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6GNC

Millimeter Waves and Vehicle to Vehicle and Infrastructure Communications (V2X)

Professor Robert W. Heath Jr.

Joint work with Professor Nuria Gonzalez-Prelcic

www.6GNC.org

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Thanks to sponsors including the National Science Foundation ECCS-1711702, CNS-1702800, and CNS-1731658, Toyota, Honda, Samsung and Nokia.

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Our vision at 6GNC

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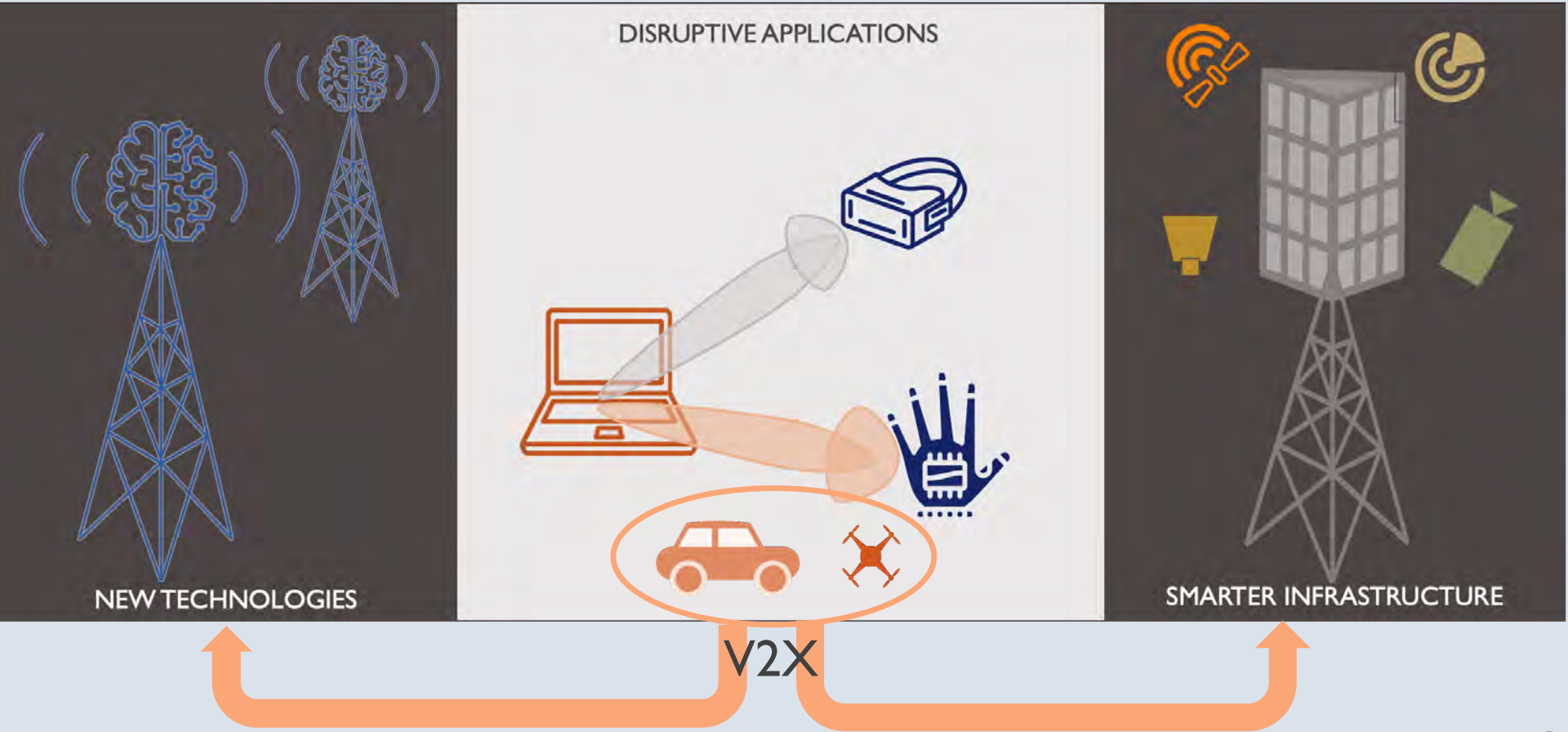

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Technical expertise in 6GNC

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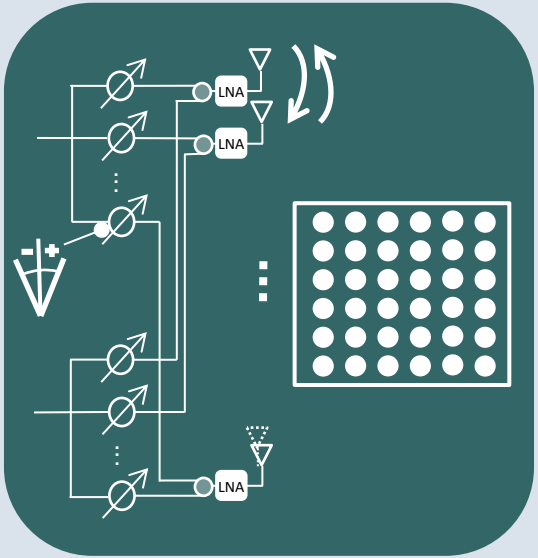

Antenna and circuits

SP and AI/ML

Networking

Developing V2X will require continued collaborations with transportation experts

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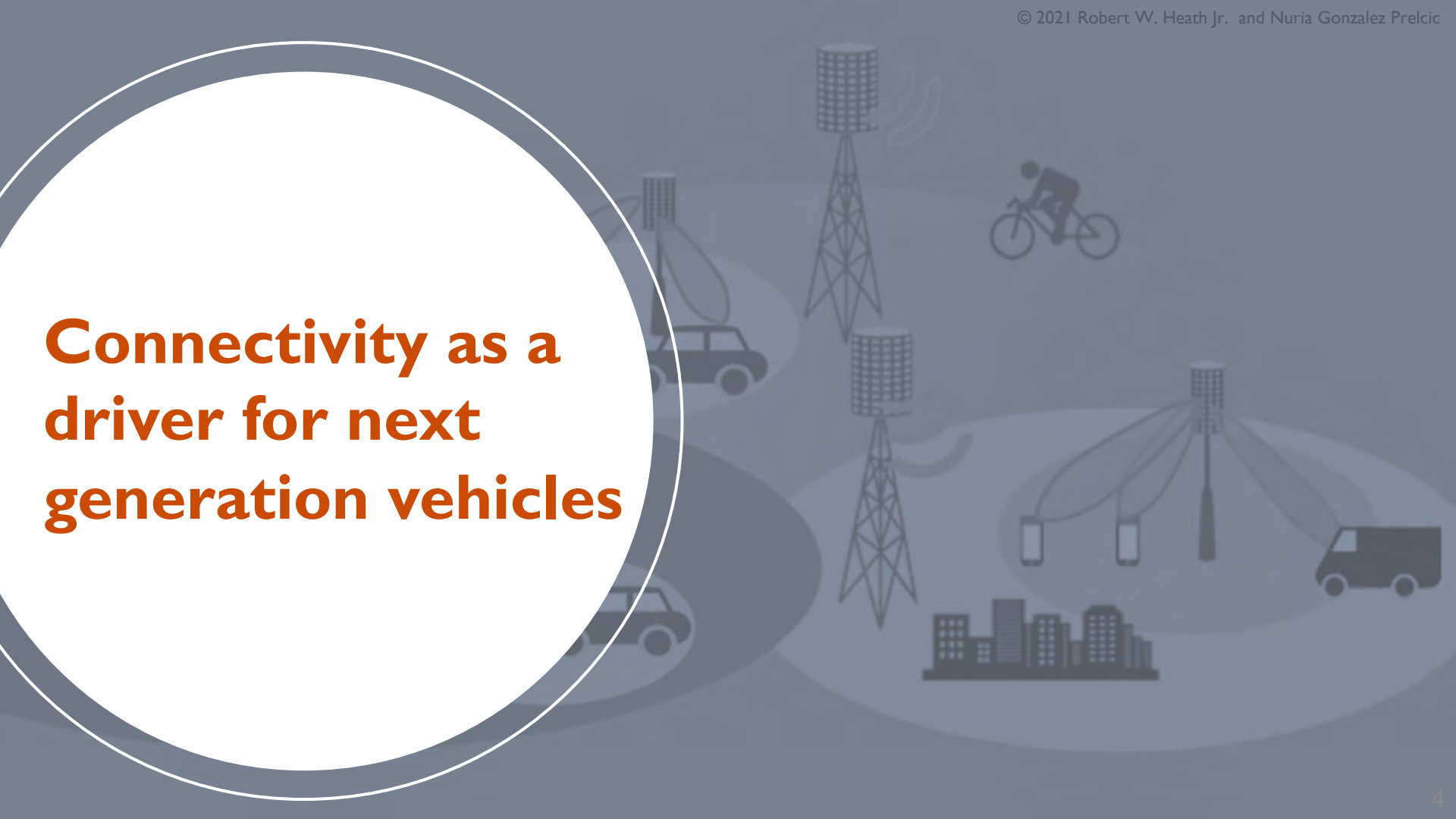
Connectivity as a driver for next generation vehicles



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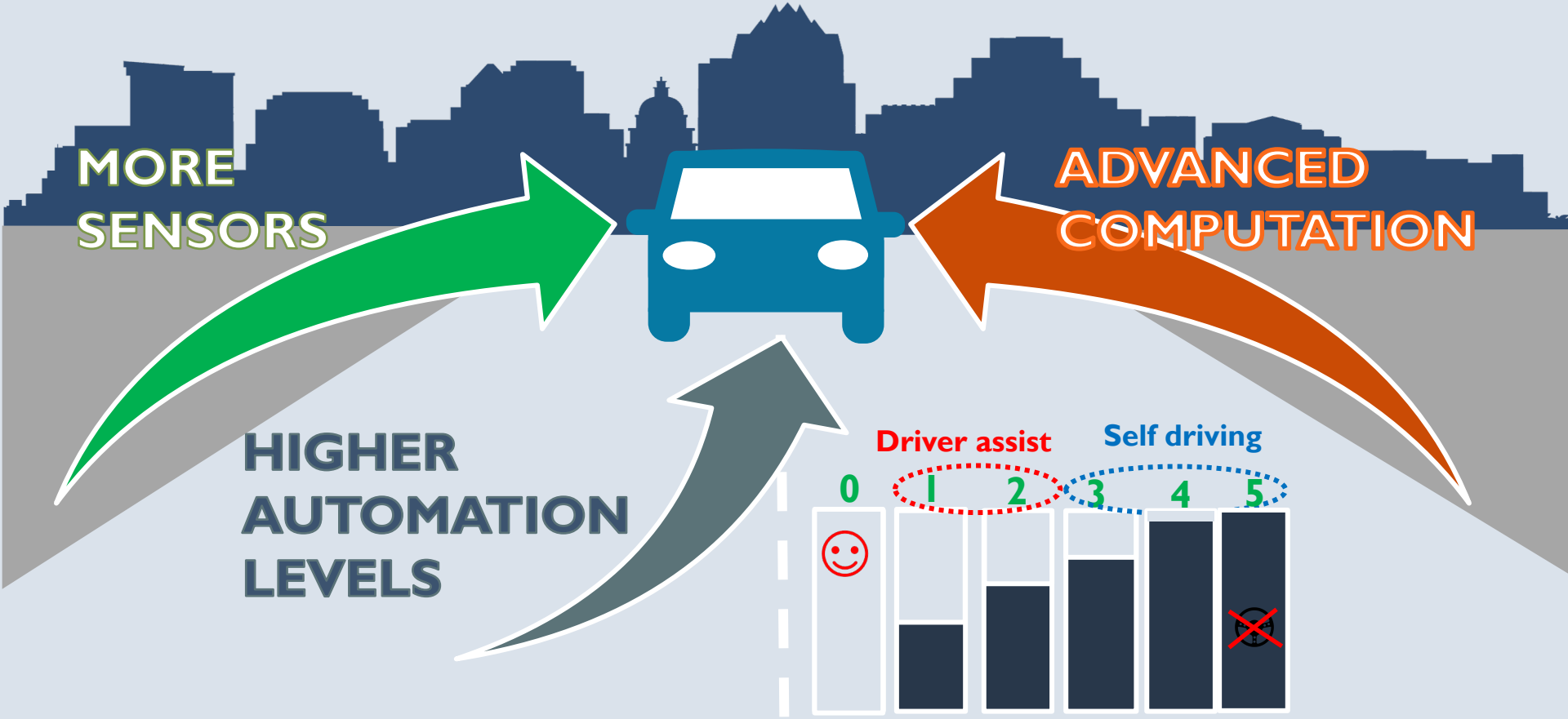
Vehicles are becoming smarter



[1] 5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/

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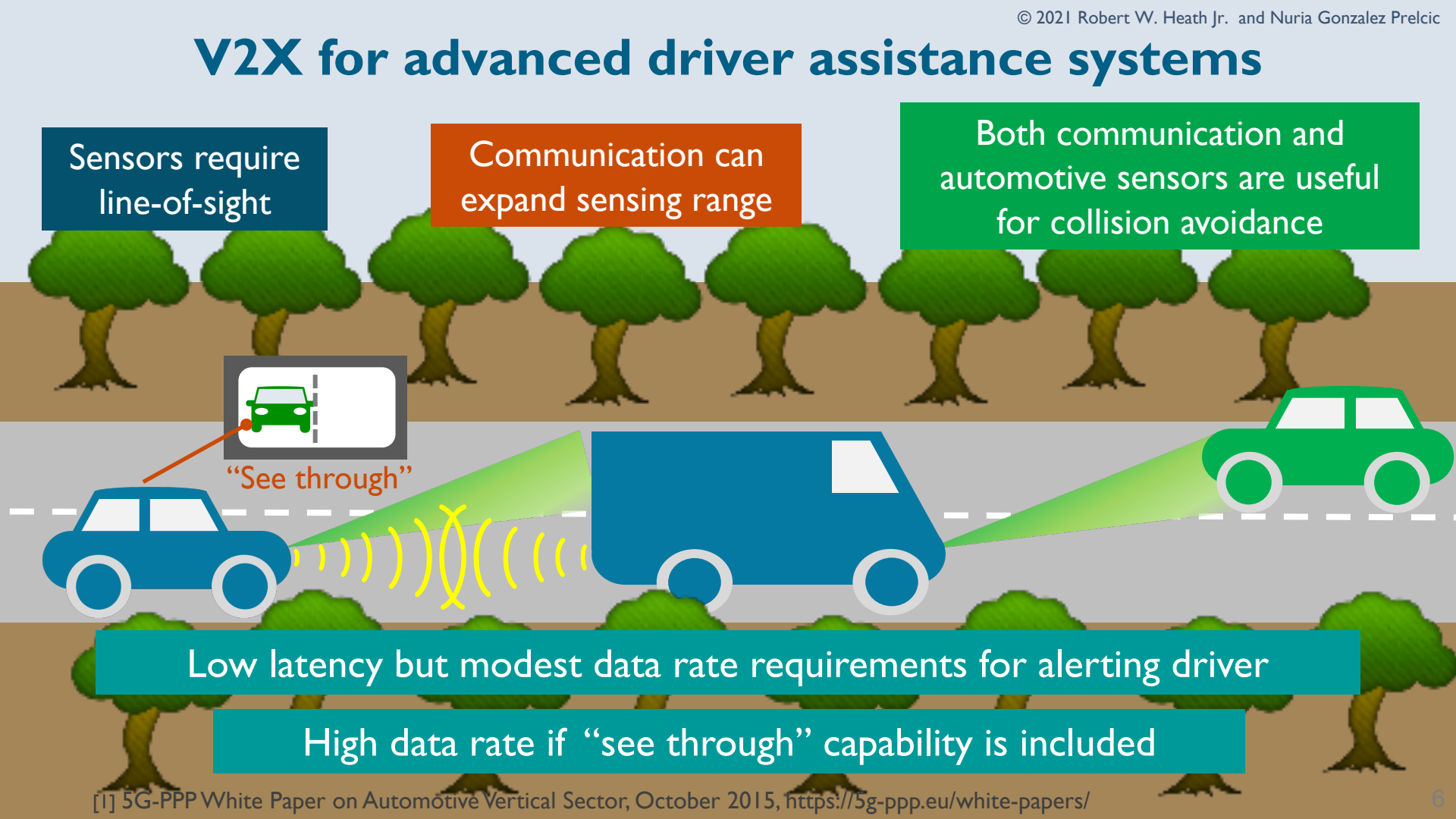
V2X for advanced driver assistance systems

Sensors require line-of-sight

Communication can expand sensing range

Both communication and automotive sensors are useful for collision avoidance

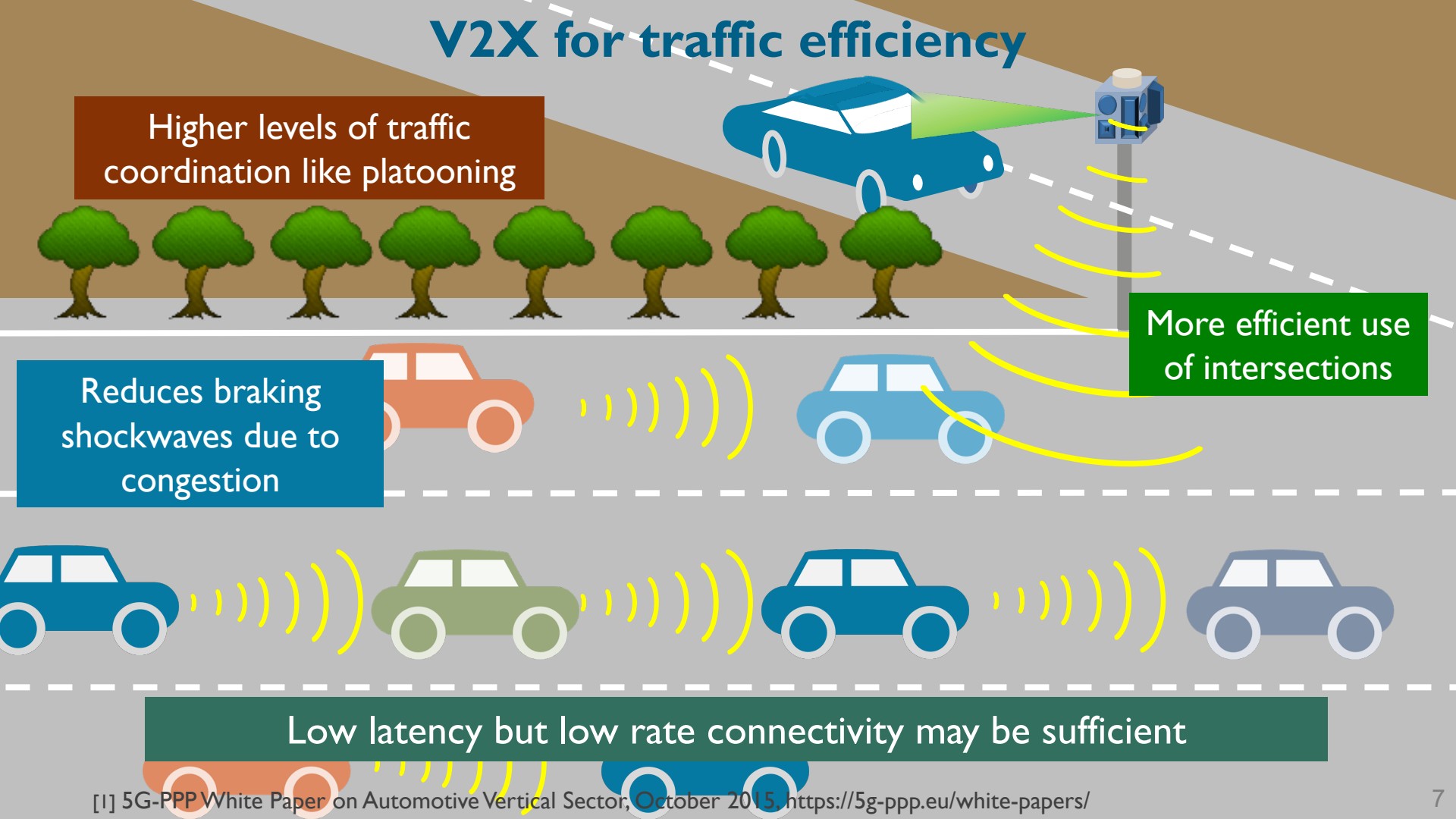


Low latency but modest data rate requirements for alerting driver

High data rate if "see through" capability is included

[1] 5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/

V2X for traffic efficiency



[1] 5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/

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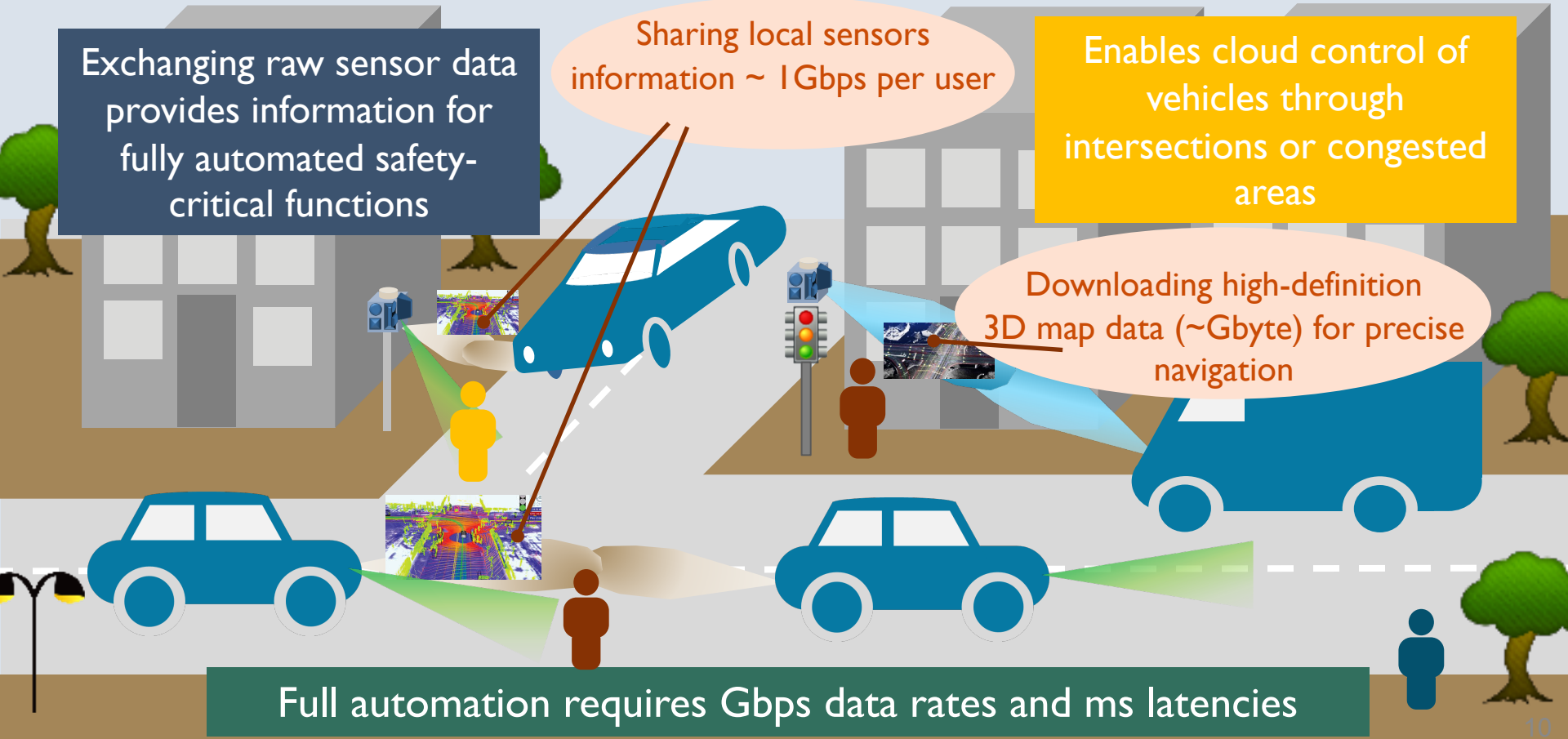
V2X for fully automated driving

Exchanging raw sensor data provides information for fully automated safety-critical functions

Sharing local sensors information ~ 1Gbps per user

Enables cloud control of vehicles through intersections or congested areas

Downloading high-definition 3D map data (~Gbyte) for precise navigation



Full automation requires Gbps data rates and ms latencies

[1] 5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/

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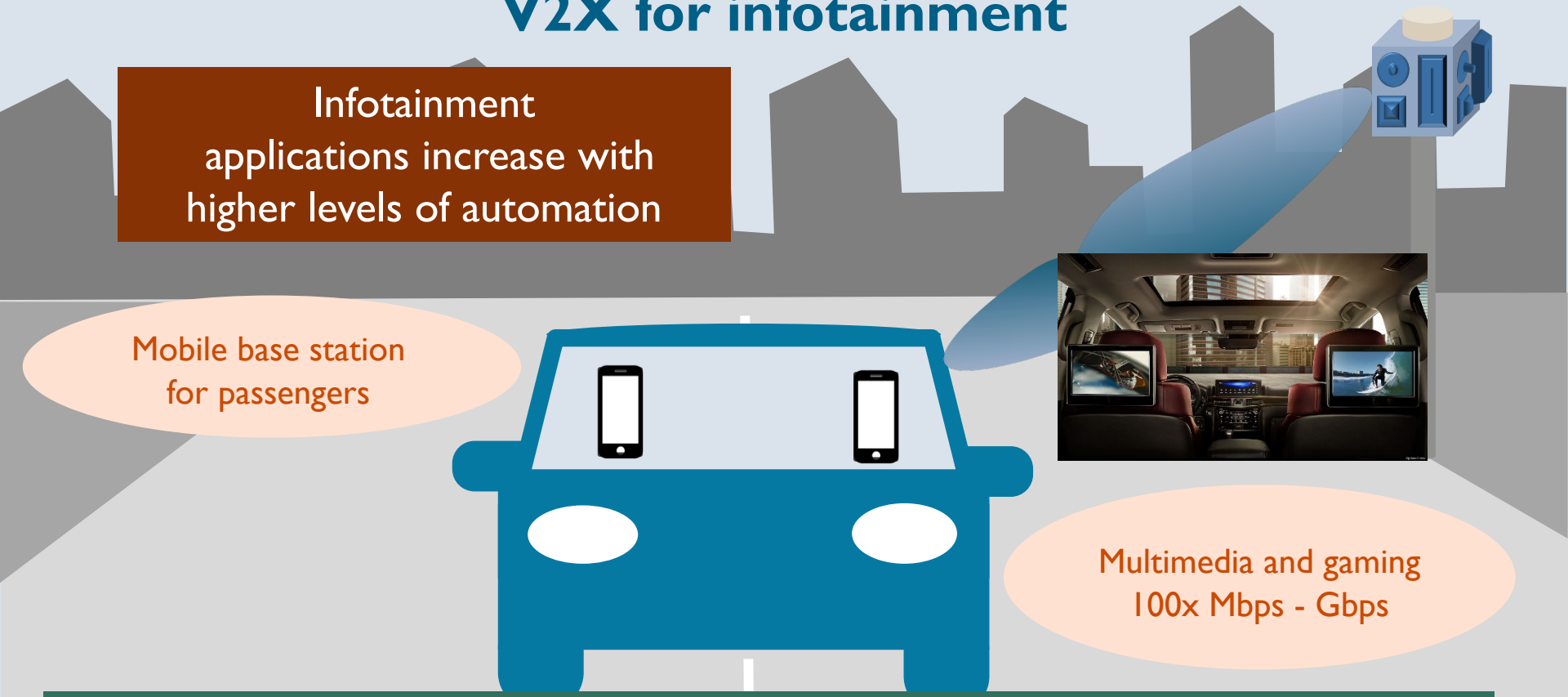
V2X for infotainment

Infotainment applications increase with higher levels of automation



High rate and low latency Internet access required to keep passengers happy

[1] 5G-PPP White Paper on Automotive Vertical Sector, October 2015, https://5g-ppp.eu/white-papers/

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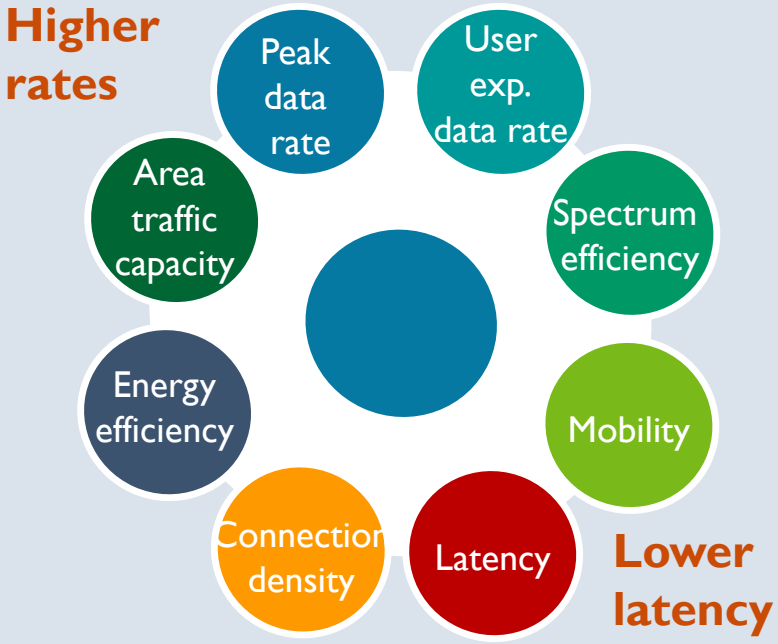
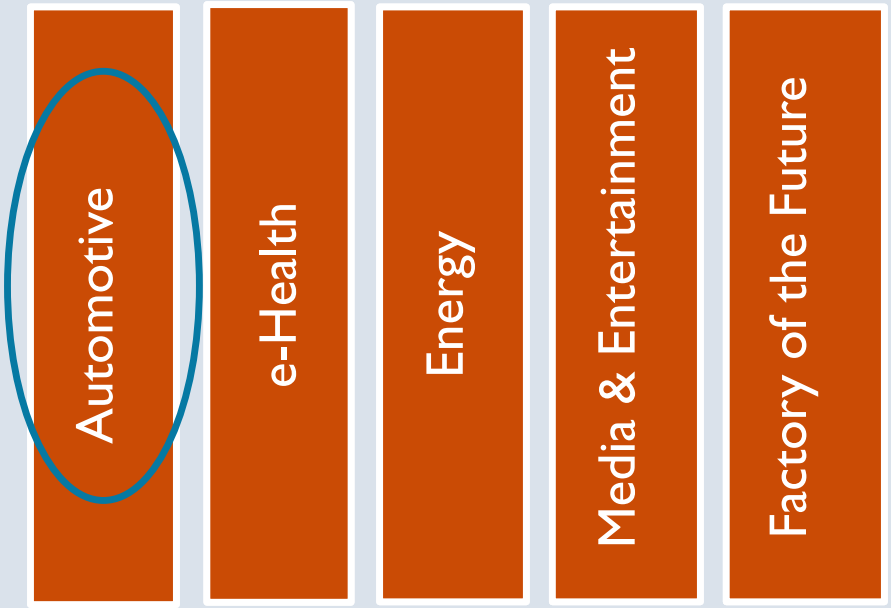
Fifth generation (5G) cellular communication

Multidimensional objectives*



New industry verticals**



Automotive industry provided requirements for the evolution of 5G and

* Recommendation ITU-R M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," September 2015

** "5G empowering vertical industries," 5GPPP White Paper, Feb. 2016

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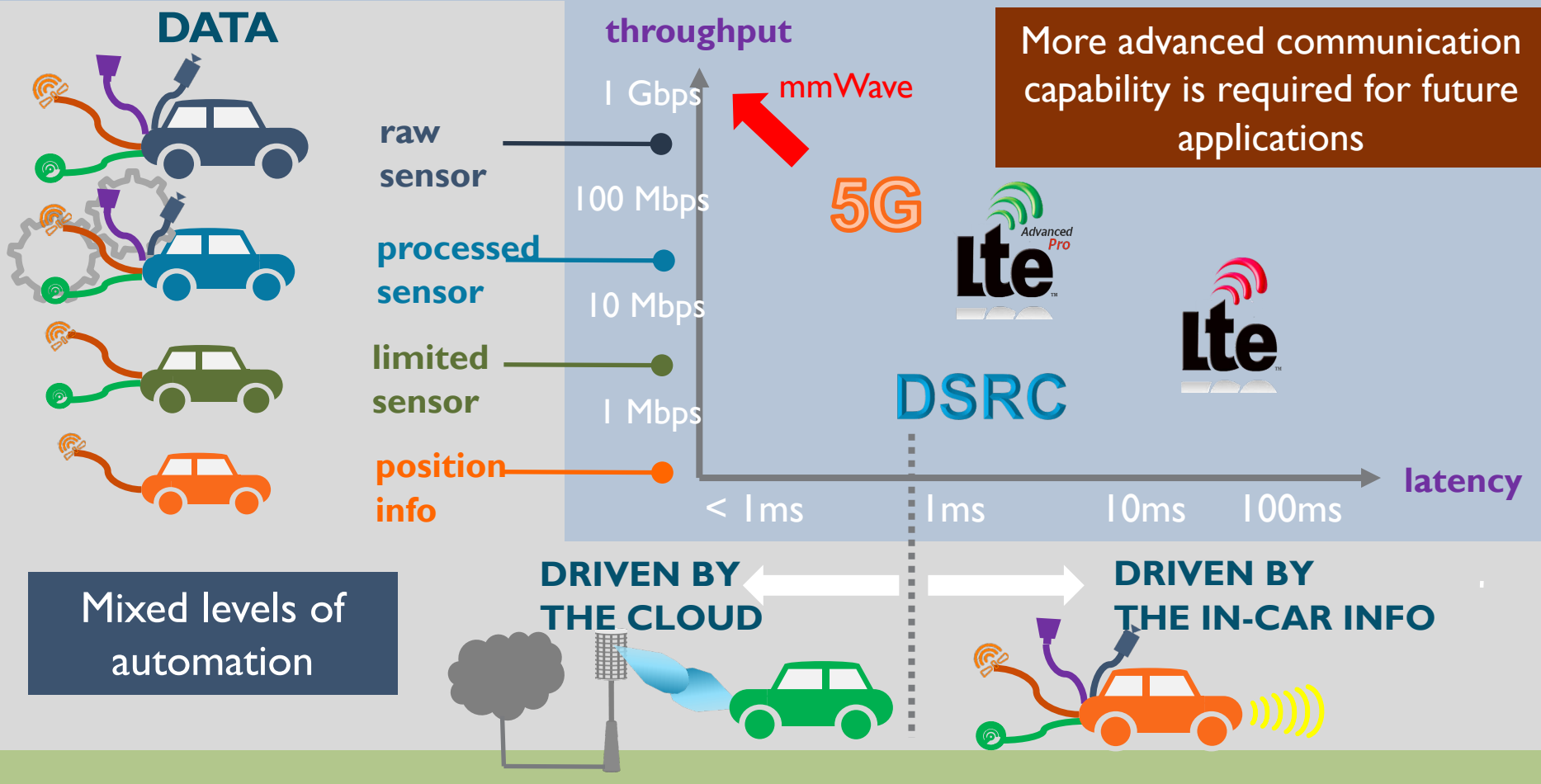
Connectivity options



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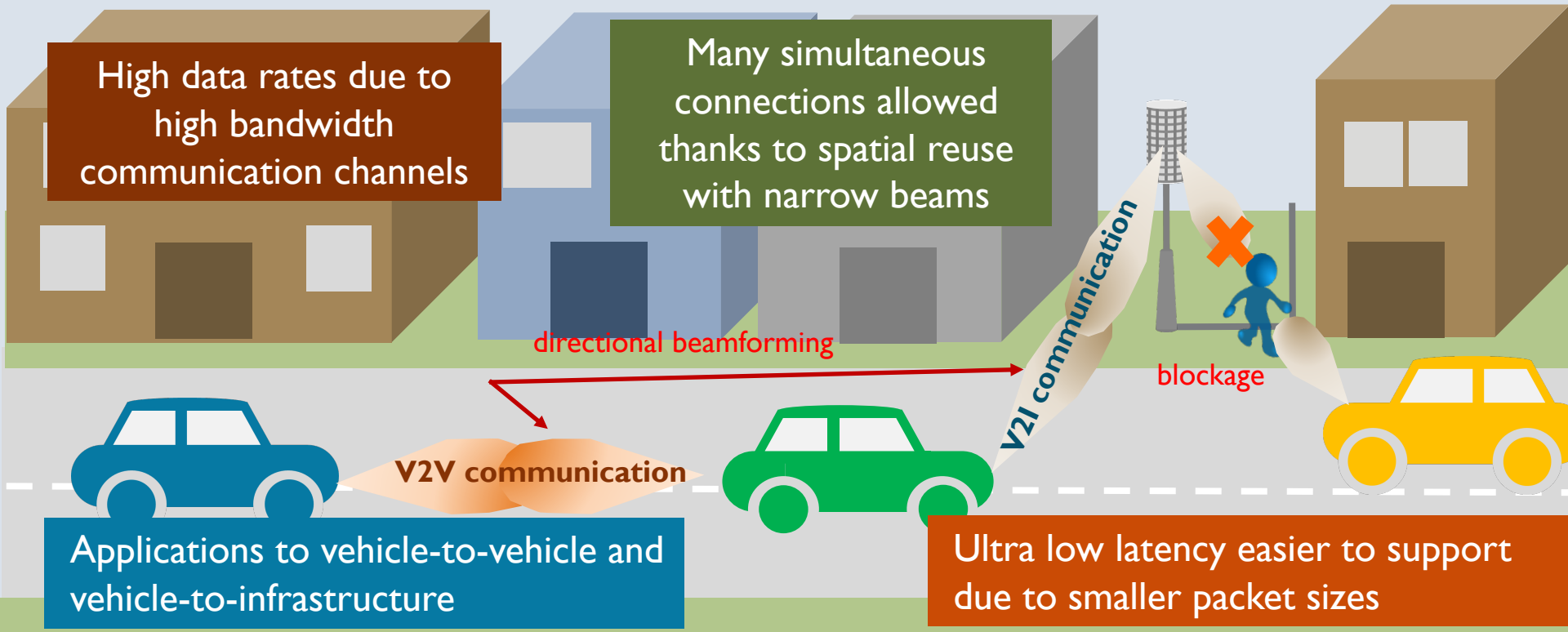
MmWave bands will enable Gbps V2X data rates



MmWave is the only viable approach for high bandwidth connected vehicles [1]

[1] 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, vol. 54, no. 12, pp. 160-167, December 2016.

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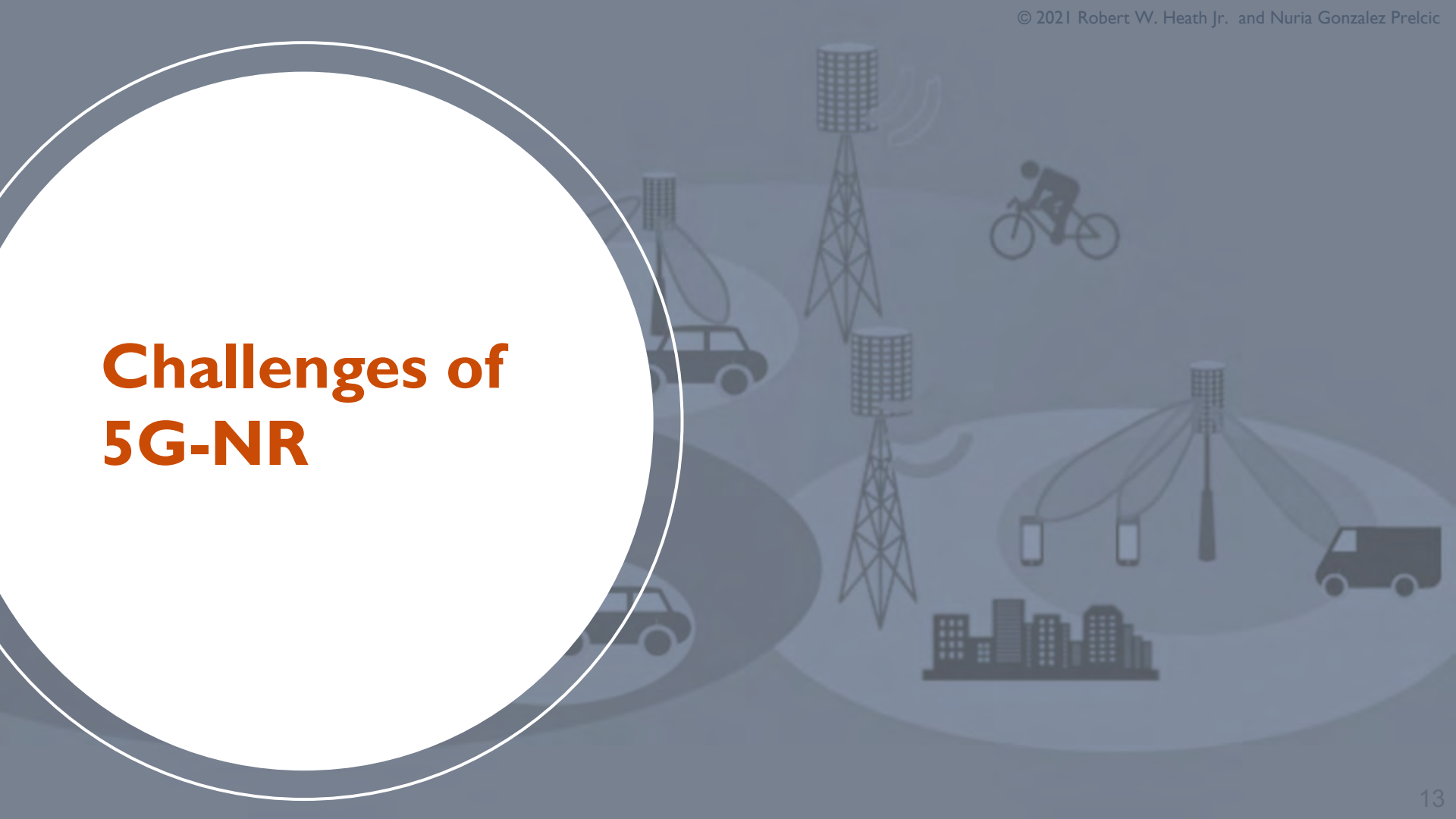
Challenges of 5G-NR



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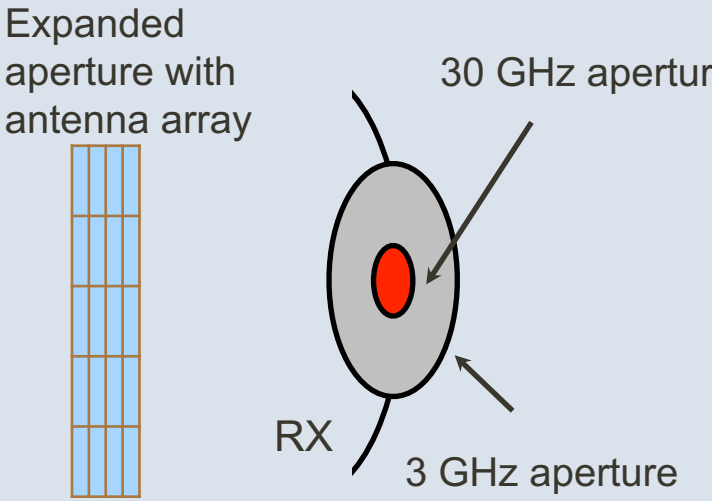
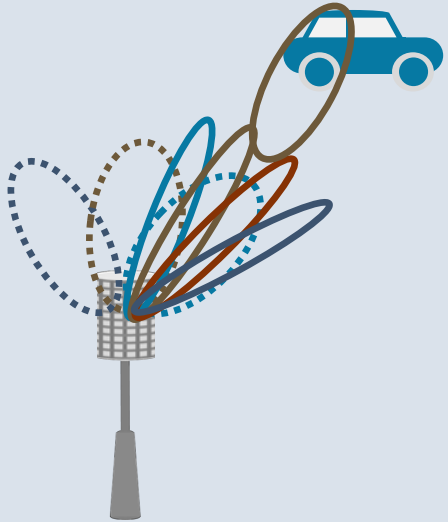
Beam-based design





Many antennas are used at higher frequencies to give larger effective aperture through the virtues of beamforming

5G adopts a beam-based design to support analog beamforming at base station and user equipment

Requires beam acquisition and tracking

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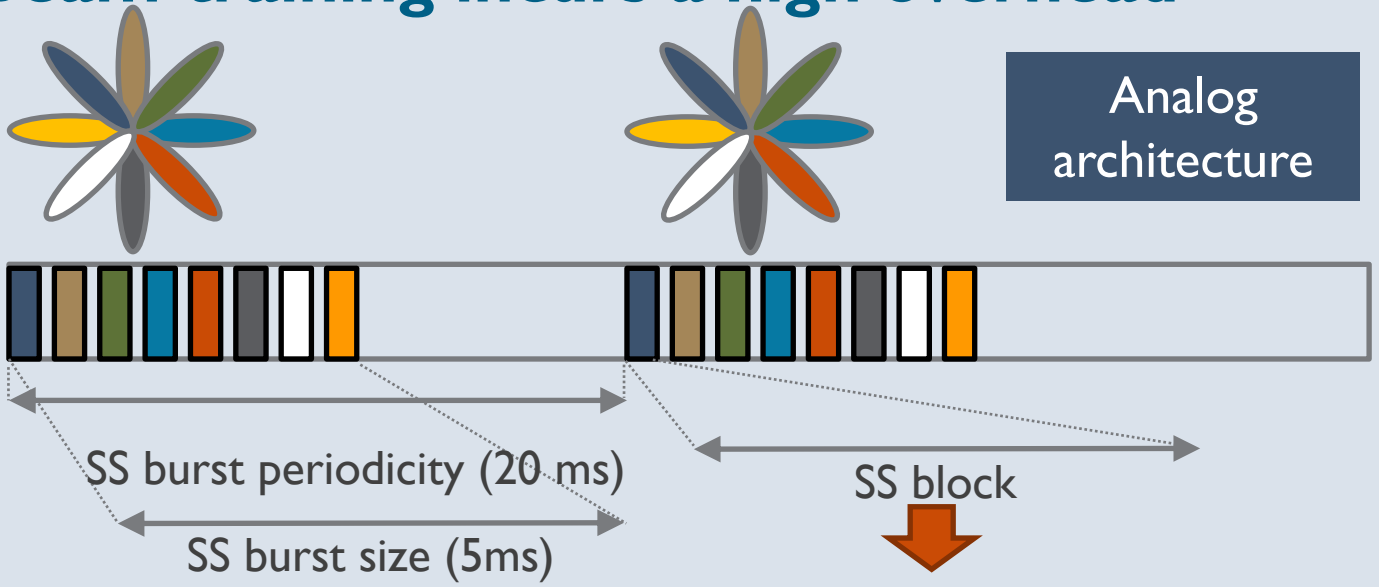
Beam-training incurs a high overhead



64 UE antennas

64 SS blocks per burst

64 gNB antennas

64*64/64*20e-3
=1.28 seconds

1.28 sec for Initial Access

More than 300 ms with 16 UE antennas

[1] 3GPP "NR - Physical layer procedures for control - Release 15," TS 38.213, 2018.
[2] 3GPP "NR - Physical layer measurements - Release 15," TS 38.215, 2017.

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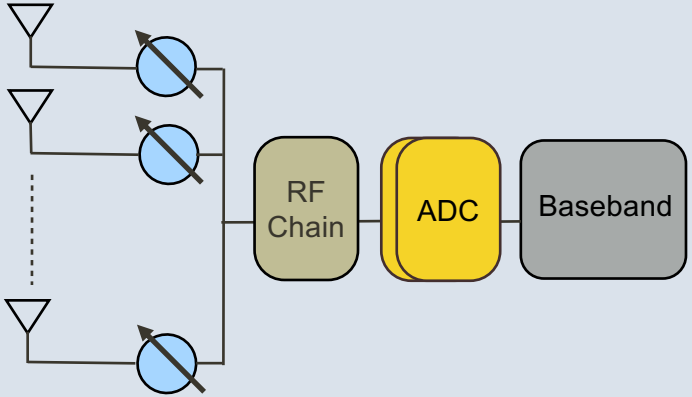
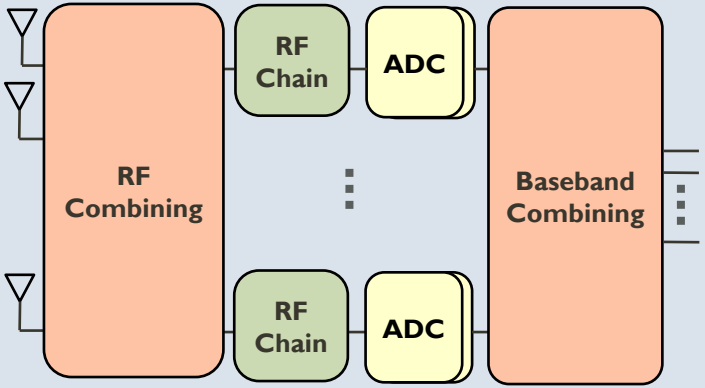
Other architectures are possible

Analog beamforming supports single user and single stream



Hybrid beamforming supports few beams and streams / users with more RF complexity



Beam training overhead greatly depends on the MIMO architecture choice

[1] E. Onggosanusi *et al.*, "Modular and High-Resolution Channel State Information and Beam Management for 5G New Radio," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 48-55, March 2018.

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AI/ML for beam training in V2X

Vutha Va, Junil Choi, Takayuki Shimizu, Gaurav Bansal, and R. W. Heath, Jr., `` Inverse Fingerprinting for Millimeter Wave V2I Beam Alignment," IEEE Trans. on Veh. Tech., vol. 67, no. 5, pp. 4042-4058, May 2018.

V. Va, T. Shimizu, G. Bansal and R. W. Heath, "Online Learning for Position-Aided Millimeter Wave Beam Training," in IEEE Access, vol. 7, pp. 30507-30526, 2019.

N. J. Myers, Y. Wang, N. González-Prelcic, and R. W. Heath, "Deep Learning-Based Beam Alignment in Mmwave Vehicular Networks," in ICASSP 2020 - 2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), May 2020, pp. 8569–8573.

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Machine Learning Billboard Collection

Do you still think that ML stands for maximum likelihood?

Are your papers getting the visibility you want?

Is your work missing that energy associated with the next hot topic?

Machine learning-for-everything (ML4X)!!!

From R. W. Heath and N. González-Prelcic, "Machine-Learning Billboard Collection [Humor]," in *IEEE Signal Processing Magazine*, vol. 36, no. 1, pp. 176-176, Jan. 2019.

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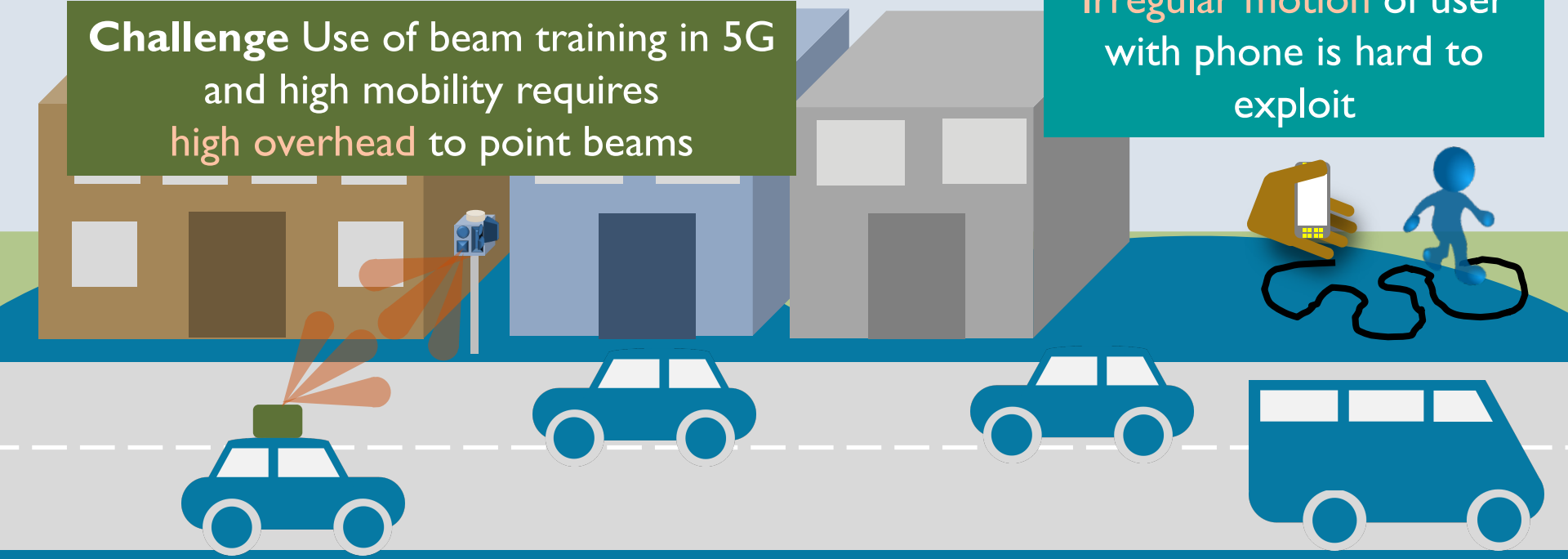
Vehicular applications of millimeter wave

Challenge Use of beam training in 5G and high mobility requires high overhead to point beams

Irregular motion of user with phone is hard to exploit



The regular motion in V2X is an opportunity to improve the efficiency of millimeter wave communication systems

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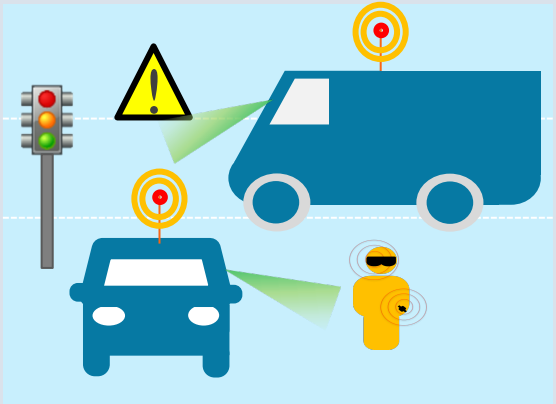
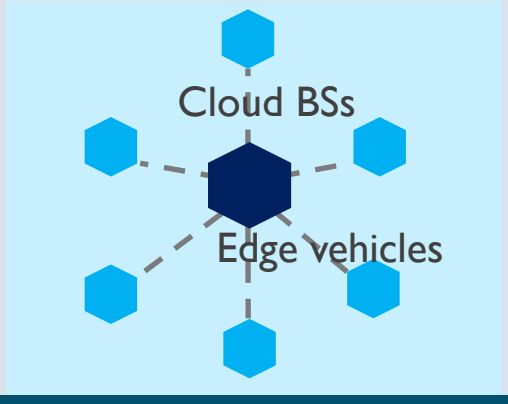
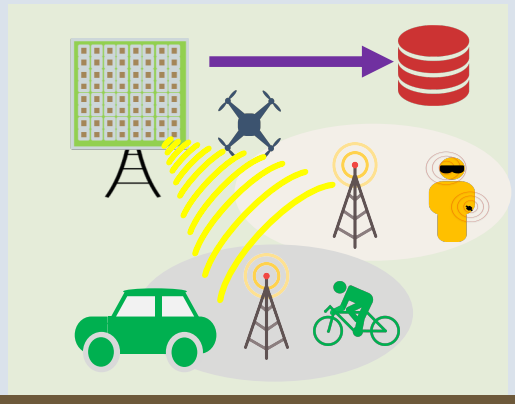
Opportunities in ML4V2X: data-driven solutions



Situational awareness, regularity of environment



Huge computation resources @ BS/devices



Data from previous transmission records

Data-driven solutions are promising for mmWave vehicular beam alignment

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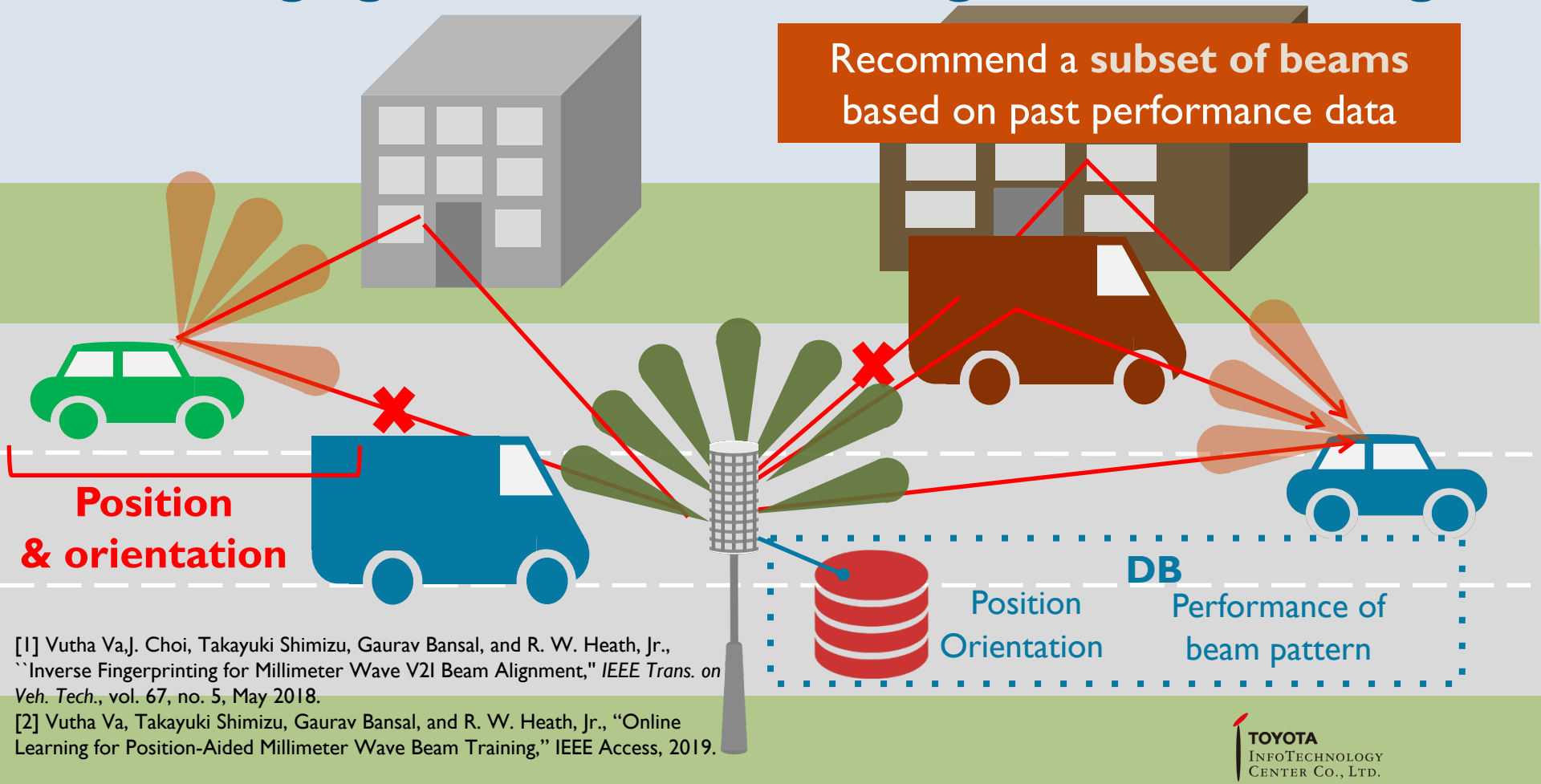
Leveraging side information using machine learning



[1] Vutha Va,J. Choi, Takayuki Shimizu, Gaurav Bansal, and R. W. Heath, Jr., ``Inverse Fingerprinting for Millimeter Wave V2I Beam Alignment," *IEEE Trans. on Veh. Tech.*, vol. 67, no. 5, May 2018.
[2] Vutha Va, Takayuki Shimizu, Gaurav Bansal, and R. W. Heath, Jr., "Online Learning for Position-Aided Millimeter Wave Beam Training," IEEE Access, 2019.

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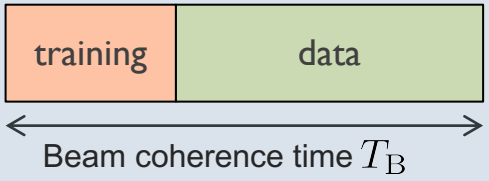
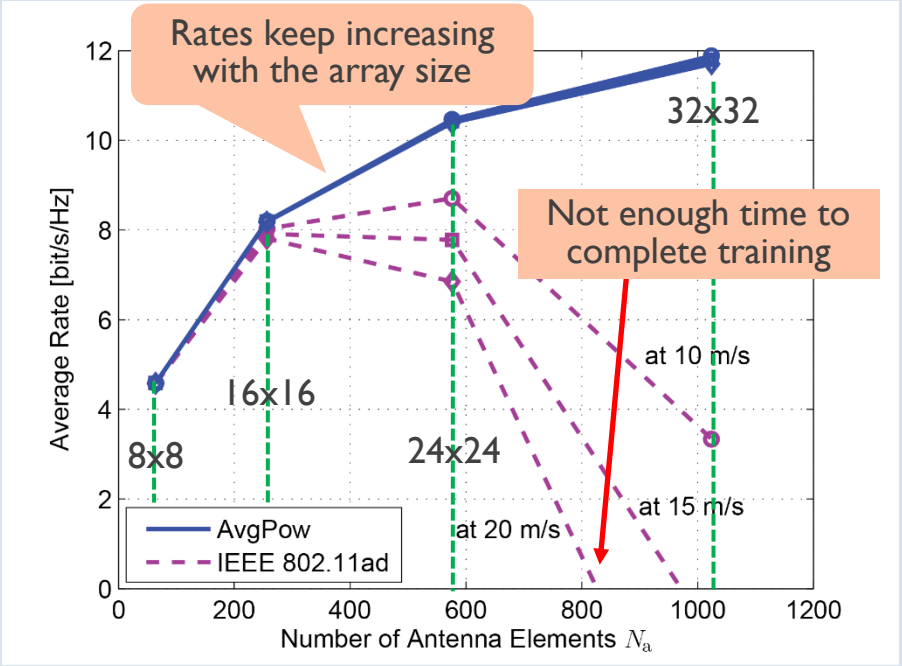
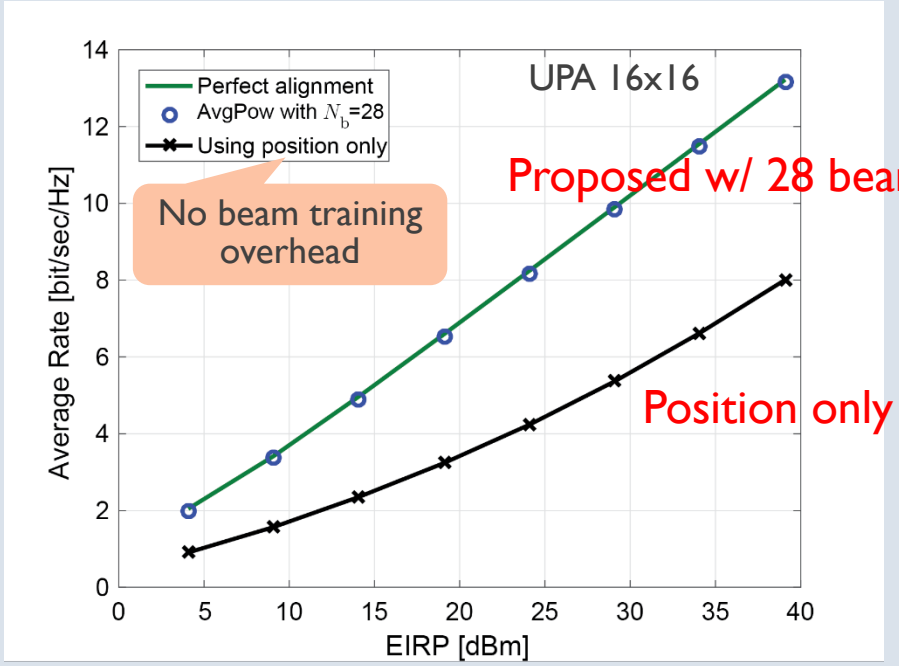


Rates with large arrays





Proposed method can support large arrays at high speeds

The value of fingerprint database increases with blockage probability

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Evolving infrastructure

A. Ali, N. Gonzalez-Prelcic, R. W. Heath and A. Ghosh, "Leveraging Sensing at the Infrastructure for mmWave Communication," in *IEEE Communications Magazine*, vol. 58, no. 7, pp. 84-89, July 2020.

Y. Wang, A. Klautau, M. Ribero, A. C. K. Soong and R. W. Heath, "MmWave Vehicular Beam Selection With Situational Awareness Using Machine Learning," in IEEE Access, vol. 7, pp. 87479-87493, 2019.

M. L. Rahman, J. A. Zhang, X. Huang, Y. J. Guo and R. W. Heath, "Framework for a Perceptive Mobile Network Using Joint Communication and Radar Sensing," in IEEE TAES 2020.

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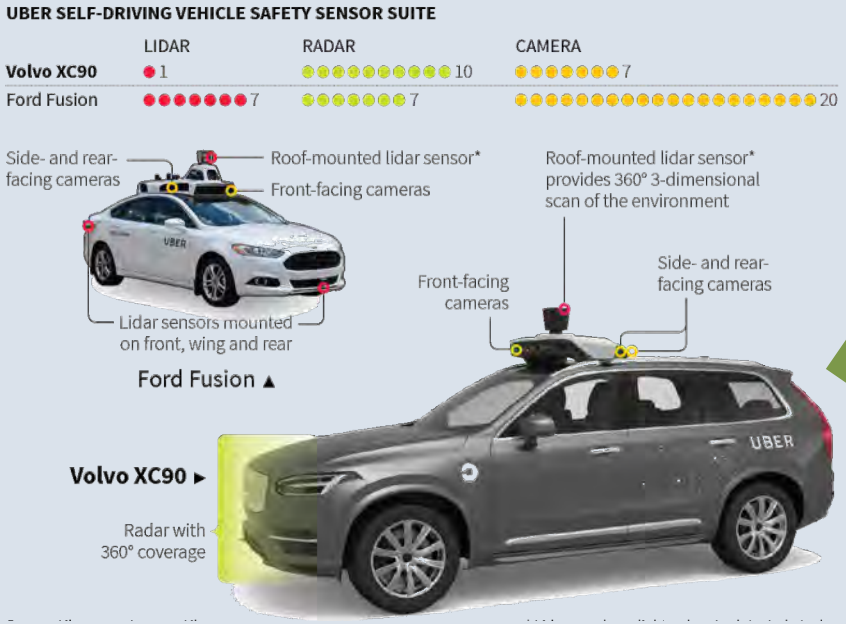
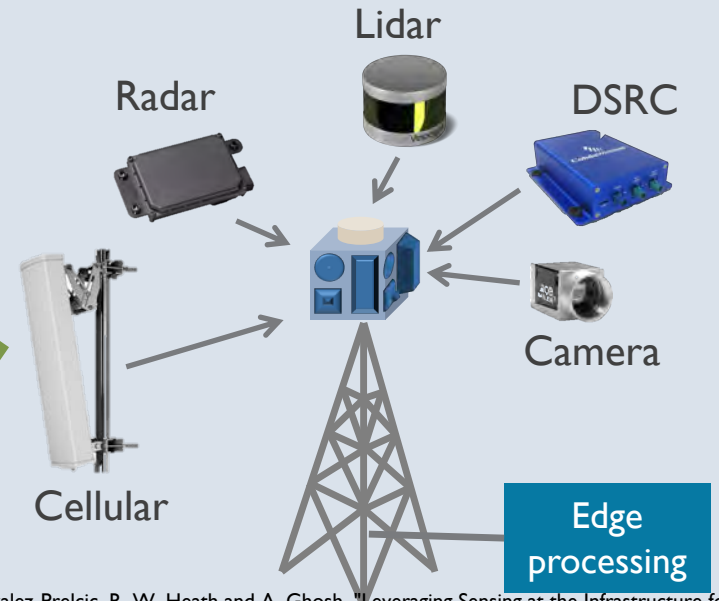
Explosion of sensors to support vehicles

Near term: more sensors on vehicles



https://fingfx.thomsonreuters.com/gfx/rngs/UBER-SELFDRIVING-SENSORS/010061BR2TH/UBER-SELFDRIVING-SENSORS.jpg

Longer term: sensors collocated with BS



A. Ali, N. Gonzalez-Prelcic, R. W. Heath and A. Ghosh, "Leveraging Sensing at the Infrastructure for mmWave Communication," in *IEEE Communications Magazine*, vol. 58, no. 7, pp. 84-89, July 2020.
M. L. Rahman, J. A. Zhang, X. Huang, Y. J. Guo and R. W. Heath, "Framework for a Perceptive Mobile Network Using Joint Communication and Radar Sensing," in IEEE TAES 2020.

Sensing expands situational awareness, has many applications to automation

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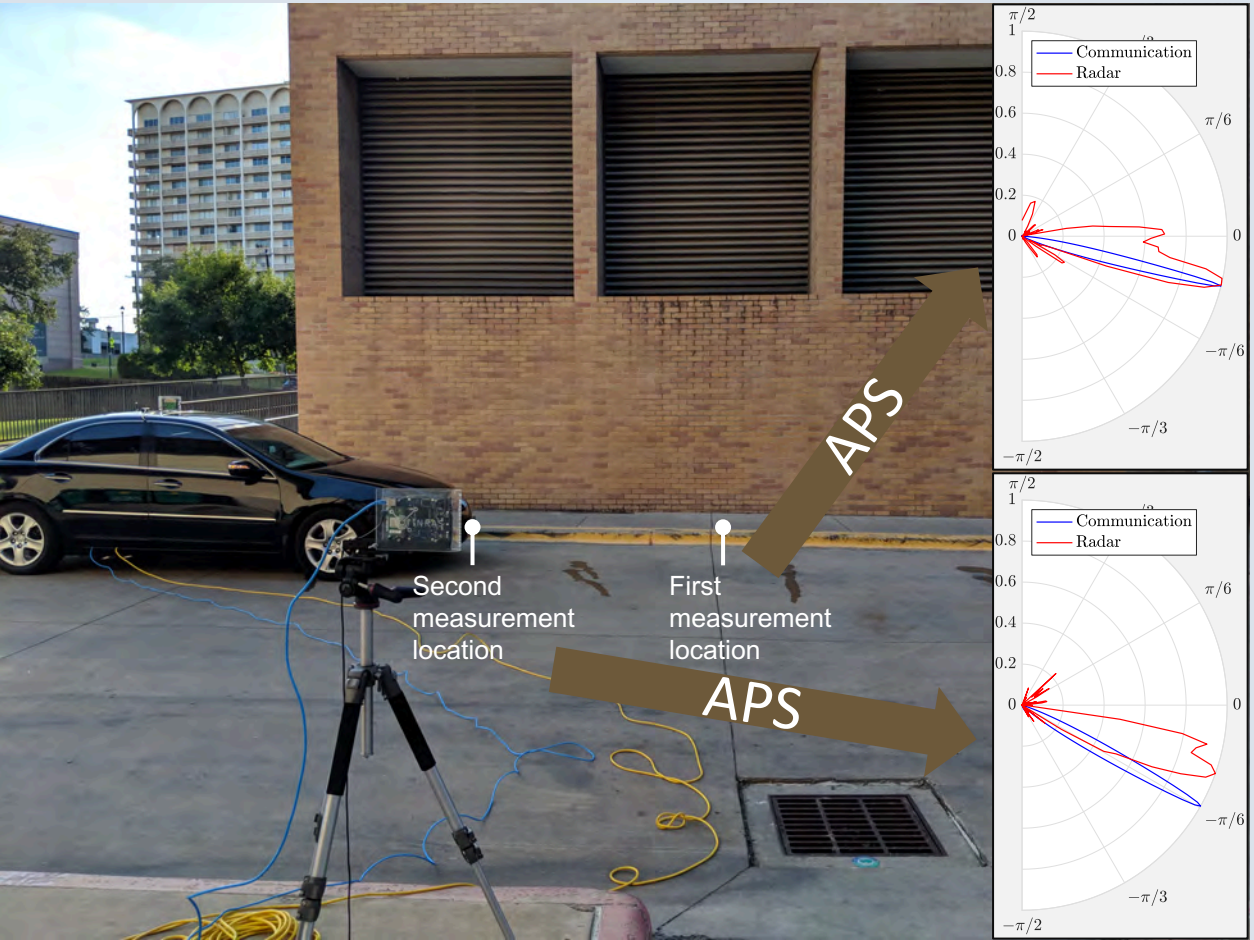
Sensors also can aid communication



A. Ali, N. Gonzalez-Prelcic, R. W. Heath and A. Ghosh, "Leveraging Sensing at the Infrastructure for mmWave Communication," in *IEEE Communications Magazine*, vol. 58, no. 7, pp. 84-89, July 2020.

A. Graff, A. Ali, and N. González-Prelcic, "Measuring radar and communication congruence at millimeter wave frequencies," in Proc. Asilomar *conference on signals, systems, and computers*, Nov. 2019, pp. 925–929.

Congruence between radar and communication channels

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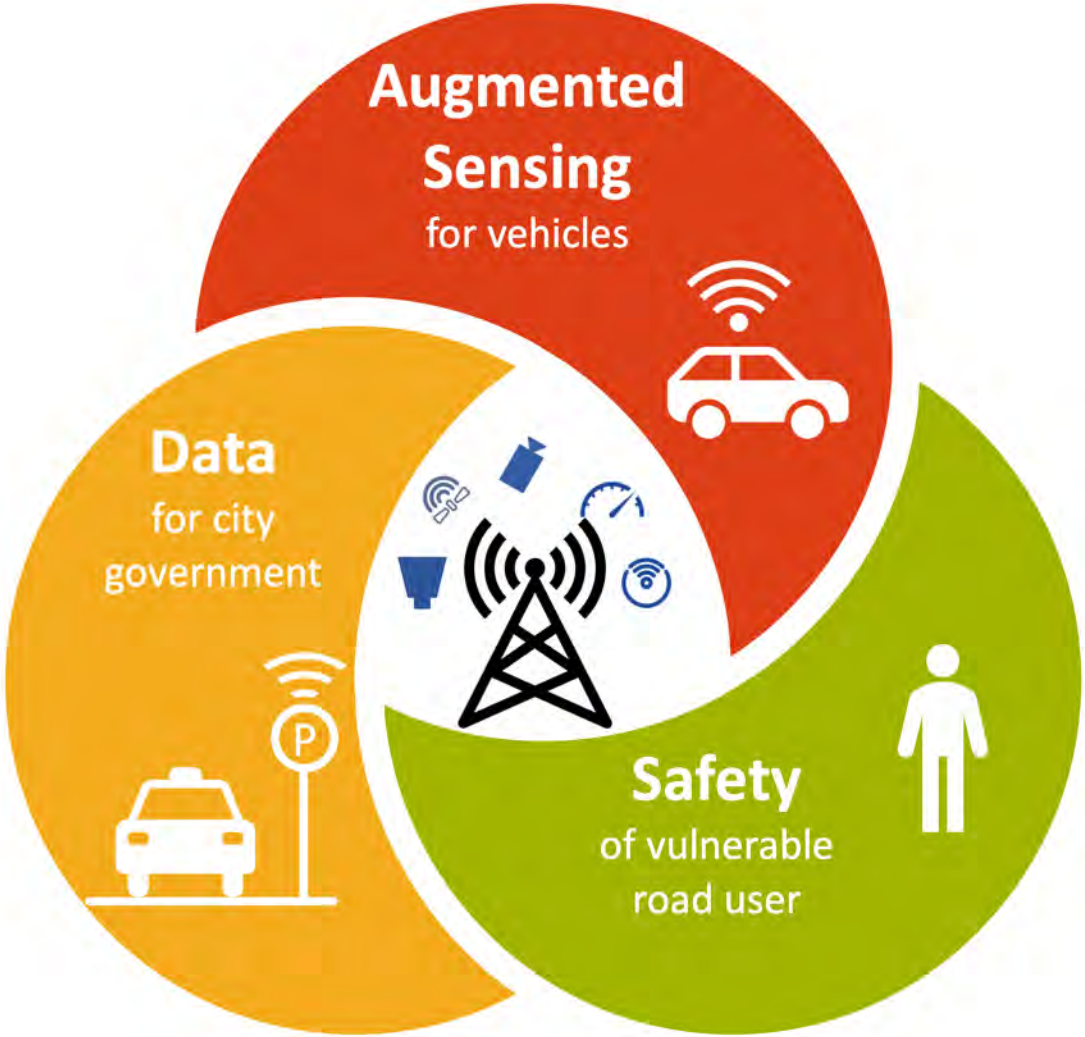

Sensing makes the infrastructure more valuable

A. Ali, N. Gonzalez-Prelcic, R. W. Heath, and A. Ghosh, "Leveraging Sensing at the Infrastructure for mmWave Communication," *IEEE Communications Magazine*, vol. 58, no. 7, pp. 84–89, Jul. 2020

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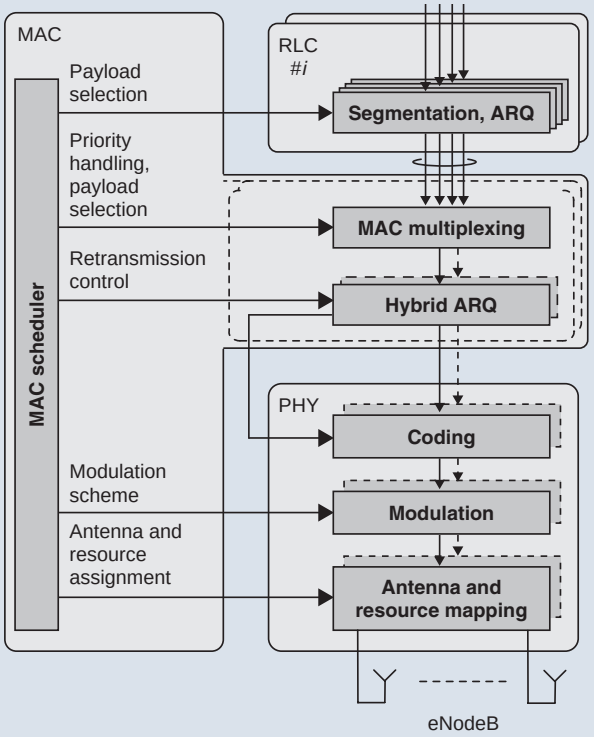
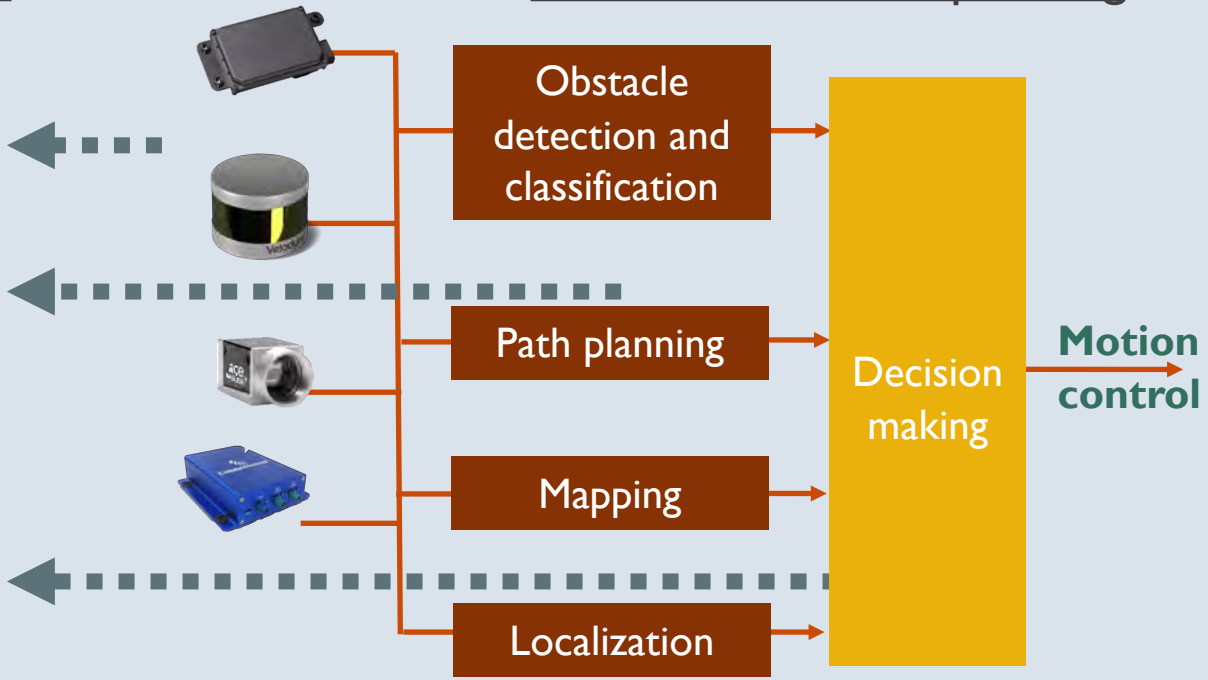
Exploiting sensors for communications

LTE protocol architecture



Automated vehicle planning



How to connect sensing and communication stacks?

N. González Prelcic, et. al., ``Millimeter Wave communication with out-of-band information," IEEE Com Mag, Dec. 2017.
Part of Fig 15.1 from E. Dahlman, S. Parkvall, J. Sköld, and Per Beming, 3G Evolution: HSPA and LTE for Mobile Broadband, Academic Press, 2007.

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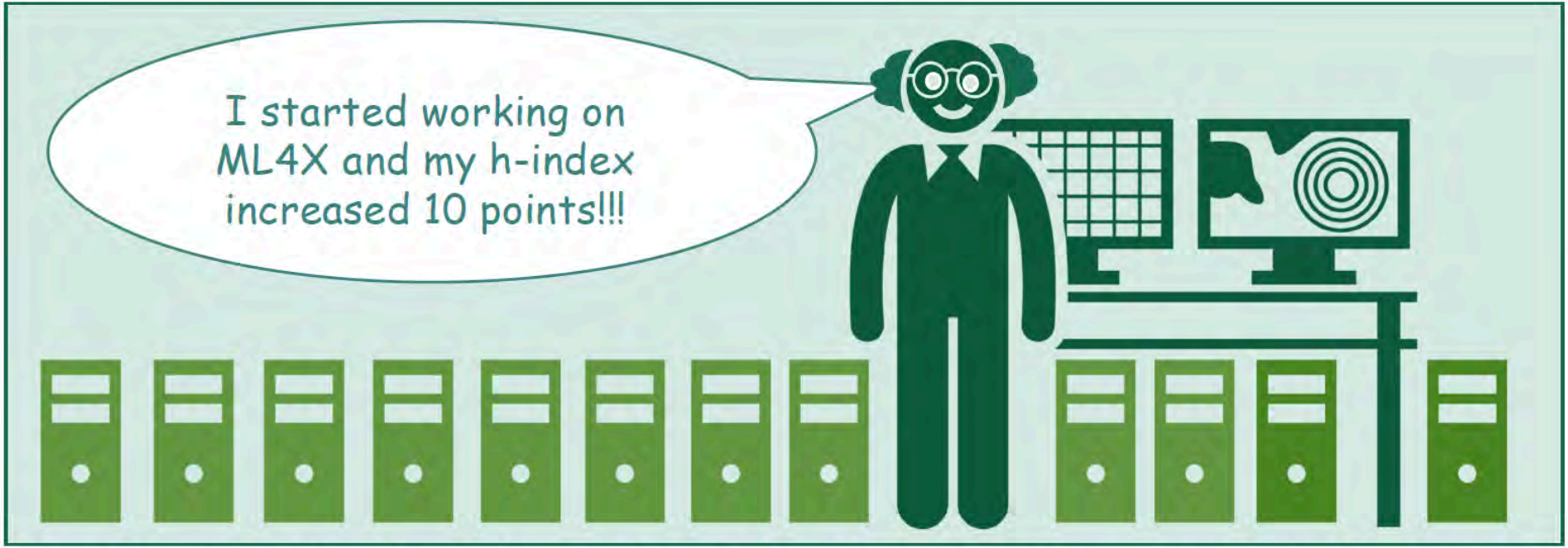

Warnings: Claims made here are based on absolutely no facts. Applying machine learning to your research may not lead to more publications, more funding, or a higher citation index. Using machine learning might cause periodic frustration due to the challenges of getting the software to actually work, the search for large enough data sets, or the constant acquisition of more processing power.

(c) Robert W. Heath Jr. and Nuria González-Prelcic 2018

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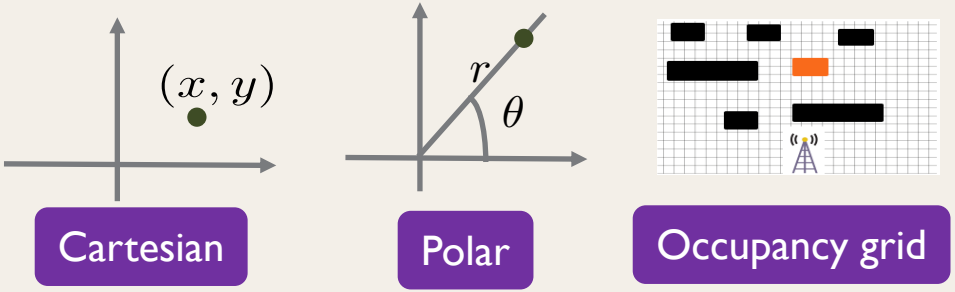
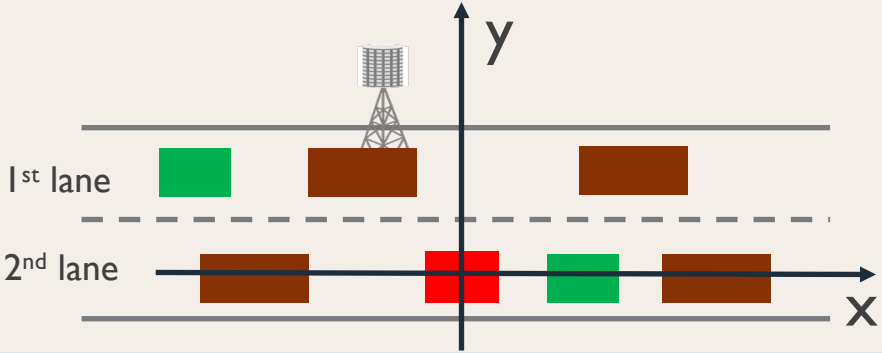
Exploiting knowledge of vehicle locations

Encode the geometry into different coordinates



Set the RX location as coordinate origin



Order vehicles based on **types** and **locations**

First lane vehicles
Trucks with larger size
Vehicles *closer* to the RX

→ Have larger impacts on reflections & beam selection

$$\mathbf{v} = [\mathbf{r}, \mathbf{t}_1, \mathbf{t}_2, \mathbf{c}_1, \mathbf{c}_2]$$

Location of RSU; 1st & 2nd lane trucks; 1st & 2nd lane cars

Constrain the number of vehicles in features as N_{veh}

Cartesian coor., e.g.,

$$\mathbf{t}_1 = [x_{i_1}, y_{i_1}, x_{i_2}, y_{i_2}, \cdots, x_{i_N}, y_{i_N}],$$
$$|x_{i_1}| < |x_{i2}| < \cdots < |x_{iN}|.$$

Vehicles on each lane of a certain type are ordered based on the relative distance to RX

Y. Wang, A. Klautau, M. Narasimha, and R. W. Heath Jr., "MmWave beam selection with situational awareness", in preparation for submission.

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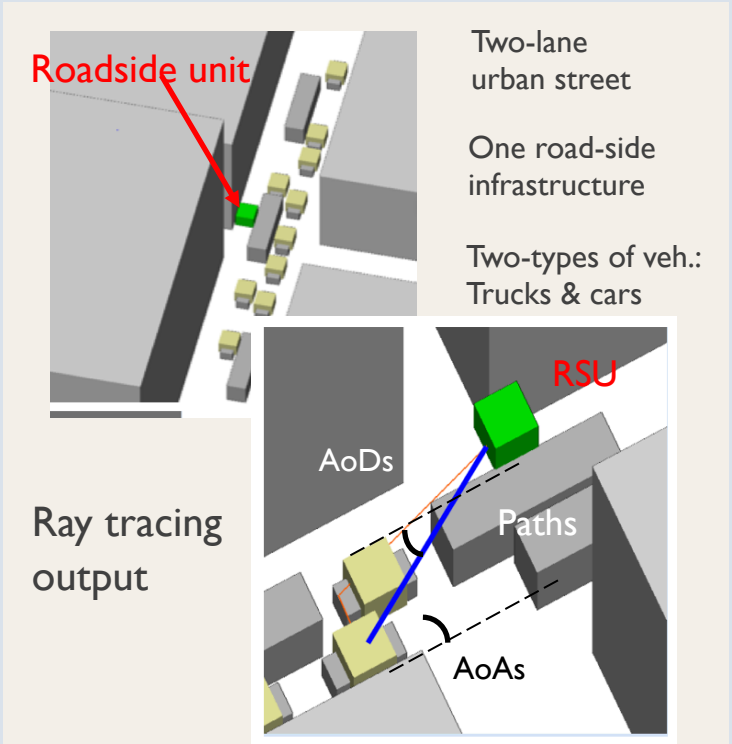
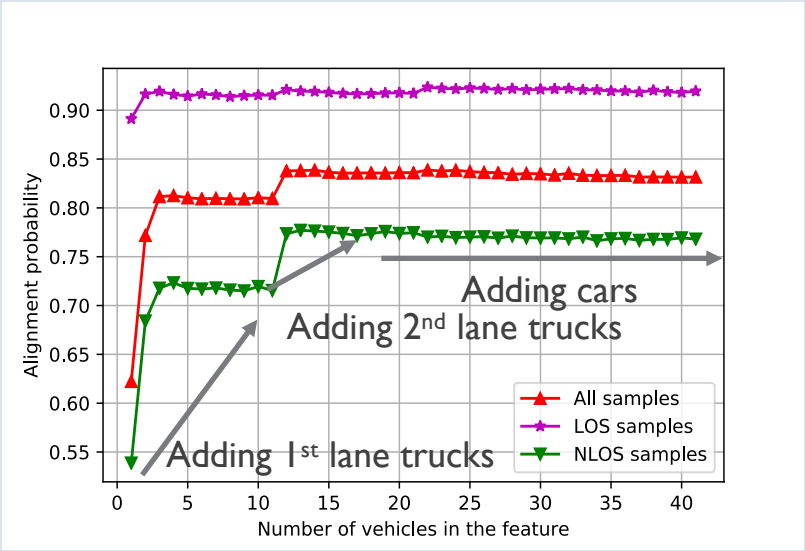
Smart link configuration



$$\mathbf{H}[n] = \sqrt{N_{\mathrm{t}} N_{\mathrm{r}}} \sum_{\ell=1}^{L_{\mathrm{p}}} g(nT - \tau_\ell)\mathbf{a}_{\mathrm{r}}(\phi_\ell^A)\mathbf{a}_{\mathrm{t}}^*(\phi_\ell^D)\alpha_\ell e^{j\phi_\ell},$$

$$0 \leq n \leq L_c - 1,$$



Situational awareness can be leveraged for fast vehicular beam alignment

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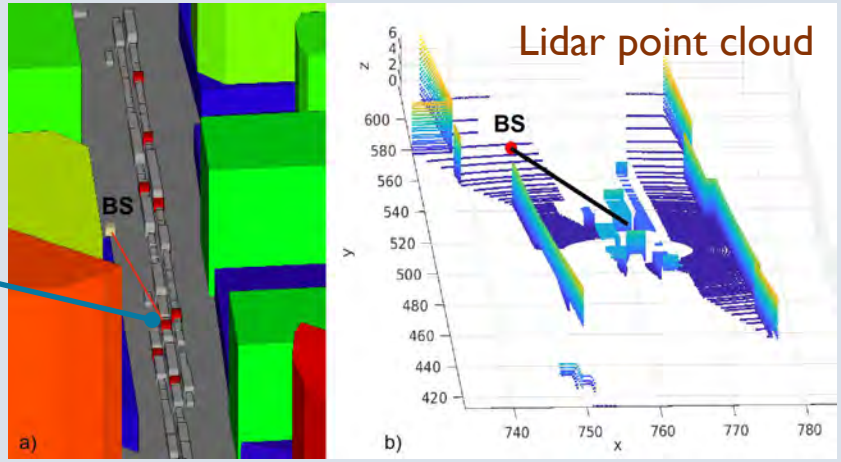
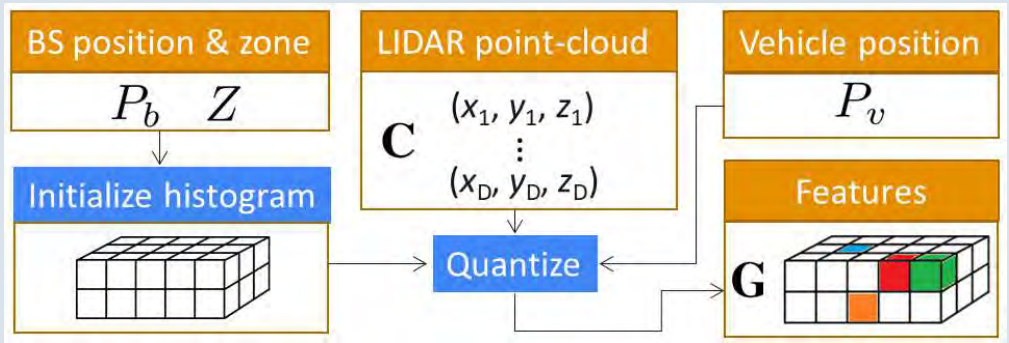
Lidar aided beam training

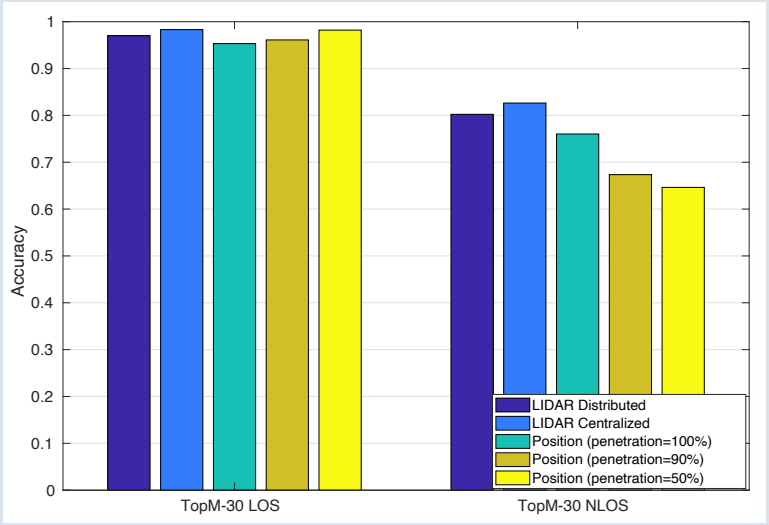


Urban canyon in ray tracing simulation



Selection of top beam pairs using deep learning [1]

Prediction with 30 pairs



LOS NLOS

[1] Aldebaro Klautau, Nuria González-Prelcic and Robert W. Heath Jr. "LIDAR Data for Deep Learning-Based mmWave Beam-Selection", IEEE Wireless Communication Letters, 2019.
[2] Marcus Dias, Aldebaro Klautau, Nuria González-Prelcic and Robert W. Heath Jr. "Position and LIDAR-Aided mmWave Beam Selection using Deep Learning", in Proc. of SPAWC 2019.

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Obtaining meaningful data sets is a challenge

5G system deployment is too late to start collecting data for 6G

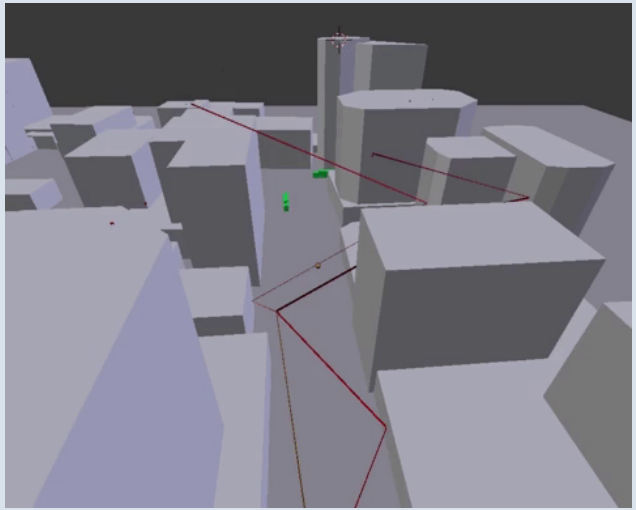
Need to obtain communication and sensing data at the appropriate spatial / frequency / temporal -scales with enough detail but not a computational burden

Some data sets like Raymobtime are available, including multi-modal, used in ITU challenge

https://www.lasse.ufpa.br/raymobtime/

https://research.ece.ncsu.edu/ai5gchallenge/

Figure from Prof. Klautau



Drones Vehicles Pedestrians

Need hybrid models that trade interpretability, accuracy and speed

A. Klautau, P. Batista, N. González Prelcic, Yuyang Wang, and R. W. Heath, Jr., ``5G MIMO Data for Machine Learning: Application to Beam-Selection using Deep Learning," (invited) Proc. of the Information Theory and Applications, San Diego, California, February 11-16, 2018.

NC STATE UNIVERSITY

ML5G-PHY
[channel estimation]

ITU Challenge AI/ML for 5G

Site specific-channel estimation with hybrid mmWave MIMO systems

Prof. Nuria González Prelcic

https://research.ece.ncsu.edu/ai5gchallenge/

Joint work with Prof. Robert Heath, Prof. Aldebaro Klautau and Prof. Ismail Guvenc

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Combining radar and communications

P. Kumari, J. Choi, N. González-Prelcic, and R. W. Heath, "IEEE 802.11ad-Based Radar: An Approach to Joint Vehicular Communication-Radar System," IEEE Transactions on Vehicular Technology, vol. 67, no. 4, pp. 3012–3027, Apr. 2018.

P. Kumari, S. A. Vorobyov, and R. W. Heath, "Adaptive virtual waveform design for millimeter-wave joint Communication–Radar," IEEE Transactions on Signal Processing, vol. 68, pp. 715–730, 2020.

M. L. Rahman, J. A. Zhang, X. Huang, Y. J. Guo and R. W. Heath, "Framework for a Perceptive Mobile Network Using Joint Communication and Radar Sensing," in IEEE TAES 2020.

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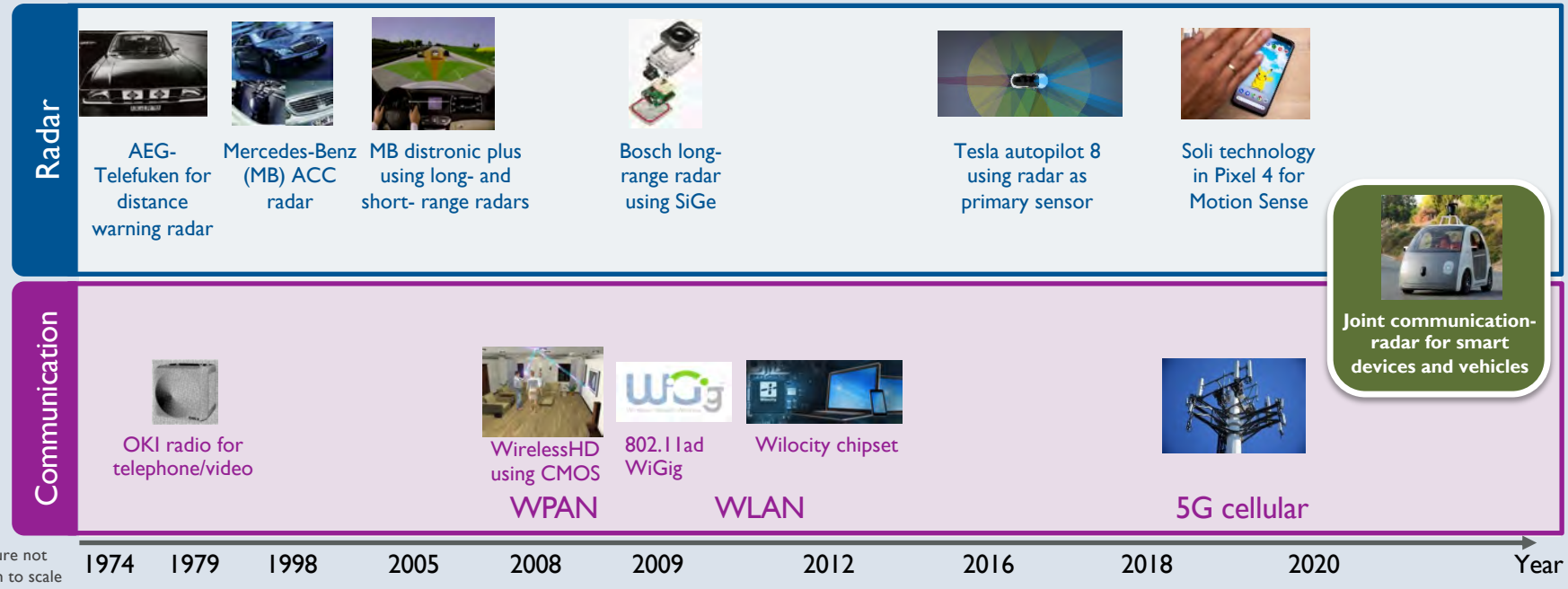
Milestones for mmWave systems in civilian applications



Traditionally, mmWave communications and radars developed independently

[1] H. H. Meinel and Juergen Dickmann. "Automotive radar: From its origins to future directions." Microwave Journal, 56(9), 2013.
[2] H. H. Meinel, "Commercial applications of mmWaves: history, present status, and future trends." IEEE Trans. on MTT 43, no. 7, pp. 1639-1653, 1995.

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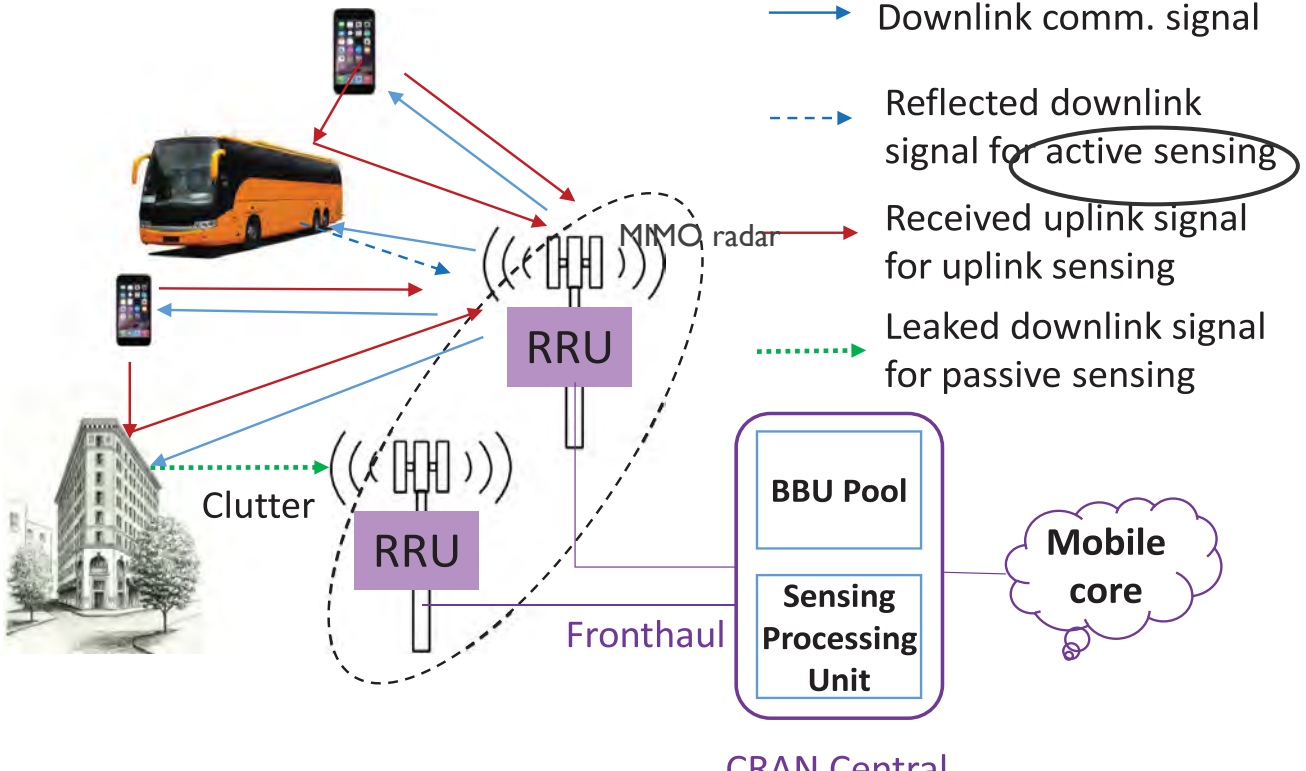
Many types of joint radar and communication



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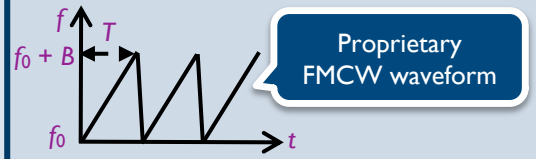
MmWave JCR system challenges

Waveform

Radar

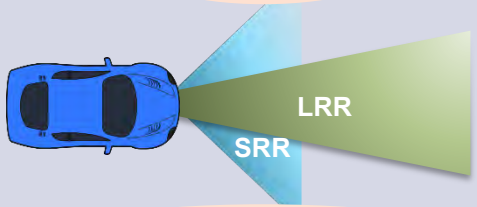


Communication

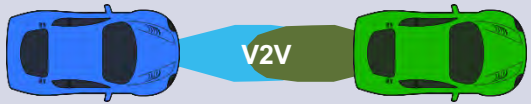
Use high data rate waveform for radar detection/estimation

Beamforming

Radar



Communication



Exploit antennas for more flexible beamforming design

Experimental evaluation

Radar

Communication

Validate theory in implementation

*LRR: Long-range radar

*SRR: Short-range radar

*V2V: Vehicle-to-vehicle communication

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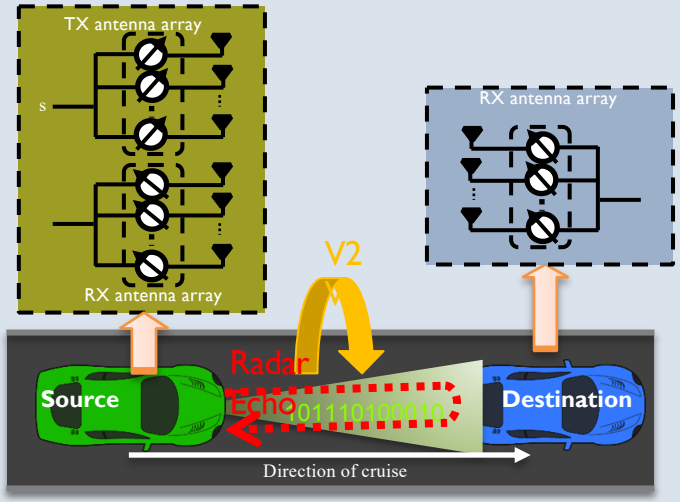
IEEE 802.11ad WLAN-based JCR

IEEE 802.11ad is a mmWave WLAN standard at 60 GHz, which provides a good baseline for designing a future vehicular standard at higher mmWave frequencies[1]

Single-carrier physical layer IEEE 802.11ad frame structure

Preamble consists of Golay complementary sequences that has good auto-correlation properties for radar



As a next step, advanced adaptive mmWave JCR algorithms were developed to achieve high radar performance, at the cost of minimal data rate reduction

[1] P. Kumari, J. Choi, N. G. Prelcic, and R. W. Heath, "IEEE 802.11ad-based radar: An approach to joint vehicular communication-radar system," in IEEE TVT, 2018.
[2] P. Kumari, N. Gonzalez-Prelcic, and R. W. Heath Jr, "Investigating the IEEE 802.11ad Standard for Millimeter Wave Automotive Radar," in Proc. VTC, 2015.

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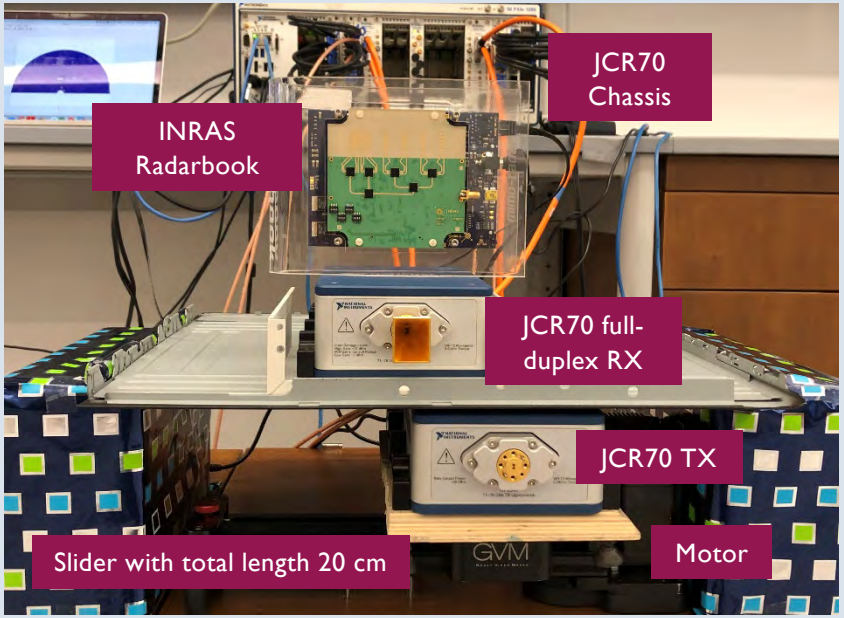
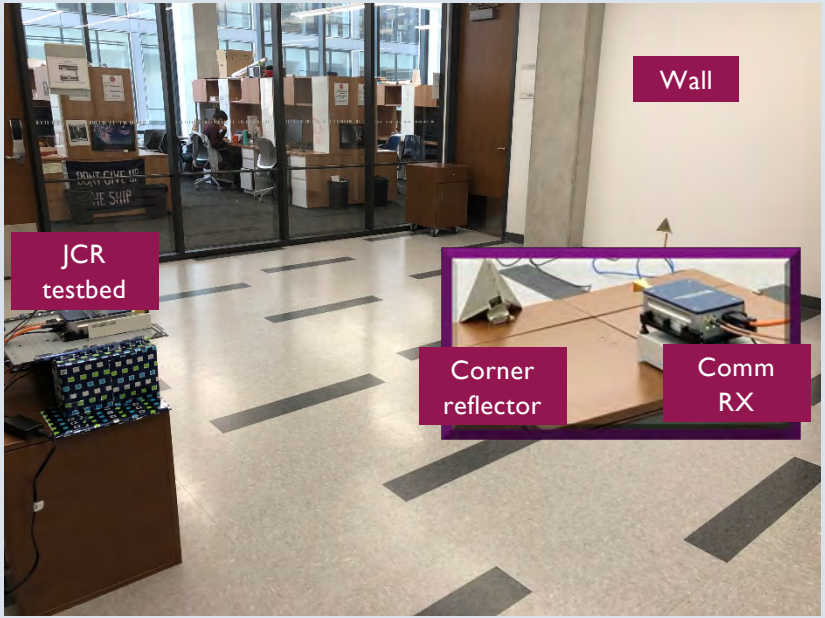
JCR70 MIMO mmWave JCR hardware platform



SIMO hardware platform with sliding motor



Experimental setup for JCR measurements

Our fully-digital wideband MIMO JCR at 73 GHz with a software-defined architecture

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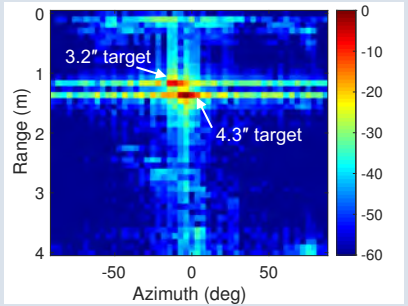
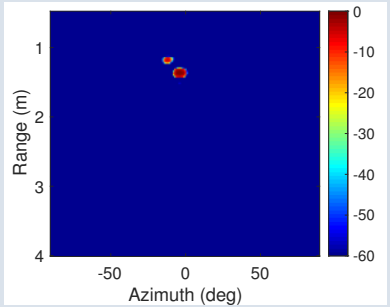
Algorithms and experiments

JCR70 Platform



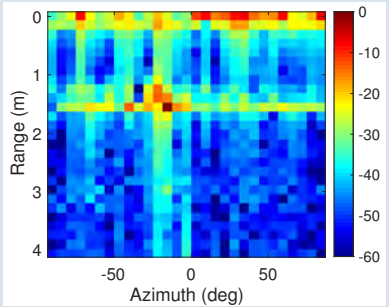
(a) Traditional



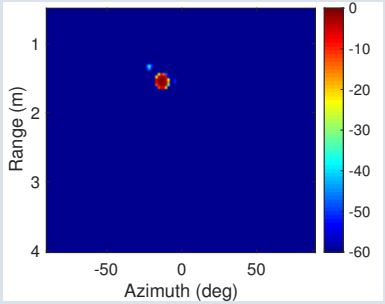
(b) EM-BG-GAMP

Good channel amplitude recovery with 30 steps and 2 GHz BW

INRAS Radarbook



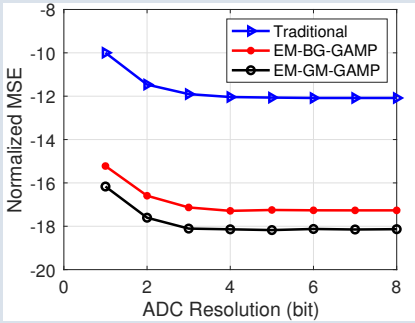
(a) Traditional

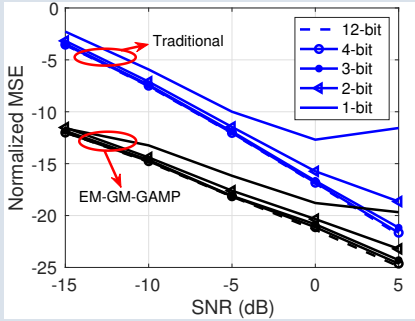


(b) EM-BG-GAMP

Poor channel amplitude recovery with 29 virtual elements and 1 GHz BW

NMSE Vs. ADC resolutions





3-bit ADC perform very closely to the high-resolution ADCs

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Questions

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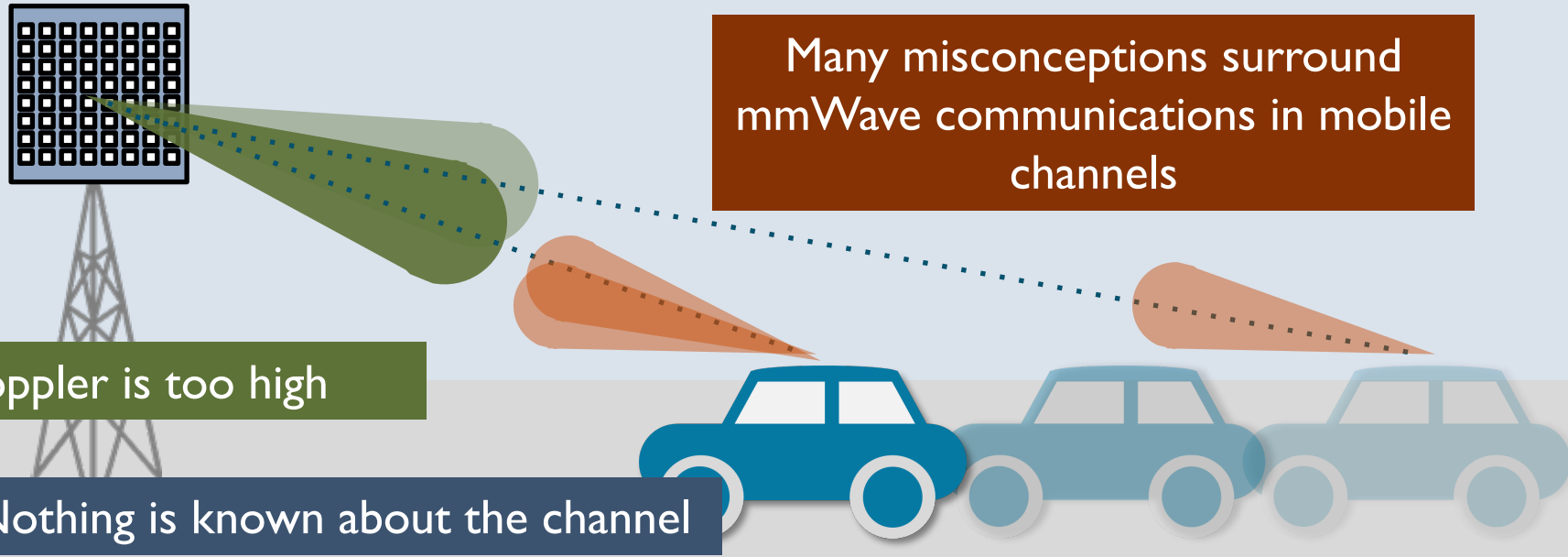
Can mmWave really work with high mobility?



Many misconceptions surround mmWave communications in mobile channels

Doppler is too high

Nothing is known about the channel

Beams are too hard to configure

Ongoing research to establish and maintain mmWave links in vehicular scenarios

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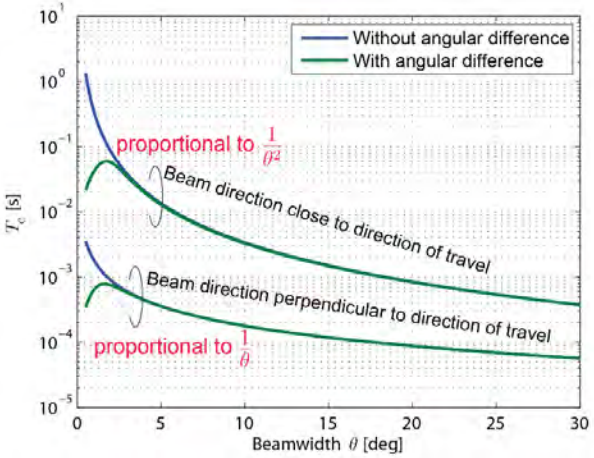
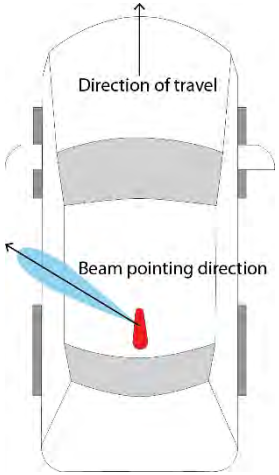
Channel coherence time and directional reception

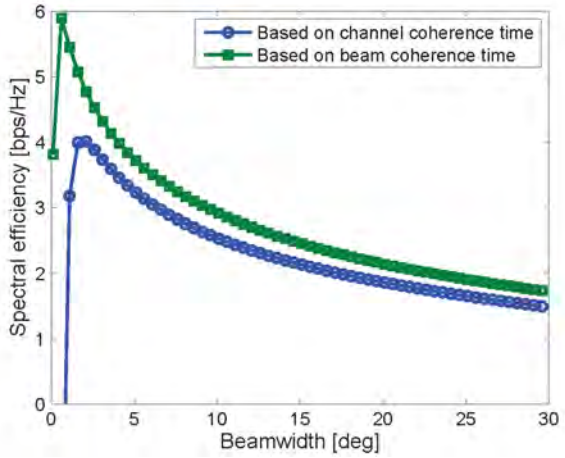
Mathematical expression relating coherence time and beamwidth



Beams should be narrow but not too "pointy"



Optimum beamwidth is a tradeoff between pointing error and Doppler



Long term beamforming can be used

Beam training not Doppler

*V. Va, J. Choi, and R. W. Heath Jr. The impact of beamwidth on temporal channel variation in vehicular channels and its implications, IEEE TVT, vol. 7, no. 5, 2018