Automotive radar radiations as signals of opportunity for millimeter wave V2I links

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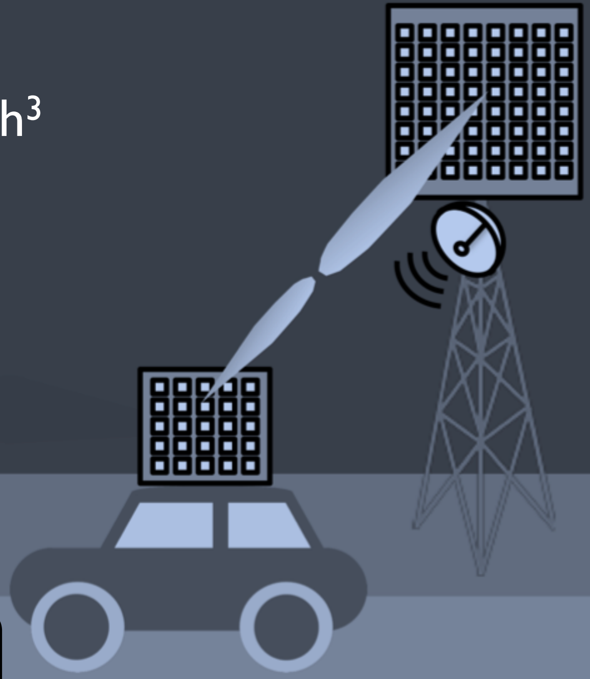
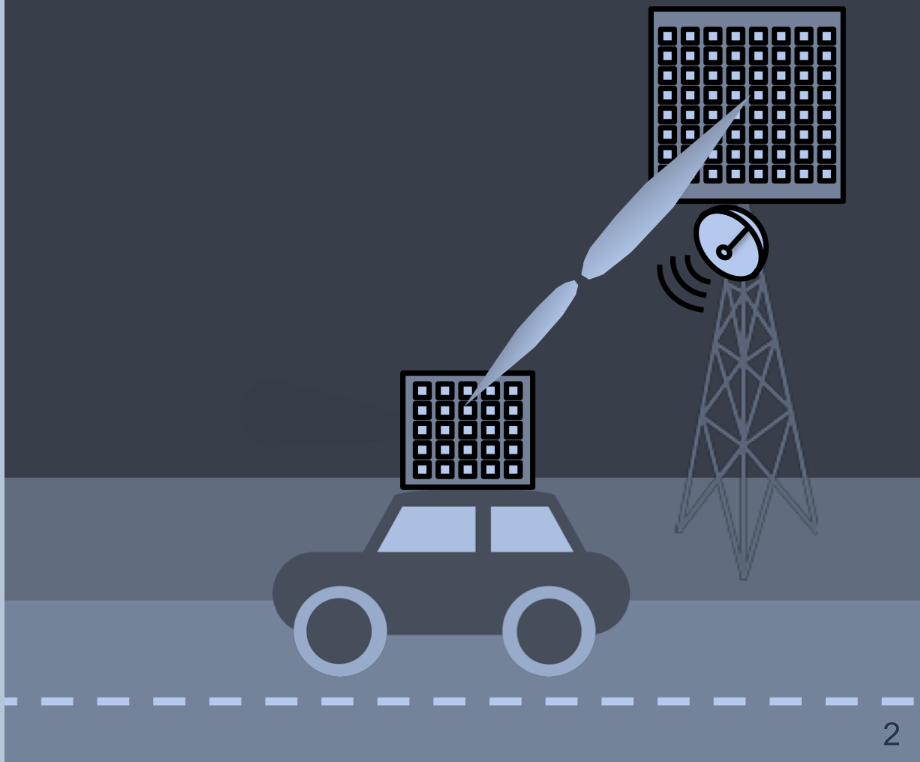


This material is based upon the work supported a gift from Nokia.

Outline



Outline

Use of out-of-band information for mmWave link configuration

Motivation

Main idea

Passive radar to tap transmissions of automotive radar on the vehicles

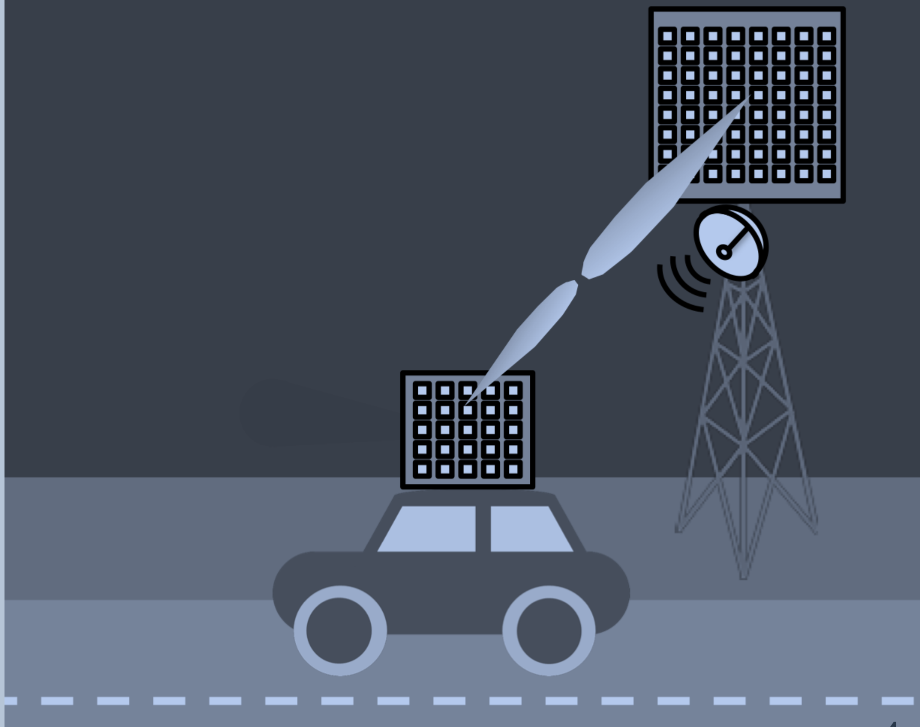
Ray-tracing simulation scenario and simulation results

Simulation

Challenges

How to overcome challenges in using FMCW transmissions for mmWave

Motivation



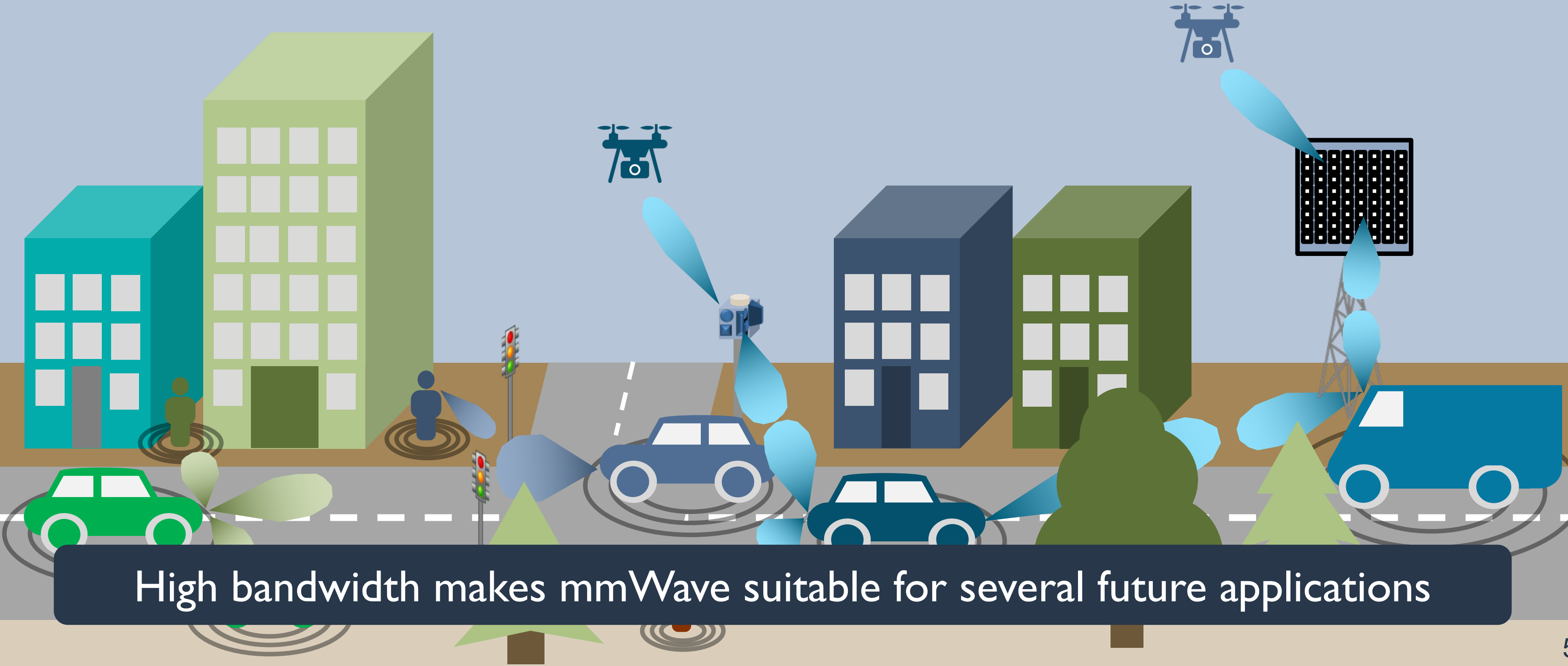
Why millimeter wave communication?

High definition 3D map download (~Gbyte)

Infotainment & cloud services

Sharing local sensor data for cooperative perception

High speed internet access

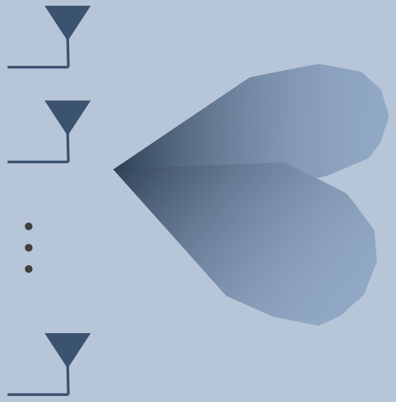


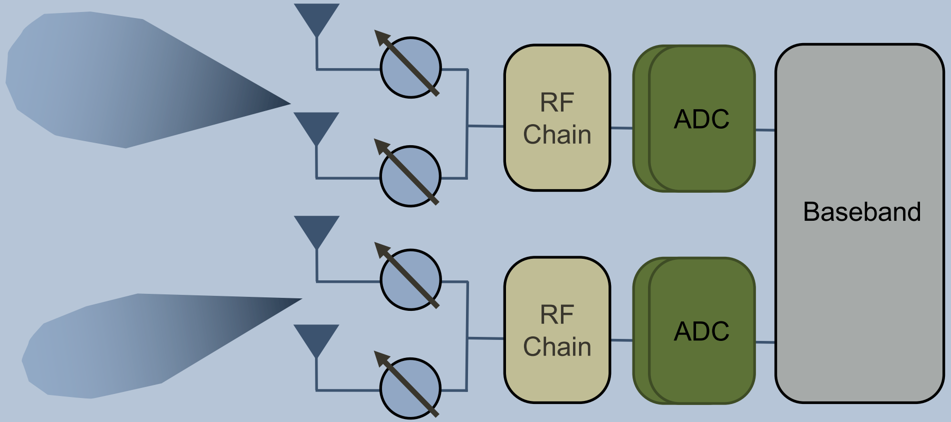
High bandwidth makes mmWave suitable for several future applications

More antennas and hardware constraints

Many antennas at the TX and RX

Hardware constraints impact how the antennas are used





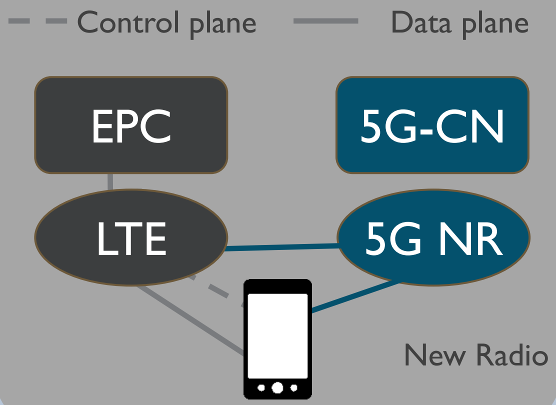
Directional transmission/reception for sufficient link margin

Significant fraction of channel coherence time spent in training

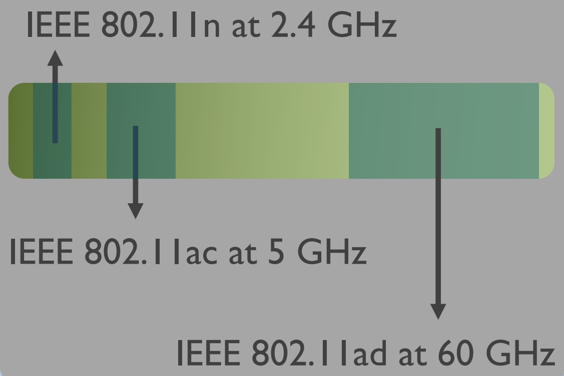
Low overhead link configuration challenging for mmWave

Out-of-band information for mmWave

Cellular commun. [1]



WiFi [2][3]



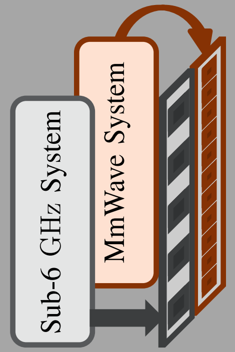
V2X commun. [4]

Out-of-band info. available to help configure mmWave links

[1] www.3gpp.org/news-events/3gpp-news/1929-nsa_nr_5g
[2] L. Verma, M. Fakharzadeh, and S. Choi, "Wifi on steroids: 802.11 ac and 802.11 ad", IEEE Wireless Commun., vol. 20, no. 6, pp. 30–35, Dec. 2013.
[3] T. Nitsche, A. B. Flores, E. W. Knightly, and J. Widmer, “Steering with eyes closed: mm-wave beam steering without in-band measurement,” in Proc. INFOCOM, Apr. 2015, pp. 2416–2424.
[4] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath Jr., “Millimeter wave vehicular communication to support massive automotive sensing,” IEEE Commun. Mag., vol. 54, no. 12, pp. 160–167, Dec. 2016.

Prior work

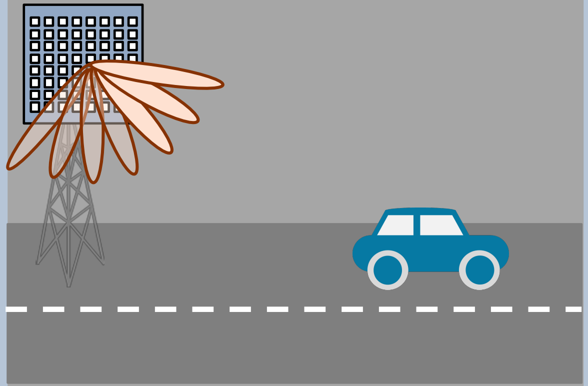
Sub-6 GHz info. [1][2]



Co-located arrays

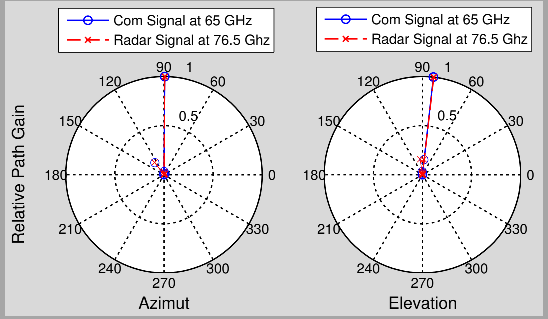
Sub-6 GHz assisted beam-training [1] and covariance estimation [2]

Position info. [3][4]



Reduced number of possible beams

Active radar info. [5]

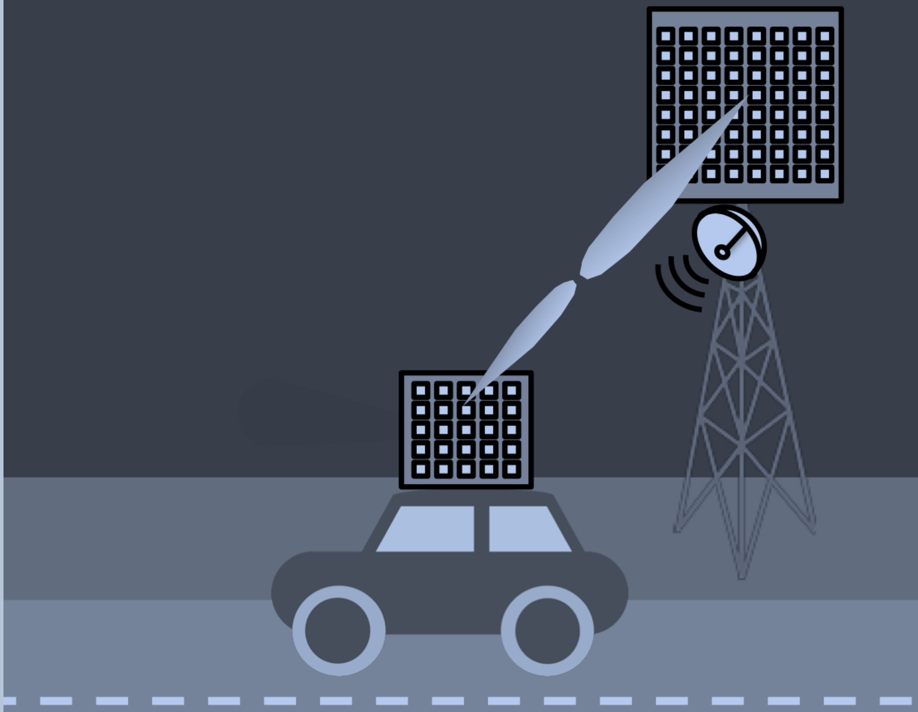


Common paths in radar echo and communication channel

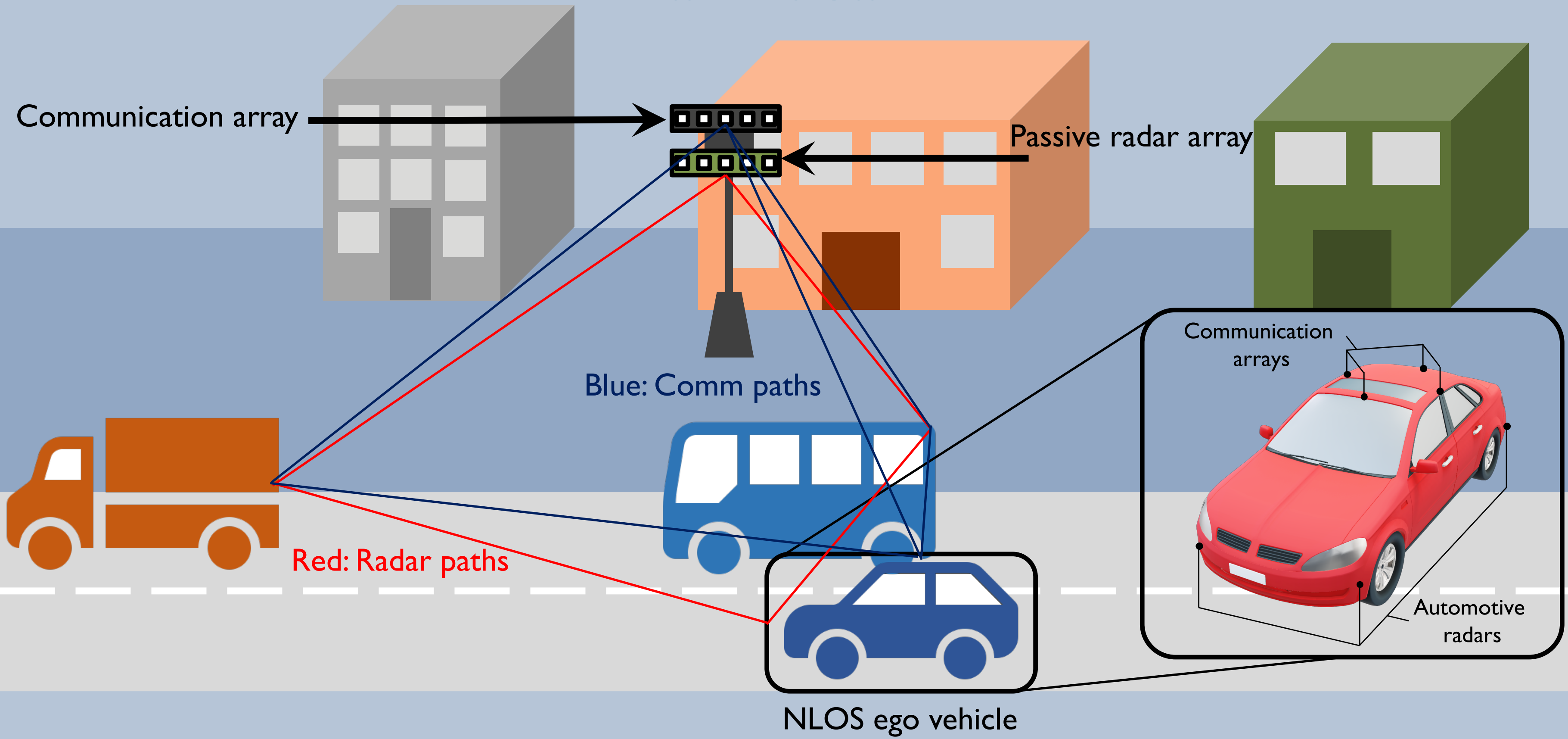
No prior work on using passive radar for mmWave systems

[1] A. Ali, N. González-Prelcic, and R. W. Heath Jr., "Millimeter wave beam-selection using out-of-band spatial information," IEEE Trans. Wireless Commun., vol. 17, no. 2, pp. 1038–1052, 2018.
[2] A. Ali, N. González-Prelcic, and R. W. Heath Jr., "Spatial Covariance Estimation for Millimeter Wave Hybrid Systems using Out-of-Band Information," arXiv preprint arXiv:1804.11204, 2018.
[3] N. Garcia et al., "Location-aided mm-wave channel estimation for vehicular communication," in Proc. IEEE Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC), Jul. 2016, pp. 1–5.
[4] V. Va et al., "Position-aided millimeter wave V2I beam alignment: A learning-to-rank approach," in Proc. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC), Oct. 2017, pp. 1–5.
[5] N. González-Prelcic, R. Méndez-Rial, and R. W. Heath Jr., "Radar aided beam alignment in mmwave V2I communications supporting antenna diversity," in Proc. Inf. Theory Appl. (ITA) Wksp, Feb. 2016.

Passive radar at RSU



Main idea



Communication array

Passive radar array

Blue: Comm paths

Red: Radar paths

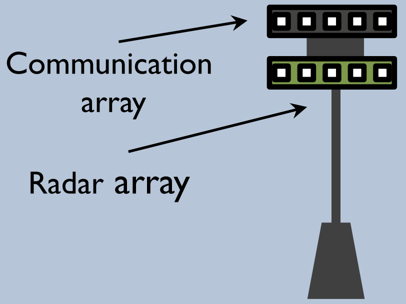
Communication arrays

Automotive radars

NLOS ego vehicle

Similarity expected in radar and comm. azimuth power spectrum (APS)

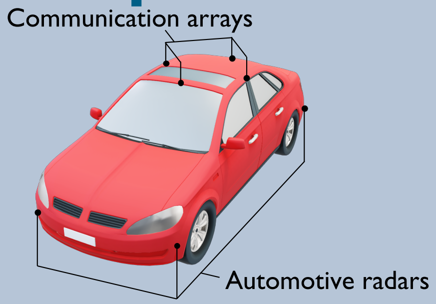
Communication and radar system setup



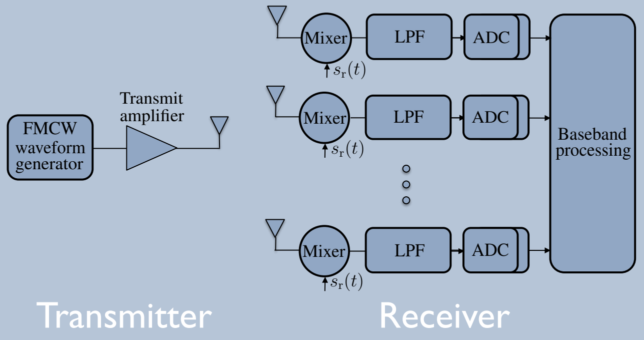
Co-located arrays at RSU, separated at the vehicle

FMCW radar and OFDM communication system

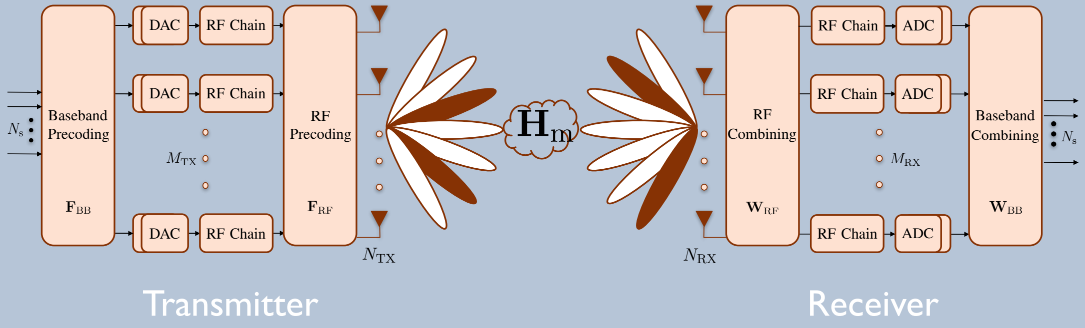
Same number of antennas in radar and communication array



Fully digital radar system

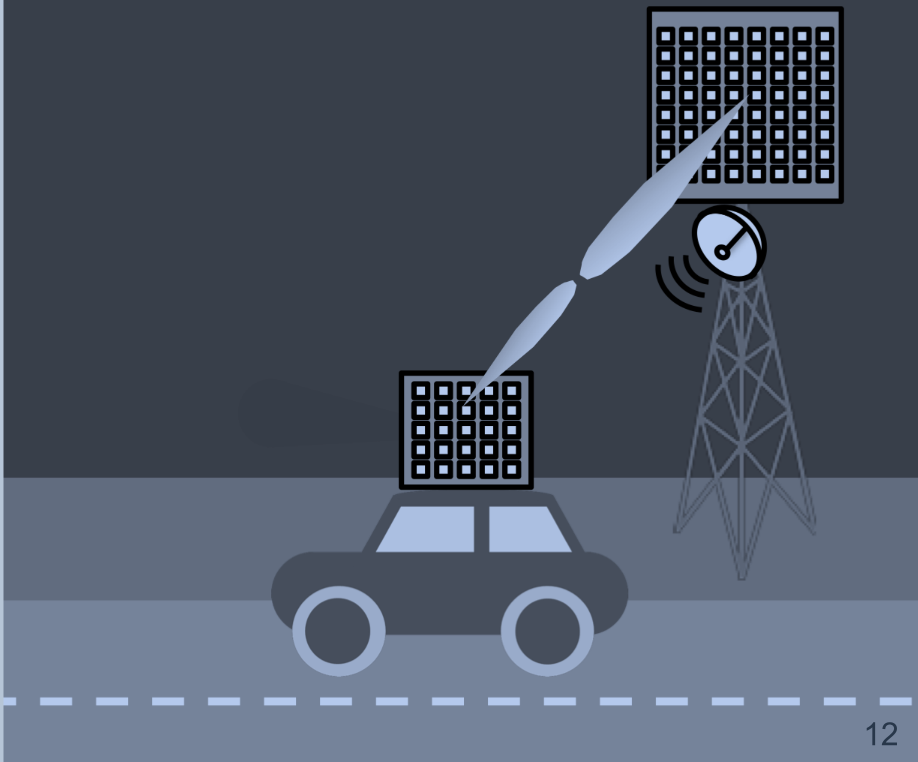


Hybrid mmWave system



Estimate radar receive covariance and use it for mmWave link configuration

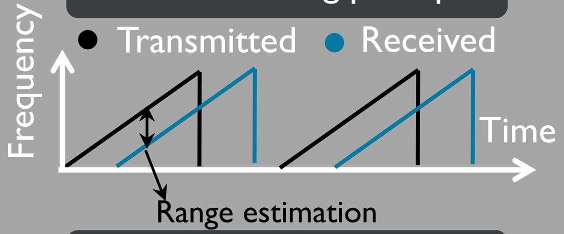
Challenges



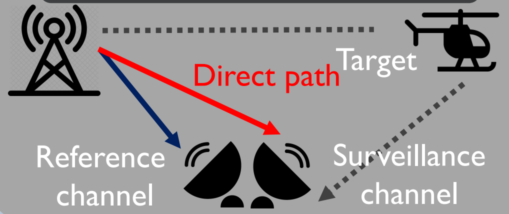
Challenges in using FMCW passive radar

Waveform knowledge in passive radar

FMCW working principle



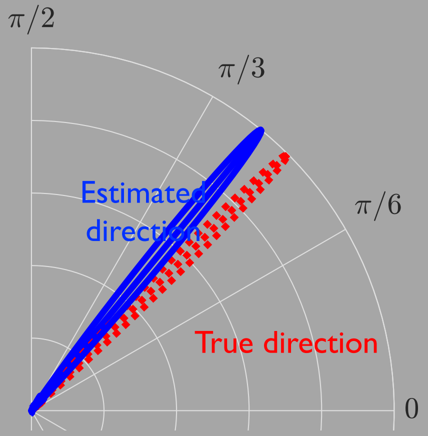
Passive radar



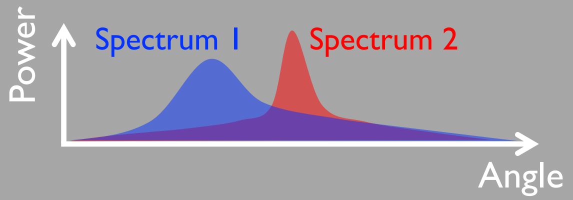
Bias in angle estimation

Estimated angle $\hat{\theta} \neq \theta$ True angle

Critical in large antenna systems



Similarity metric



Are spectrum1 and 2 similar?

↓

Relate spectrum similarity to a comm. metric e.g., rate?

Extended version [1]

Recover APS/covariance w/o waveform, correct bias, and measure similarity

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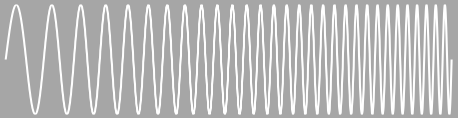
[1] A Ali, N González-Prelcic, A Ghosh, "Passive Radar at the Roadside Unit to Configure Millimeter Wave Vehicle-to-Infrastructure Links", arXiv preprint arXiv:1910.10817, 2019.

Lack of waveform knowledge at roadside unit

Perfect FMCW waveform knowledge



Freq. of FMCW waveform

Initial frequency → $f_{\mathrm{r}} + \frac{\beta}{2}t$ → Chirp rate

Freq. of processed signal

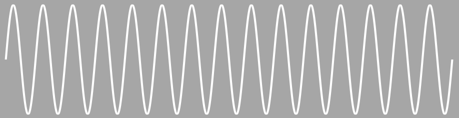
$\beta\tau$ → Used in range estimation

Phase of processed signal

$$2\pi f_{\mathrm{r}}\tau - \pi\beta\tau^2$$

Used in Doppler estimation

Simple mixing



Proposed mixing

Freq. → $f_{\mathrm{r}} + \Delta f$ Phase → ϵ

Freq. of processed signal

$\beta\tau + \Delta f - \frac{\beta t}{2}$ → Random

Phase of processed signal

$$2\pi f_{\mathrm{r}}\tau - \pi\beta\tau^2 + \epsilon$$

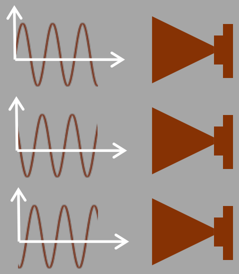
↓

Random

Spatial covariance

No time dependence

Depends only on phase-difference across antennas



Proposed architecture has same spatial covariance as perfect waveform

Proposed architecture recovers spatial cov. perfectly (not range or doppler)

Bias correction for FMCW radar

Bias in FMCW [1]

$$\sin\hat{\theta} = \left(1 + \frac{B_{\mathrm{r}}}{2f_{\mathrm{r}}}\right)\sin\theta$$

$\downarrow$ Estimated angle

$\downarrow$ True angle

Particularly problematic in large antenna systems

Example: 256 antennas

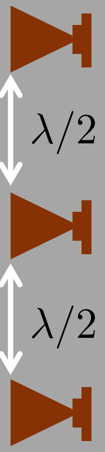
$f_{\mathrm{r}} = 76\,\mathrm{GHz}$

$B_{\mathrm{r}} = 1.2\,\mathrm{GHz}$

Possibly null in the direction of true angle

Bias in frequency division duplex systems

Same array in uplink and downlink



Array set to downlink wavelength, observations made in uplink

$$\sin\hat{\theta} = \frac{\overset{\text{DL wavelength}}{\lambda_{\mathrm{DL}}}}{\underset{\text{UL wavelength}}{\lambda_{\mathrm{UL}}}}\sin\theta$$

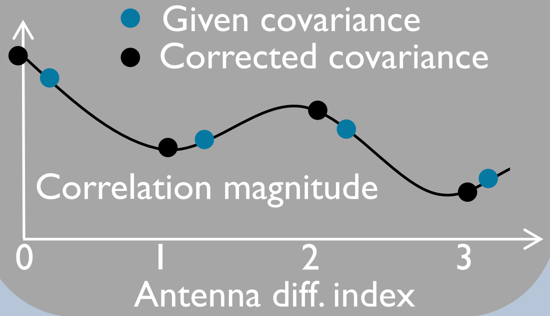
Similar bias in FDD

Covariance correction to rectify bias

Why covariance?

Alternate uses (precoding based on singular vectors)

A cov. correction strategy [2]



Established a connection with a well studied problem to correct the bias

[1] J. Kim, J. Chun, and S. Song, "Joint Range and Angle Estimation for FMCW MIMO Radar and Its Application," arXiv preprint arXiv:1811.06715, 2018.

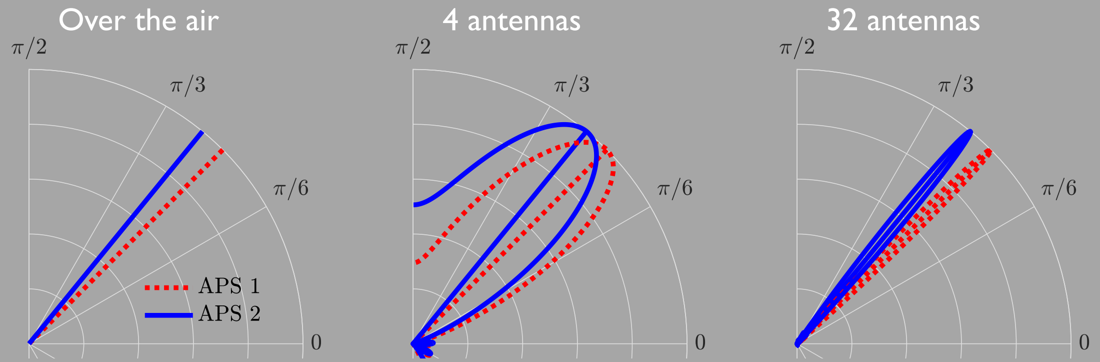
[2] M. Jordan, X. Gong, and G. Ascheid, "Conversion of the spatio-temporal correlation from uplink to downlink in FDD systems," in Proc. IEEE WCNC, Apr. 2009, pp. 1–6.

Similarity metric to compare power spectra

Why a similarity metric?

- Intuitive understanding of congruence but not formal
- A metric that informs about the system performance
- Useful also in FDD covariance correction strategy

Role of system dimension


Over the air

4 antennas

32 antennas

Useful

Not so useful

Need a similarity metric for spectra that informs about system performance

Proposed similarity metric

Definition

For two N point spectra $\mathbf{d}_1$ and $\mathbf{d}_2$

$$S_{1\rightarrow 2}(L,N)=\frac{\sum_{i\in\mathcal{I}_1}\mathbf{d}_2[i]}{\sum_{i\in\mathcal{I}_2}\mathbf{d}_2[i]}$$

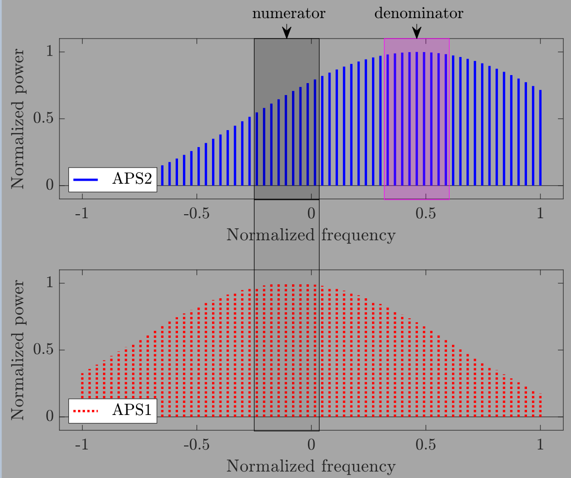
$\mathcal{I}_1$ $(\mathcal{I}_2)$ is the index set of cardinality $L \leq N$

Consists of indices of L largest entries of $\mathbf{d}_1$ $(\mathbf{d}_2)$

N related to antennas, L to streams

S normalized in [0,1]

Intuitive explanation



Generally sim. increases (decreases) with L (N)

Relation with rate

Similarity related with RPE

Dominant singular vectors of R1

$$\text{RPE}=\frac{\text{tr}(\mathbf{U}_1^*\mathbf{R}_2\mathbf{U}_1)}{\text{tr}(\mathbf{U}_2^*\mathbf{R}_2\mathbf{U}_2)}$$

Dominant singular vectors of R2

Similarity identical to RPE

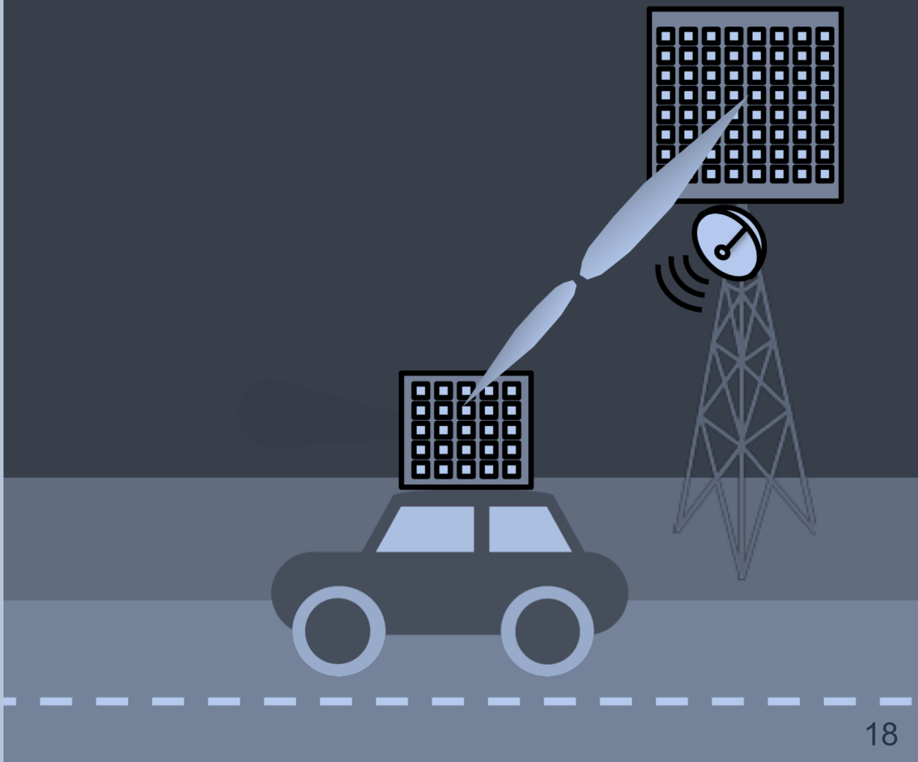
Angles on DFT grid or infinite antennas

RPE related with rate [1]

The proposed similarity metric for power spectra informs about relative rate

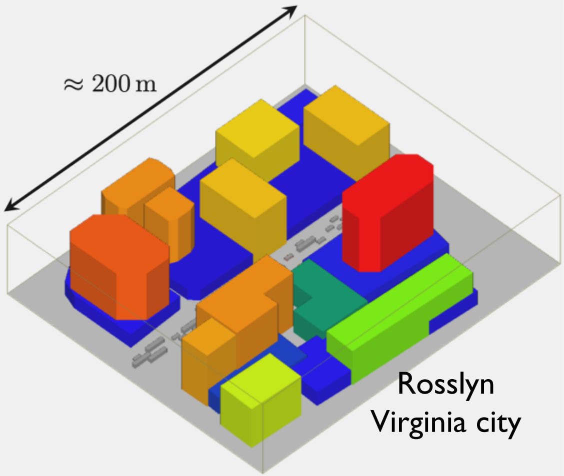
[1] S. Park et. al., ``Spatial Channel Covariance Estimation for Hybrid Architectures Based on Tensor Decompositions", submitted to IEEE Trans. Wireless Commun.

Simulation scenario and results



Ray-tracing simulation scenario

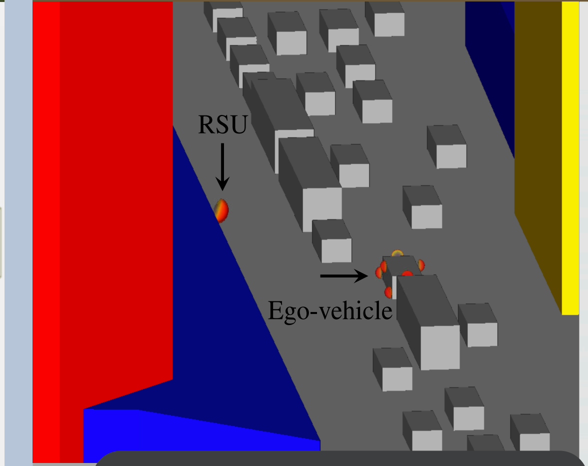
City, buildings, and vehicle position

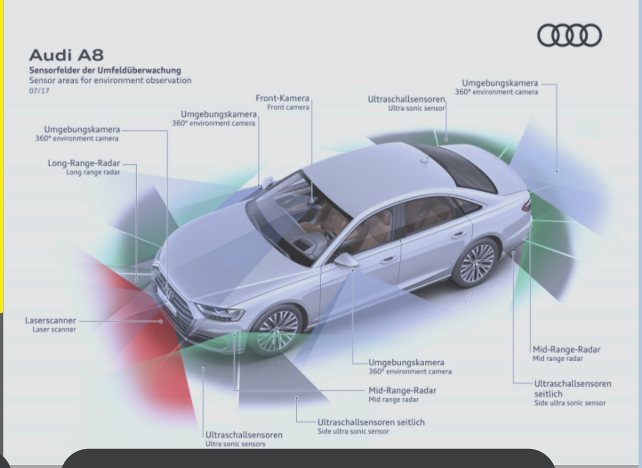


Cars and trucks in 4 lanes

Lane widths, car and truck ratio, inter-vehicle distance, lane speeds [1]

Communication and radar





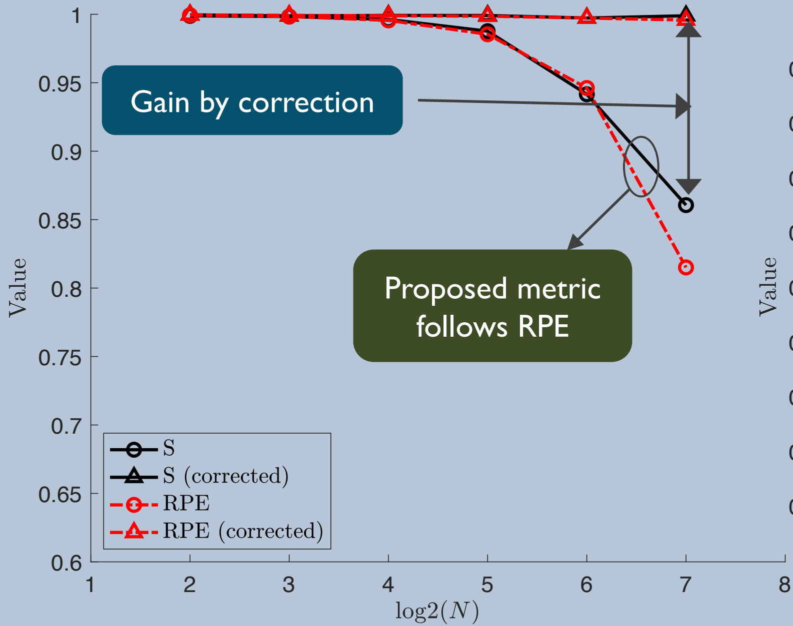
Location of communication antennas on vehicle and RSU height [1]

Position of radars not standardized
Used Audi A8 as an example

Ray-tracing simulation consistent with 3GPP-V2X evaluation methodology

[1] 3GPP, "Study on evaluation methodology of new Vehicle-to-Everything V2X use cases for LTE and NR," 3GPP, TR 37.885, Sep. 2018, version 15.1.0.

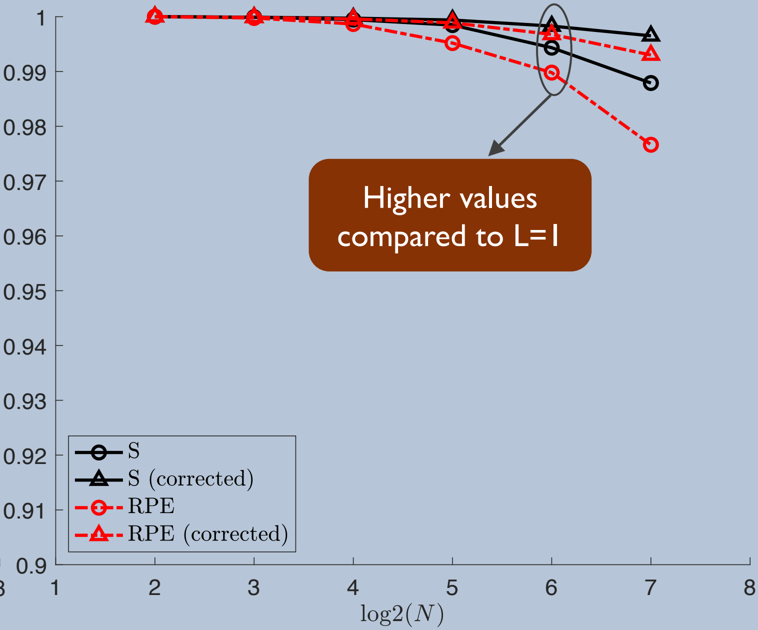
Simulation result: Bias correction



Gain by correction

Proposed metric follows RPE

N_s=L=1



Higher values compared to L=1

N_s=L=4

Purpose

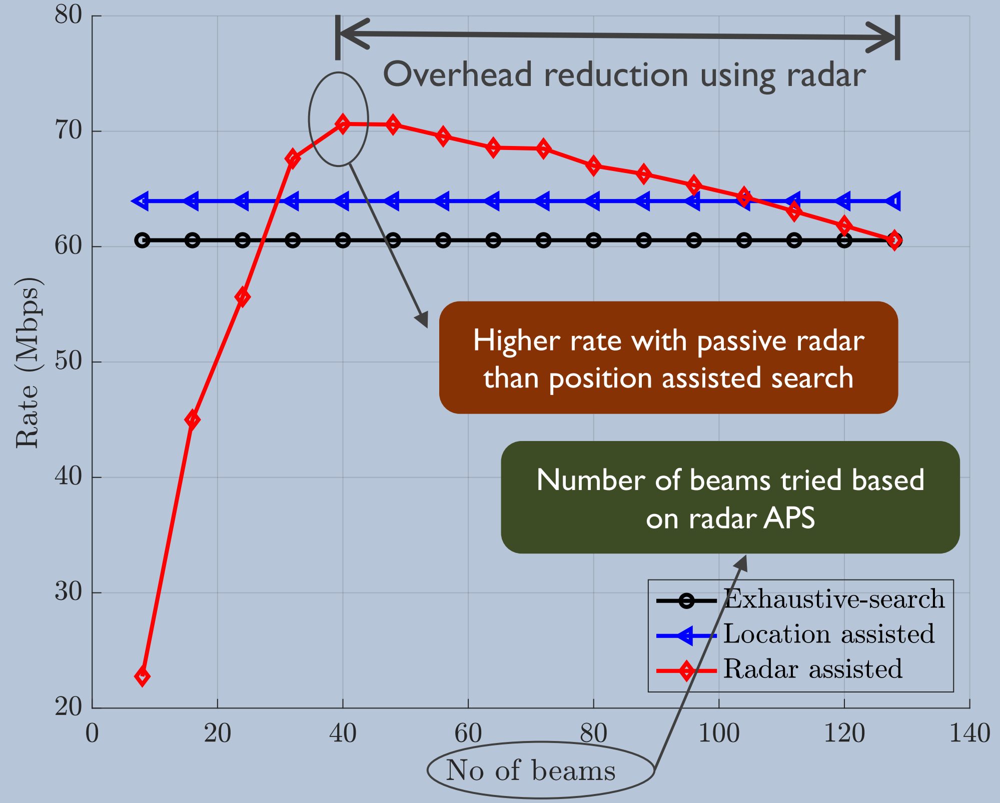
- RPE and similarity metric behavior for off-grid case
- Bias correction benefit
- Dependence on L and N

Simple set-up

- Co-located antennas
- Same frequency band

Bias correction improves the similarity between radar and communication

Simulation result: NLOS beam-selection



Overhead reduction using radar

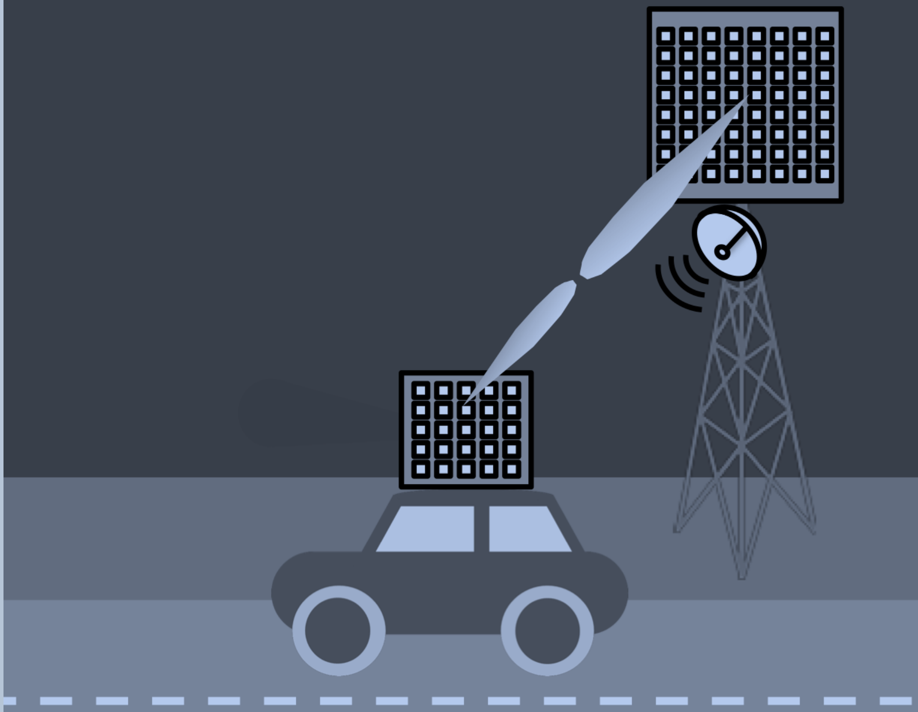
Higher rate with passive radar than position assisted search

Number of beams tried based on radar APS

Parameter	Value
Radar frequency	76 GHz
Communication frequency	73 GHz
Antennas at RSU	128
Comm. antennas at Vehicle	16
Radar and Communication BW	1 GHz
GNSS error	10 m
Transmit power	30 dBm

Proposed radar assisted strategy particularly useful in NLOS scenario

Summary



Summary

Contributions

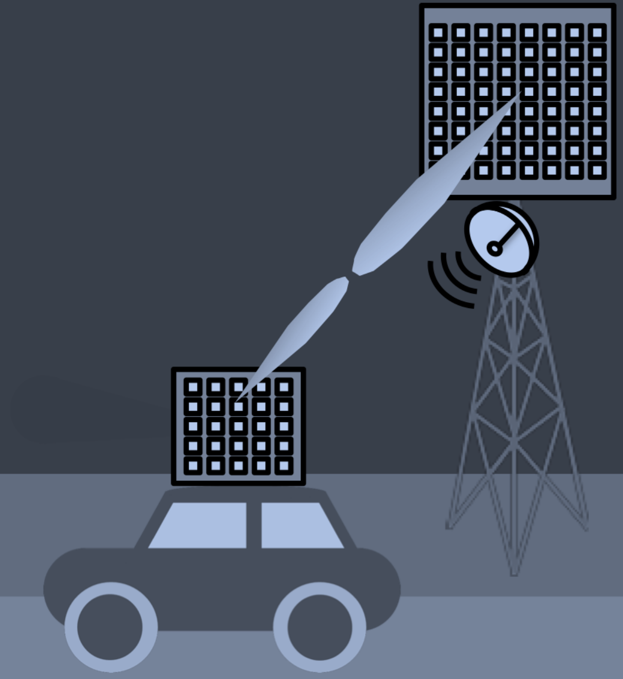
- Proposed a simplified radar receiver to recover spatial info.
- Proposed a radar bias correction strategy
- Proposed a similarity metric to compare power spectra

Results

- Bias correction improves the similarity between radar and communication covariance
- Passive radar assisted beam-selection has high rate in NLOS

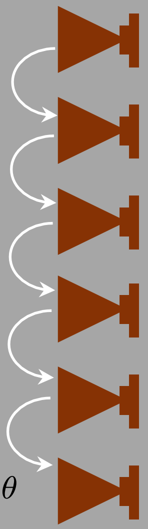
Thank you!

TEXAS
The University of Texas at Austin



Bias in FMCW radar

Angle dependent phase offset in comm.



1

$e^{\mathrm{j}\frac{2\pi d}{\lambda}\sin\theta}$

$\vdots$

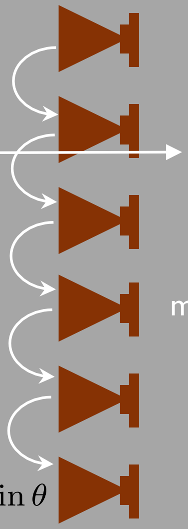
$e^{\mathrm{j}m\frac{2\pi d}{\lambda}\sin\theta}$

mth antenna

$\vdots$

$e^{\mathrm{j}(M-1)\frac{2\pi d}{\lambda}\sin\theta}$

Angle dependent phase offset in FMCW



1

$e^{\mathrm{j}\frac{2\pi d}{\lambda}\sin\theta}e^{\mathrm{j}\frac{2\pi d}{\gamma}\sin\theta}$

Does not depend on m

$\vdots$

$e^{\mathrm{j}m\frac{2\pi d}{\lambda}\sin\theta}e^{\mathrm{j}m\frac{2\pi d}{\gamma}\sin\theta}$

mth antenna

$\vdots$

$e^{\mathrm{j}(M-1)\frac{2\pi d}{\lambda}\sin\theta}e^{\mathrm{j}(M-1)\frac{2\pi d}{\gamma}\sin\theta}$

Additional phase variation causes bias in FMCW radar