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Wireless Innovation Allows Networks to Compete & Compliment Fiber

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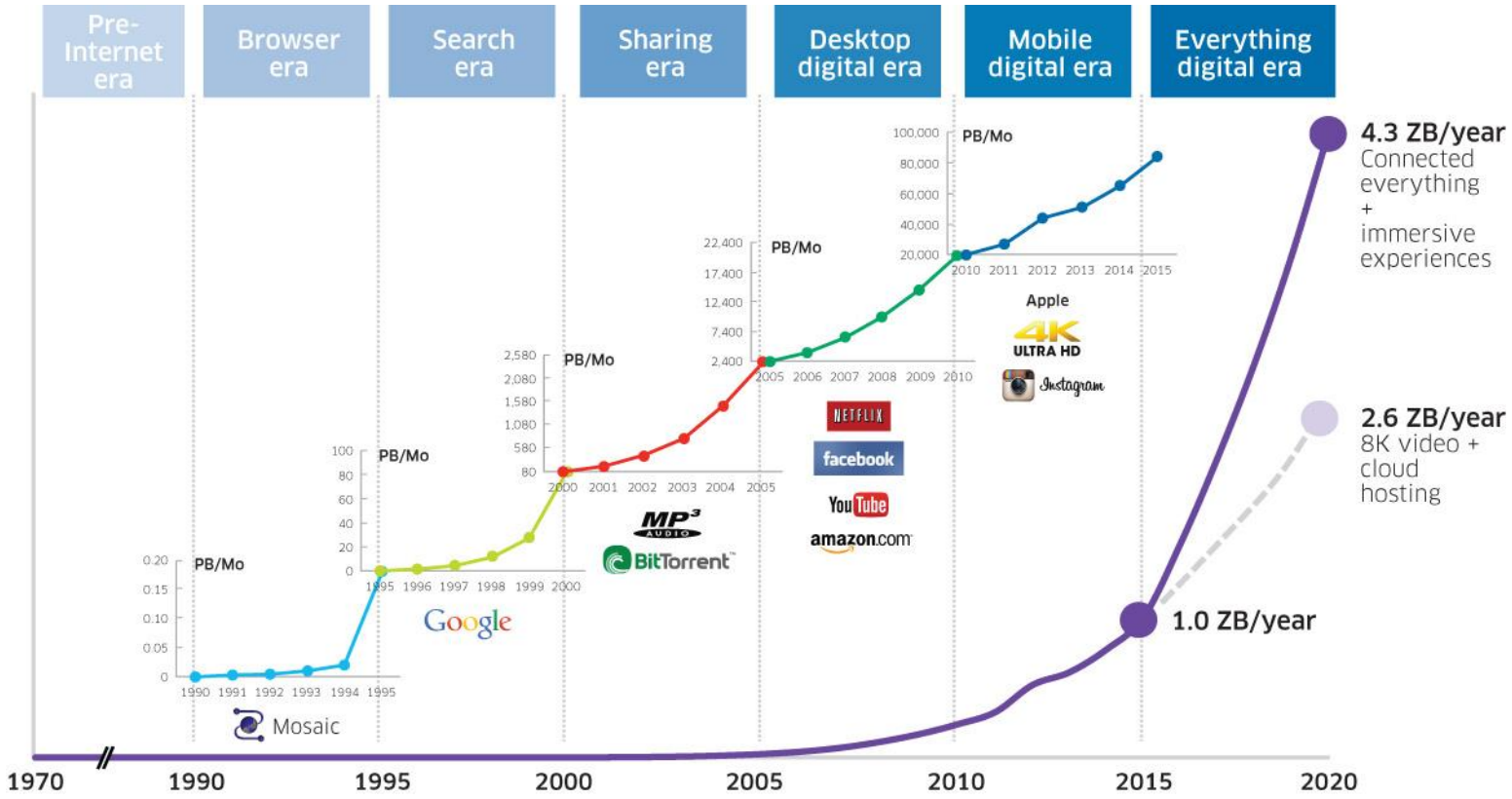
Cambium Networks at a Glance

- **Spun out of Motorola Solutions** in October 2011, **IPO on NASDAQ (CMBM) in June, 2019**
- Pioneer in Point-to-Multipoint & Point-to-Point **IP Wireless Broadband Solutions**
- Focused on wireless connectivity; **2 meters to 246km** – people, places & things
- HQ outside of **Chicago, IL**
- **600+ employees** across **6 continents**
- More than **7 million nodes** shipped totaling over **$1.5B**
- Emerging leader in **IIoT** and **5G like solutions**

Cambium Networks' Wireless Fabric

Overall global market trends and opportunities

- Increasing bandwidth demand drives market trends, opportunities and development strategies



Increasing number of sophisticated and bandwidth-hungry devices

Constant increase in high quality and complex web content

NEED

Ever increasing performance of network infrastructure

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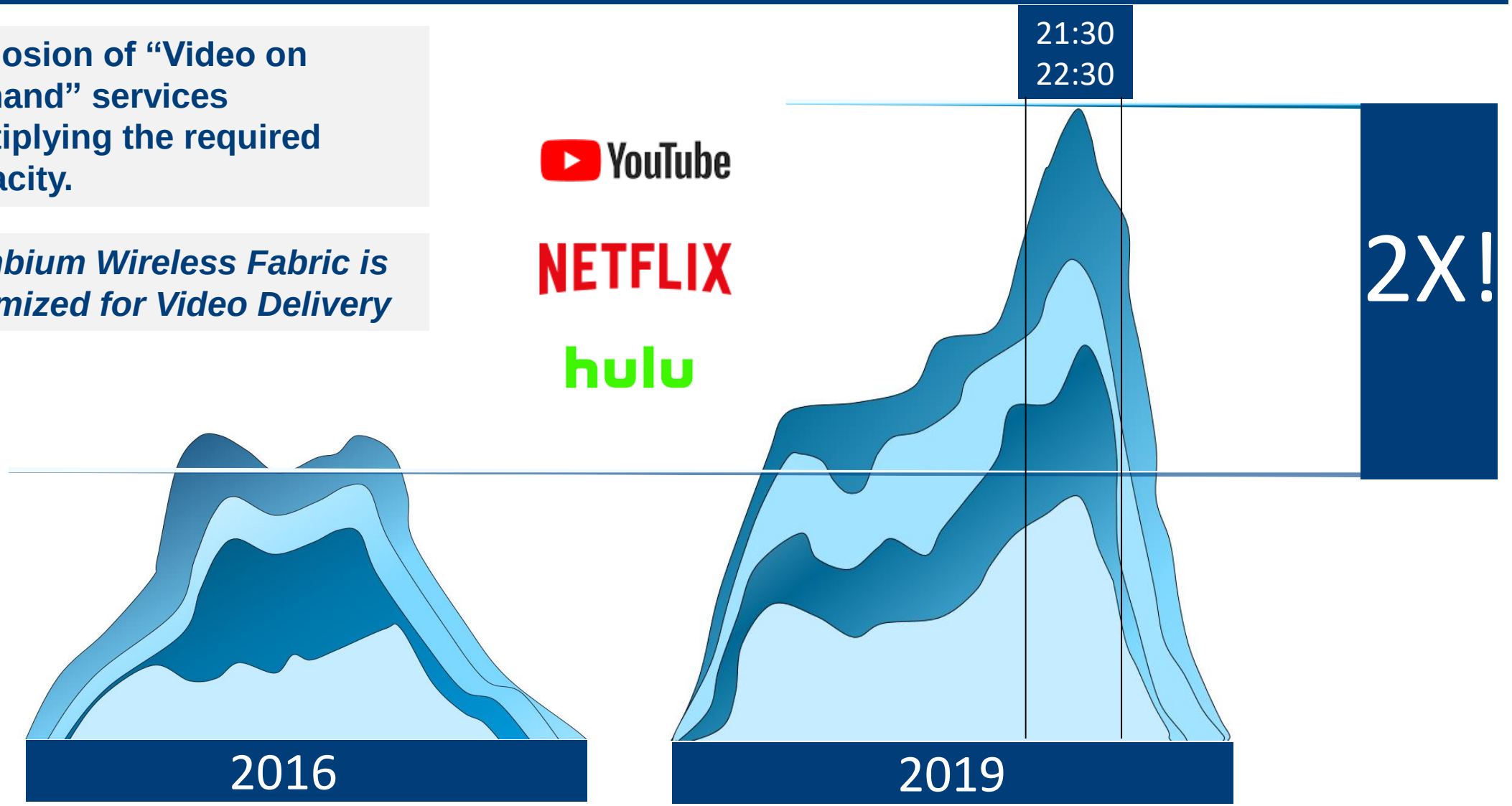
Evolving Traffic Profiles of Networks - Consumer

Explosion of "Video on Demand" services multiplying the required capacity.

Cambium Wireless Fabric is optimized for Video Delivery



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Key Example

A regional operator using Fixed Wireless Solutions:

- **Netflix report (Italy 2017): ISP Speed Index** https://ispspeedindex.netflix.com/country/italy
  - Average speed of Netflix users based on Italian providers' connections in «prime time» evening.

ITALY

ISP LEADERBOARD - MAY 2017

RANK	ISP	SPEED Mbps	PREVIOUS Mbps	RANK CHANGE	TYPE
1	Vodafone Italy	3.53	3.47		
2	Fastweb	3.50	3.42		
3	Telecom Italia	3.39	3.32		
4	Wind	3.19	3.14		
5	Tiscali	3.17	3.08		
6	EOLO - NGI	2.98	2.95		
7	Vodafone TeleTu	2.86	2.67		
8	Linkem	2.61	2.50		

Today's Results

Netflix report (January, 2020): ISP Speed Index, https://ispspeedindex.netflix.com/country/italy

ITALY

ISP LEADERBOARD - JANUARY 2020

RANK	ISP	SPEED Mbps	PREVIOUS Mbps	RANK CHANGE	TYPE
1	EOLO	4.25	4.39		Wireless
2	Vodafone Italy	4.19	-		Fiber, DSL
3	Telecom Italia	4.14	4.30		Fiber, DSL, Satellite
4	Fastweb	4.09	4.24		Fiber, DSL
5	Wind	4.03	4.18		Fiber, DSL
6	Tiscali	3.80	3.98		Fiber, DSL
7	Linkem	3.25	3.41		Wireless

Fiber Cable DSL Satellite Wireless

#1

The only pure wireless company in top 7

- Eolo has led the chart for the past 7 months in a row.

Advances in Wireless Radio Technology

Implementation of 5G and 5G-like Features

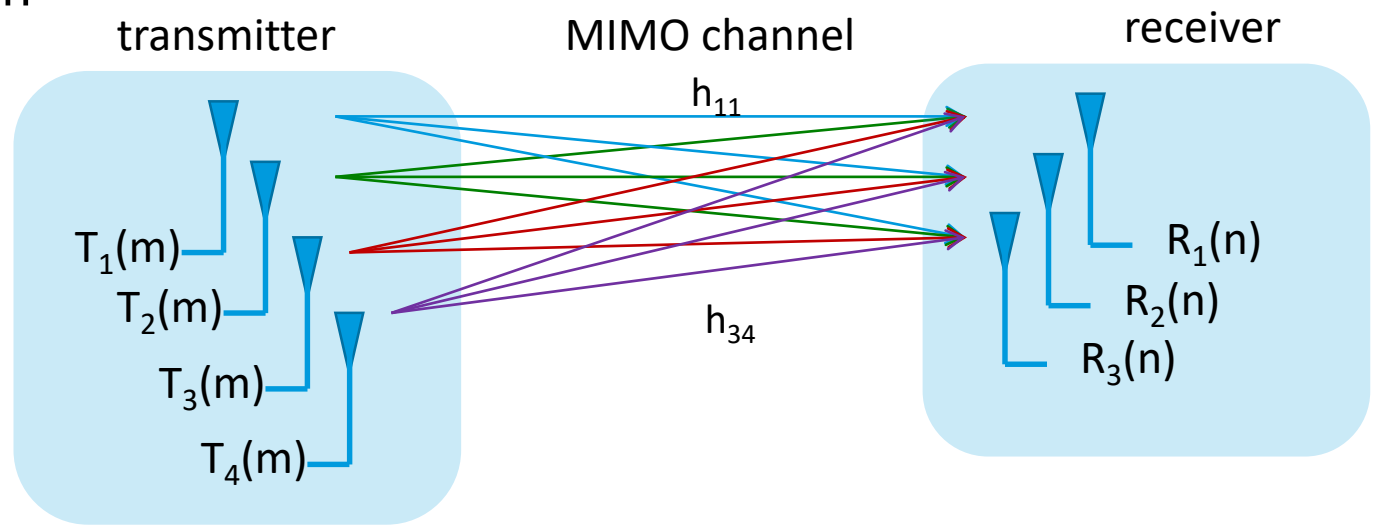
Advances in the RAN (radio access network) can exploit 5G mobile innovations for FWA (fixed wireless access)

- MU-MIMO, Massive MIMO, Beamforming
- Key 5G NR features for FWA
- Hardware for multi-antenna wireless
- “Openness” in the RAN

MIMO, MU-MIMO

Approaching Shannon channel capacity limits in SISO systems

- MIMO : Multiple Input Multiple Output
  - channel H matrix with elements h_{ij}
    - h_{ij} : individual SISO channels
  - with random h_{ij} also get min(M,N) capacity improvement
    - relevant to multipath rich environments
  - requires Channel State Information
- MU-MIMO : Multi-user MIMO
  - separated users at one end
    - Same H channel capacity
    - Exploit diversity of paths
  - keep complexity at base station



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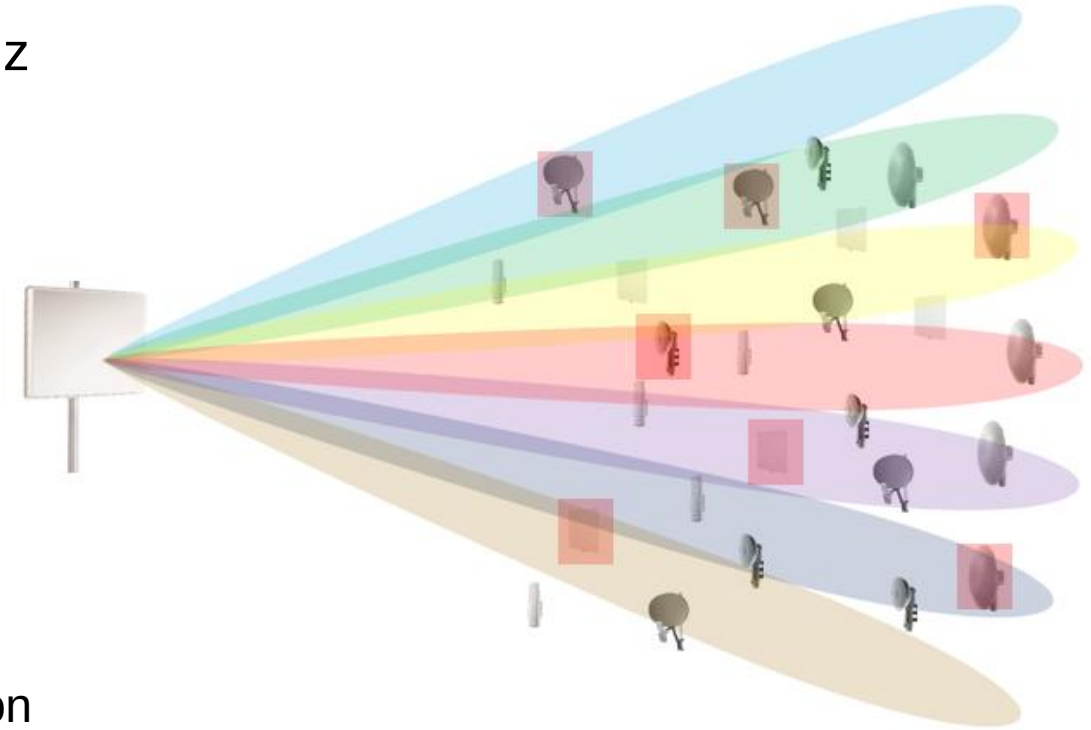
Massive MIMO

- MU-MIMO where base station M >> user N
  - term originated by Dr. Marzetta of Bell Labs around 2010
    - was considering the mobile use case
  - M=200 with 0.5 x 0.5 m planar array at 3.5 GHz
  - approach capacity gain N
    - exploits 3D separation of users
  - TX power reductions
    - high array gain
  - reduced NLOS fading
    - high diversity gain
  - how to get and process the h's ?
    - TDD reciprocity to obtain CSI at the base station
      - 200 x 2 per user
    - simple beamforming strategies

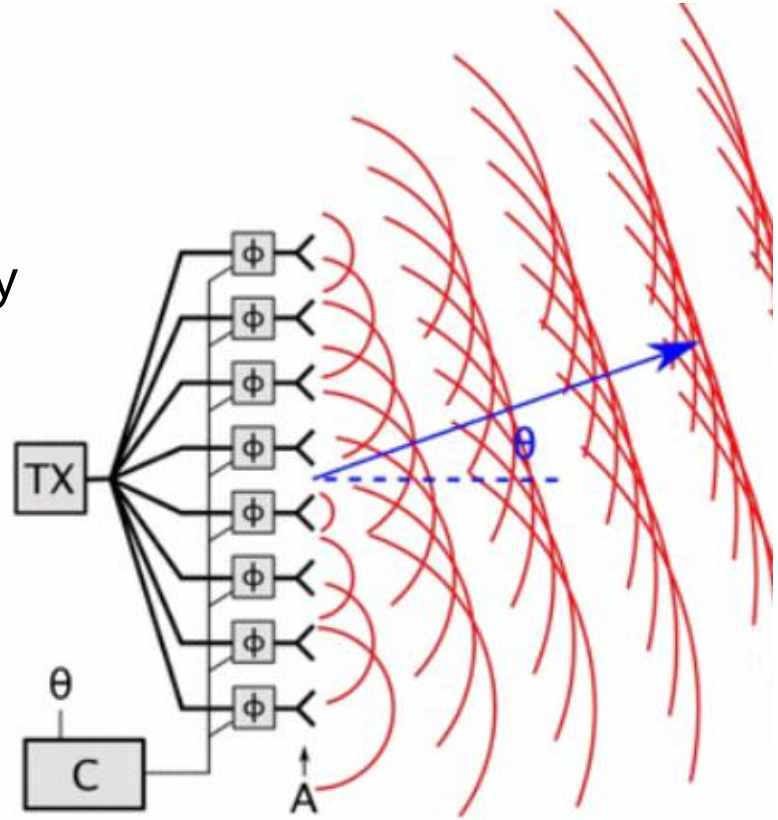


Dynamic Beamforming

Needed for mobility at higher frequencies

- effective area drops with wide beam width antennas

- Dynamically synthesize propagating wave fronts
  - beam steered by applying varying phase offset across an array
  - requires calibrated controls and defined antenna array
- Digital domain
  - precise – enable forming deep nulls
  - multiple beams from array at any instance
- Analog domain
  - lower power consumption and cost
  - single beam from array at a time



NOMA : Non-orthogonal multiple access

Simultaneous uplink from two users : constellation

User 1 : low SNR

User 2 : high SNR

Composite RX signal

Decode both using successive interference cancellation

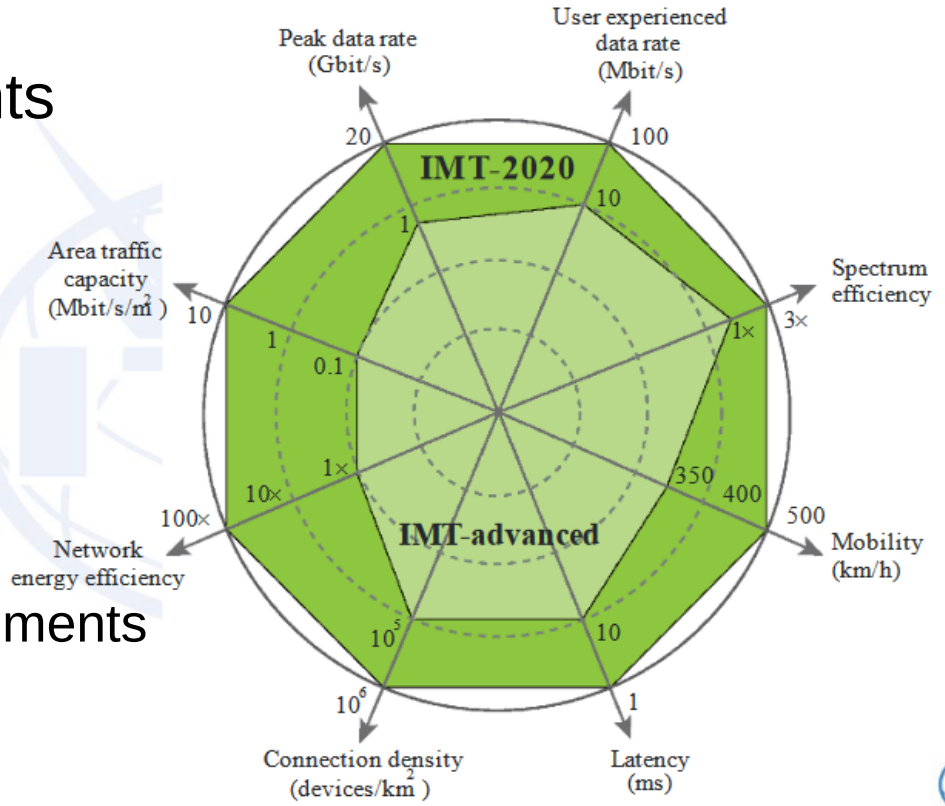
- Decode user 2
- Regenerate user 2 RX and subtract from RX signal
- Decode user 1

NOMA offers potential capacity gains compared to OFDMA/TDMA

- Lower gains compared to spatial multiplexing ~50%

5G and 5G NR

- 5G mobile communication standard requirements
  - IMT-2020 published by the ITU-R in 2012
    - enhanced Mobile Broad Band
    - Ultra Reliable Low Latency Communications
    - massive Machine Type Communications
- 3GPP's 5G NR standard
  - Part of composite standard to meet IMT-2020 requirements
  - New air interface required
    - Higher frequency/bandwidth operation
    - Beam centric design/multi-antenna transmission
    - Ultra lean design/forward compatibility
    - Flexible duplex scheme/Dynamic TDD
    - Lower latency



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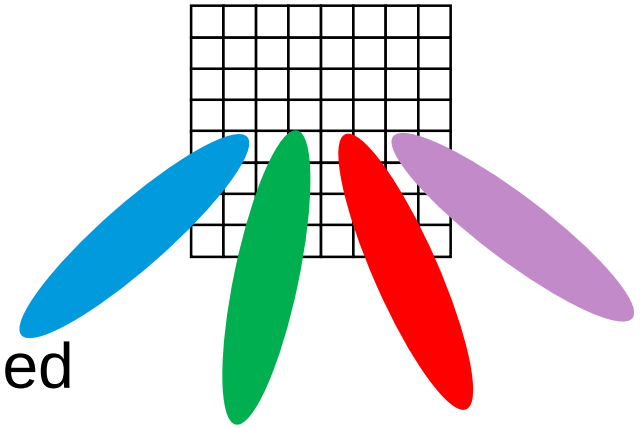
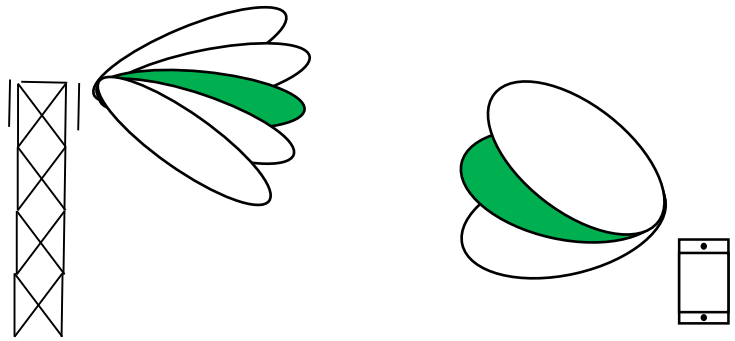
Key 5G NR features for FWA : Beam centric design

- Support for a large number of steerable antenna elements
  - 100’s to 1000’s elements : no hard limit
  - Suitable for
    - beamforming
    - Massive MIMO
- All physical channels and reference signals can be beam formed
  - A necessity in mm-wave bands
    - Up to 64 SSBs (Synchronisation Signal Blocks)
  - Minimal always on transmissions : SSB and SIB1 (system information block)
    - UE can request data from additional SIBs during attachment
    - 1/100 reduction in transmissions for inactive cell
  - Front loaded DMRS (demodulation reference signals)
    - Reduced latency forming channel estimate
  - Flexible ACK timing



Key 5G NR features for FWA : Beam centric design

- MU-MIMO users
  - Up to 12 layer DMRS
    - MU-MIMO channel estimates not affected by inter-beam interference
- Channel sounding
  - Sounding : CSI-RS (channel state information RS), SRS (sounding RS)
  - Type II CSI feedback targets MU-MIMO
    - UE provides high resolution mag/phase from the strongest beams
    - Low mobility
      - PMI report uses 100’s bit
      - relevant to FWA
- Extensive beam management facilities and processes
  - Support beam forming at both sides of the link
  - Facilities support analog and digital domain beamforming



Key 5G NR features for FWA

- New spectrum
  - ~ 5 GHz in mm-wave bands
  - Additional spectrum around 3-4 GHz

REMARKS OF FCC CHAIRMAN AJIT PAI on 21 JUNE, 2019 "All in all, our auctions this year will free up for the commercial marketplace almost 5 gigahertz of spectrum for flexible use."

- OFDM with flexible numerology
  - Multiple subcarrier spacing
  - Steerable antenna support
  - Phase Tracking Reference Signals

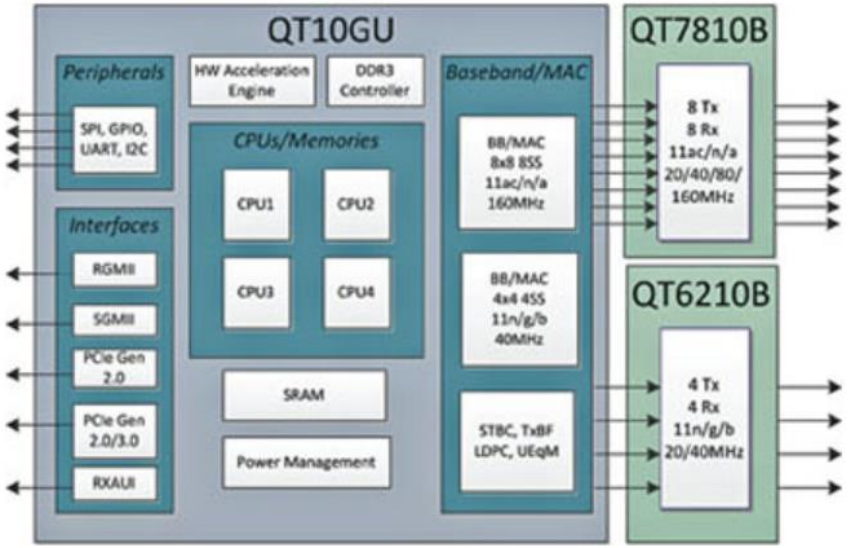
subcarrier spacing	Max bandwidth	Min bandwidth	symbol duration	cyclic prefix	slot time
kHz	MHz	MHz	us	us	us
15	50	3.6	71.35	4.69	1000.00
30	100	7.2	35.68	2.34	500.00
60	200	14.4	17.84	1.17	250.00
120	400	28.8	8.92	0.59	125.00

  - mm-wave compromise at high SNR

Hardware for multi-antenna wireless

- Ongoing semiconductor improvements
  - Moore's law : 5nm from TSMC and Samsung
  - Cheaper processes for RF

- WiFi RFIC chips
  - Standards support for increasing antennas
  - Trend to separate baseband and RFICs
  - Significant cost reductions/chain
- Component miniaturization
  - SMT packages
  - High frequency multi-pin connectors



Quantenna .11ac chipset

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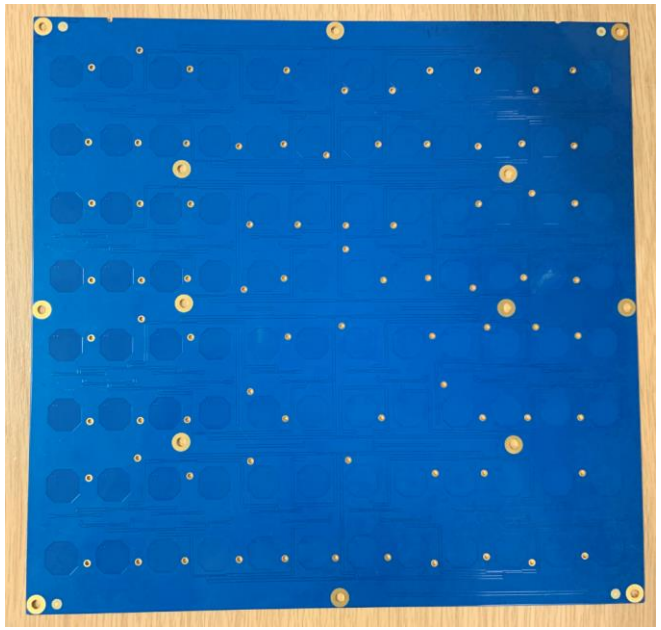
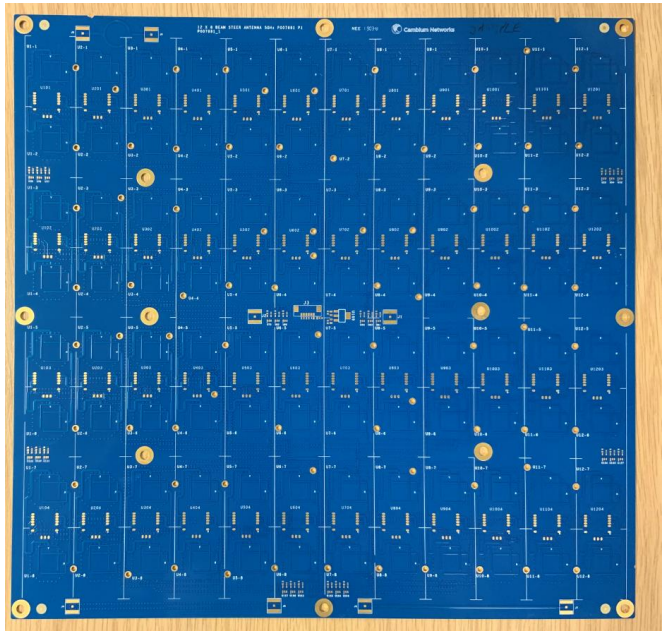
Hardware for multi-antenna wireless

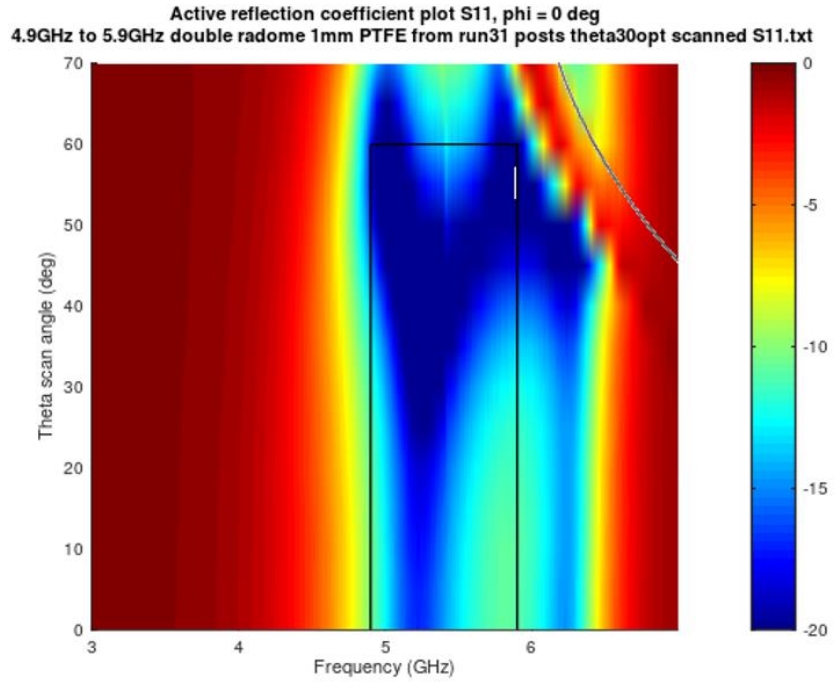
Antenna technology

- Improving RF materials
  - Lower loss at higher frequencies
  - Lower cost substrates
  - FR4 like substrates
    - Easier manufacturing vs soft PTFE

- Scanned antenna design methods
  - 0.5 wavelength element spacing
    - high mutual coupling between elements
  - maximise the number of beams in given aperture







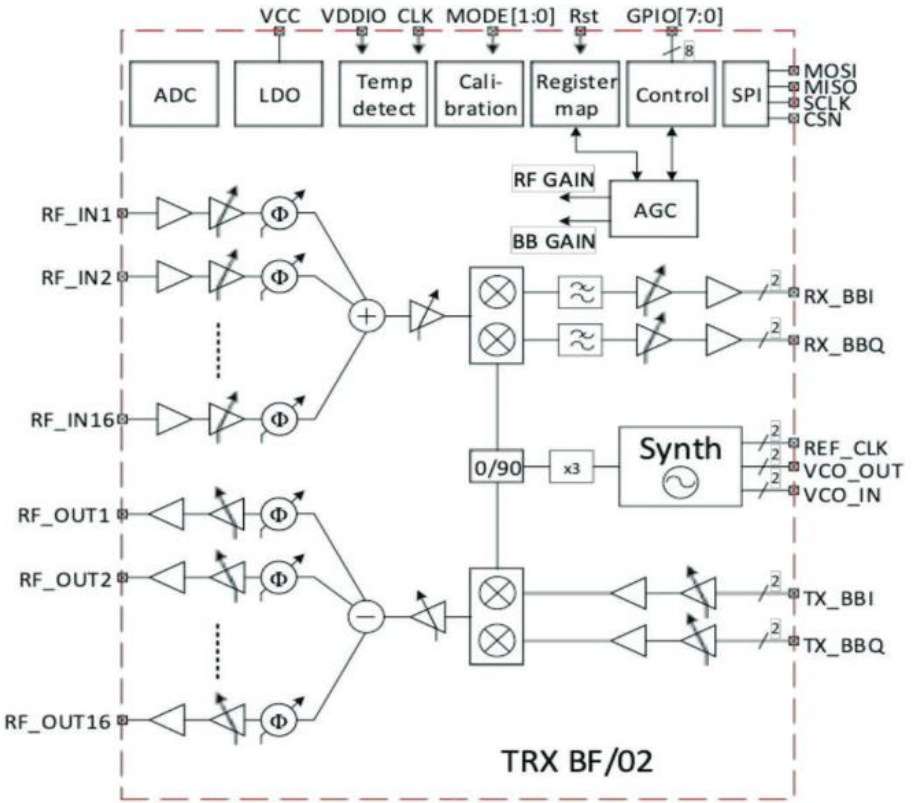
Hardware for multi-antenna wireless

RFICs and modules for 28 GHz

- Highly integrated devices
- Analog beamforming
- TDD

Low Latency Beam Steering™ by Anokiwave

SIVERSIMA PRODUCT BRIEF
TRX BF/02



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Openness in the RAN

- RAN processing on x86 processors
  - Phy processing enabled by AVX2/AVX512 instructions
    - LDPC Forward Error Correction is a challenge
      ~10 iterations of min-sum algorithm/bit
  - Software supporting LTE/5G NR
    - Amarisoft
    - OpenAirInterface Alliance (open source)
    - srsLTE (open source)
    - Intel's FlexRAN libraries

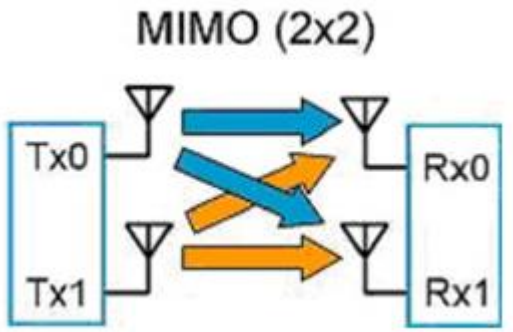
- Flexible RAN architectures
  - Multiple efforts to partition the RAN
  - RRH/Centralised Unit/Distributed Unit interfaces in 5G NR TR 38.801
  - nFAPI standard from Small Cell forum details functional split interfaces
  - transmission requires regulatory approval

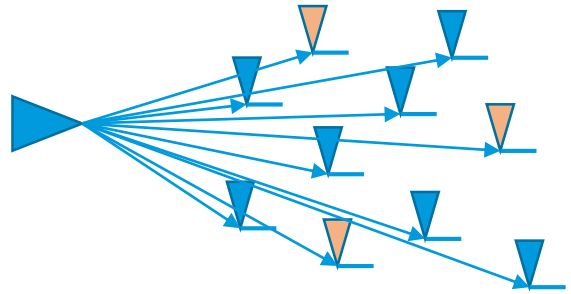
Practical Implementation in a Proprietary System

- All the innovations discussed are driven by 5G and advancing applications
- But what about the applicability to a Fixed Wireless Solution?
- What follows is true innovation in making these techniques work to produce an affordable, purpose-built, fixed wireless system that allows Operators to compete with and compliment alternative networks such as fiber.

Road to Massive MU-MIMO

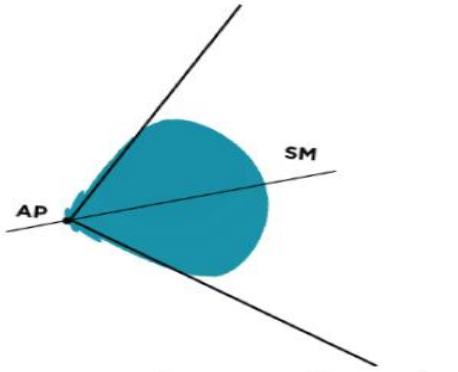
- MIMO: technology to multiply the capacity of the wireless connection without requiring additional spectrum
  - Single polarization → Dual polarization: double the throughput (2x2 system)
- More antennas can be added, with diminishing returns
  - Potential capacity increase at the expense of higher complexity of signal processing and antenna design
- Beyond 8x8 MIMO: “Massive” systems
- Increases capacity between two wireless nodes: benefits one subscriber at a time
  - If a subscriber does not have the same capabilities (same number of antennas), there is no benefit for the system
- MU-MIMO: allow an Access Point (AP) to communicate to several subscribers simultaneously



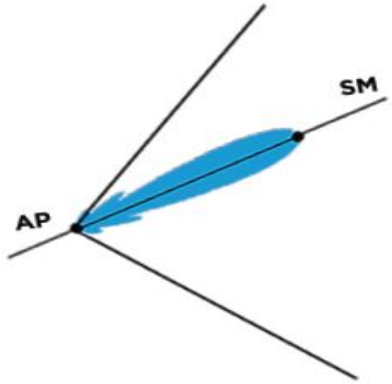


Spatial Multiplexing

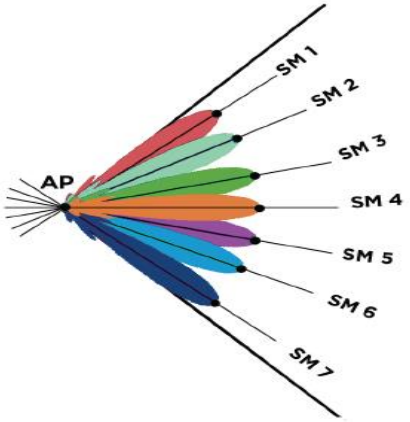
- Making concurrent transmissions possible in the same wireless spectrum by using physically separated radio beams
- Beamforming: antennas are tuned such that their radio beam is targeted (or formed) to overlap a specific subscriber
- Each beam in spatial multiplexing is much narrower than a typical sector beam, allowing multiple beams to be formed without overlapping
- Channel State Information (CSI) available at the AP through the *sounding* process



Antenna Pattern for Sector Mode Operation



Beamforming to a single user



Beamforming to 7 users simultaneously

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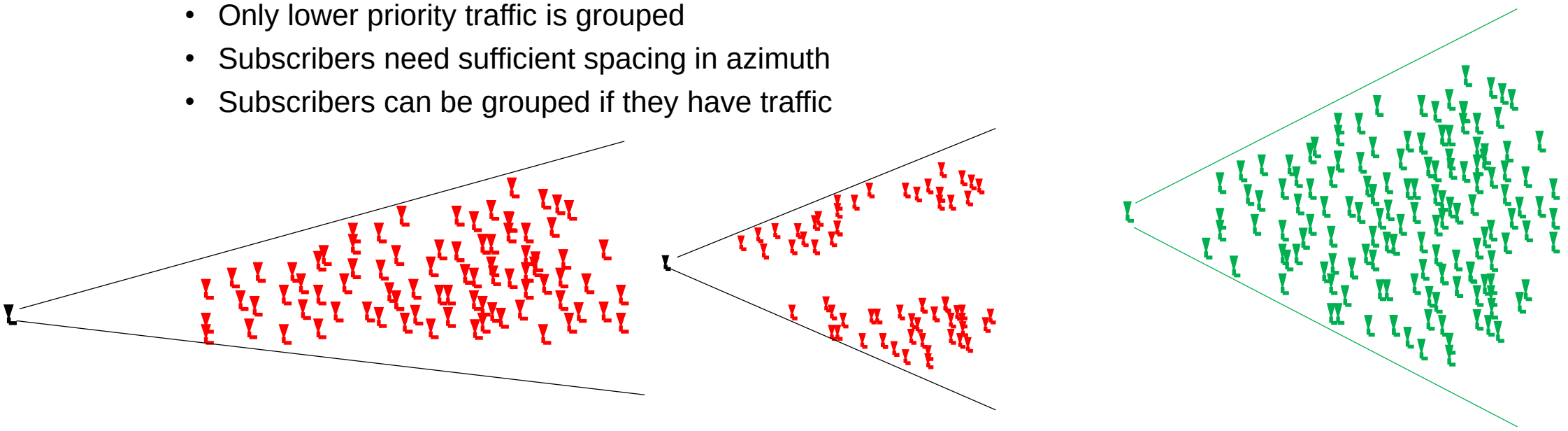
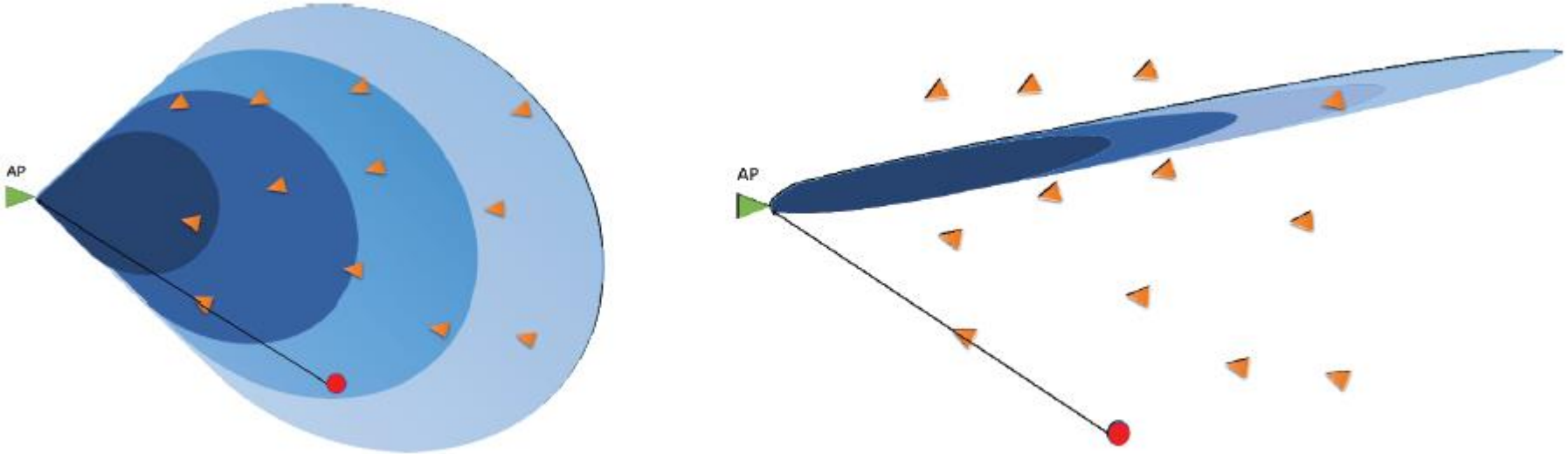
Advantages of Massive MU-MIMO: higher sector throughput

- Able to demonstrate up to 900 Mbps in 20 MHz
- Spectral efficiency up to 45 b/s/Hz per sector and 90 b/s/Hz per site
  - 3x to 4x Improvement against prior generation technology
  - Practical limits
    - Possible lower modulation when grouped
    - Only lower priority traffic is grouped
    - Subscribers need sufficient spacing in azimuth
    - Subscribers can be grouped if they have traffic



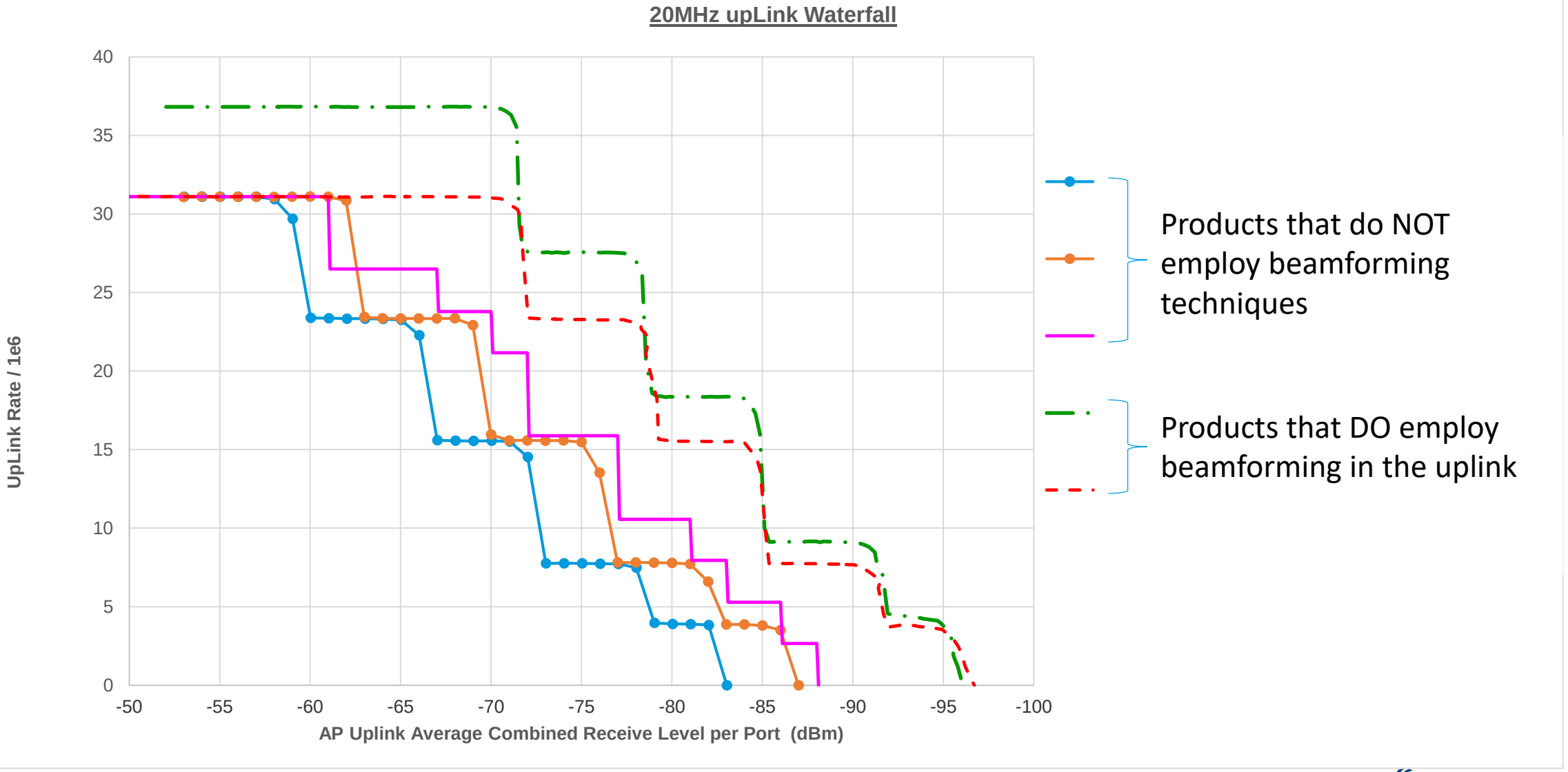
Advantages of Beamforming

- Beamforming array gain
  - Downlink
    - EIRP limited regions: same link budget, but radio operates in more linear region (less distortion, more likely to operate at higher modulation)
    - Non-EIRP limited regions: increased link budget (increased range, higher average modulation)
  - Uplink: better sensitivity, increased link budget, higher average modulation, increased sector throughput
- Reduced interference: both in downlink and uplink



Examples of Uplink throughput and interference rejection improvement

Performance compared to Wi-fi



In Practice Today

Eolo has more than 400k subscribers throughout Italy, and plans to cover nearly 100% of the country within 2 years, deploying thousands of additional customers per month.

Rise Broadband covers 16 states in the US with varying levels of rural broadband connectivity. Their highest bandwidth packages are served by MU-MIMO technology.

Skytel deploys across rural Wexford county Ireland, and offers customers the choice: Connect now using wireless, or wait until fiber is deployed in the area (up to 6 months later). Most customers end up staying with wireless, even after fiber becomes available.

HeroTel covers all of South Africa with its network of operators that utilize MU-MIMO wireless technology and deploy where fiber would be prohibitively expensive.

Wireless Fabric - Pillars for the Service Provider

- Subscriber Acquisition - Fortify Service Providers' First Mover Advantage – capture the "other 50%" of new subs
  - Time to market is faster with wireless
  - Cost to deploy wireless is typically less than fiber
- Combined Fiber/Wireless Strategy – enable technology optimization based on customer and needs.
  - Using both Fiber and Wireless can balance bandwidth and coverage, while minimizing cost, and reducing time to market.

Thank You!

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