# From Innovation to Transformation

## – Next Generation Mobile Broadband as the Infrastructure for a Connected World

Jerry Pi

Chief Technology Officer

Straight Path Communications Inc.

March 12, 2015

# Overview of Straight Path

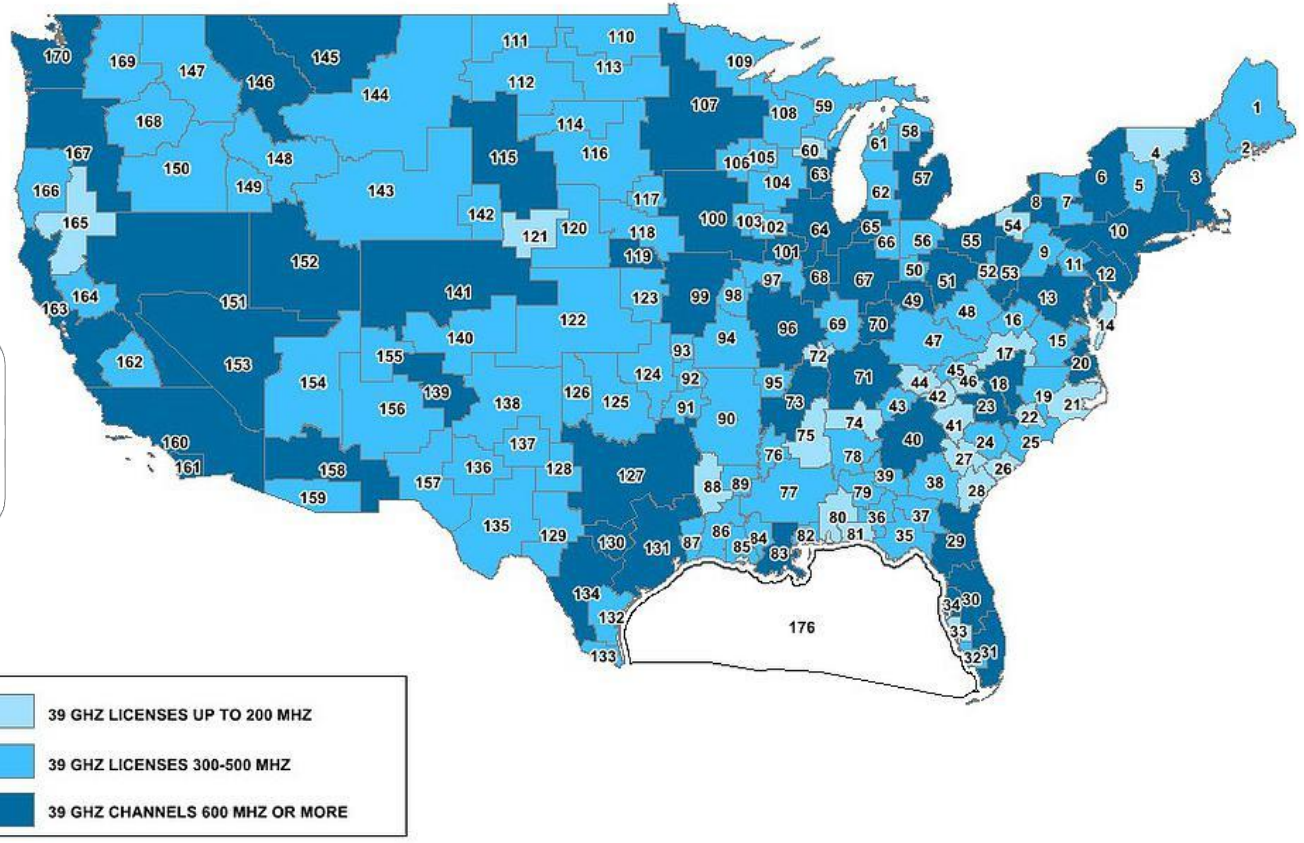
## Incumbent operator in the mmW bands

- Extensive spectrum holdings in 39 GHz (828 licenses) and LMDS (133 licenses)
- Nationwide coverage
- Average 833 MHz in top 30 markets (39 GHz)
- Provide backhaul services to WISPs and MNOs

## Business and technology innovator in mmW communication

- Developing fundamental technologies for next generation broadband and mobile communication in mmW bands
- Develop innovative business models that maximize the utilization of mmW spectrum

Straight Path Spectrum Holdings at 39 GHz



# The Big Picture – A Growing ICT Industry

## Mobility

- 1G ➔2G➔3G➔4G➔5G
- 11b➔11g➔11n➔11ac & 11ad ➔11ax & NG60

## Computing

- Mainframe➔PC➔Smartphone➔Wearable➔Sensor

## Internet

- Email➔Web➔Search➔Social Network➔Cloud Computing & IoT

## Content

- Voice➔Video➔HD/UHD➔360° Video➔Virtual Reality➔…

## Big Data

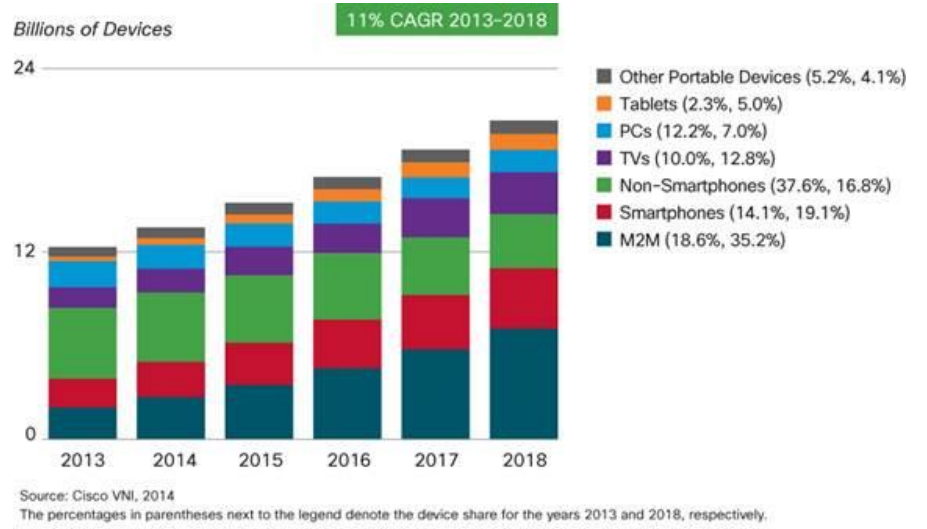
- Big data analytics, Deep Learning, …

## The Rise of Machines

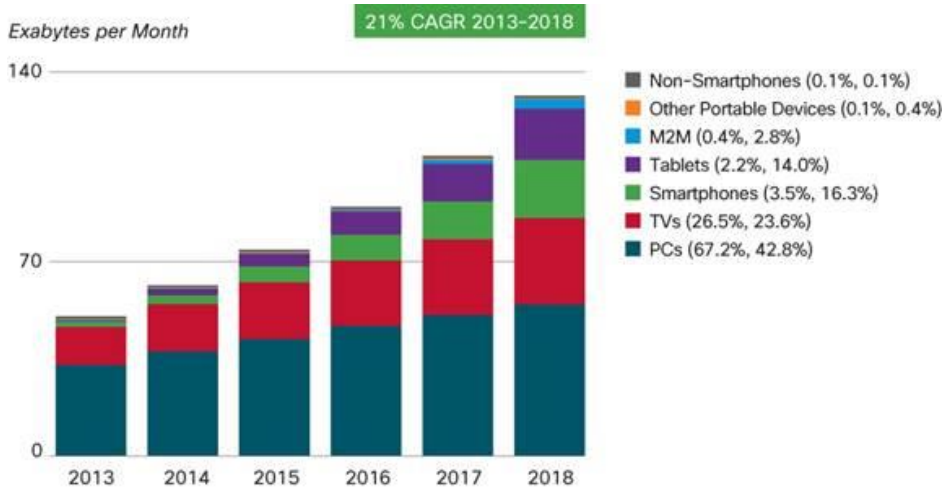
- Remotely controlled and self-operating cars, drones, robots, …

## Applications and Services

- Think of anything? There is an app for that (If not, somebody will make one)
- Everything is possible (although not everything will be successful)




Source: Cisco VNI, 2014
The percentages in parentheses next to the legend denote the device share for the years 2013 and 2018, respectively.



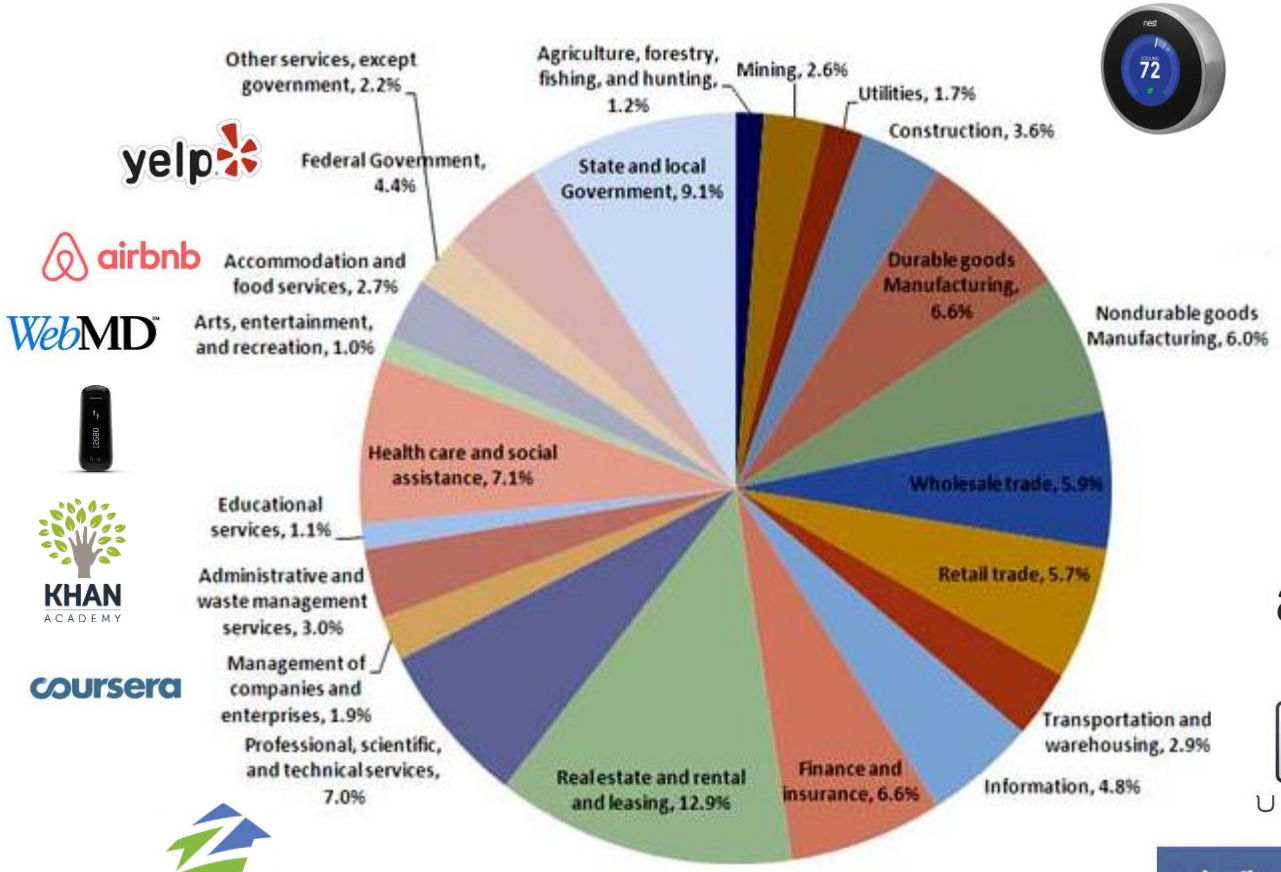

Source: Cisco VNI, 2014
The percentages in parentheses next to the legend denote the device traffic shares for the years 2013 and 2018, respectively.

# The Bigger Picture - A Connected World

A rising tide lifts all boats

- ICT accounts for 4.8% of U.S. GDP (2012)
- ICT contributes to
  - 60% of U.S. total factor productivity growth in 1996 - 2007
  - Virtually all growth in labor productivity in U.S. in 1995 – 2002

The society, the economy, and our lives are being digitized, connected, and mobilized



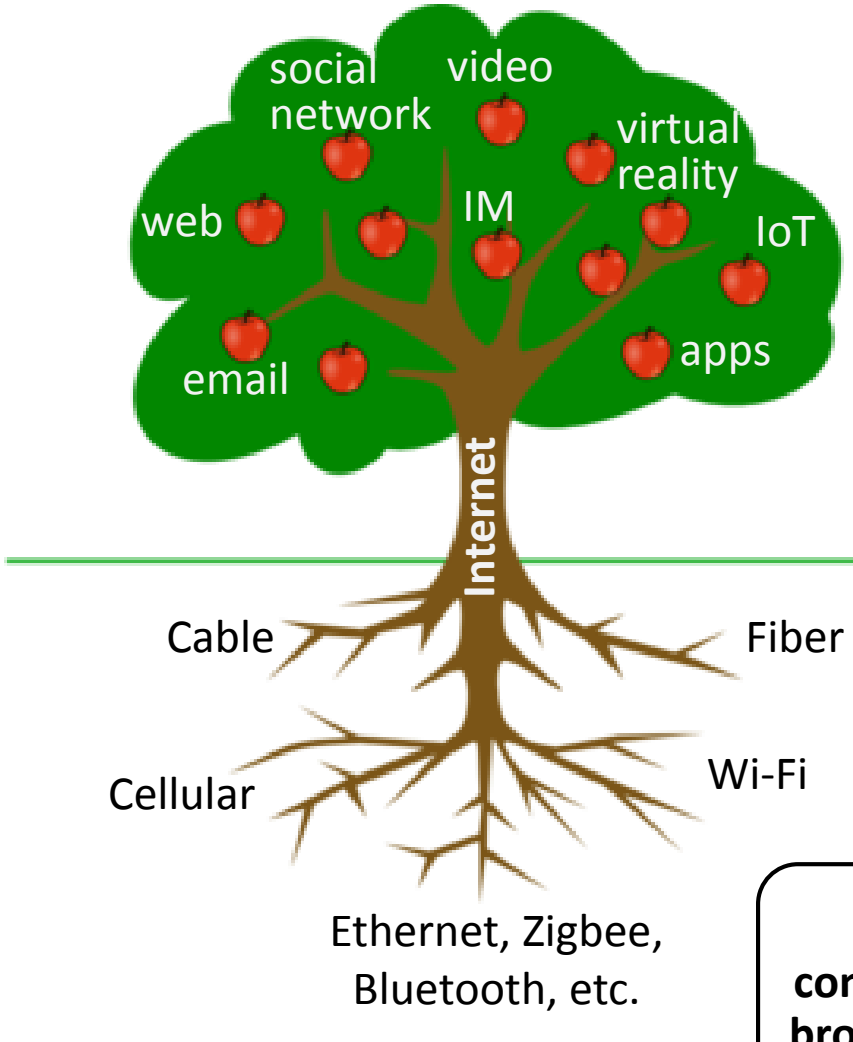

Source: http://www2.itif.org/2014-raising-eu-productivity-growth-ict.pdf

Source: http://www.economicpopulist.org/content/gdp-industry-2012-5511

Data source: BEA

# Trends as the World Become Connected

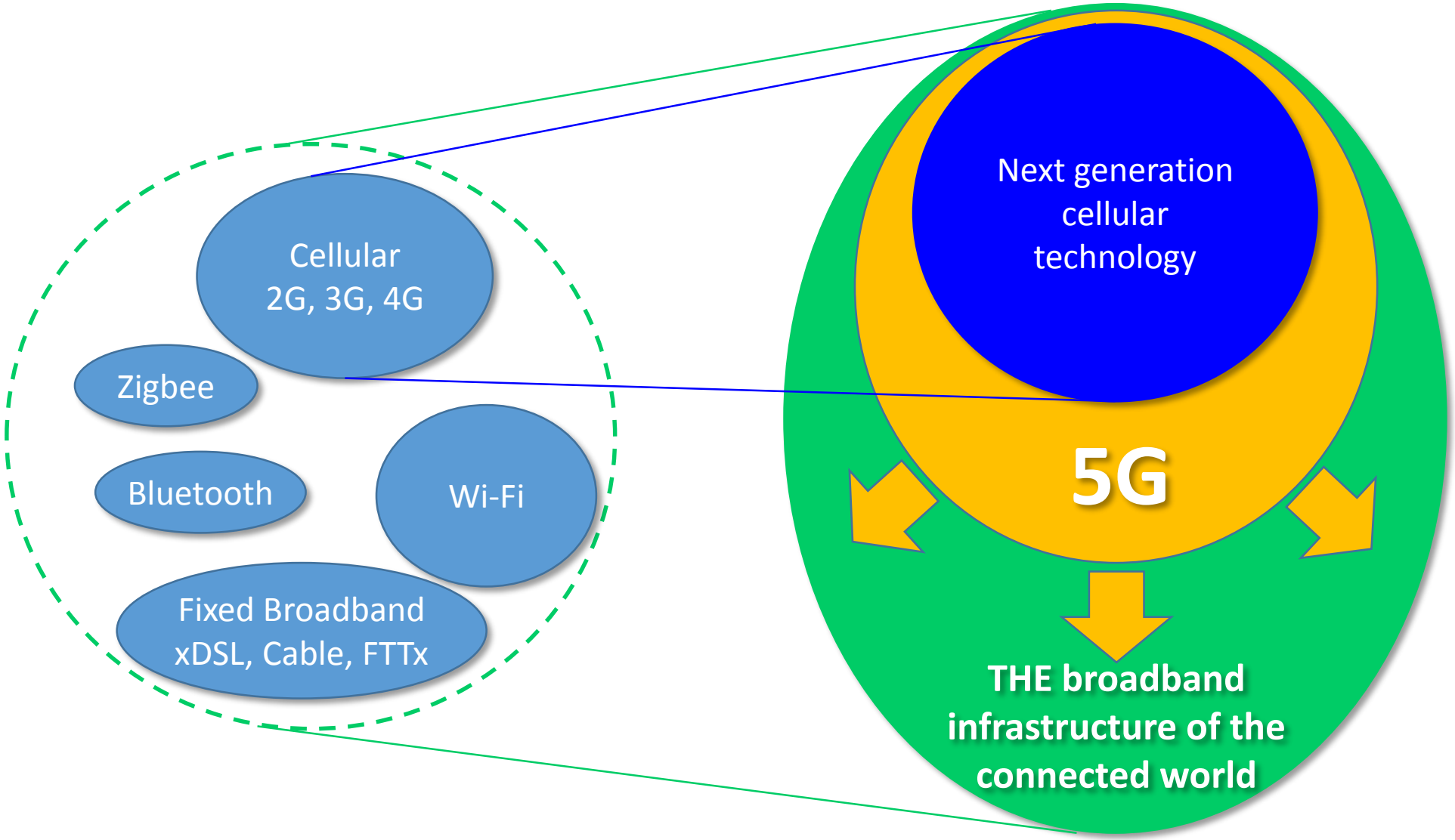
**Diversification of applications and services spanning across every part of our life**




**Horizontalization of ecosystem as economy of scale and efficiency drives specialization**

**Consolidation of connectivity into a single broadband infrastructure**

# The *Focused* vs. *Expanded* View of 5G



# 100 Giga Bps (& 100 Billion Devices)

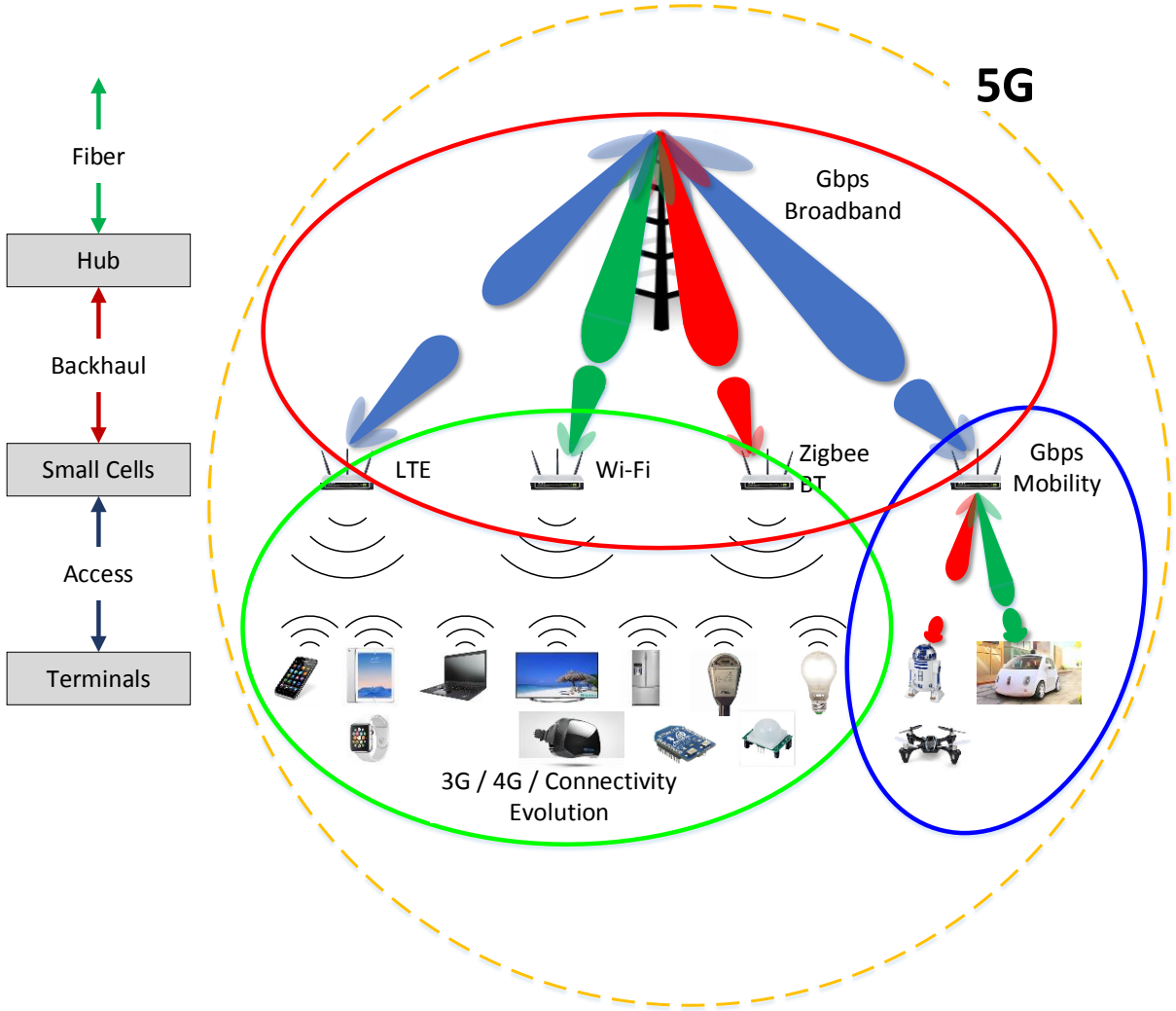
## In a nut shell

- **5G = 100 Giga bps (& 100 billion devices)**


## The challenges

- **Capacity** ➔ How to achieve the 1000x capacity increase?
- **Complexity** ➔ How to build the broadband infrastructure for all verticals, applications, and services with multiple radios and networks?
- **Economics** ➔ How can we create value in achieving these overarching capacity and complexity goals?

# 5G Broadband Infrastructure

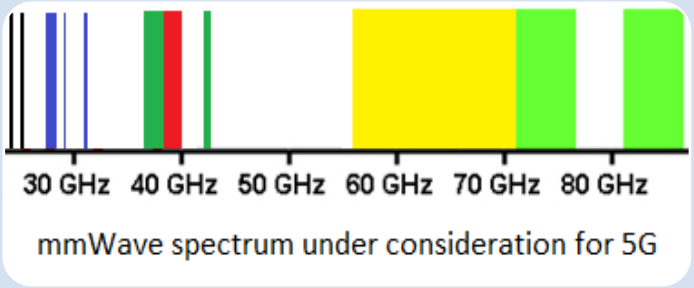


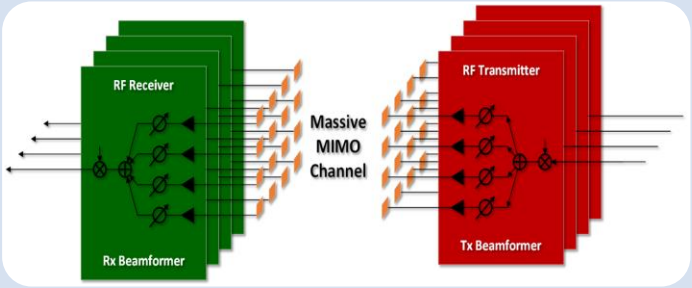

Gbps Broadband (& Backhaul)

Gbps Mobility

Multi-Radio Access Technology Integration

# 5G Key Technologies

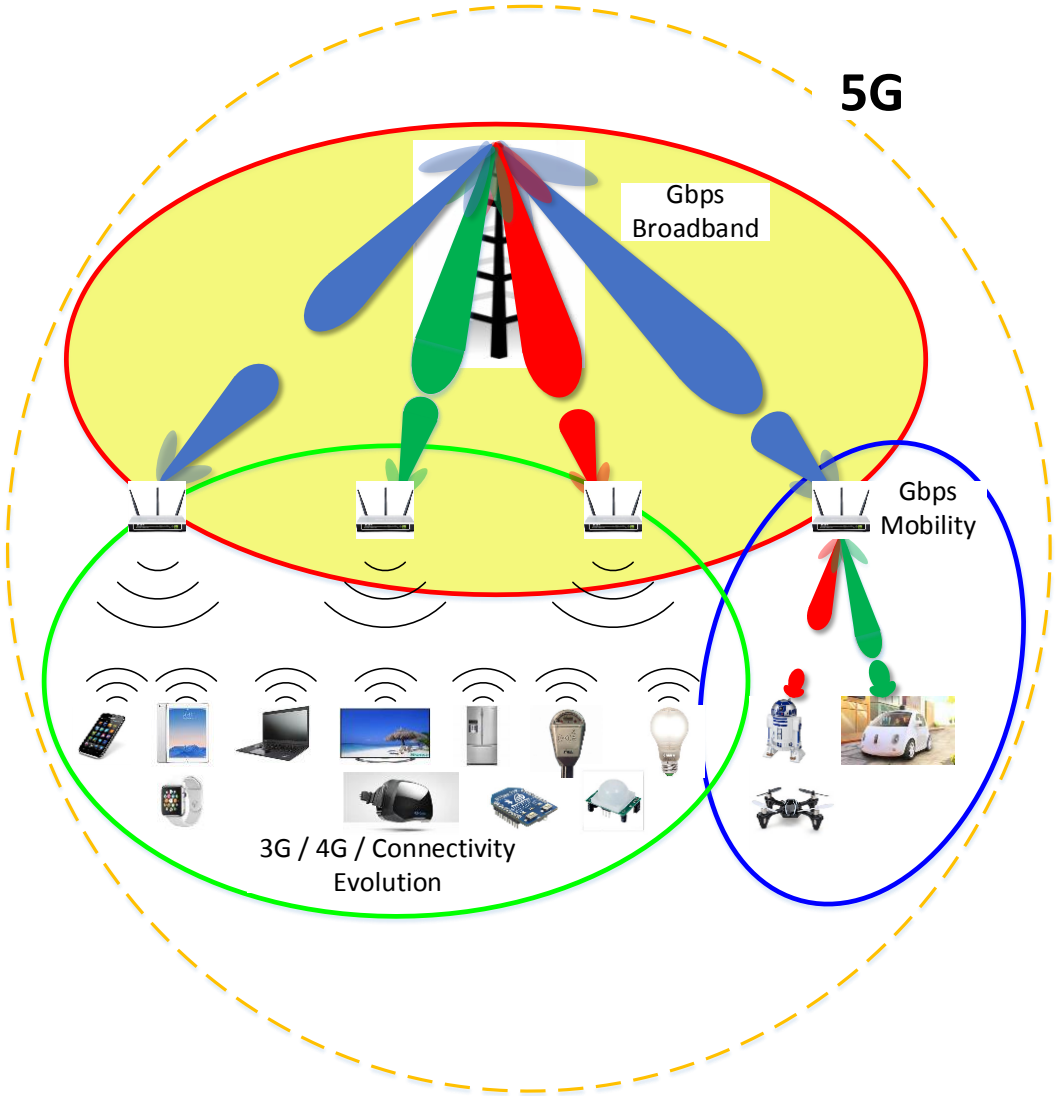



| Millimeter Wave | Massive MIMO | Small Cells |
|---|---|---|
| More Spectrum | Better Spectral Efficiency | Higher Frequency Reuse |

**Strong Value Proposition and Great Synergy in Gbps Broadband and Gbps Mobility**

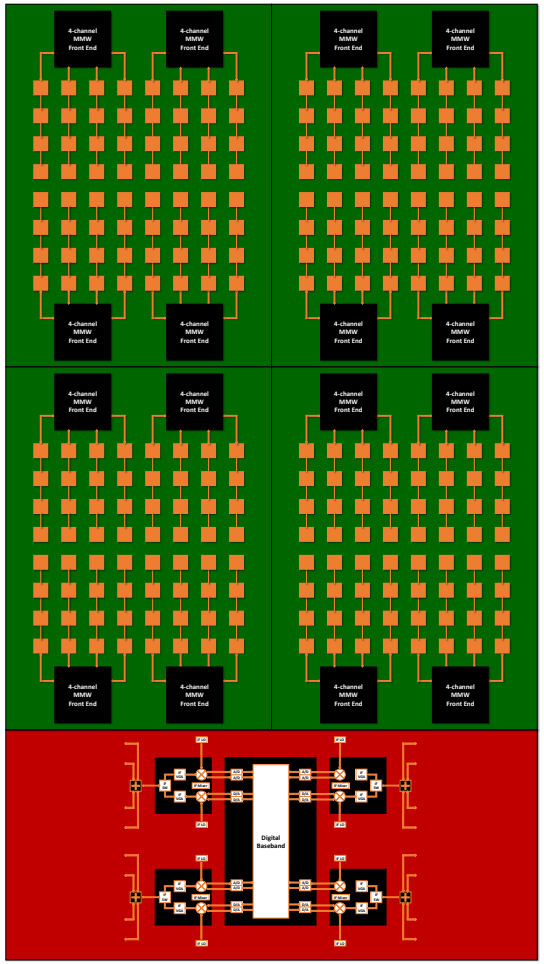
# Millimeter-wave Gbps Broadband

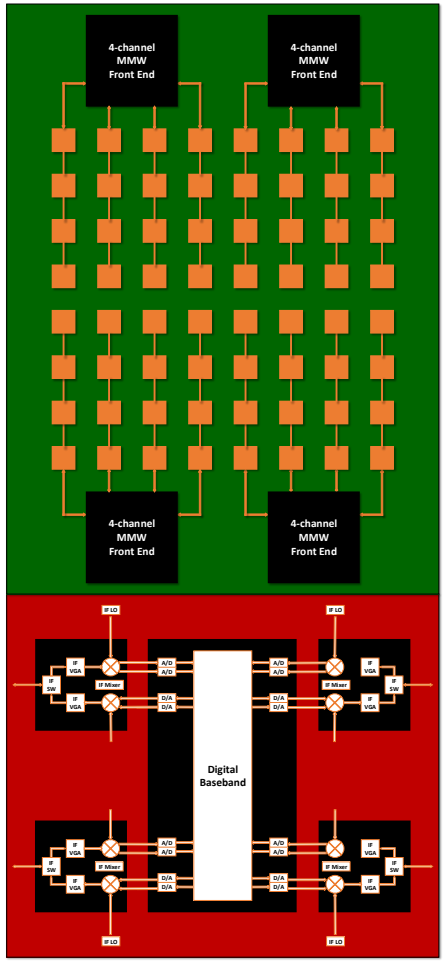



| 39 GHz Gbps Broadband link budget | Downlink long range | Uplink long range | Downlink MU 4-Stream | Uplink MU 4-Stream |
|---|---|---|---|---|
| PA output power (dBm) | 10 | 10 | 10 | 10 |
| Number of PAs | 64 | 16 | 64 | 16 |
| **Total output power (dBm)** | **28** | **22** | **28** | **22** |
| Number of Tx antenna element | 256 | 64 | 256 | 64 |
| Tx antenna element gain (dB) | 6 | 6 | 6 | 6 |
| Antenna & feed network loss (dB) | 3 | 3 | 3 | 3 |
| **Total Tx antenna array gain (dB)** | **27** | **21** | **27** | **21** |
| **EIRP (dBm)** | **55.14** | **43.10** | **55.14** | **43.10** |
| Distance (m) | 1000 | 1000 | 707 | 707 |
| Carrier Frequency (GHz) | 39 | 39 | 39 | 39 |
| Reference point from transmitter (m) | 1.00 | 1.00 | 1.00 | 1.00 |
| Pathloss exponent | 2.00 | 2.00 | 2.00 | 2.00 |
| Propagation loss (dB) | 124.26 | 124.26 | 121.25 | 121.25 |
| Additional pathloss - 50 mm/hr rain (dB) | 15.00 | 15.00 | 10.61 | 10.61 |
| **Total path loss (dB)** | **139.26** | **139.26** | **131.86** | **131.86** |
| Received power (dBm) | -84.12 | -96.16 | -76.71 | -88.75 |
| **Bandwidth (MHz)** | **300** | **300** | **300** | **300** |
| Thermal noise (dBm) | -89.23 | -89.23 | -89.23 | -89.23 |
| Noise Figure (dB) | 7.00 | 7.00 | 7.00 | 7.00 |
| SNR (dB) per Rx antenna element | -1.89 | -13.93 | 5.52 | -6.52 |
| Number of Rx antenna element | 64 | 256 | 64 | 256 |
| Rx antenna element gain (dB) | 6 | 6 | 6 | 6 |
| Rx antenna feed network loss (dB) | 3 | 3 | 3 | 3 |
| **Total Rx antenna array gain (dB)** | **21** | **27** | **21** | **27** |
| Number of MIMO streams | 1 | 1 | 4 | 4 |
| SNR after beamforming per MIMO stream (dB) | **19.17** | **13.15** | **14.54** | **14.54** |
| Implementation loss (dB) | 3.00 | 3.00 | 3.00 | 3.00 |
| Spectral efficiency (bit/channel use) | 5.41 | 3.51 | 15.72 | 15.72 |
| **Throughput throughput (Mbps)** | **1,622** | **1,052** | **4,717** | **4,717** |

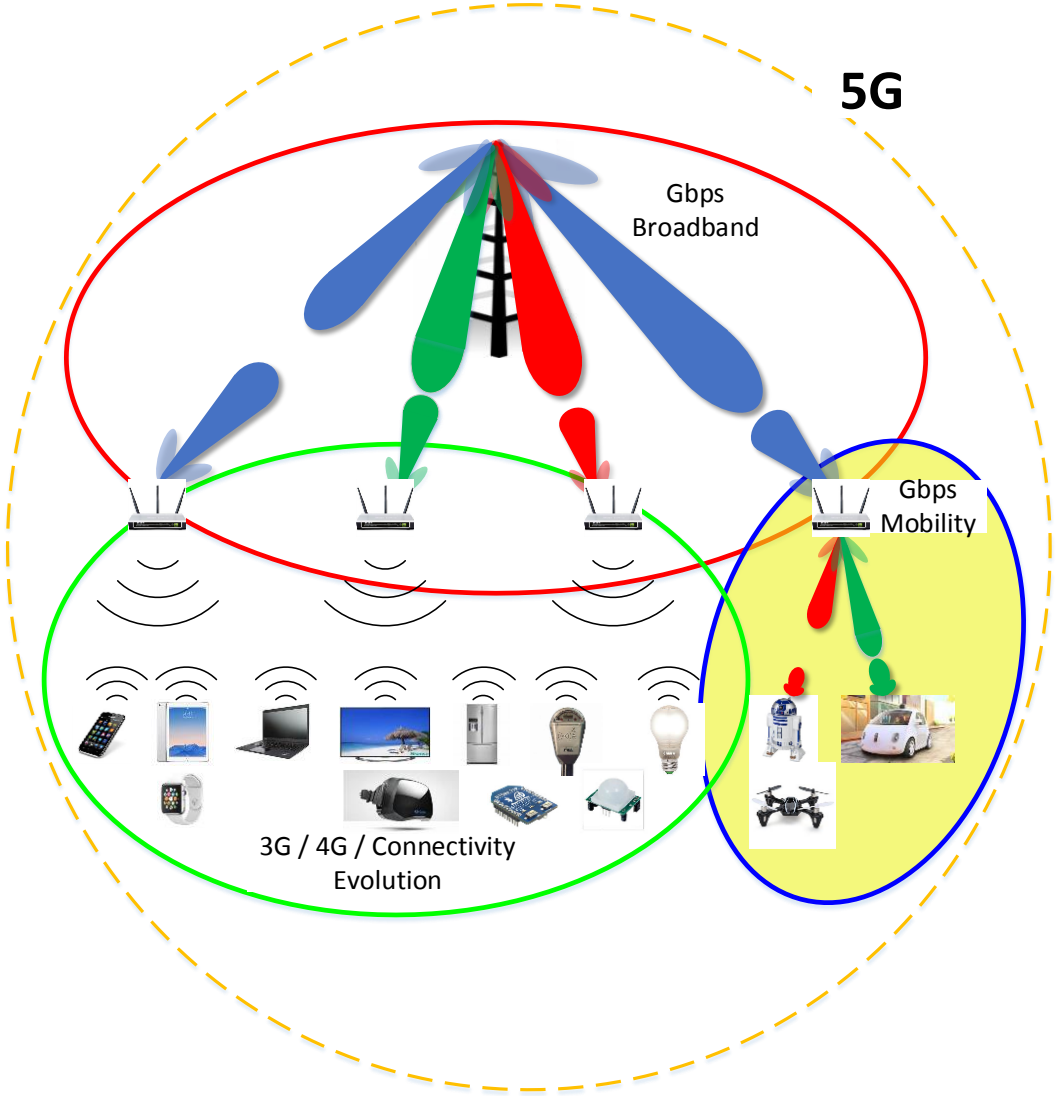
# Gbps Broadband Hub and CPE

- Hub (example)
  - EIRP: 55 dBm
  - Antenna array
    - 256 elements / panel
  - Power Amplifier
    - 10 dBm / PA
    - 64 PAs
- CPE (example)
  - EIRP: 43 dBm
  - Antenna array
    - 64 elements / array
  - Power Amplifier
    - 10 dBm / PA
    - 16 PAs





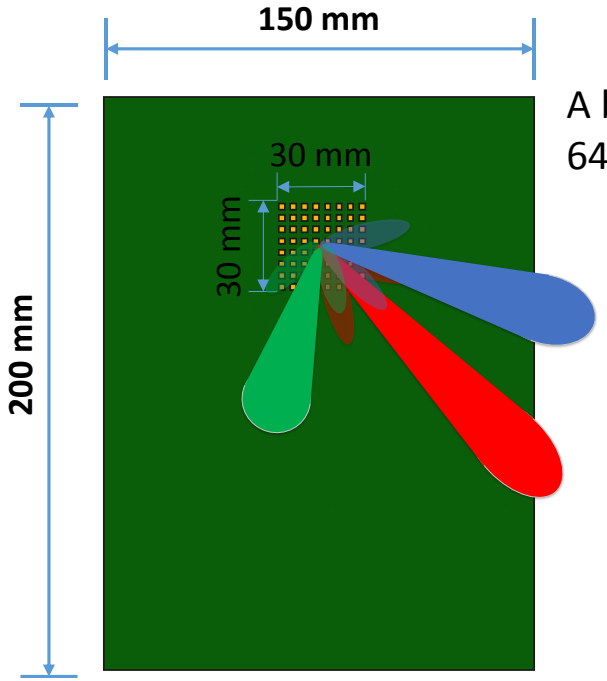
# Millimeter-wave Gbps Mobility



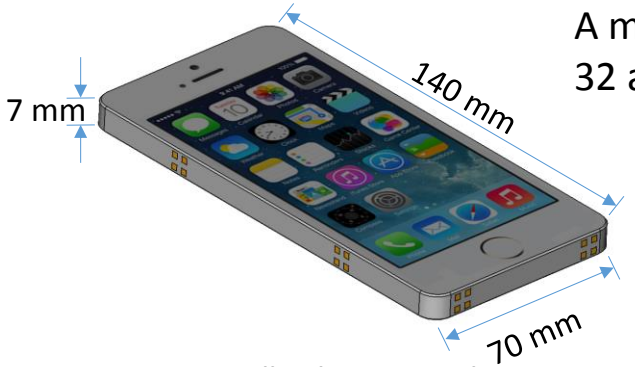

| 39 GHz mobile network link budget | Downlink cell edge | Uplink cell edge | Downlink cell center | Uplink cell center |
|---|---|---|---|---|
| PA output power (dBm) | 20 | 18 | 20 | 18 |
| Number of PAs | 64 | 16 | 64 | 16 |
| **Total output power (dBm)** | **38** | **30** | **38** | **30** |
| Number of Tx antenna element | 256 | 16 | 256 | 16 |
| Tx antenna element gain (dB) | 6 | 6 | 6 | 6 |
| Antenna & feed network loss (dB) | 3 | 5 | 3 | 5 |
| **Total Tx antenna array gain (dB)** | **27** | **13** | **27** | **13** |
| **EIRP (dBm)** | **65.14** | **43.08** | **65.14** | **43.08** |
| Distance (m) | 500.00 | 500.00 | 100.00 | 100.00 |
| **Path loss = 72 + 29.2log10(d) (dB)** | **150.81** | **150.81** | **130.40** | **130.40** |
| Received power (dBm) | -85.67 | -107.73 | -65.26 | -87.32 |
| Bandwidth (MHz) | 500.00 | 500.00 | 500.00 | 500.00 |
| Thermal noise (dBm) | -87.01 | -87.01 | -87.01 | -87.01 |
| Noise Figure (dB) | 7.00 | 5.00 | 7.00 | 5.00 |
| SNR (dB) per Rx antenna element | -5.66 | -25.72 | 14.75 | -5.31 |
| Number of Rx antenna element | 16 | 256 | 16 | 256 |
| Rx antenna element gain (dB) | 6 | 6 | 6 | 6 |
| Rx antenna feed network loss (dB) | 5 | 3 | 5 | 3 |
| **Total Rx antenna array gain (dB)** | **13** | **27** | **13** | **27** |
| SNR after beamforming (dB) | **7.39** | **1.37** | **27.80** | **21.78** |
| Implementation loss (dB) | 3.00 | 3.00 | 3.00 | 3.00 |
| Number of MIMO streams | 1 | 1 | 8 | 8 |
| Spectral efficiency (bit/channel use) | 1.91 | 0.75 | 42.20 | 27.06 |
| System overhead | 40% | 40% | 40% | 40% |
| Duty cycle | 62.50% | 37.50% | 62.50% | 37.50% |
| **Throughput throughput (Mbps)** | **357.20** | **84.81** | **7912.07** | **3044.15** |

# Gbps Mobility Base and Mobile Station

- Base Station
  - EIRP: 53 – 65 dBm
  - Antenna array
    - 64 – 256 elements / panel
  - Power Amplifier
    - 17 – 27 dBm / PA
    - 16 – 64 PAs
- Mobile Station
  - EIRP: 30 – 43 dBm
  - Antenna array
    - 4 – 32 elements / array
  - Power Amplifier
    - 10 – 20 dBm / PA
    - 4 – 16 PAs



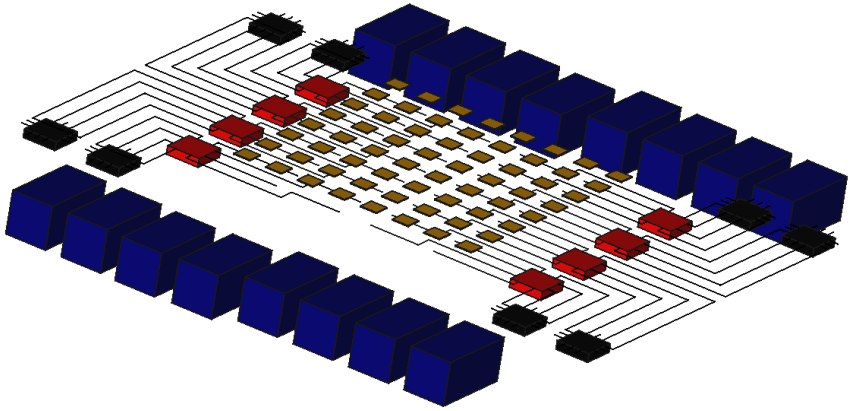

A base station panel with
64 antennas at 39 GHz

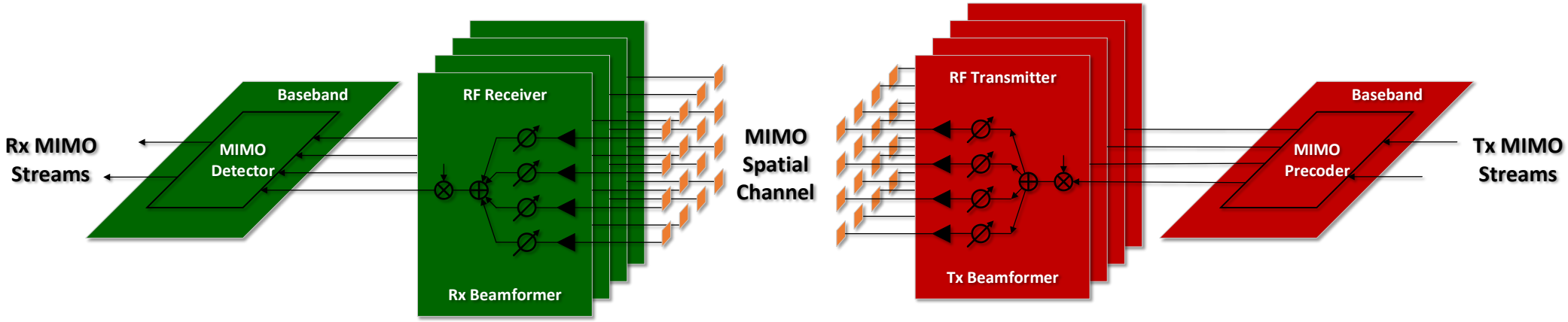



A mobile station with
32 antennas at 39 GHz

# Hybrid Spatial Processing with Massive Antenna Arrays

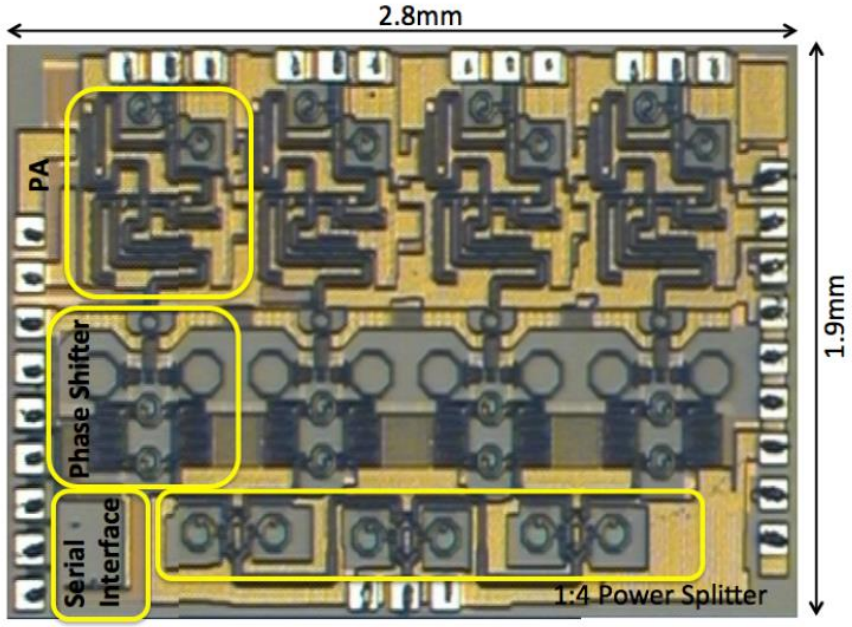
- Antenna array – Millimeter wave meets massive MIMO
  - Advances in high-frequency low-loss PCB materials (e.g., ceramic filled PTFE) makes it possible to design complicated mmW systems on a single PCB
  - Possible to include sophisticated passive filters and antennas on PCB due to advances in PCB fabrication and the small dimension of antenna elements
- How to deal with massive antenna arrays
  - Antenna sub-arrays – Only keep the useful spatial DoF
  - Analog Beamforming – Long term spatial characteristics
  - Digital Beamforming – Short term spatial characteristics

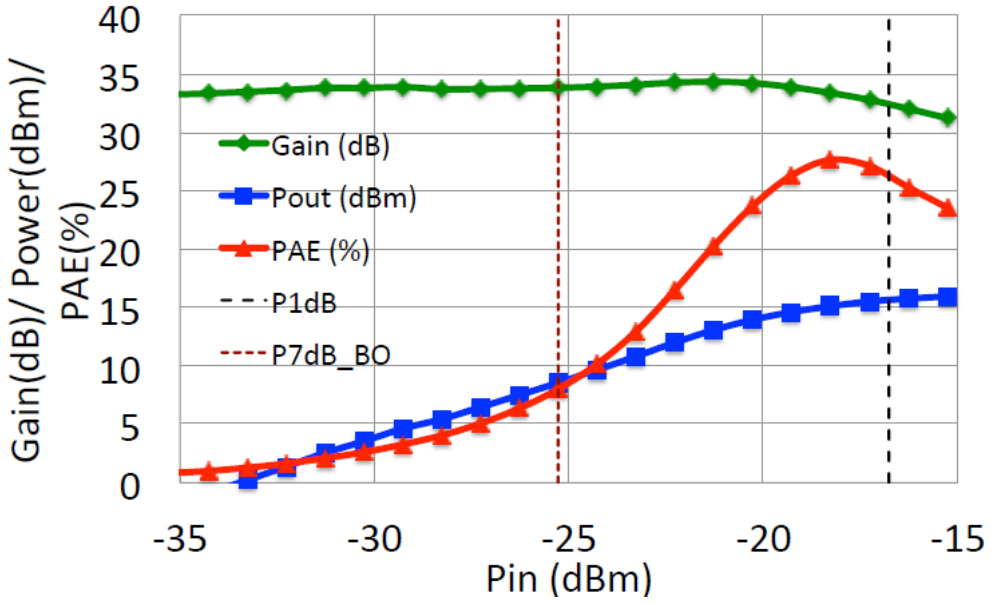




# Power Amplifiers

- One or few big amplifiers ➔ Lots of small amplifiers
- Higher integration and lower cost by using SiGe or GaAs
- Good linear PAE efficiency at mmWave frequencies (5 – 10%)
- Multi-element beamformer & PA an attractive solution for driving large antenna arrays




Reference: Sarkar, A.; Greene, K.; Floyd, B., "A power-efficient 4-element beamformer in 120-nm SiGe BiCMOS for 28-GHz cellular communications," *Bipolar/BiCMOS Circuits and Technology Meeting (BCTM), 2014 IEEE* , vol., no., pp.68,71, Sept. 28 2014-Oct. 1 2014

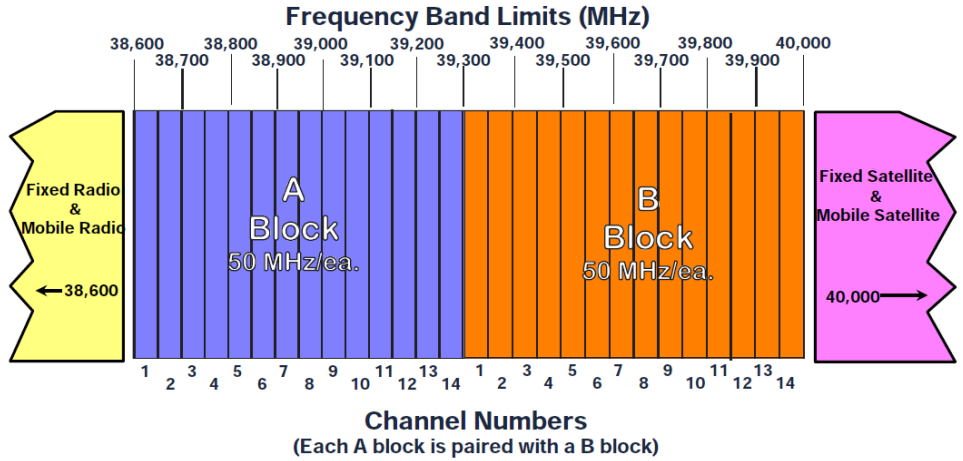
# 5G Gbps Mobility in the Making

| | |
|---|---|
| Mar 2011 | • **WCNC 2011 Tutorial**, "Beyond 4G mobile broadband: Unleashing 3-300GHz spectrum" |
| Dec 2012 | • NTT Docomo, 10 Gbps uplink in 11 GHz band, 400 MHz bandwidth |
| May 2013 | • Samsung, 1 Gbps up to 2 km in 28 GHz band, 500 MHz bandwidth |
| Jun 2014 | • Ericsson, 5 Gbps in 15 GHz band, 400 MHz bandwidth |
| Oct 2014 | • Samsung, 7.5 Gbps stationary (1.2 Gbps @ >100 kmph) in 28 GHz band, 800 MHz bandwidth |
| Dec 2014 | • Nokia, 2 Gbps in 70 GHz band, 1 GHz bandwidth |
| Mar 2015 | • Ericsson, 5.8 Gbps in 15 GHz band, 400 MHz bandwidth<br>• NTT Docomo, 4.5 Gbps in 15 GHz band, 400 MHz bandwidth |

# Spectrum, Spectrum, Spectrum

## Millimeter-wave Spectrum for Gbps Broadband available today

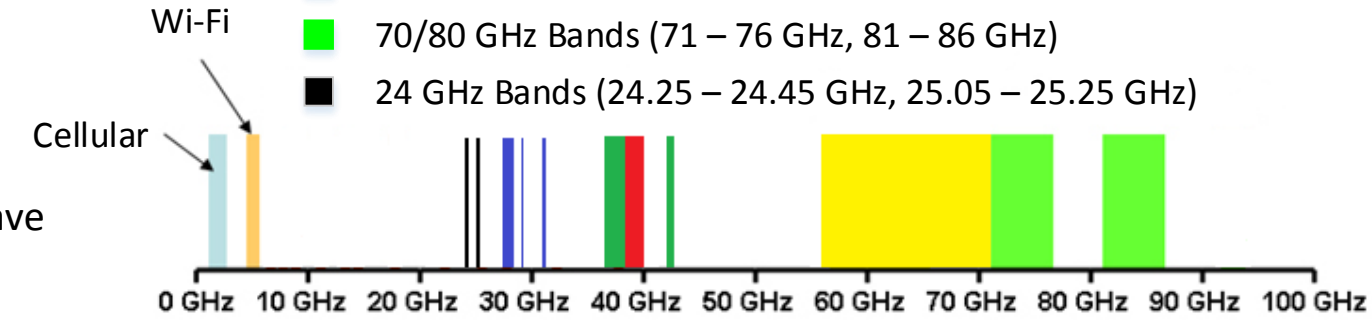
- LMDS band (1.3 GHz) & 39 GHz band (1.4 GHz)
- Exclusively licensed in geographic service areas




## Millimeter-wave Spectrum for Gbps Mobility

- FCC issued NOI for 5G mobile services on 10/17/2014
  - 6 bands under discussion
- Comments closed on 1/15/2015
  - 48 comments received
- Reply comments closed on 2/18/2015
  - 18 reply comments received
- Overwhelming support of using millimeter wave spectrum for 5G mobile services

- LMDS Bands (27.5 – 28.35 GHz, 29.1 – 29.25 GHz, 31 – 31.3 GHz)
- 39 GHz Band (38.6 – 40 GHz)
- 37/42 GHz Band (37.0 – 38.6 GHz, 42.0 – 42.5 GHz)
- 60 GHz Bands (57 – 64 GHz, 64 – 71 GHz)
- 70/80 GHz Bands (71 – 76 GHz, 81 – 86 GHz)
- 24 GHz Bands (24.25 – 24.45 GHz, 25.05 – 25.25 GHz)

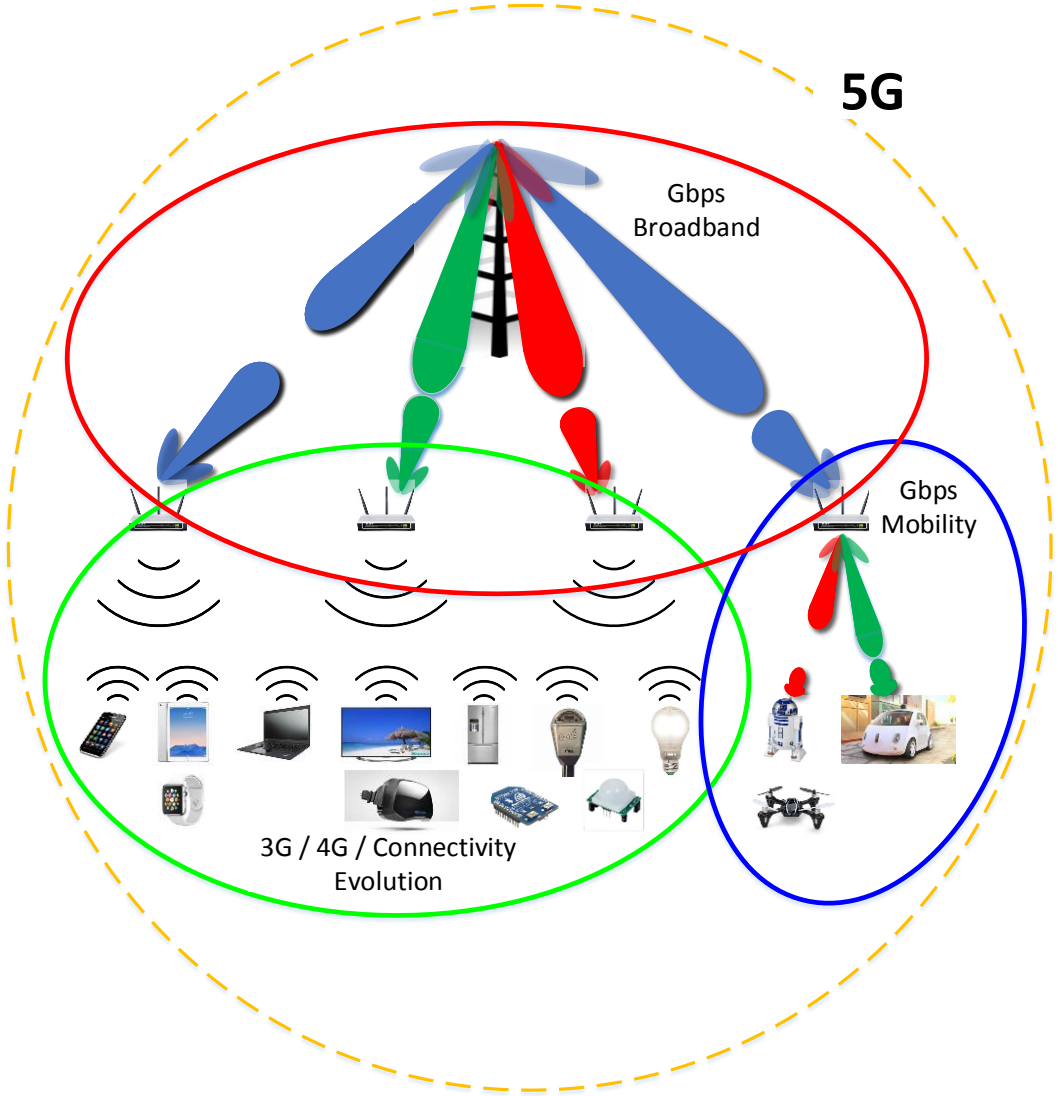


# Network Transformation towards 5G

Multi-RAT integration to expand support for new applications & services

MMW Gbps Broadband to facilitate massive cell densification

MMW Gbps Mobility to strengthen value proposition and foster killer applications



# Summary

Our world is being digitized, connected, and mobilized

5G *can* be the communication infrastructure of this new world

Takeaway points in transforming the current networks into 5G

- Create value beyond existing applications services and integrate with radio access technologies that best suit the application
- Build a broadband infrastructure that is flexible, scalable, and cost effective
  - Significant technology and spectrum synergy between mmW Gbps Broadband and mmW Gbps Mobility
  - Spectrum and technology are available **NOW** for mmW Gbps Broadband