Exploiting Virtual Array Diversity for Accurate Radar Detection

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UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

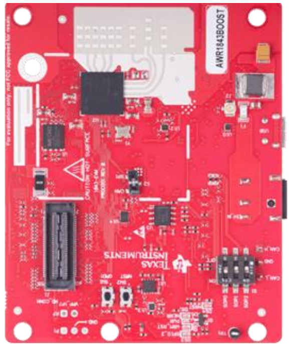
EPFL

vayyar

UHNDER

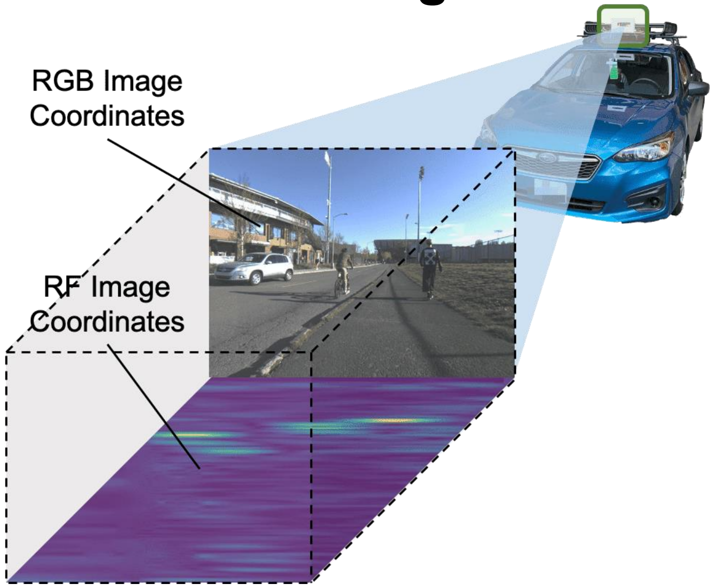
arbe

Millimeter Wave Radar



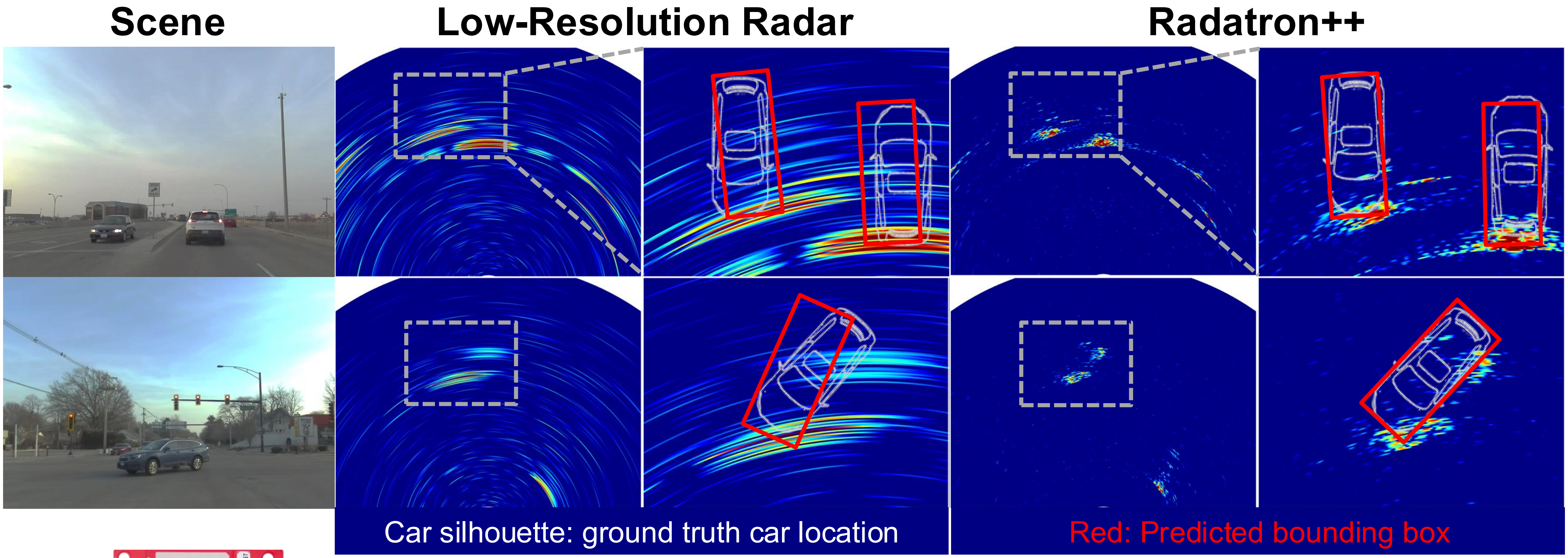
Waymo

Univ. of Washington CRUW

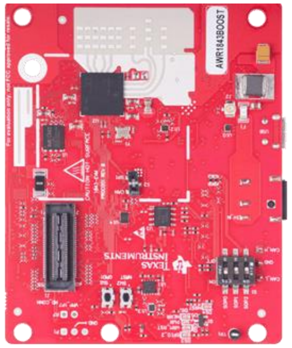


KAIST K-Radar

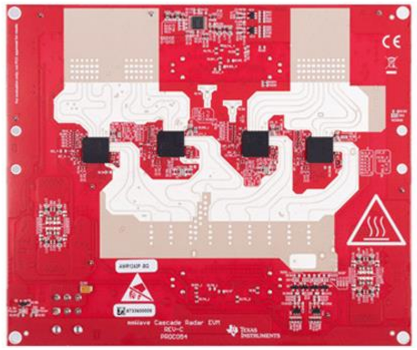
Oxford RobotCar



Low angular resolution hinders semantic scene understanding!

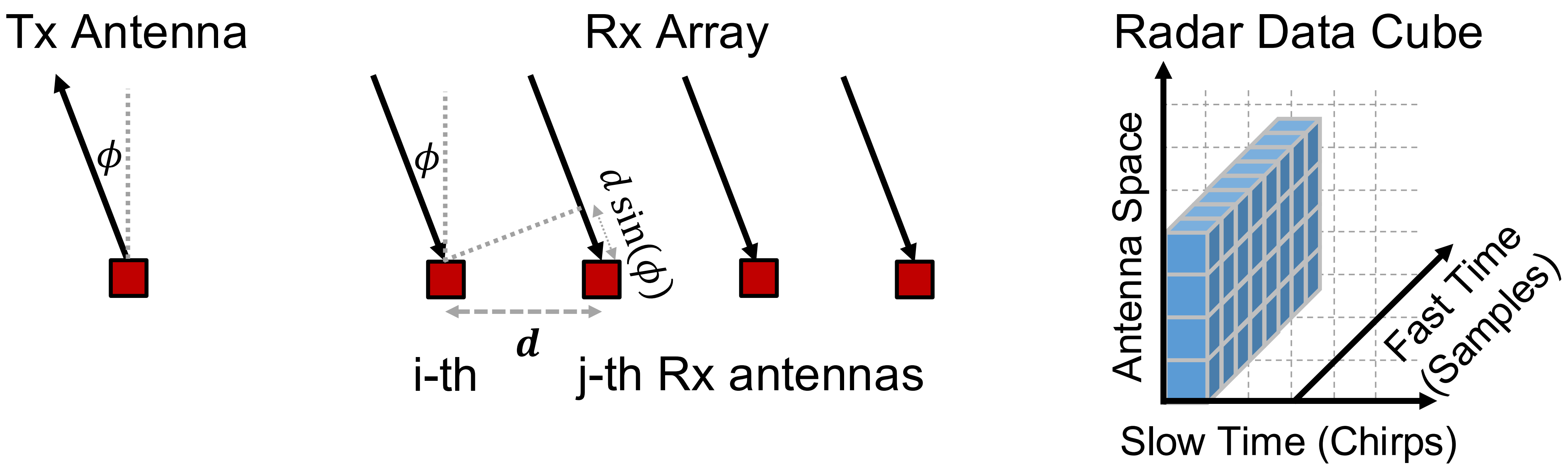


Low-Resolution Single Chip Radar



Cascaded MIMO Radar

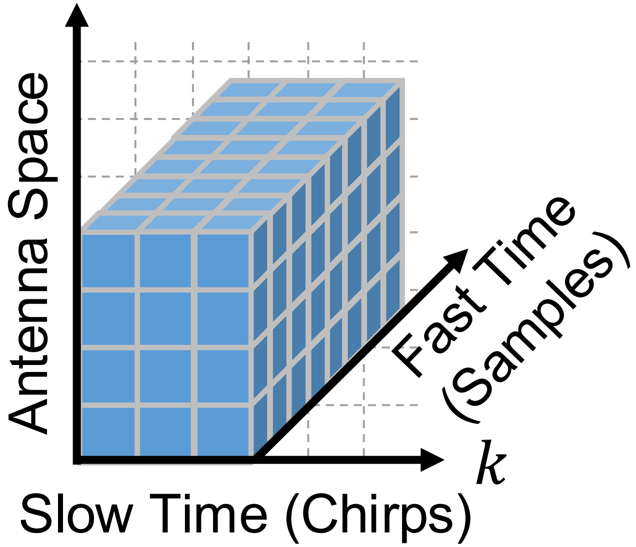
Imaging Radar Background



Phase difference of the i-th and j-th Rx antennas

$$= \frac{2\pi}{\lambda} d(j-i)\sin \phi$$

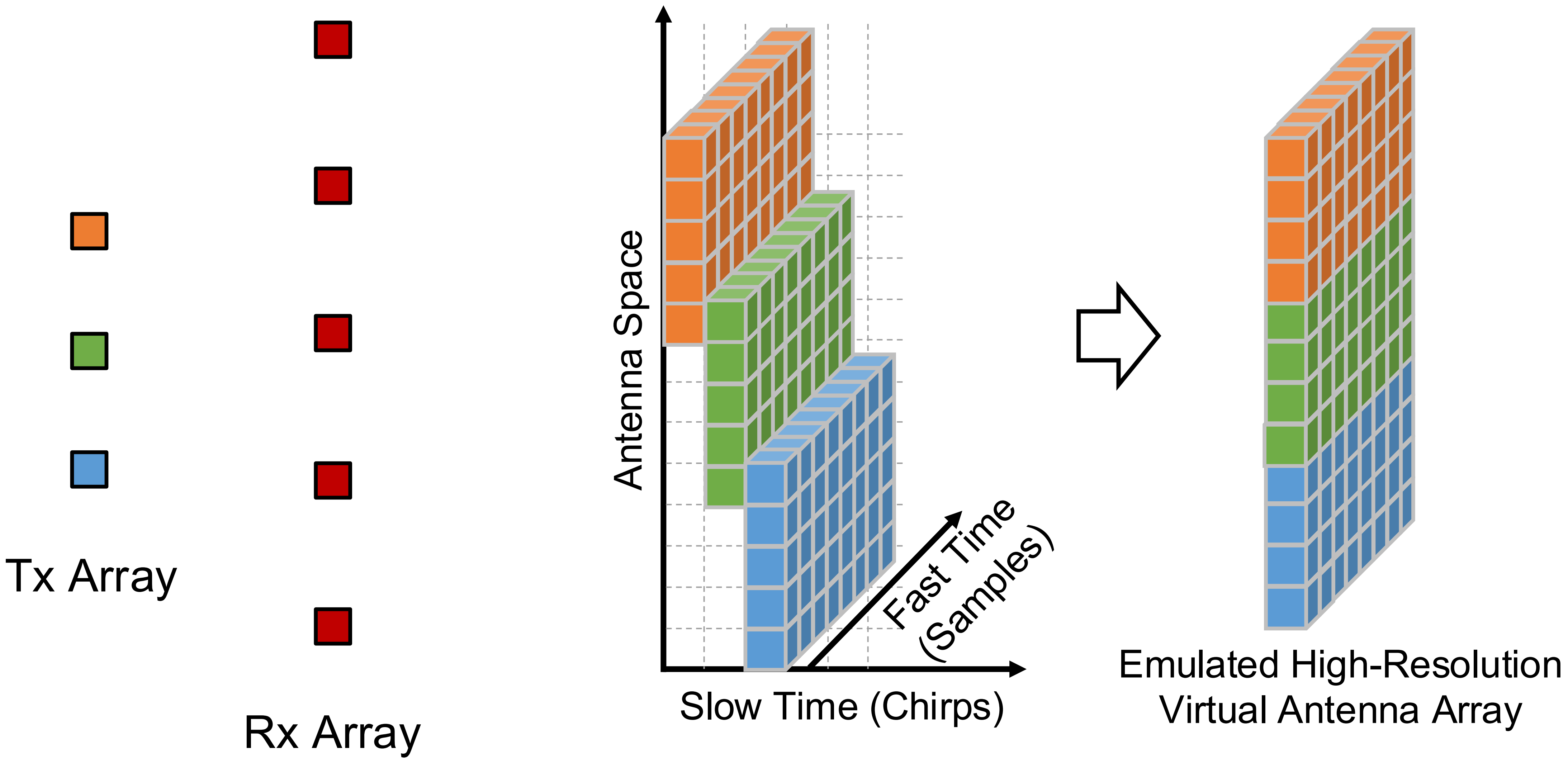
Doppler Velocity Estimation

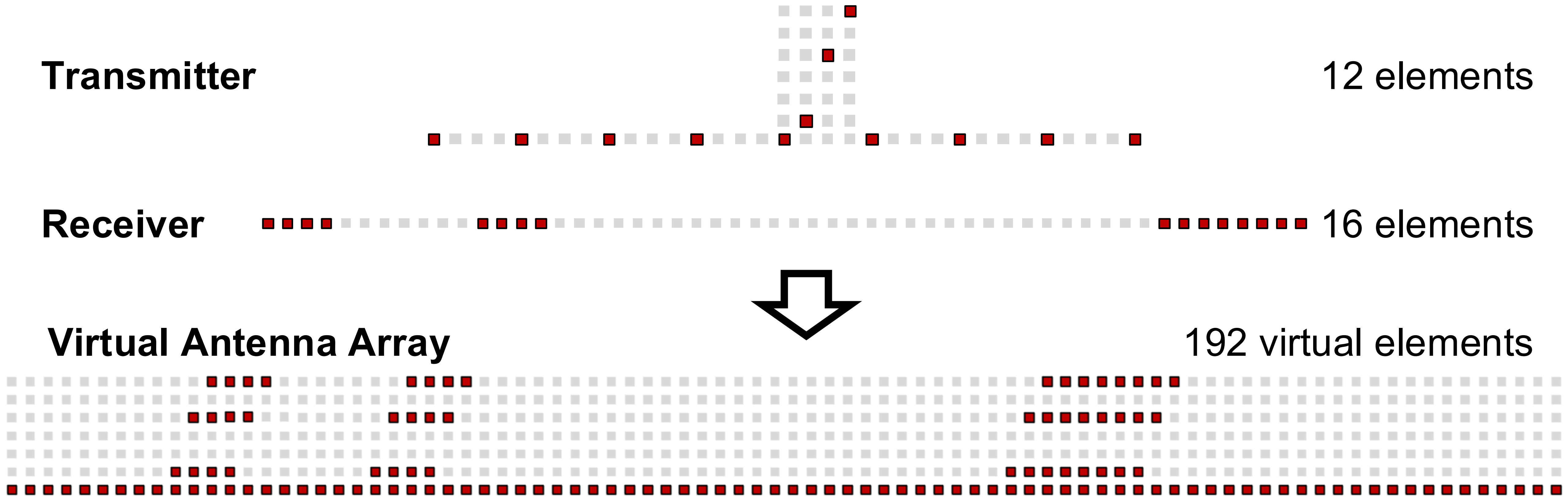


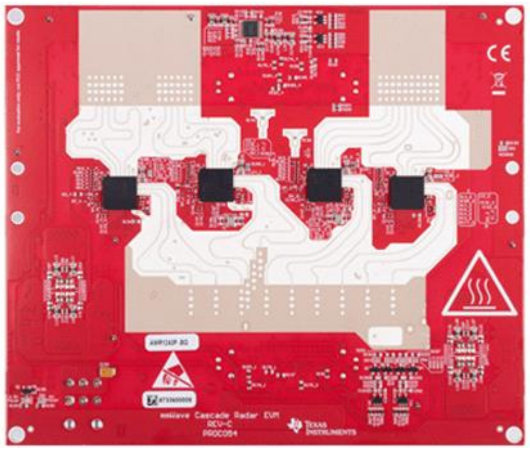
Phase variation in the k-th Tx frame due to Doppler phase shift

$$= \frac{4\pi}{\lambda} v k T$$

MIMO Radar


Tx Array
Rx Array
Antenna Space
Slow Time (Chirps)
Fast Time
(Samples)
Emulated High-Resolution
Virtual Antenna Array

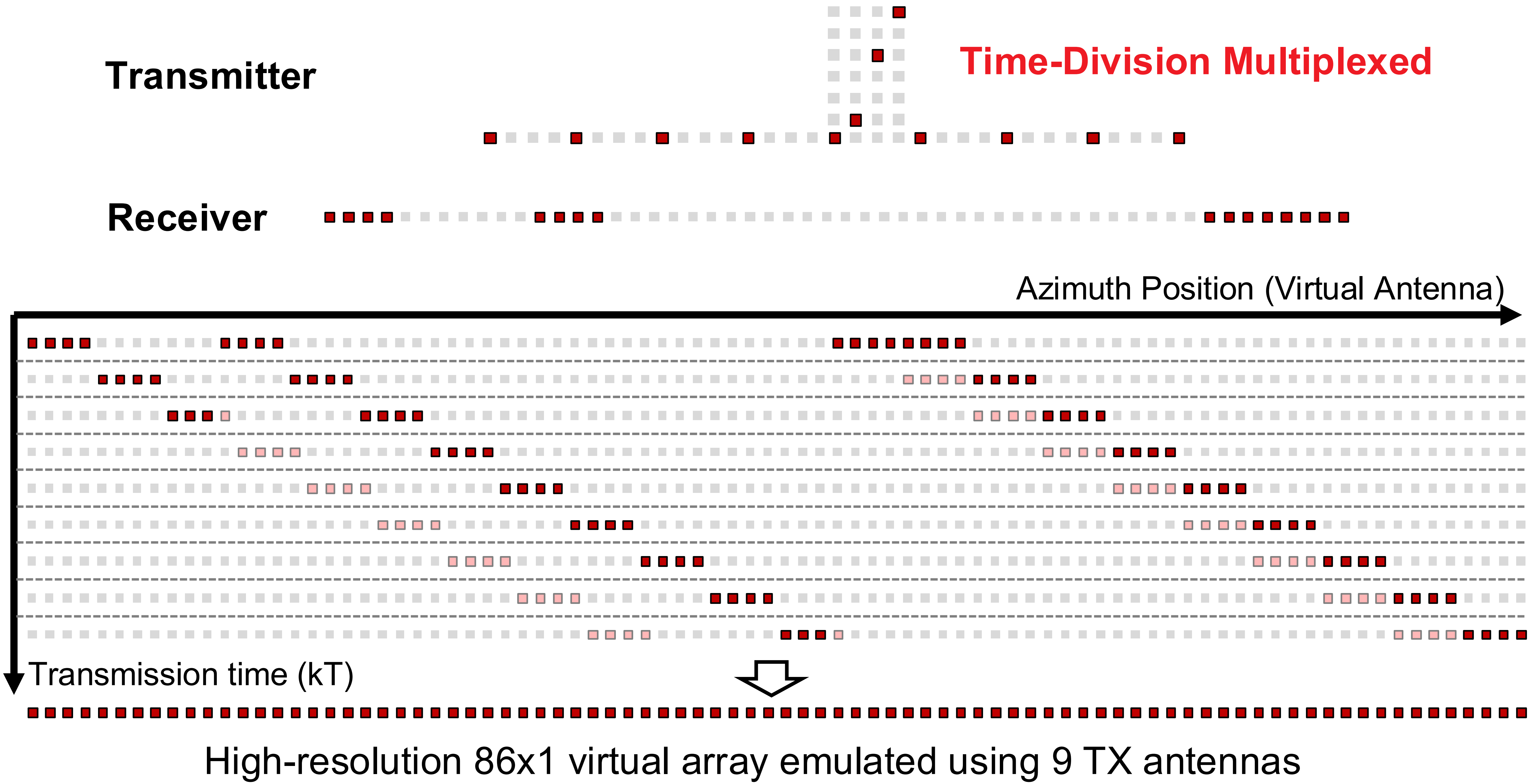




Cascaded MIMO Radar

1.8º Azimuth Resolution

10x higher than single-chip radars



Transmitter
Time-Division Multiplexed
Receiver
Azimuth Position (Virtual Antenna)
Transmission time (kT)
High-resolution 86x1 virtual array emulated using 9 TX antennas

Challenges

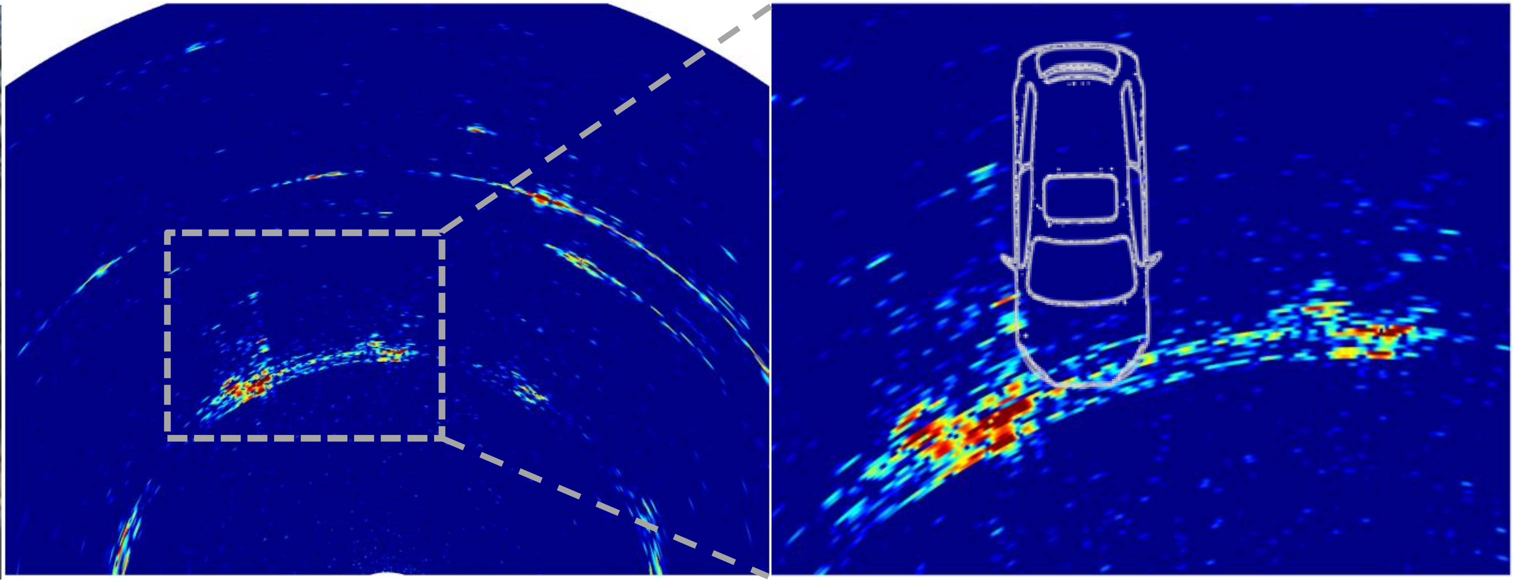
1. Doppler Phase Shift Entanglement ⇒ Heatmap Distortions
2. Low Frame Rate ⇒ Ambiguity in Doppler Velocity

More severe in highly dynamic scenes!

Radatron++

1. Jointly leveraging a variety of virtual antenna array topologies.
2. Hybrid radar signal processing and deep learning solution.
3. Accurate vehicle detection from raw radar heatmaps.

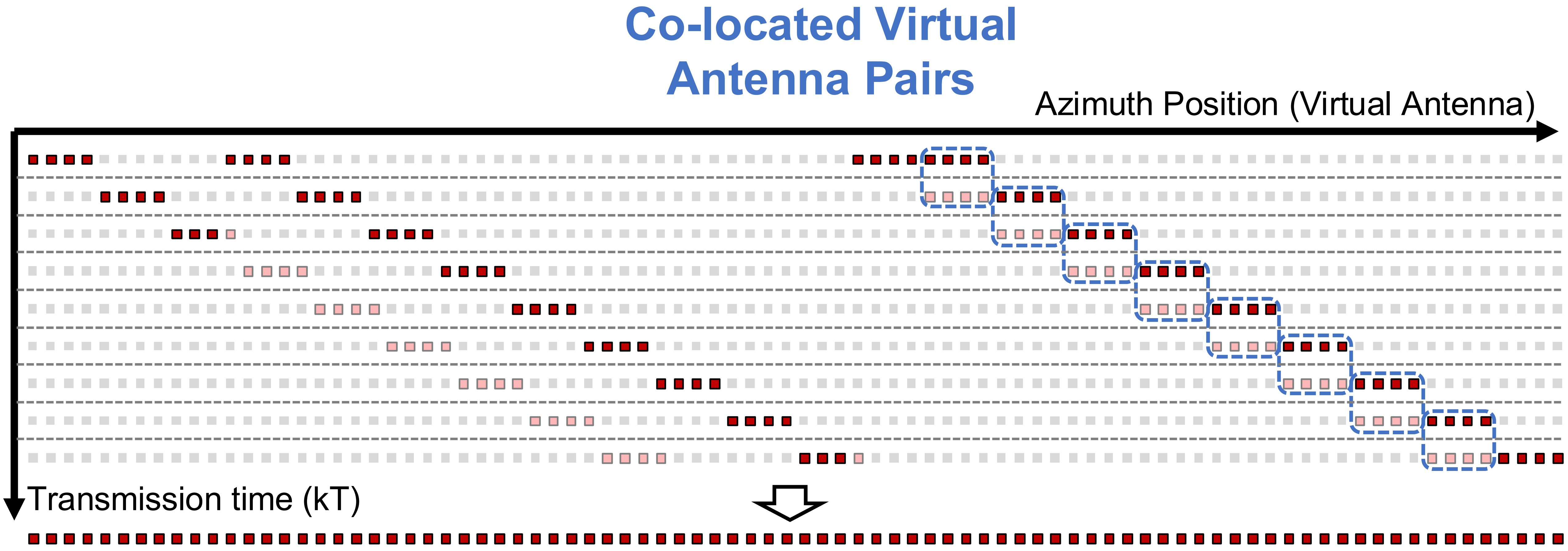
Challenge 1: Doppler Phase Entanglement



Phase difference between virtual antenna links (kTx, iRx), (lTx, jRx)

$$= \frac{2\pi}{\lambda}[\underbrace{d(j-i)\sin\phi}_{\substack{RX\ Antenna \\ Spatial\ Diversity}}$$

Doppler Phase Compensation Leveraging Redundancies



High-resolution 86x1 virtual array emulated using 9 TX antennas

Doppler Compensation Using Co-Located Virtual Antennas

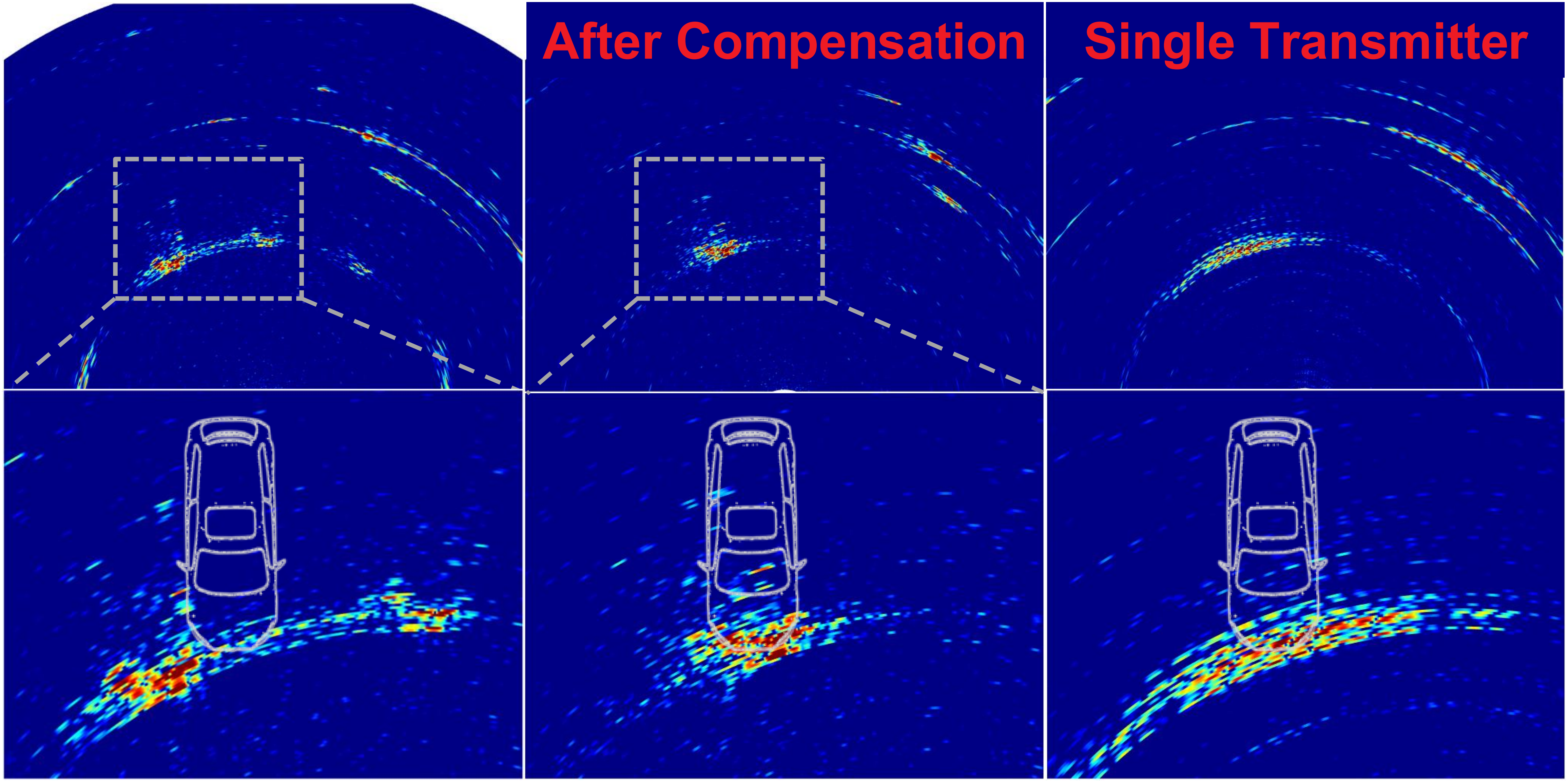
(k-1)-th k-th Tx antennas i-th (i+1)-th Rx antennas

Phase difference between co-located virtual antenna pairs (i,k) and (i+1,k-1)

$$= \frac{2\pi}{\lambda}\left[\underbrace{\cancel{(i+1-i)dsin\phi}}_{RX\ Spatial\ Diversity} + \underbrace{\cancel{(k-1-k)dsin\phi}}_{TX\ Spatial\ Diversity} + \underbrace{2vT(k-1-k)}_{Doppler\ Shift}\right]$$

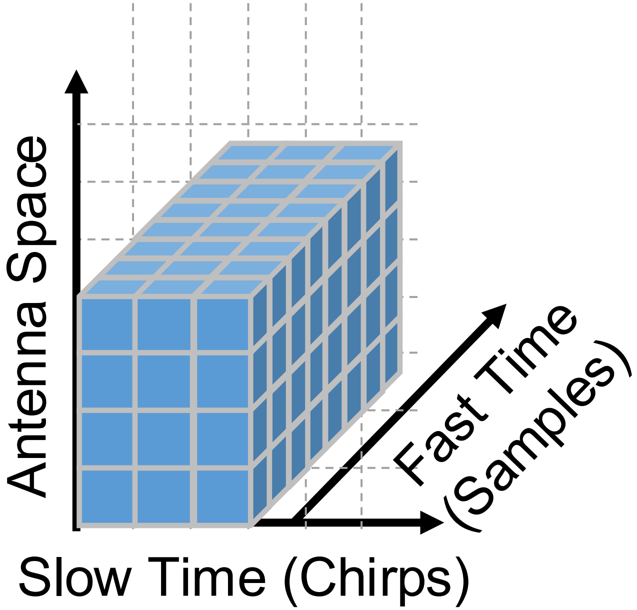
$$= \frac{2\pi}{\lambda} \cdot \underbrace{2vT}_{Doppler\ Shift}$$

Residual Doppler Phase Entanglement



Jointly leverage the high- and low-resolution radar heatmaps.

Challenge 2: Ambiguity in Velocity Estimation

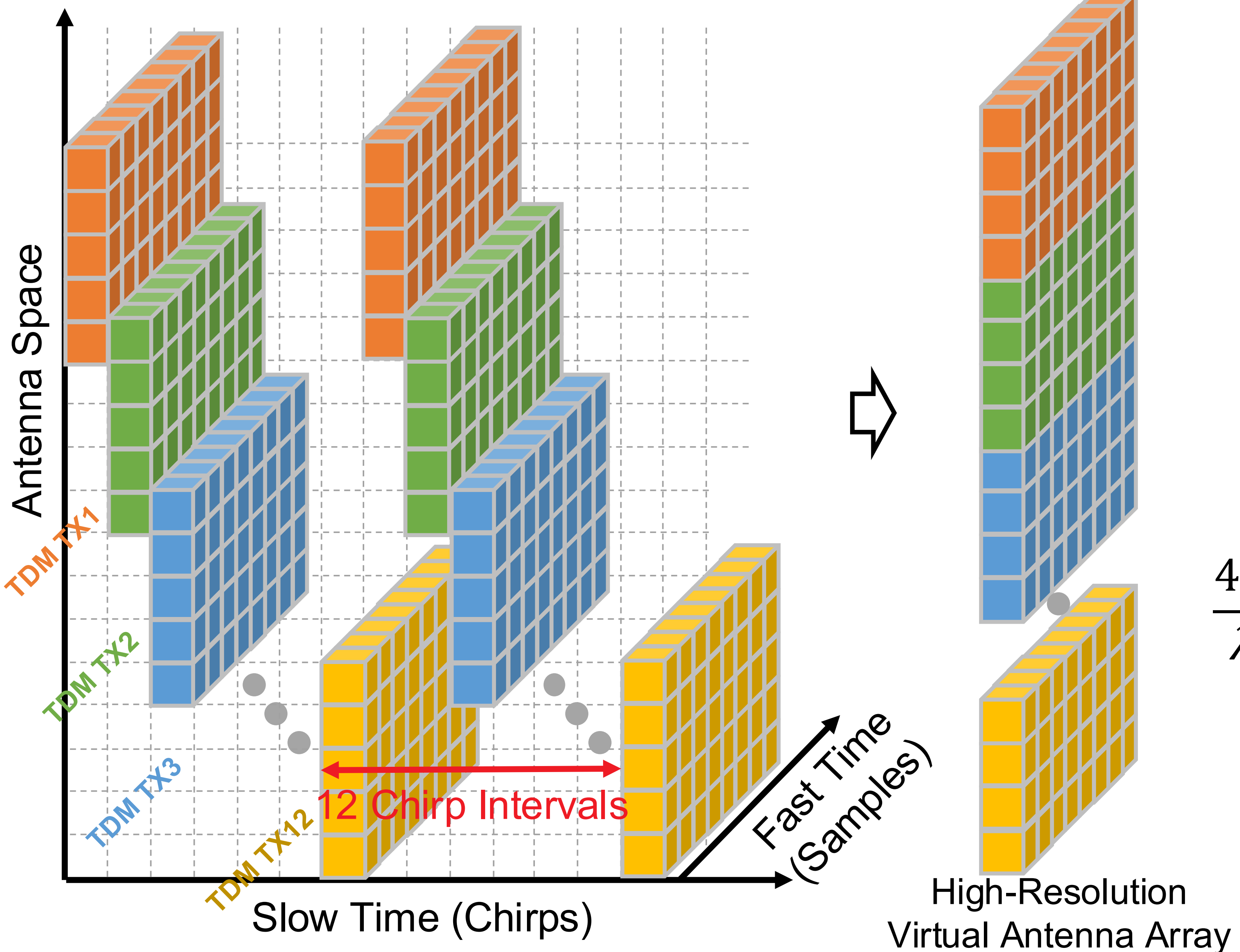


Single−Tx Radar

k-th and k+1-th chirps

$$\frac{4\pi}{\lambda} \cdot vT(k+1-k) = \frac{4\pi}{\lambda} \cdot vT$$

Challenge 2: Ambiguity in Velocity Estimation



Single−Tx Radar

k-th and k+1-th chirps

$$\frac{4\pi}{\lambda}\cdot vT(k+1-k)=\frac{4\pi}{\lambda}\cdot vT$$

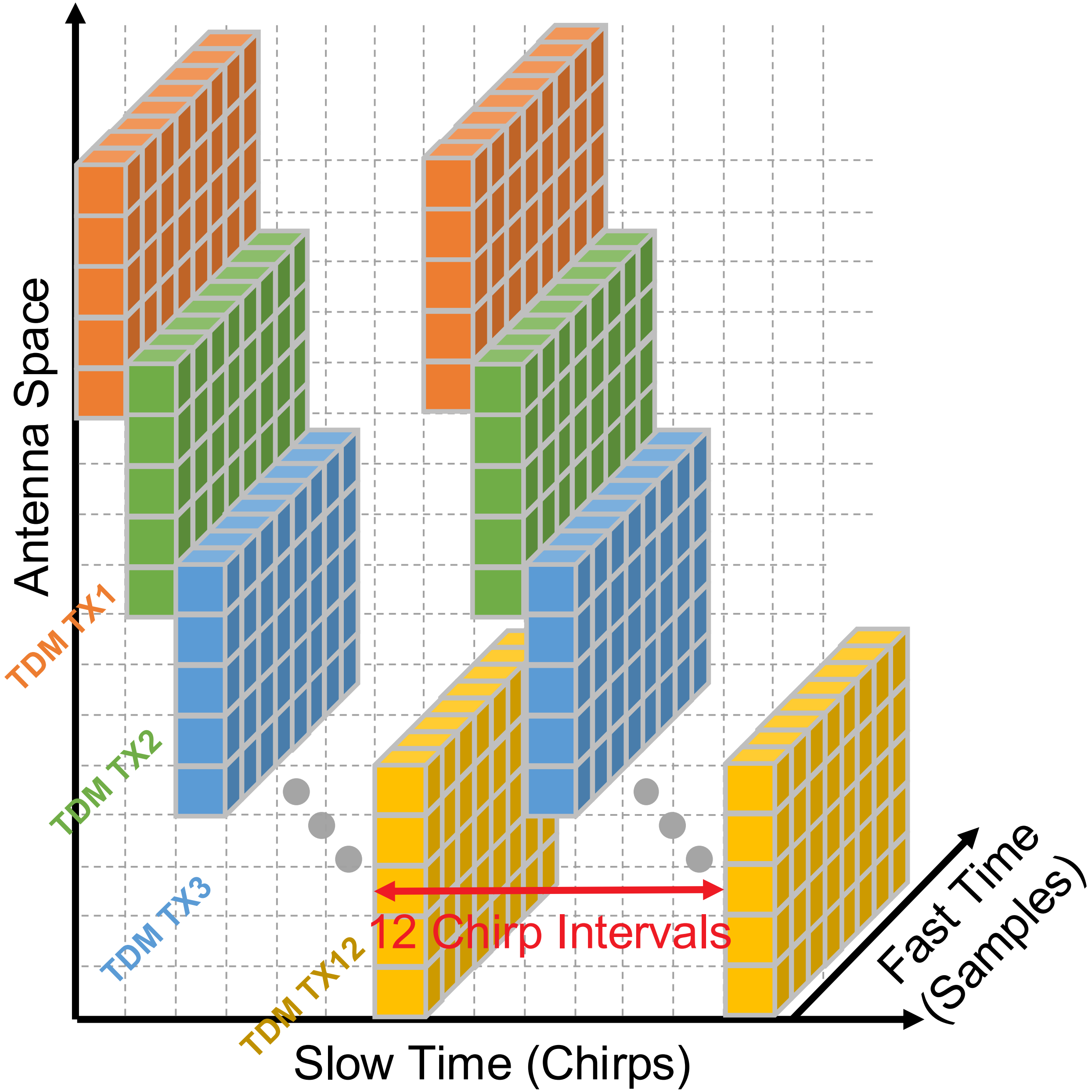
Cascaded MIMO Radar

k-th and k+12-th chirps

$$\frac{4\pi}{\lambda}\cdot vT(k+12-k)=\frac{4\pi}{\lambda}\cdot 12vT$$

12x lower maximum unambiguous velocity!

Low-Ambiguity Doppler Processing



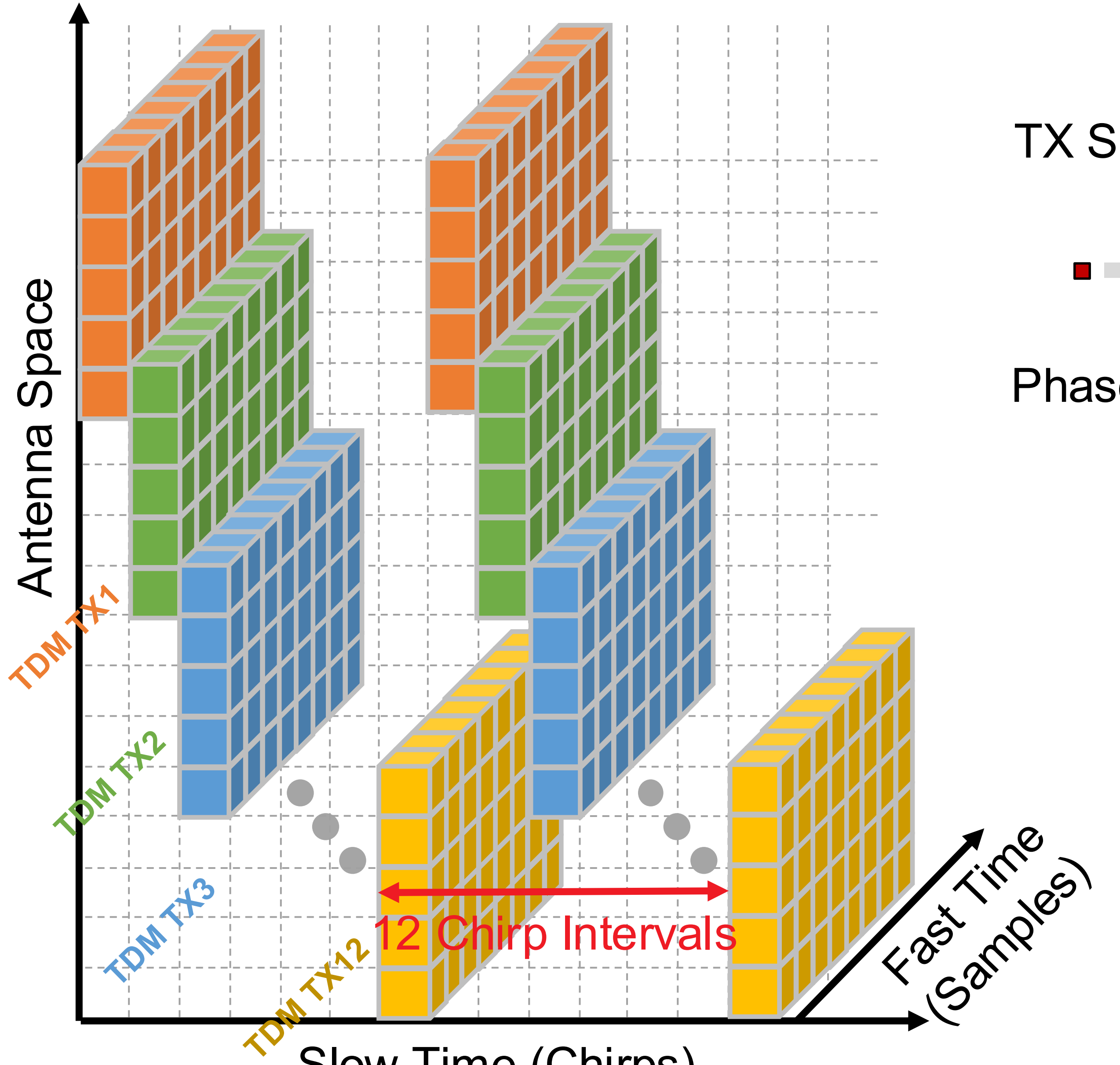
Leverage all consecutive Tx chirps for Doppler estimation

12x Doppler sampling rate

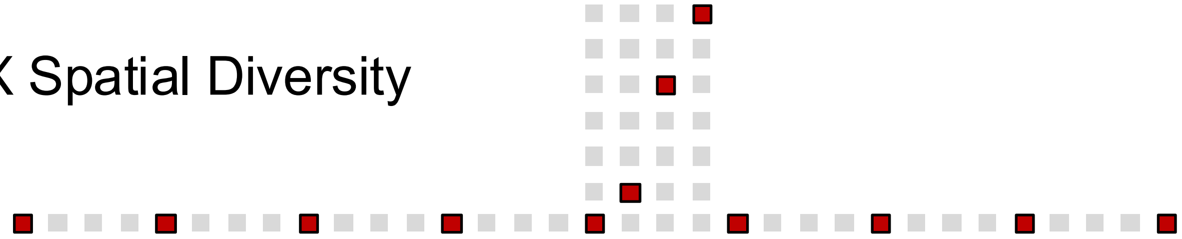
⇩

12x max unambiguous Doppler velocity

Low-Ambiguity Doppler Processing



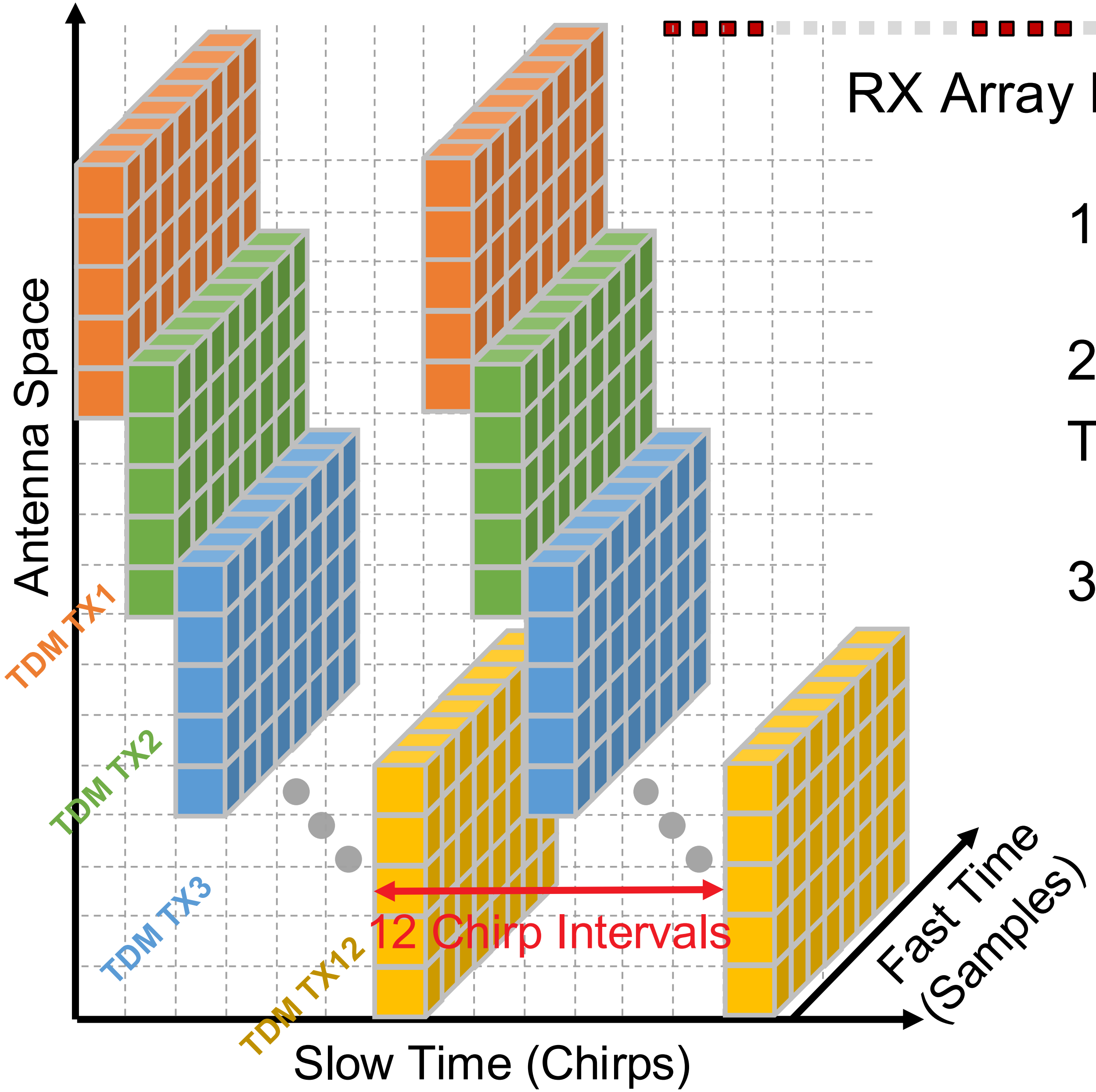
TX Spatial Diversity



Phase Difference between consecutive chirps

$$= \frac{2\pi}{\lambda}\left[\underbrace{kd\sin\phi}_{TX\ Spatial\ Diversity} + \underbrace{2vTk}_{Doppler\ Shift}\right]$$

Low-Ambiguity Doppler Processing



RX Array Beamforming using Single-TX Virtual Array

1. Rx Array Phase Diversity $= \frac{2\pi}{\lambda} i d sin\phi$

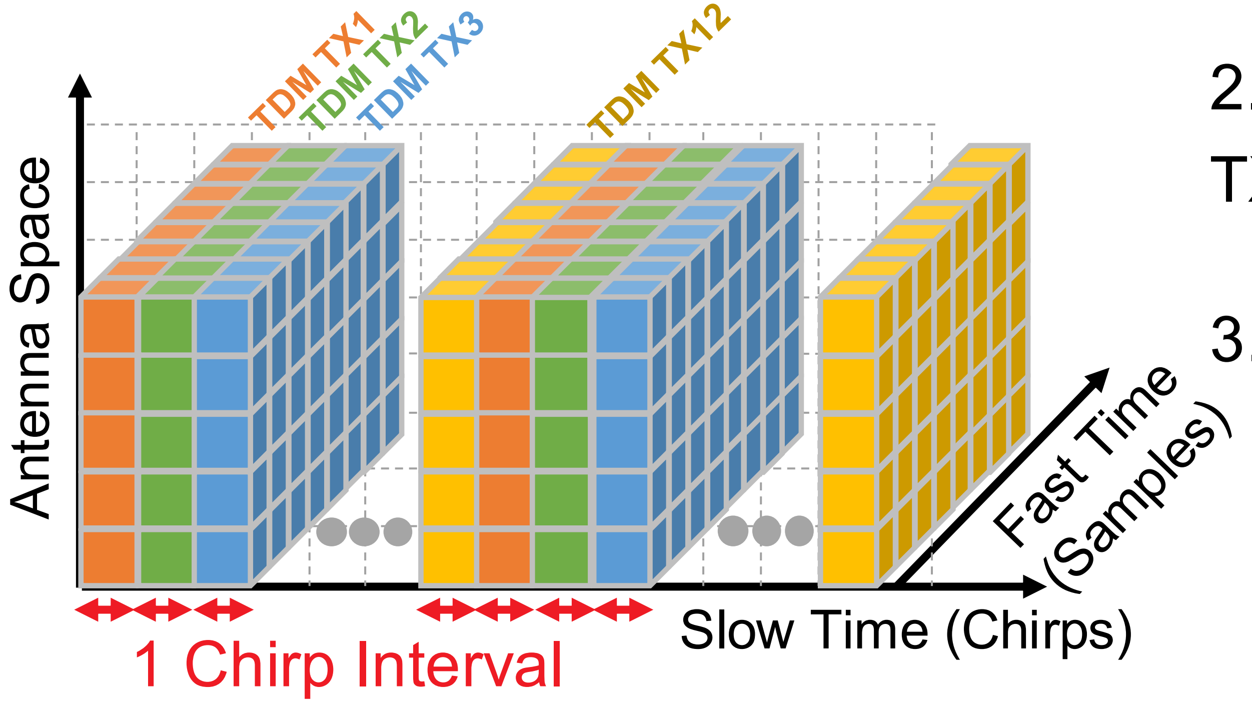
2. For every Angle of Reflection ϕ, compute TX steering vector $\frac{2\pi}{\lambda} k d sin\phi$

3. Multiplying with the complex conjugate

$$\cancel{-\frac{2\pi}{\lambda} k d sin\phi} + \frac{2\pi}{\lambda}[\cancel{k d sin\phi} + 2vTk]$$

$$= \frac{4\pi}{\lambda} vT$$

Low-Ambiguity Doppler Processing



1. Rx Array Phase Diversity $= \frac{2\pi}{\lambda} idsin\phi$

2. For every Angle of Reflection ϕ, compute TX steering vector $\frac{2\pi}{\lambda} kdsin\phi$

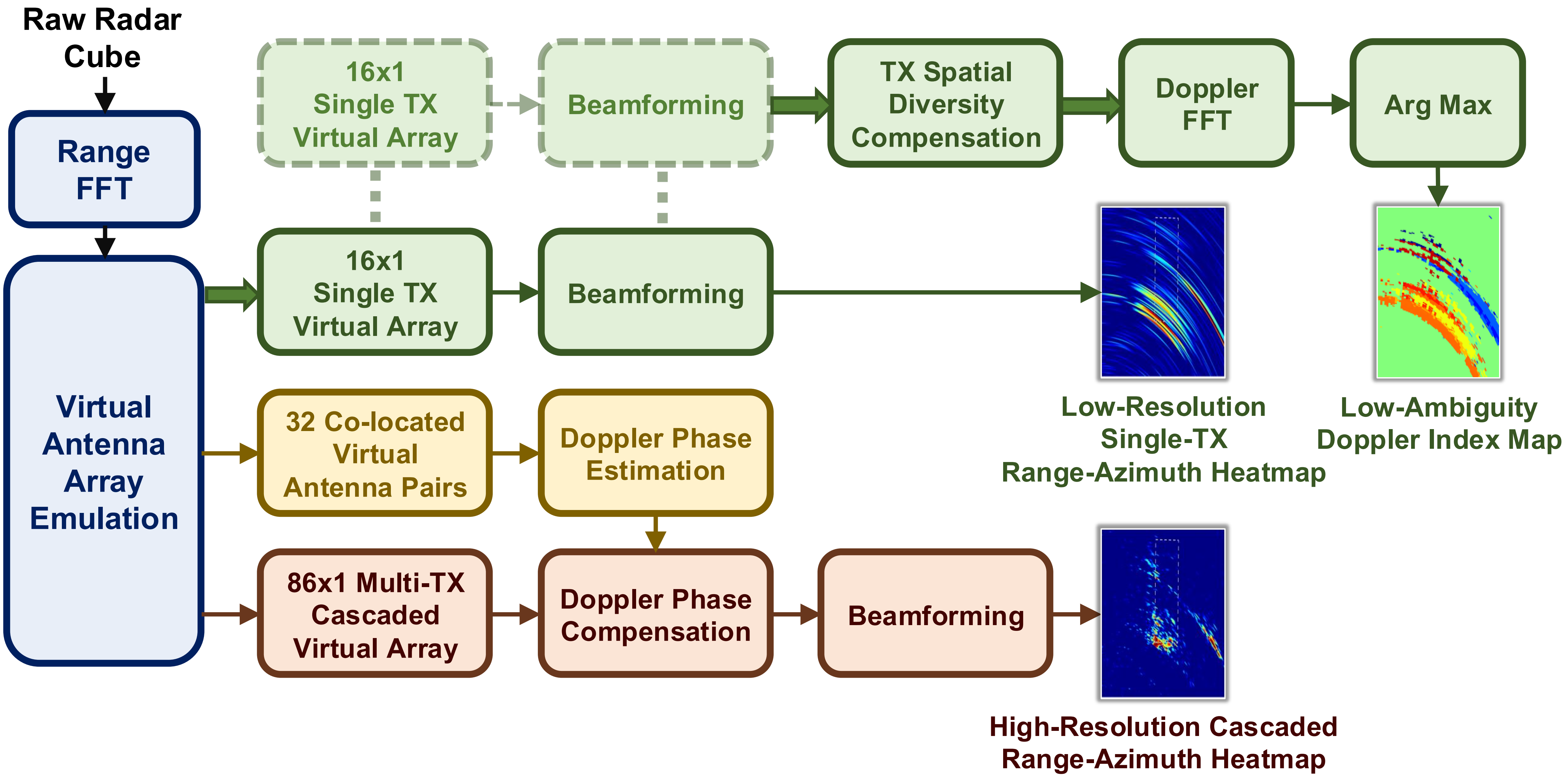
3. Multiplying with the complex conjugate

$$\cancel{-\frac{2\pi}{\lambda} kdsin\phi} + \frac{2\pi}{\lambda}[\cancel{kdsin\phi} + 2vTk]$$

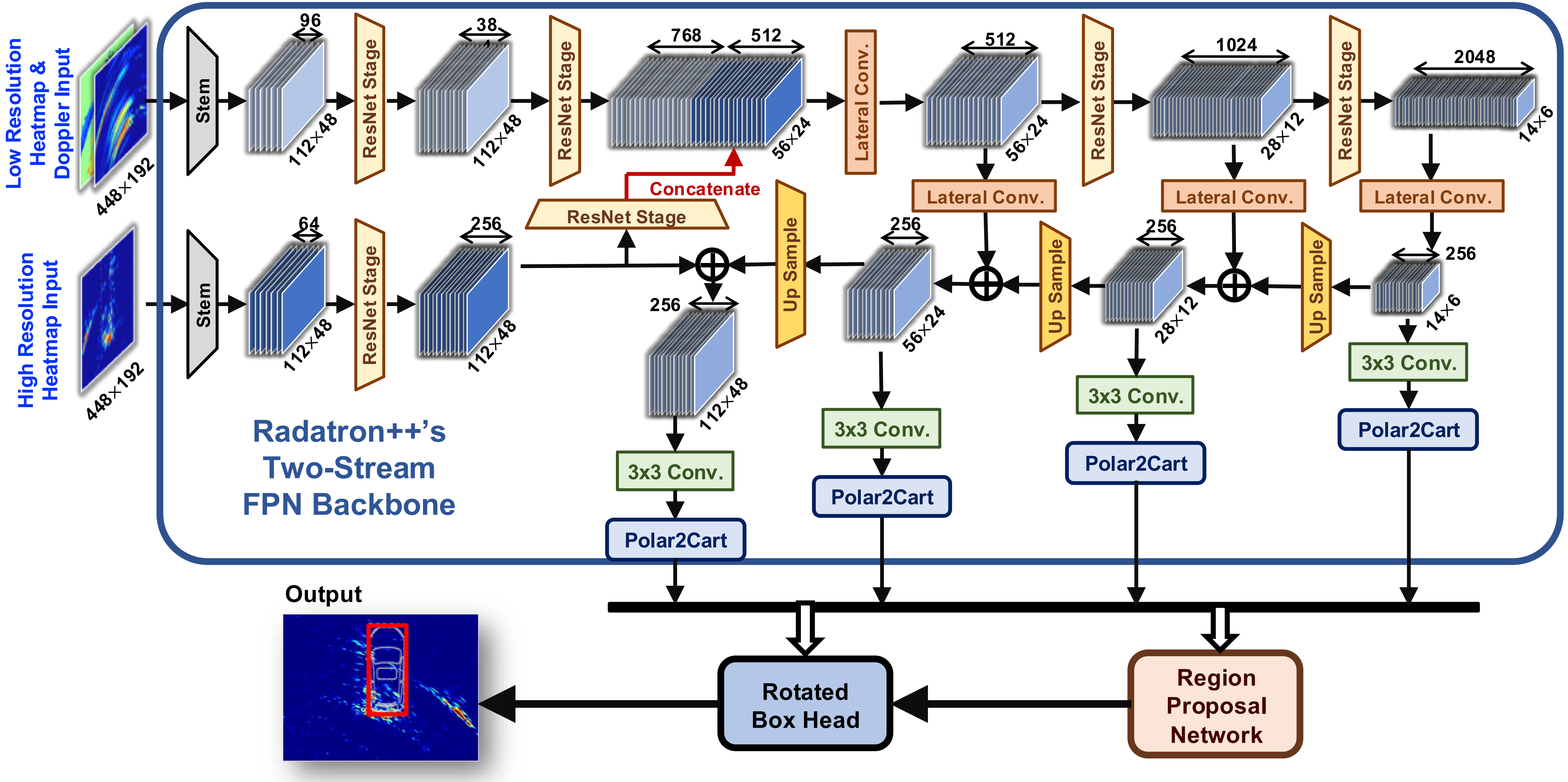
$$= \frac{4\pi}{\lambda} vT$$

TX spatial diversity eliminated!

Signal Processing Pipeline of Radatron++



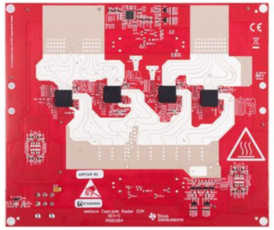
Network Architecture of Radatron++

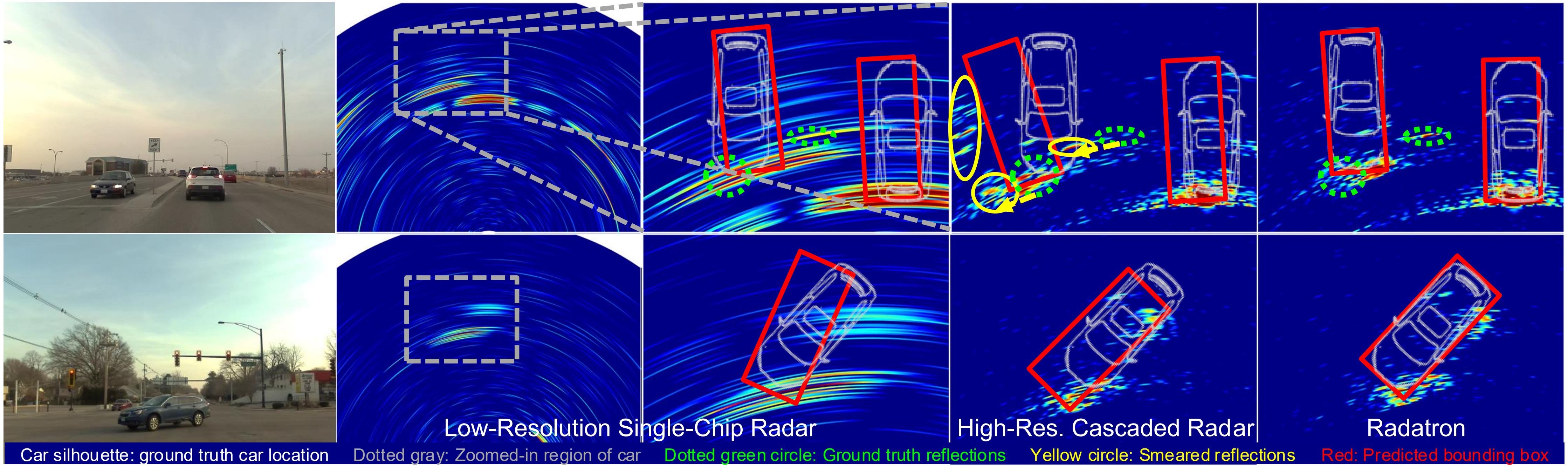


Demo Video of Radatron++

No Temporal Post Processing
Frame to frame detection in the range of 25 meters.

Radatron++ Conclusion





- Jointly leveraging a variety of virtual antenna array topologies.
- Hybrid radar signal processing and deep learning solution.
- 2D bounding box detection accuracy outperforms prior work using low-resolution radars by 9.3% (AP_{50}) and 18.1% (AP_{75}) respectively.
- Radatron dataset is available on our website:

https://jguan.page/Radatron/