5G Cellular:
How and why it will differ from 4G

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A Brief History of Cellular Technology (1985-2000)

- 1985
  - There were about 300,000 subscribers in the USA
    - Luxury item; mostly installed in cars
    - For handhelds, talk time of ½ hour; 10 hours to charge
  - AMPS (1G) had been rolled out in 1983
    - Cell sizes on order of 100's of square miles
    - Analog FDMA, no security (like a radio station), inefficient
    - Lasted until 2008 when it was finally shut off

- 1990
  - Up to 5m subscribers
  - Flip phone first introduced in 1989 by Motorola
  - GSM standardized in 1991, first global digital standard (TDMA)
  - USA continued to IS-54 (TDMA) which built on AMPS

- 1995
  - Now 34m subscribers, becoming mainstream
  - First CDMA standard (IS-95), developed entirely by Qualcomm
  - GSM rapidly gaining global market dominance
  - SMS introduced, became popular in late 90's (but not in US)

A Brief History of Cellular Technology (2000-2010)

- 2000
  - Height of the Internet Bubble: Global (wired) Internet traffic doubling annually
  - Increasingly miniature cell phones were the rage
  - Mobile traffic metrics: *subscribers* and *minutes*
  - SMS popular internationally but not (yet) in US
- 2005
  - Not that much had fundamentally changed from 2000
  - “Device of the year” was Motorola Razr (stylish with nice form-factor, very rudimentary web browsing)
  - Mobile sector still dreaming of killer data apps
  - 3G rollout commencing slowly and cautiously
  - Mobile WiMAX standardized at very end of the year (802.16e), began to spur interest in 4G (LTE), but mostly from a “defensive” standpoint

Starting around 2010, things quickly changed

- Wireless networks in major cities suddenly at point of failure during peak hours
- Global mobile traffic increasing at well over 100% a year, no sign of relenting
- Largely attributed to introduction of iPhone (2007), but many factors contributed
- Cellular industry starts getting serious about improving their networks

Cisco's VNI'10 vs. VNI'13

(Visual Networking Index, a great resource)

Cisco VNI June 2010

- Mobile Data Traffic
  - 0.23 Exabytes/month (2010)
  - 3.5 Exabytes/month (2014)
  - 108% CAGR (2009-14)
- Internet Video in 2013:
  - 14.8 PB (predicted)
  - 48% CAGR (2009-14)
- Video predicted to be 66% of mobile traffic by 2014
  - Cellular networks increasingly are video networks

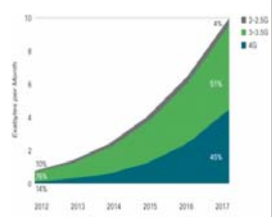
Cisco VNI May 2013

- Mobile Data Traffic
  - 2.8 Exabytes/month (2014)
  - 11.2 Exabytes/month (2017)
  - 66% CAGR (2012-17)
- Internet Video in 2013:
  - 19.86 PB (measured/predicted)
  - 23% CAGR (2012-17)
- Mobile video traffic was 51% of all mobile traffic at end of 2012
- Video now predicted to be 66% of mobile traffic by 2017

Mobile data increases slowed (pricing); Internet video exploded

Since the the "Data Apocalypse"

- Bandwidth available nearly unchanged from 2010
  - About 500 MHz each for cellular networks and WiFi
  - Very little gain there, FCC plans are modest
- 4G has improved spectral efficiency by a small amount
  - Most devices using the network still not LTE-enabled
  - LTE is not actually that much faster than 3G per unit of spectrum
  - It is much better suited to data for other reasons
- Compression ratios for video virtually unchanged, while resolutions have meanwhile increased

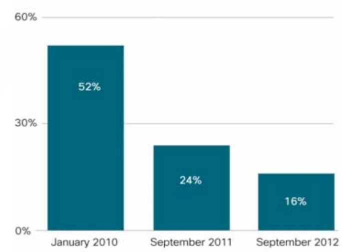


How in the world have things gotten better since 2010?

Answer #1: Tiered Pricing

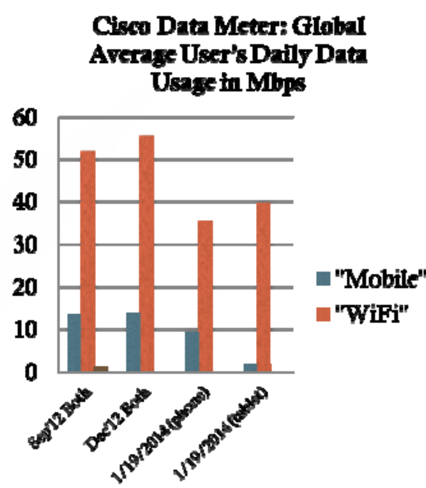
- Tiered pricing and elimination of "all you can eat" data plans has helped a great deal
- Spurred the development of data-efficient applications
- Restrained the data gluttons (see plot to right)
- Slowed the data growth rate
- And helped lead to answer #2…

Percentage of data traffic from top 1% of users



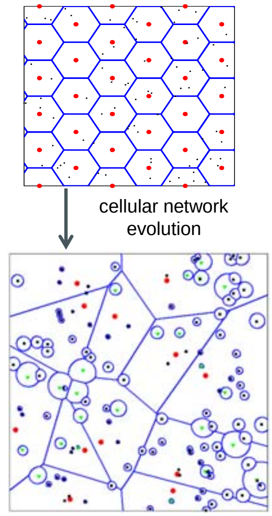
Answer #2: Offloading

- Overall, about 50% of mobile data traffic is offloaded [VNI'13]
  - This is "mobile to fixed" offloading
  - "Fixed" equated with "WiFi" but could also be home (non-enterprise) femtos with their own backhaul
- For Cisco Data Meter users
  - About 5,000 currently, smart phone users on tiered data plans
  - **Offloading is about 4x higher with such users**
  - Stats on the right
- Improved and seamless offloading has provided a great deal of help



Answer #3: Densification and Backhaul

- Related to Offloading
- Network has become much denser, will continue to do so
  - Picocells and DAS deployed by operators
  - Femtocells for home users
  - WiFi APs by both operators and home users
- Amount of rate supportable by a BS is basically unchanged as you densify
  - Imbalances between the loads on BSs is a serious problem
  - Ongoing efforts to more aggressively offload users from the "macrocells" to small cells
  - Interference management is very important with aggressive offloading (biasing)

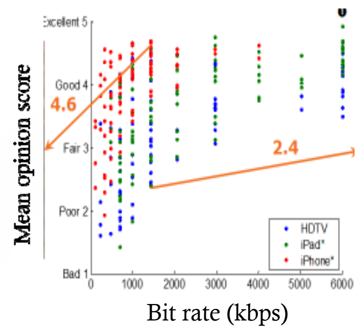


Cellular trends towards 2020

- Data usage per device will continue to greatly increase
  - Smart phones forecast to consume 3GB/month by 2018 [VNI'13]
  - Tablets and laptops about 6 GB
- Number of networked mobile data devices will also increase
  - Already more than global population [VNI'13]
  - Median person in USA probably may have 3 such devices in 2020
  - Machine-to-machine (M2M) and Internet of Things are "X factors" that could radically increase number of cellular devices
    - AT&T predicts M2M devices will be 10-100x more than conventional devices
- New-ish Applications
  - Increased migration to Cloud computing
  - "Tactile Internet" [Fettweis, TU Dresden], extreme latencies
  - 2-way video calls and multiplayer gaming
  - 3D video and augmented reality, e.g. Google glass or the "next iPhone"

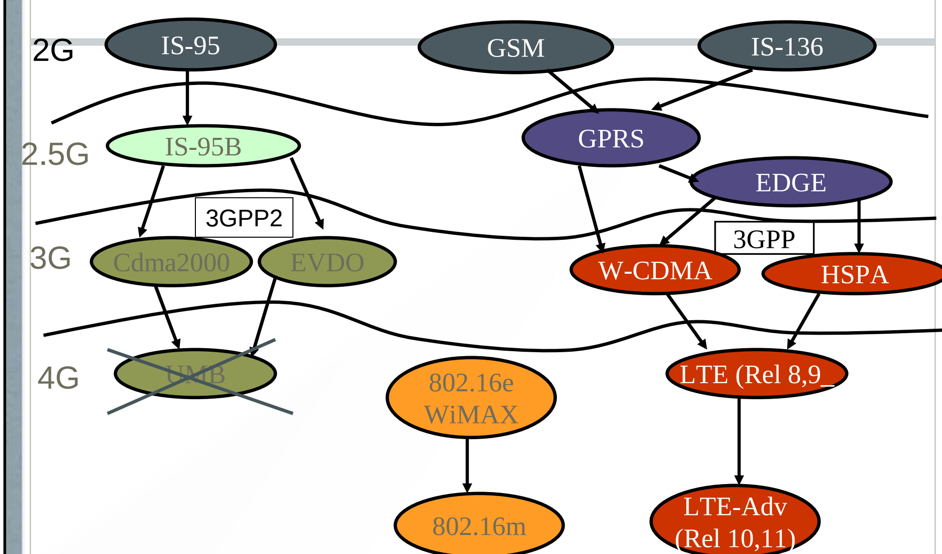
HD Video Anytime Anywhere

- HD video increasingly viewed as an “entitlement”
  - DVD quality is widely considered unacceptable, fairly recently
  - Need HD everywhere
- What does HD require?
  - TV: 10-20 Mbps
  - Tablet: 5-10 Mbps
  - Smartphone: ~ 5 Mbps
  - A sufficient buffer (stored video)
  - High link reliability, low latency/jitter (if real-time)
  - All the above numbers include video compression



- Plot courtesy of Jeffrey Foerster, Intel
- A couple years old, so bump up the numbers

The Cellular Family Tree



Key Features of LTE

- Scalable OFDMA physical layer for the Downlink
  - Usually 1024 subcarriers, 600 of which are used for data
  - Uplink uses SC-FDMA which is functionally very similar
  - Very robust to multipath and computationally and bandwidth efficient
- Highly flexible scheduling of user traffic via time-frequency "resource blocks" which are reallocated every 1 msec
- Flat IP architecture, no notion of a "call"
- Variable bandwidth but usually 10 MHz *paired* spectrum [wasteful]
- Multi-antenna techniques are supported and blend nicely with OFDMA
- Rapid retransmissions and time diversity via hybrid ARQ
- Versus 3G CDMA
  - Perhaps double the spectral efficiency (data rate per bandwidth)
  - More scalable to large bandwidths and antenna arrays, more flexible scheduling
  - More sensitive to interference

The What, Why, and When of 5G

- 5G generically refers to:
  - The next suite of standards <u>after LTE</u>
  - Something nontrivially different and "better" than LTE
  - Whatever the person using it wants it to mean
- 5G is needed to manage the demands on the mobile Internet expected in the 2020's
  - Support the applications we just discussed, inc. HD video
  - Support M2M, 1000x traffic increase vs. 4G (10 years)
- When?
  - Standardization will begin in a few years
  - Perhaps 5.0G completed around 2020
  - Commercial products in early 2020's: exactly when depends a lot on what 5G turns out to be

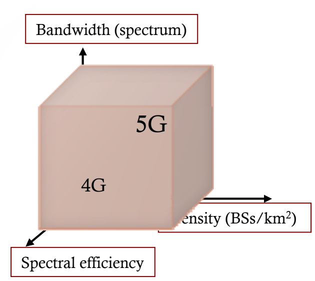
Plausible 5G System Requirements
(these are my own opinions)

- Peak Rate: 10 Gbps
  - Peak rate is a marketing number, not an engineering number
  - I expect someone to claim 100 Gbps. This can be ignored.
- **5% Rate: 10-100 Mbps**
  - This is a real engineering number and very challenging
  - This is what a "typical" bottom 5% user gets over time
- Latency: 1 millisecond roundtrip
- Cost per bit: 10-100x below 4G
- Power consumption: similar to LTE (Joules/bit to drop 10-100x)
- Implicit but crucial: Backhaul that supports all the above

All of these require 10-100x improvement vs. 4G (e.g. LTE Release 10)

Where will these gains come from?

- To get 1000x in 2022 vs. 2012, need something like:
  - 10x more spectrum
  - 25x more density
  - 4x more spectral efficiency
- 5G will be an "all of the above" integrative solution
  - 4G integrated
  - WiFi integrated
  - Backhaul possibly integrated



For 10x the spectrum…

- Virtually no "beachfront" spectrum available
- FCC's boldest plan calls for re-releasing 500 MHz of below 6 GHz
  - That's a 50% increase, best case (unlikely)
  - But we need 1000% more
- About 20 GHz available between 20-60 GHz (mmWave)

	ITU-R*		USA (Non Federal)	
Frequency designation	Frequency Range (GHz)	Available Spectrum (GHz)	Frequency Range	Available Spectrum (GHz)
6GHz	5.925-8.500	2.575	6.425-7.125	0.35
10GHz	10.5-13.25	2.63	12.7-13.25	0.55
14GHz	14.4-15.35	0.95		
17GHz	17.7-17.81	0.11		
18GHz	18.1-19.7	1.6		
21GHz	21.2-23.6	2.4	21.2-23.6	2.4
25GHz	25.25-25.5	0.25		
28GHz	27-29.5	2.5	27.5-29.5	2
31GHz	31-31.3	0.3	31-31.3	0.3
36/38/40GHz	36-47	11	36-42.5 45.5-47	8
50GHz	47.2-52.6	5.4	47.2-52.6	5.4
55GHz	55.78-57	1.22	55.78-57	1.22
60GHz	57-64	7	57-64	7
65GHz	64-71	7	64-71	7
70GHz	71-76	5	71-76	5
80GHz	81-86	5	81-86	5
90GHz	92-94	2	92-94	2
90GHz	94.1-95	0.9	94.1-95	0.9
95GHz	95-100	5	95-100	5
	Total	62.835		52.12

Why is mmWave so challenging?

- A dipole quasi-omnidirectional antenna is about ½ a wavelength, so on the order of millimeters
  - Too small to radiate or collect much energy
  - From basic electromagnetics, we see that path loss is proportional to the frequency squared
  - Thus, 28 GHz has 100x the path loss of 2.8 GHz, i.e. a 20 dB disadvantage
- Very large bandwidths exacerbate the problem, since noise is proportional to the bandwidth
- Circuit design/power consumption challenges at these frequencies and large bandwidths
  - 802.11ad is at 60GHz, and work there can be ported over
  - By the time mmWave standardized, these implementation challenges expected to be manageable

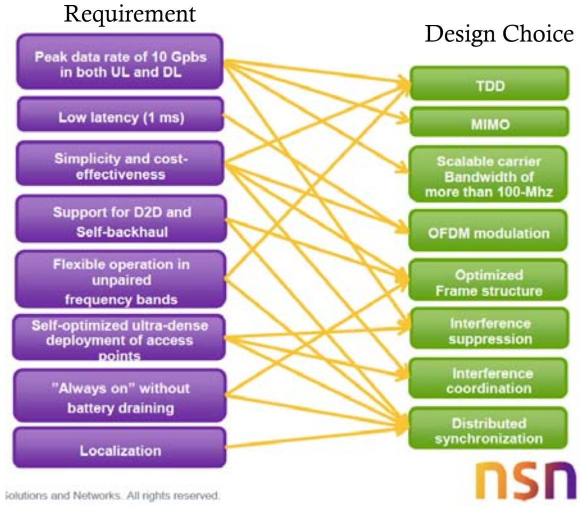
Turning lemons into lemonade at mmWave

- Antennas are now tiny, which causes the "problem", <u>but:</u>
  - Can fit a huge number of them on the devices
  - For example, 256 transmit (BS) and 64 receive (UE) antennas in the downlink in a 2D or 3D pattern
- As long as they work together (i.e. adaptive beamsteering) this loss can be recovered or even turned into a gain
- However, making this work will be very challenging
  - Adapting the beams in face of even limited mobility is very hard to do, links become very "brittle"
  - Blocking (from objects) becomes a dominant challenge, new to mmWave, which cannot penetrate e.g. tainted glass
  - Exciting research topic in both industry and academia
    - See recent papers/talks from Samsung, NSN, Ted Rappaport (NYU), Robert Heath (UT Austin)

Implications of Ultradense Networks
(courtesy of P. Mogensen of NSN)

Requirement

Design Choice



- Logistical challenges to densification
  - Affordable deployments (especially Opex)
  - Inflexible municipalities used to $2K/mo rentals for macrocells
- mmWave benefits from density also
  - Imagine a ultradense mmWave network
  - WiFi network
  - LTE providing the "control" and connectivity backbone

Assembling all this: A view of 5G

<u>5G will consist of:</u>

1. A dense mmWave network (new 5G standard, ~2020)
2. A more "cellular-like" WiFi network
   - Trends in WiFi include more centralized control, better allocation of resources
   - "Hotspot 2.0" includes further features for cellular integration and load balancing, handoffs
   - Enterprise WiFi networks already closely resembling cellular networks
   - Key thing in my view is to provide better mechanisms for AP sharing (i.e. automated password sharing), which is mostly about backhaul sharing
3. LTE providing the "control" and connectivity backbone at conventional licensed frequencies
4. A great deal of integration between these standards