Millimeter wave communication:
From Origins to Disruptive Applications

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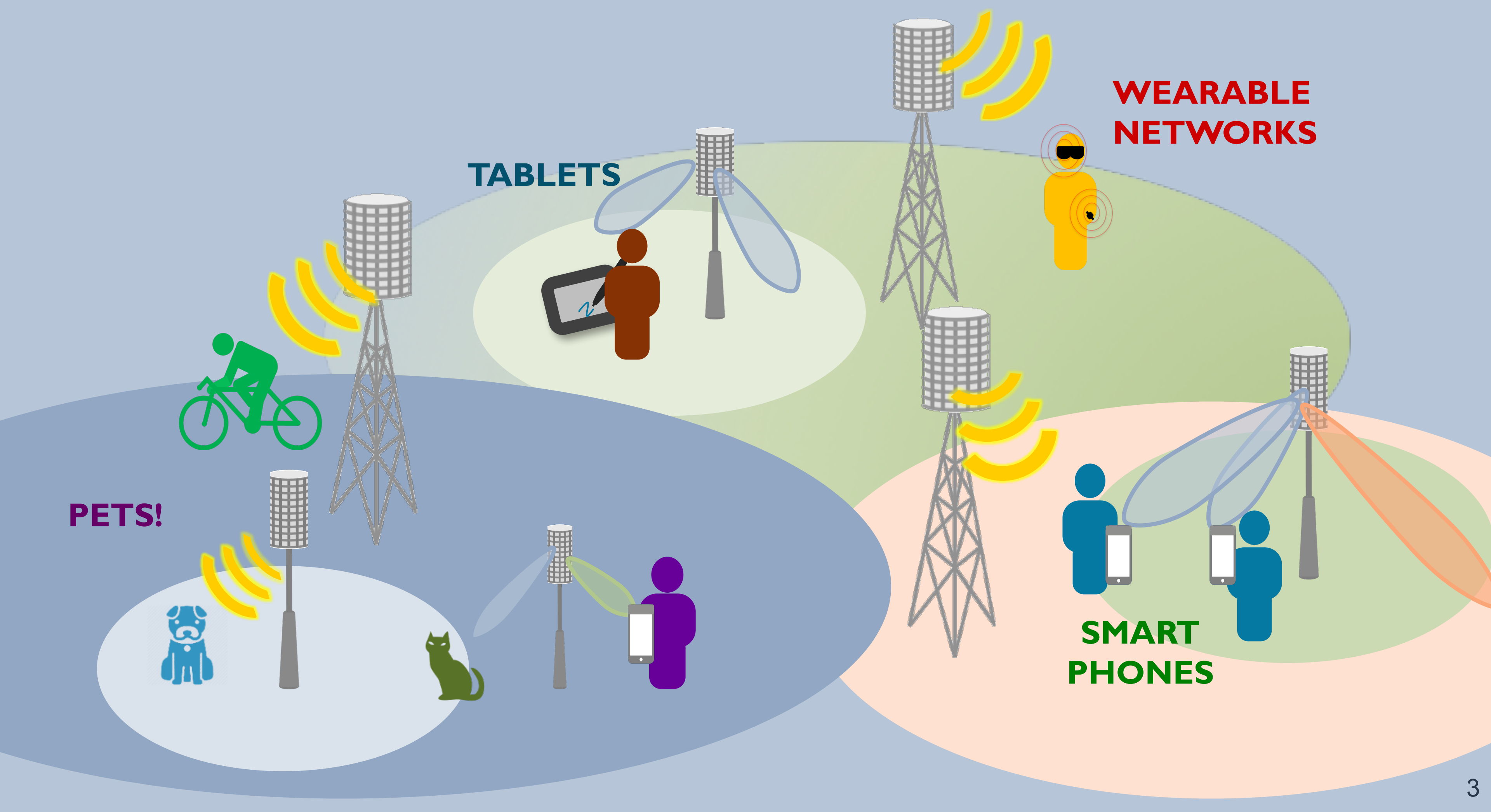
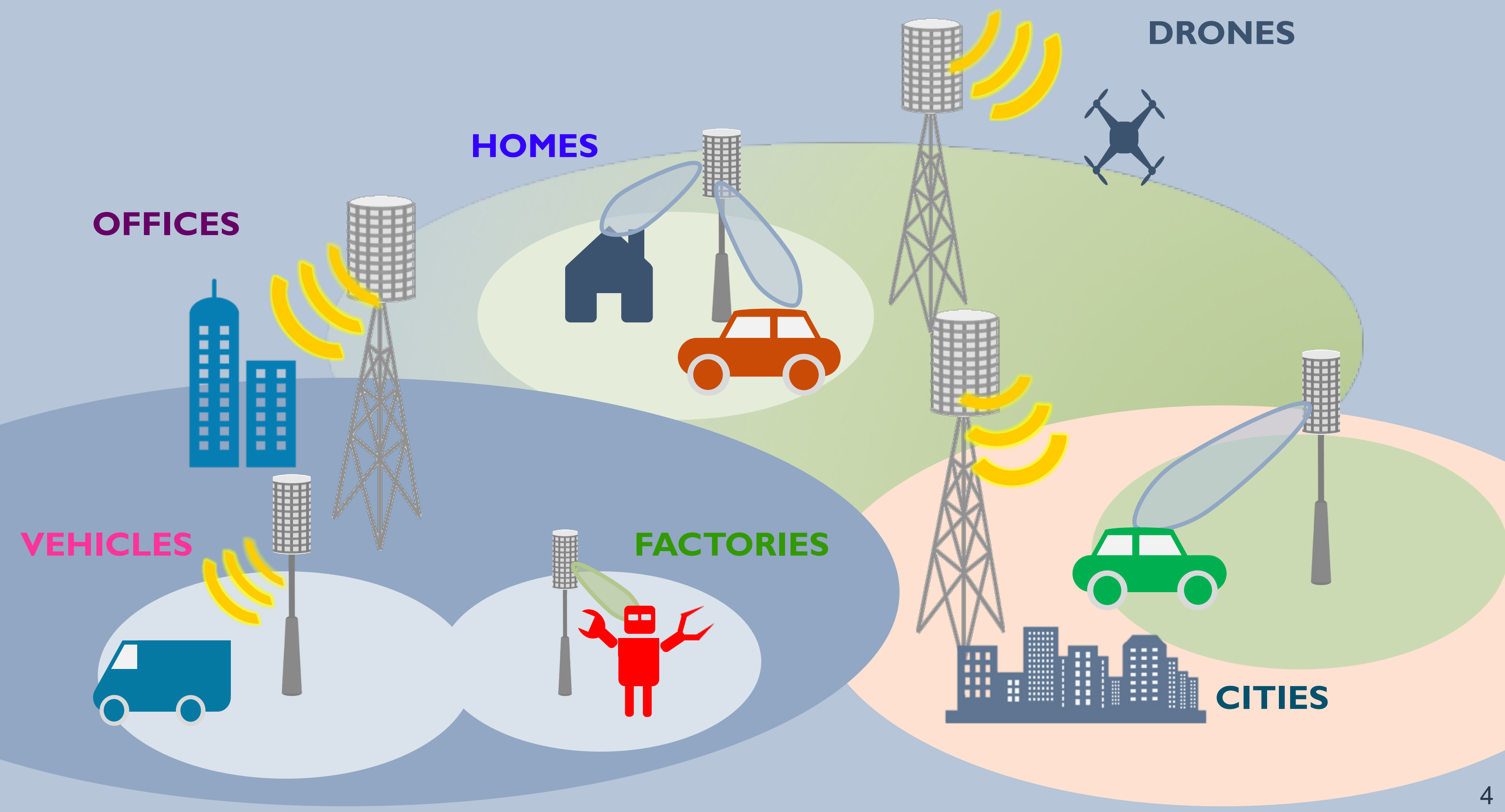
Introduction

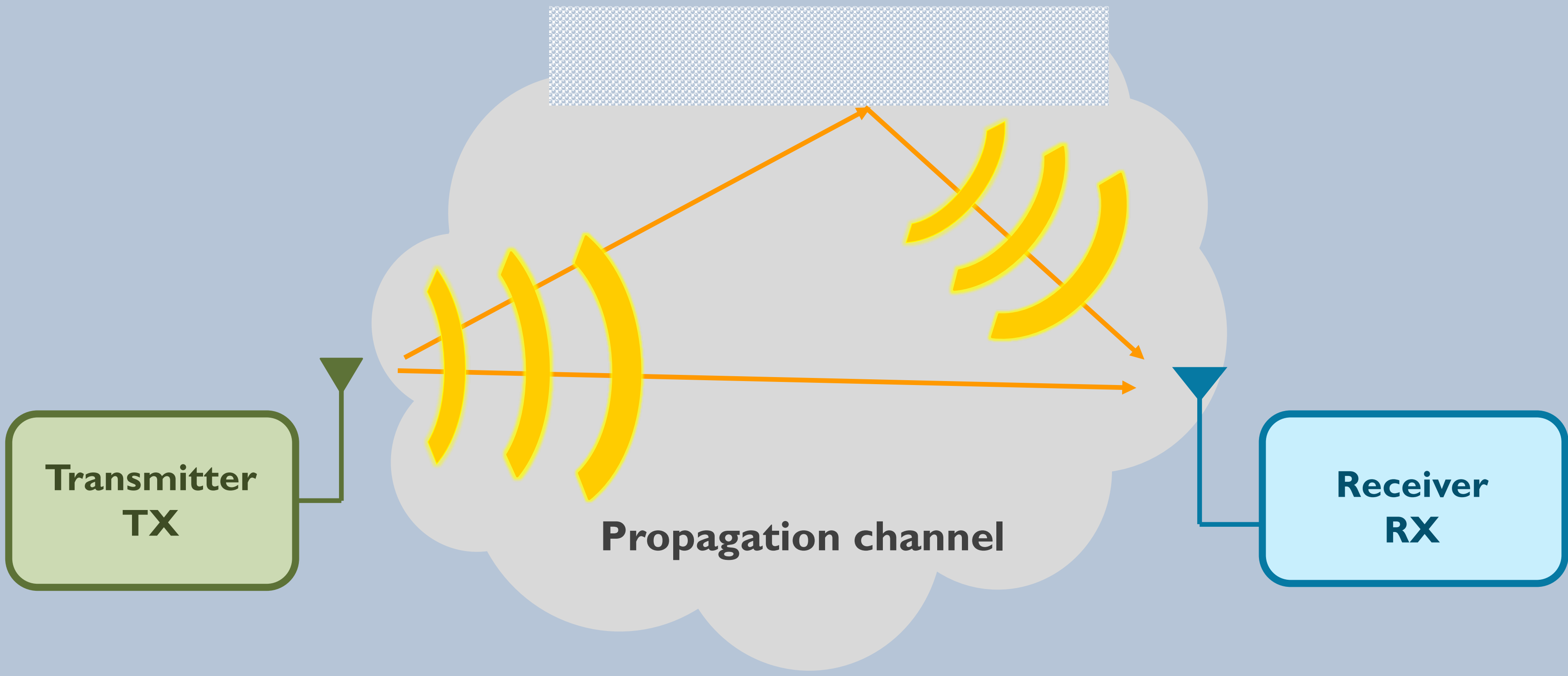
Cellular networks are connecting everyone (wirelessly)



Future networks will connect things beyond people

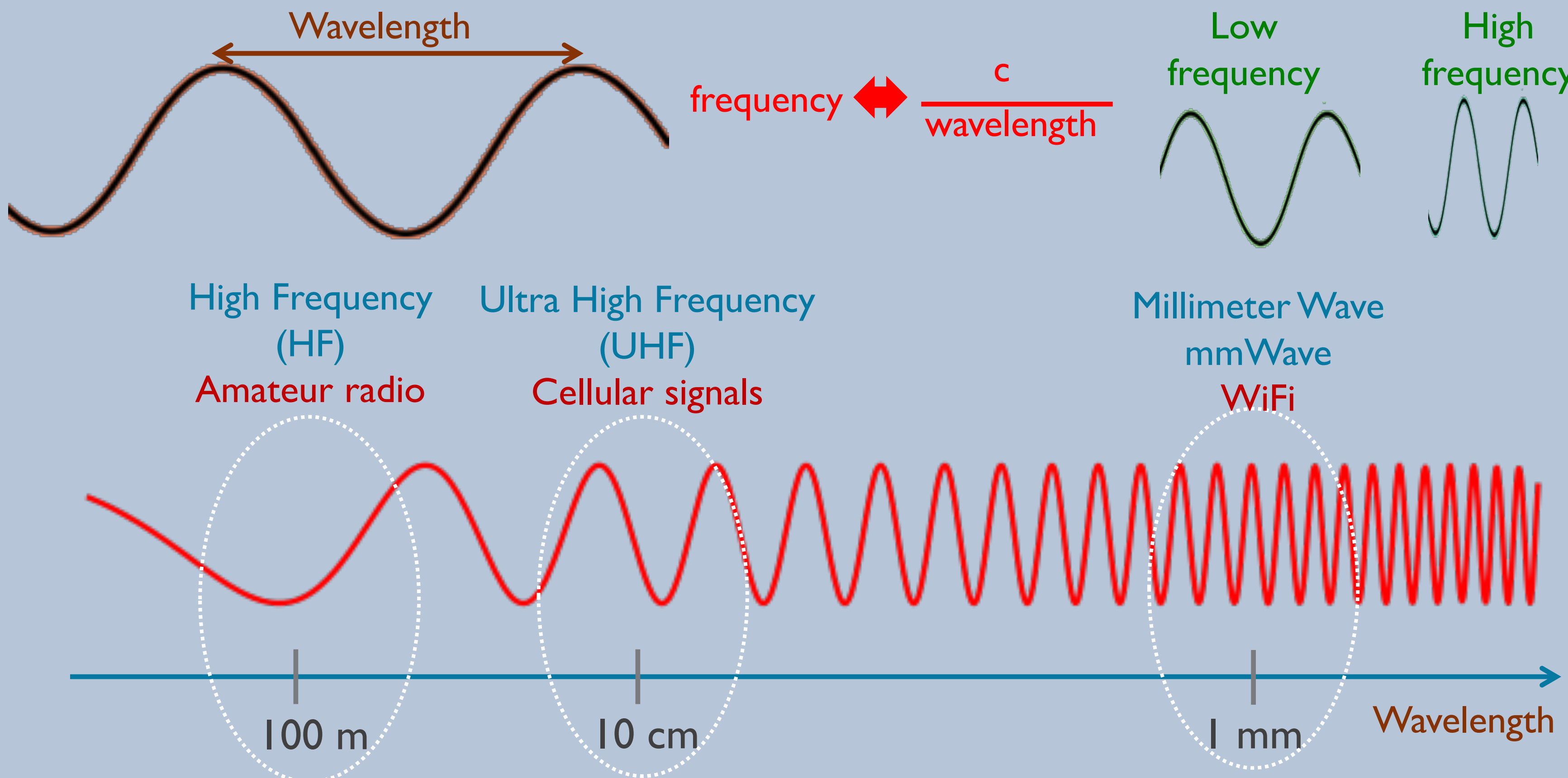


Wireless communication



Wireless systems send information using radio frequency signals

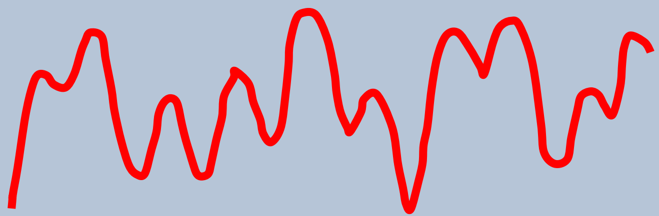
Frequency and wavelength



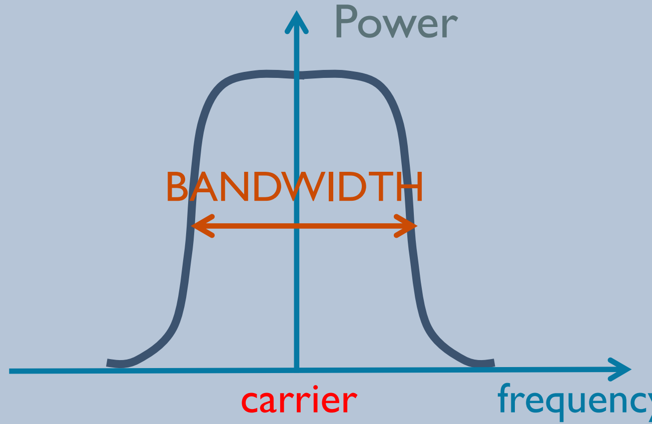
Wireless communication occurs and different frequencies

Carrier and bandwidth

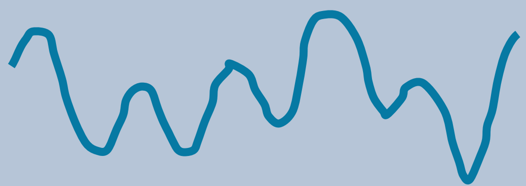
Information rides on
fluctuations of the carrier



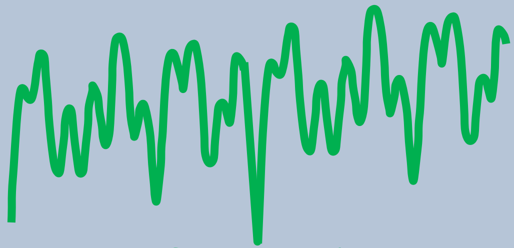
Fluctuations carry
different frequencies



More rapid fluctuations
consume more bandwidth



Less fluctuations,
lower bandwidth

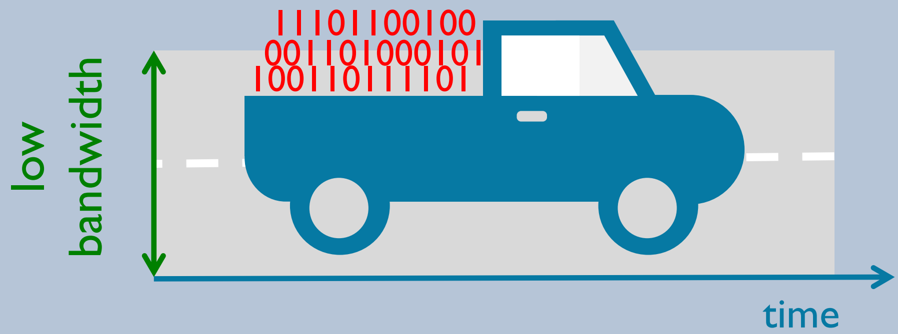


More fluctuations,
higher bandwidth

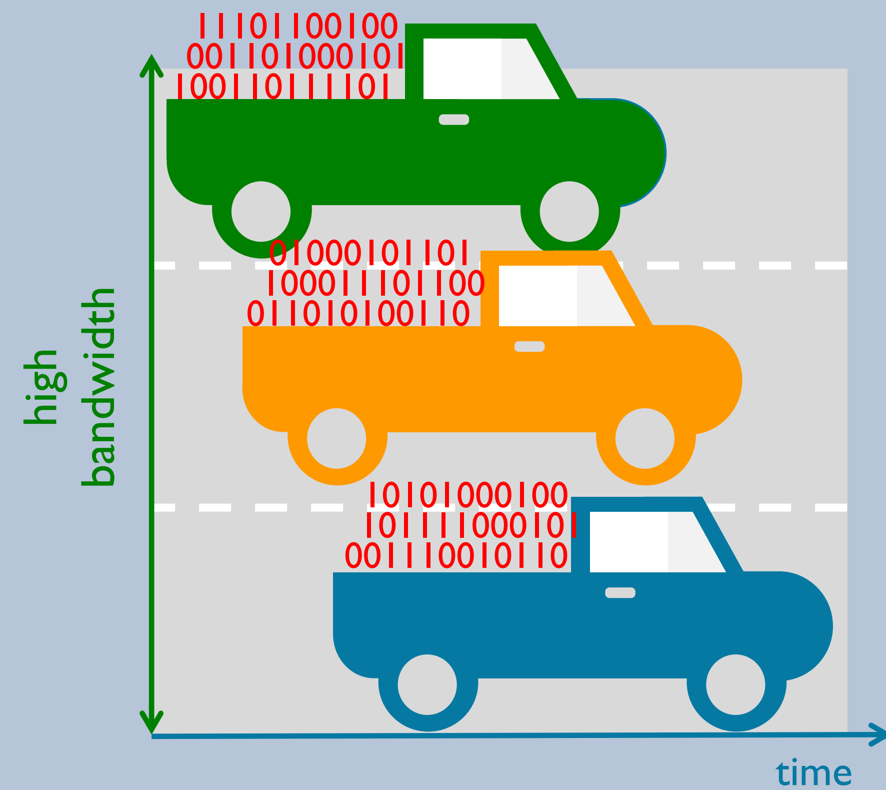
Bandwidth is the basic resource in a communication system

Data rate

low bandwidth → few bits per second

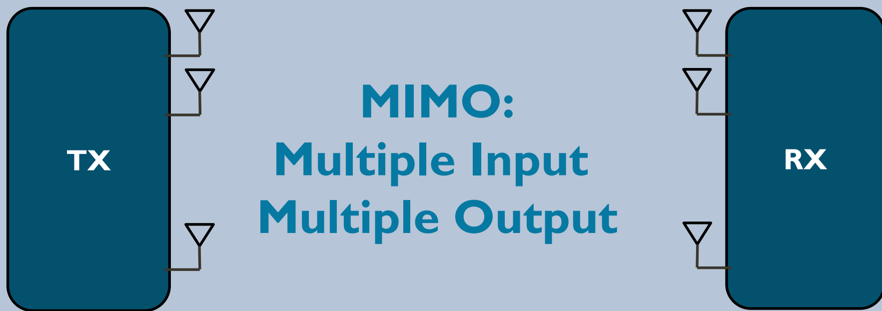


high bandwidth → many bits per second

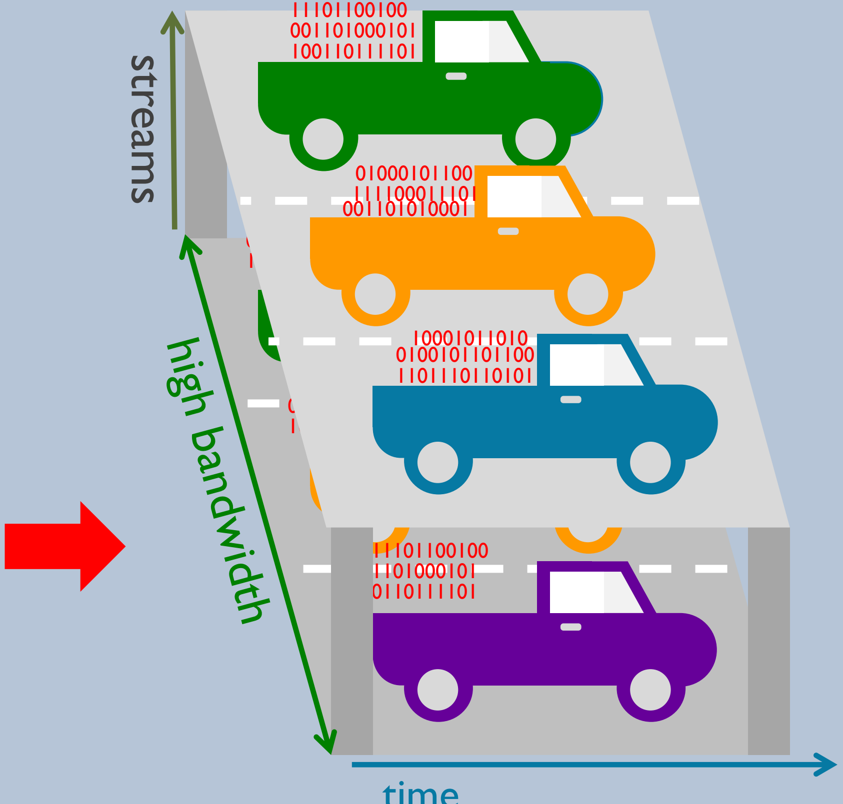


The higher the bandwidth, the higher the data rate the system can achieve

Wireless systems can also exploit multiple antennas

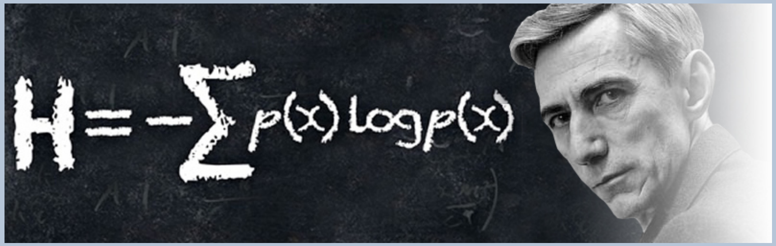


Multiple antennas enable transmission of several parallel data streams using the same frequency resources



MIMO spatial multiplexing makes better use of bandwidth

What influences the rate experienced by a user?



Claude Shannon
Inventor of Information Theory

MIMO spatial multiplexing gain depends on the number of antennas in the system

$$\textbf{rate per user} = \frac{\text{bandwidth} \times \text{MIMO}}{\#\text{ of users}} \times \text{spectral efficiency}$$

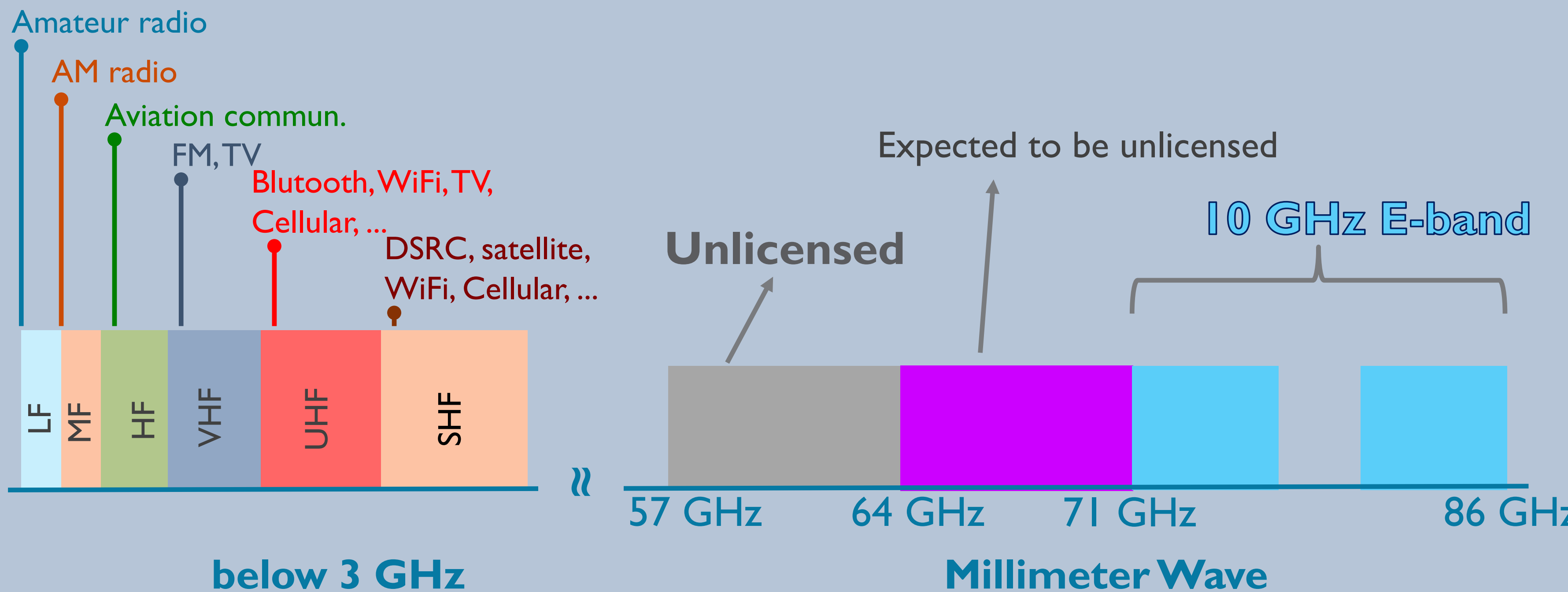
(bits per second)

Depends on signal power, noise power and interference power, improves with interference cancellation

Bandwidth is the easiest leverage for higher data rates

Millimeter wave spectrum

Spectra below 3 GHz is packed and $$/Hz of bandwidth is huge



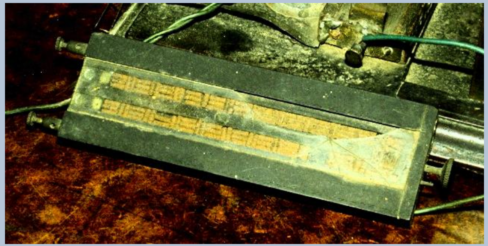
Lots of potential spectrum available at mmWave for consumer applications currently used for backhaul or legacy systems

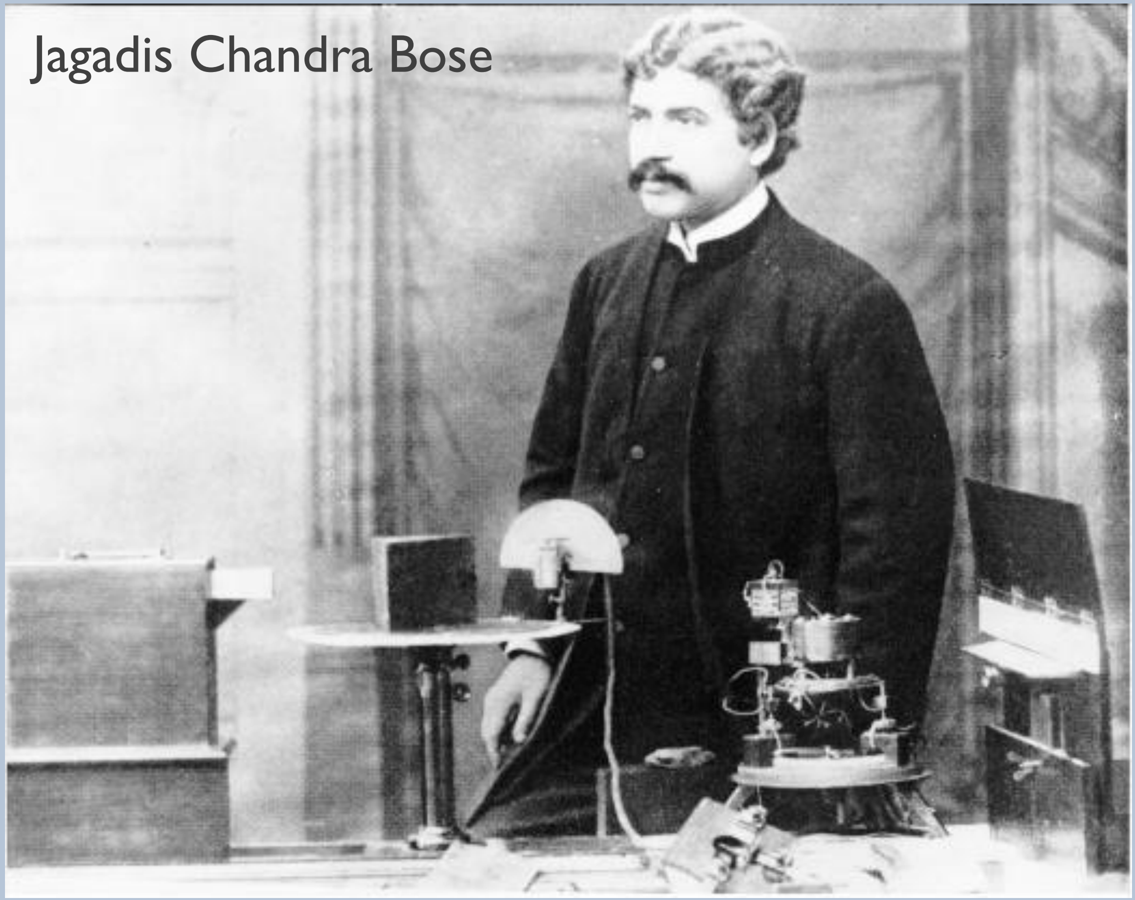
First millimeter wave experiments

Transmitter antennas

* Pictures from D. T. Emerson, “The work of Jagadis Chandra Bose: 100 years of millimeter-wave research”, IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 45, NO. 12, DECEMBER 1997

Radiation receiver

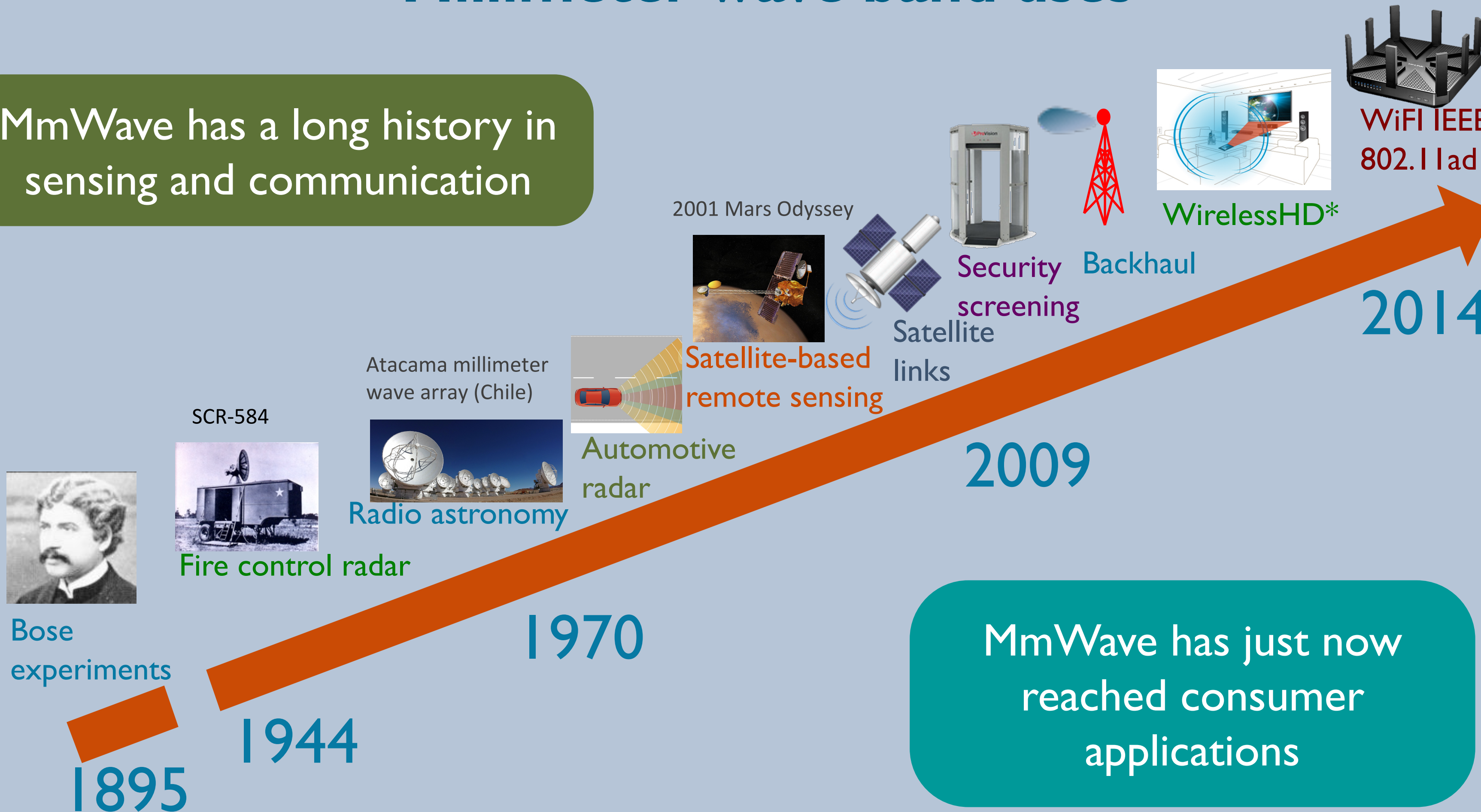




First mmWave experiments were undertaken more than 100 years ago!

Millimeter wave band uses

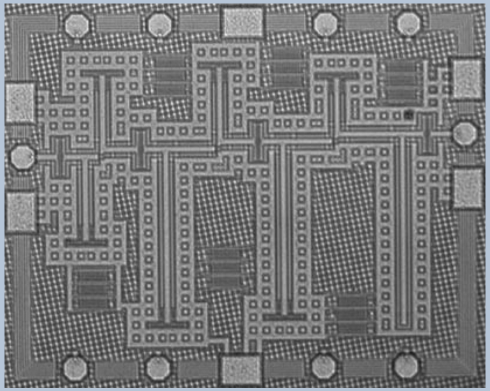
MmWave has a long history in sensing and communication



MmWave has just now reached consumer applications

*http://www.electronicdesign.com/communications/qa-exploring-millimeter-waves-new-breed-devices

Consumer challenge #1: device size and cost



0.87 x 0.70mm!

OKI 35V11 millimeter wave klystron[1,2]

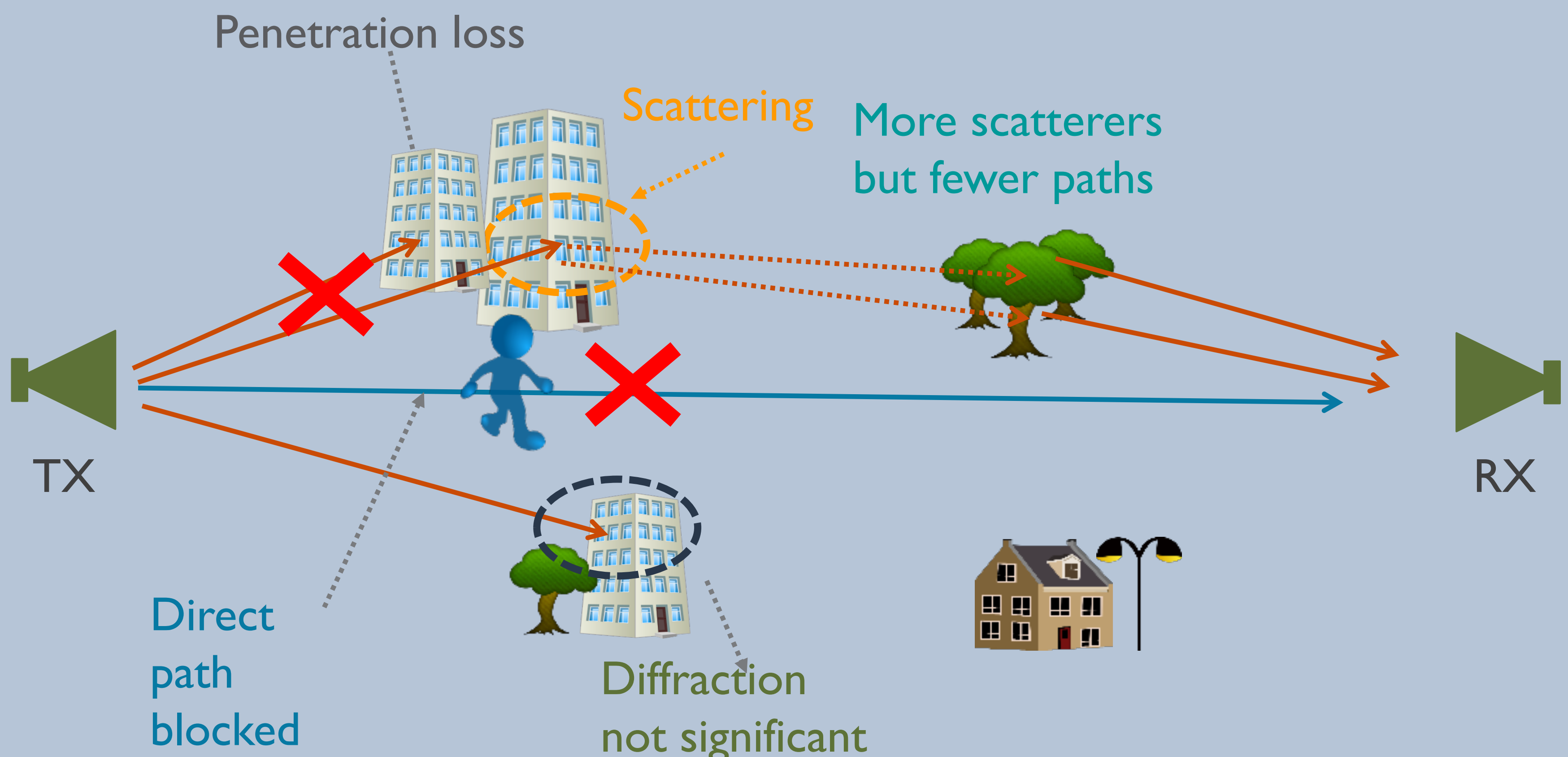
60 GHz amplifier, 2008[3]

[1] http://www.oki.com/en/130column/07.html
[2] R. True, "The Evolution of Microwave and Millimeter Wave Tubes", 2012

[3] M. Varonen, Mi. Kärkkäinen, M. Kantanen, and K. A. I. Halonen, "Millimeter-Wave Integrated Circuits in 65-nm CMOS," IEEE Transactions on Solid State Circuits, 2008

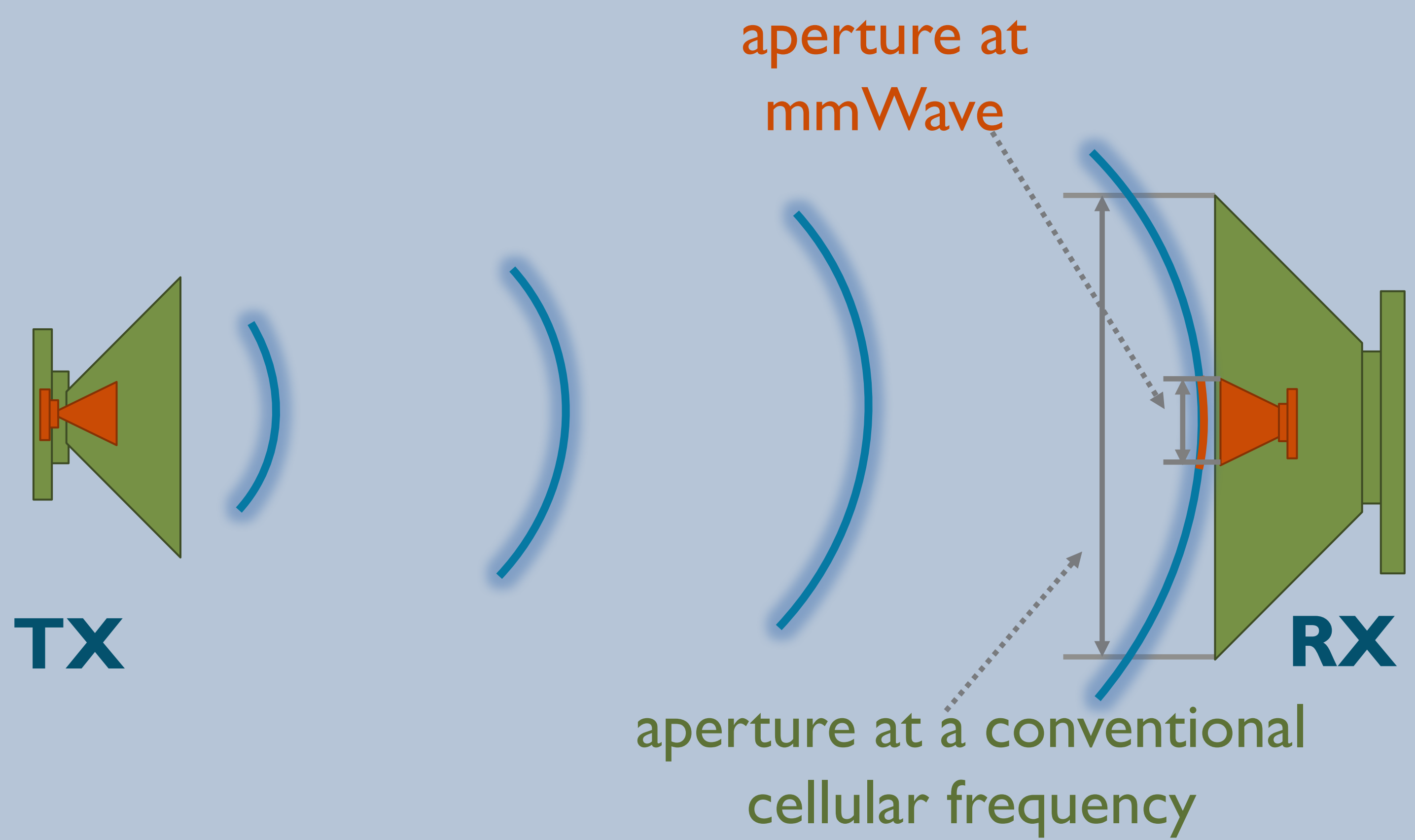
Until recently, mmWave devices were expensive, bulky, or made with expensive semiconductor processes

Consumer challenge #2: propagation effects



Propagation has not been well understood by systems engineers

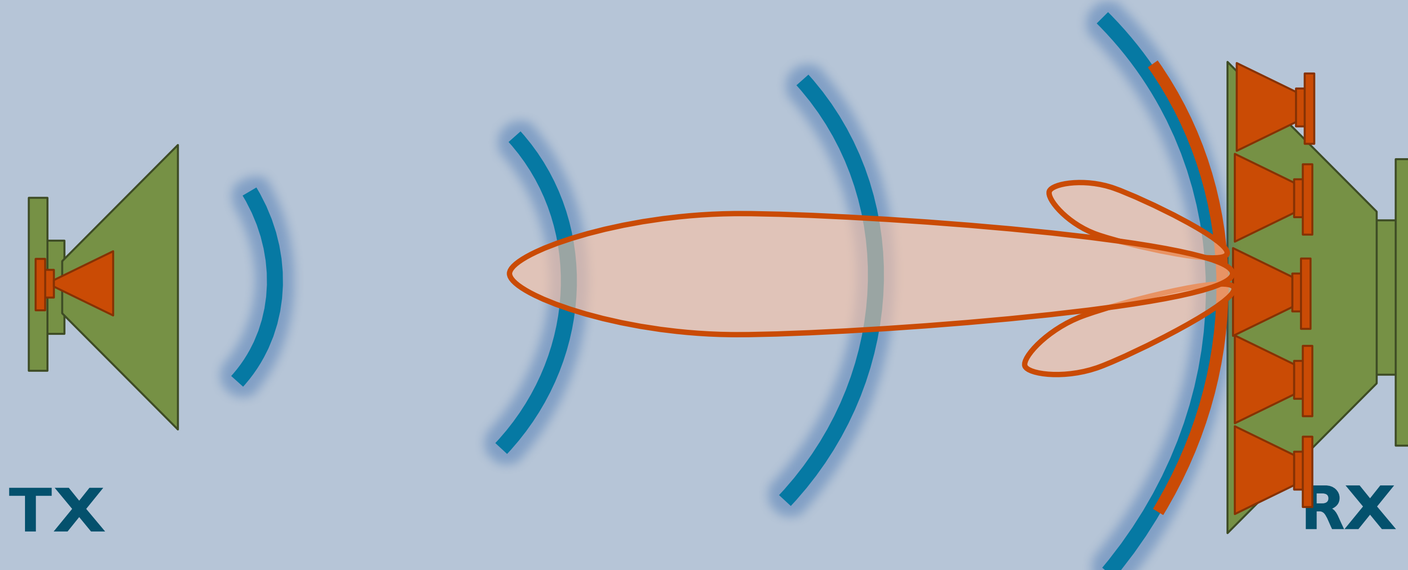
Consumer challenge #3: antennas become too small



Small antennas do not capture as much of the impinging wave

Making mmWave viable for consumers

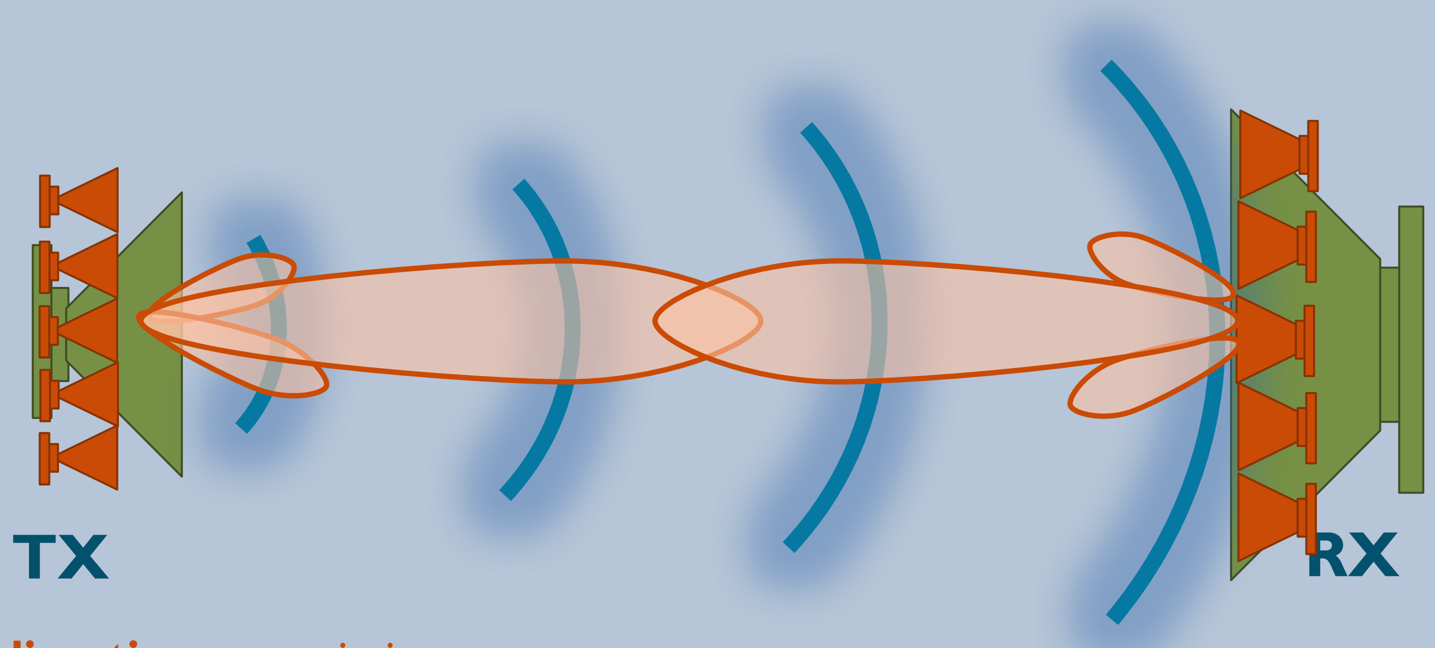
Idea 1: An antenna array at the receiver fixes shrinkage



highly **directive** reception
leads to **array gain**

Large antenna array captures the same amount of energy avoiding the misconception that losses increase with frequencies

Idea 2: An antenna array at the transmitter focuses energy



Beamforming at the transmitter adds additional array gain and reduces caused interference

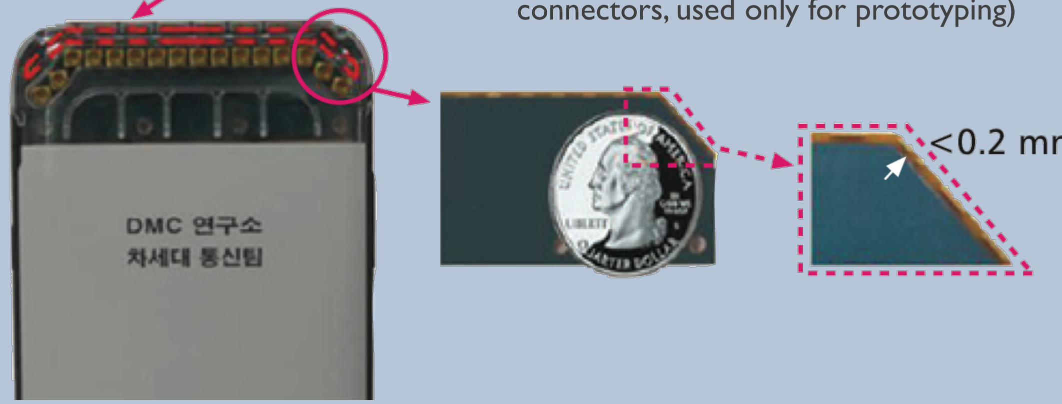
The antenna arrays are small at mmWave

antennas are about 10 mm

Samsung Galaxy S7*

16-element array 1

(the large objects are antenna connectors, used only for prototyping)



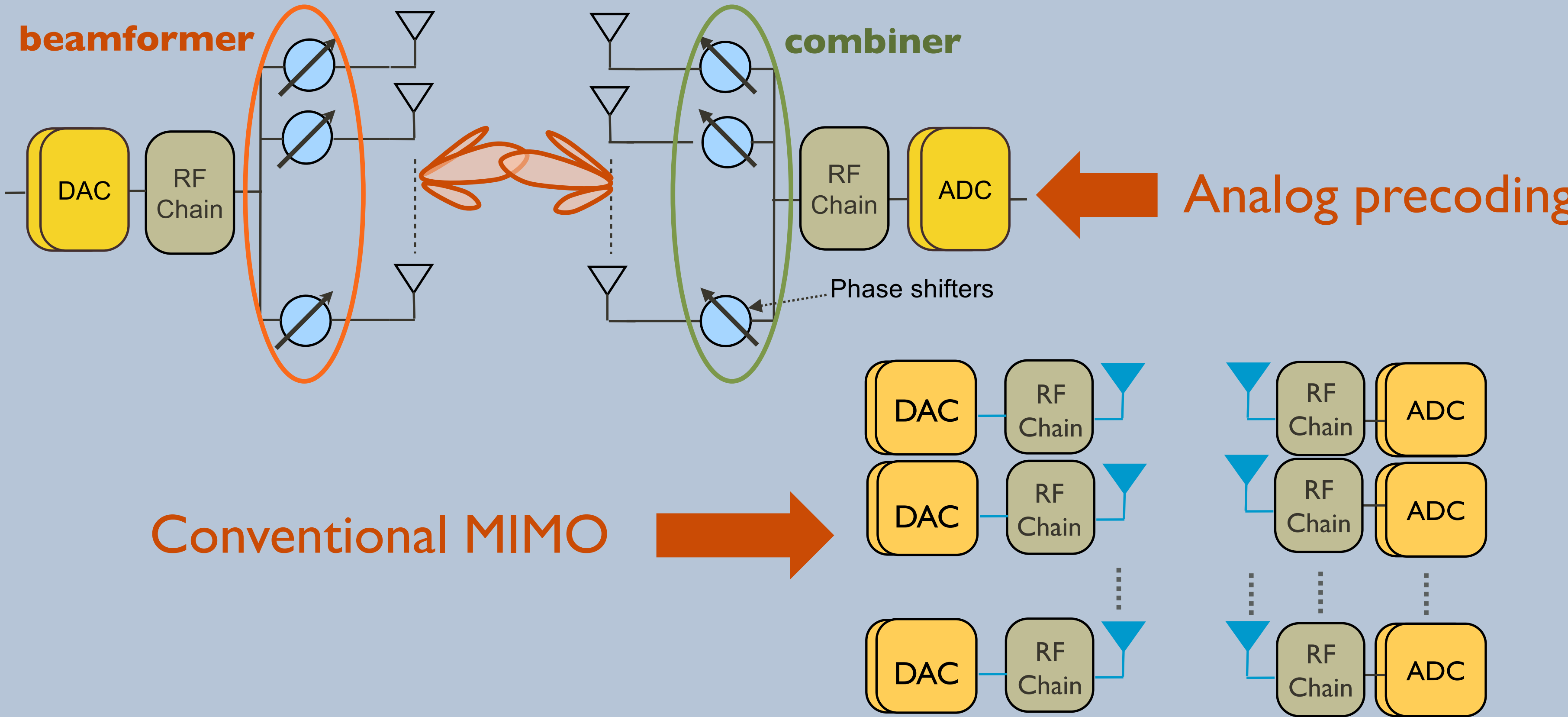
Mockup of a Galaxy with mmWave**

Base station may have 64 to 512 antennas

Mobile station may have 4 to 32 antennas

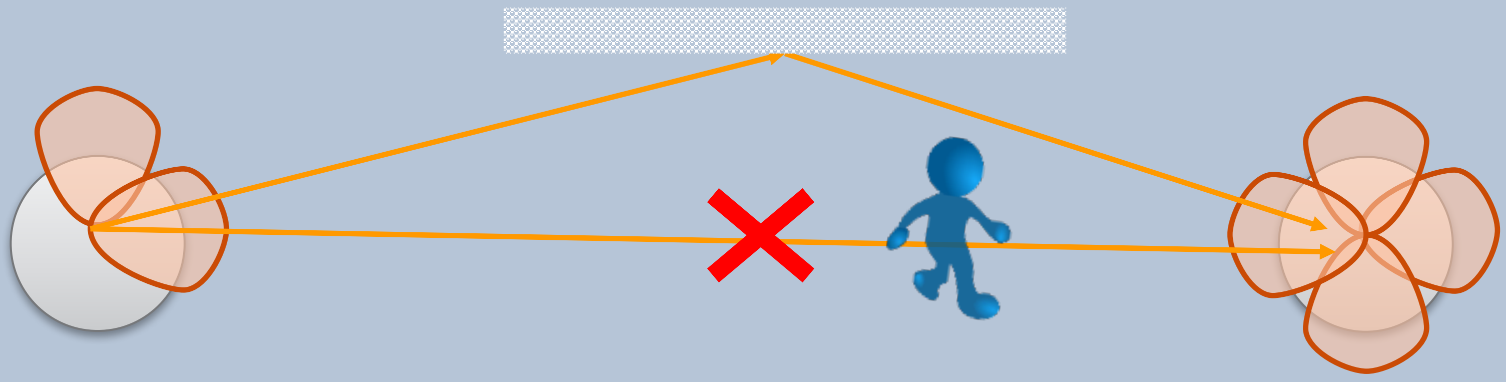
[1] From https://www.ifixit.com/Teardown/Samsung+Galaxy+S7+Teardown/56686
[2] W. Roh et al. "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," in *Communications Magazine, IEEE* , vol.52, no.2, pp.106-113, February 2014

Idea 3: Analog processing



Forming beams using analog components reduces the amount of RF hardware and subsequent baseband processing required

Idea 4: Beam training



TX sends training sectors on each RX sector

TX

RX

Antennas need to be adaptively pointed

Beam training finds the best beam pair over the air

Commercial mmWave applications

Sony wearable HDTV *

Talon Multi-Band Wi-Fi Router

Standard	Bandwidth	Rates	Approval
WirelessHD	2.16 GHz	3.807 Gbps	Jan. 2008
WirelessHD 1.1	2.16 GHz	4 x 7.138 Gbps	Jan. 2010
IEEE 802.11ad	2.16 GHz	6.76 Gbps	Dec. 2012

Zyxel AeroBeam HDTV kit *

Epson projector *

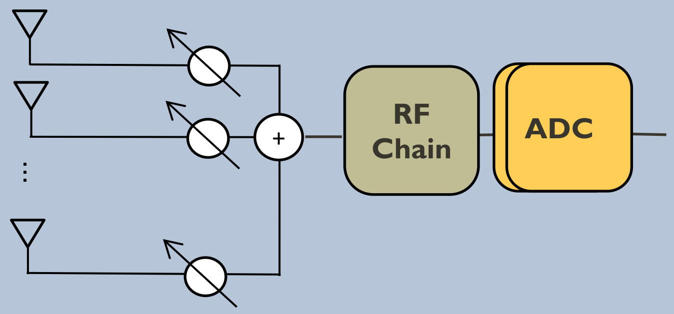
Dell Laptop *

Current standards for personal networks and WiFi support arrays and beam training

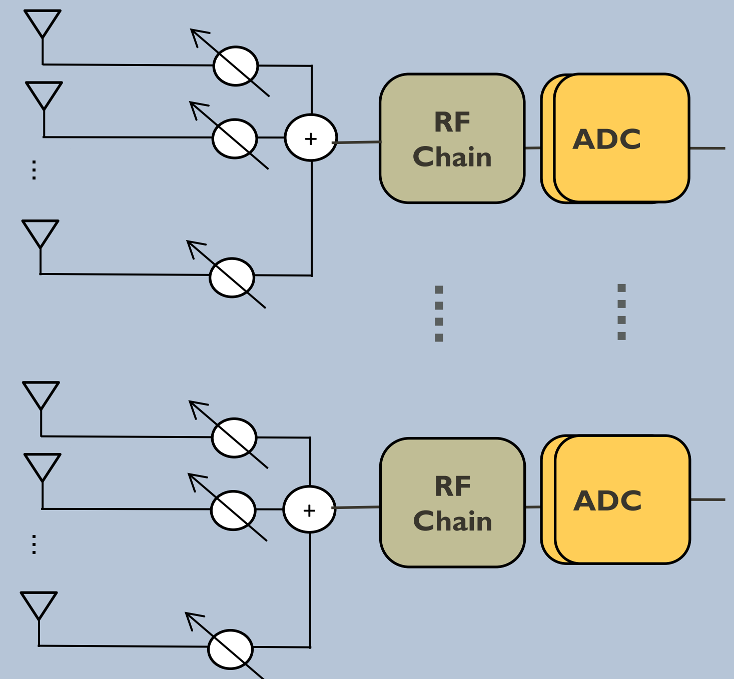
* http://www.wirelesshd.org/consumers/product-listing/

Bringing mmWave to 5G and beyond

Taking advantage of MIMO processing



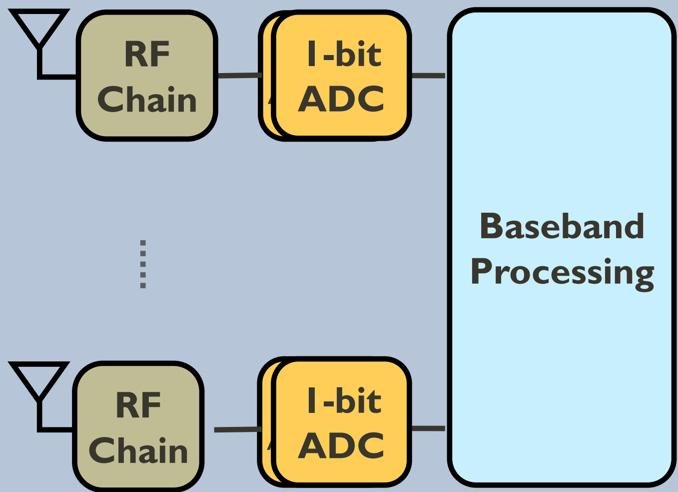
Analog precoding

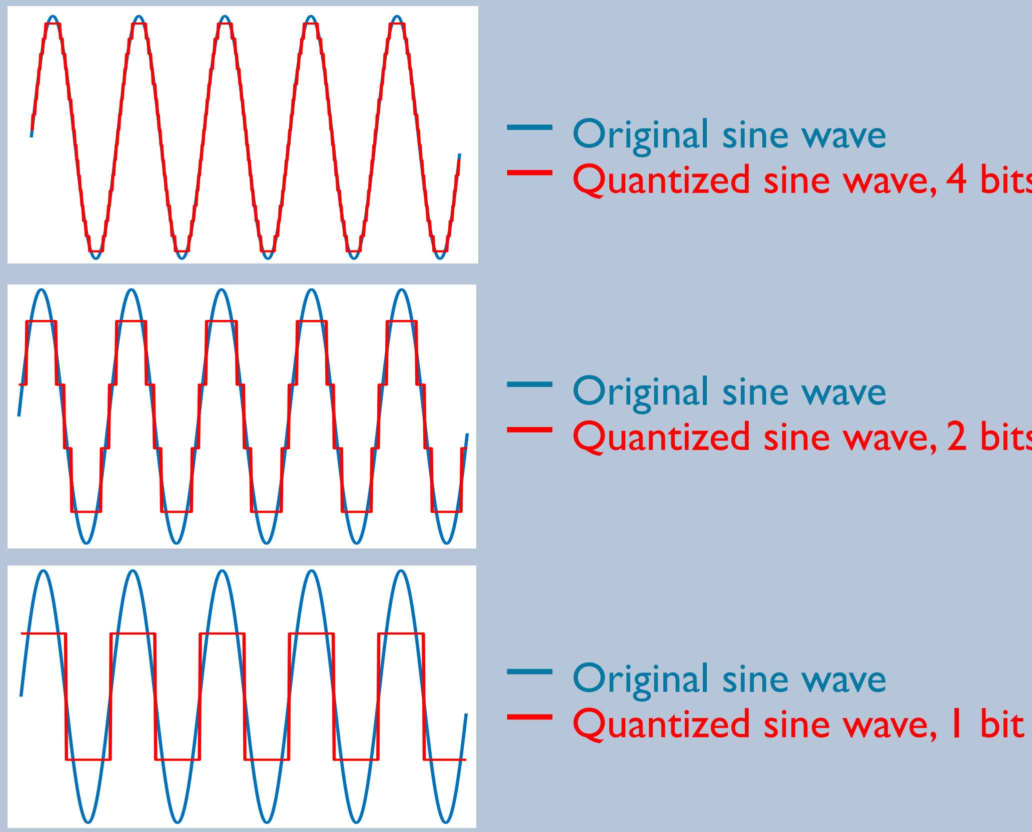


Hybrid precoding

Hybrid precoding enables multi stream transmission with low power, but requires changes in conventional MIMO algorithms

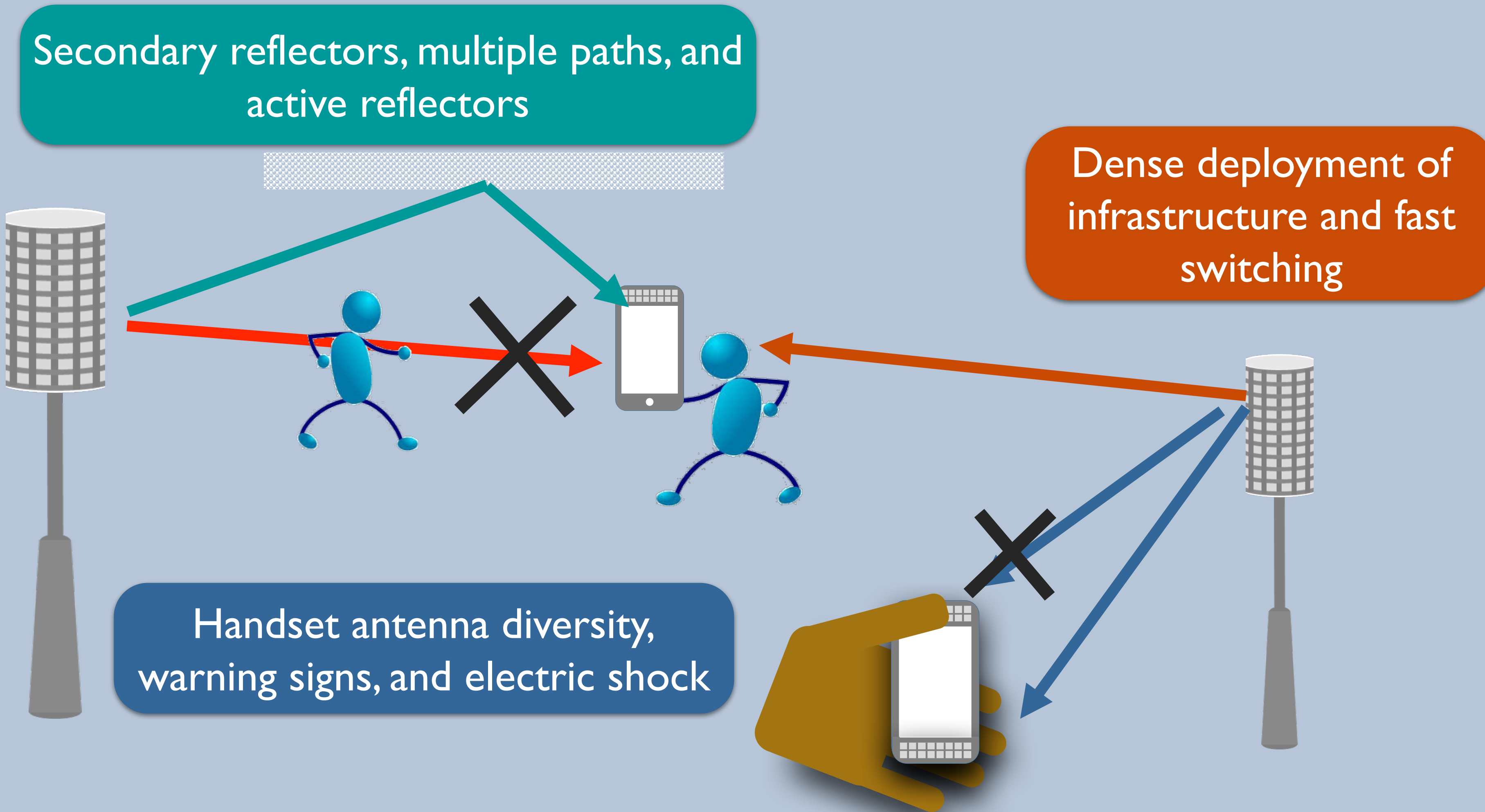
Reducing resolution in data converters





Higher levels of quantization dramatically reduce power consumption, but require new algorithms that can deal with extra distortion

Overcoming different types of blockage

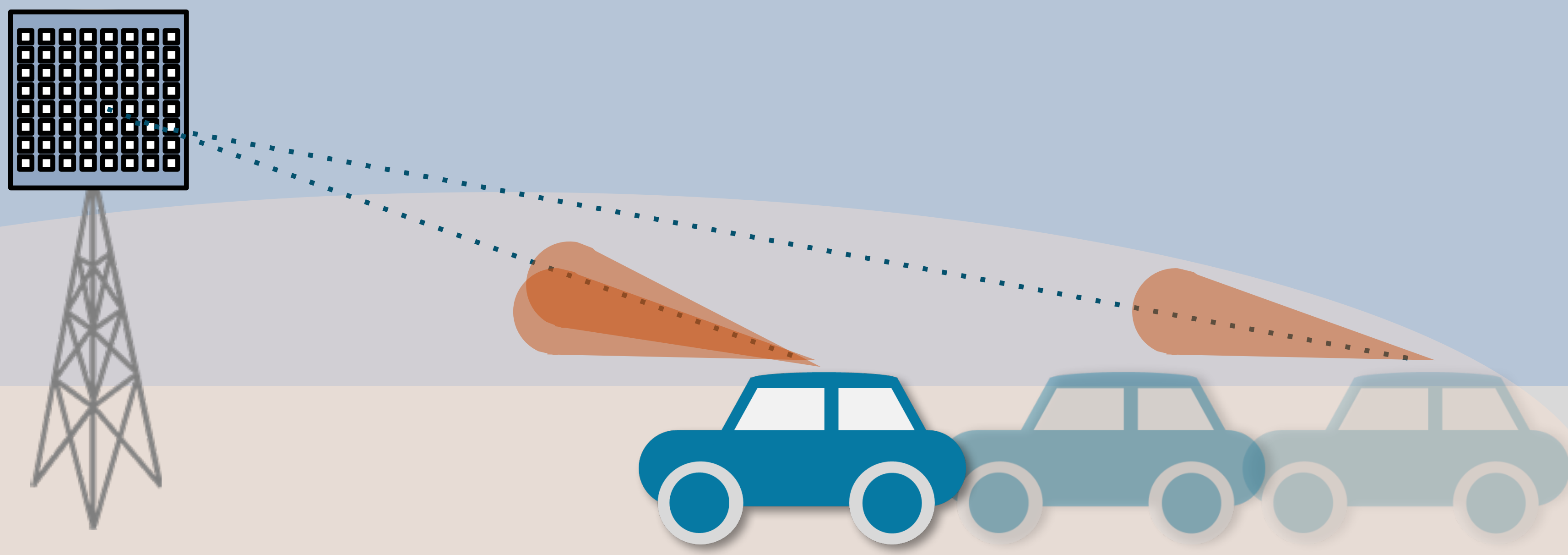


Alternatives to conventional beam training

Simultaneously sampling from multiple spatial directions

Exploit the fact that there are a few good paths via compressive sensing

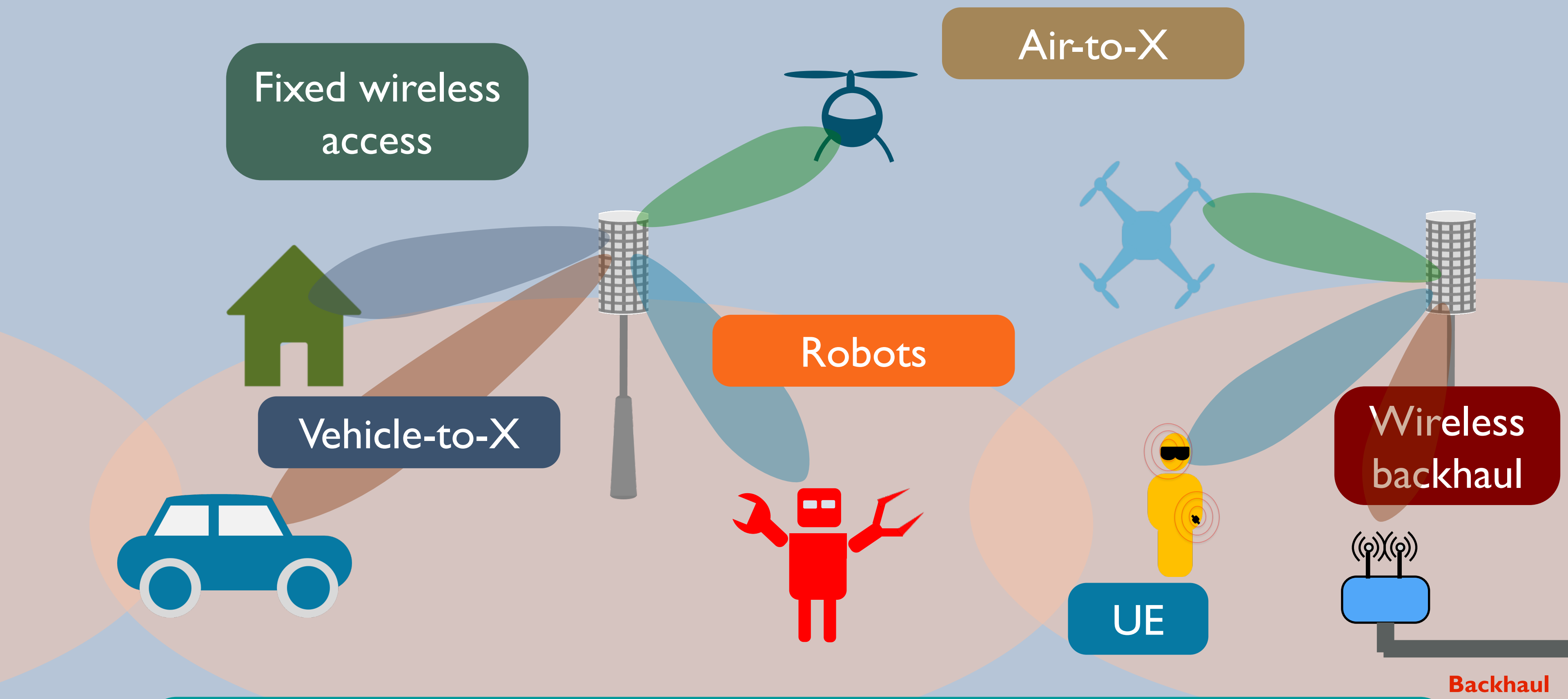
Adaptive reconfiguration in high mobility



Leverage out-of-band information, multi-band communication, position, sensors, and machine learning to reduce overheads during beam reconfiguration

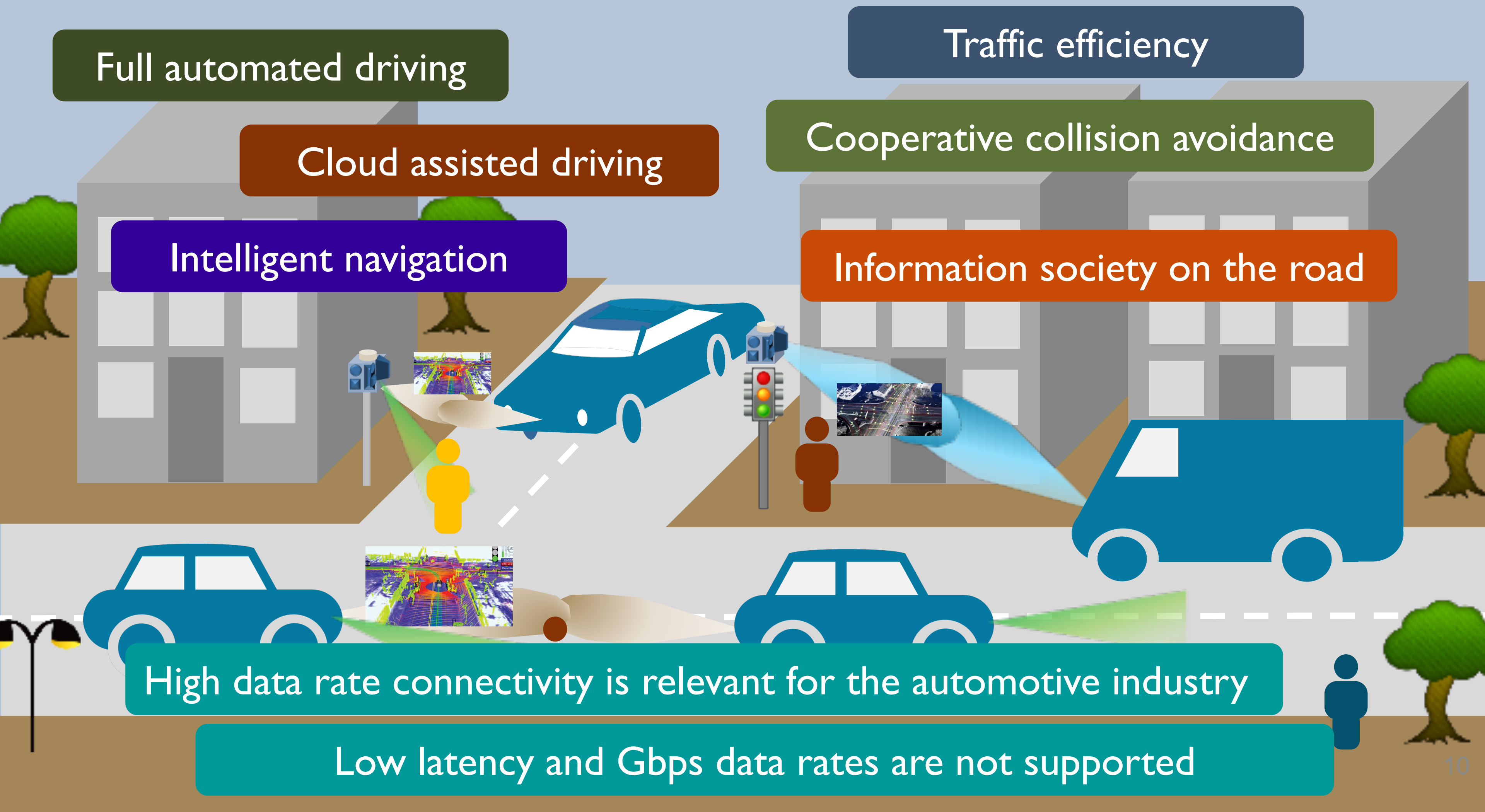
Disruptive applications

5G cellular networks will exploit mmWave

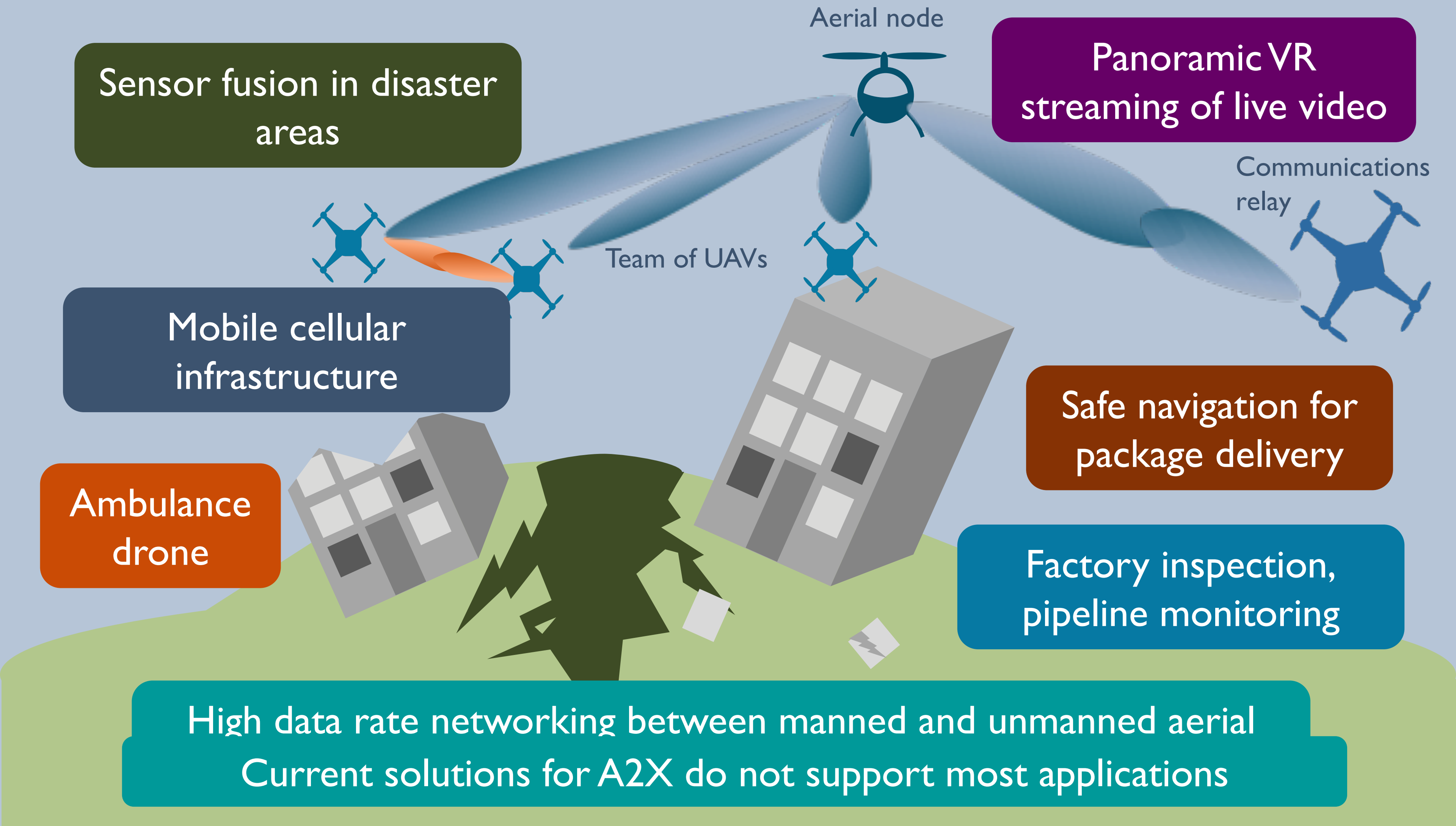


5G @ mmWave will provide high data rate connectivity for different types of applications

Vehicle-to-everything (V2X) communication



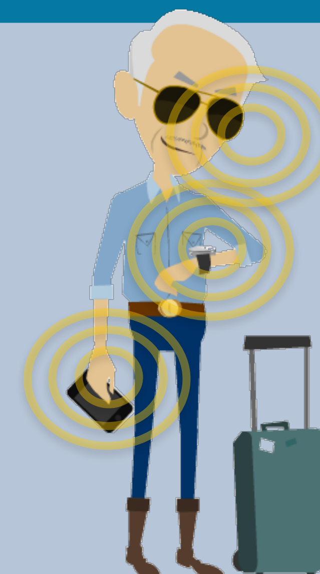
Communications for aerial vehicles



People (going beyond smart phones)

Virtual reality: high-resolution multi-view video in real-time

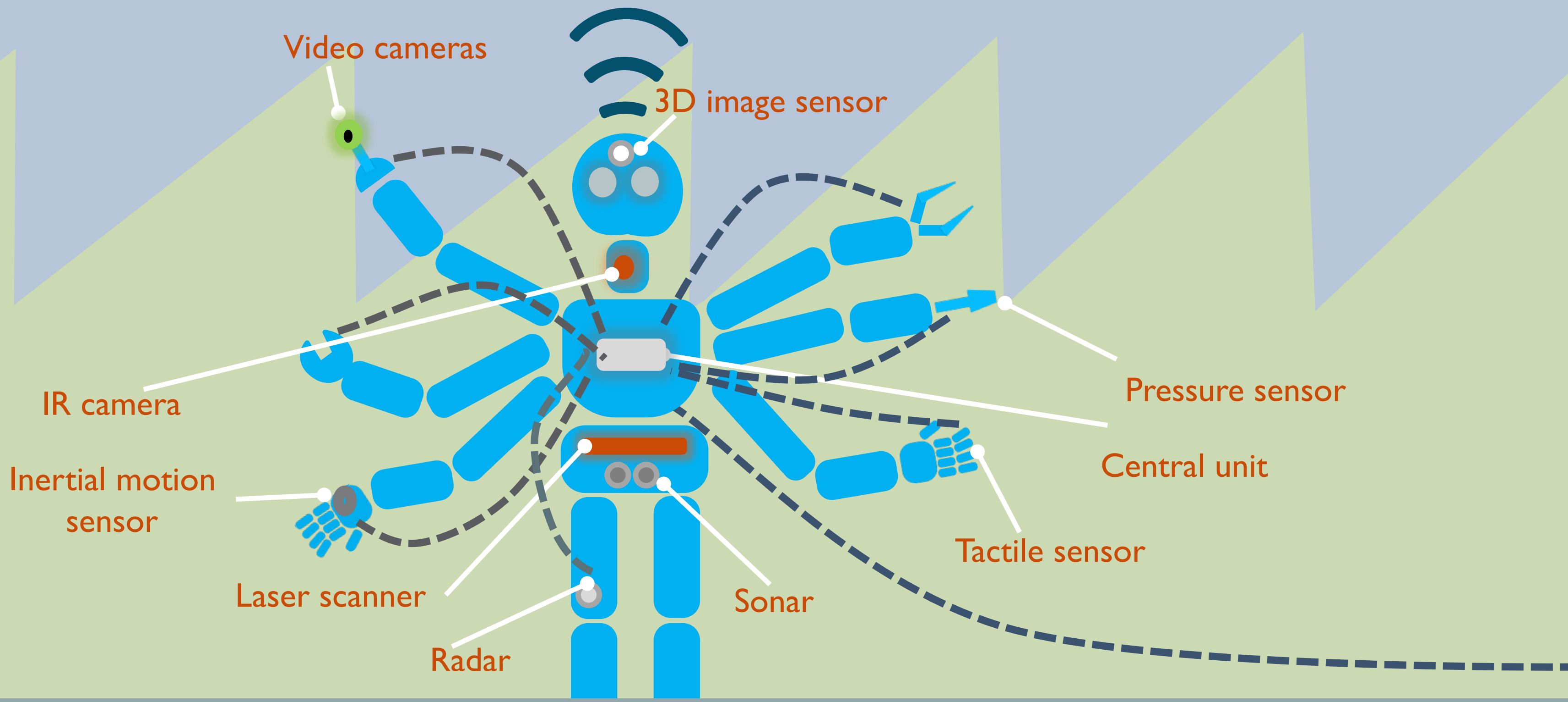
Wearable networks: multiple communicating devices in and around the body (>5 according to market trends)



Augmented reality: real-time overlay of information

High data rates are required for virtual and augmented reality and wearable networks

Connected robots



Questions?

www.profheath.org
www.utsaves.org
www.wncg.org
www.ece.utexas.edu

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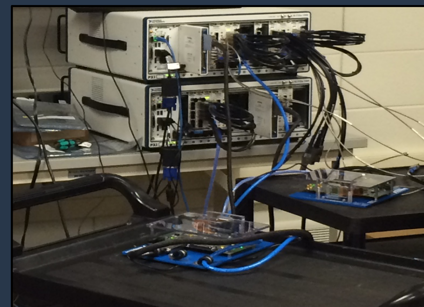
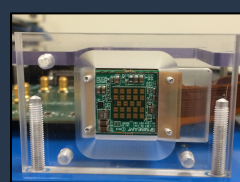
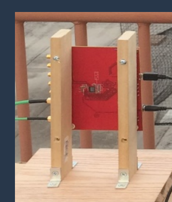
MmWave communication prototyping



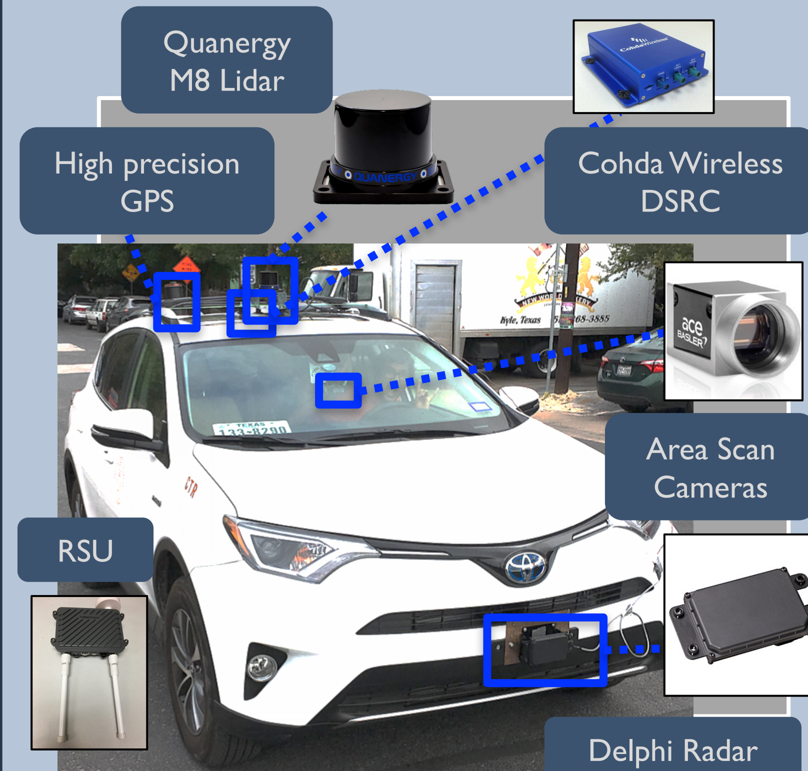
State of the art research platform





Phased array platforms

Sensors and communication equipment for V2X



Three different type vehicles