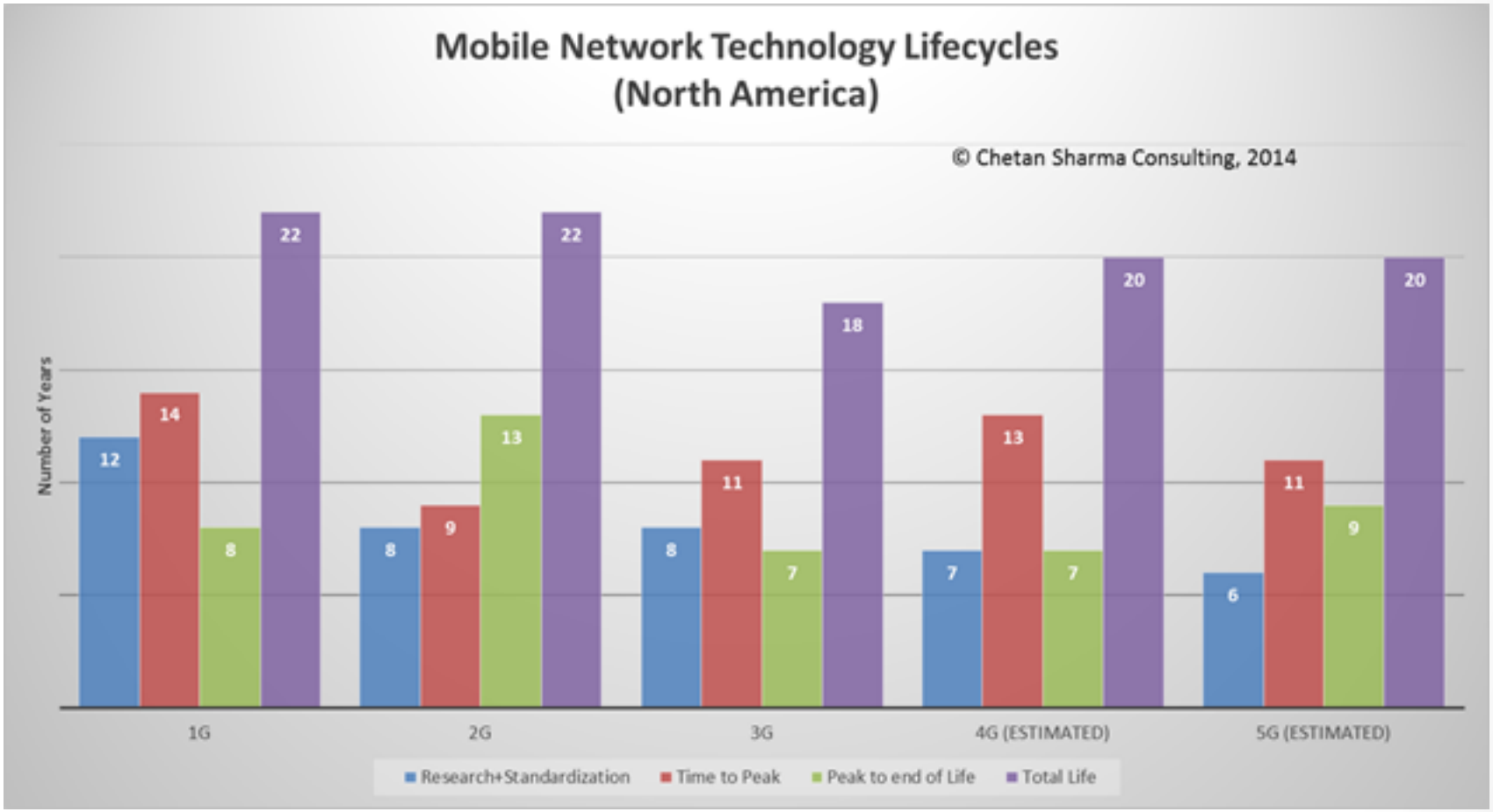
5G: What can we learn from the previous four generations?

Henning Schulzrinne
Columbia University

Design for 20 years



Generations are distinct

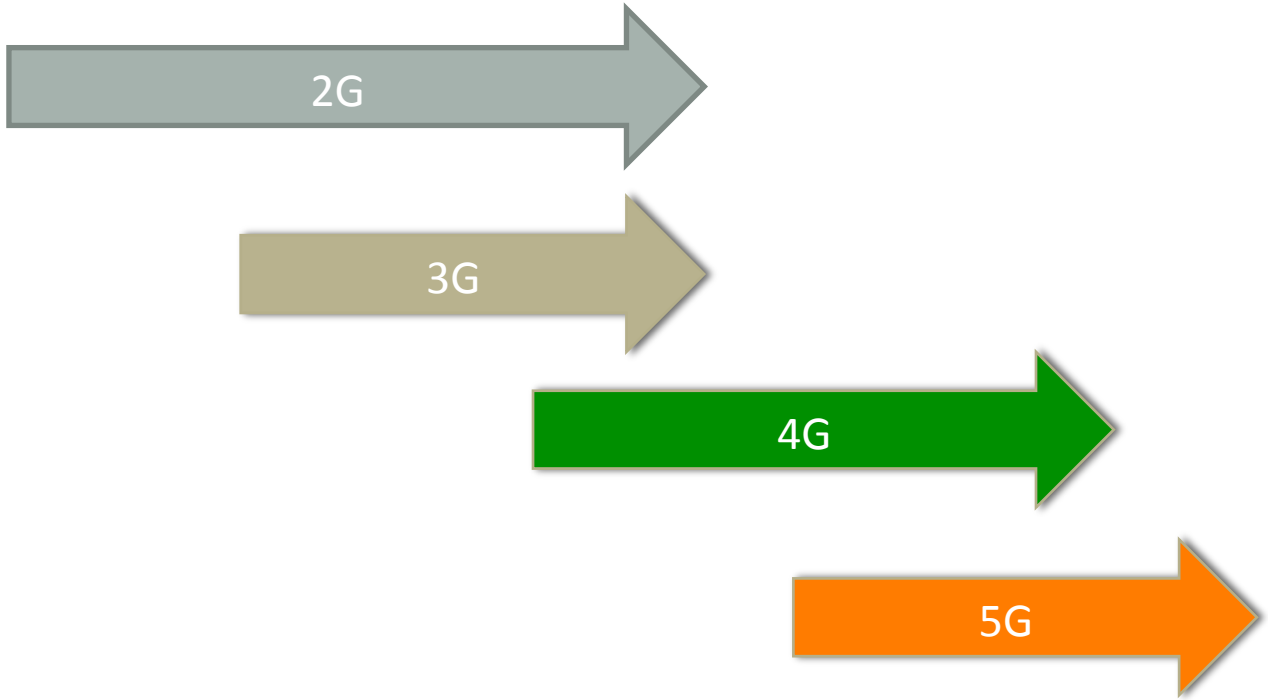
Talking a different language

	Maturists (pre-1945)	Baby boomers (1945-1960)	Generation X (1961-1980)	Generation Y (1981-1995)	Generation Z (Born after 1995)
Formative experiences	Wartime rationing Rock'n'roll Nuclear families Defined gender roles - particularly for women	Cold War 'Swinging Sixties' Moon landings Youth culture Woodstock Family-orientated	Fall of Berlin Wall Reagan/Gorbachev/ Thatcherism Live Aid Early mobile technology Divorce rate rises	9/11 terrorists attacks Social media Invasion of Iraq Reality TV Google Earth	Economic downturn Global warming Mobile devices Cloud computing Wiki-leaks
Percentage in UK workforce	3%	33%	35%	29%	Employed in either part-time jobs or apprenticeships
Attitude toward career	Jobs for life	Organisational - careers are defined by employees	"Portfolio" careers - loyal to profession, not to employer	Digital entrepreneurs - work "with" organisations	Multitaskers - will move seamlessly between organisations and "pop-up" businesses
Signature product	Automobile	Television	Personal computer	Tablet/smartphone	Google glass, 3-D printing
Communication media	Formal letter	Telephone	E-mail and text message	Text or social media	Hand-held communication devices
Preference when making financial decisions	Face-to-face meetings	Face-to-face ideally but increasingly will go online	Online - would prefer face-to-face if time permitting	Face-to-face	Solutions will be digitally crowd-sourced

Source: Barclays, University of Liverpool

land line 2G 3G 4G

Generations overlap



Generational surprises

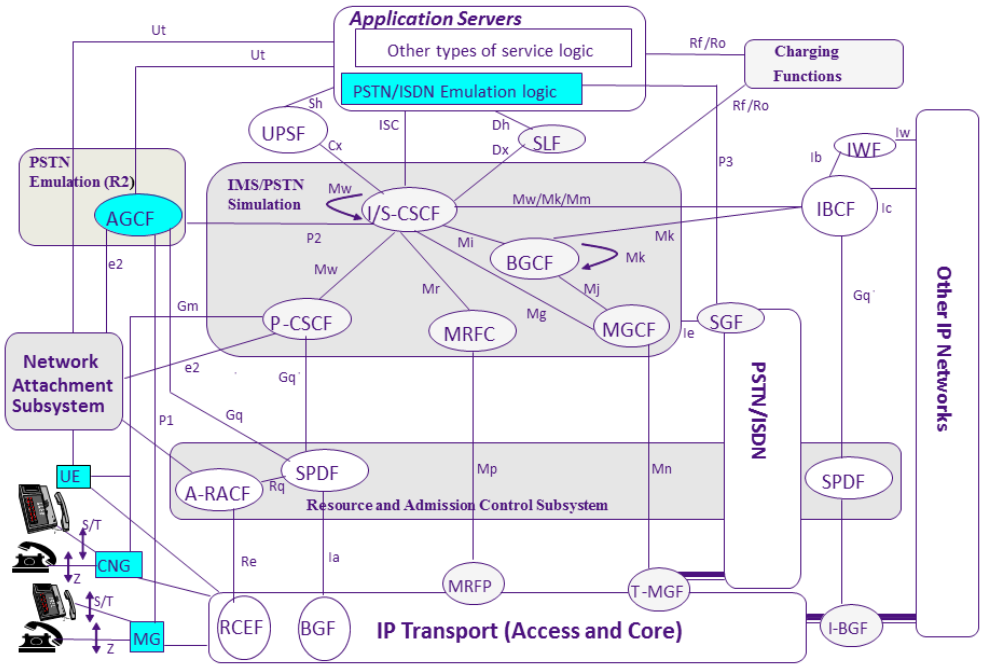
Generation	Expectation	Surprise
2G	better voice quality (“digital!”)	SMS
3G	WAP	web
4G	IMS	YouTube, WhatsApp, notifications
5G	IoT (low latency)	?

underestimated cost and fixed-equivalence as drivers

Lessons, in brief

Experience	Lessons
VoLTE, IMS	avoid complexity avoid entanglement plan intercarrier interfaces
Wi-Fi	don't trust the RAN/AP
disaggregation of functions	clear & simple interfaces don't assume trust between elements
app stores	keep it application-neutral
FTTH, backhaul cost	re-use backhaul where you can find it

Complexity kills



IMS

Niche networks

short range

ZigBee®

low energy; mesh

Bluetooth®

ubiquity; low cost

Wi Fi™

speed; public APs

Long-range networks

FEATURE	LTE Rel 13	Combined Narrow Band (NB) and Spread Spectrum (SS) (Semtech)	Cooperative Ultra Narrow Band (Sigfox)	Narrow Band M2M Clean Slate (Huawei/ Neul)
Bandwidth	1.4 MHz	400 Hz to 12.8 KHz NB and 200 KHz SS UL / 3.2 KHz to 12.8 KHz DL	160 Hz UL / 600 Hz DL	2 or 3.75 KHz UL / 15 KHz DL per channel
UL Data Rate	TBD	122 bps – 7.8 Kbps	160 bps / 600 bps	200 bps to 45 Kbps
Range / MCL	155.7 dB (24 dBm Tx Pwr)	164 dB (20 dBm TX Pwr)	164 dB (24 dBm Tx Pwr)	162 dB (24 dBm Tx Pwr)
Broadcast/Multicast	Yes	Yes	No	No?
Duplex	Full/Half Duplex (FDD)	Full-Duplex	Full Duplex	Full-duplex
Synchronization	Yes	Yes	No	Yes

Wide-area Wireless Communication Challenges for the Internet of Things
Harpreet S. Dhillon, Howard sHuang, Harish Viswanathan

SIGFOX, Ingenu and LoRa

	SIGFOX™	Ingenu™	LoRa™
Coverage range (km)	rural: 30–50 urban: 3–10	≈ 15	rural: 10–15 urban: 3–5
Frequency bands (MHz)	868 or 902	2400	various, sub-GHz
ISM band	✓	✓	✓
Bi-directional link	✓	✗	✓
Data rate (Kbps)	0.1	0.01–8	0.3–37.5
Nodes per BS	$\approx 10^6$	$\approx 10^4$	$\approx 10^4$

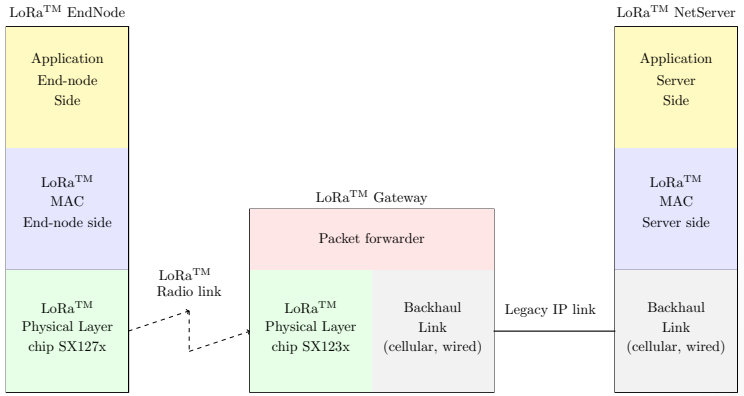


Fig. 2: LoRa™ protocol architecture.

Long-Range Communications in Unlicensed Bands: the Rising Stars in the IoT and Smart City Scenarios

Marco Centenaro, *Student Member, IEEE,* Lorenzo Vangelista, *Senior Member, IEEE,* Andrea Zanella, *Senior Member, IEEE,* and Michele Zorzi, *Fellow, IEEE*

New cellular domains

- Fixed wireless → compete with DSL and maybe cable
  - > 10 Mb/s bandwidth
  - probably more rural than urban → ample spectrum available
  - Comcast median usage:
    - August 2013: 16 GB
    - mid-2015: 40 GB ➔ roughly 50% YoY growth
    - → 2020 usage of 300 GB
  - typical cost: cellular $10/GB → $400 today, $3,000 in 2020
    - median wireline: $55 month for unlimited
    - ➔ cost problem (differentiate fixed from mobile)
- IoT and other embedded applications
  - many (most?) IoT applications are *not* mobile
  - but are very cost-sensitive

What happens if this moves to IP?

Manage Bandwidth Usage

If you are interested in setting a limit on how much data our service will use, you can adjust your video quality setting. Navigate to Netflix.com/VideoQuality to manage the amount of data you use when playing movies and TV shows on Netflix.

There are 3 settings to choose from:

- Good quality (uses up to 0.3 GB per hour)
- Better quality (uses up to 0.7 GB per hour)
- Best quality (uses up to 1 GB per hour, up to 2.8 GB per hour if watching HD, or up to 4.7 GB per hour if watching 3D)

Thus, for 146 hours/month of HD → 410 GB/month
(does *not* count separate viewing among household members)

Example wireless plan

verizon

IoT requirements

Application	Range	Mo-bility	Device characteristics	Service characteristics	Suitable networks
• Connected car • Fleet management • Remote health monitoring	~1000m	Yes	Rechargeable battery	Managed service, highly secure	• Cellular • Satellite
• Smart metering • Parking meter	~1000m	No	Low rate, low power, low cost	Managed service	• Cellular • Dedicated network
• Hospital asset tracking • Warehouse logistics	~100m	Yes	Low rate, low power, low cost	Enterprise-deployed	• WiFi • RFID
• Industrial automation • Home automation	~10m	No	Low rate, low power, low cost	Subscription-free	• Zwave • Zigbee • Wifi • Powerline
• Personal activity • Local object tracking • Point of sale	~1m	No	Low rate, low power, low cost	Subscription-free	• Bluetooth • NFC

Wide-area Wireless Communication Challenges for the Internet of Things
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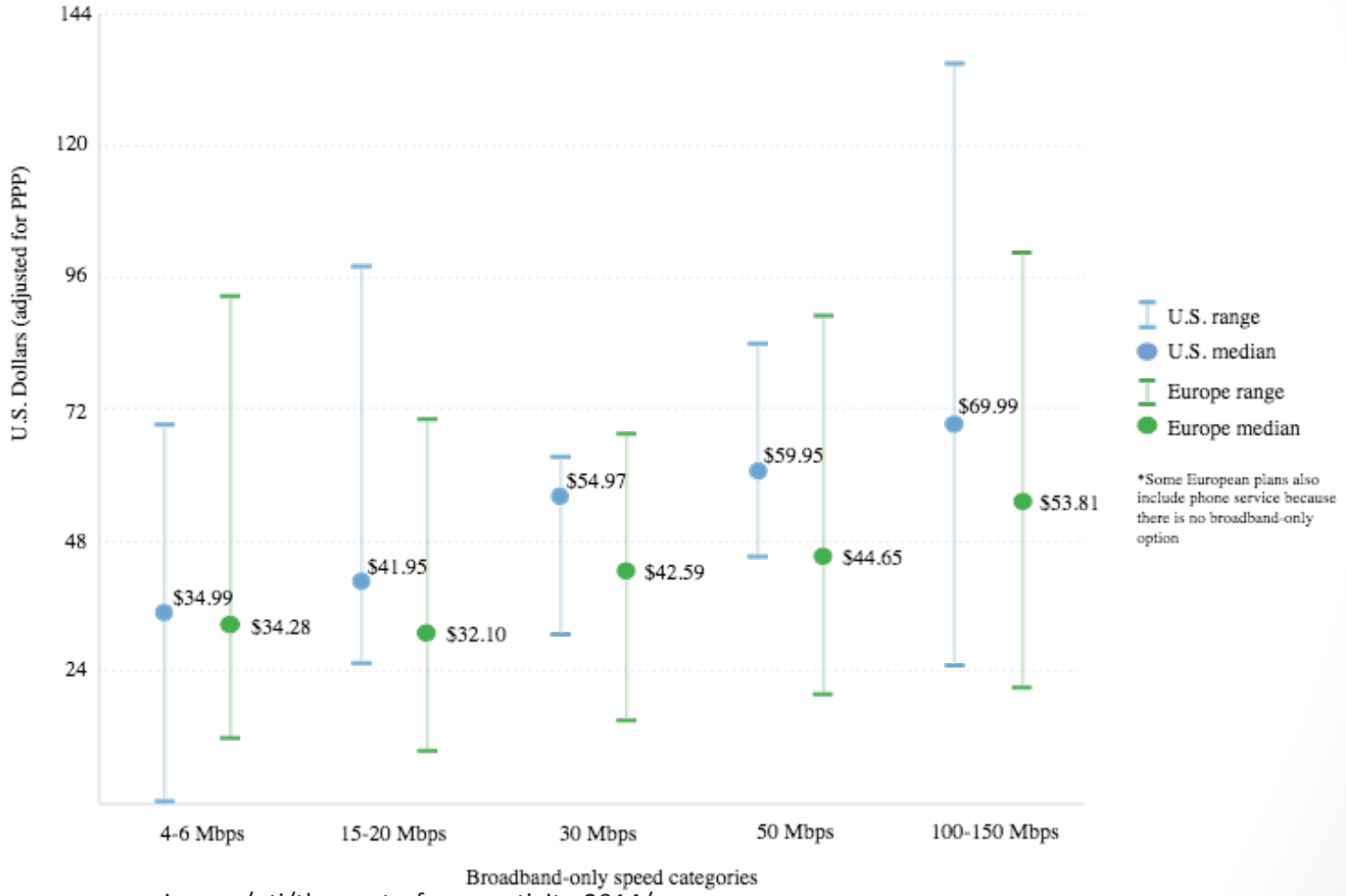
Broadband pricing



https://www.newamerica.org/oti/the-cost-of-connectivity-2014/

Attenuation by frequency

Materials	0.57 GHz (dB)	1 GHz (dB)	2 GHz (dB)	5.7 GHz (dB)	0.57 to 5.7 GHz (dB)
Brick 89 mm	–1.5	–3.5	–5.4	–15	13.5
Brick 267 mm	–4.8	–7	–10.5	–38	33.2
Composite Brick 90 mm/ Concrete Wall 102 mm	–12	–14	–18	–42	30
Composite Brick 90 mm/ Concrete Wall 203 mm	–21.5	–25	–33	–71.5	50
Masonry 203 mm	–9.5	–11.5	–11	–12.75	3.25
Masonry 610 mm	–26.5	–27.5	–30	–46.5	20
Glass 6 mm	–0.4	–0.8	–1.4	–1.1	0.7
Glass 19 mm	–2.5	–3.1	–3.9	–0.4	–2.1
Plywood (dry) 6 mm	–0.15	–0.49	–0.9	–0.1	–0.05
Plywood (dry) 32 mm	–0.85	–1.4	–2	–0.9	0.05
Reinforced concrete 203 mm/ 1% steel	–23.5	–27.5	–31	–56.5	33
Reinforced concrete 203 mm/ 2% steel	–27.5	–30	–36.5	–60	32.5

Propagation issues

- **Rural (low density)** → coverage limited
  - √ tower height (ft) ≈ coverage range (miles)
  - e.g., 400 ft (120 m) tower → 20 miles
  - but 4-5 miles more typical
  - GSM: timing advance → 35 km
- **Urban outdoors**
  - cell spacing: 100 ft
  - capacity-limited
  - power-limited (5-20 W base station, 2 W mobile) → 5-8 miles
- **Urban indoors**
  - radio propagation

28 GHz attenuation & reflection

Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
	WWH	Brick	185.4	-34.7	-63.1	28.3
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
	WWH	Tinted Glass	<1.3	-34.7	-59.2	24.5
		Clear Glass	<1.3	-34.7	-38.3	3.6
		Wall	38.1	-34.0	-40.9	6.8

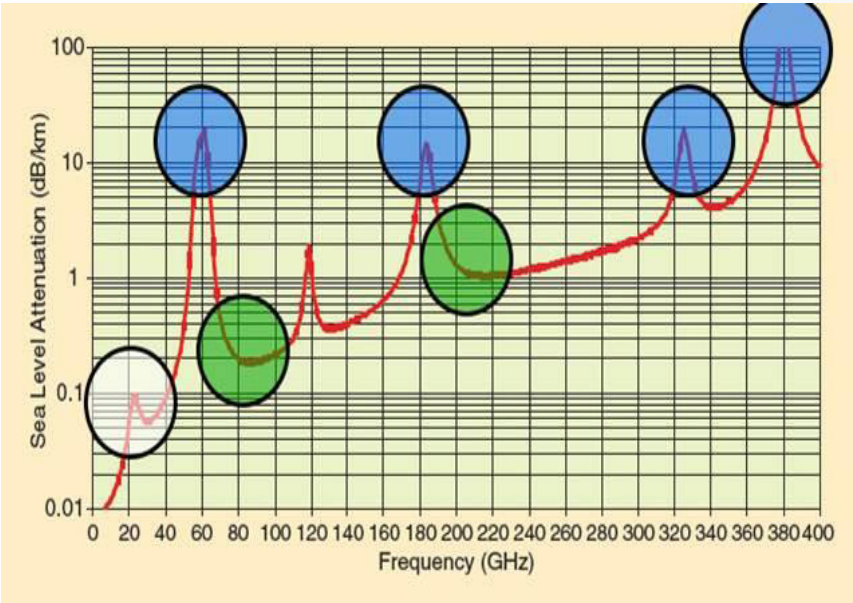
Environment	Location	Material	Angle (°)	Reflection Coefficient ($\lvert\Gamma_{\parallel}\rvert$)
Outdoor	ORH	Tinted Glass	10	0.896
		Concrete	10	0.815
			45	0.623
Indoor	MTC	Clear Glass	10	0.740
		Drywall	10	0.704
			45	0.628

➔ multipath reflections
➔ highly directional antennas

Rappaport, 2013

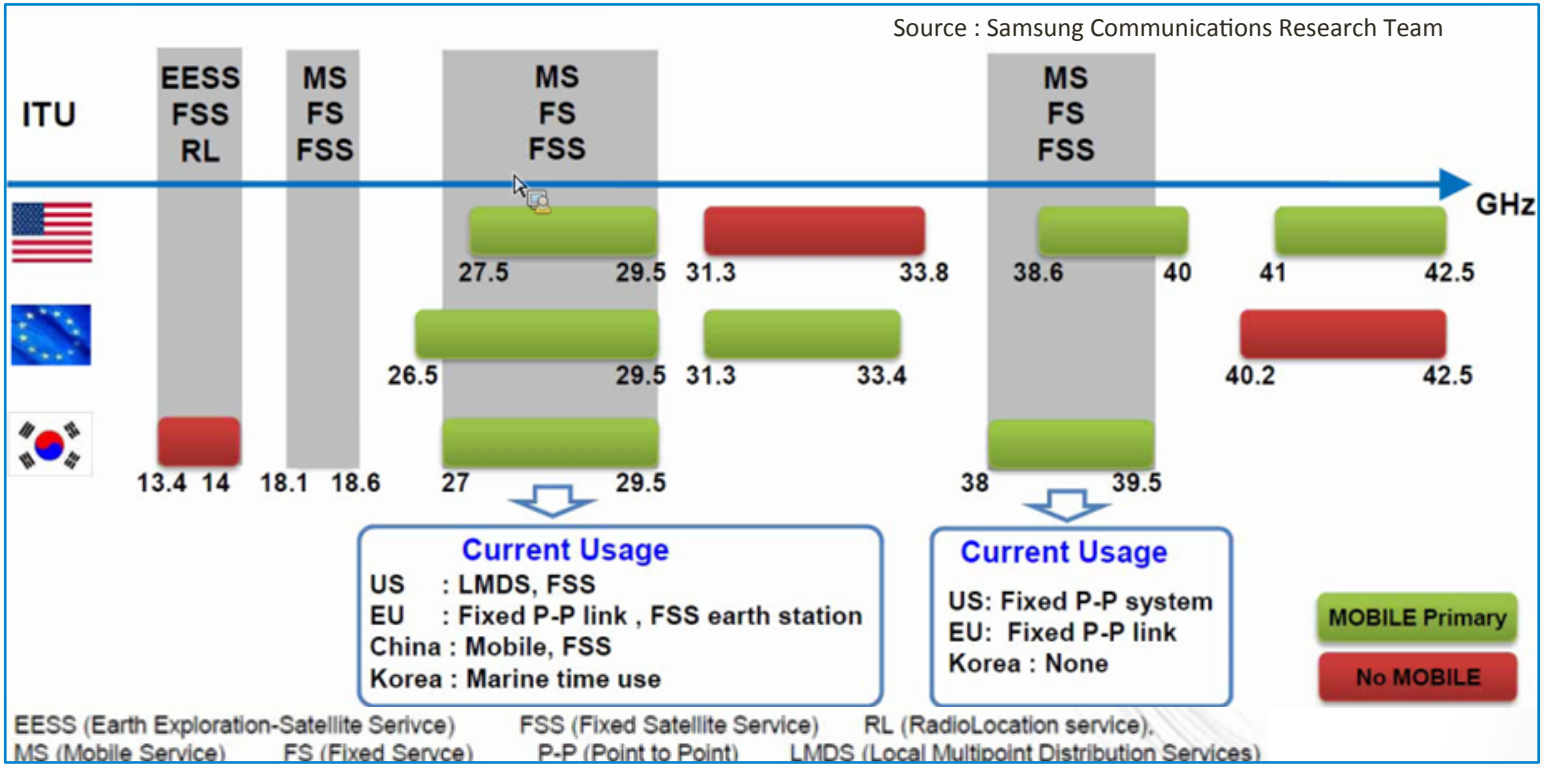
10 GHz+

- Unlicensed



	PRODUCTS					
	AR60	GE60	FE60	AR60X	GE60X	
Maximum Distance	1,470 Meters	990 Meters	1,470 Meters	2,380 Meters	1,820 Meters	2
Maximum Distance	.91 Miles	.62 Miles	.91 Miles	1.5 Miles	1.13 Miles	
Bandwidth Full-Duplex	1.25Gbps	1.25Gbps	100Mbps	1.25Gbps	1.25Gbps	

30-40GHz mmW – Spectrum Overview



- Note: The Commission's Fixed Microwave (Part 101) and Satellite Communications (Part 25) service rules govern most of US Mobile allocations shown above

Changing spectrum environment

- Except at highest frequencies, all new spectrum likely to be shared
  - e.g., 3.5 GHz
  - in time & space
- → need frequency-agile systems that can shift capacity to different bands, quickly

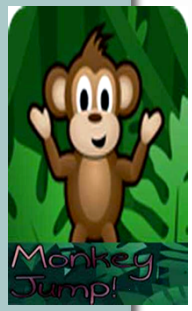
Example: 3.5 GHz (April 2015)

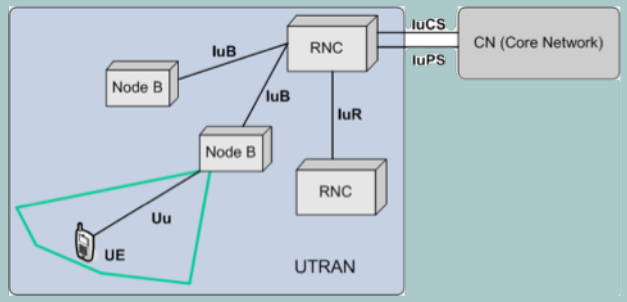
- 150 MHz at 3.550 GHz
- incumbents: DoD radars + fixed satellite service (FSS) receive-only
- exclusion zones: 60% pop. unsuitable for macrocell
- access: incumbent, priority (PAL), general authorized
  - Incumbent: authorized federal & grandfathered Fixed Satellite Service
  - PAL: 3 years non-renewable, 10 MHz channel, census tract
  - hospitals, utilities, state/local gov't

see also TVWS, MBAN

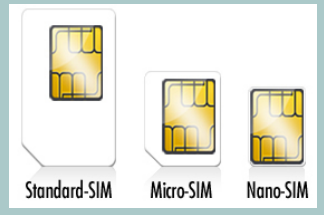
Networks 1G through 4Gish

national carrier

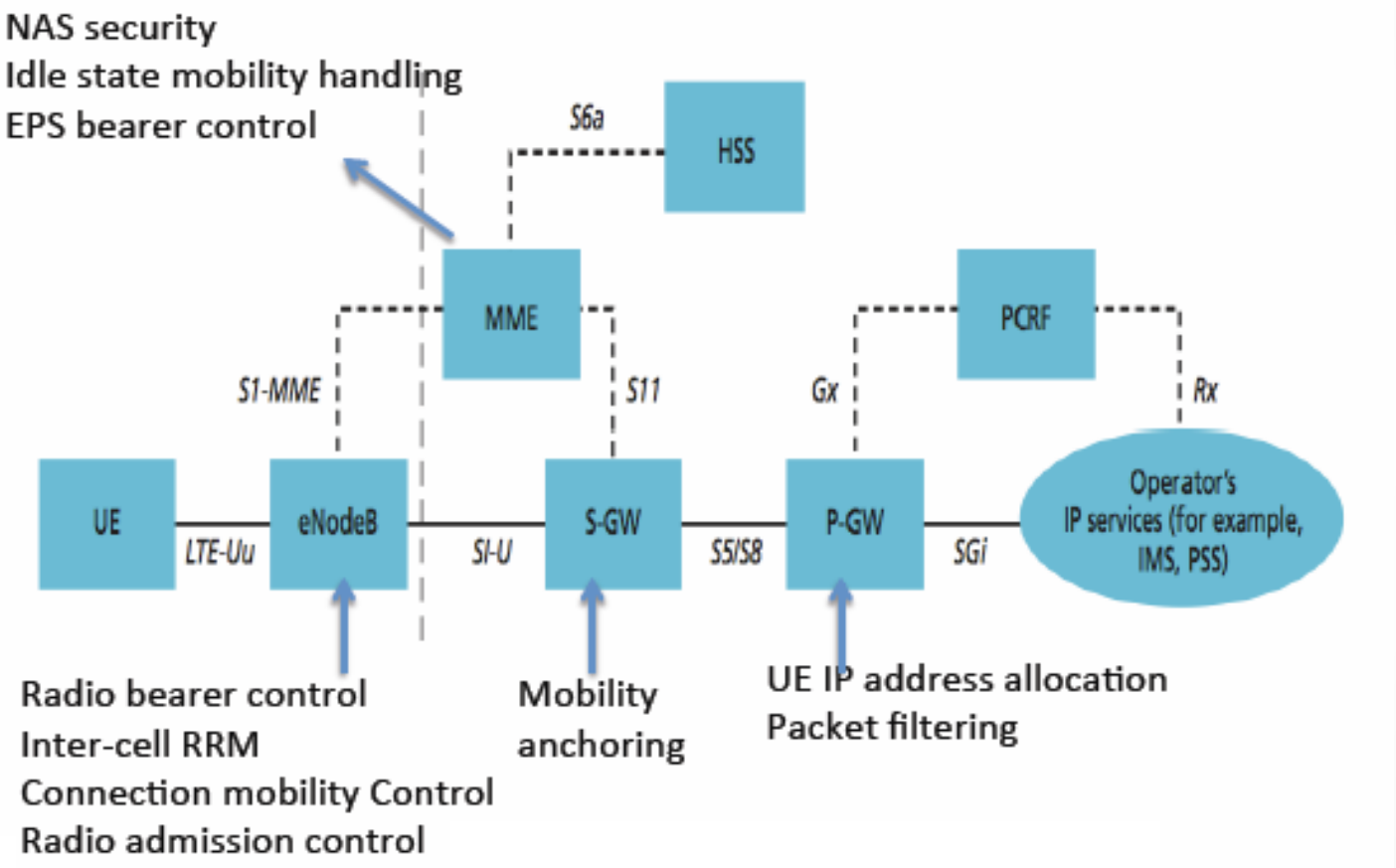




one subscriber,
one phone,
one provider



LTE – one carrier, plus roaming



5G – what exactly is a carrier?

AMERICAN TOWER®
40k towers each (US)

CROWN CASTLE

Spectrum DB

Google play

Level3
Cogent

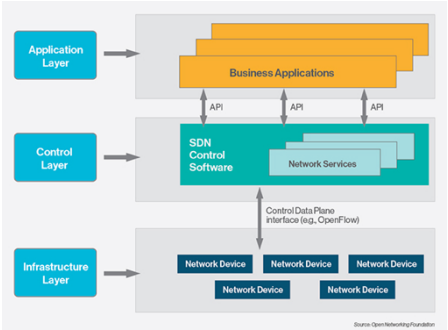
comcast

LTE-U
802.11n
LTE

FiberLight

lightower

zayo

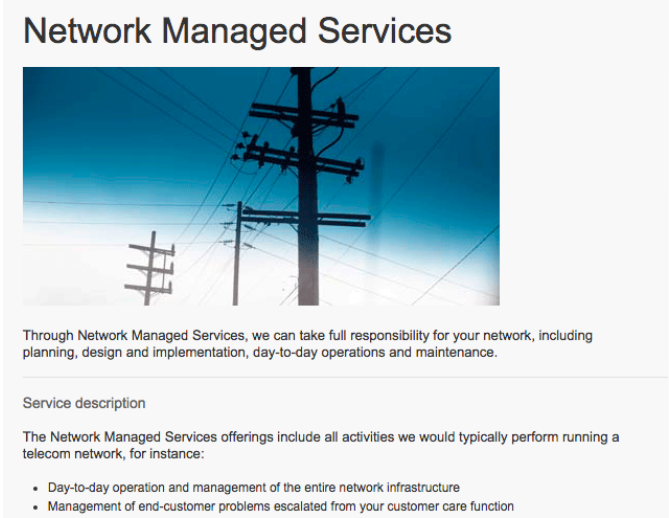


ERICSSON

5G: Carriers as consumer brand

Outside

Inside



Cell towers

Tower owner	Number of towers
Crown Castle	39,739
American Tower	40,000 (with VZW)
SBA Communications	15,151
United Cellular Co.	4,802
Verizon Wireless	1,400
T-Mobile Towers	1,003
Time Warner	950
Mediacom Communications	750
Charter Communications	650
Diamond Communications	637
Trillion Partners	635

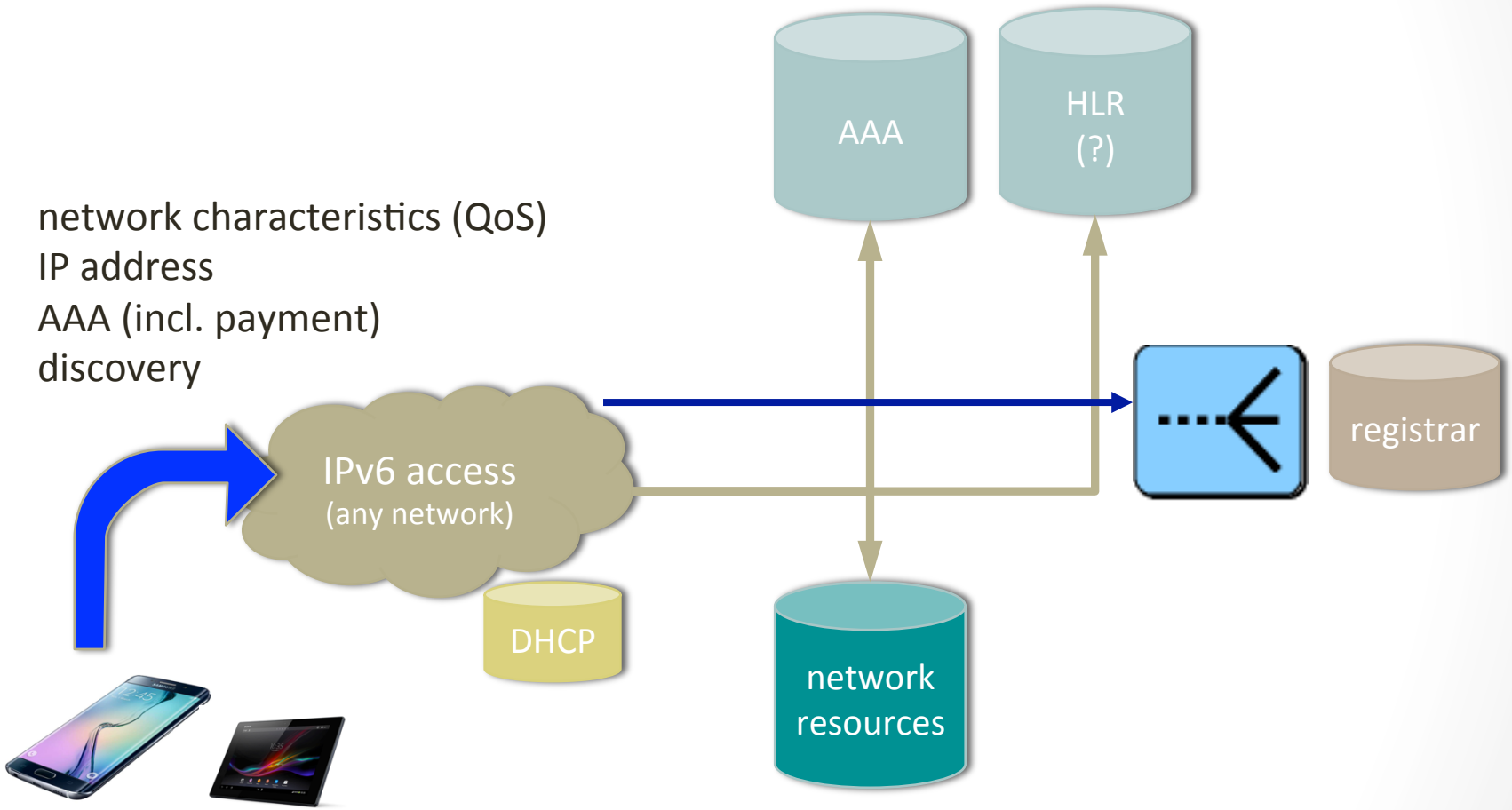
cost/tower: $150k
total US: 205k

What are carriers good at?

- Research?
- Software development?
  - Who is going to develop those 5G SDN applications?
- OTT applications?
- API-based services?
  - Why did Twilio and Tropo offer voice service APIs and not the ILECs?

What's the simplest network?

network characteristics (QoS)
IP address
AAA (incl. payment)
discovery



one subscriber, multiple devices, multiple providers

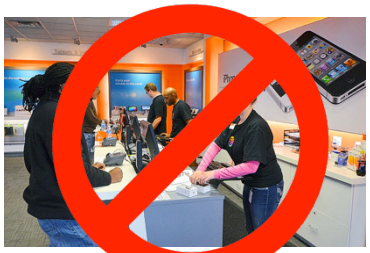
Where do we need mobility?

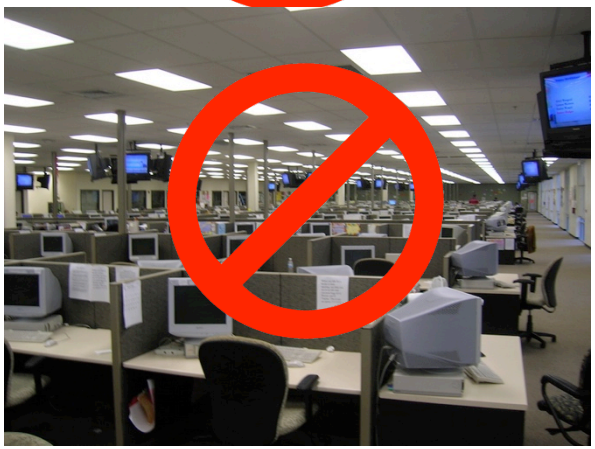
- likely to have access provider diversity
  - what is expected lifetime of IP address?
- PMIP and MIP complex
  - need to re-create application-layer security at L3
- not really needed for HTTP video
  - use mTCP?
  - or HTTP restart?
- maybe not even for real-time media
  - registrar for new-call reachability
  - application layer (SIP) mobility for mid-call hand-off?
- or tunnels, tunnels everywhere?

Make the network location-aware

- 2G/3G/4G are location-ignorant: “I only know your cell sector”
- All mobile devices will be location-aware to the ~5 m
- Some know where they will likely be in the near future
  - public transit
  - road navigation systems
  - ➔ predict access and hand-off
- All devices will have multiple radios
  - use macro cell network to query for local access

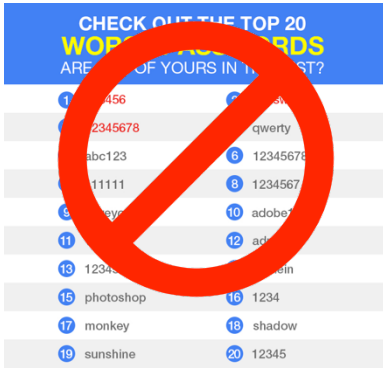
Simplify enrollment





Bluetooth 4.0 Low Energy

enable access



The law of new networks

- *"Any new network technology will be justified on (finally) providing QoS"*
- To succeed, they have to provide good-enough QoS for best effort
  - at least with competition
- The business model for QoS is difficult
  - see bypass toll roads
- QoS is usually not accessible to applications
  - or not end-to-end

I-495 Express Lanes Endure Big Losses Early On Way To Potential Profit

By: Martin Di Caro
February 20, 2015

PLAY comments 2 g+1

WAMU/Martin Di Caro

The 495 Express Lanes offer a paid respite from the usual Beltway traffic, but fewer drivers than expected are using them.

The private sector firm that operates the 495 Express Lanes along the Beltway in Northern Virginia is down more than $230 million on its investment in the two and a half years since the highway opened, but company officials say toll revenues are beginning to consistently exceed operating costs, a sign the project is winning over commuters in one of the region's most congested corridors.

Transurban, the Australia-based toll road builder that operates high-speed HOT (high-occupancy toll) lanes on I-495 and I-95, has said all along it would take years to turn a profit on its enormous investments in Northern Virginia.

Providing a network API

- Currently, applications can detect Wi-Fi vs. cellular
- What is the correct API for discovering network properties?
  - available options (“BE”, “LBE”, “low latency”)
  - not RSVP flow specs…

public int getType () Added in API level 1

Reports the type of network to which the info in this `NetworkInfo` pertains.

Returns

one of `TYPE_MOBILE`, `TYPE_WIFI`, `TYPE_WIMAX`, `TYPE_ETHERNET`, `TYPE_BLUETOOTH`, or other types defined by `ConnectivityManager`

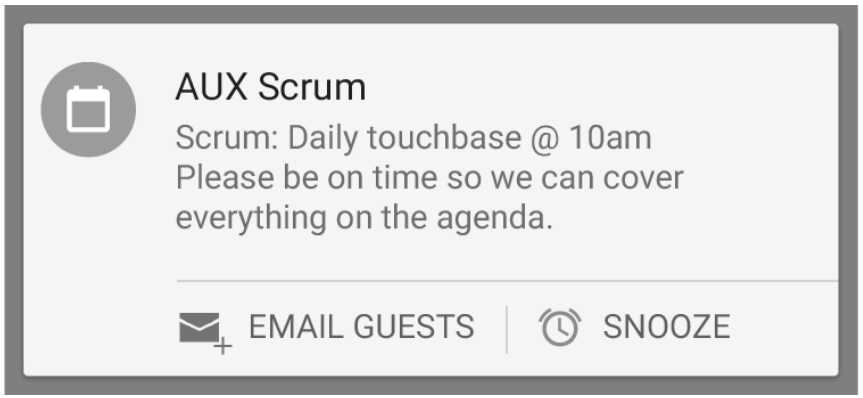
NetworkInfo.DetailedState	AUTHENTICATING	Network link established, performing authentication.
NetworkInfo.DetailedState	BLOCKED	Access to this network is blocked.
NetworkInfo.DetailedState	CAPTIVE_PORTAL_CHECK	Checking if network is a captive portal
NetworkInfo.DetailedState	CONNECTED	IP traffic should be available.
NetworkInfo.DetailedState	CONNECTING	Currently setting up data connection.
NetworkInfo.DetailedState	DISCONNECTED	IP traffic not available.
NetworkInfo.DetailedState	DISCONNECTING	Currently tearing down data connection.
NetworkInfo.DetailedState	FAILED	Attempt to connect failed.
NetworkInfo.DetailedState	IDLE	Ready to start data connection setup.
NetworkInfo.DetailedState	OBTAINING_IPADDR	Awaiting response from DHCP server in order to assign IP address information.
NetworkInfo.DetailedState	SCANNING	Searching for an available access point.
NetworkInfo.DetailedState	SUSPENDED	IP traffic is suspended
NetworkInfo.DetailedState	VERIFYING_POOR_LINK	Link has poor connectivity.

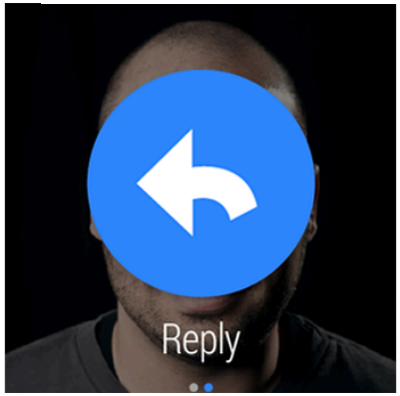
cost?
($ or count for bucket?)

predicted performance?

Mobile = events, not (just) video

- Focus on bandwidth, but wearables and
- Polling (outbound) and events (inbound)
  - sleeping apps
- Current models difficult for developers





IMS /VoLTE

IMS = It Mostly Speaks
VoLTE = Voice-Only Later than Expected

VoLTE: Taking Carriers Beyond Voice

Mon, 06/06/2011 - 12:43pm

by Maisie Ramsay

Get today's wireless headlines and news - Sign up now!

Project yourself into the future – let's say mid-2012. It's been about a year and a half since Verizon Wireless first launched its LTE network in December 2010, and after a long wait, the company has finally come out with the first smartphone running voice over LTE (VoLTE) technology.

You go out and buy the device, turning it on the second you have it out of the box. One of the first things you notice: The phone's native voice application isn't limited to just voice. It has an option for video calls, and there's also an option to send multimedia messages, along with presence indicators that show when people on your contact list can participate in a video call.

AT&T, Verizon Target VoLTE Interop in 2015, RCS Later

By Doug Mohney / November 04, 2014

AT&T and Verizon have officially declared they are working on Voice over LTE (VoLTE) connections between their respective networks and customers. VoLTE calls between Verizon and AT&T customers "is expected" in 2015, according to a statement from the companies. And, there's also some Rich Communications Services (RCS) news buried in the text.

The announcement comes as three out of four major U.S. carriers promote LTE networks and a number of countries plan to turn up LTE and VoLTE in the next 15 months. "Interoperability among VoLTE service providers in the United States and around the world will create a better and richer mobile experience for customers," declares Verizon's press release.

Vodafone Germany announces VoLTE rollout

17 Mar 2015

Germany

Vodafone Germany claims it has become the first German operator to initiate the rollout of voice-over-LTE (VoLTE), having demonstrated the first live VoLTE call on its network at the CeBIT 2015 technology fair in Hanover. The UK-owned operator says that the technology offers customers an 'unprecedented voice service and telephony experience', ensuring 'crystal clear voice quality, super-fast call set-up and encrypted phone calls' across its LTE network, which currently covers 70% of Germany. Vodafone revealed that it will soon be launching new LTE smartphones for VoLTE, including handsets from manufacturers such as Samsung, Sony and HTC. The announcement follows reports last week that Vodafone plans to introduce both Wi-Fi calling and VoLTE in the UK this summer, following trials of the technologies in laboratory conditions.

Surge pricing – non-telecom

Uber surprised a 26-year-old Baltimore woman with a spooky Halloween bill that hit $326 on a routine ride, resulting in her inability to pay her rent and general Internet outrage.

Gabrielle Wathen posted to the site GoFund.me, saying that she went out for her 26th birthday on the night of Halloween and, after taking an Uber an approximately 22-minute ride home around 3am, was charged $326. This means she can't pay her $450 rent, and so she hit the crowd-funding site to ask for help. She raised upwards of $500 by using Instagram to build up

Gett, The Uber Without Surge Pricing, Cuts Ride Fares In NYC

Posted Mar 10, 2015 by Jordan Crook (@jordanrcrook)

People love Uber because it's convenient. You tap a couple buttons on your phone and a car comes and whisks you away.

If there's one customer complaint about the company, though, it's probably surge pricing, when the company drives up fare prices during times of high demand.

Uber's surge pricing policy — as well as the "dynamic pricing" policies of other startups like Lyft — came under fire Monday at a New York City Council transportation committee hearing.

BI, 1/13/2015

Aggressive competitors compete on simplicity

No rate increases. No annual service contracts. No data overages. No limits.

We are on a mission to make mobile make sense.

We offer simple ideas that save people a lot of money on their monthly mobile bills. We are real people that pick up the phone when you call. We believe in a better way to do mobile.

May 14, 2014, Santa Rosa, California: Sonic.net, a leading Internet and telephone service provider, has announced the build-out of Gigabit Fiber Internet service in the Bay Area City of Brentwood, California. Sonic.net will offer Gigabit Fiber Internet + Unlimited Phone service for $40 per month.

Capital investment

Company	Revenue	Capital expenditures	%
Comcast (US) [3Q14]	$11.04B	$1.644B	14.9
Telekom (DE) [3Q14]	€15.6B	$2.58B	16.5
Safaricom (KE) [H1FY15]	Ksh 79.34B	Ksh 12.37	15.5

Comcast's Q2 2014 Capital Spending Trends

Category	Growth CapEx ($ mil.)	% of Total (%)	Maintenance CapEx ($ mil.)	% of Total (%)	Total CapEx* ($ mil.)	% of Total (%)
Consumer Premises Equipment	668	65	72	16	740	50
Network Infrastructure	107	10	287	64	394	27
Support Capital	48	5	89	20	137	9
Commercial	209	20	0	0	209	14
Total*	**1,032**	-	**448**	-	**1,480**	-

As of Aug. 2014. * Total excludes $13 million in discretionary capital. Total including discretionary spending was $1,493 mil. Source: Comcast.

The value of bits

- Technologist: A bit is a bit is a bit
- Economist: Some bits are more valuable than other bits
  - e.g., $/bit(email) >> $/bit(video)
  - no-QoS bits dominate in volume

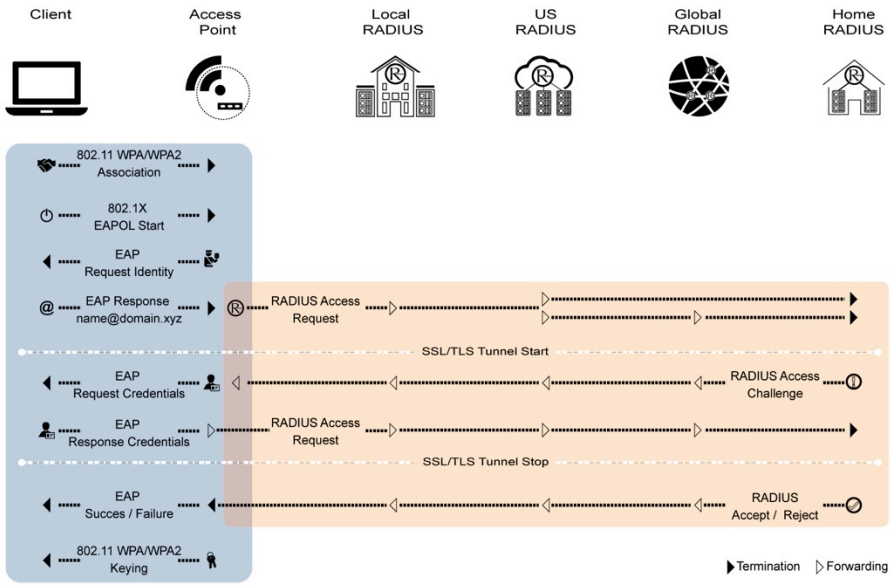
Application	Volume	Cost per unit	Cost / MB	Cost / TB
Cable video	660 GB		$0.06	$60
Voice (13 kb/s GSM)	97.5 kB/minute	10c	$1.02	$1M
Mobile data	5 GB	$40	$0.008	$8,000
MMS (pictures)	< 300 KB, avg. 50 kB	25c	$5.00	$5M
SMS	160 B	10c	$625	$625M

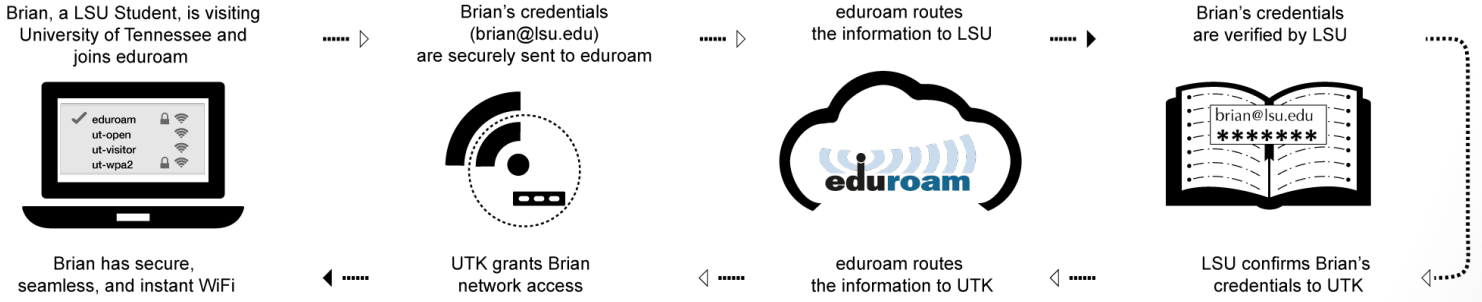
5G prototype: Eduroam

eduroam

Global WiFi Roaming For Academia

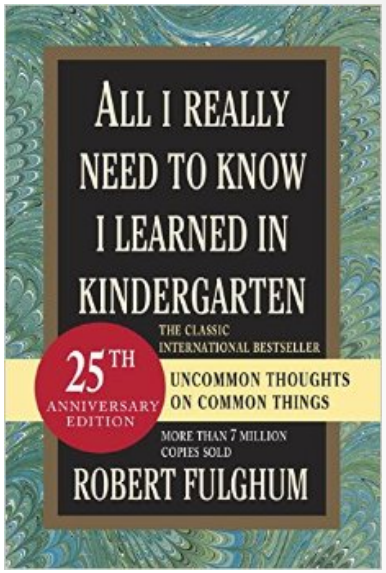
an Internet2 NET+ service





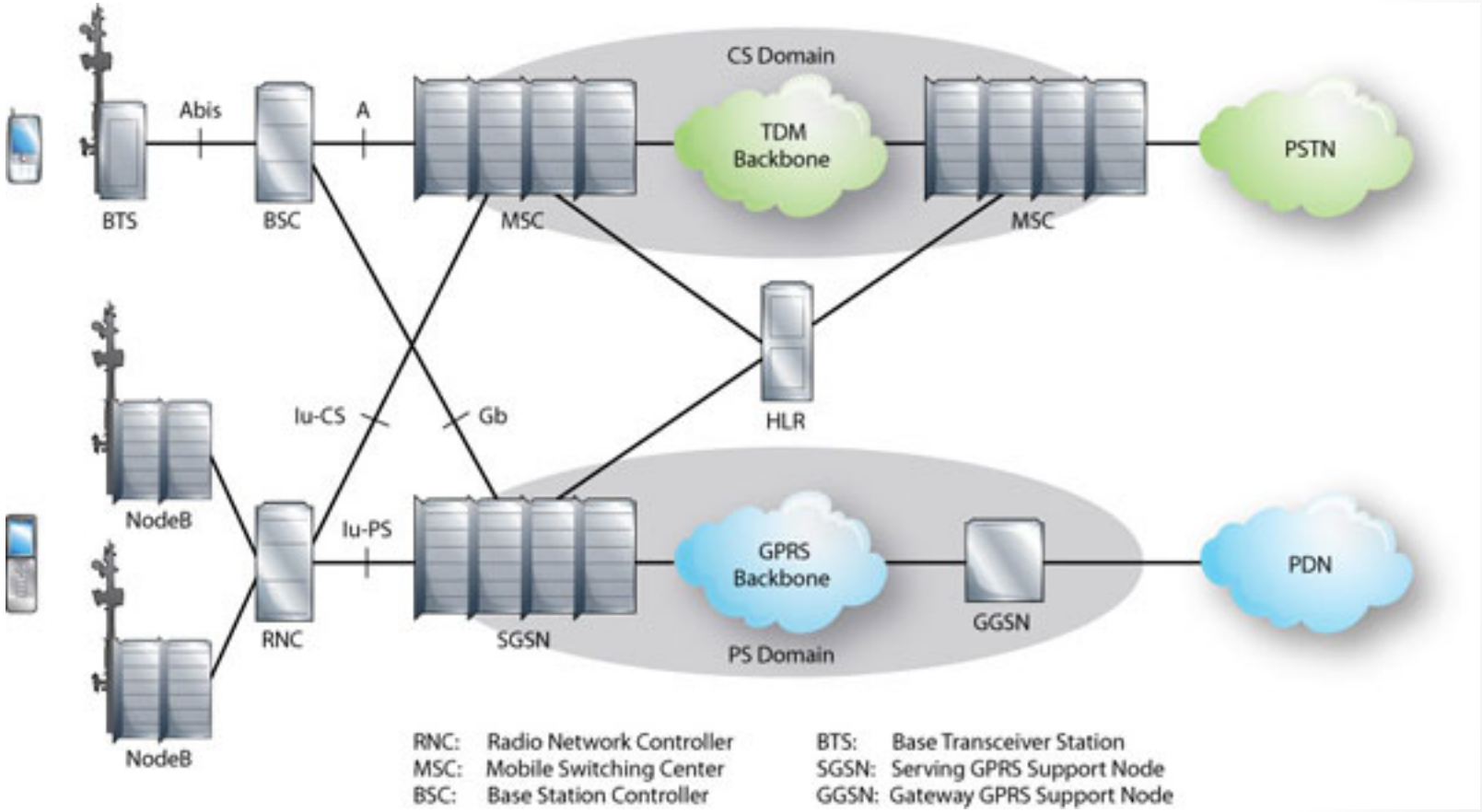
Growing-up lessons

- Complexity kills
- Play fair
- CapEx is once, OpEx is forever
- Know where you are
- Share everything
- Don’t trust strangers



BACKUP

LTE architecture



Wireless market evolution