Millimeter Wave Communication with Out-of-Band Information

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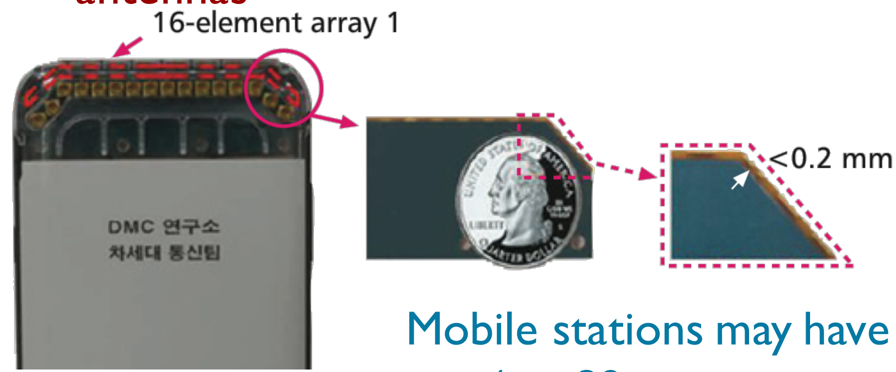
INTRODUCTION

MmWave as the rebirth of MIMO

@sub 6 Ghz only 2-8 antennas supported

@mmWave BSs may have 64 to 512 antennas



Mobile stations may have 4 to 32 antennas

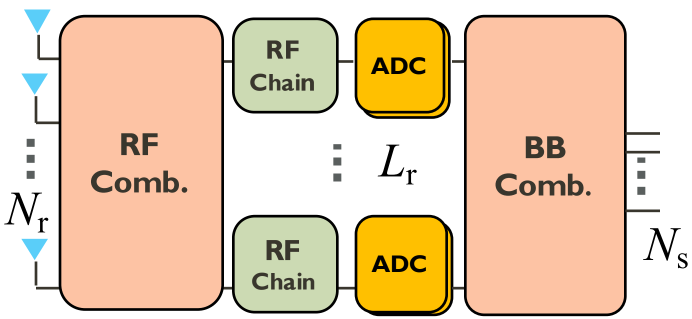
1 W. Roh et al. "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," in *Communications Magazine, IEEE* , February 2014.

Large arrays focus and capture more energy, outperforming lower frequency solutions

Antenna elements are small and array sizes are large

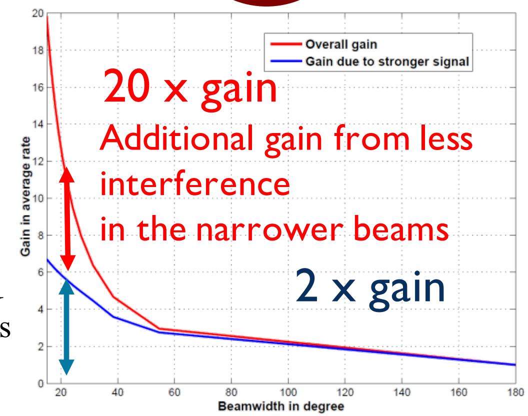
The power of large arrays at mmWave

1



Single and multiuser MIMO

2



System-level rate multiplication

3

spectrum

Carrier 1 | Carrier 2

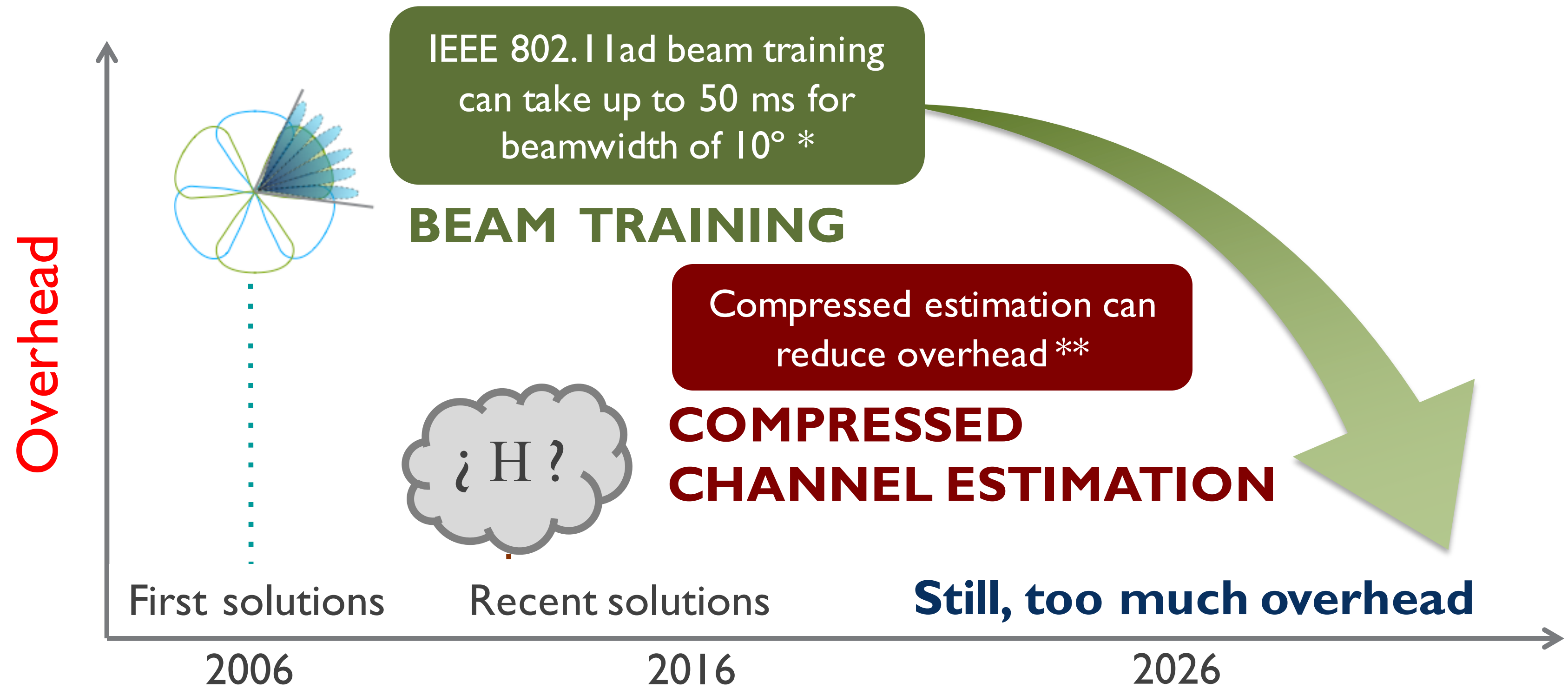
vs.

Carrier 1 and Carrier 2

Better spectrum sharing

1 R. W. Heath, Jr., N. González Prelcic, S. Rangan, Wonil Roh, and A. Sayeed, `` An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems ,'' IEEE Journal on Sel. Topics in Sig. Proc. (special issue on Millimeter Wave MIMO), vol. 10, no. 3, pp. 436-453, April 2016.
2 Tianyang Bai and R. W. Heath, Jr., `` Coverage and Rate Analysis for Millimeter Wave Cellular Networks,'' IEEE TWC, vol. 14, no. 2, pp. 1100-1114, Feb. 2015.
3 A. Gupta, J. Andrews, R.W. Heath Jr., “On the Feasibility of Sharing Spectrum Licenses in mmWave Cellular Systems, “, arxiv 1512.01201290v1, Dec. 2015.

Configuring the arrays remains a challenge



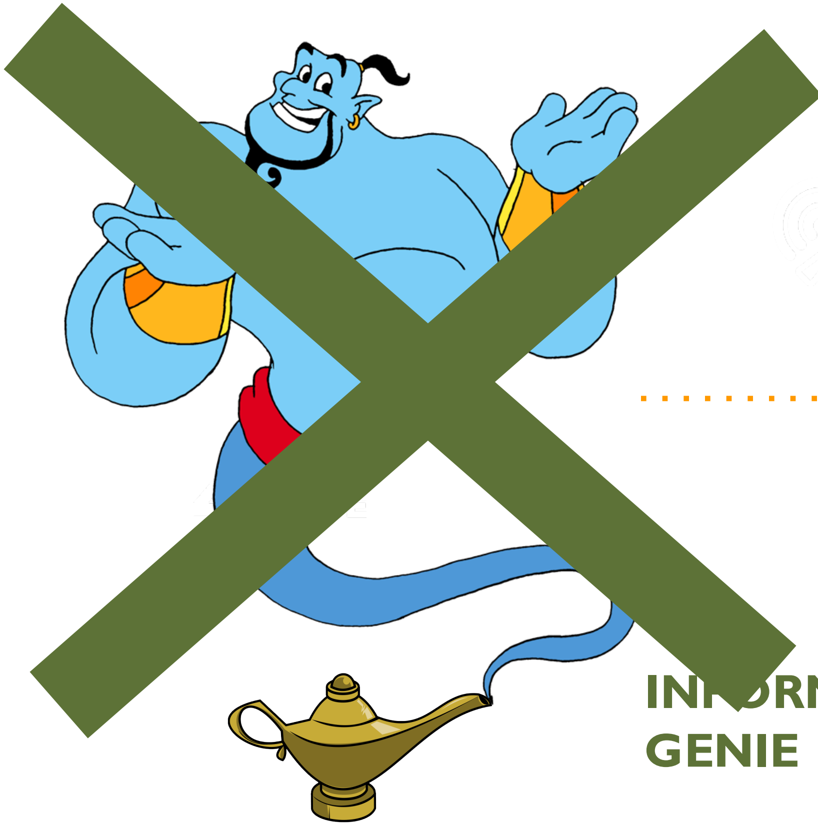
Implicit or explicit channel estimation leads to high overhead

* S. Sur et al., "60 GHz indoor networking through flexible beams: A link-level profiling," in *Proc. of ACM SIGMETRICS*, 2015.

**K. Venugopal, A. Alkhateeb, N. Gonzáez Prelcic, and R. W. Heath, Jr Channel Estimation for Hybrid Architecture Based Wideband Millimeter Wave Systems, submitted to IEEE JSAC, 2016

GOING OUT OF BAND

The potential of using out-of-band information

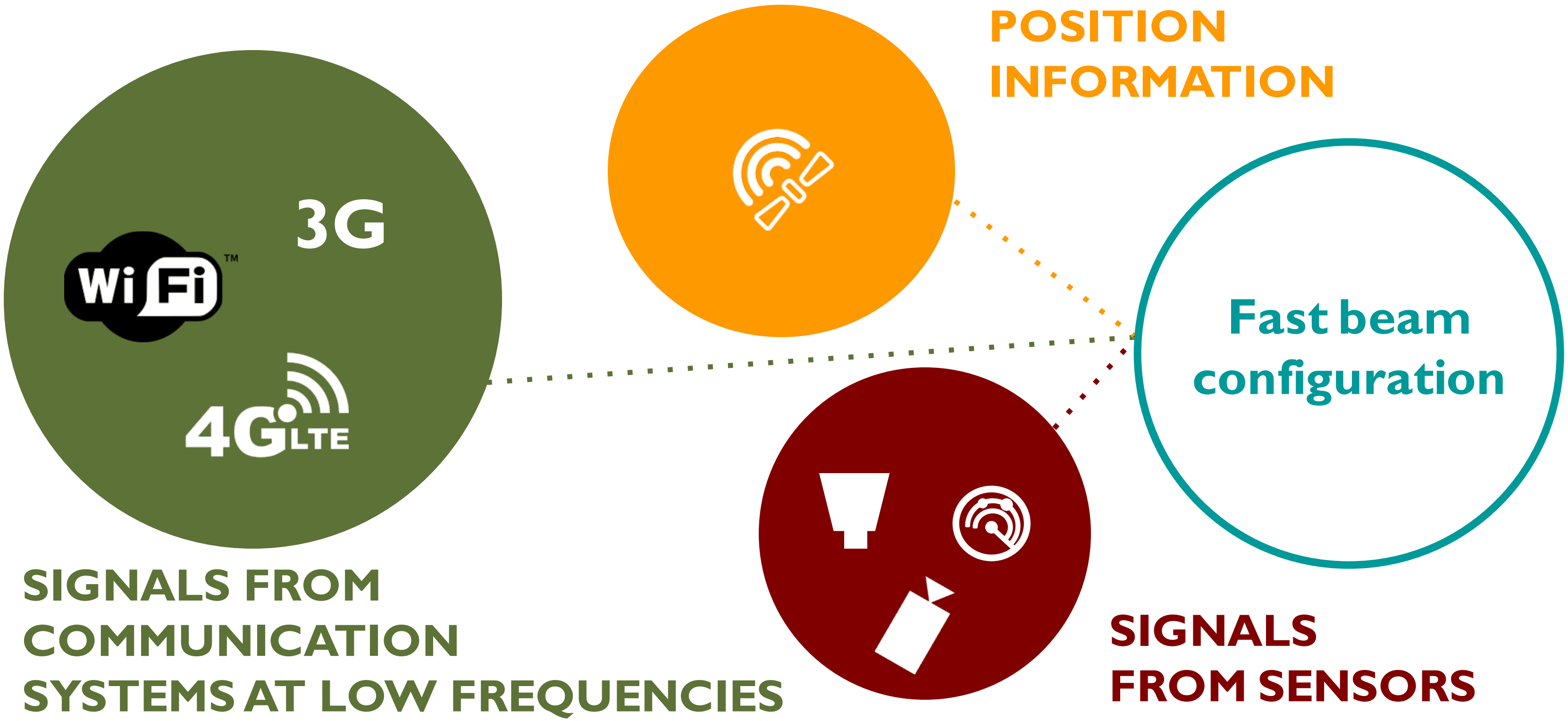


Fast beam configuration

INFORMATION FROM THE ALL-KNOWING GENIE IS USED TO POINT THE BEAMS

Thanks to the Genie, mmWave beam configuration can be done efficiently with no overhead

The real out-of-band information opportunities



Some channel information extracted without taxing the communication resources!

Is out-of-band a crazy idea?

Channel parameters reciprocity in FDD

Forward channel

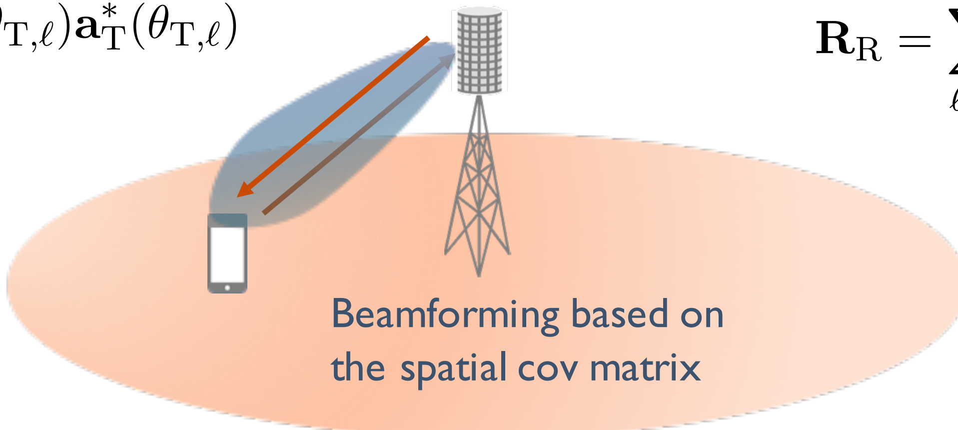
$$\mathbf{R}_{\mathrm{T}} = \sum_{\ell=1}^{L} \rho_{\mathrm{T},\ell} \mathbf{a}_{\mathrm{T}}(\theta_{\mathrm{T},\ell}) \mathbf{a}_{\mathrm{T}}^{*}(\theta_{\mathrm{T},\ell})$$

Reverse channel

$$\mathbf{R}_{\mathrm{R}} = \sum_{\ell=1}^{L} \rho_{\mathrm{R},\ell} \mathbf{a}_{\mathrm{R}}(\theta_{\mathrm{R},\ell}) \mathbf{a}_{\mathrm{R}}^{*}(\theta_{\mathrm{R},\ell})$$

if frequencies are close enough together

$$\rho_{\mathrm{R},\ell} \approx \rho_{\mathrm{T},\ell}, \quad \theta_{\mathrm{R},\ell} \approx \theta_{\mathrm{T},\ell}.$$

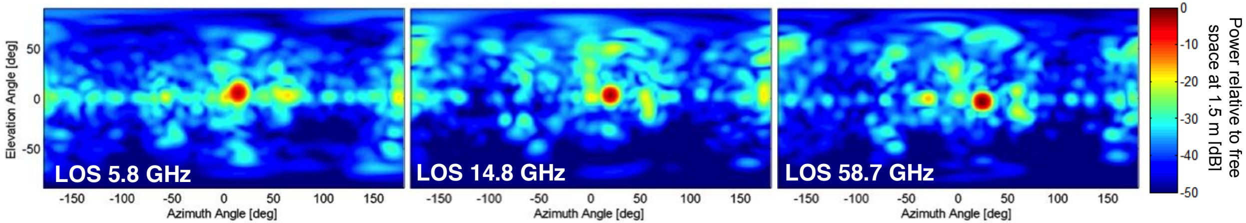


Infer the DL covariance from the UL covariance

The concept of exploiting information from another band has already been extensively studied, but between close bands

See e.g. this paper and the references therein M. Jordan, X. Gong, and G. Ascheid, "Conversion of the spatio-temporal correlation from uplink to downlink in FDD systems," in Proc. IEEE Wireless Commun. Netw. Conf. (WCNC), 2009, pp. 1–6.

How different are spatial characteristics between different bands?



From [2]

Spatial characteristics across frequencies on the order of few MHz are similar

Surprisingly some channel parameters also similar across several GHz!

What if comparing sub-6GHz and mmWave bands?

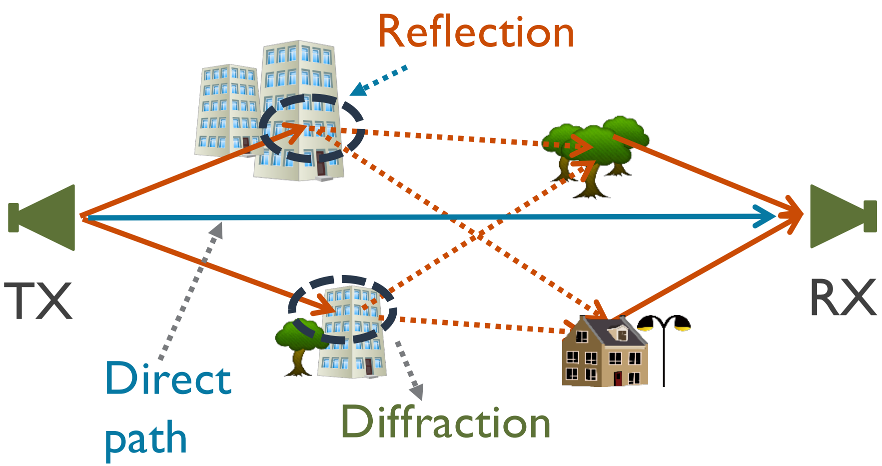
Well established in the 90s [1]

Measurements from legacy WiFi have been used to configure 60 GHz WiFi [3]

We have estimated DL correlation of mmWave systems using sub-6 GHz correlation [4]

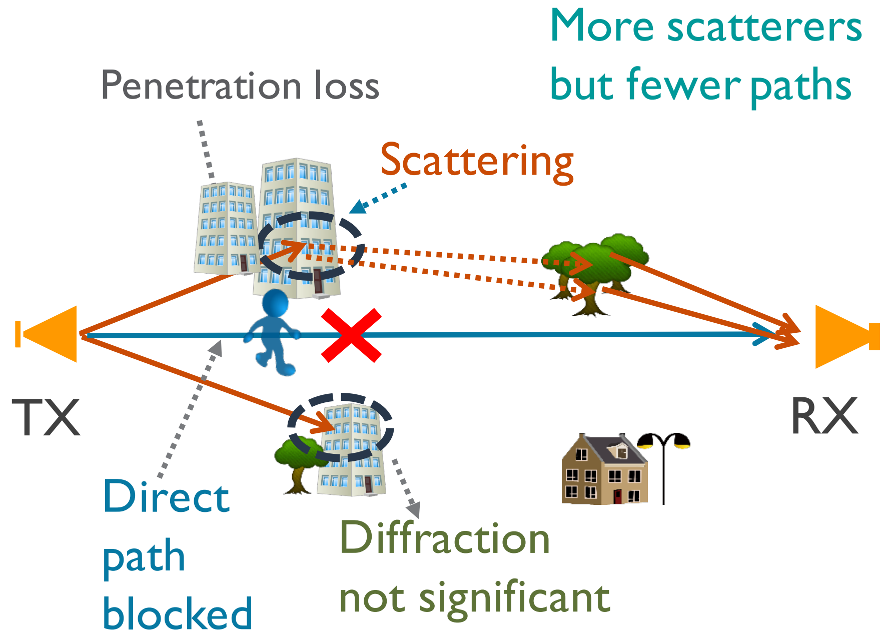
[1] T. Asté, P. Forster, L. Féty, and S. Mayrargue, "Downlink beamforming avoiding DOA estimation for cellular mobile communications," in Proc. ICASSP), 1998
[2] M. Peter et al., "Measurement campaigns and initial channel models for preferred suitable frequency ranges," Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications, Tech. Rep., 2016.
[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. IEEE Int. Conf. Comput. Commun. (INFOCOM), 2015, pp. 2416–2424.
[4] A. Ali, N. González-Prelcic and R. W. Heath Jr., " Estimating Millimeter Wave Channels Using Out-of-Band Measurements," ITA 2016

Propagation differences



Sub-6 GHz

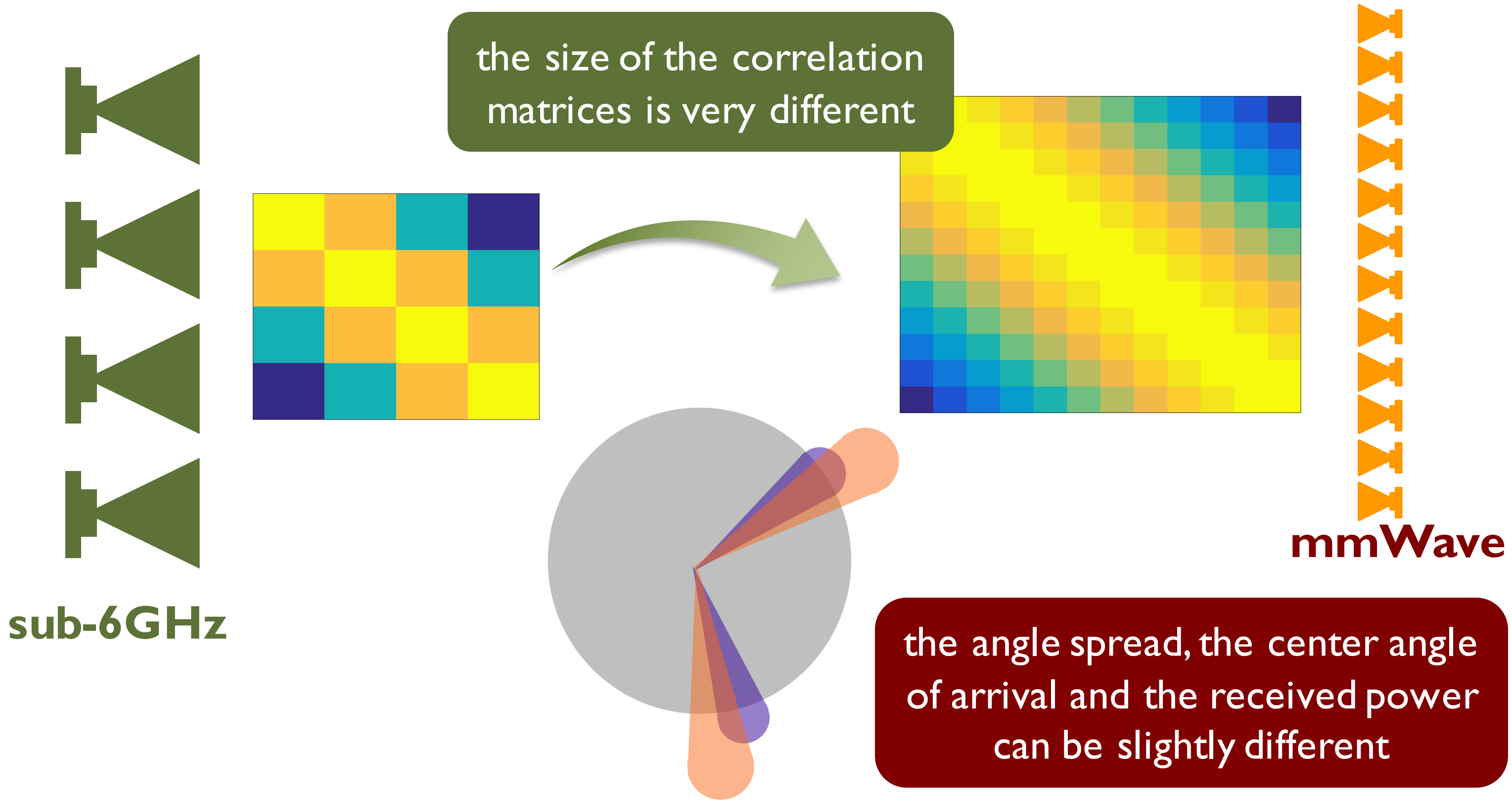
Direct path, reflections and diffraction



MmWave

Higher sensitivity to blockages

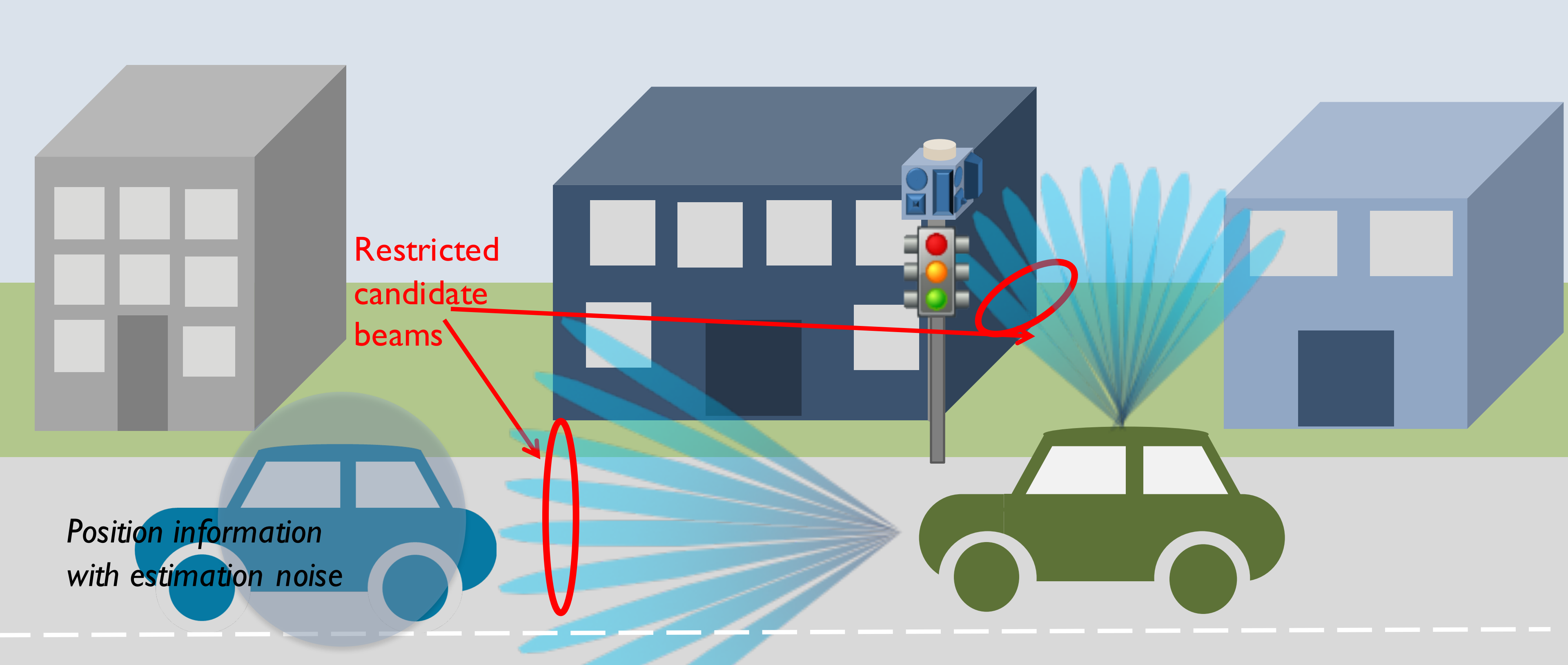
Translating channel information between vastly different bands



Spatial characteristics and dimension mismatch creates challenges, but out-of-band-sensing can provide partial channel information

EXPLOITING POSITION INFORMATION

Exploiting position information in mmWave V2X



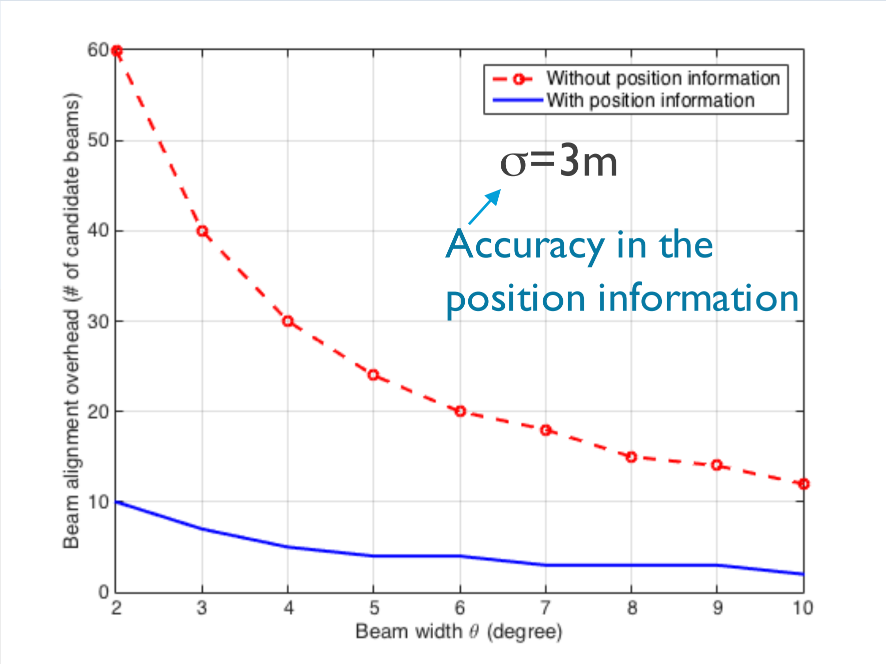
Postion information derived from GPS (possibly through DSRC modules), or other position location means

Junil Choi, Vutha Va, Nuria González-Prelcic, Robert Daniels, Chandra R. Bhat, and Robert W. Heath Jr, “Millimeter Wave Vehicular Communication to Support Massive Sensing”, IEEE Communications Magazine, 2016.

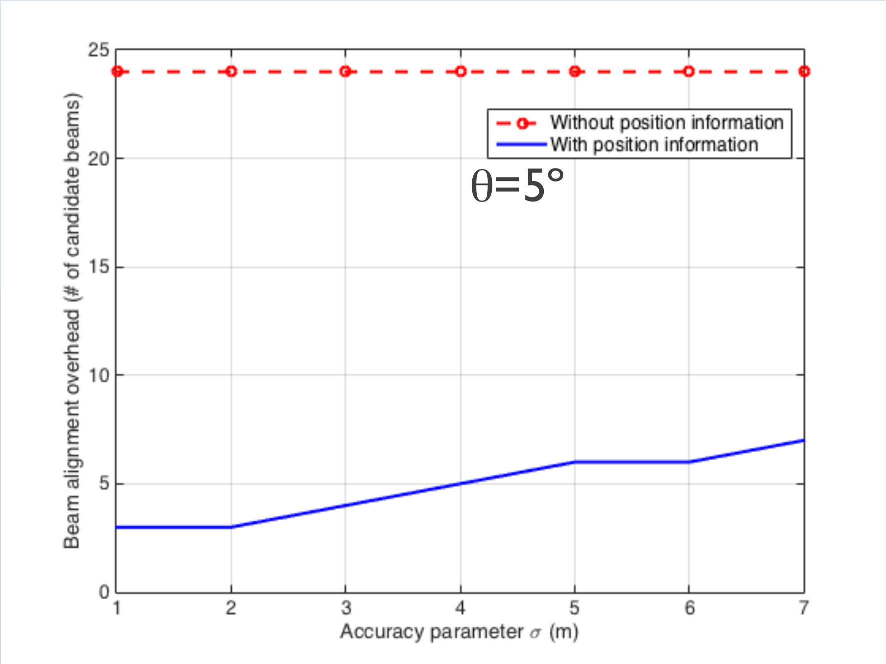
How much overhead can be reduced using position info?

Reduced beam alignment overhead may allow a smaller beam width (larger beamforming gain)

Even with poor accuracy of position information the beam alignment overhead is reduced



6x



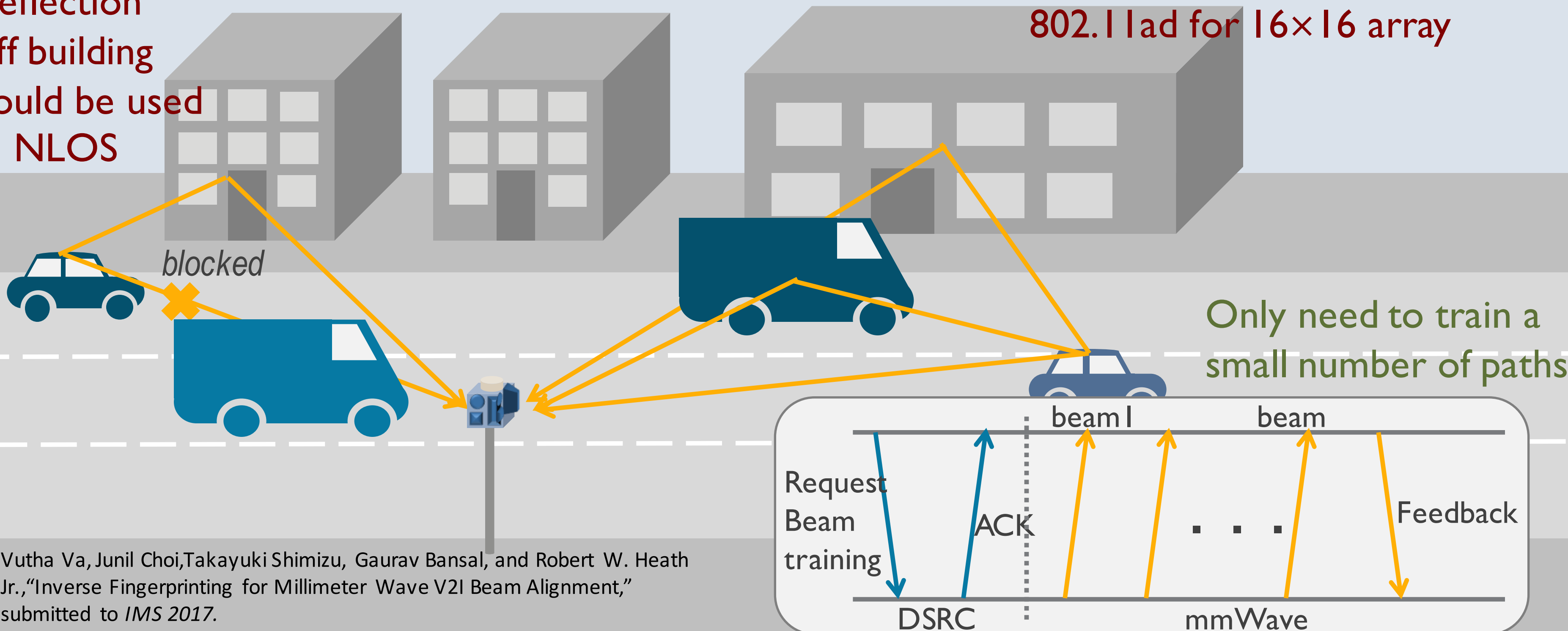
Junil Choi, Vutha Va, Nuria González-Prelcic, Robert Daniels, Chandra R. Bhat, and Robert W. Heath Jr, "Millimeter Wave Vehicular Communication to Support Massive Sensing", IEEE Communications Magazine, 2016.

Inverse fingerprinting for mmWave V2I beam alignment

Reflection off building could be used in NLOS

Less than 4% overhead of IEEE 802.11ad for 16×16 array

Only need to train a small number of paths

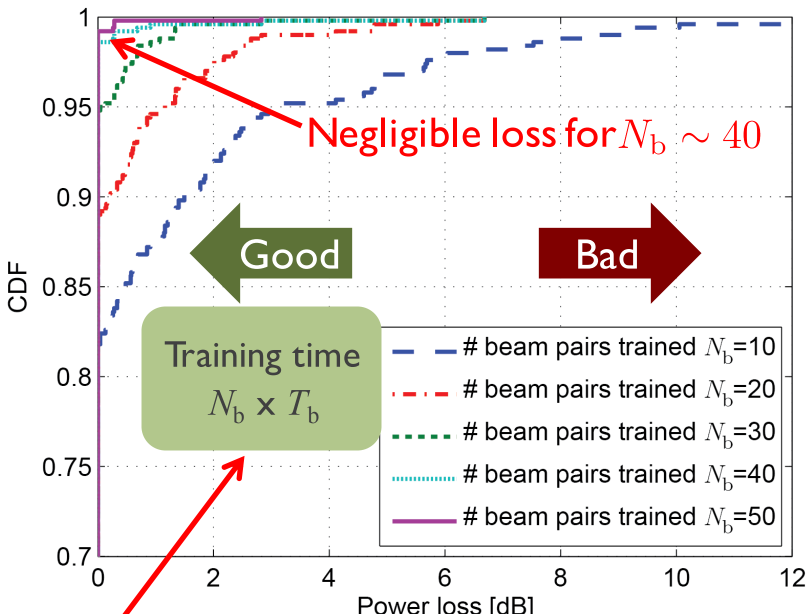


Vutha Va, Junil Choi, Takayuki Shimizu, Gaurav Bansal, and Robert W. Heath Jr., "Inverse Fingerprinting for Millimeter Wave V2I Beam Alignment," submitted to *IMS 2017*.

Infrastructure collects database of multipath fingerprint (i.e., AoA/AoD) of paths indexed by location

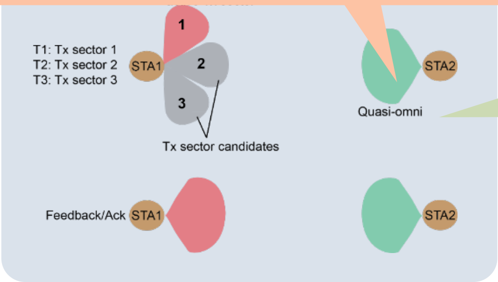
Overhead reduction with inverse finger printing

Power loss [dB] = RX power w/ exhaustive search – RX power w/ proposed method



Training at beam level w/o spreading

Low antenna gain needs spreading (32x used in 80211ad)

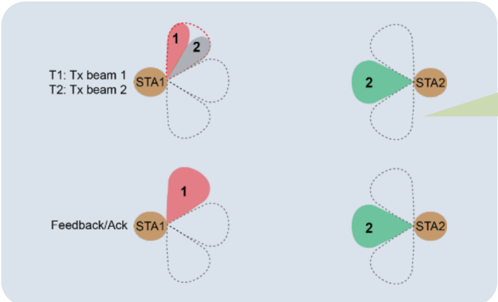


Sector level search

Spreading factor

Training time
$32 \times \#\text{sectors} \times 2 \times T_b$

Required training at both sides



Beam level search

Training time
$1 \times \#\text{beams} \times 2 \times T_b$

Example 16 x 16 array
$(32 \times 15 + 1 \times 18) 2T_b = 996 T_b$

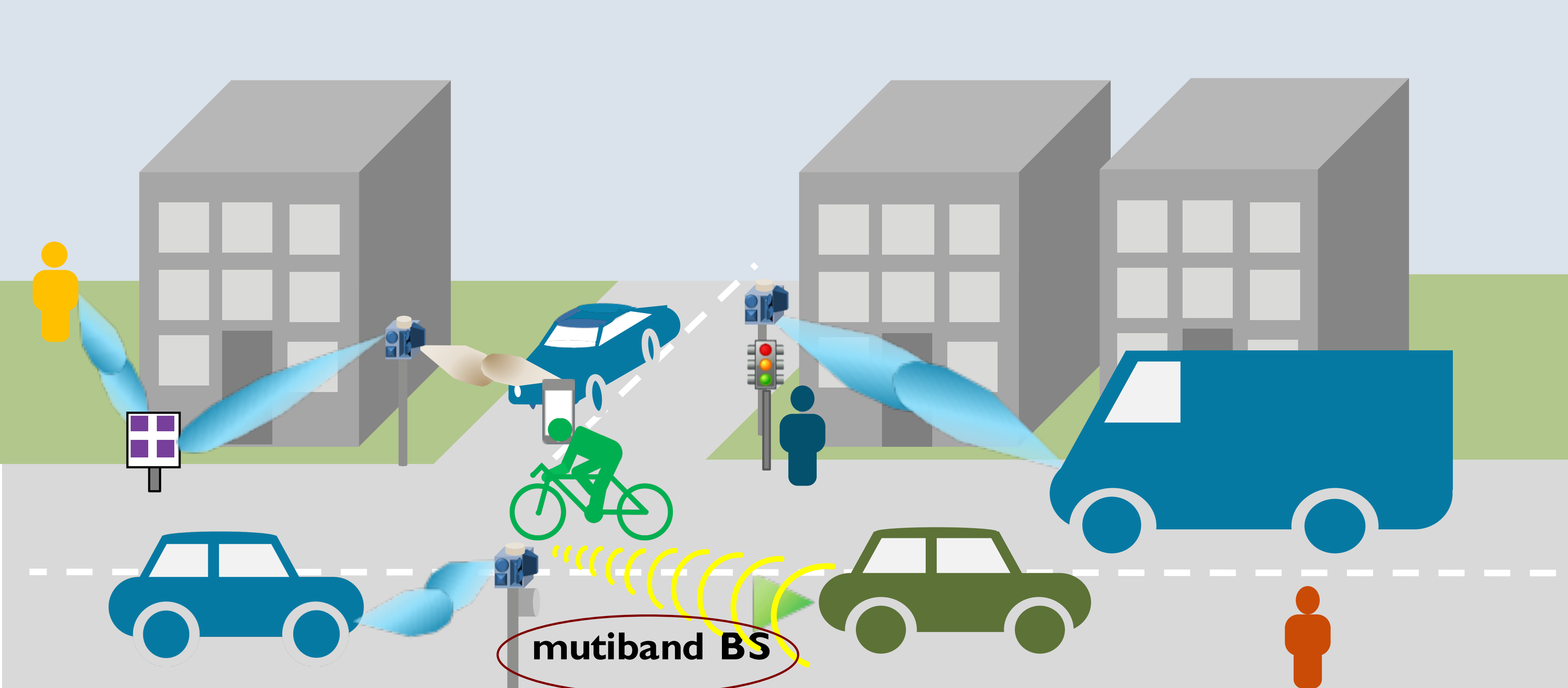
96% of 802.11ad beam training overhead can be saved using fingerprint

Challenges exploiting position information

- Power efficient means for acquiring location
- Incorporating device orientation
- Combine with other side information like time-of-day, velocity, etc.
- Resiliance to dynamic blockages in the environment
- Combining with other out-of-band information to improve accuracy

EXPLOITING COMMUNICATION SIGNALS AT LOW FREQUENCIES

Vision of future mmWave networks



Multiband connectivity is one of the features of future cellular networks
Why not to exploit it?

Covariance translation from sub-6 GHz to mmWave

mmWave spatial correlation matrix

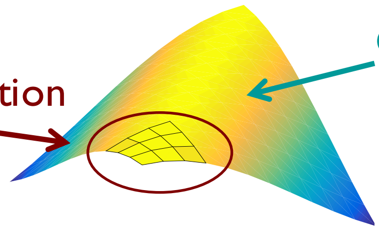
Construct an estimate of the mmWave spatial correlation matrix

$$\hat{\mathbf{R}}_{\mathrm{H}} = f(\mathbf{R}_{\mathrm{L}})$$

Sub 6 GHz spatial correlation matrix

Non-Parametric

Exploit correlation structure
Use interpolation/extrapolation to obtain R_{H}



Parametric

Theoretical expressions of correlation

$$[\mathbf{R}]_{i,j} = e^{\mathrm{j}2\pi\Delta(i-j)\sin(\bar{\theta})}\Phi\left(2\pi\Delta(i-j)\sin(\bar{\theta})\sigma_{\theta}\right)$$

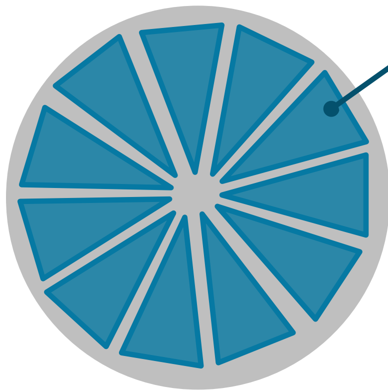
Estimates of angles and angle spreads
e.g. using subspace algorithms

Correlation translation possible but dimension and spatial mismatch makes it challenging

A. Ali, N. González-Prelcic, and R. W. Heath Jr., "Estimating millimeter wave channels using out-of-band measurements," in *ITA Wksp*, 2016, pp. 1–5.

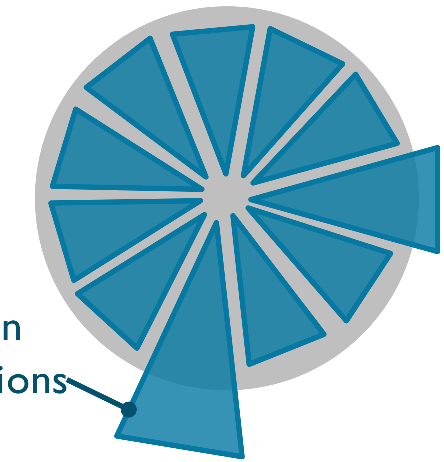
Compressed beam-search and partial support information

No prior information



AoA can be any direction with equal probability

Prior information



Out-of-band-information about likely AoA directions

Weighted compressed sensing →

$$\text{minimize} \quad \|\mathbf{x}\|_{\mathbf{w},1}$$
$$\text{subject to} \quad \|\mathbf{y} - \mathbf{A}\mathbf{x}\|_2 \leq \epsilon$$

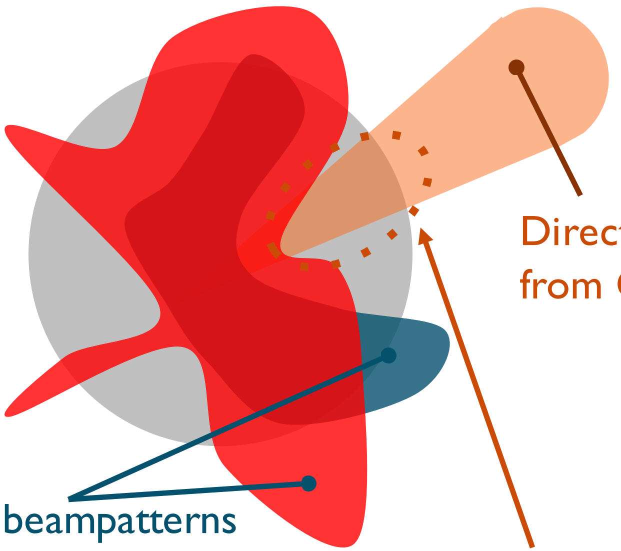
$$\|\mathbf{x}\|_{\mathbf{w},1} = \sum_{i=1}^{I} w_i |x_i|$$

Sparse channel estimation based on out-of-band prior

A. Ali and R. W. Heath Jr., “Compressed beam-selection in millimeter wave systems with out-of-band partial support information,” submitted to *ICASSP*, 2017.

Smarter random dictionaries

Random beam patterns

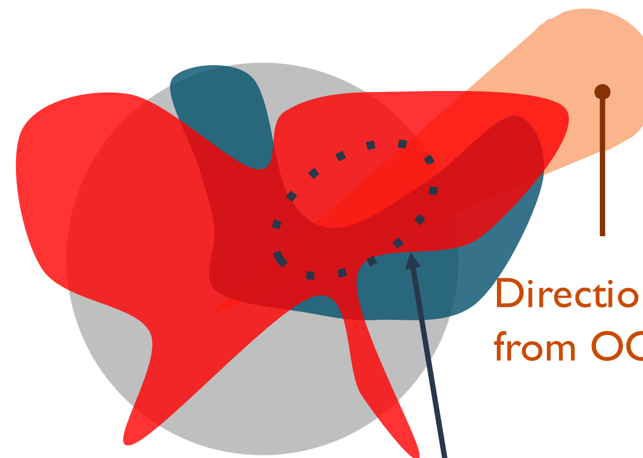


Direction estimate from OOB

Random beampatterns for compressed beam search

➡ Possibly low gain in the strong channel direction

Structured random



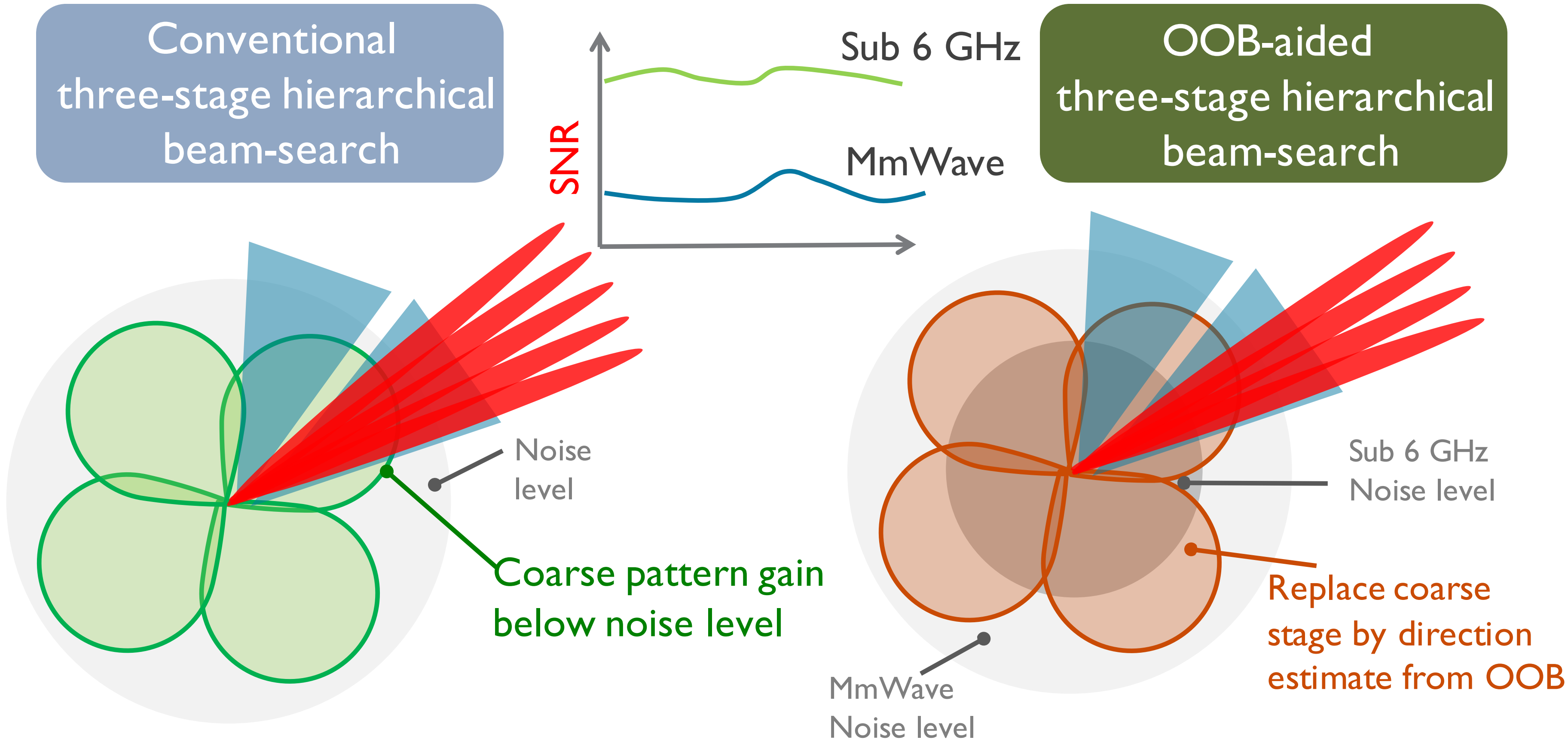
Direction estimate from OOB

Fair gain in the strong channel direction from OOB

Out-of-band information shapes dictionary for better channel estimation

A. Ali, N. González-Prelcic, and R. W. Heath Jr., "Millimeter Wave Beam-Search Using Out-of-Band Spatial Information", under preperation.

Hierarchical beam-search with out-of-band info



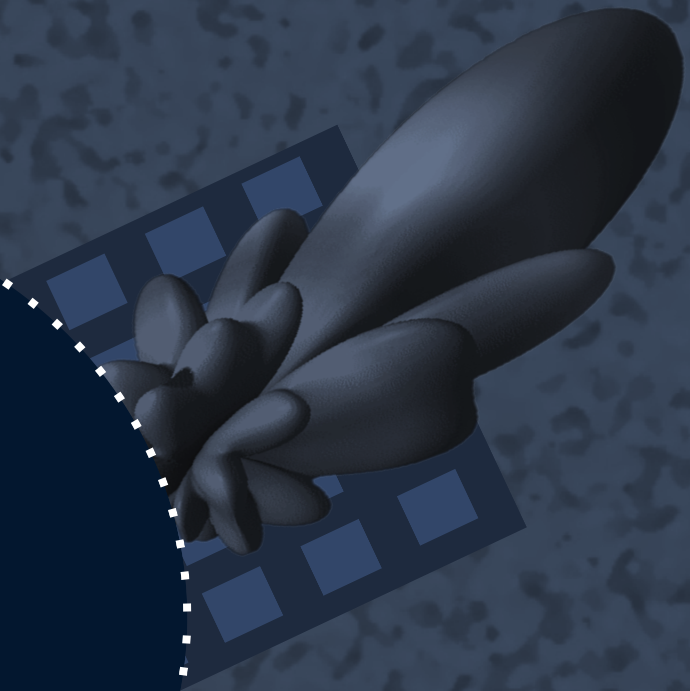
Reduce number of stages based on out-of-band information

A. Ali, N. Gonza´lez-Prelcic, and R. W. Heath Jr., "Millimeter Wave Beam-Search Using Out-of-Band Spatial Information", under preperation.

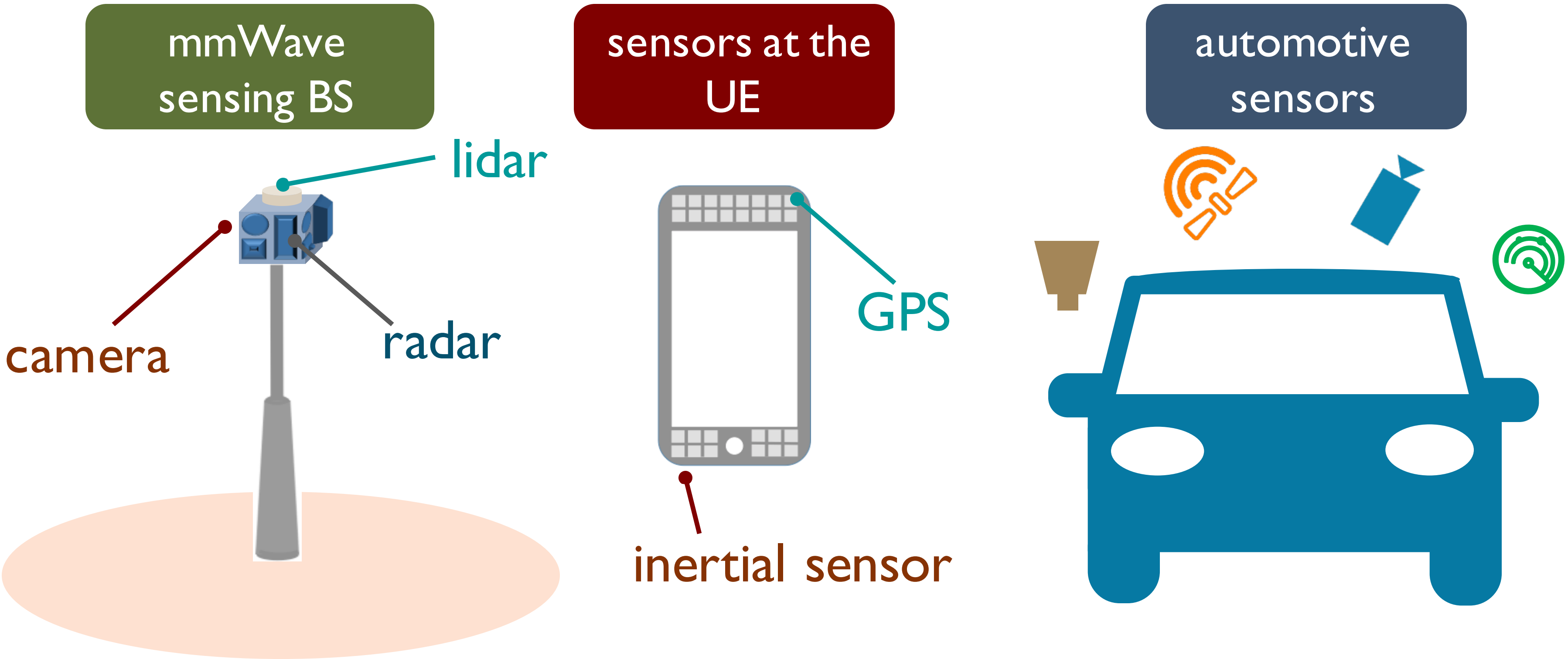
Challenges exploiting communication signals

- Covariance translation algorithms supporting different array sizes
- Developing an integrated protocol that allows joint training at low and high frequencies
- Optimal ways to exploit out-of-band information for channel estimation
- Simultaneous multi-band channel measurements, to develop better multi-band models

EXPLOITING SIGNALS FROM SENSORS



Sensor aided communication



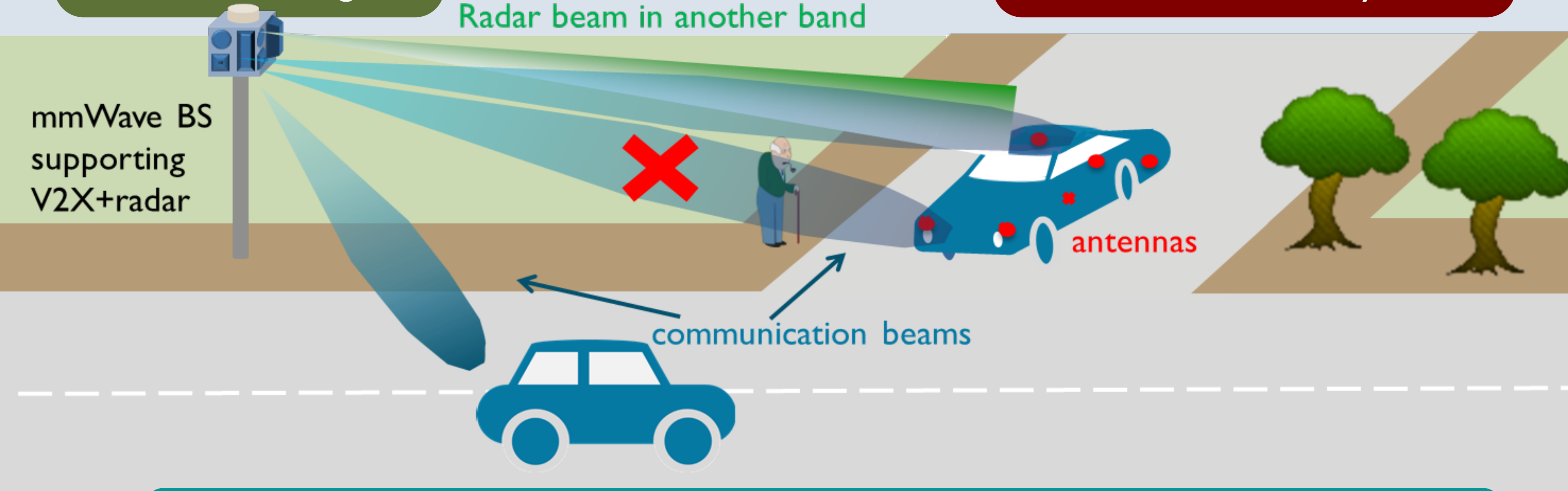
Sensors are everywhere…

Why not to exploit sensing info to aid mmWave communication?

Radar-aided millimeter wave V2X

Radar can be used to design multiuser beamforming

Radar can be used to configure communication link more efficiently

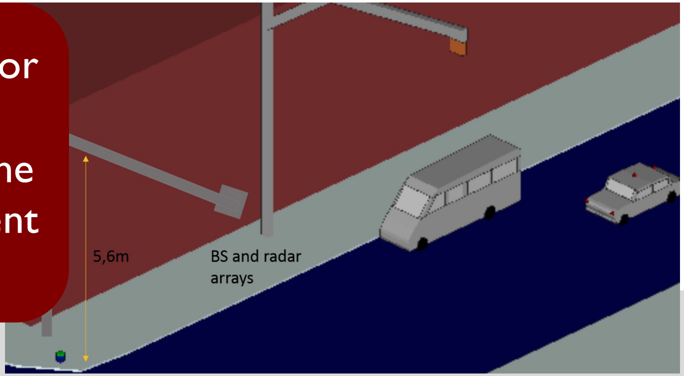


Algorithms for hybrid precoder & combiner design based on covariance information of the radar signal

* N. González-Prelcic, Roi Mendez-Rial, and R. W. Heath Jr., "Radar aided beamforming in mmWave V2I communications supporting antenna diversity," Proc. of ITA 2016 .

Spatial congruence berween mmWave radar and communication

The dominant DoAs for the communication signal also appear at the radar echo in a different band



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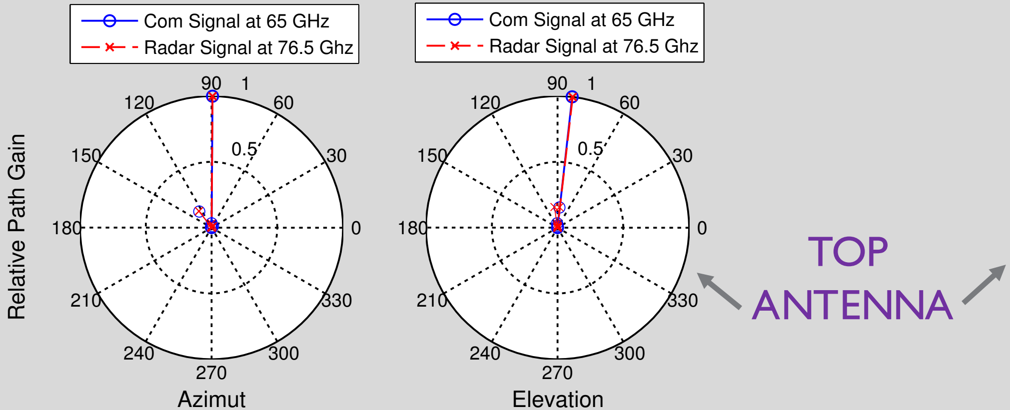

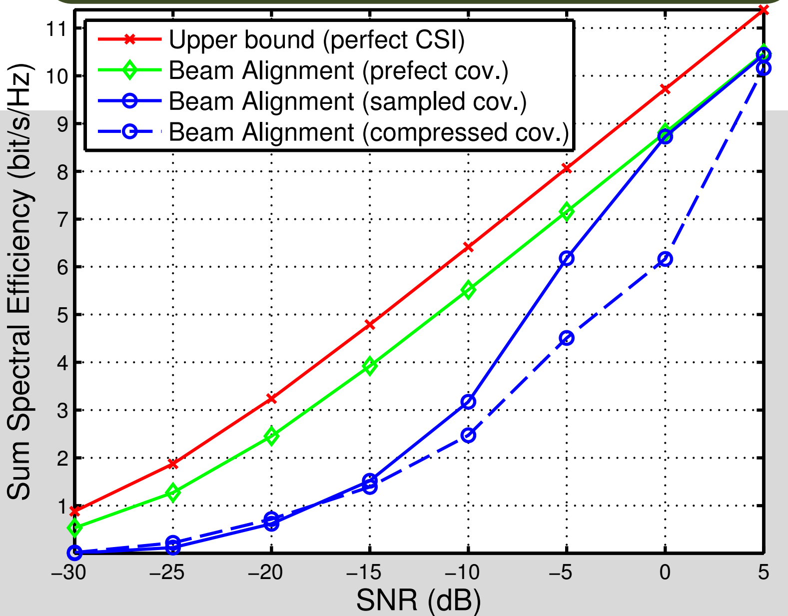

Most of the dominant DoAs for the communication signal also appear at the radar echo in a different band

* N. González-Prelcic, Roi Mendez-Rial, and R. W. Heath Jr., "Radar aided beamforming in mmWave V2I communications support antenna diversity," ITA 2016 .

Challenges exploiting sensor informartion

- Extracting channel parameters from raw sensor signals other than radar
- Establishing the spatial congruence between radar and communications
- Simultaneous sensor and communication measurements, to develop simularity models
- Machine learning algorithms that can combine sensor and communcation information

CONCLUSIONS

Conclusions

Configuring the antennas in a millimeter wave system is a signifcant source of overhead

Side information is available in many forms, which can be exploited to reduce these overheads

Many research challenges involving signal processing, machine learning, and communication

Conclusions

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- Configuring the antennas in a millimeter wave system is a signifcant source of overhead
- Side information is available in many forms, which can be exploited to reduce these overheads
- Many research challenges involving signal processing, machine learning, and communication