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Millimeter Wave for 5G

Finding a New Spectrum Mother Load

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www.profheath.org

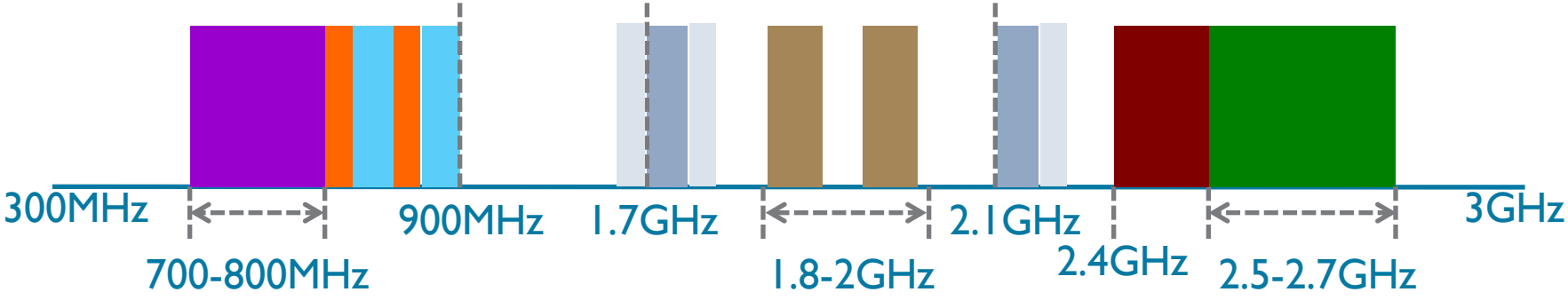
Current cellular spectrum in US

Total available bandwidth = ~600MHz

700MHz auctioned in 2008
- $18,957,582,150
- 1090 licenses

AWS-3 auctioned in 2015
- $41,329,673,325
- 1611 licenses

: CLR
: PCS
: AWS-1
: AWS-3
: 700 MHz
: 800 MHz
: Unlicensed
: BRS/EBS

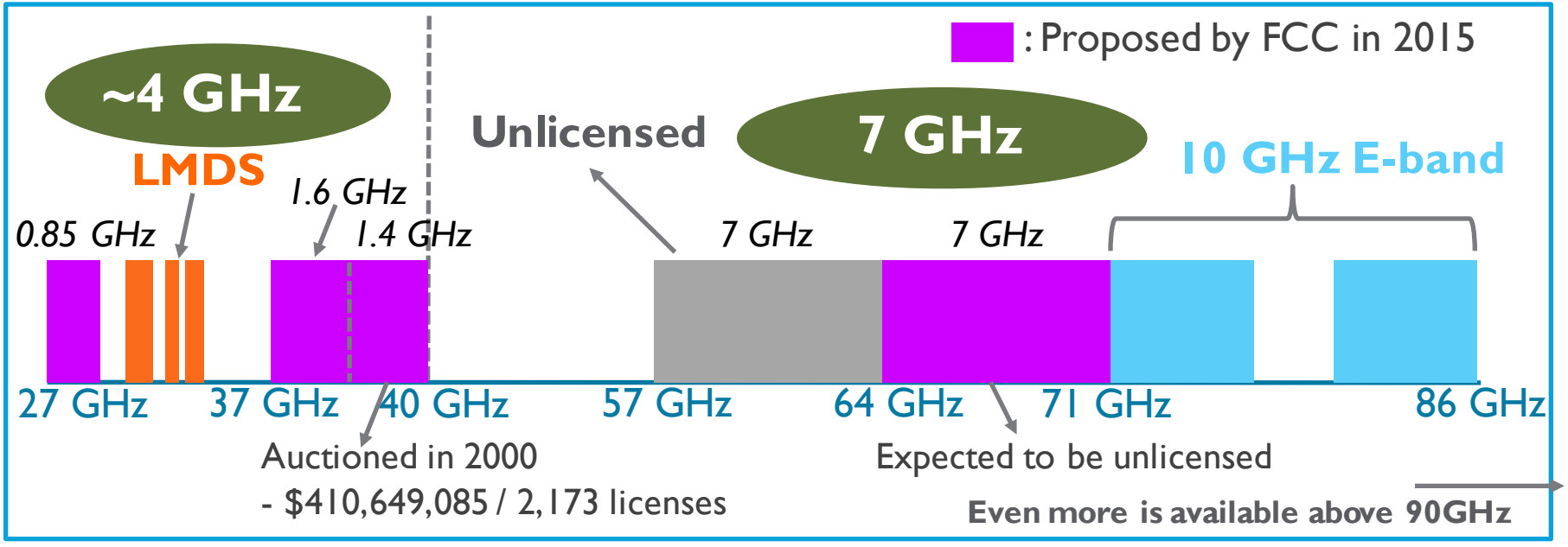


- Spectra below 3 GHz is packed and $$/Hz of bandwidth is huge

See e.g. http://wireless.fcc.gov/auctions/default.htm?job=auction_summary&id=73

To get more bandwidth, need to go to higher carrier frequencies

Future cellular spectrum could be in the mmWave bands (30GHz to 300GHz)

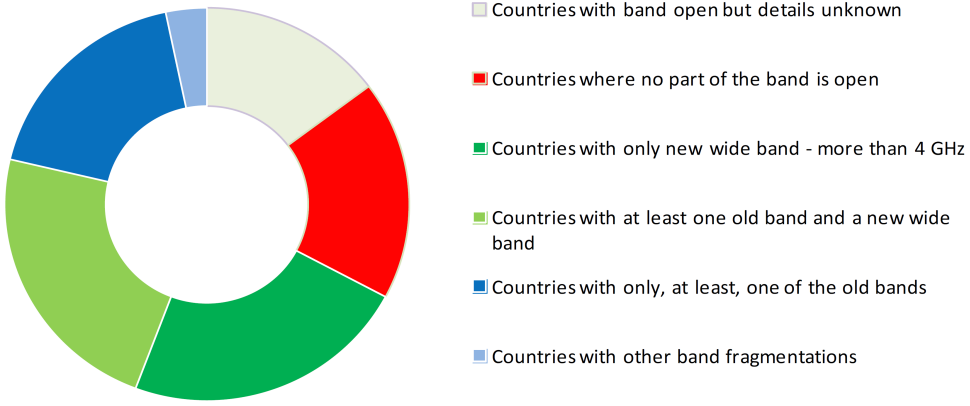


- Lots of potential spectrum currently used for backhaul or legacy systems
- Different licensing options available for many bands

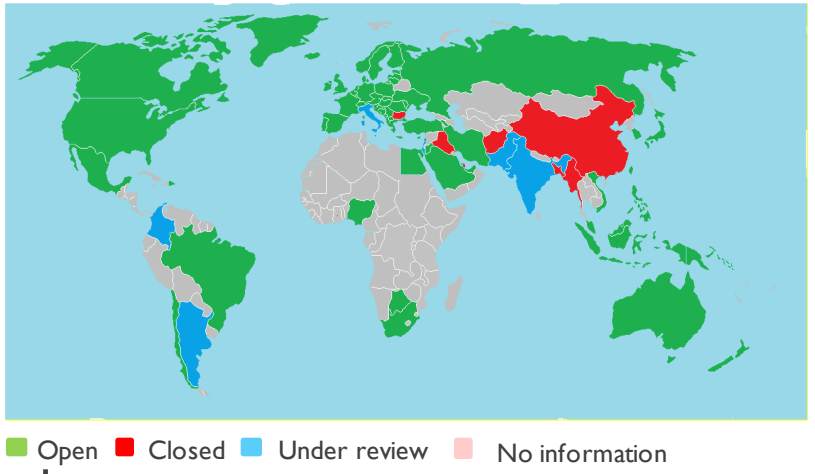
Spectrum for 5G is ready!!!

MmWave regulation worldwide

V-band



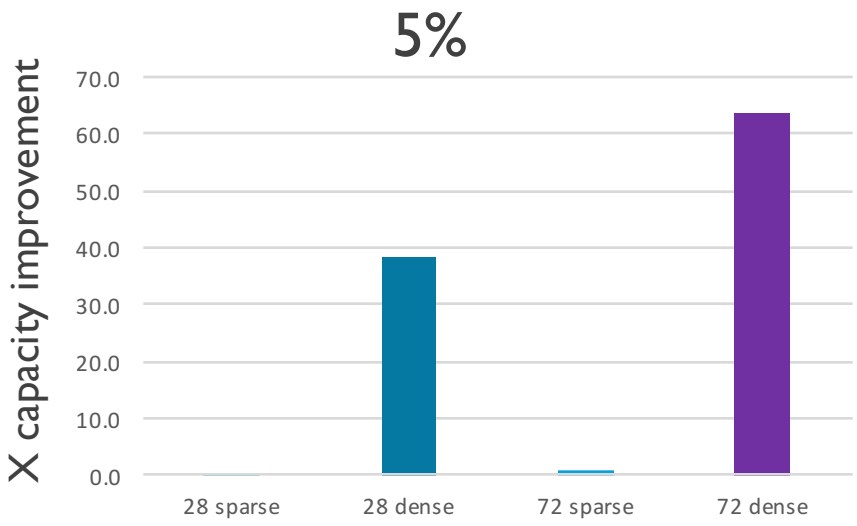
E-band

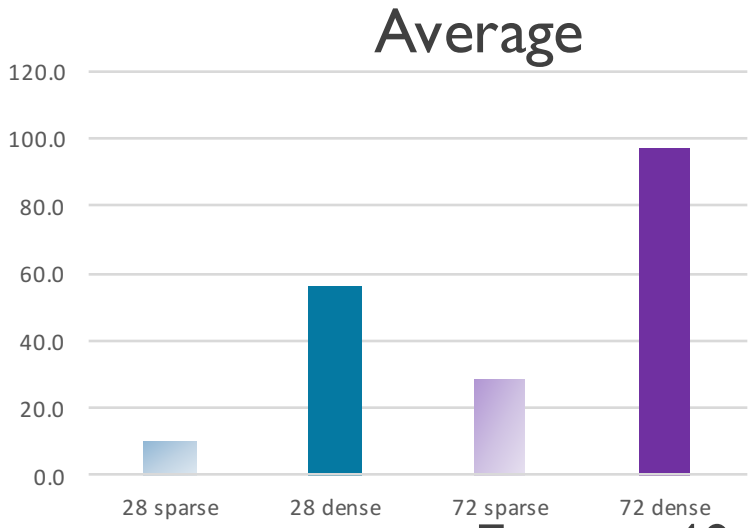


- Special interest on the V-band and the E-band
  - Fragmention of the V-band in many countries
  - FCC has just proposed rulemaking of mmWave bands for mobile cellular

Situation today is still not well harmonized

What are the potential rate gains with mmWave?





Baseline 2 GHz w/ 50 MHz BW

Upper cmWave 28 GHz: 500 MHz (expect 10x)

Expect 40x

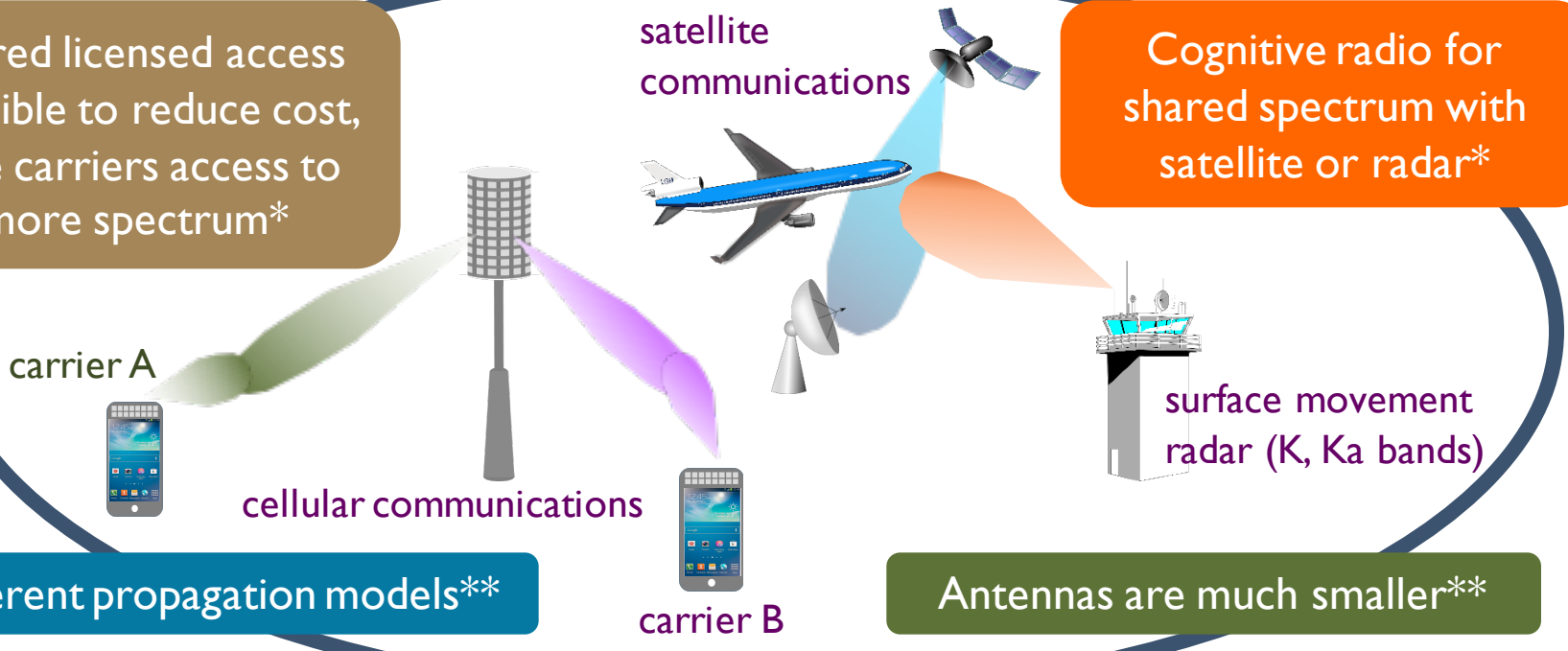
mmWave 72 GHz: 2 GHz (expect 40x)

MmWave gains are more than a spectrum multiplier

Implications of using millimeter wave spectrum

Shared licensed access possible to reduce cost, give carriers access to more spectrum*

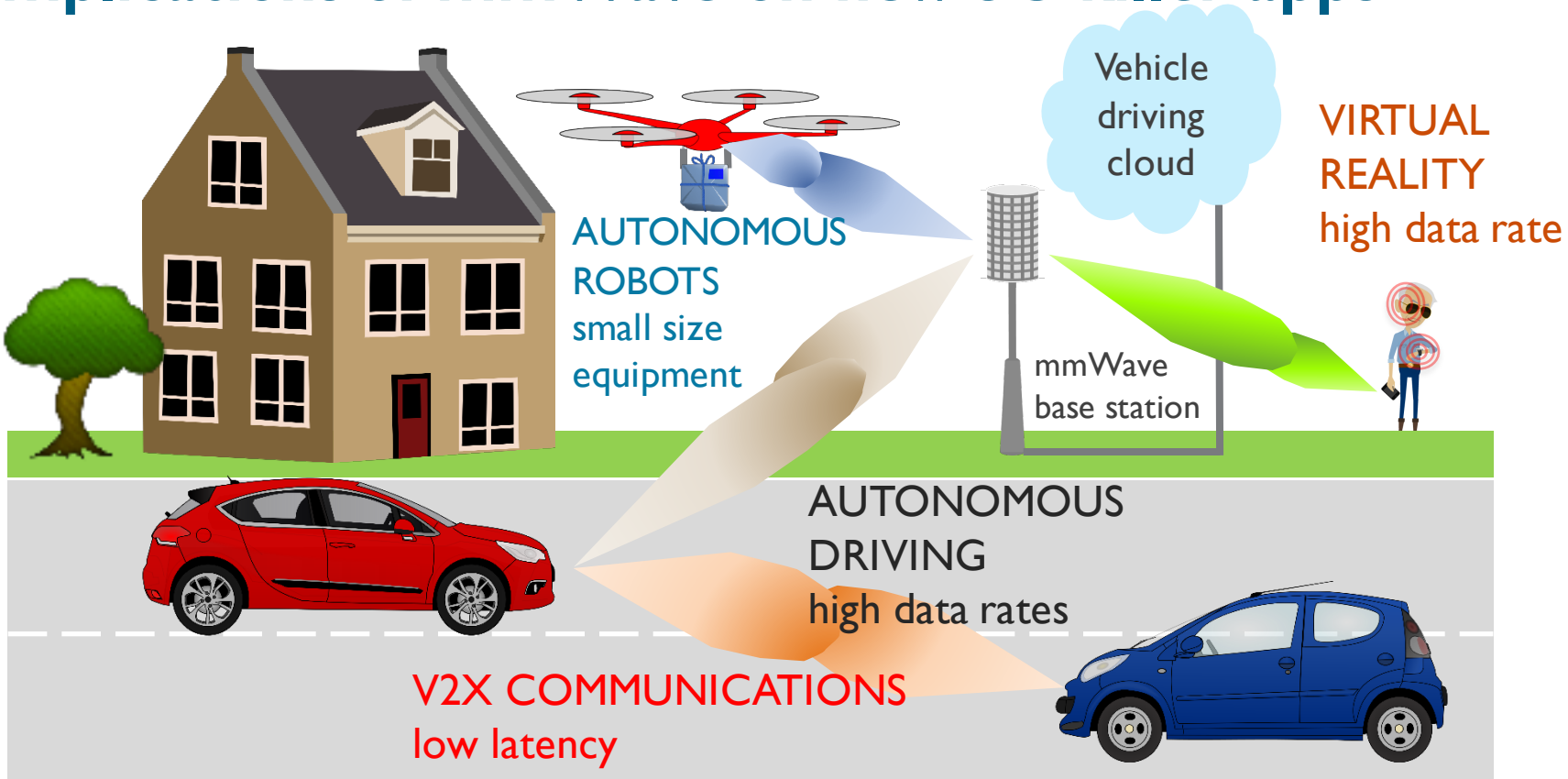
Cognitive radio for shared spectrum with satellite or radar*



Different propagation models**

Antennas are much smaller**

Implications of mmWave on new 5G killer apps

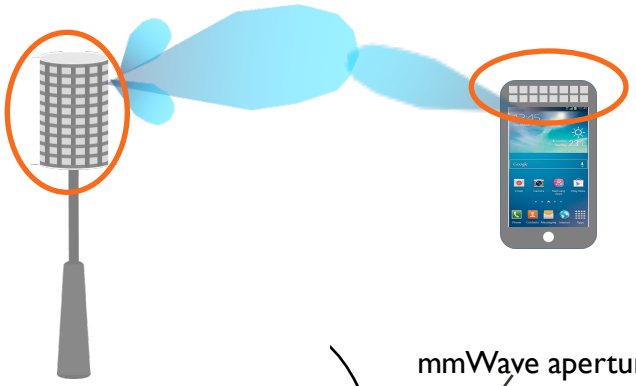


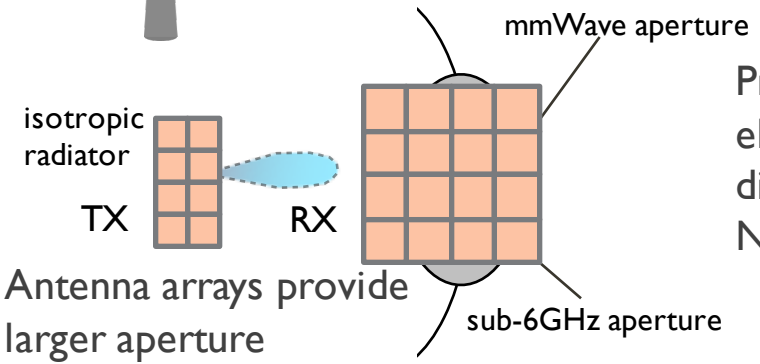
MmWave high data rates are required in different 5G scenarios

Differentiating features of mmWave

Directional and adaptive antenna arrays

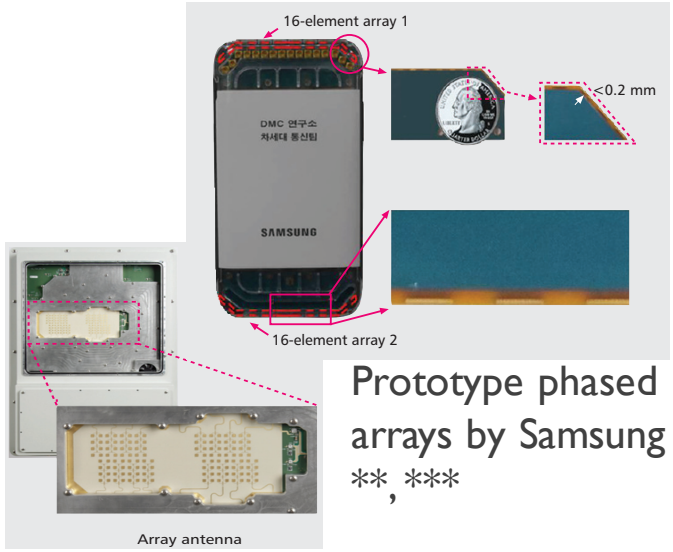
Use of directional and adaptive antenna arrays





Antenna arrays provide larger aperture

Prototype 64 element dielectric lens by Nokia*



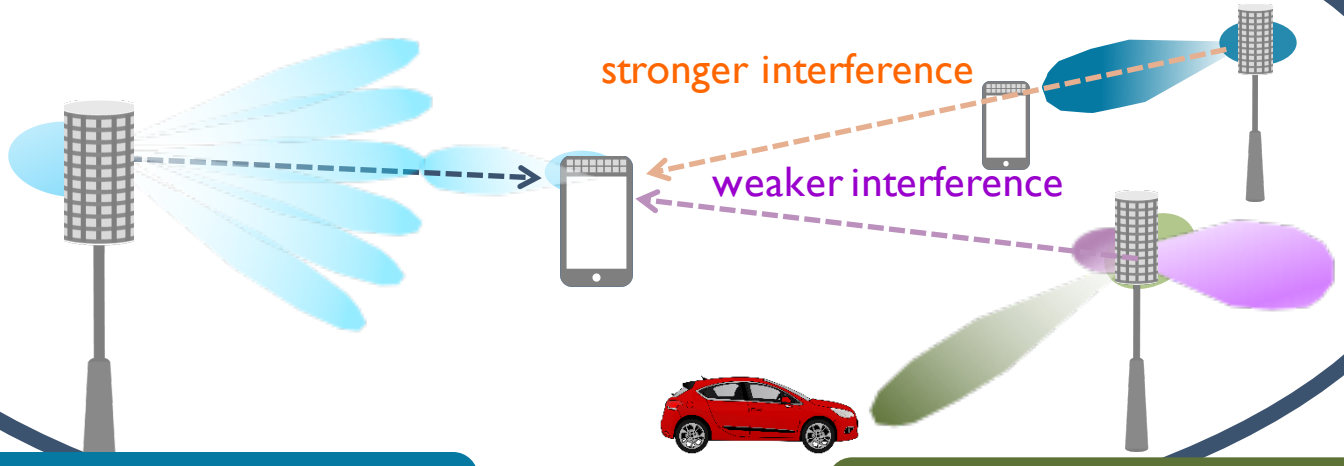
Prototype phased arrays by Samsung **, ***

Early mmWave devices will use simple adaptive beam steering

Implications of adaptive arrays

New antennas, cables, infrastructure, baseband

Interference is bursty, less severe



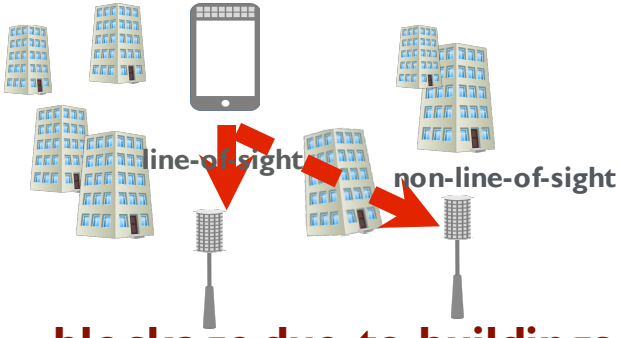
Configuring the link (beam pointing) is hard

Beams should not be too pointy due to mobility

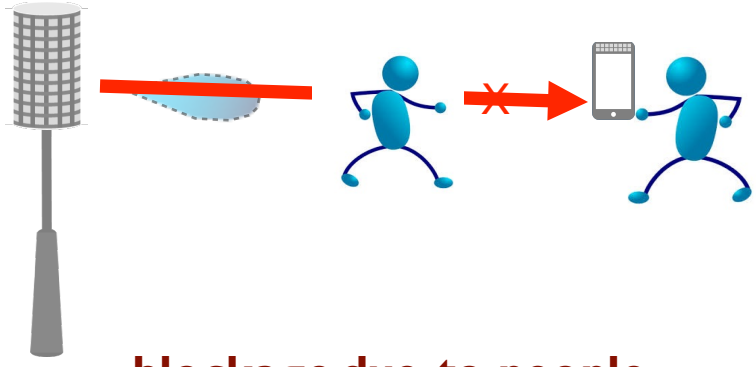
Differentiating features of mmWave

Blockage

Blockage is a major channel impairment



blockage due to buildings



blockage due to people

hand blocking

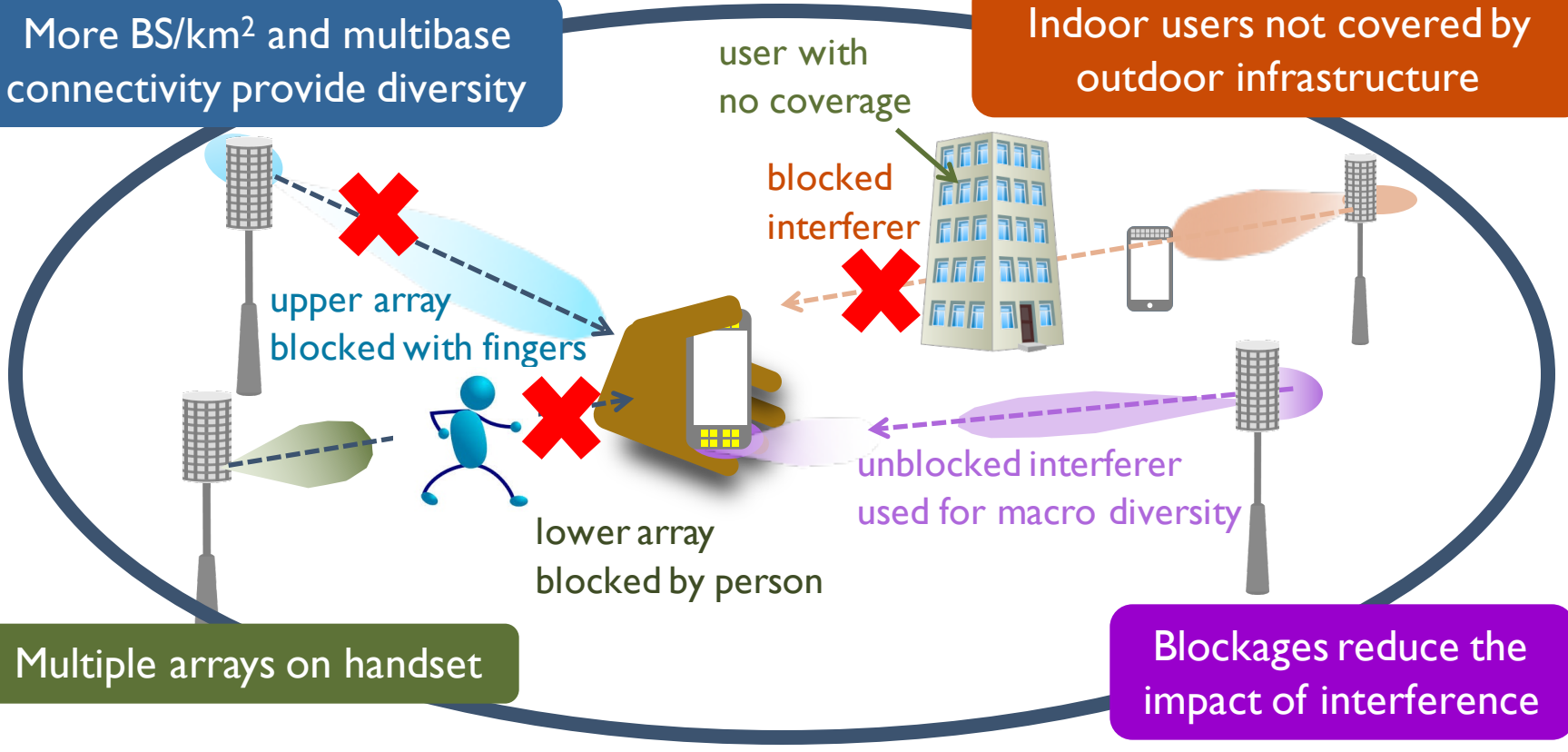
self-body blocking

Need models for blockage & system analysis including blockage

Implications of blockage

More BS/km^2 and multibase connectivity provide diversity

Indoor users not covered by outdoor infrastructure



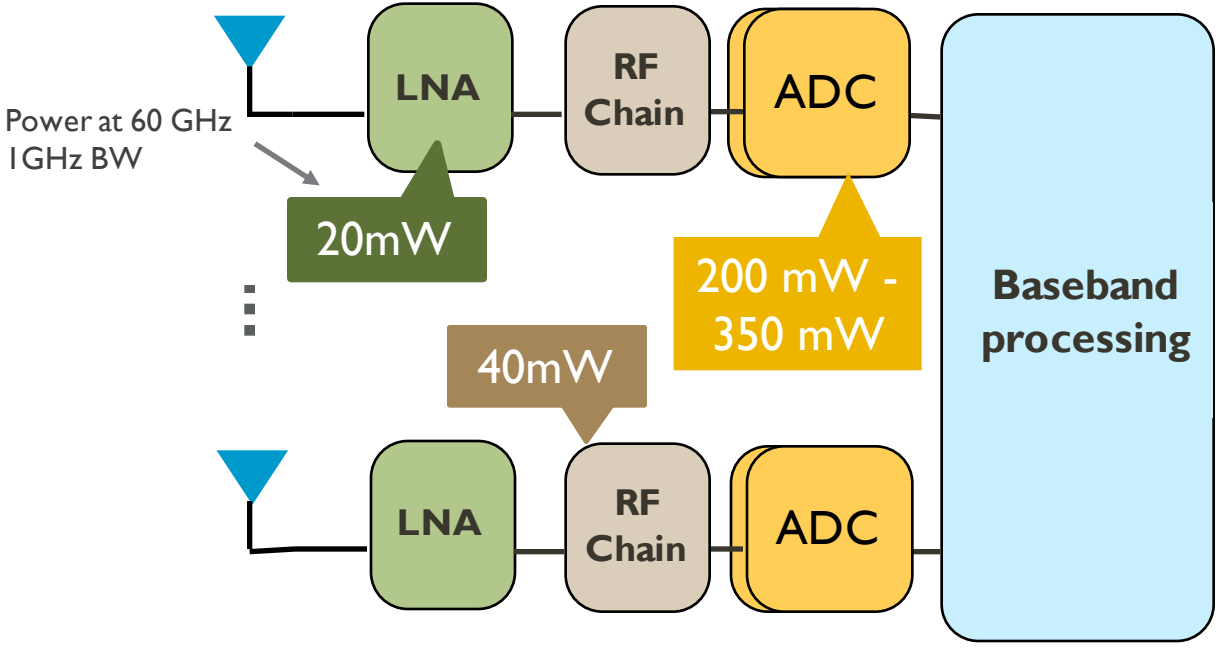
Multiple arrays on handset

Blockages reduce the impact of interference

Differentiating features of mmWave

Power consumption

Power consumption may be high with mmWave



For a receiver with 4 antennas, the power consumed by this front end at mmWave would be 2W !!!

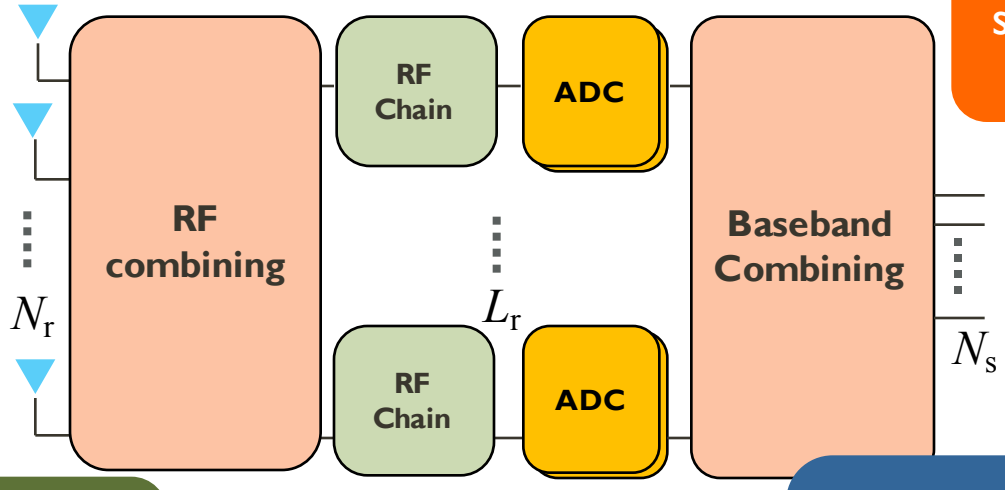
Power consumed by a 2.4 GHz, 20 MHz BW front end would be 120 mW

Alternative mmWave MIMO architectures are needed

Implications of power consumption

Small size cell to reduce PA power consumption

Process more signals with lower resolution

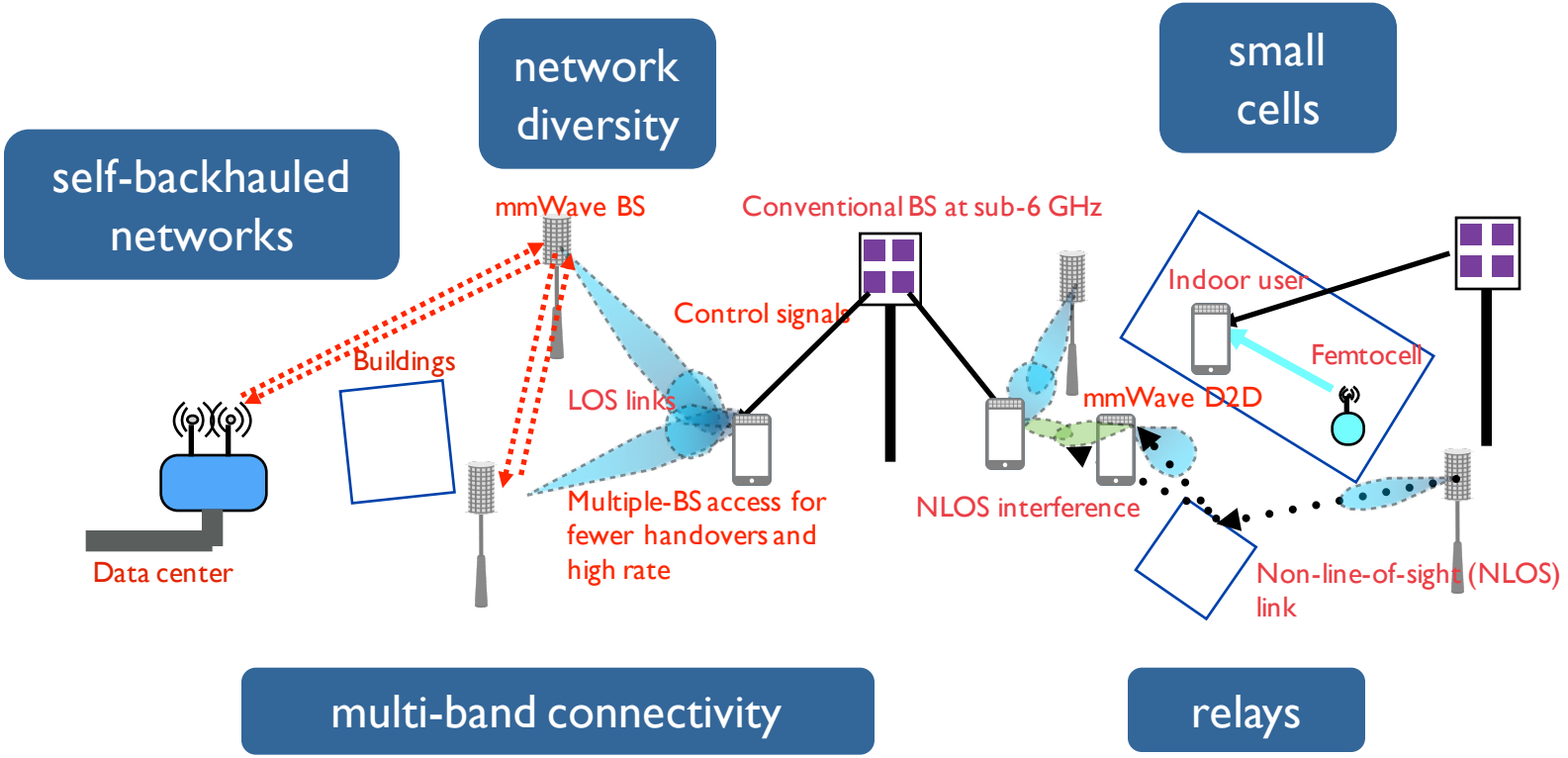


Hybrid architecture at the BS and the UE with many fewer RF chains than antennas

Process a fraction of the band per time slot at the UE to reduce baseband power consumption

MmWave for 5G cellular

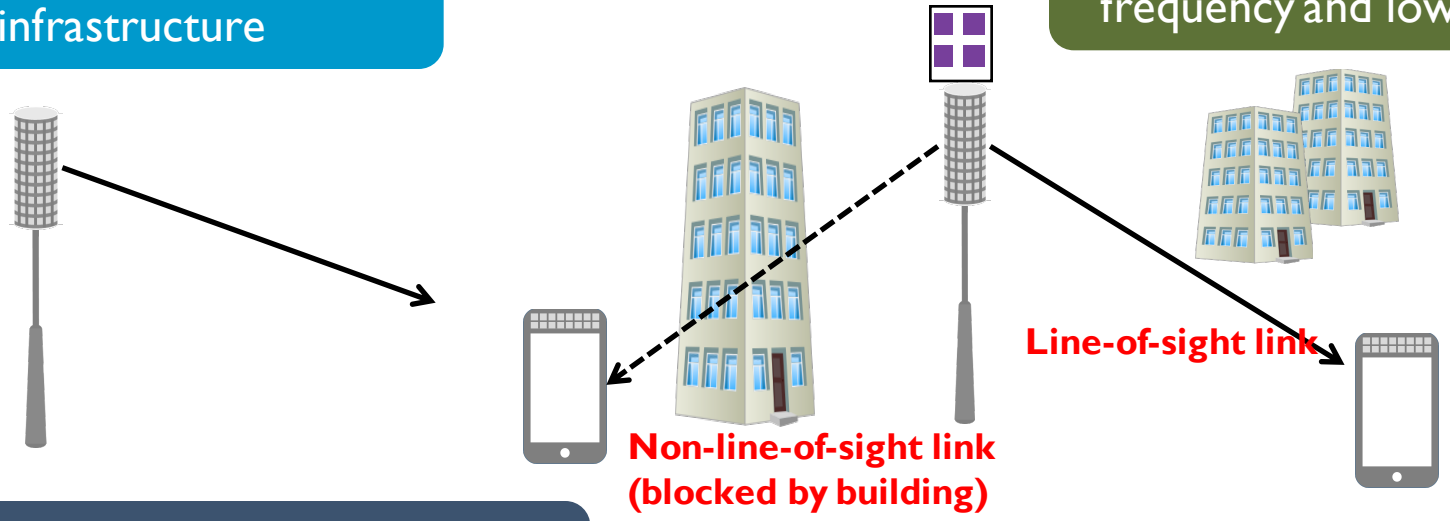
Infrastracture becomes complicated w/ mmWave



Revisiting building blockage

Option 1: Add more infrastructure

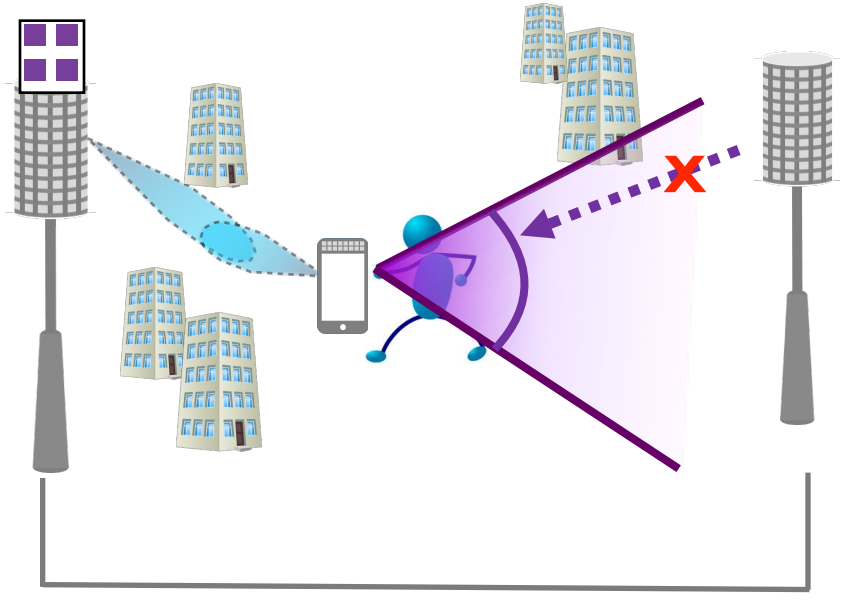
Option 2: Resort to lower frequency and lower rate



Option 3: User…go around the building if you want coverage

Need to cover the non-line-of-sight user

Revisiting body and self-body blocking

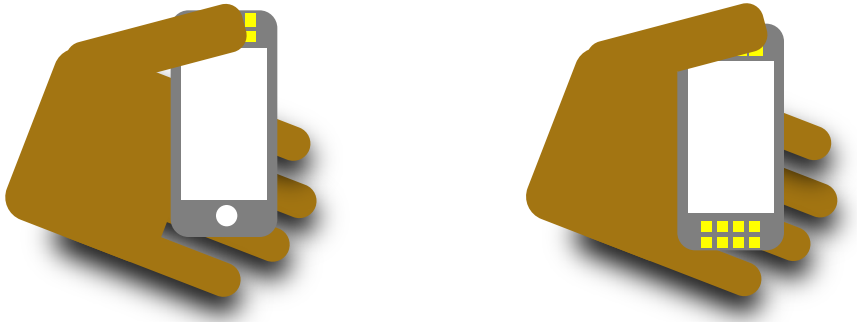


System must detect blockage

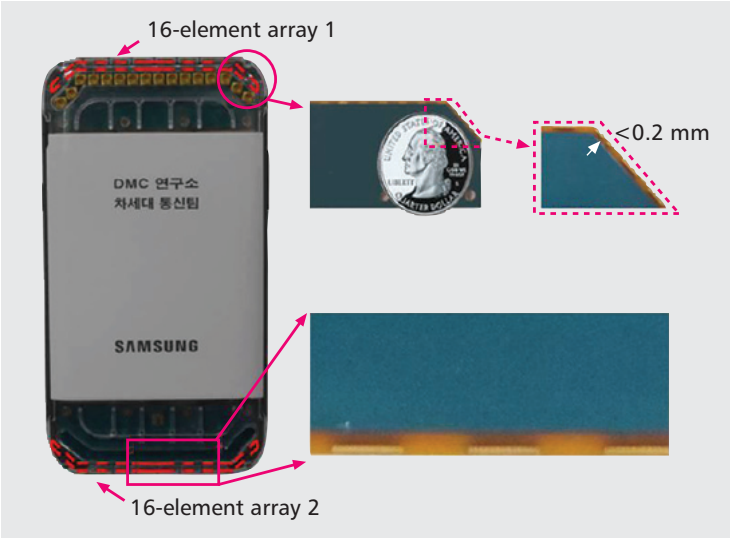
Network must support fast switching

Similar infrastructure requirements as building blockage

Revisiting hand blockage



no handset diversity handset diversity

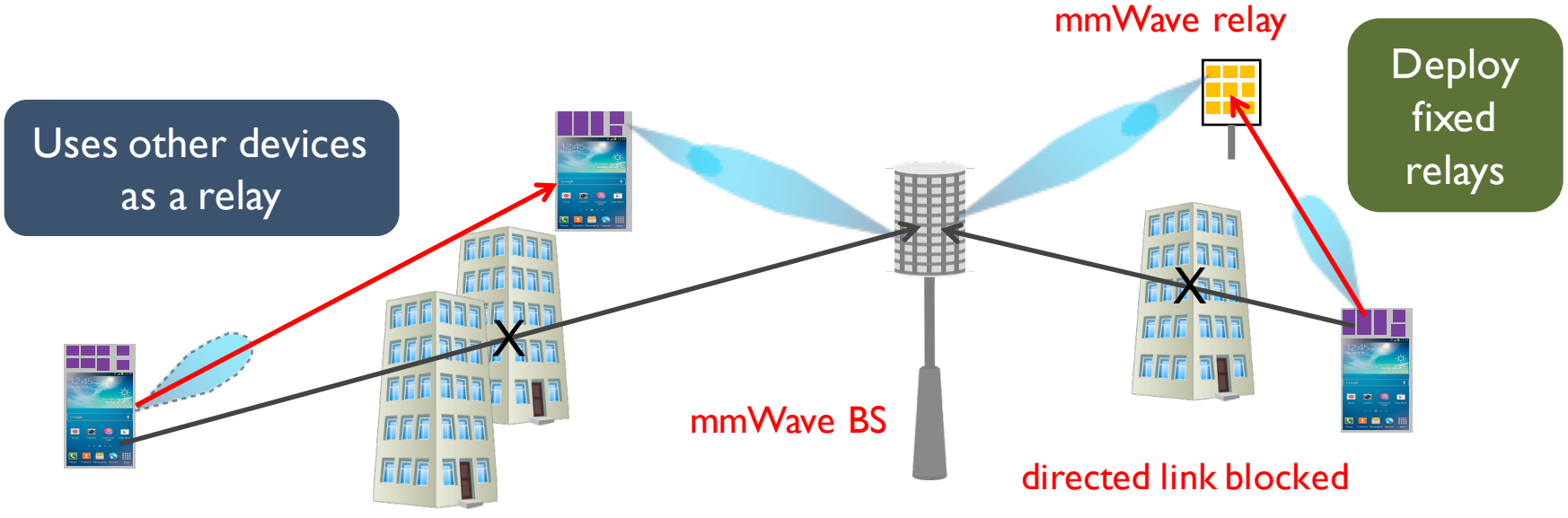


- Multiple arrays on handset if space is available (hard with multi-band)
- Train users not to block the arrays with their fingers (warning labels or shock)

Hand blockages and variable orientation require careful device engineering

Device picture from 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

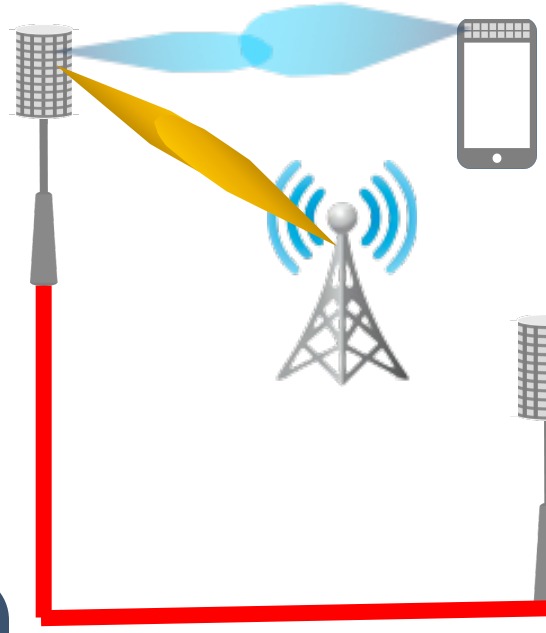
Alternatives to more base stations



Relays seem unlikely to be a long-term solution

How to backhaul mmWave base stations?

Out-of-band wireless backhaul possible in other mmWave spectra



Inband wireless backhaul will work due to pointy beams with low overlap

Wired backhaul will require very high capacity Tens of Gbps

Backhaul is a 5G killer

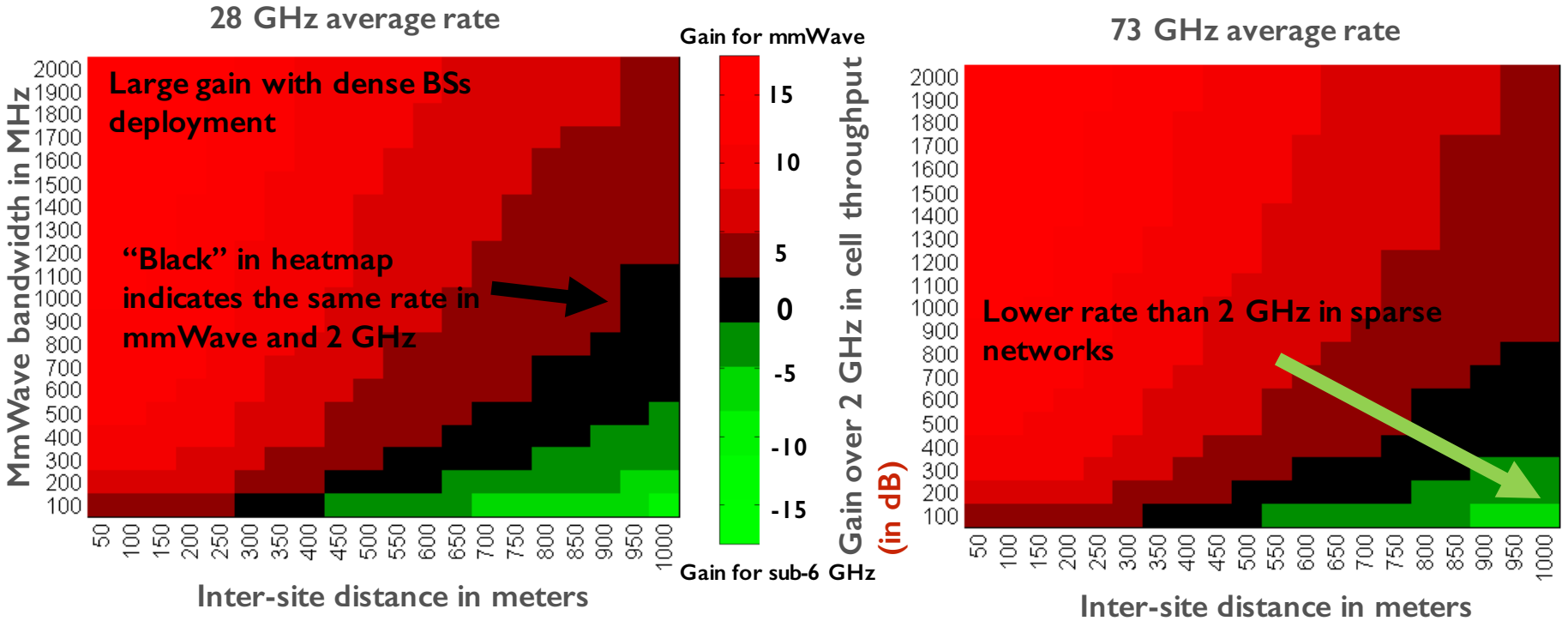
Estimating potential performance gains

Carrier freq.	2 GHz	28 GHz	73 GHz
bandwidth	100 MHz	Varies	Varies
# of base station antennas	2	8X8	20X20
# of UE antennas	2	2X2	5X5
TX power	46	30	30

Keep the same aperture in 28 and 73 GHz

Performance comparison including building blockages and reasonable channel modeling assumptions

Comparing single-user downlink performance



2GHz setup: bandwidth fixed as 100 MHz, while ISD varies

100 m in ISD = 128 BS/ km^2

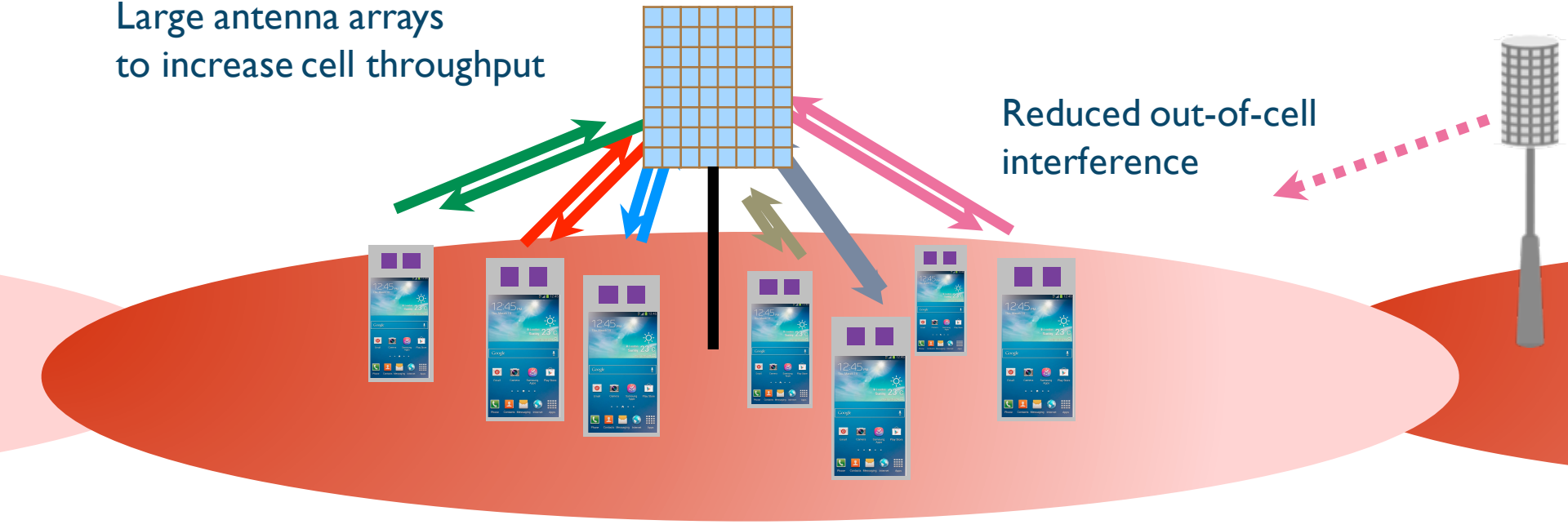
200 m in ISD = 32 BS/ km^2

MmWave cellular requires dense BSs to achieve high rate

mmWave massive MIMO

Massive MIMO is a sub-6 GHz 5G technology

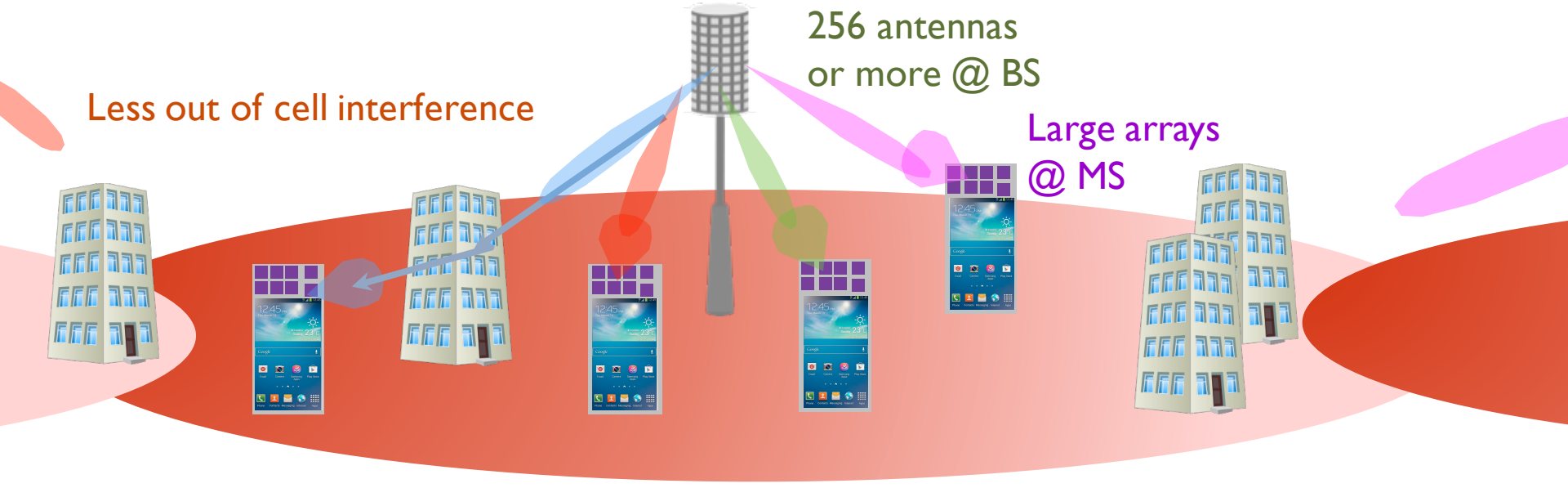
Large antenna arrays
to increase cell throughput



Reduced out-of-cell
interference

Massive MIMO supports many users at the same time

Massive MIMO also works at mmWave

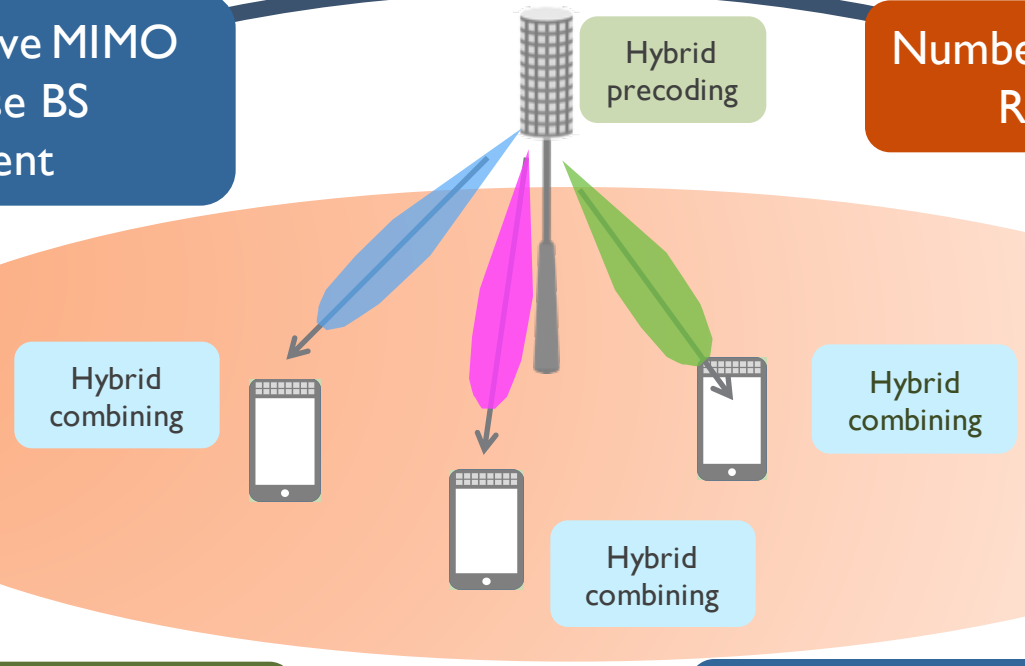


Large arrays are a natural application of massive MIMO techniques

Implications of using mmWave for massive MIMO

MmWave massive MIMO needs dense BS deployment

Number of users limited by RF configuration



Choice of carriers depends on base station density

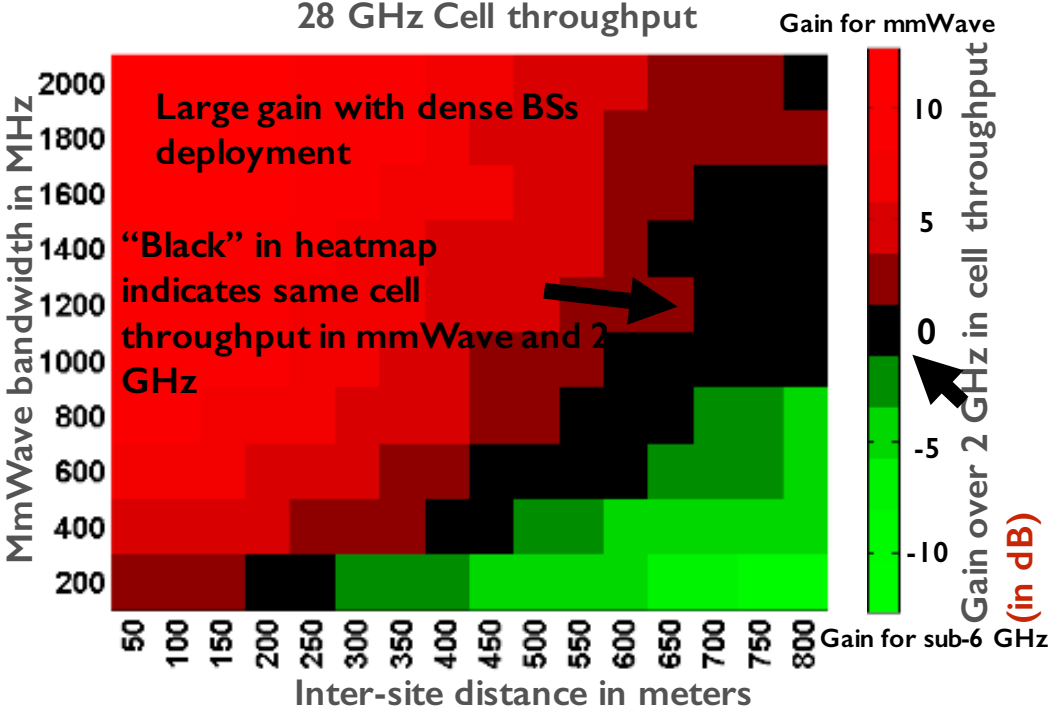
MmWave provides large gain in area throughput in small-cell regime

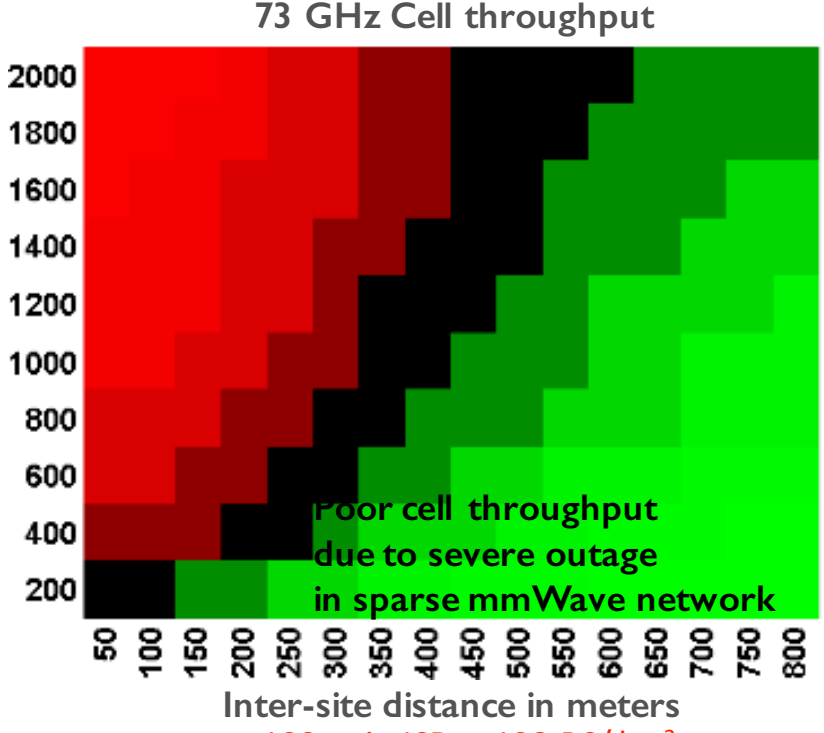
Comparing sub-6 GHz and mmWave massive MIMO

Carrier freq.	2 GHz	28 GHz	73 GHz
bandwidth	100 MHz	Varies	Varies
# of scheduled user per cell	10	4	1
# of base station antennas	8X8	16X16	40X40
# of UE antennas	1	2X2	5X5
TX power (DL/ UL)	46/ 20 dBm	30/ 20 dBm	30/ 20 dBm

Keep the same aperture in 28 and 73 GHz

Comparison of average cell throughput





2GHz setup: bandwidth fixed as 100 MHz, while ISD varies

100 m in ISD = 128 BS/ km^2

200 m in ISD = 32 BS/ km^2

MmWave massive MIMO benefits more from network densifications

Comparing mmWave massive vs. small cells

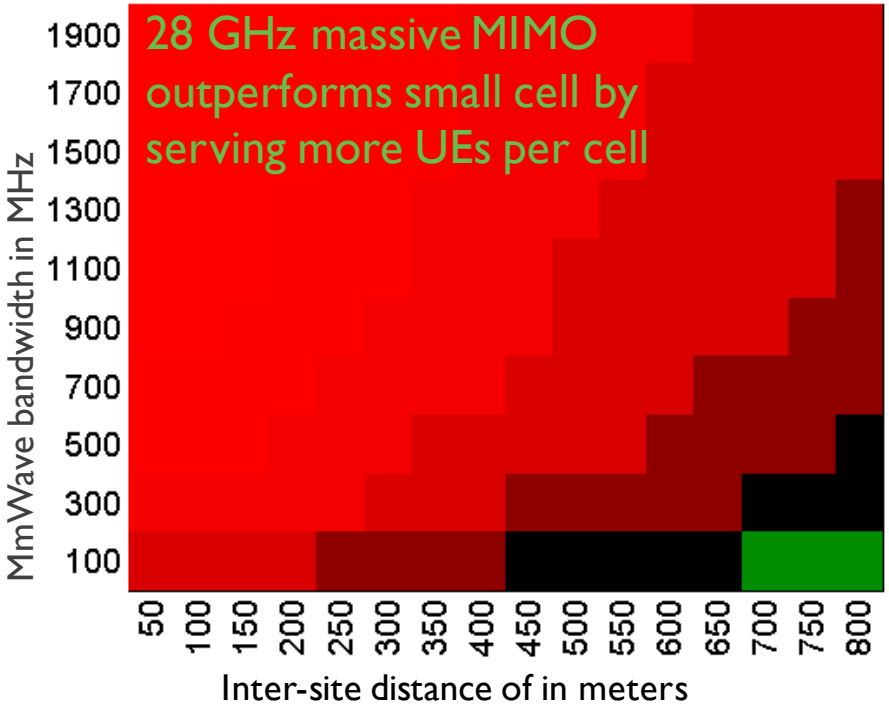
	28 GHz massive MIMO	73 GHz massive MIMO	Sub-6 GHz Small cell MIMO
# user/ cell	4	1	1
# BS antenna	16 x 16	40 x 40	2
# User antenna	2x2	5x5	2
Bandwidth	varies	varies	100 MHz

1. Small cell serves its user by 2x2 spatial multiplexing or SISO
2. Assume perfect channel knowledge for small cell case
3. Assume user density 40x macro massive MIMO BS density

Compare throughput per unit area b/w massive MIMO and small cell

MmWave massive MIMO vs. sub-6 GHz small cell

Keep the same BS density for both



28 GHz vs 2x2 SM small cell

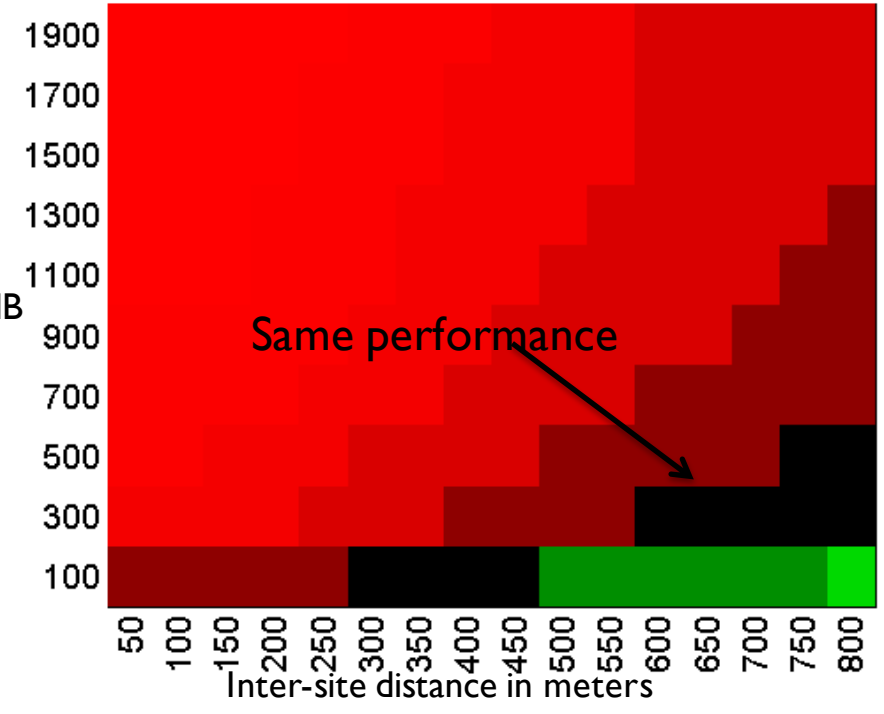
Gain for massive MIMO

15 dB

0 dB

15 dB

Gain for small cell

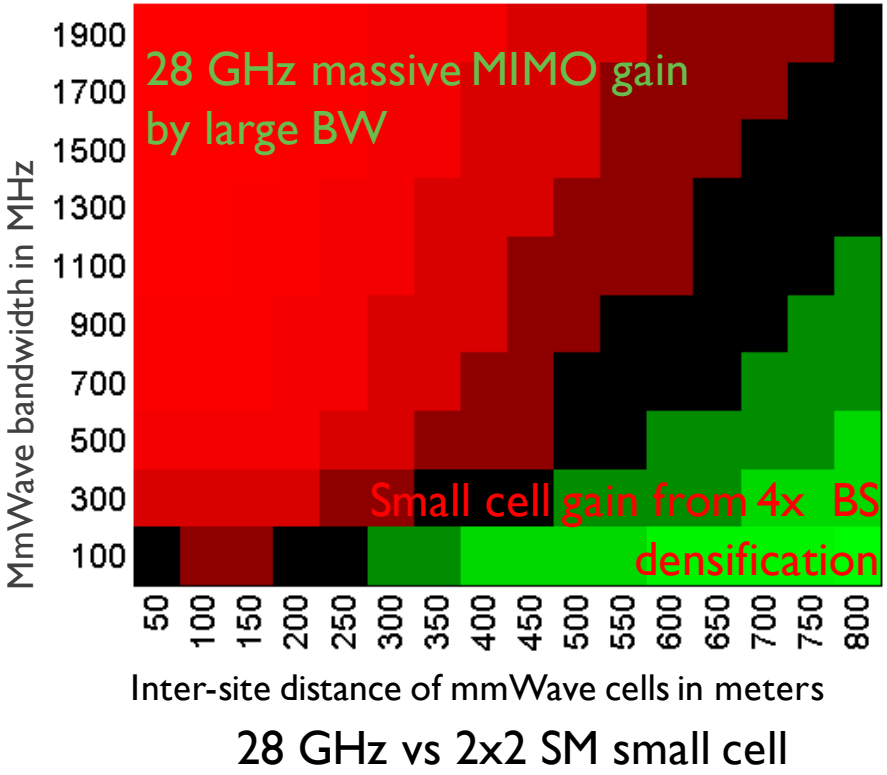


73 GHz vs 2x2 SM small cell

MmWave provides large gain in area throughput in small-cell regime

MmWave massive MIMO vs. sub-6 GHz small cell

Keep the same scheduled UE density for both



28 GHz vs 2x2 SM small cell

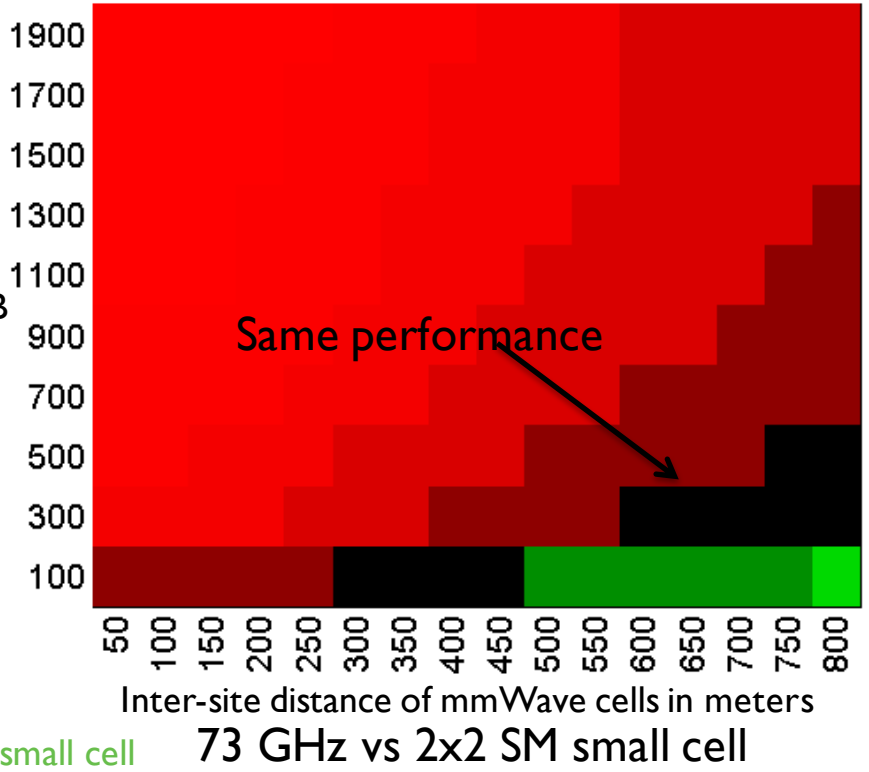
Gain for massive MIMO

15 dB

0 dB

15 dB

Gain for small cell

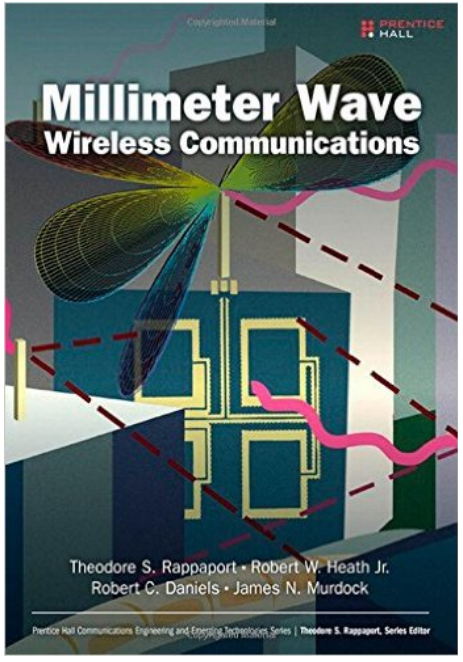


73 GHz vs 2x2 SM small cell

MmWave provides large gain in area throughput w/ small ISD

Conclusions

- MmWave will be a part of 5G – the only way for per-user Gbps
- Infrastructure is a key component of a mmWave network
- The future is bright for mmWave



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