

An aerial photograph of the University of Colorado Boulder campus, showing a large red brick building with a central tower and a flagpole, surrounded by dense green trees. A semi-transparent white text box is overlaid on the center of the image.

mmWave Communications: Opportunities and Challenges for IoT

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Outline

- **Some observations**

- The IoT Market
- Internet Connections
- The Growth of Wireless

- **mmWave Challenges for IoT**

- Range
- Coverage
- Penetration

- **The Opportunities of mmWave for IoT**

- Range
- Coverage
- Penetration

- **Summary**



The First IoT Device

INTERESTING FACT

The first IoT device came in 1982 when Carnegie Mellon University modified a Coke machine to report its inventory and give updates on whether newly loaded drinks were cold.



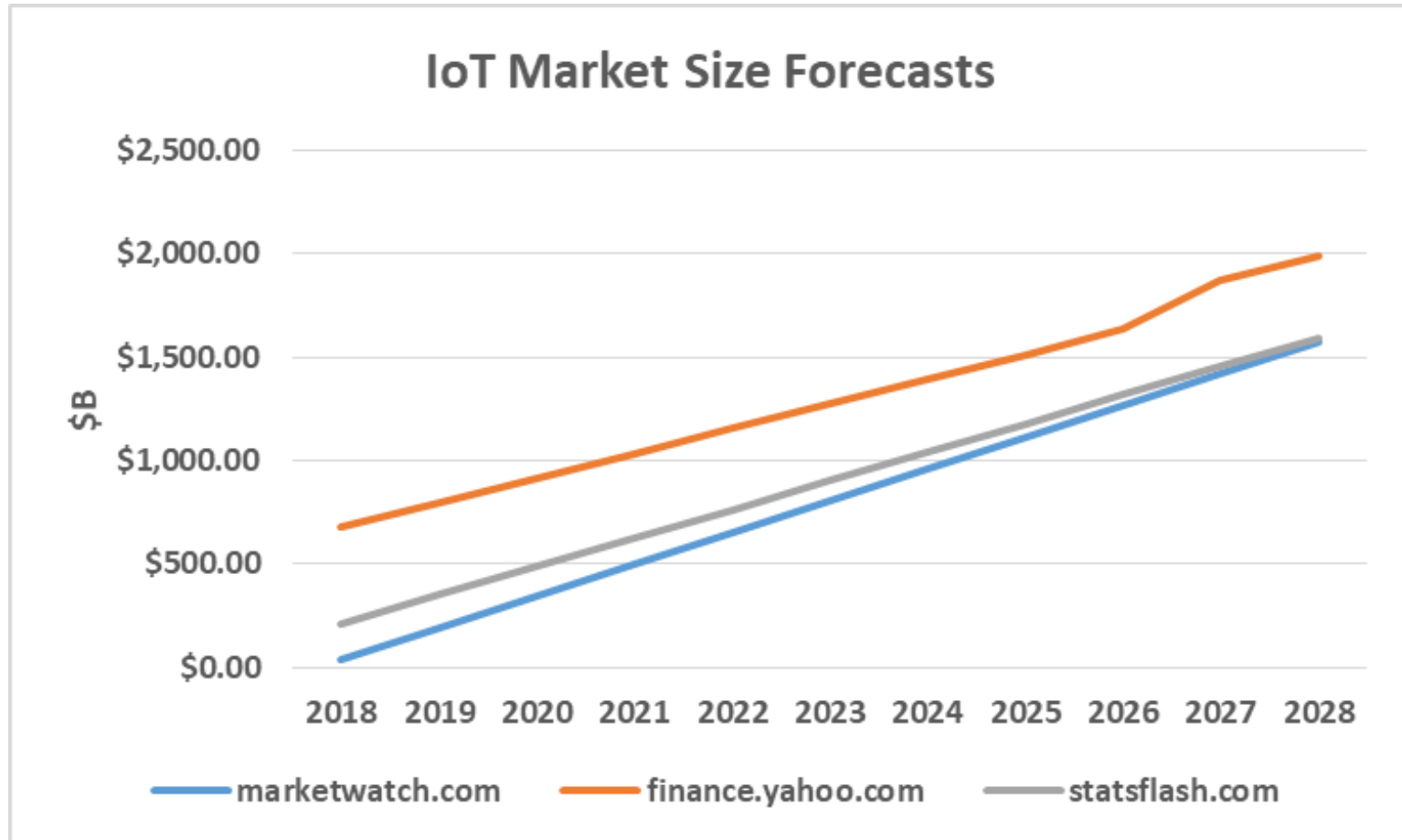
Reference: https://www.cs.cmu.edu/~coke/history_long.txt

Figure: <https://safeatlast.co/blog/iot-statistics/>



University of Colorado **Boulder**

IoT Market Growth



The Number of IoT Devices

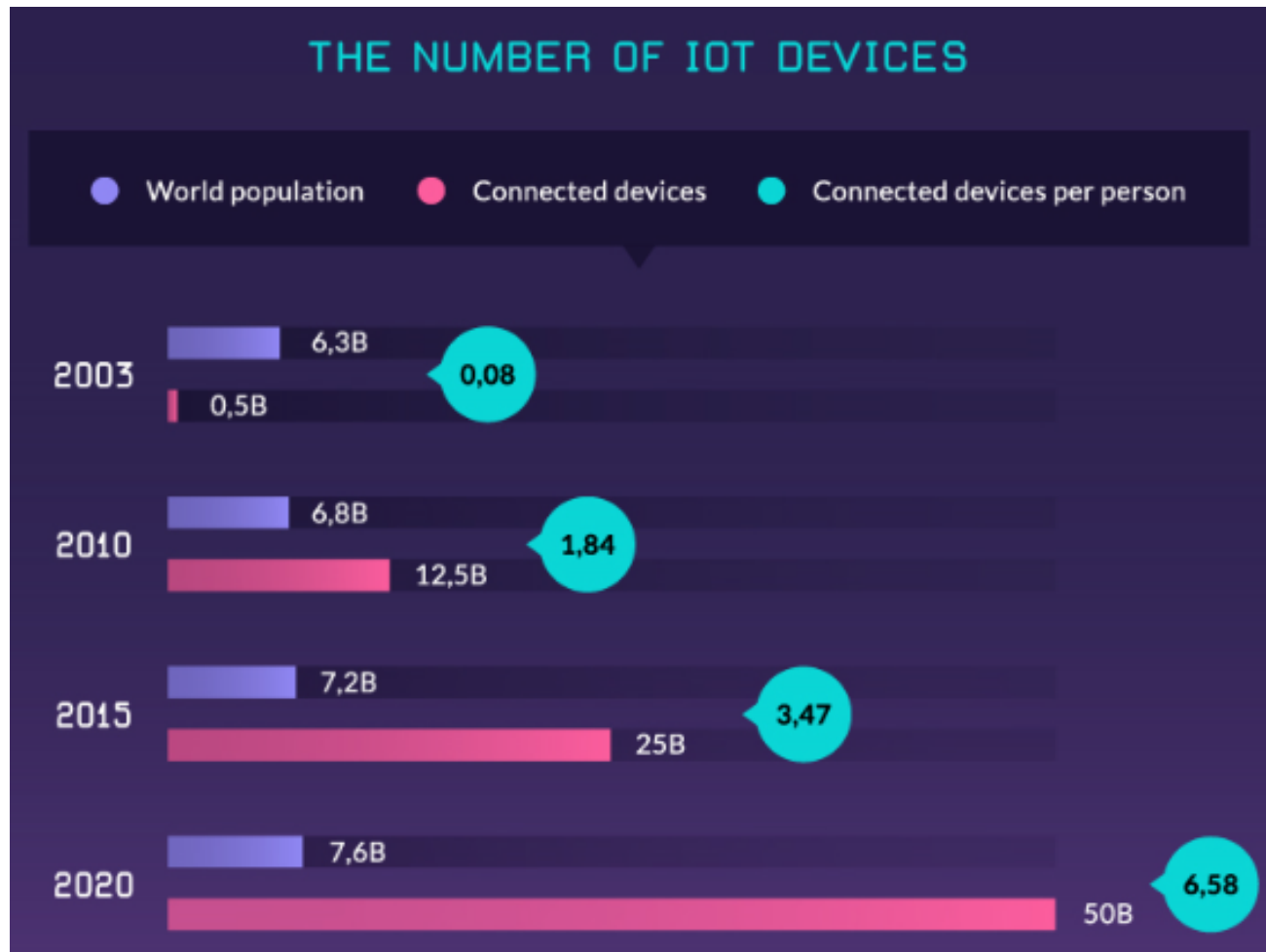
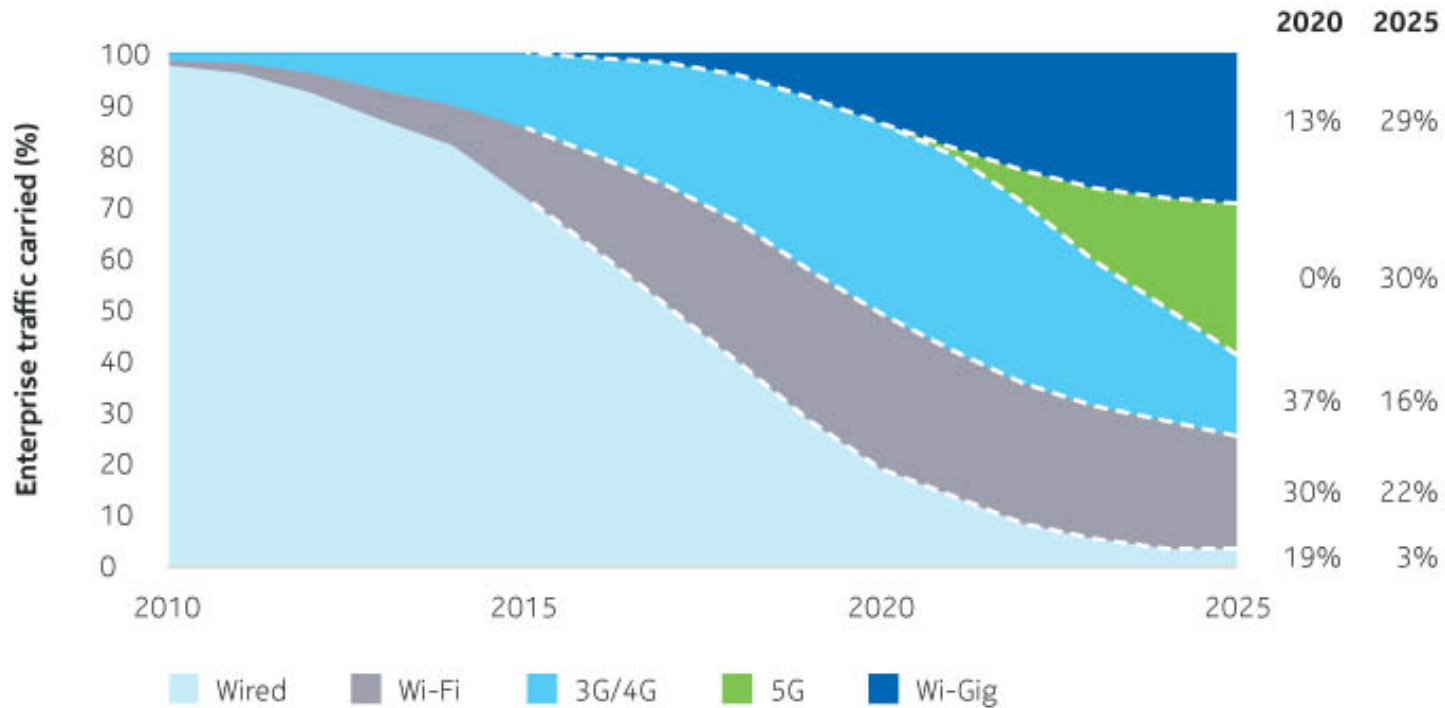


Figure: <https://safeatlast.co/blog/iot-statistics/>



The Expansion of Wireless

97% Wired → 97% Wireless



Marcus K. Weldon, *The Future X Network: A Bells Labs Perspective* (2016)

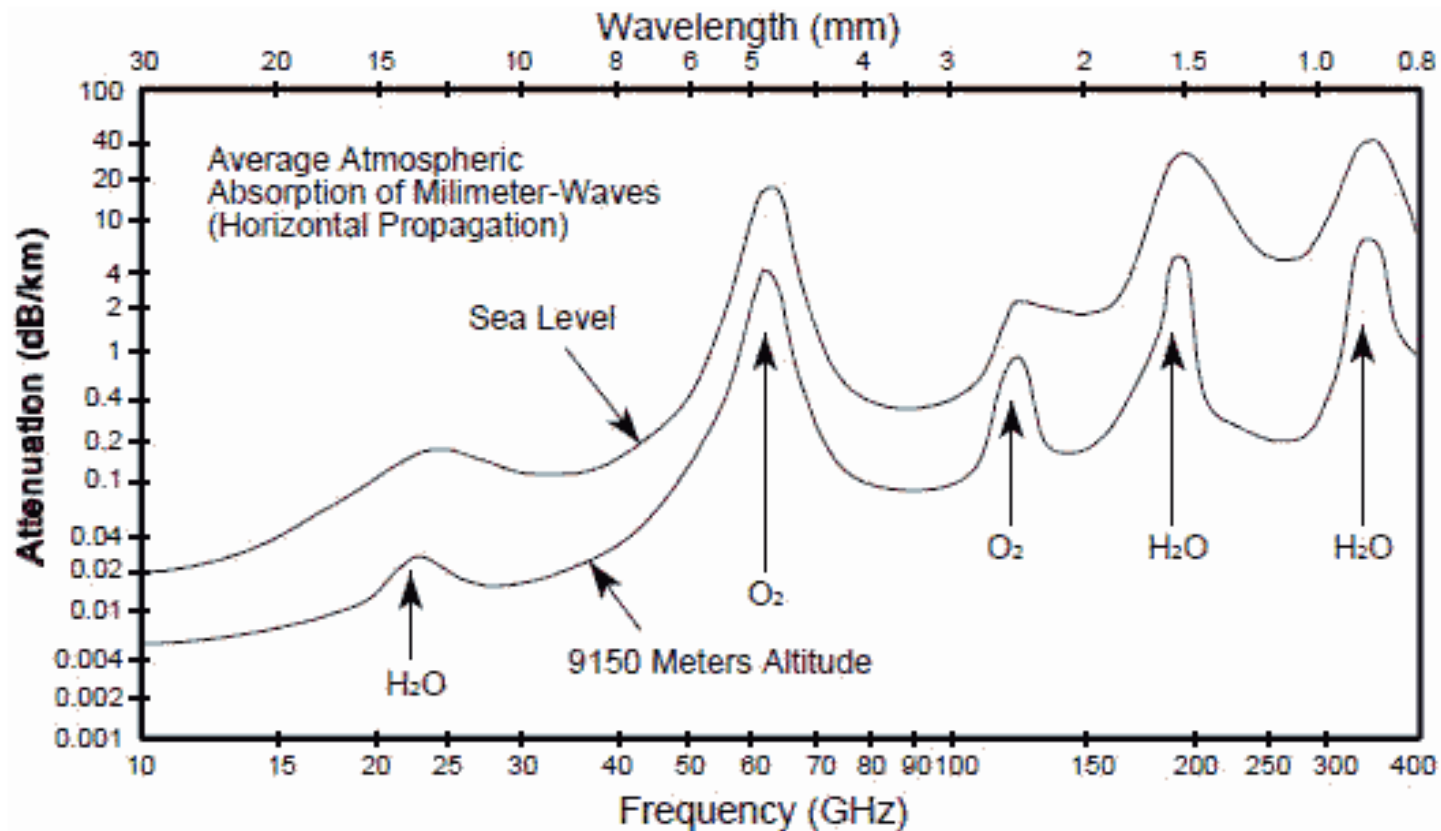


5G and mmWave

- 5G promises to deliver Gbps capacity to mobile users
 - The key to high bandwidth is high frequencies
 - Current cellular and WiFi operate at < 6 GHz
 - 5G proposes to use mmWave spectrum: 30 – 300 GHz
- High frequency RF has properties very different from low frequency
 - Propagation becomes less wave-like, more ray-like
 - *refraction is reduced, so need to account for geometry*
 - Signals do not penetrate obstacles well
 - *walls, foliage, and the human body block signals*
 - Increased signal absorption by water, O₂, etc
 - *significant signal loss in rain and fog*
 - Increased scattering by rain drops, dust, etc
- In general, terrestrial propagation of mmWave presents challenges
 - Industry estimates predict 10x cell towers to cover same area as 4G with mmWave
 - Understanding reflection, refraction, absorption, and scattering at high-resolution is critical



mmWave Attenuation by H₂O and O₂



Source: <http://www.rfcafe.com/references/electrical/ew-radar-handbook/rf-atmospheric-absorption-ducting.htm>



RF Propagation and Geometry

- Diffraction properties vary by frequency
 - Difficult to find comparable measurements
 - Clear drop in diffraction with increasing frequency

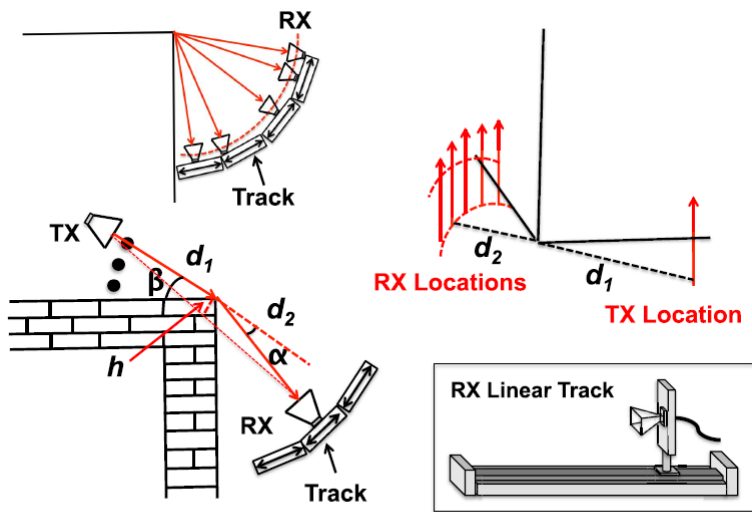
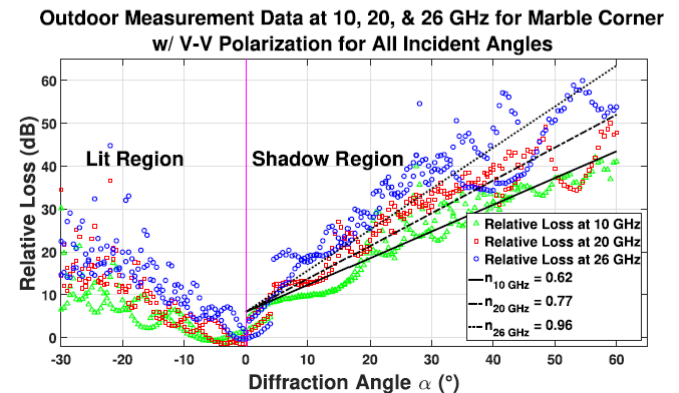
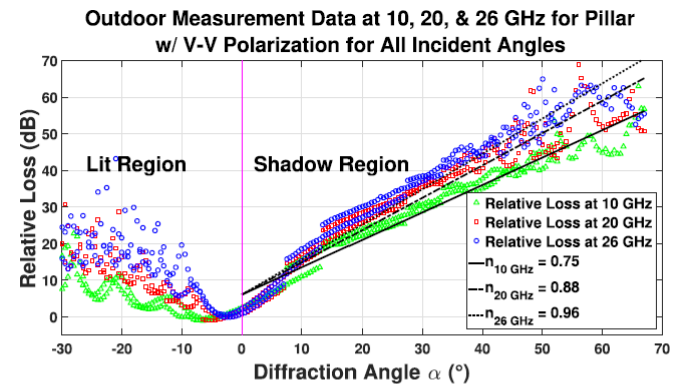


Fig. 1. Top view of the corner diffraction geometry [17].



T. S. Rappaport, et al, "Small-scale, local area, and transitional millimeter wave propagation for 5G communications", IEEE Transactions on Antennas and Propagation, 65:12 pp 6474-6490, Dec. 2017

mmWave and Building Materials

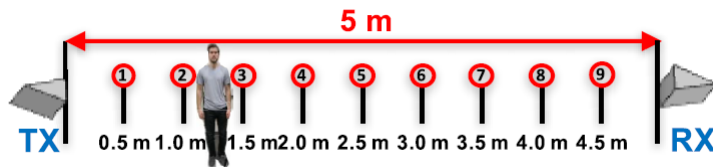
Material	Thickness (cm)	Roughness (mm)	Reflectance 30° (dB loss)	Reflectance 60° (dB loss)	Transmission 0° (dB loss)
Granite	3	0.6	13.8	5.5	≥ 30.0
Marble	1.7	0	2.7	2.1	5.2
Limestone	3	0	5.5	3.1	≥ 30.0
Concrete	5	0.1	6.7	4.1	≥ 30.0
Brick	11	2, 0.3	13.4	8.6	16.9
Tiles	0.5	0.1	4.1	7.6	≥ 30.0
Plasterboard	1	0	8.1	8.9	2.1
Plasterwork rough	1	1.7	≥ 30.0	≥ 30.0	≥ 30.0
Plasterwork smooth	1	0.25	6.9	5	4.5
Polyfoam	3.8	0.4	≥ 30.0	29.3	0
Wood Fibreboard	1.2	0.2	15.8	10.7	3.4
Wooden Panels	1.9	0	18.4	9.3	8.6
Wooden Chipboard	1.3	0.2	9.5	5.5	6.2
Glass rough	0.4	0.3	5.2	2.2	4.5
Glass smooth	0.4	0	10.8	3.8	2.4
Glass metallized	0.4 +1.5 (gap)+0.4	0	3.1	2.7	≥ 30.0

Source: B. Langen, G. Loger, and W. Herzig, "Reflection and transmission behavior of building materials at 60 GHz," 1994 *IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC 1994)*, pp 505-509, 1994

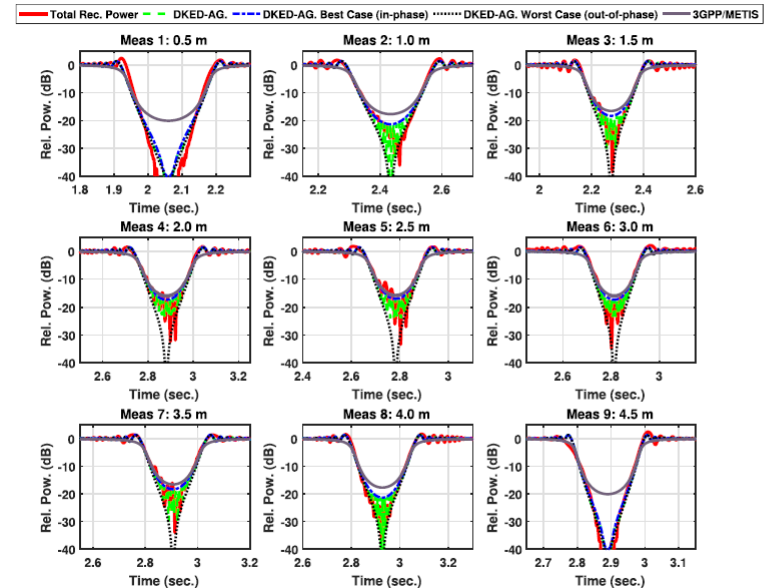


Other Obstacles

- The human body is virtually impenetrable to mmWave
“You make a better door than a window!”



Experimental procedure



Experimental results

T. S. Rappaport, et al, “Small-scale, local area, and transitional millimeter wave propagation for 5G communications”, IEEE Transactions on Antennas and Propagation, 65:12 pp 6474-6490, Dec. 2017

So Why mmWave for IoT?

- **Spectrum availability**

- Sub-6 GHz spectrum is getting crowded
- Over 10 GHz being freed up (so far) in mmWave frequencies!

- **Capacity**

- Projections have 5G mmWave delivering high capacity¹
 - *100 Mbps per user (minimum); 20 Gbps per user (peak)*
 - *1M devices / km²*

- **Beamforming**

- Overcome losses due to atmospheric attenuation
- Reduce interference from multiple installations

- **Propagation limitations**

- Encourages small cells and spectral re-use

¹<https://www.smallcellforum.org/blog/mmwave-small-cells-boost-capacity-tenfold-use-cases/>



The “Sweet Spots” for mmWave

- High-density environments (eMBB)
 - Small cells with limited coverage
 - Reduced indoor->outdoor leakage
- Wireless interconnects (mMMC)
 - Rapid power loss with distance
 - Flexible reconfiguration
- Fixed wireless access (FWA)
 - Beamforming for last link to home/business
 - Reduced installation cost (no digging!)
- Short- to mid-range backhaul
 - Beamforming for backhaul
 - Flexible deployment and reconfiguration



mmWave Small Cells

- **Use cases:**

- Hyper-dense environments
- High demand for bandwidth

- **Advantages:**

- Gbps speeds
- 100x capacity (over LTE)

- **Challenges:**

- Poor propagation: line-of-sight (LOS) or near-LOS (NLOS)
- Interference and congestion
- Infrastructure for connection of 10x cell sites

- **Solution features:**

- Dense deployment of cell sites
- Propagation properties reduce interference and congestion problems
 - *Limits cell coverage area*
 - *Limits leakage through walls, windows, ...*
 - *Enhances spatial re-use of frequencies*
- Wireless interconnect reduces infrastructure needs, increases flexibility

A. Sadri, “mmWave technology evolution from WiGig to 5G small cells”, Intel Corporation, June 2013
Small Cell Forum, SCF197, “mmw 5G-eMBB use cases and small cell based HyperDense networks”, Dec. 2017



Wireless Interconnect

- **Use cases:**

- Computing facilities
- Data centers
- Dense industrial facilities

- **Advantages:**

- Reduced cost in fiber, copper
- Enhanced reconfigurability

- **Challenges:**

- Fiber-like capacity
- Line-of-sight (LOS) between units
- Security

- **Solution features:**

- IEEE 802.15.3c 60 GHz mmWave supports up to 6 Gbps connections
 - *roughly Ethernet speeds*
- Security provided by limits on mmWave propagation range and penetration
- No re-wiring required for reconfiguration

S. Kutty and D. Sen, "Beamforming for millimeter wave communications: an inclusive survey," IEEE Communications Surveys & Tutorials, 18(2), 2016

H. Vardhan, et al, "Wireless data center with millimeter wave network," IEEE Globecom 2010

T. S. Rappaport, R. W. Heath Jr., R. C. Daniels, J. N. Murdock, **Millimeter Wave Wireless Communications**, Prentice Hall 2014



Fixed Wireless Access and Backhaul

Beamforming can overcome mmWave propagation problems

- **Use cases:**

- Fixed wireless access (FWA) for “last mile” links
- Wireless backhaul

- **Advantages:**

- Minimal interference
- Minimal physical infrastructure – no digging!

- **Challenges:**

- Power, cost, & complexity
- Adaptation to environmental changes

- **Solution Features:**

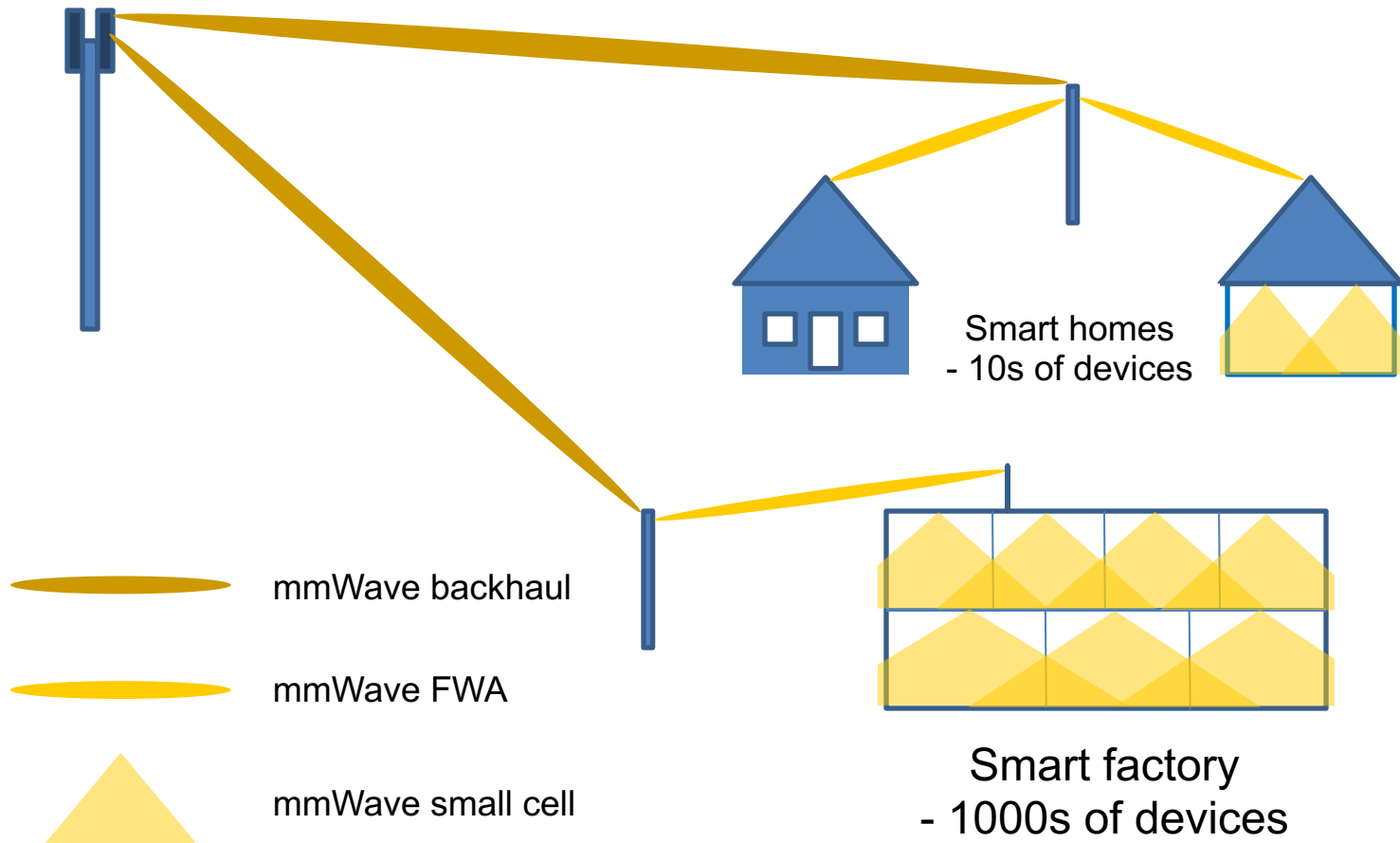
- 10 Gbps bandwidth
- Reconfigurable

S. Kutty and D. Sen, “Beamforming for millimeter wave communications: an inclusive survey,” IEEE Communications Surveys & Tutorials, 18(2), 2016

T. S. Rappaport, R. W. Heath Jr., R. C. Daniels, J. N. Murdock, **Millimeter Wave Wireless Communications**, Prentice Hall 2014



Conceptual mmWave Deployment



The Potential of 5G mmWave - Example

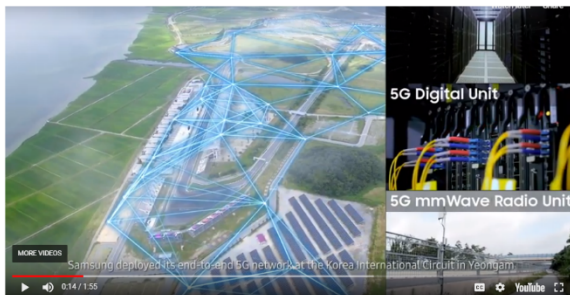
Samsung and SK Telecom, August 2019

- **Korea International Circuit racetrack**

- Race car moving at 130 mph
- 5G mmWave network
- 200 MHz bandwidth at 28 GHz

- **Stable performance**

- Communication speeds of ≤ 1 Gbps
- Handover between base stations at 130 mph
- Multiple continuous video streams from race car



<https://news.samsung.com/global/samsung-and-sk-telecom-showcase-real-world-5g-use-case-in-high-speed-motor-racing>



References

- 1) S. Kutty and D. Sen, "Beamforming for millimeter wave communications: an inclusive survey," *IEEE Communications Surveys & Tutorials*, 18(2), 2016
- 2) B. Langen, G. Loger, and W. Herzig, "Reflection and transmission behavior of building materials at 60 GHz," *1994 IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC 1994)*, pp 505-509, 1994
- 3) A. Sadri, "mmWave technology evolution from WiGig to 5G small cells," Intel Corporation, June 2013
- 4) Small Cell Forum, SCF197, "mmw 5G-eMBB use cases and small cell based HyperDense networks," Dec. 2017
- 5) T. S. Rappaport, et al, "Small-scale, local area, and transitional millimeter wave propagation for 5G communications," *IEEE Transactions on Antennas and Propagation*, 65:12 pp 6474-6490, Dec. 2017
- 6) T. S. Rappaport, R. W. Heath Jr., R. C. Daniels, J. N. Murdock, **Millimeter Wave Wireless Communications**, Prentice Hall 2014
- 7) H. Vardhan, et al, "Wireless data center with millimeter wave network," IEEE Globecom 2010
- 8) M. K. Weldon, *The Future X Network: A Bells Labs Perspective* (2016)
- 9) <https://finance.yahoo.com/news/global-iot-market-technology-forecast-172908012.html>
- 10) <https://news.samsung.com/global/samsung-and-sk-telecom-showcase-real-world-5g-use-case-in-high-speed-motor-racing>
- 11) <http://www.rfcafe.com/references/electrical/ew-radar-handbook/rf-atmospheric-absorption-ducting.htm>
- 12) <https://safeatlast.co/blog/iot-statistics/>
- 13) <https://statsflash.com/internet-of-things-iot-market-analysis-size-trends-2019-2026/210663/>
- 14) https://www.cs.cmu.edu/~coke/history_long.txt
- 15) <https://www.marketwatch.com/press-release/internet-of-things-iot-market-2019-global-industry-analysis-size-share-growth-trends-key-players-and-forecast-2019-2025-2019-11-12>
- 16) <https://www.smallcellforum.org/blog/mmwave-small-cells-boost-capacity-tenfold-use-cases/>

