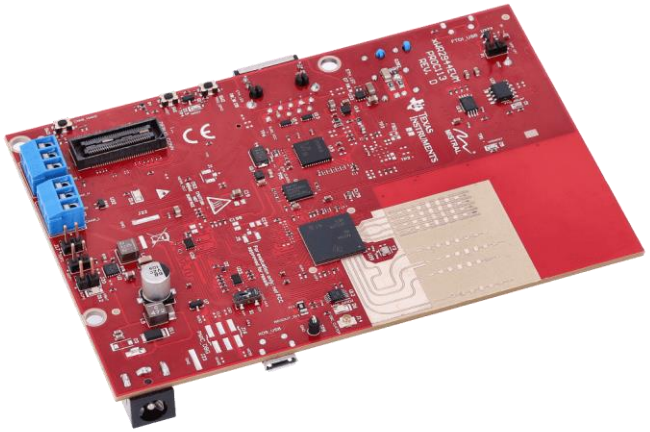
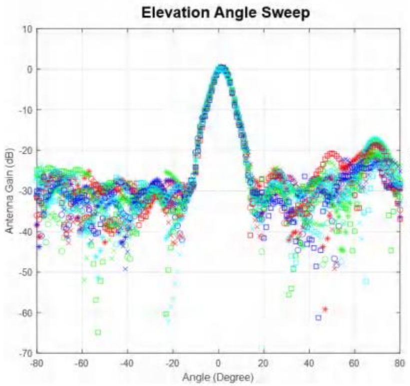
Implementing MIMO in mmWave Automotive Radar

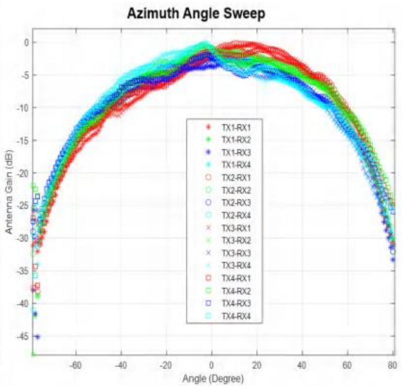
AWR2944 Single-Chip 76-81GHz FMCW Radar Sensor

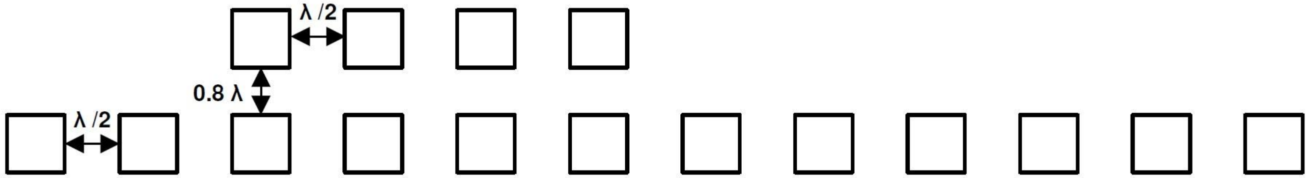












User's Guide - AWR2944 Evaluation Module, Texas Instruments

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Implementing MIMO in mmWave Automotive Radar

TEXAS INSTRUMENTS

AWR2944 Single-Chip 76- and 81-GHz FMCW Radar Sensor

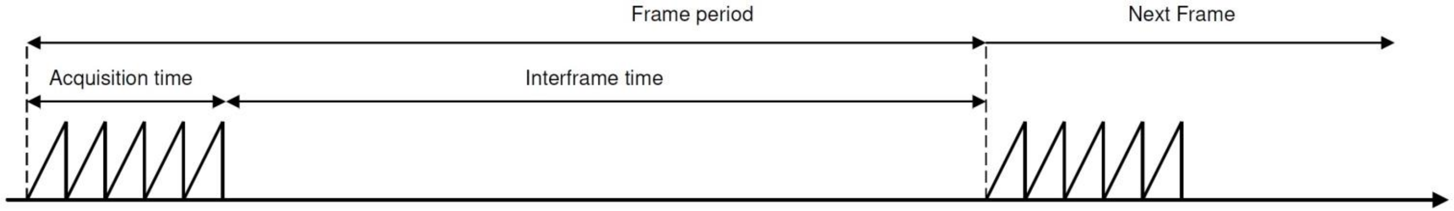
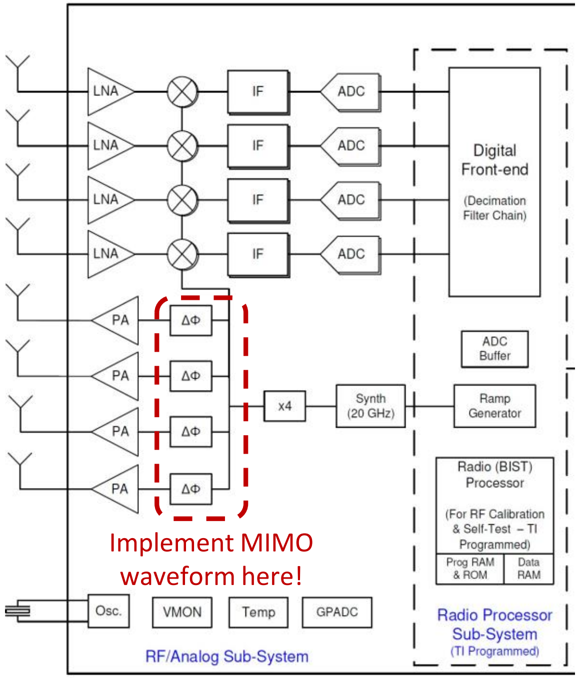


Table 2-1. Chirp Configuration

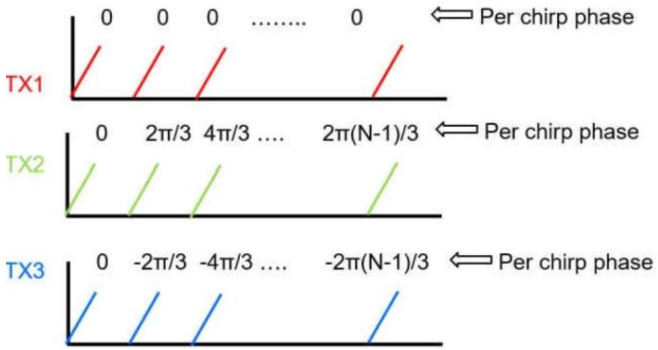
PARAMETER	CONFIGURATION
Idle time (µs)	5
ADC start time (µs)	5
Ramp end time (µs)	18.83
Number of ADC samples	384
Frequency slope (MHz/µs)	8.883
MIMO (1 → yes)	1
Number of chirps per profile	768
Effective chirp time (µs)	23.83
Bandwidth (MHz)	114
Frame length (ms)	250

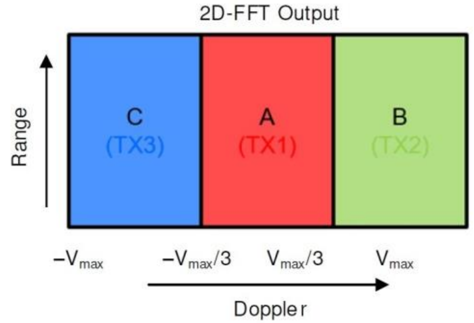
Table 2-2. System Performance Parameter

PARAMETER	SPECIFICATIONS
Range resolution (m)	1.3
Maximum distance (m)	200
Native maximum velocity (kmph)	140



DDMA: If there are N_e transmitters, each transmitter is modulated with phase $\omega_k = 2\pi(k-1)/N_e$, k is the pulse index.

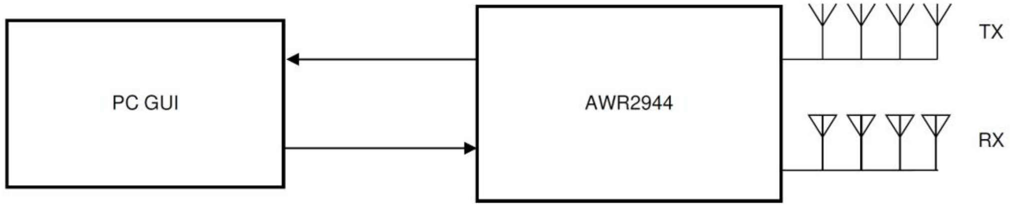




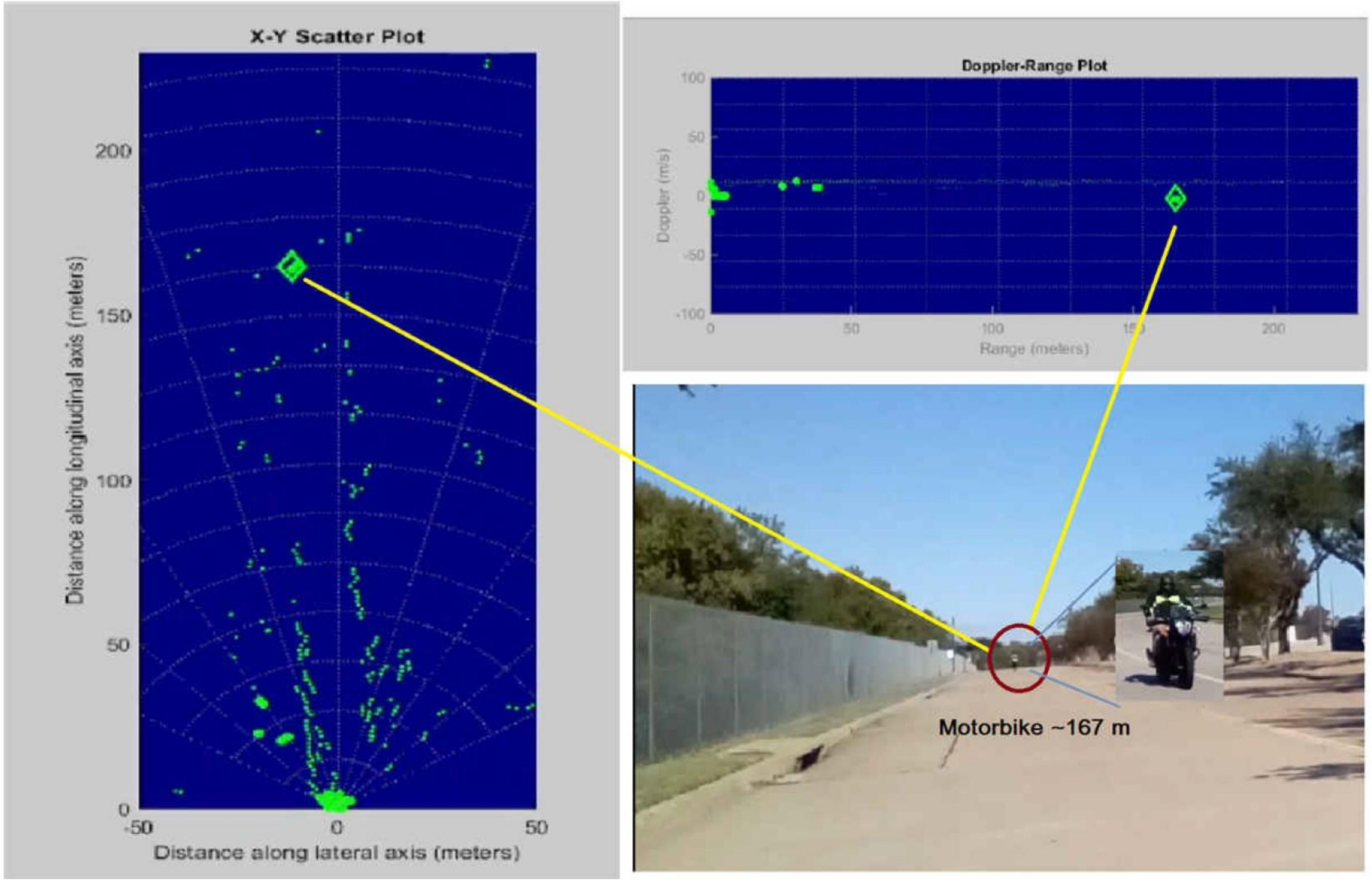
* Hadamard coding and slow-time CDMA waveforms can also be implemented.

Design Guide: TIDEP-01027, "High-End Corner Radar Reference Design“, Texas Instruments

Field Trial Results



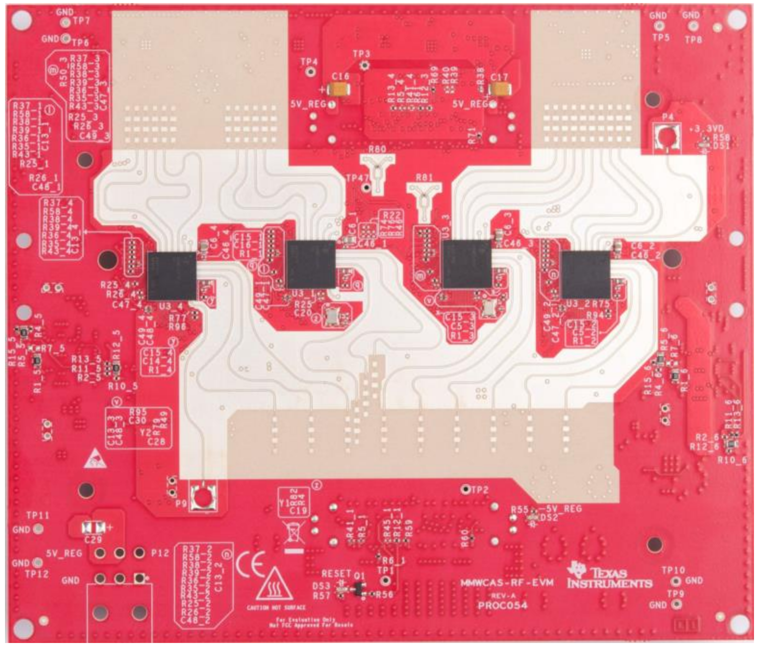
Motorbike detection with AWR2944 Evaluation Module

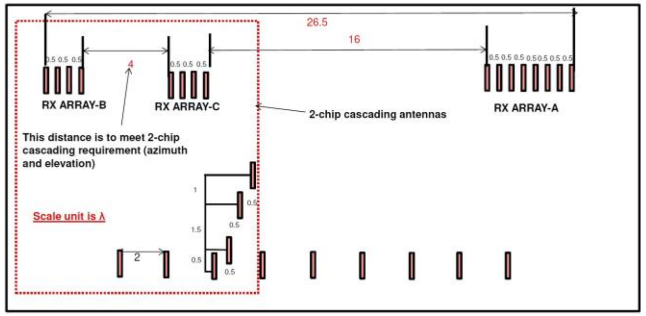


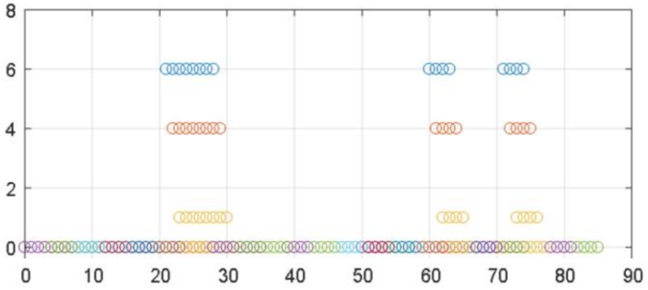
Design Guide: TIDEP-01027, "High-End Corner Radar Reference Design", Texas Instruments

Form Larger Aperture Using Cascaded mmWave Radar Sensor

AWR2243 Four-Device Cascade Radar RF Radar Board



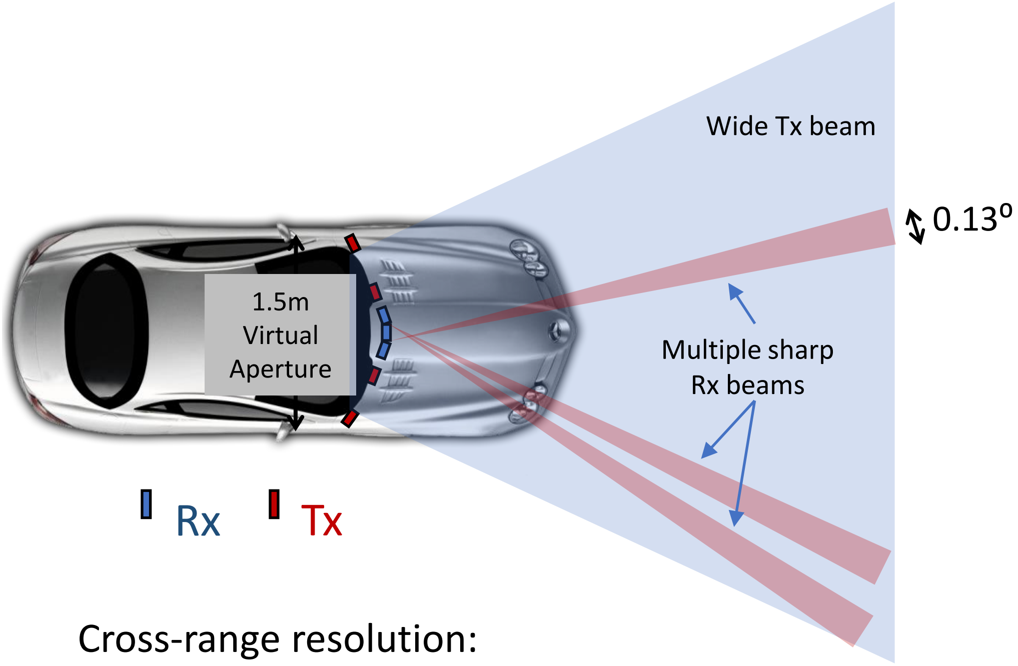




- 4 × AWR2243 76-81GHz Radar SoC: Integrated VCO, LO distribution, PA, LNA, ADC, 3 TX and 4 RX Arm MCU R4 Controller
- 12 × TX and 16 x RX across all 4 AWR2243 devices
- Azimuth Array: 86 element virtual array – **enabling 1.4º angular resolution**
- Elevation Array: 4 element virtual array – enabling 18º angular resolution

Design Guide TIDEP-01012 Imaging Radar Using Cascaded mmWave Sensor Reference Design, Texas Instruments

Potentially, a distributed large-aperture conformal MIMO array can be formed to significantly enhance the angular resolution of automotive radar.



Cross-range resolution:
- 4.6cm @ 20m
- 11.4cm @ 50m
- 22.8cm @100m

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