Emerging Wireless and Cognitive Radio Standards

SDR ‘10

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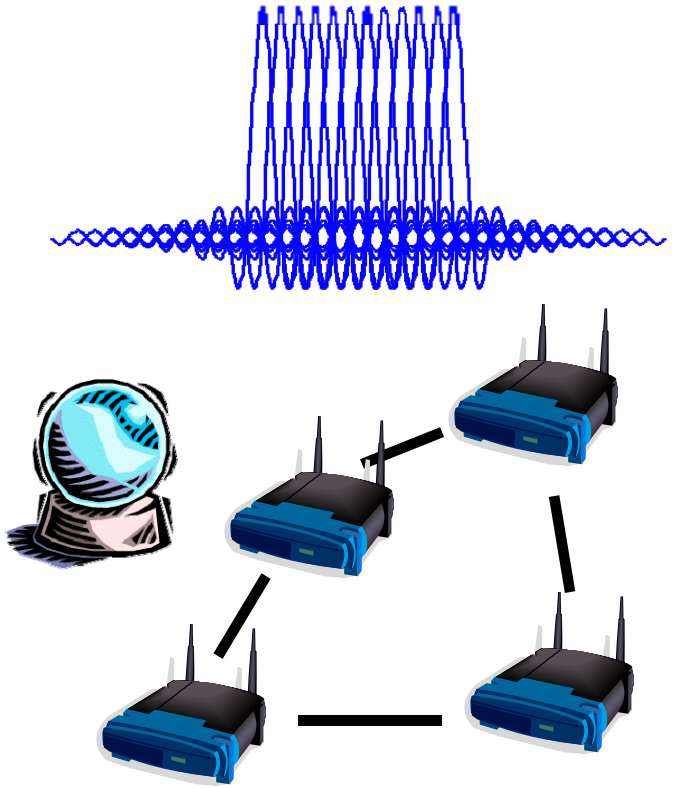
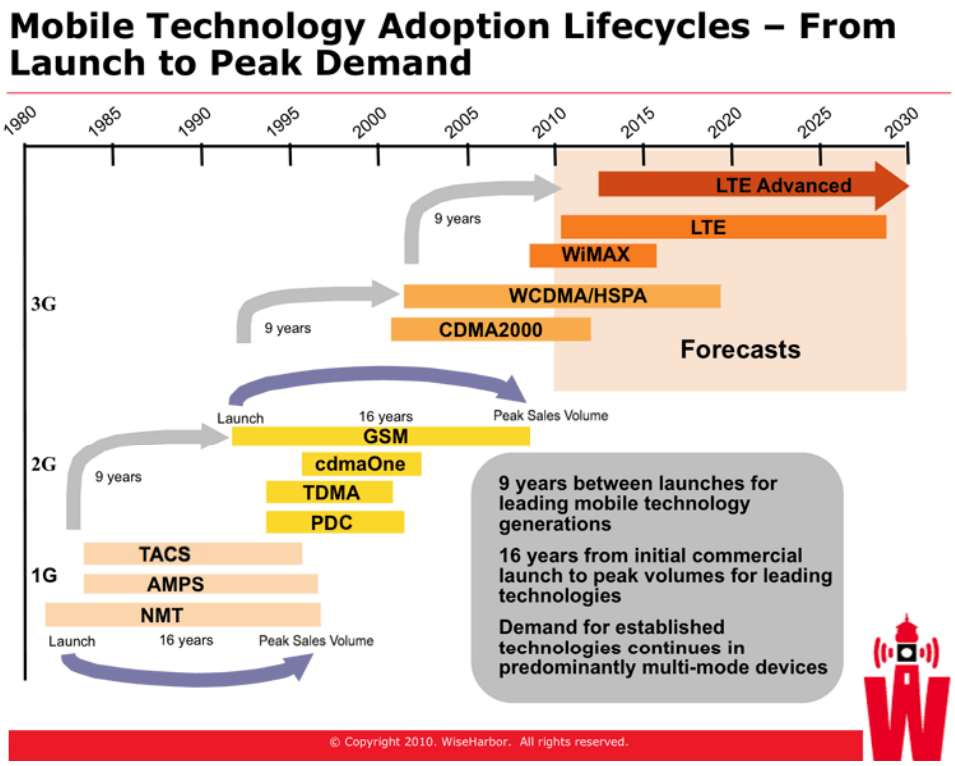


Emerging Wireless Standards

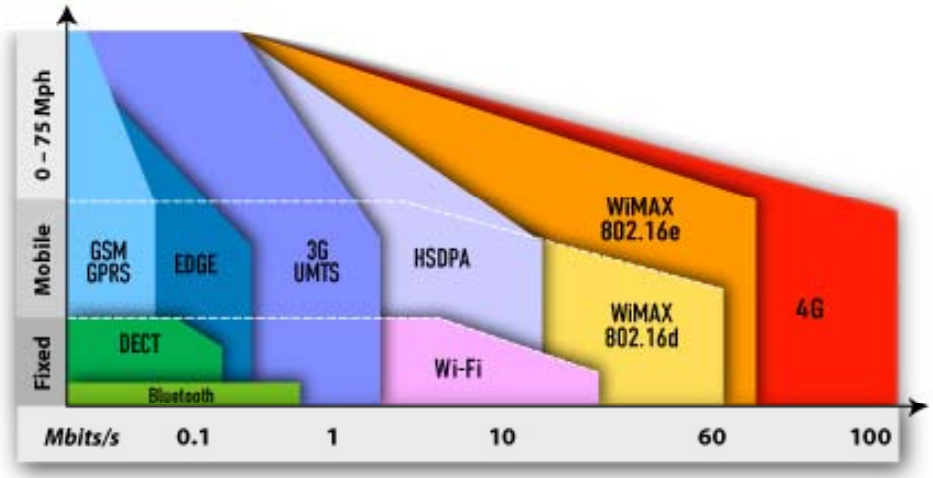
- Focus on standards just coming out
- Current market context for best guesses on which standards will make it and which ones will not
- Consumer:
  - 5 to 10 years out
- Researcher / Developer:
  - Now



http://gigaom.com/2010/05/21/its-a-long-way-to-widespread-lte/

Presentation Overview

Emerging Standards



http://www.wisoa.net/members_logos/mobile_internet-big.jpg

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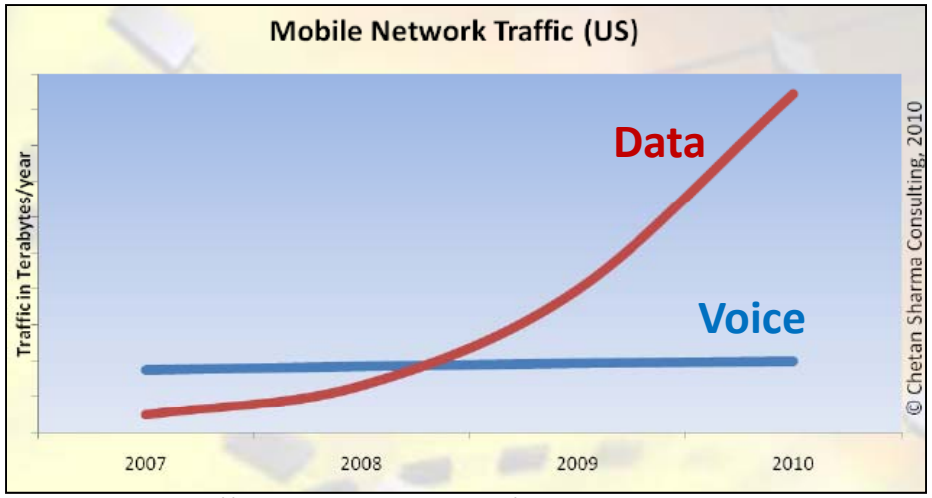
Market Drivers

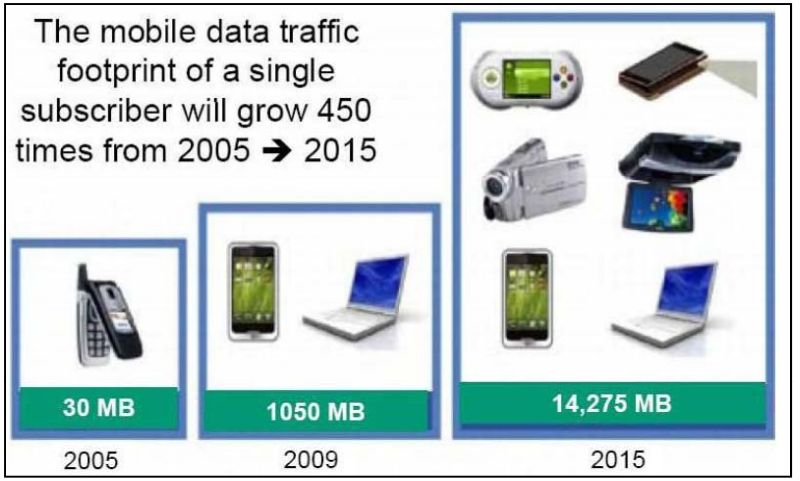


http://www.chetansharma.com/usmarketupdateq12010.htm

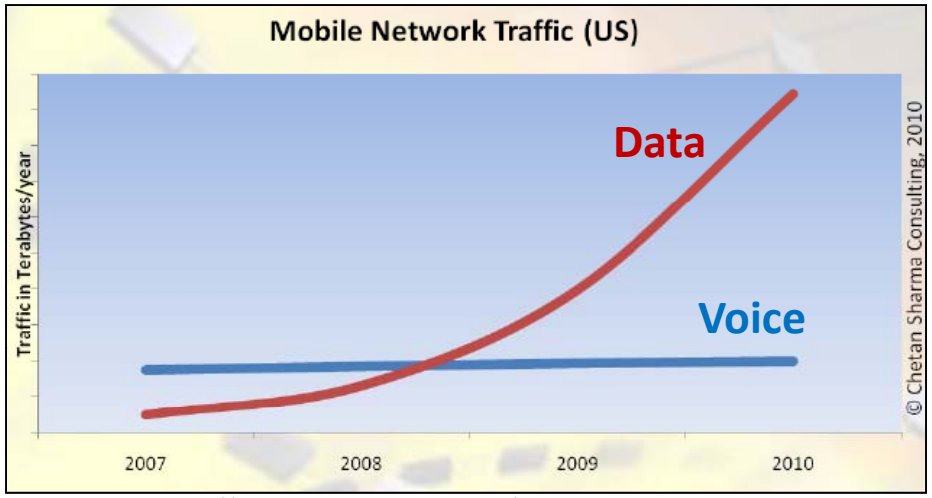
Exponential Data Usage Increase

Owners of the iPhone 3GS, the newest model, "have probably increased their usage by about 100 percent," said Chetan Sharma, an independent wireless analyst. "It's faster so they are using it more on a daily basis.

J. Wortham, "Customers Angered as iPhones Overload AT&T" New York Times, September 2, 2009.



A. Gothard, "Managing Femtocells and the Evolved Packet Core"



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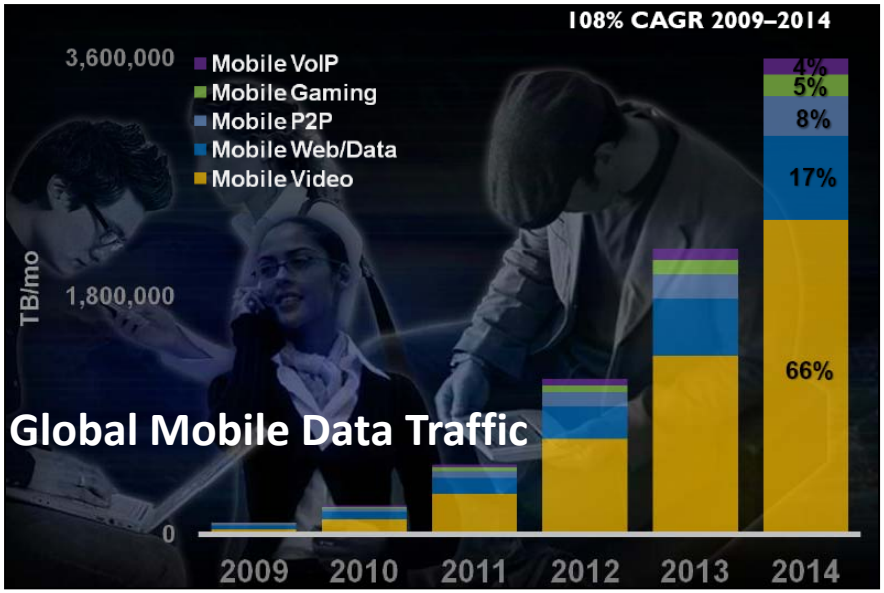
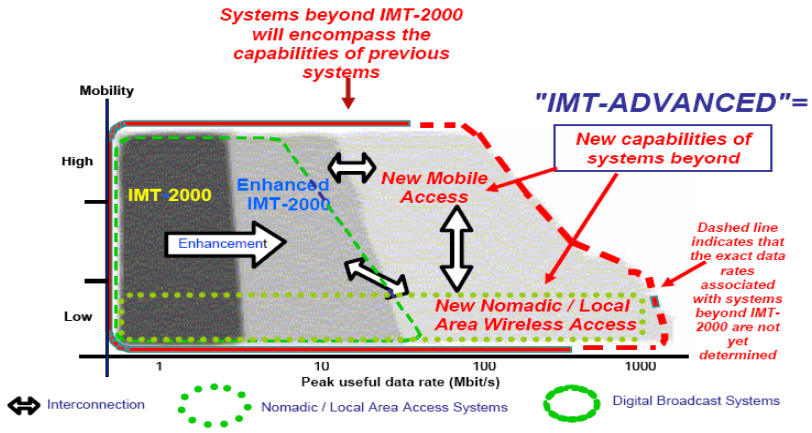


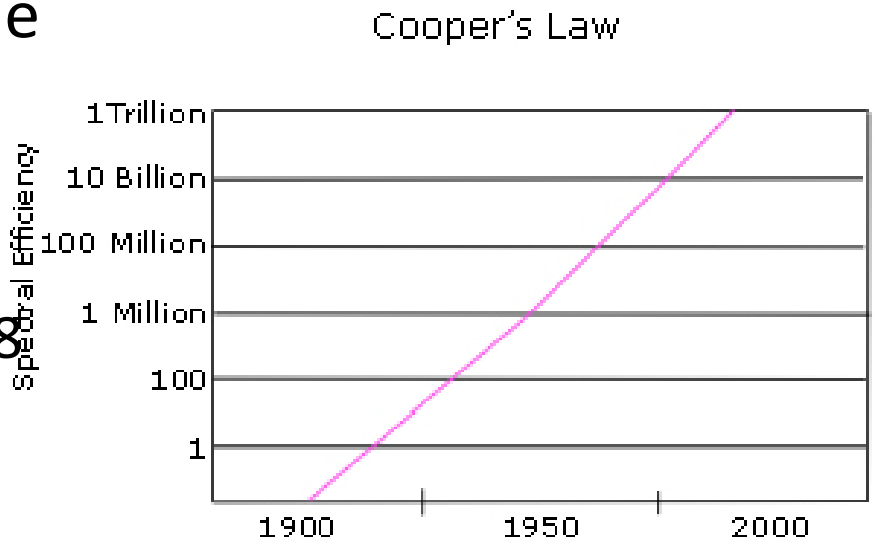
A. Gothard, "Managing Femtocells and the Evolved Packet Core"

More bits per Hz / km^2 / sec

- Chetan Sharma 09
  - –Mobile Data traffic > Mobile Voice Traffic
  - –1 Exabyte Data Traffic
  - –2010: more mobile broadband connections than fixed
- Further need due to ¼ of US households not having a landline
- Aiming for x10 increase in capacity for 4G
- Cooper's Law (Arraycom):
  - –Spectral efficiency doubles every 18 months
  - –> 112x since Marconi



http://3gamericas.com/PDFs/3G_Americas_Defining_4G_WP_July2007.pdf

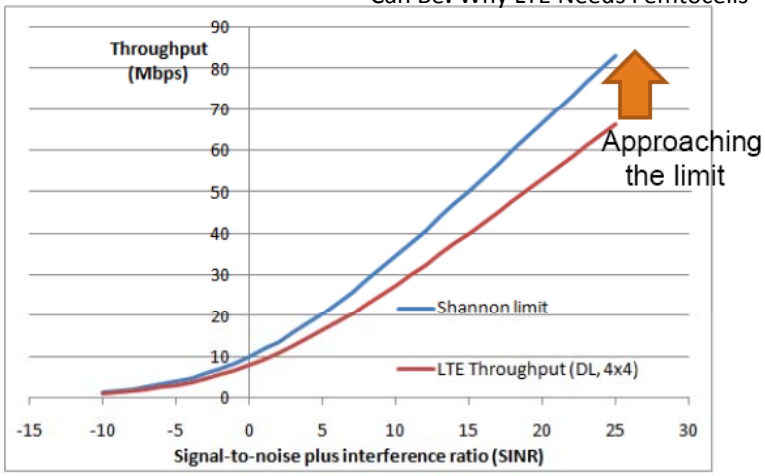


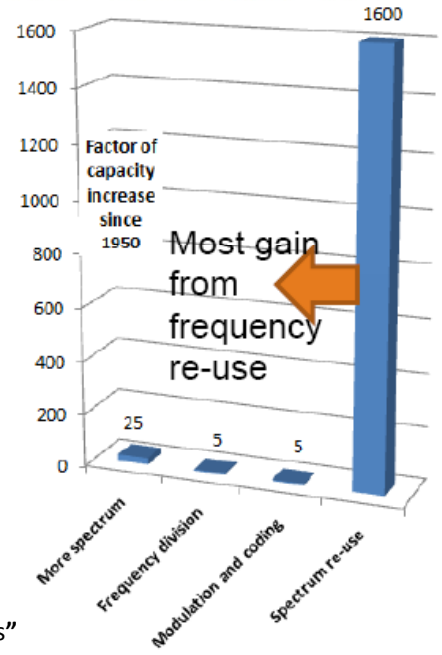
http://www.arraycomm.com/serve.php?page=Cooper

Need better frequency reuse and interference management

- Already close to limit of what modulation and coding can buy
- Historically capacity gains came from frequency re-use
  - Parallel communications
  - Sectorization, smaller cells, beamforming

Rupert **Baines, "The Best** That LTE Can Be: Why LTE Needs Femtocells"





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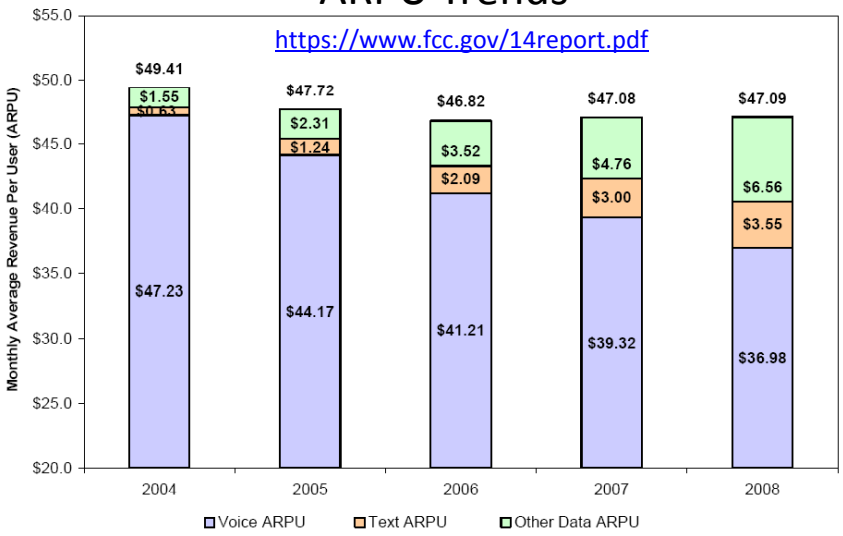
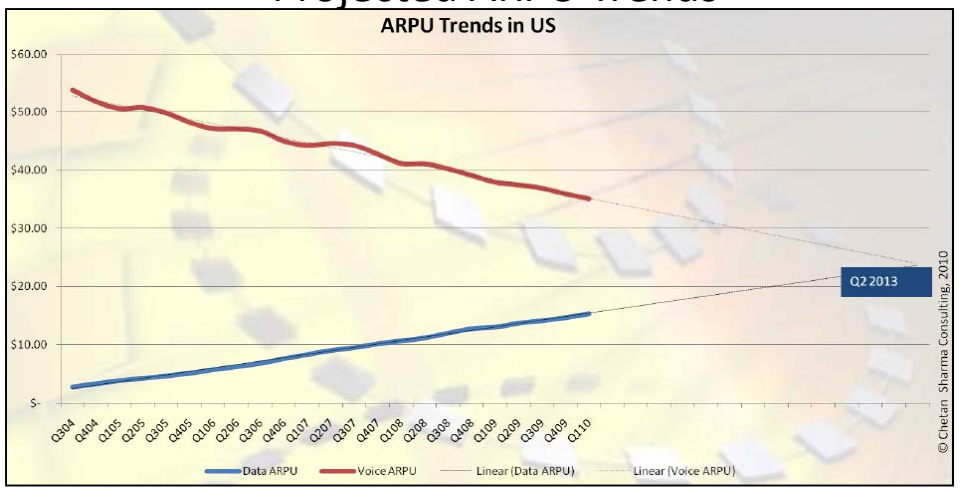
Data Increasing Share of Revenue

ARPU Trends



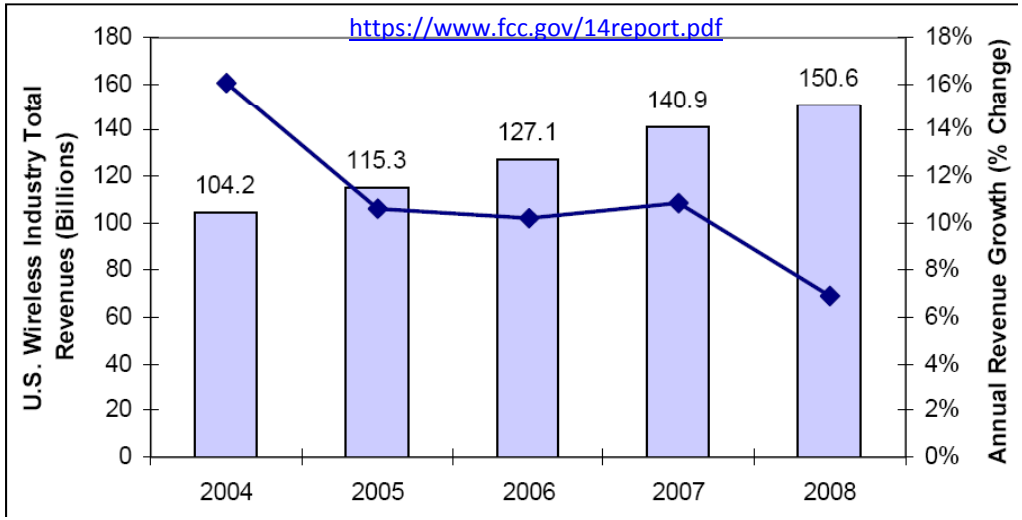
Projected ARPU Trends



http://www.chetansharma.com/usmarketupdateq12010.htm

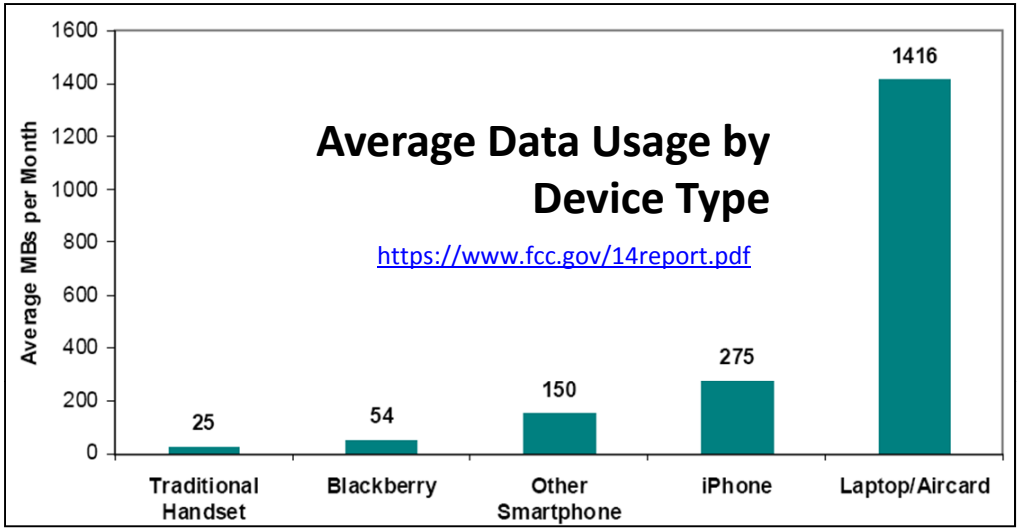
- Revenues increasing
- ARPU flat
- Growing percentage from data
- Exponential increase in data demand + linear increase in data revenues
  - Need to cut expenses to keep growth trajectories

Cellular Revenue Trends

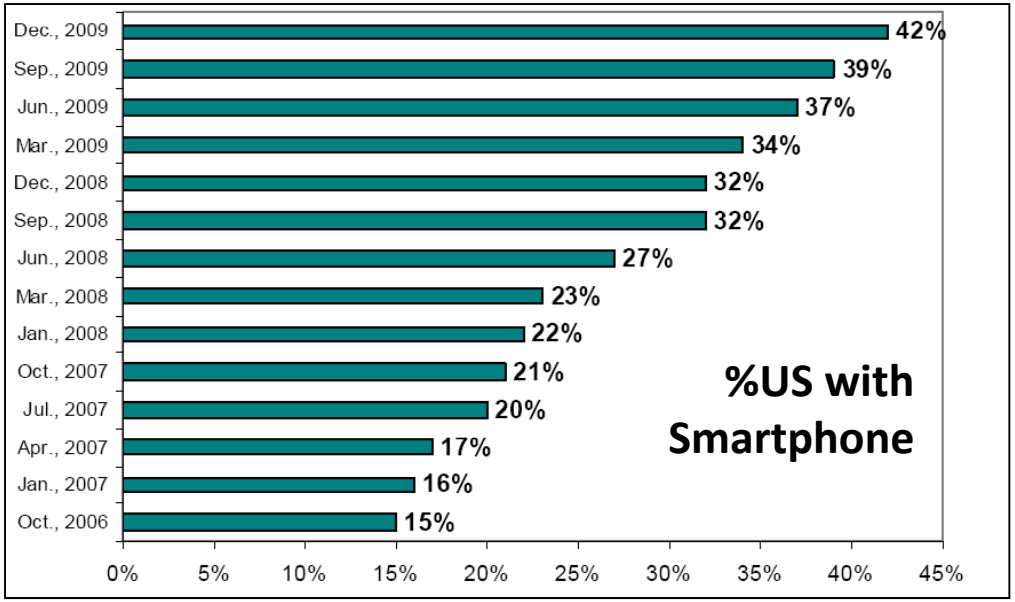


Apps and smartphones > networks

- Smartphone +67% yoy Q1 09 t0 Q1 10
- Well-known iPhone and Android App stores
  - **7 BILLION** app downloads 2009
- Kindle, Smart Grid, Android for GM
- AT&T may be strongest case that the apps and phones now matter more than the network



IMG: http://blog.jjhelp.com/?p=417



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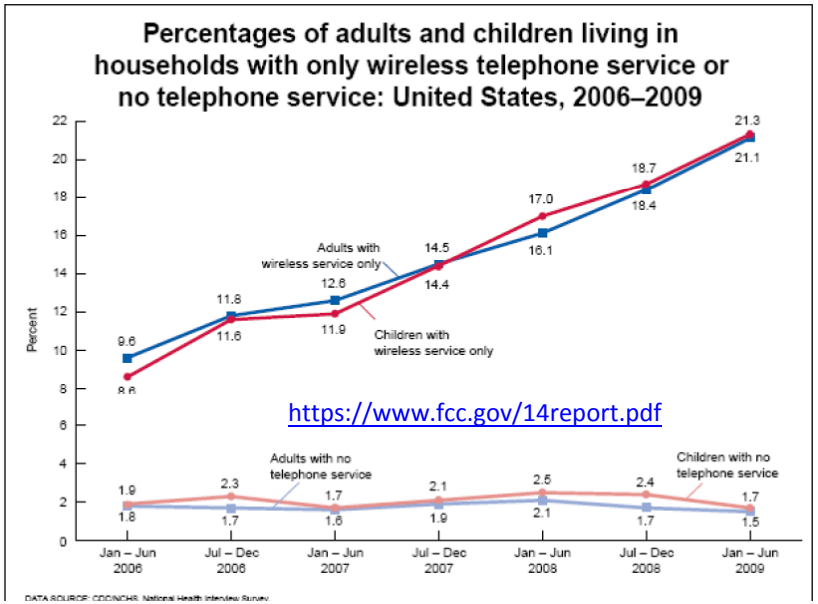
The action is moving indoors

According to Saw, early lessons Clearwire learned from active WiMAX networks shows customers "**using more bandwidth than I've ever seen in my years of working with wireless networks**" and that they are **using these mobile services primarily indoors**, where they work or or live. "No longer is mobile broadband limited to what you would call the road warriors," Saw said.

https://www.sidecutreports.com/order-sidecut-reports/free-report-download/?rid=6



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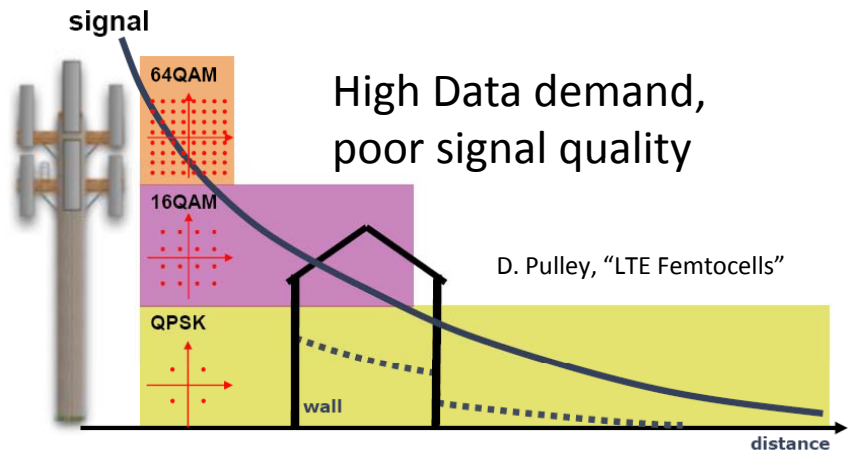
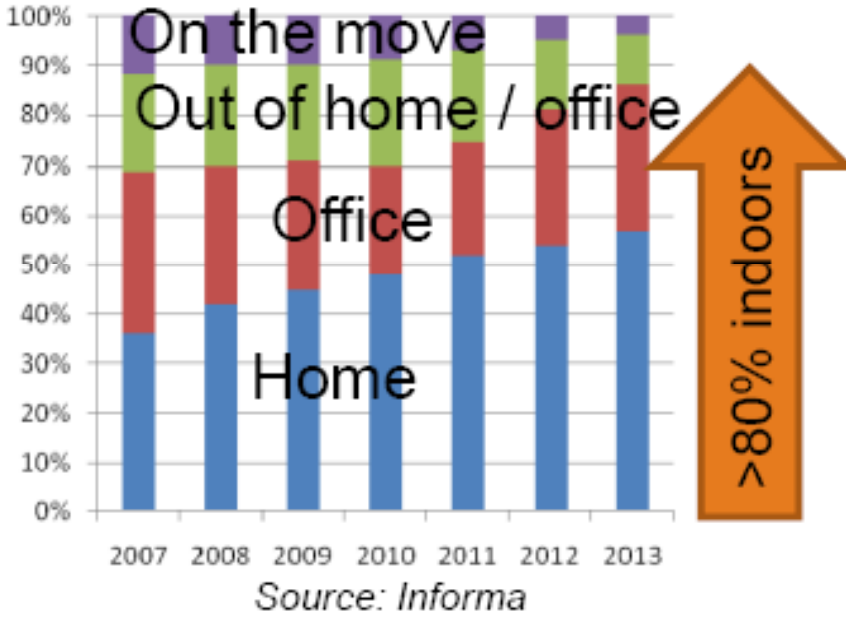


High Data demand, poor signal quality

D. Pulley, "LTE Femtocells"



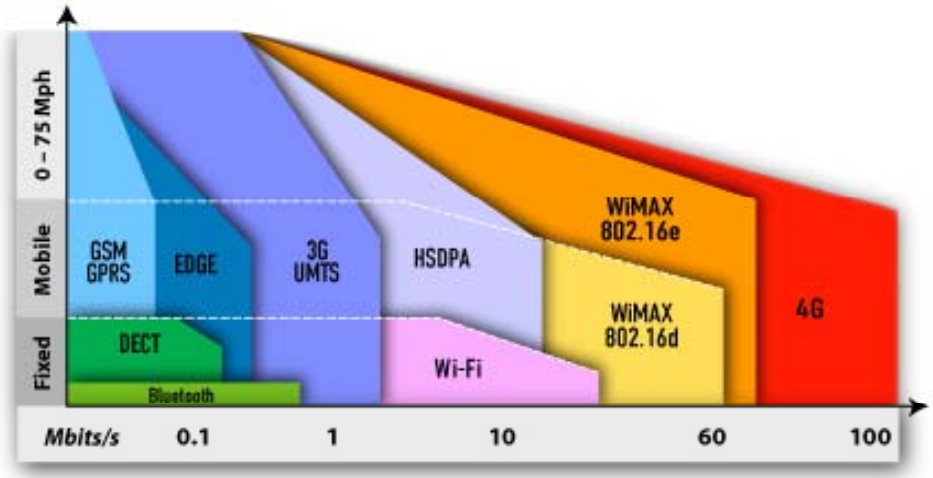
Rupert **Baines, "The Best** That LTE Can Be**:** Why LTE Needs Femtocells**"**

Technology Implications of Trends

- Femtocells
  - Greater capacity + frequency reuse + movement indoors
- Cognitive radio
  - Reuse spectrum + better interference management
  - Access more spectrum
- Self-organizing networks
  - Lower cost + CR reasons + femtocells
- mm-Wave standards
  - Expensive spectrum + greater capacity + frequency reuse

Presentation Overview

Emerging Standards



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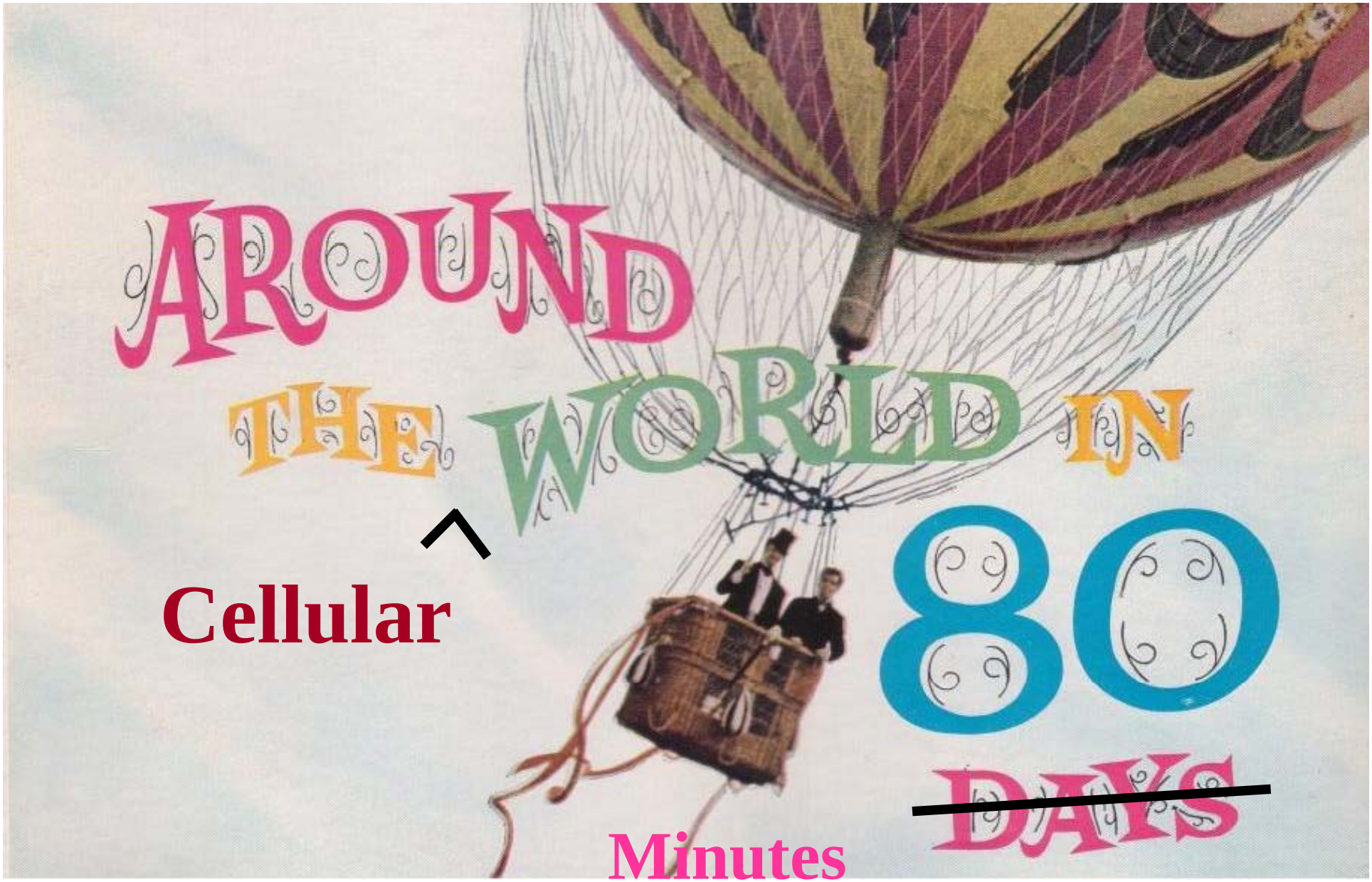

Shamelessly modified from cover art to Michael Todd's soundtrack to "Around the World in 80 Days", see http://www.phys.uu.nl/~gdevries/objects/80days_todd.html for original context

Global Stats: Or Why the US Matters

- 26% 2009 Revenues Data
  - Recall equal voice, data traffic
- India subscribers catching China
- US talks the most (per user)
- Japan has greatest %Data of ARPU

Rank	By Subs	By Data Revenue	By Service Revenue
1	China	US	US
2	India	Japan	China
3	US	China	Japan
4	Russia	UK	France
5	Brazil	Italy	Italy
6	Indonesia	Germany	UK
7	Japan	France	Germany
8	Germany	Australia ↑	Brazil ↑
9	Pakistan	Spain	Spain
10	Italy	Korea ↓	India ↓

http://www.chetansharma.com/

Table 40
Mobile Market Performance in Selected Countries[965]

Country	Penetration (% of Pops)	Prepaid (% of Subs)	MOUs	Revenue per Minute ($)	ARPU ($)	Data (% of ARPU)
Receiving Party Pays						
USA	88.9	17.1	829	0.05	51.54	25.5
Canada	64.8	21.2	444	0.09	49.24	17.8
Hong Kong	147.6	44.9	447	0.04	20.40	26.7
Singapore	135.8	48.6	377	0.06	32.08	27.3
Calling Party Pays						
UK	125.5	62.0	192	0.12	35.35	27.8
Germany	130.6	56.6	102	0.16	20.59	25.3
Italy	152.7	88.3	131	0.16	26.87	24.7
Sweden	123.6	35.0	206	0.10	28.05	20.9
France	91.9	34.2	246	0.14	44.37	18.3
Finland	127.5	12.7	244	0.12	33.91	18.9
Japan	85.7	1.4	139	0.26	56.82	41.0
South Korea	93.9	3.0	320	0.08	30.34	17.0
Australia	109.9	44.9	218	0.11	34.57	32.4

https://www.fcc.gov/14report.pdf

http://www.chetansharma.com/

General Handheld Stats

US Market

Handset Manufacturer	Share of Mobile Devices in Use
Motorola	23.5%
LG	21.9%
Samsung	21.2%
Nokia	9.2%
RIM	7.0%
All Others	17.2%

https://www.fcc.gov/14report.pdf

Growth in non-voice app usage in US

	Share (%) of U.S. Mobile Subscribers	
	September 2009	December 2009
Sent text message to another phone	61.0%	63.1%
Used browser	26.0%	27.5%
Played games	21.4%	21.6%
Used downloaded apps	16.7%	17.8%
Accessed social networking site or blog	13.8%	15.9%
Listened to music on mobile phone	11.7%	12.1%

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World Market

Company	2009 Sales	2009 Market Share (%)	2008 Sales	2008 Market Share (%)
Nokia	440,881.6	36.4	472,314.9	38.6
Samsung	235,772.0	19.5	199,324.3	16.3
LG	122,055.3	10.1	102,789.1	8.4
Motorola	58,475.2	4.8	106,522.4	8.7
Sony Ericsson	54,873.4	4.5	93,106.1	7.6
Others	299,179.2	24.7	248,196.1	20.3
Total	**1,211,236.6**	**100.0**	**1,222,252.9**	**100.0**

http://www.gartner.com/it/page.jsp?id=1306513

Usage by Device Class

	iPhone	Smartphone	Average Mobile User
Music	65%	35%	12%
Games	61%	48%	21%
Social Networking	58%	43%	14%
Web Search	52%	40%	12%
Instant Messaging	48%	42%	15%
News	40%	31%	9%
Video	23%	16%	4%
Personal Banking	22%	16%	4%
Restaurant Guides	18%	14%	4%
Online Shopping	14%	9%	2%

https://www.fcc.gov/14report.pdf

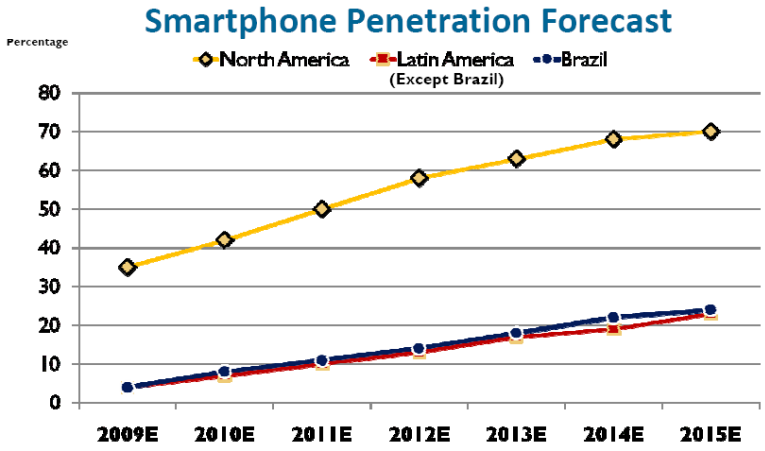
Smart Phone and Apps

- 67% Growth YoY Growth
  - http://www.fiercemobilecontent.com/press-releases/global-smart-phone-market-growth-rises-67
- World: iPhone > Android but US: Android > iPhone
  - http://digitaldaily.allthingsd.com/20100511/apple-on-npd-android-outselling-iphone-claim/
- 9->38 App stores in 2009
- iPhone Stats
  - 206,297 apps in iPhone store
  - >3 billion apps downloaded
  - Average approval delay < 7days
  - App store for jail broken iphones
    - http://cydia.saurik.com/
- Android Stats
  - 100,000 Android-based phones are activated every day.
  - On 60 devices from 21 OEM makers on 59 carriers in 48 countries.
  - >50,000 apps in the Android Market Place
  - http://gigaom.com/2010/05/24/android-vs-chrome-os/

Worldwide smart phone market
Market shares Q1 2010, Q1 2009

Vendor	Q1 2010 shipments	% share	Q1 2009 shipments	% share	Growth Q1'10/Q1'09
Total	55,201,280	100.0%	33,066,560	100.0%	66.9%
Nokia	21,429,680	38.8%	13,683,920	41.4%	56.6%
RIM	10,589,260	19.2%	7,298,820	22.1%	45.1%
Apple	8,752,180	15.9%	3,792,470	11.5%	130.8%
HTC	2,840,120	5.1%	1,379,860	4.2%	105.8%
Motorola	2,602,490	4.7%	1,099,100	3.3%	136.8%
Others	8,987,550	16.3%	5,812,390	17.6%	54.6%

Source: Canalys estimates, © Canalys 2010



ftp://ftp.3gpp.org/workshop/2010_04_Rio_LTEseminar/Marketplace_update.pdf

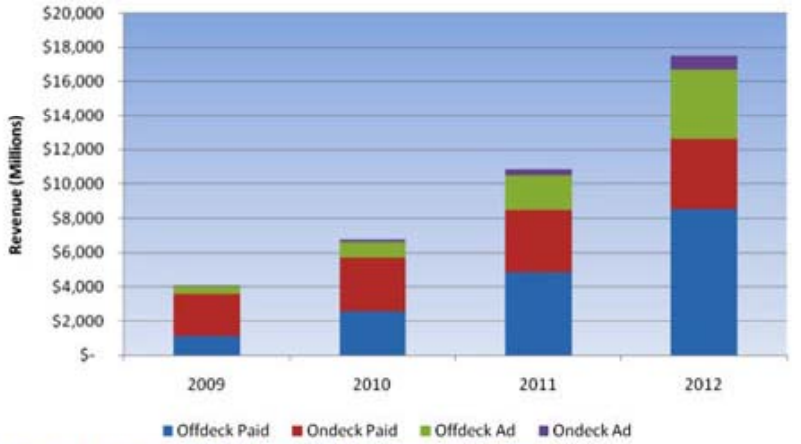
Smart Phone Trends / Predictions

- Gut feeling: Android will "win" out over iPhone
- Not like how LTE is winning over WiMAX
  - Apple is still going to make its money and may even be the single largest smart phone manufacturer; definitely most profitable
- Why:
  - More types of devices
  - Increasing trend to offdeck
  - Increasing importance of ads
  - Open OS leads to unexpected applications
    - DARPA Android BAA
      - https://www.fbo.gov/download/35b/35bddd6bb5d6118f8f6c16317ea61cb5/TA_BAA_10-41_FINAL.pdf
    - Android for GM
      - http://earth2tech.com/2010/05/23/why-googles-android-could-rule-connected-cars/
  - Foreign Market growth, e.g., Japan (DoCoMo, KDDI)
    - http://www.mobile-ent.biz/features/273/Android-rising-in-Japan
  - MS Kin: Too Little, too late?
    - http://paidcontent.org/article/419-microsofts-kin-too-little-too-late-/

Smart Phone OS Share

Company	2009 Units	2009 Market Share (%)	2008 Units	2008 Market Share (%)
Symbian	80,878.6	46.9	72,933.5	52.4
Research In Motion	34,346.6	19.9	23,149.0	16.6
iPhone OS	24,889.8	14.4	11,417.5	8.2
Microsoft Windows Mobile	15,027.6	8.7	16,498.1	11.8
Linux	8,126.5	4.7	10,622.4	7.6
Android	6,798.4	3.9	640.5	0.5
WebOS	1,193.2	0.7	NA	NA
Other OSs	1,112.4	0.6	4,026.9	2.9
Total	**172,373.1**	**100.0**	**139,287.9**	**100.0**

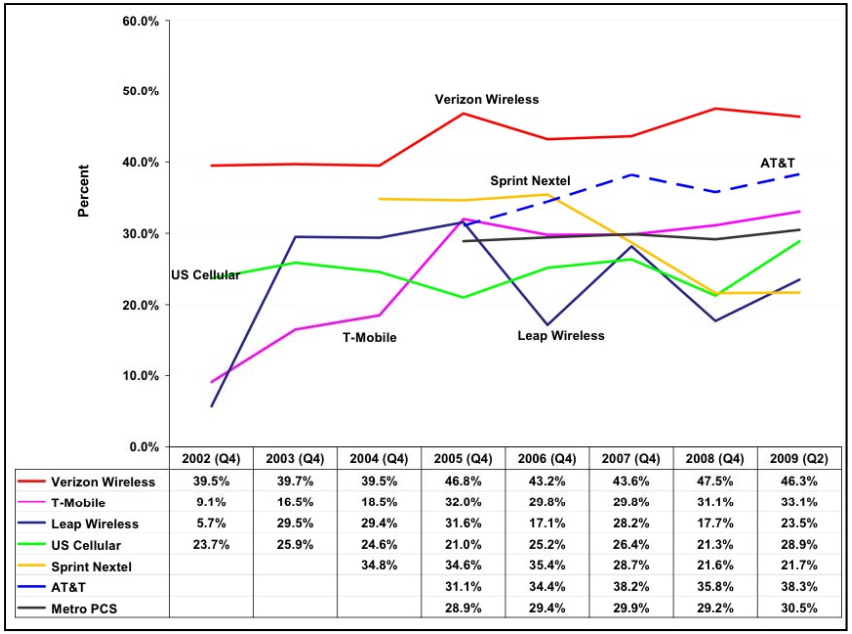
http://www.gartner.com/it/page.jsp?id=1306513



Global Mobile Apps Market Revenue by Type

US-Specific Stats

- AT&T and Verizon growth
- Sprint lost A LOT of subscribers
  - Customer service
- Sprint / Clearwire very well positioned in terms of spectrum
- Verizon is making the most



	2002 (Q4)	2003 (Q4)	2004 (Q4)	2005 (Q4)	2006 (Q4)	2007 (Q4)	2008 (Q4)	2009 (Q2)
Verizon Wireless	39.5%	39.7%	39.5%	46.8%	43.2%	43.6%	47.5%	46.3%
T-Mobile	9.1%	16.5%	18.5%	32.0%	29.8%	29.8%	31.1%	33.1%
Leap Wireless	5.7%	29.5%	29.4%	31.6%	17.1%	28.2%	17.7%	23.5%
US Cellular	23.7%	25.9%	24.6%	21.0%	25.2%	26.4%	21.3%	28.9%
Sprint Nextel			34.8%	34.6%	35.4%	28.7%	21.6%	21.7%
AT&T				31.1%	34.4%	38.2%	35.8%	38.3%
Metro PCS				28.9%	29.4%	29.9%	29.2%	30.5%

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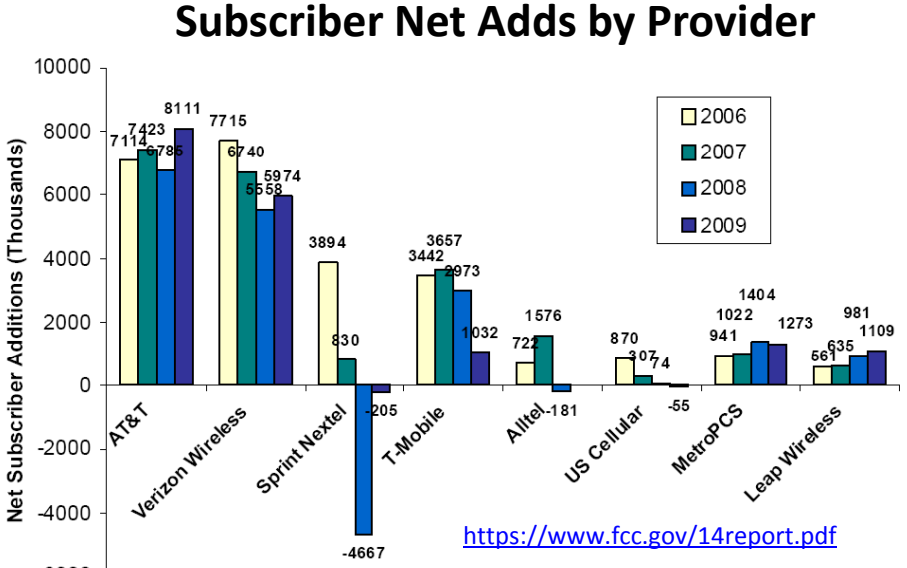

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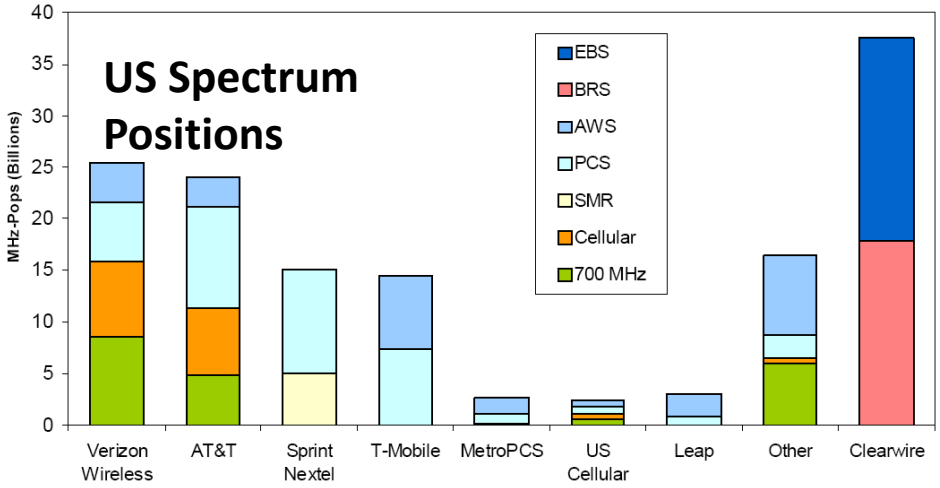

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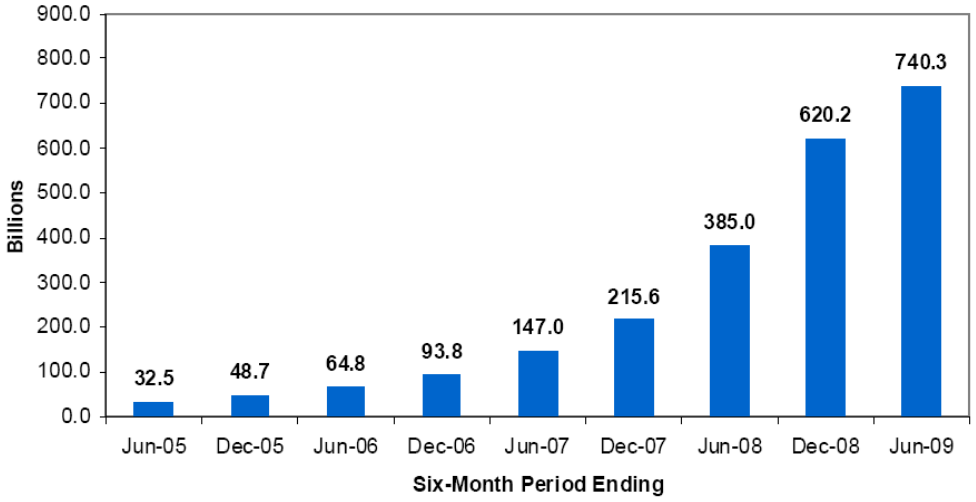
Text and the teenager

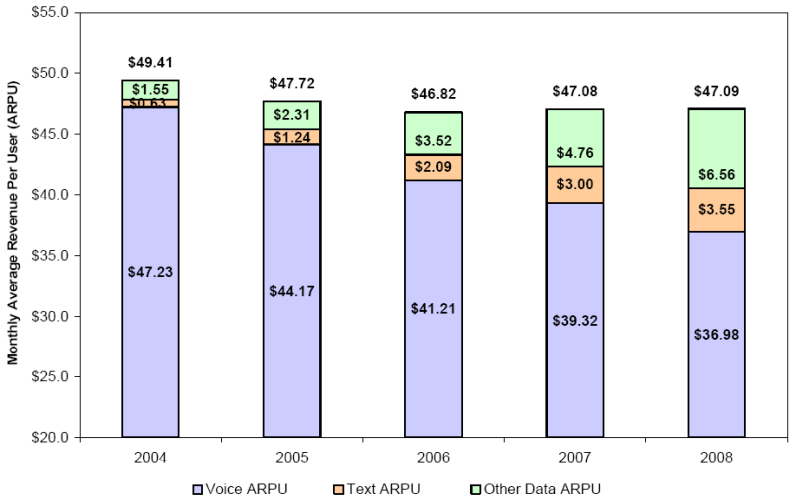


Mobile Usage

Age	Penetration Rate
12 yrs	58%
13 yrs	73%
14 yrs	76%
15 yrs	79%
16 yrs	82%
17 yrs	83%

Age Range	Smartphone Ownership Rate	SMS Adoption Rate
18 to 24 year-olds	29%	83%
25 to 44 year-olds	29%	65%
45 to 54 year-olds	24%	52%
55 to 64 year-olds	13%	33%

Six-Month Period Ending	Average Text Messages Per User Per Month	Average MMS Messages Per User Per Month
Jun-05	29	0.3
Dec-05	40	0.7
Jun-06	51	0.9
Dec-06	69	1.2
Jun-07	103	1.8
Dec-07	144	2.3
Jun-08	248	3.6
Dec-08	388	5.8
Jun-09	451	6.3

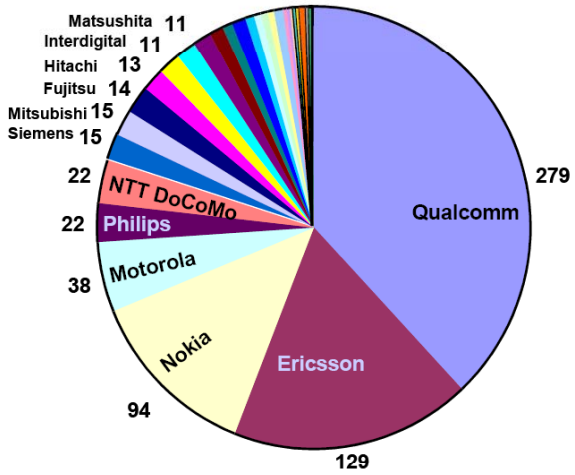


All charts from: https://www.fcc.gov/14report.pdf

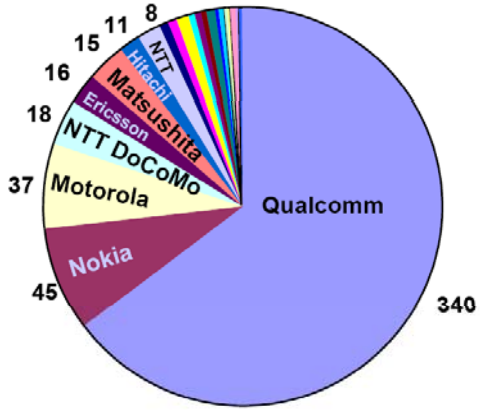
3G Cellular Overview

- Two primary competing approaches to 3G
  - 3GPP Family
    - GSM, GPRS, EDGE, WCDMA, TD-SCDMA (WCDMA-TDD), HSCSD, HSPDA, LTE, LTE Advanced
    - Promotional www.gsmworld.com
    - Standards www.3gpp.org
  - 3GPP2 Family
    - CDMAOne (IS-95a,b), 1xRTT, 1xEVDO, 1xEVDV, UMB
    - Promotional http://www.cdg.org
    - Standards www.3gpp2.org
  - One vision
    - Voice + high speed data + mobility
  - One dominant IP holder (Qualcomm)
- Other Player
  - Mobile WiMAX and WiMAX II (802.16m)
  - Standard http://wirelessman.org/
  - Promotional http://www.wimaxforum.org
  - Lower cost IP
    - 350 companies own essential IP
    - http://www.eetimes.eu/design/197007324

3GPP Declared IP



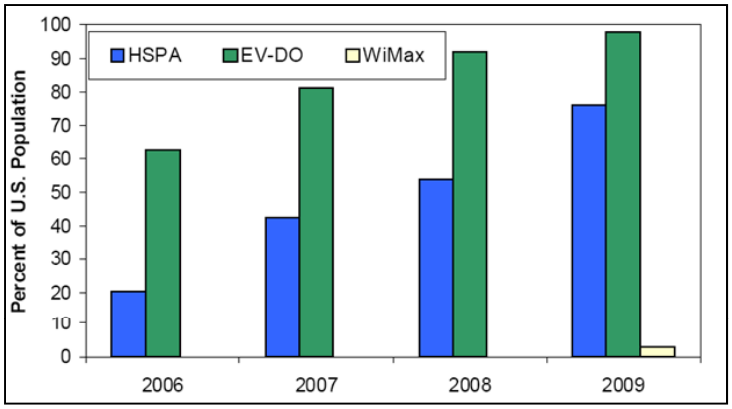
3GPP2 Declared IP



Source: "3G Cellular Standards and Patents", David J Goodman and Robert A. Meyers

Cellular Trends

US Networks



https://www.fcc.gov/14report.pdf

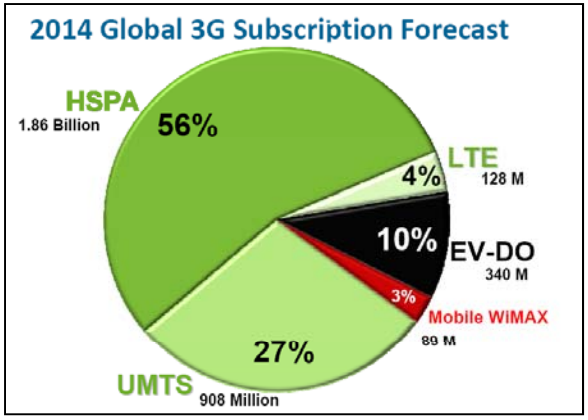
Carrier	Real-world download speeds	Real-world upload speeds	People covered by the end of 2010
Verizon (LTE)	5-12 Mbps	2-5 Mbps	100 million
AT&T (HSPA+)	7 Mbps	?	250 million
T-Mobile (HSPA+)	3.12 Mbps - 8.26 Mbps	1.26 Mbps - 2.5 Mbps	185 million
Sprint (WiMAX, via Clearwire)	3-6 Mbps	500 Kbps	120 million

http://www.fiercewireless.com/story/real-world-comparing-3g-4g-speeds/2010-05-25

Global Data

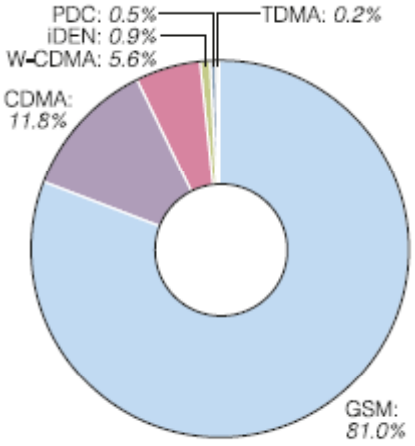
Class	Numbers
GSM	3,450,410,548
3GPP2	441,239,979
3GPP	389,741,282
iDEN	22,172,858
WiMAX	6,800,000
Other	2,749,913

Total	4,310,295,611
cdmaOne	2,449,937
CDMA2000 1X	309,907,068
1xEV-DO	118,688,849
1xEV-DO Rev. A	12,644,062
GSM	3,450,410,548
WCDMA	255,630,141
WCDMA HSPA	133,286,097
TD-SCDMA	825,044
TDMA	1,480,766
PDC	2,740,320
iDEN	22,172,858
Analog	9,593



ftp://ftp.3gpp.org/workshop/2010_04_Rio_LTEseminar/Marketplace_update.pdf

GSM Dominates the Landscape



http://www.coveragemaps.com/gsmposter_world.htm

- 3GPP (GSM/WCDMA) has most of the market (77% in 2005, 83% in 2006, 86.6% in 2008)
  - Most of that lead is in GSM
- 3GPP2 (cdma2000) got a massive jump on 3GPP
  - 418/431 million of CDMA is 3G (www.cdg.org)
  - 3GPP2 = 11.4%, 3GPP = 5.6%
- WiMAX just cranking up but will be deploying years ahead of LTE

3GPP Technologies

- Generic Access Network (UMA)
  - Supports handoffs between GSM networks and 802.11 or Bluetooth networks
- Packet Switched Handoffs
  - Enables easier handoffs between different 3GPP networks
- Multimedia Broadcast/Multicast Services
  - Simultaneous broadcast of data streams to multiple recipients

Feature	HSDPA	1xEV-DV
Downlink Frame Size	2ms TTI (3 Slots)	1.25, 2.5, 5, 10 ms Variable Frame Size (1.25 ms Slot size)
Channel Feedback	Channel quality reported at 2ms rate or 500 Hz	C/I feedback at 800 Hz (every 1.25 ms)
Data user multiplexing	TDM/CDM	TDM/CDM (variable frame)
Adaptive Modulation and Coding	QPSK & 16-QAM Mandatory	QPSK, 8-PSK & 16-QAM
Hybrid-ARQ	Chase or Incremental Redundancy (IR)	Async. Incremental Redundancy (IR)
Spreading Factor	SF=16 using UTRA OVSF Channelization Codes	Walsh Code Length 32
Control Channel Approach	Dedicated Channel pointing to Shared Channel	Common Control Channel

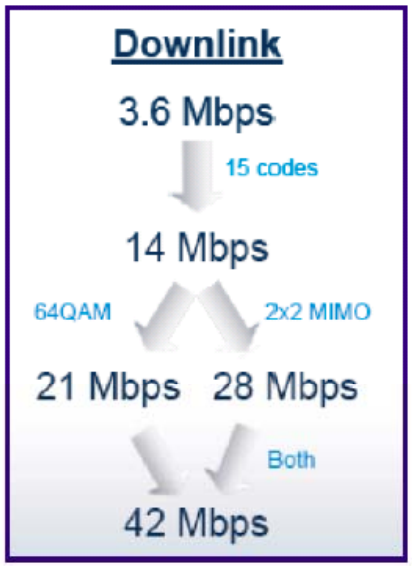
Table from: http://www.umtsworld.com/technology/images/hsdpa.png

- High Speed Downlink Packet Access
- W-CDMA downlink
  - 8-10 Mbps (and 20 Mbps for MIMO systems) over a
  - 5MHz bandwidth
  - Adaptive Modulation and Coding (AMC),
  - MIMO (Release 6)
  - Hybrid ARQ
  - All IP core network
    - (Release 4)
    - Originally ATM
- High Speed Uplink Packet Access (Enhanced UpLink)
  - Similar technologies to HSDPA on uplink
  - AT&T in 350 markets
    - http://www.mobileburn.com/news.jsp?Id=4660
    - Loosely coincides with launch of 3G iPhone

High-Speed Packet Access Evolution (HSPA+)

- Evolution to HSPA and last 3GPP update before LTE
- Deployments - Global mobile Suppliers Association (GSA)
  - 36 commercial HSPA+ systems in operation worldwide (Nov. 2009)
  - 33 support peak downlink of 21 Mbps
  - 3 support 28 Mbps using MIMO
- Next mobile broadband baseline will be 21 Mbps
  - From current baseline of 7.2 Mbps
  - http://www.gsacom.com/downloads/pdf/MBB_baseline_survey_report_191109.php4
- Limited HSPA+ device support
  - 12 HSPA+ device launches (GSA, Oct 2009)
  - Compared to 1,739 HSPA devices available

- 3GPP Release 7 HSPA+
  - 21 Mbps DL with 64 QAM
  - 11.5 Mbps UL with 16 QAM
- 3GPP Release 8 HSPA+
  - 42 Mbps DL with 2x2 MIMO
  - 11.5 Mbps UL



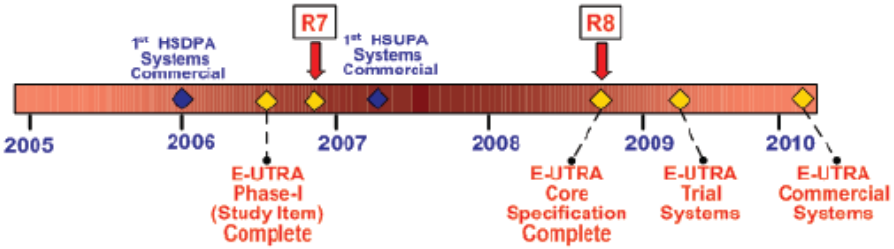
Source: Global mobile Suppliers Association (GSA), *"Global HSPA+ Network Commitments and Deployments,"* Nov. 19, 2009

3GPP Long Term Evolution (LTE)

E-UTRA Air Interface

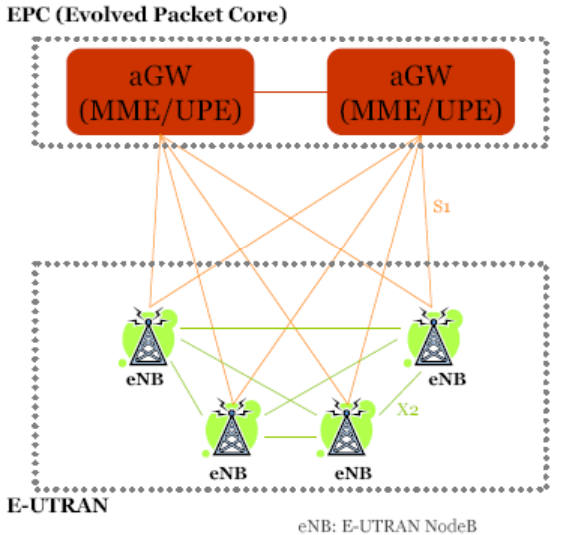
- Evolved Universal Terrestrial Radio Access
- Downlink: Adaptive multilink OFDM (AML-OFDM), which means different bandwidths based on demand
  - Variable prefix size
    - 4.7 ms to 16.7 ms
    - Intent to support up to 120 km cells
  - Called High Speed OFDM Packet Access or HSOPA
- Uplink: SC-FDMA (more later)
- DL 100 Mbps in 20 MHz (5 bps/Hz)
- UL 50 Mbps in 20 MHZ (2.5 bps/Hz)
- Reduced transition time between states (such as between idle and active states)
- Variable bandwidth allocations: 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz in both the uplink and downlink
- At least 200 users/cell
- Load sharing/policy across radio access technologies
- Support for antenna arrays
  - Beamforming, MIMO
  - Space Division Multiple Access

Approximate Deployment Schedule



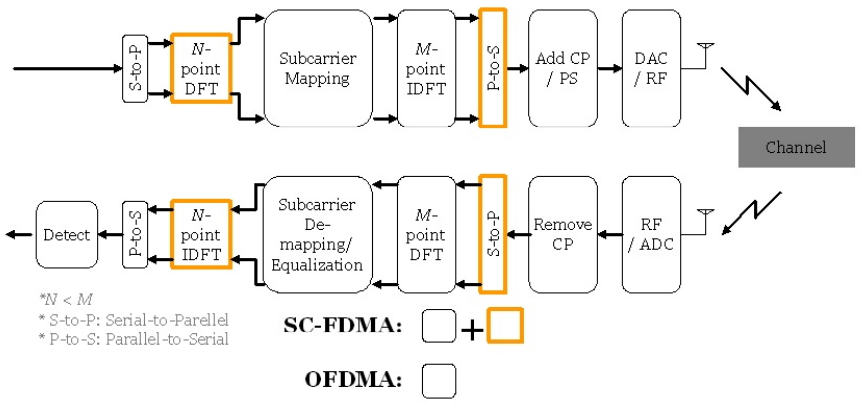
http://www.motorola.com/staticfiles/Business/Solutions/Industry Solutions/Service Providers/Wireless Operators/LTE/_Document/6993_MotDoc.pdf

All IP Core Network



http://hgmyung.googlepages.com/3gppLTE.pdf

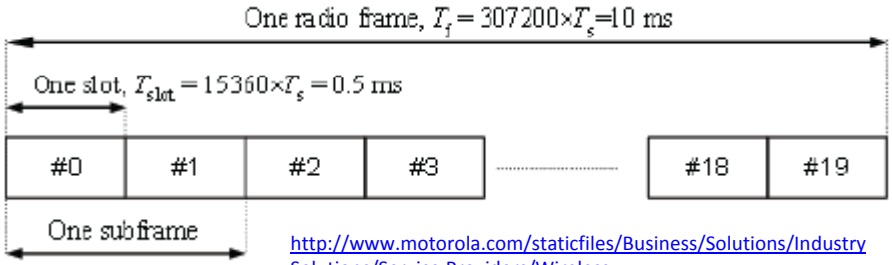
More LTE Details



http://en.wikipedia.org/wiki/SC-FDMA

- SC-FDMA (UL)
  - Applies frequency domain equalization to single-carrier system
  - Transmits serially (single-carrier)
  - Better PAPR (single carrier)
  - Less sensitivity to carrier offset
  - Similar complexity for just equalization
    - But extra steps to implement SC-FDMA
  - Better battery life
  - Possibly worse performance in fading channels

Frame Structure



http://www.motorola.com/staticfiles/Business/Solutions/Industry Solutions/Service Providers/Wireless Operators/LTE/_Document/6993_MotDoc.pdf

  - Subframes 0,5 must be DL
  - Otherwise arbitrary TDD structure
- Other Features
  - Interference Mitigation
  - Extensions

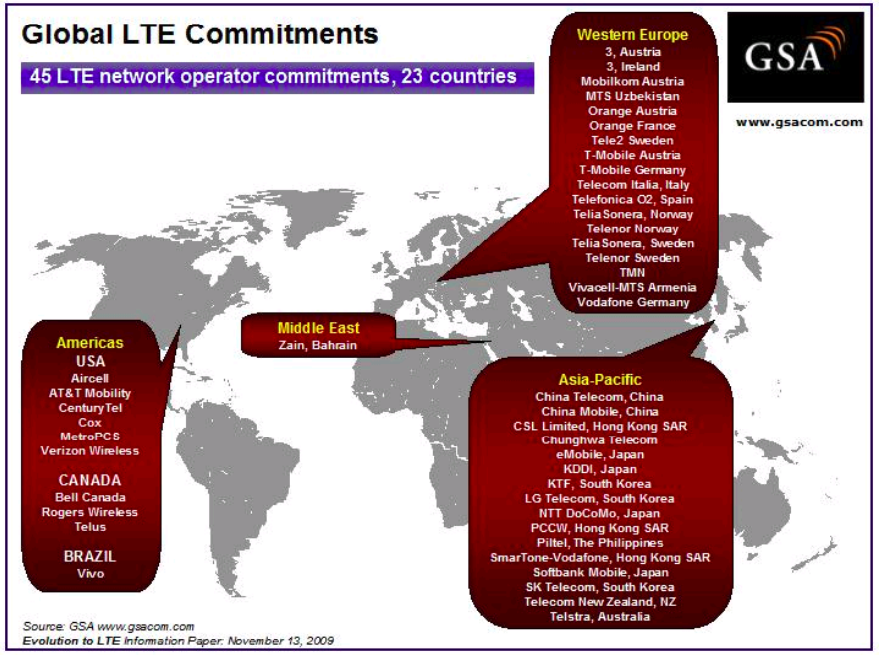
Feature	Rel-6 HSxPA	LTE E-UTRA
TTI Size	2 msec	1.0 msec
Modulation	QPSK, 16-QAM DL, QPSK, 2-QPSK UL	QPSK, 16-QAM, 64-QAM DL, QPSK, 16-QAM UL
HARQ + N-channel Stop-and-Wait	N=6 DL, N=8 UL Async DL, Sync UL IR is default	Synchronous UL / Asynchronous DL IR is default
Coding	Conv & Turbo Code	Advanced coding with lower base rate
Fast Scheduling	TDS	TDS and FDS

http://www.motorola.com/staticfiles/Business/Solutions/Industry Solutions/Service Providers/Wireless Operators/LTE/_Document/6993_MotDoc.pdf

LTE Deployment

- Live network Stockholm &Oslo TeliaSonera
  - http://www.3gpp.org/LTE-Networks-go-live
- Verizon covers 100 million in 2010 (30 cities)
  - http://news.vzw.com/LTE/Overview.html
- Samsung Phone Now (cdma/LTE) for MetroPCS
  - http://www.informationweek.com/news/mobility/smart_phones/showArticle.jhtml?articleID=224200357
- 45 LTE network commitments worldwide in 23 countries
- 16 LTE networks scheduled to be in service by end of 2010
- 45 networks in service by end of 2012
- Selected examples and spectrum
  - Verizon (U.S.A) – 700 MHz band starting in 2010
  - AT&T (U.S.A) – 700 MHz band starting in 2011
  - Vodafone Germany – Digital Dividend (790 – 862 MHz) in Q2 2010
  - France Telecom / Orange - 2.6 GHz in 2011 subject to availability in 2011
  - KDDI (Japan) – 1.5 GHz and 800 MHz
  - eMobile (Japan) – 1.7 GHz 2010 / 2011
- Additional deployment information
  - Global mobile Suppliers Association
  - http://www.gsacom.com/

- Future wideband communications will face fragmented spectrum
  - Re-farmed bands differ by country
  - Challenges identified by 3G Americas
  - http://www.3gamericas.org/documents/3GA%20Underutilized%20Spectrum_Final_7_23_092.pdf



Source: Global mobile Suppliers Association, "Evolution to LTE Information Paper," Nov. 13, 2009

LTE Voice and SMS

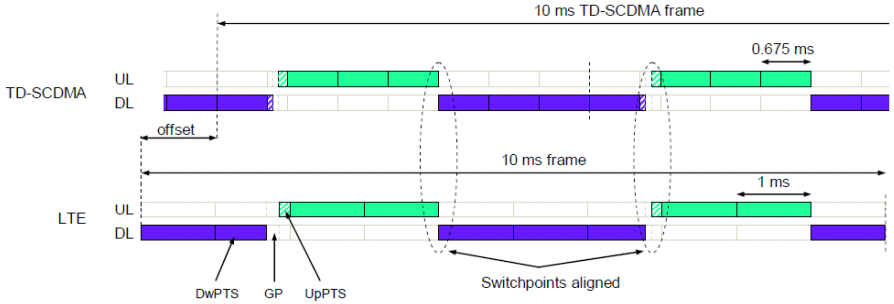
- Packet switched core of LTE requires significant changes for voice and SMS support
  - No native voice and SMS support in LTE
  - Voice and SMS remain primary revenue sources in 2009 and near future
- IP-Multimedia Subsystem (IMS)
  - Long-term voice solution for 3G and 4G networks
  - 3GPP architecture for delivering IP-based multimedia services on evolved GSM networks
  - Limited progress due to high complexity of fundamental changes
- Circuit-switched (CS) fallback
  - Traditional solution for voice delivery
  - Long call setup times of multiple seconds have detrimental effect on user experience

Voice and SMS Initiatives

- One-Voice
  - Initiated by Verizon, AT&T, and other operators (Nov 2009)
  - http://news.vzw.com/OneVoiceProfile.pdf
  - Agreed upon minimal IMS subset for voice and SMS traffic
  - Complete solution still a few years off
- VoLGA Forum
  - http://www.volga-forum.com/
  - Formed by a number of equipment manufacturers and T-Mobile (March 2009)
  - Positioned as a interim step toward IMS
  - http://www.volga-forum.com/pdfs/Forum_Positioning_on_OneVoice_Nov09.pdf
- Over-the-top
  - Skype / Nokia

LTE-TDD (TD-LTE)

- Evolutionary upgrade path of TD-SCDMA
  - Supported by China Mobile
  - Reuses existing TD-SCDMA network deployments for reducing CAPEX
- LTE-TDD and TD-SCDMA can operate on the same spectrum band with compatible DL/UP configurations
- Large synergies between LTE-FDD and LTE-TDD with similar performance
- China Mobile
  - Reusing existing TD-SCDMA cell sites for LTE-TDD
  - Scheduled commercially availability 2012 (GSA)

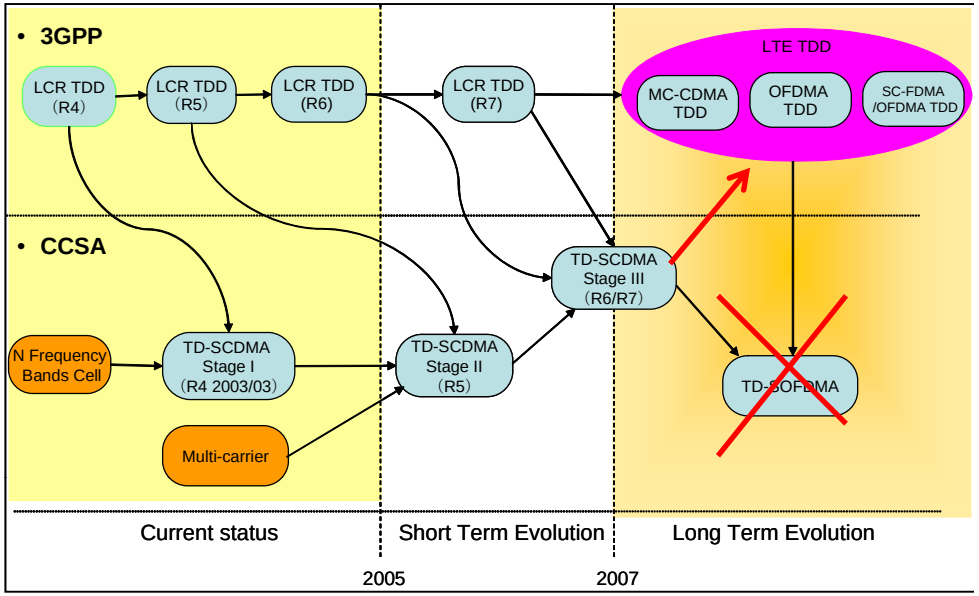


Coexistence LTE-TDD and TD-SCDMA on Adjacent Carriers
Source: 3G Americas, "*3GPP LTE for TDD Spectrum in the Americas*," Nov. 2009

- Opportunities outside of China
  - ClearWire, Qualcomm in India
  - Future usage possibilities presented by 3G Americas
  - http://www.3gamericas.org/documents/2009_LTE%20TDD_11_19_09_final_.pdf
- Fragmented and unpaired spectrum bands may drive future use of LTE-TDD
  - Broadband Radio Service (BRS) and Educational Broadband Service (EBS) in 2496-2690 MHz
  - Wireless Communications Service (WCS) in 2.3 GHz
- LTE-FDD and LTE-TDD are coexisting technologies
  - Motorola providing significant support to LTE-FDD and LTE-TDD solutions
  - Providing LTE-TDD broadband coverage at World Expo 2010 in Shanghai
  - http://mediacenter.motorola.com/content/detail.aspx?ReleaseID=12130&NewsAreaID=2
- Initial deployments
  - First dongle from Moto
    - http://mobile.engadget.com/2010/04/16/motorola-shows-off-worlds-first-td-lte-usb-dongle/
  - Showcase ChinaMobile Network
    - http://www.tdscdma-forum.org/en/events/luntan/117.asp
- TD-SCDMA Forum On Board
  - http://www.tdscdma-forum.org/en/events/luntan/117.asp

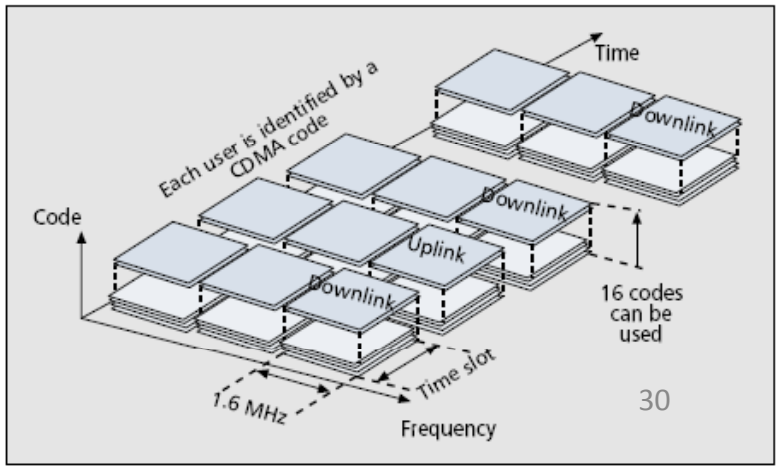
TD-SCDMA

- **T**ime **D**ivision – **S**ynchronous **CDMA**
  - Synchronized uplink channels aided by joint detection
  - China's 3G technology
- Core network is almost the same as WCDMA
  - Requires mature 2G (GSM) network for implementation
- Part of the 3GPP (3rd Generation Planning Partnership Project)
- Multiple chip rates
  - LCR: 1.28 Mcps, 1.6 MHz BW
  - HCR: 3.84 Mcps, 5 MHz BW
- TDD link
  - Does not use paired frequency bands
    - Optimum for symmetric and asymmetric data services
  - 1.6 MHz bandwidth allows flexibly spectrum allocation
- Partially motivated by avoiding paying Qualcomm royalties and standing up China manufacturers



ZTE Corporation, "3GPP Specification Evolution"

TD-SCDMA Multiple Access Options

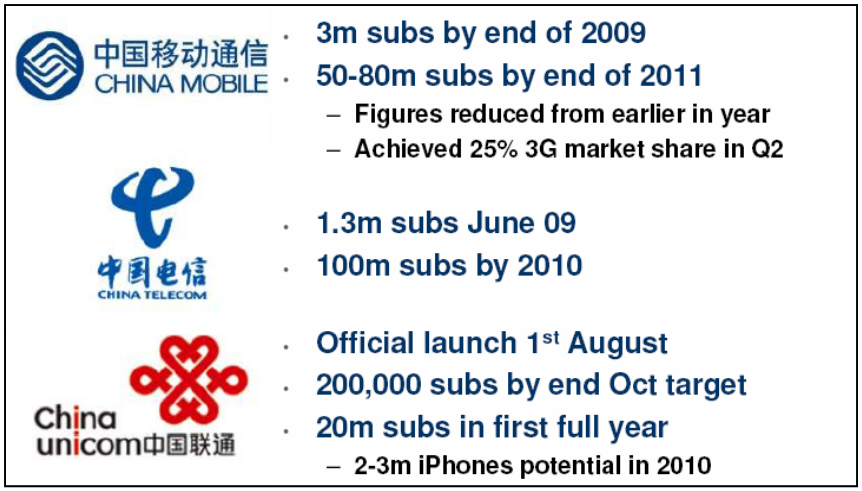


B. Li, D. Xie, S.Cheng, J. Chen, P. Zhang, W.Zhu, B. Li; "Recent advances on TD-SCDMA in China," IEEE Comm. Mag, vol 43, pp 30-37, Jan 2005

Significant Issues Deploying

- Standardized in 1999
- Was going to roll out in 2004
  - http://www.commsdesign.com/news/market_news/OEG20030102S0009
- Then 2005
  - http://www.chinadaily.com.cn/english/doc/2004-06/23/content_341749.htm
- Then 2006
  - http://www.accessmylibrary.com/premium/0286/0286-9623636.html
- Then 2007
  - http://www.theage.com.au/news/Technology/China-Mobile-to-launch-3G-mobile-services-end2007/2007/02/12/1171128898337.html
- Now will reportedly issues licenses in 2008
  - http://news.zdnet.com/2110-1035_22-6207356.html
- Delays make Chinese state-owned service providers unhappy
  - Grumblings about forgoing TD-SCDMA from ChinaMobile (primary deployer)
  - http://www.forbes.com/markets/feeds/afx/2006/01/31/afx2489964.html
- However, China has made it a point of national pride to have the network running for the 2008 Olympics
  - http://www.highbeam.com/doc/1G1-150687033.html
  - Is already being tested in 10 cities (includes the Olympic cities) but nationwide licenses may not even be issued by the Olympics
    - http://www.thestandard.com.hk/news_detail.asp?pp_cat=1&art_id=54099&sid=15557306&con_type=1
  - First commercial trials supposed to begin April 1, 2008
    - http://www.tdscdma-alliance.org/english/news/list.asp?id=4426
  - First public demos in May went badly
    - http://www.pcworld.com/businesscenter/article/146128/china_shows_off_olympic_techsort_of.html
- China won't allow 3G or WiMAX until TD-SCDMA takes off
- Developed a bad reputation
  - http://homepage.mac.com/dwbmbeijing/iblog/SiHu/C520534961/E20060302210839/index.html
  - Unnamed China Mobile engineer – "**you GIVE me a TD-SCDMA network, and I wouldn't take it**."
- Eventually deployed
  - GSC14-PLEN-003
  - Moving to LTE-TDD as quickly as possible

Notes on 3G China



S. Hire, "From TD-SCDMA to TD-LTE"

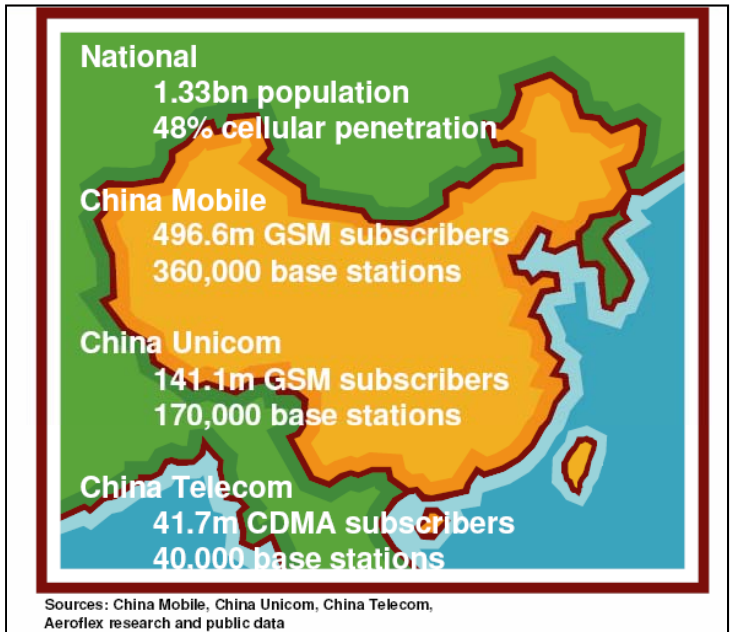
2013

TD-LTE

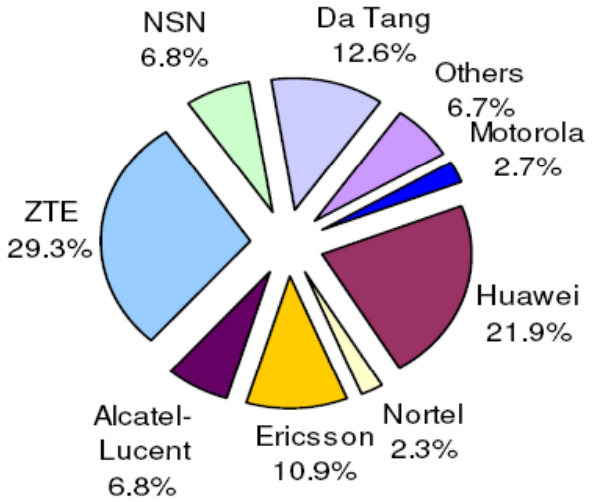
FD-LTE

FD-LTE

S. Hire, "From TD-SCDMA to TD-LTE"



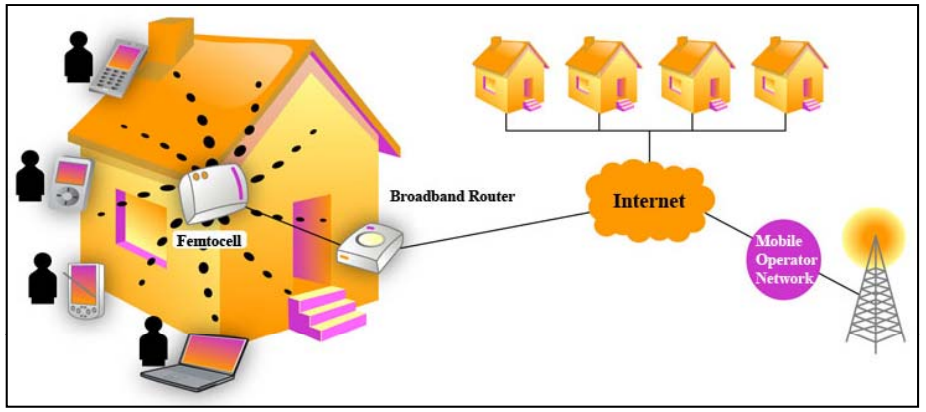
3G Market Shares



http://www.hkstp.org/HKSTPC/image/editor/4%20Stephen%20Hire%20TD-SCDMA%20to%20TD-LTE%20-%20Aeroflex%20Asia%20-%20Sept0920090914095048.pdf

Femtocells

- WLAN in licensed spectrum
  - Operator management
  - Internet backhaul
    - Fiber-to-home
- Femtocell Forum
  - http://www.femtoforum.org/femto/
- Recent launches
  - AT&T http://www.lightreading.com/document.asp?doc_id=192708&f_src=lightreading_gnews
  - Vodafone Spain
    - http://lteworld.org/news/vodafone-spain-launches-femtocell-service
  - Femtocell based 3G service revenue $9bn per annum by 2014
    - D. Pulley



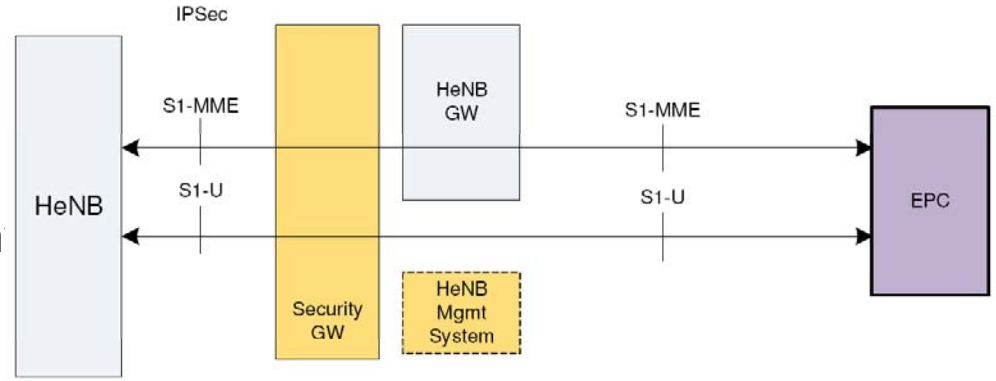
http://mobiledevdesign.com/tutorials/MDD-femtocell-ap-basestations-Figure01-1117.jpg

Operators	Offering	Technology	Launch Date
at&t	3G MicroCell	HSDPA	September 2009
verizon wireless	Network Extender	cdma 1xRTT	January 2009
StarHub	Home Zone	HSDPA	November 2008
Sprint	Airave	cdma 1xRTT	September 2007
vodafone	Access Gateway	HSDPA	July 2009
NTT docomo	My Area	HSDPA	November 2009
SoftBank	IMS based Femtocells	HSDPA	January 2009
China unicom中国联通	3G Inn	HSDPA	November 2009

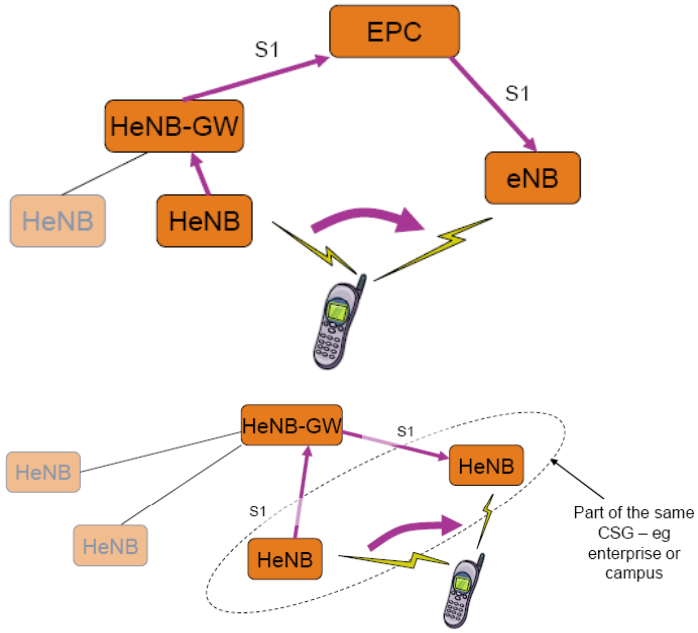
ftp://ftp.3gpp.org/Inbox/Marcoms/Conference_Presentations/2010_05_Moscow/Femto_Forum_Germano.pdf

Femto and LTE

- Home enhanced Node B
- Release 8/9
  - Identfication, location, gatewa management, handoffs
  - Lower power
- Access modes (Closed Subscriber Group):
  - Closed access (residential deployment):
  - Open access (enterprise deployment):
  - Hybrid (prioritized) access
- Handoffs
  - Femto-femto, femto-macro, macro-femto

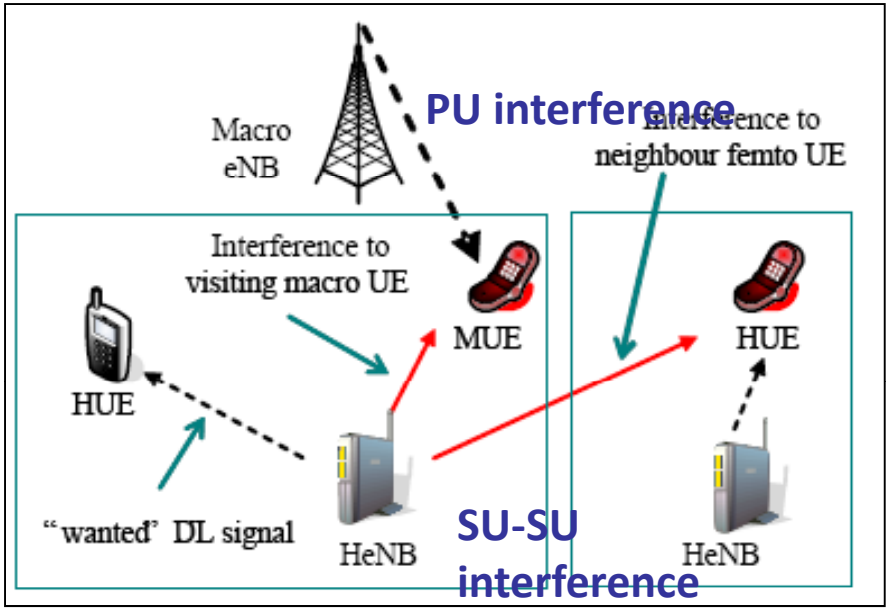


http://www.nomor.de/root/downloads/white-paper/2010-04_lte_homenb_rel9_overview.pdf

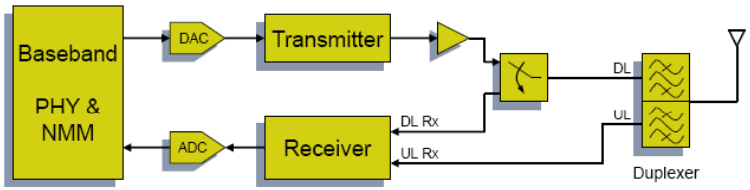


Femtocell Like a TVWS Device

- Interference between cells and to cellular spectrum
  - So “sniff” spectrum
- Need to discover policy
  - Follow local operators spectrum rules
- Location might be hard, so creative solutions
  - 911, policy, billing



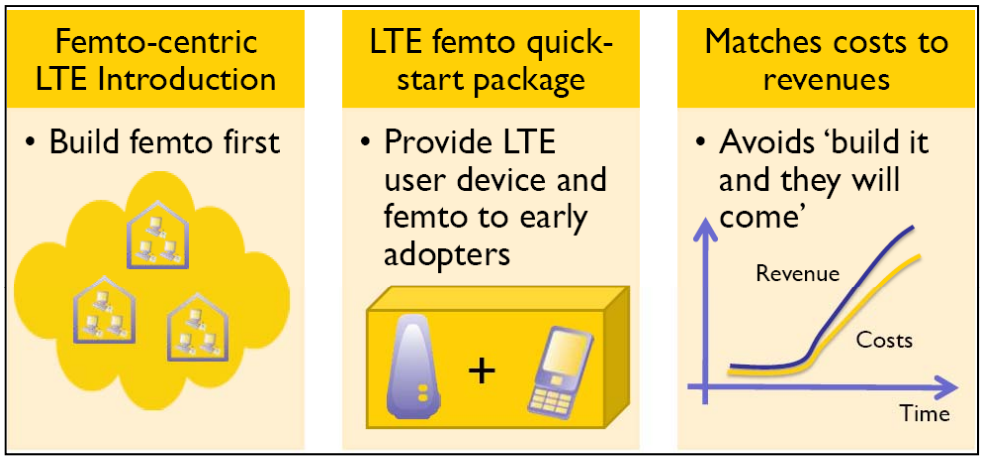
D. Pulley, LTE Femtocells



Measurement Type	Purpose
Co-channel RSRP	Setting femto Tx power for desired coverage and protection of co-channel MUEs (incl. hybrid access)
Co-channel RSRQ	
Adjacent-channel carrier RSRP	Setting femto Tx power for protection of adjacent-channel MUEs, including adjacent channel operators
Adjacent-channel ref signal Rx power	
Uplink Ref Signal Detection	Detection of Victim UEs
Read system info	Tx power (for pathloss calc), CSG status, Cell ID etc

Why Femtocells? Data. Why not WiFi? Hmmm…

- Some think solution in search of problem
  - http://gigaom.com/2009/11/02/who-needs-femtocells-if-we-have-wi-fi/
- Versus offloaded WiFi data traffic?
  - Cheaper to both user and provider
  - WiFi already deployed
  - (My speculation) Only happens if provider covers cost of femtocell or incentivizes data plan
  - LTE vs WiFi faceoff or both in a box?
  - $150 box from AT&T? Free Time Square WiFi?



A. Germano, "The Impact of Femtocells on Next Generation LTE Mobile Networks"

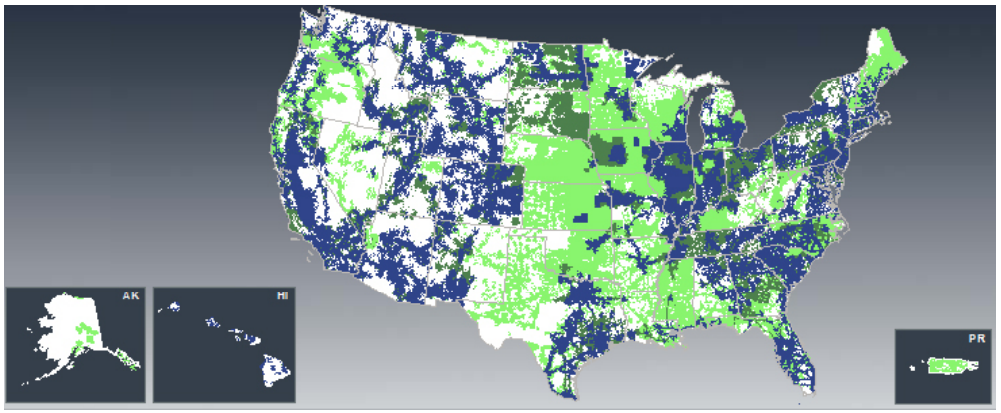
- My best WAG
  - Joint WiFi / Femto
  - User on WiFi, other subscribers on Femto (hybrid CSG)
  - Options:
    - Free, discount on data plan, partnerships with ISPs

Older 3GPP2 Technologies

- cdma2000 1xRTT
  - Packet-switched (always on)
  - Maximum of 144kbps
    - Typical 40-60 kbps
  - 2G / 3G
- 1x EVDO
  - CDMA EVolution Data Only
    - Designed to support only data applications
      - VOIP
    - Also known as:
      - CDMA 1x EV-DO
      - CDMA EV-DO
  - Can offer data rates of 384kbps - 2.4Mbps
    - Does not mix voice traffic with data traffic
    - Changes modulation, # timeslots
- EVDV (Voice + Data)
  - Dead on arrival
    - http://telephonyonline.com/mag/telecom_evdv_dead/index.html
    - Qualcomm halted work on the standard in 2005
      - http://news.com.com/Cell+phone+makers+to+adopt+Internet+calling/2100-7352_3-5618191.html
      - Slow to field

- EVDO Rev A
  - Wide deployment
    - Verizon, Sprint, Kindle best known
  - Features
    - Higher modulation uplink
    - Multi-user packets (time-slots)
    - Lower Latency
    - Couple new data rates downlink (changed code rate)
- Promotional
  - http://www.evdoinfo.com

Verizon EVDO-Rev A Coverage Map



http://www.verizonwireless.com

EVDO Rev B (TIA-856 RevB)

- Adds Multiple carriers – 2xEVDO, 3xEVDO,…
  - Up to 15 1.25 MHz carriers within 20 MHz
- Adds support for 64-QAM modulation
- DL 73.5 Mbps
- UL 27 Mbps
- Dynamic non-contiguous carrier allocation
- Support for single carrier and multiple carrier subscribers
- Standardized 2006
- Trials mid-2007
- Software upgrade (at BTS) to Rev A
- Disputed claims of roll-outs for Rev B for Verizon and Sprint
  - http://www.fiercewireless.com/story/are-verizon-and-sprint-rolling-out-cdma-rev-b/2010-05-17
  - Would be backup / filler net for 4G networks
  - Russia: Sky Link
  - India: Tata
  - China Telecom
  - Japan's KDDI
  - Indonesia: Smart Telecom Rev. B

EVDO Rev C (UMB)

- Spec published Sep 24, 2007
  - http://www.cdg.org/news/press/2007/Sep24_07.asp
  - 3GPP2 (UMB) beats 3GPP to market again
  - Chipsets available nowish
    - http://www.qualcomm.com/press/releases/2007/070327_complete_solution_ultra.html
- Data rates, mobile with 20 MHz bandwidth
  - DL: 288 Mbps
  - UL: 75 Mbps
- Key technologies
  - OFDMA, MIMO, beamforming
  - Flexible spectrum allocation
  - Enhanced QoS
  - Support for multiple access technologies
  - Reduced latency
- Likely killed when Verizon went with LTE
  - http://www.phoneplusmag.com/hotnews/79h20122346.html
  - Dead on Arrival
    - http://www.abiresearch.com/products/research_brief/Wireless_Infrastructure_Research_Briefs/112
  - Qualcomm differs (ineffectually)
    - http://www.fiercebroadbandwireless.com/story/qualcomm-ceo-umb-not-dead-yet/2008-01-14
  - Alltel didn't even say they had considered it (WiMAX vs LTE – chose LTE)
    - http://www.betanews.com/article/Report_Alltels_choice_of_LTE_a_big_loss_for_WiMAX_UMB/1210956891

802.16 Family (WiMAX)

802.16	Apr 2002	LOS 10-66 GHz
802.16a	Apr 2003	2-11 GHz
802.16c	Jan 2003	2-11 GHz
802.16d	Oct 2004	Combined 802.16,a,c
802.16e	Dec 2005	Mobile WiMAX
802.16f	Dec 2005	Net Management Database
802.16g	Spring 2007	Network management plane
802.16h	2010?	License-exempt Coexistence
802.16i	Fall 2008	Mobile MIB
802.16j	2009	Mobile Multihop Relay
802.16k	Aug 2007	Network Management
802.16m	2010	4G

Projections based on data at
http://grouper.ieee.org/groups/802/16/published.html

Commercialization Roadmap

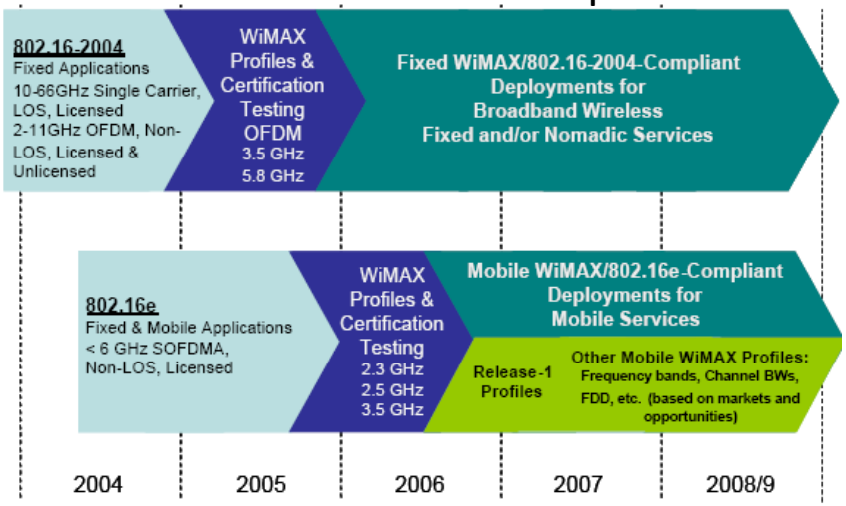


Figure 19: Roadmap for WiMAX Technology

WiMAX Forum (2006): Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation. Available at www.wimaxforum.org

802.16e (Mobile WiMAX, 802.16-2005)

- Ideally, 802.16 + mobility
  - Really intended for nomadic or low mobility
  - Not backwards compatible with 802.16-2004
    - http://www.unstrung.com/document.asp?doc_id=76862
- Direct competitor to 3G, 4G, 802.20 though WiMAX Forum once said otherwise
- Numerous ongoing deployments and working systems, particularly for WiBRO
- PHY
  - Scalable OFDM + Optional MIMO
  - Convolutional turbo codes
  - Optional block turbo codes, LDPC

PHY Spec Overview

Parameter	Downlink	Uplink	Downlink	Uplink
System Bandwidth	5 MHz		10 MHz	
FFT Size	512		1024	
Null Sub-Carriers	92	104	184	184
Pilot Sub-Carriers	60	136	120	280
Data Sub-Carriers	360	272	720	560
Sub-Channels	15	17	30	35
Symbol Period, Ts	102.9 microseconds			
Frame Duration	5 milliseconds			
OFDM Symbols/Frame	48			
Data OFDM Symbols	44			

Mod.	Code Rate	5 MHz Channel		10 MHz Channel	
		Downlink Rate, Mbps	Uplink Rate, Mbps	Downlink Rate, Mbps	Uplink Rate, Mbps
QPSK	1/2 CTC, 6x	0.53	0.38	1.06	0.78
	1/2 CTC, 4x	0.79	0.57	1.58	1.18
	1/2 CTC, 2x	1.58	1.14	3.17	2.35
	1/2 CTC, 1x	3.17	2.28	6.34	4.70
	3/4 CTC	4.75	3.43	9.50	7.06
16QAM	1/2 CTC	6.34	4.57	12.67	9.41
	3/4 CTC	9.50	6.85	19.01	14.11
64QAM	1/2 CTC	9.50	*6.85*	19.01	*14.11*
	2/3 CTC	12.67	*9.14*	25.34	*18.82*
	3/4 CTC	14.26	*10.28*	28.51	*21.17*
	5/6 CTC	15.84	*11.42*	31.68	*23.52*

WiMAX Forum (2006): Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation. Available at www.wimaxforum.org

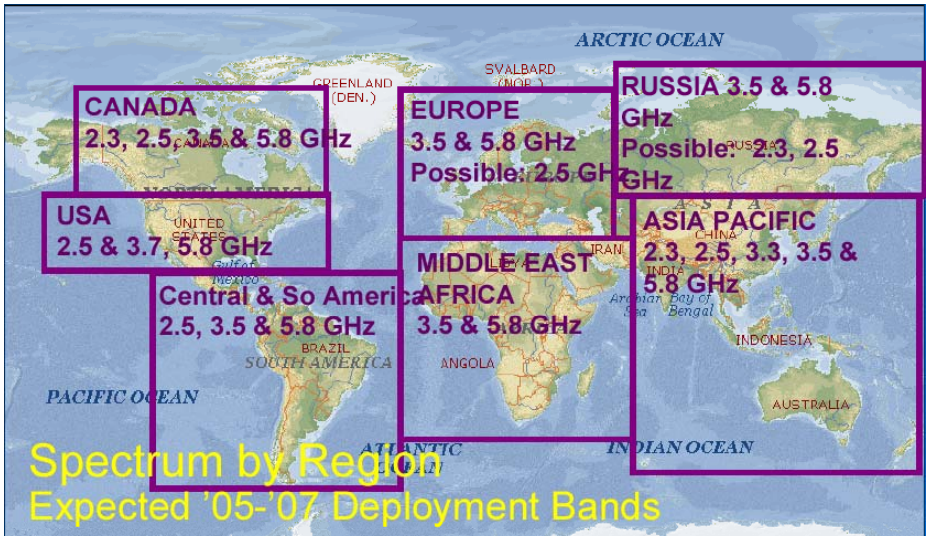
Other Mobile WiMAX Features

- Frame-by-frame resource allocation
- Hybrid Automatic Repeat Request (HARQ)
- UL and DL Scheduling
- Variable QoS
- Three handoff methods
  - A traditional Hard Handoff (HHO)
  - Fast Base Station Switching (FBSS)
    - A list of reachable base stations is maintained by mobile and base stations, but base stations discard packets if not the active BS
  - Macro Diversity (MDHO)
    - Same list is maintained, but all base stations in the list can participate in the reception and transmission of packets.

- Security
  - AES for traffic and control data
  - EAP
  - Privacy and Key Management Protocol Version 2 (PKMv2)
  - 3-way handshake on handoffs
- IP Core Network (supports Voice Over IP)
- Multicast Broadcast Services
  - Like cellular multicast services
- WiBRO
  - Defines a set of options for Mobile WiMAX for Korean deployment

WiMAX Spectrum

- WiMAX Spectrum Alliances
- Regulatory Database
  - AT4 Wireless
  - Launched November 2006
  - http://www.wimaxforum.org/join/spectrum_demo/
- WiMAX Global Roaming Alliance
  - Brought together unlicensed providers to promote global roaming
  - Now defunct
  - Will probably come back in some form
  - http://www.theregister.co.uk/2006/09/29/oz_wimax_roaming_alliance/
- WiMAX Spectrum Owners' Alliance
  - http://www.wisoa.com/
  - Promotes roaming agreements
  - Participants:
  - Unwired Australia, Network Plus Mauritius, UK Broadband, Irish Broadband, Austar Australia/Liberty Group, Telecom New Zealand, WiMAX Telecom Group, Enertel and Woosh Telecom
- 700 MHz band
  - http://www.xchangemag.com/articles/501/79h13917183935.html?cntwelcome=1



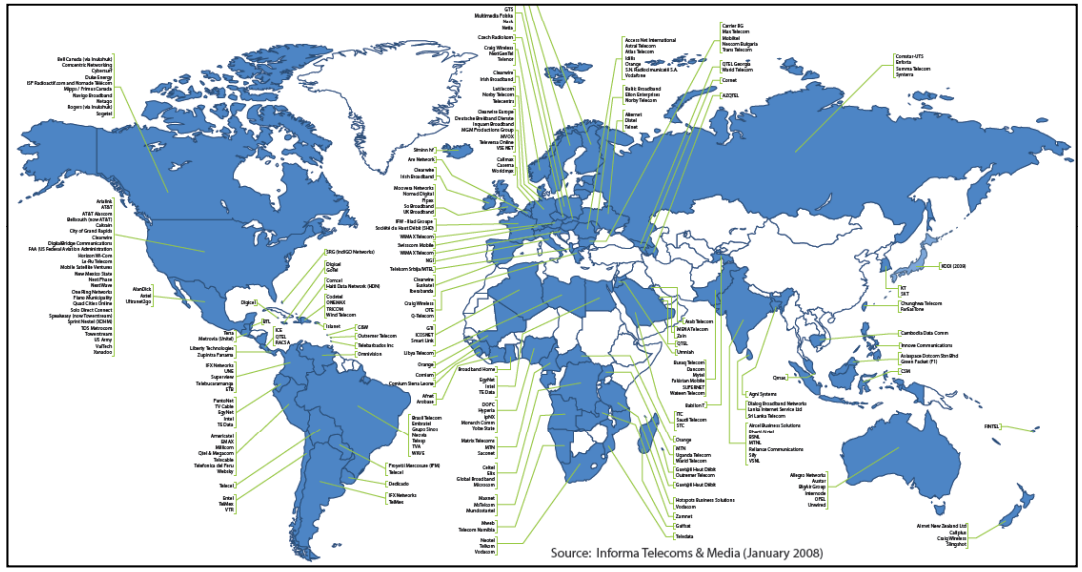
http://www.wimaxforum.org/news/downloads/supercomm_2005/WF_Day_in_a_Life_with_WiMAX_Final.pdf

- Recent reports of interference with with C-Band VSAT
  - http://www.suirg.org/pdf/SUIRG_WiMaxFieldTestReport.pdf
- Officially declared 3G so 3G spectrum
  - http://www.wirelessweek.com/WiMAX-is-3G.aspx

Mobile WiMAX Deployments

- First Mobile WiMAX products certified April 2008
  - 2.3 GHz, 4 base, 4 subscriber
  - POSDATA, Runcom Technologies Ltd, Samsung Electronics Co., LTD and Sequans Communications
  - http://www.wimaxforum.org/news/pr/view?item_key=59390fb727bfa15b5b8d11bf9341b2b1176099f8

802.16d + 802.16e + WiBRO



http://www.wimaxforum.org/technology/documents/wimax_networks_worldwide_11x17.pdf

- Success appears tied to Sprint-Nextel / Clearwire effort

Clearwire/Sprint

Clearwire Coverage

http://www.clearwire.com/

- Fixed WiMAX based wireline replacement service to home + portability within coverage area
- 2 Mbps data + voice
- Map no longer accurate, but current to the web

Sprint

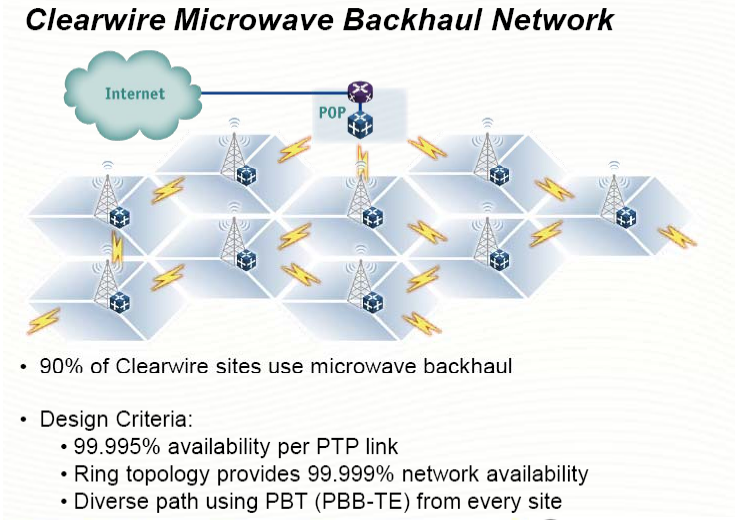
- Mobile WiMAX
- Rapid deployment to major cities
  - 10,000 sites in preparation
  - 1750 base stations delivered in 2007, 20,000 antennas
- Incorporated into numerous devices (cameras and televisions)
- Open Network (support Android)
- Federal government connectivity via WiMAX
  - http://www.wimaxday.net/site/2007/06/05/sprint-plans-wimax-for-gov%e2%80%99t-services/

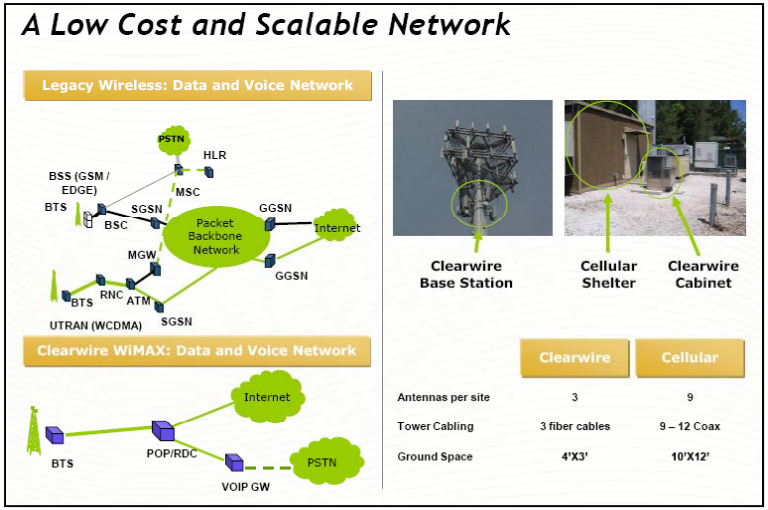
Merged Company

- http://www.clearwireconnections.com/pr/pressreleases/050708.pdf
- Clearwire + Sprint WiMAX unit
  - Called Clearwire
- Investors
  - $3.2 Billion from Google (500 M), Comcast (1.05B), Time-Warner (550M), Bright House (100M), Trilogy Equity (10M)
  - Sprint owns 51%
  - Clearwire owns 27%
  - Investors own 22%
  - Another $2 billion in late 2009
- Nationwide focus
  - 120-140 million coverage by 2010
  - Tremendous spectrum position
- Commercial agreements
  - Intel will put WiMAX in chipsets
    - Had been planning on that
  - Google services to be carried (and search provider)
  - Support Android
  - Sprint, Comcast, TimeWarner, and Bright House will be wholesale
  - Sprint contributes its 2.5 GHz holdings

More ClearWire

- Great report on Clearwire's deployment experiences
  - https://www.sidecutreports.com/order-sidecut-reports/free-report-download/?rid=6
  - "a typical WiMAX network is about eight to 10 times cheaper to build than a 3G cellular network covering the same area.:
  - Key features: open, low footprint BS, fiber to the antenna, microwave link, lots of spectrum = cheaper + more BW
  - Believe indicative of LTE rollouts
- Stats
  - http://newsroom.clearwire.com/phoenix.zhtml?c=214419&p=irol-newsArticle&ID=1422881&highlight=
  - Total Ending Subscribers of 971,000, Up 94% Year Over Year
  - Total Net Q1 Subscriber Additions of 283,000 - Greater than Full Year 2009
  - First Quarter Revenue of $107 Million - Up 72% Year Over Year
  - Company Surpasses 50 million People Covered By Its Networks
  - 4G WiMAX Smartphones By Samsung and HTC Expected to be Available Before End of 2010
  - Still losing money (OK though)





https://www.sidecutreports.com/order-sidecut-reports/free-report-download/?rid=6

WiBro

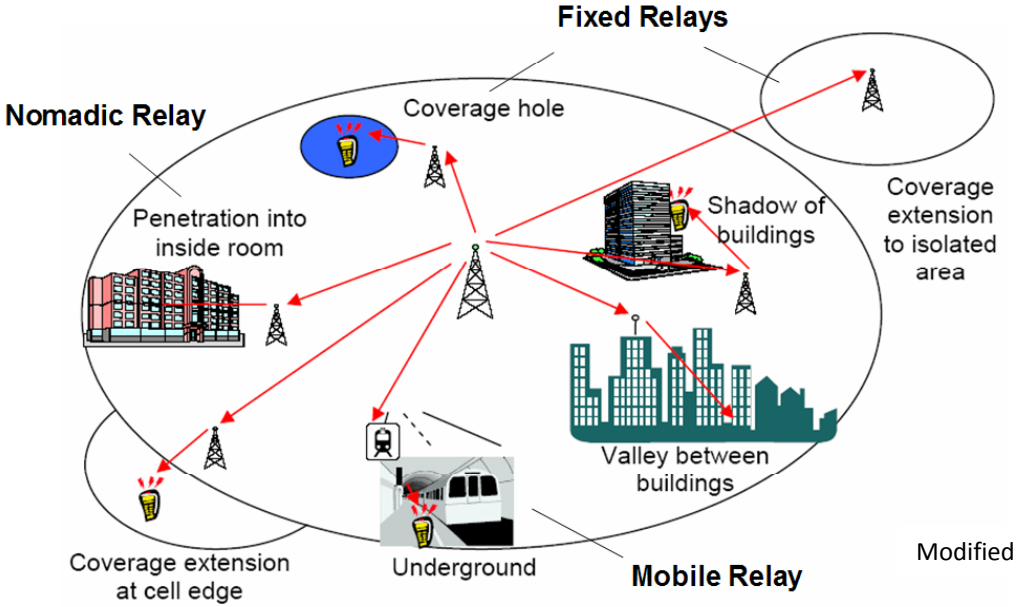
- Korean version of 802.16e
  - Phase 1 standardized by TTA of Korea (2004)
  - Phase 2 standardized in 2005
- Korean spectrum allocated 2002
  - 2.3 GHz (100 MHz)
- Harmonization 802.16e/WiBro agreed Nov 2004
  - Samsung joined WiMAX Forum Dec 2004
  - May indicate Samsung's guess on 4G direction
- Plans for Nationwide Korean deployment
  - KT & SK Telecom launched June 30, 2006 in Seoul http://kt.co.kr/kthome/kt_info/pr/news_center/news_view.jsp?page=1&no=397&gubun=1
  - KT well ahead of SK
    - http://www.wimax.com/commentary/blog/blog-2007/wibro-subscriber-numbers-korea-telecom-kt-far-ahead-of-sk-telecom

How does WiBRO relate to 802.16e?

- WiMAX Forum: (http://www.wimaxforum.org/news/press_releases/WiBro_and_Mobile_WiMAX_Backgrounder.pdf)
  - **"WiBro is the service name for Mobile WiMAX in Korea.** WiBro uses the Mobile WiMAX System Profile. The system profile contains a comprehensive list of features that the equipment is required or allowed to support, and, as a result, WiBro offers the same capabilities and features of Mobile WiMAX."
  - It's Mobile WiMAX, just with a different profile (frequency, bandwidth…)
- Vendors: WiBRO is compatible with 802.16e, but there's more to Mobile WiMAX than just 802.16e compatibility and many choices in WiBRO are different from what is mandatory in 802.16e
  - From (http://www.nortel.com/solutions/wimax/collateral/wimax_wibro_white_paper.pdf)
- Some more important differences from Nortel white paper
  - Mandatory Handoff
    - 802.16e = HHO
    - WiBRO = FBSS
  - HARQ
    - 80.16e = Chase combine HARQ
    - WiBRO = Incremental redundancy HARQ
  - Likely (though unclear) network layer differences

802.16j Mobile Multi-hop Relay

- Expand coverage, capacity by adding relay stations
- Intended for licensed operation
- Not intended as a mesh network
  - Actually a tree
- Support mobile units



- Relays controlled from base stations
- Fixed Relay
  - Permanent installation
  - Useful for coverage holes
- Nomadic Relay
  - Temporary fixed installation
  - Extra capacity for special events (military SDR conferences)
- Mobile Relay
  - Placed on mobile platform to support users on the platform
  - Useful for public transport (buses, trains)

Modified from Fig 1 in IEEE 802.16mmr-05/032

WiMAX has already lost to LTE

- Clearwire looking to TD-LTE
  - http://www.fiercebroadbandwireless.com/story/clearwire-part-group-looking-td-lte-2-6-ghz-band/2010-03-31
  - Likely moving when Intel contract ends
  - May go dual-mode
- Yota out
  - http://www.dslreports.com/shownews/Russias-Yota-Shifting-From-WiMax-To-LTE-108702
  - Was largest WiMAX (cept for Clearwire)
- Cisco out March 2010
  - http://www.intomobile.com/2010/03/05/wimax-subscribers-up-75-but-cisco-decides-to-stop-making-wimax-base-stations-focus-on-packet-core.html
  - "WiMAX, the wireless standard that no one really takes seriously, and the butt of almost every joke at Mobile World Congress 2010"
- LTE recommended for Public Safety over WiMAX
  - http://urgentcomm.com/networks_and_systems/news/700-mhz-lte-support-20090611/
  - Broadband plan: http://download.broadband.gov/plan/national-broadband-plan-chapter-16-public-safety.pdf
  - http://www.motorola.com/staticfiles/Business/Solutions/Industry%20Solutions/Government/Public%20Service/_Documents/Static%20Files/Real%20World%20LTE%20Performance%20for%20Public%20Safety%20FINAL.pdf?localeId=33
  - Option 1: Voice and coverage => fall back for voice
  - Option 2: LTE is only data for PS
- WiBro problems
  - http://www.dailywireless.org/2009/08/11/koreas-wibro-in-trouble/
  - Mostly in Seoul; more HSPA coverage
  - Rumblings of revoking licenses

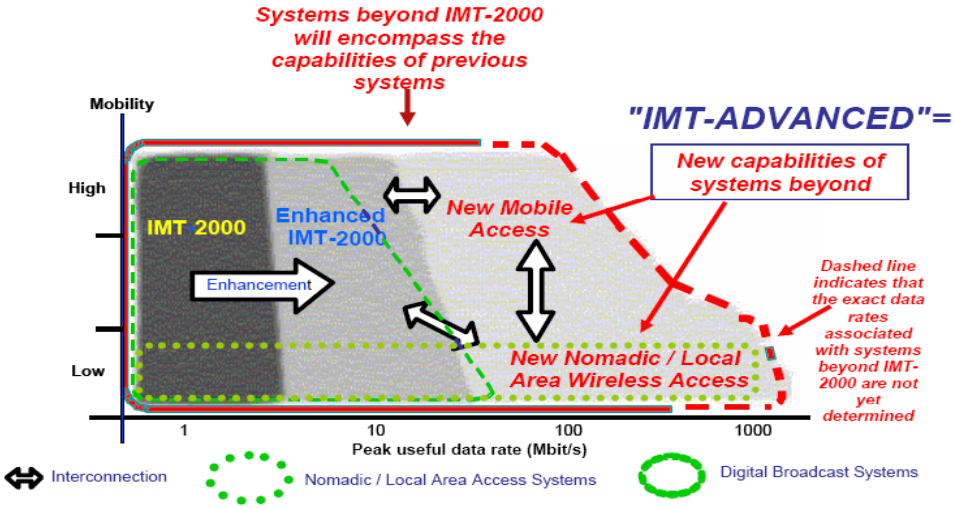
IEEE 802.20

- Fill performance gap between "high data-rate, low mobility 802 standards" and "high mobility cellular networks"
- From QTDD/QFDD Proposal
- OFDMA data channel
- CDMA control channel
- Bandwidths
  - 5 MHz – 20 MHz
- MIMO
  - Single, multiple code word
  - Pseudo- Eigen beamforming
- Space Division Multiple Access
  - Separate mode from MIMO
- Data Rate 260 Mbps
  - MIMO, 20 MHz
- Turbo coding
- Time-frequency hopping
- Supposed to support inter Radio Access Technology handoffs
- Similar to UMB
  - UMB is effectively an upgrade to MBFDD version
  - IEEE C802.20-07/14
  - Likely same fate (contributions way down)

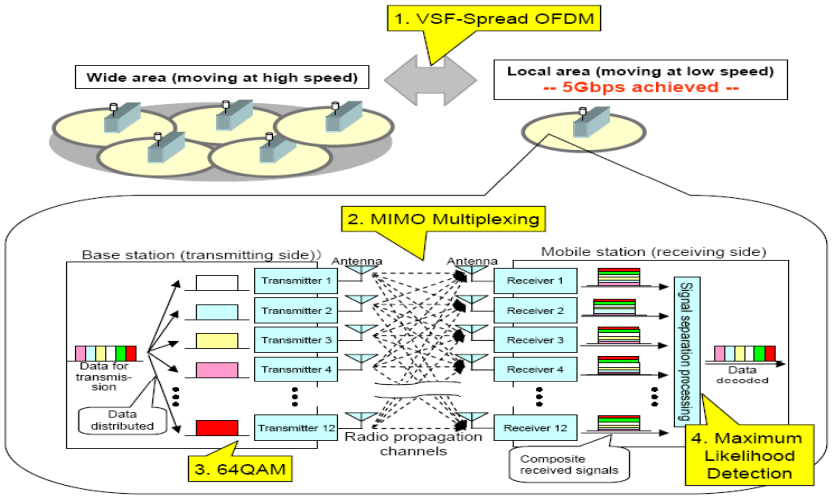
- 802.20 Shenanigans
- Allegations of process abuse brought to a screeching halt when standard suspended in September
- Project Launched 2004
- Looked to be dead in the water
  - Flarion leading proposal
  - Qualcomm leading vote holder
- Turned around when Qualcomm bought Flarion (Aug 05)
  - http://www.dailywireless.org/modules.php?name=News&file=article&sid=4532
- Went to proposal downselection process
  - Qualcomm (Flarion) TDD, FDD
  - ETRI
  - BEST-WINE (Kyocera)
- Reapproved in Dec 06
- First meeting Jan 2007
- Published 2008
  - http://standards.ieee.org/announcements/802.20approval.html

4G (IMT-Advanced)

- Wireless community already looking towards 4G
- Requirements being formalized
  - 1 Gbps fixed
  - 100 Mbps mobile (end-to-end)
  - Support for heterogeneous nets
  - Global roaming
- Several candidates already emerging
  - LTE-Advanced
  - 802.16m
  - NTT DoCoMo's 5 Gbps prototype
    - http://www.nttdocomo.com/pr/files/20070209_attachment02.pdf
  - China's home grown standard
    - http://www.forbes.com/markets/feeds/afx/2007/09/25/afx4151478.html
- Common techniques
  - OFDMA, MIMO, small cell sizes optimized for low speed, but support for high speed, IP backbone



3G Americas, "Defining 4G: Understanding the ITU Process for the Next Generation of Wireless Technology," July 2007 Available online:
http://3gamericas.com/PDFs/3G_Americas_Defining_4G_WP_July2007.pdf



http://www.nttdocomo.com/pr/files/20070209_attachment01.pdf

802.16m

- TGm System Requirements Document
  - http://wirelessman.org/tgm/docs/80216m-07_002r4.pdf
  - http://wirelessman.org/tgm/docs/80216m-07_003.pdf
- Key functionalities to be added (not defined yet)
  - Routing
  - Self Organization
  - Multi-Carrier
  - Multi-Radio Coexistence

Table 8. Relative Sector Throughput (bps/Hz/sector)

Speed (km/h)	DL	UL
TBD	>2x	>1.5x

Table 9. Relative VoIP Capacity

Speed (km/h)	Capacity (Active Users/MHz/sector)
TBD	>1.5x

IEEE C802.16m-07/002r1

Requirements

- Minimum Peak Rate
  - Downlink 6.5 bps/Hz
  - Uplink 2.8 bps/Hz
- Latency less than 802.16e
- Radio Resource Management
  - Reporting, interference management
  - Multicast broadcast service
  - "High-resolution" location determination
- Internetworking with:
  - 802.11 3GPP, 3GPP2
- Coverage optimized for 5 km, functional to 30-100 km
- Optimized for low mobility (<15kph), maintain connection up to 350 kph
- Optimized for contiguous spectrum but support discontiguous
- Reuse/share bandwidth with legacy systems
- Direct migration from 802.16e
- To Draft 6 (April 2010)
  - http://grouper.ieee.org/groups/802/16/pubs/80216m.html

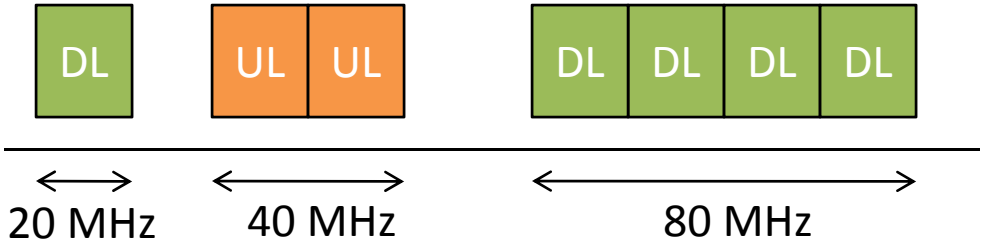
LTE-Advanced

- 3GPP submission for IMT-Advanced
  - Announcement
  - http://www.3gpp.org/3GPP-Partners-propose-IMT-Advanced
  - Specification http://www.3gpp.org/IMG/pdf/2009_10_3gpp_IMT.pdf
  - Requirements for technology, operator, and end-user requirements
- LTE-Release 10 and beyond
  - Started March 2008 based on LTE Release 8 foundation
  - Full specification scheduled for completion late 2010
- Spectrum flexibility
  - Enable wider bandwidths
  - Evolution of current 3GPP Release 8 spectrum and new bands
  - Support for continuous and fragmented spectrum use
- Proposed support for FDD and TDD technologies
- Improvements to peak data rates and spectrum efficiency
  - Improve performance at the cell-edge
  - Support increased indoor and low-mobility deployments

		LTE	LTE-Advanced	IMT-Advanced
Peak data rate	DL	300 Mbps	1 Gbps	1 Gbps (low mobility)
	UL	75 Mbps	500 Mbps	
Peak spectrum efficiency [bps/Hz]	DL	15	30	15
	UL	3.75	15	6.75

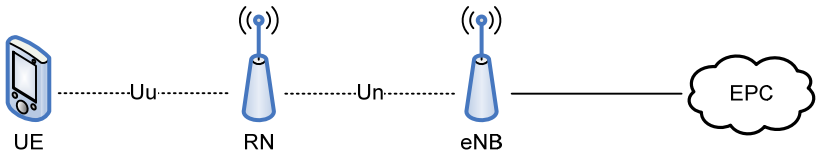
LTE-Advanced Technologies

- Carrier and spectrum aggregation
  - Support for discontinuous and fragmented spectrum to support peak data rates
  - Up to 100 MHz comprised of multiple frequency blocks
- Asynchronous bandwidth allocation
  - Multi-band flexible spectrum use (20, 40, 100 MHz) across DL and UL
- Advanced MIMO
  - Multi-user MIMO (MU-MIMO)
  - Up to 8-layer transmission on DL



Multi-band Discontinuous Spectrum Utilization

- Coordinated multipoint (CoMP) transmission and reception
  - Coordinated signaling from geographically separated points
  - Improvement to high data rate coverage at the cell edge
  - Coordinated scheduling, beamforming, and joint signal processing
- Relaying
  - Wireless backhaul for sparse locations
  - Deployed where a wired back haul is cost prohibitive



Cell-edge relay

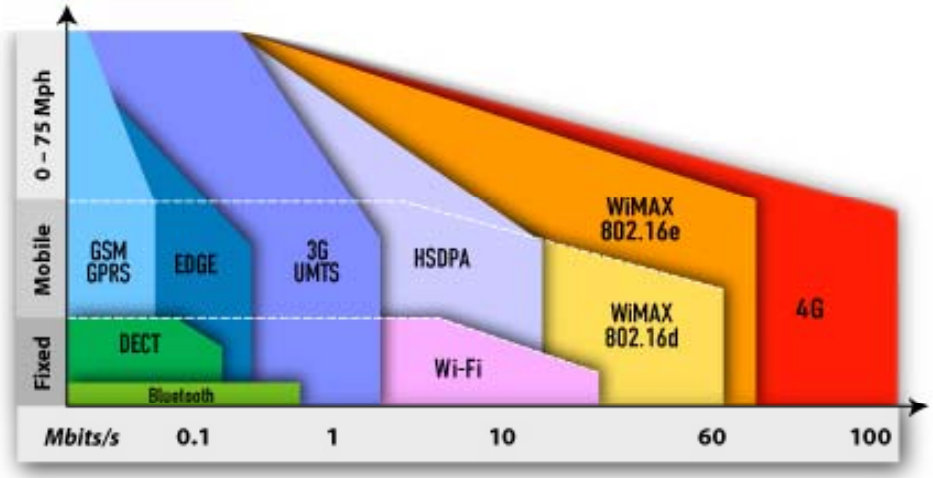
Source: 3GPP, "*3GPP TR 36.912 V9.0.0*," Oct. 2009

Cellular Summary

- Data crush causing many problems
  - Expect A LOT of shakeups as market adjusts
  - Mix of closed & open nets and devices
- Costs have to come down
  - Flat, IP-based core
  - SON
- Android / iPhone remaking the market
  - Android wins, but iPhone still very profitable
  - Symbian, RIM losing slowly, MS quickly
  - Applications > network
- Mixed relationship with WiFi
  - Small cells have to happen. Doesn't have to be in cellular spectrum.
- LTE wins out over WiMAX
  - Too many big players switching: Yota, Clearwire, Cisco, 700 MHz
  - Verizon going to beat Clearwire to 100 million covered?
    - Too long to market function of greenfield providers?
  - Niche markets for WiMAX
  - Very similar technologies though
- LTE (finally) coming
  - 3GPP still has not caught up with 3GPP2
  - Will LTE be the same?
- 4G a ways out, but preparation is underway
  - .16m first to market, but…
- UMB, 802.20 dead for different though related reasons

Presentation Overview

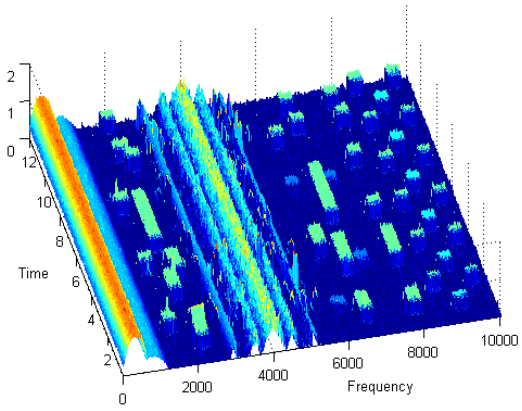
Emerging Standards



http://www.wisoa.net/members_logos/mobile_internet-big.jpg

CRT
Cognitive Radio Technologies

Emerging Commercial Cognitive Radio Standards



Why CR?

Major Regs

PHY / MAC Standards

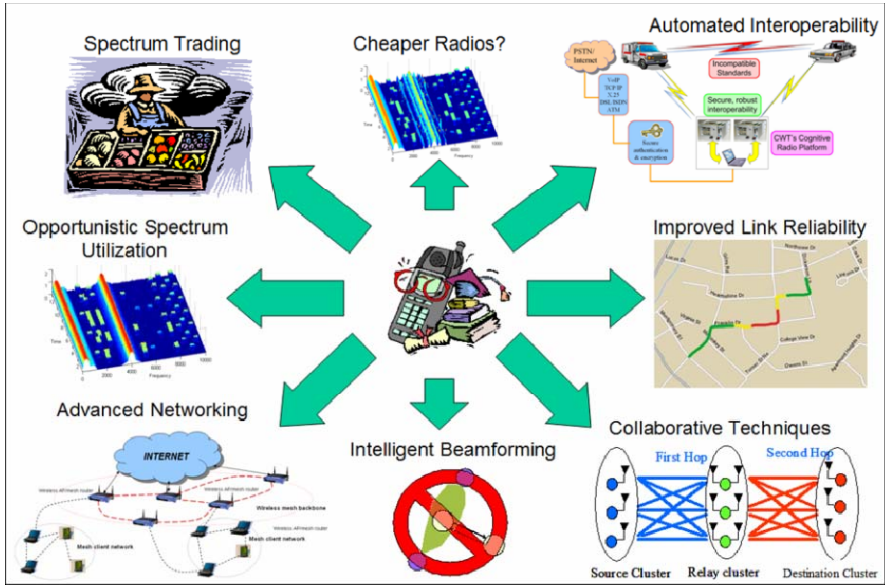
Supporting Standards

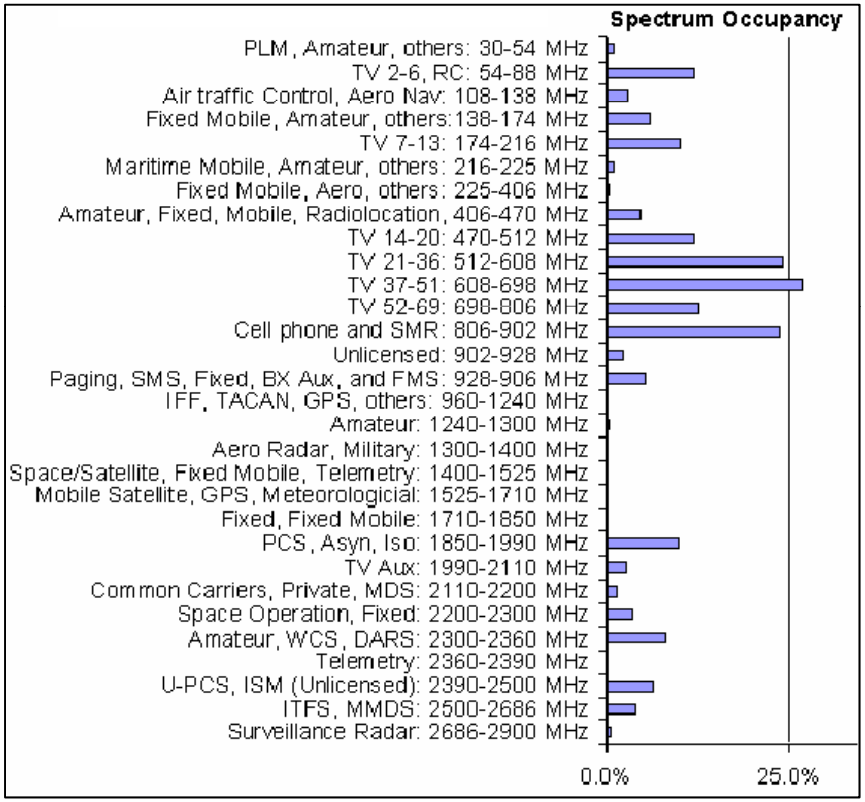
Cognitive Radio

- An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with the capacities to:
  - acquire, classify, and organize information (aware)
  - retain information (aware)
  - apply logic and analysis to information (reason)
  - make and implement choices (agency) about operational aspects of the radio, network, or wireless system in a manner consistent with a purposeful goal (intelligent).
  - "Cognitive Radio Definitions and Nomenclature," Working Document SDRF-06-R-0009-V0.08
- Wireless networks enabled by artificial intelligence

Why Cognitive Radio?

- Spectrum is expensive
  - $19.12 billion from 700 MHz Auction
  - TV white spaces at over $100 billion
  - More access via DSA
- Reduce setup time and cost
  - Self organizing networks
  - Mitigate (WNAN)
- Link quality
- CRWG presenting results of survey of quantifiable benefits of document at ERRT in Mainz June 23

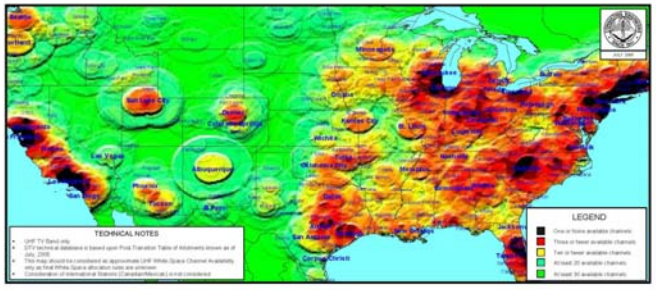




Modified from Figure 1 M. McHenry in “NSF Spectrum Occupancy Measurements Project Summary”, Aug 15, 2005. Available online: http://www.sharedspectrum.com/?section=nsf_measurements

TV White Space Overview

- Concept: DSA applied to TV bands
- Initial regulations in FCC-08-260
  - November 2008
  - Regs likely finalized in Q3-Q4 2010
    - Responding to comments **SLOWLY**
    - Delayed by broadband plan
- Key features of regs
  - Detection:
    - Sensing (needed for mics – for now)
    - Geolocation + look up database of protected transmitters
      - Check database daily
  - Multiple classes of devices
    - Allowable channels
    - Power limits
    - Direct / indirect database access



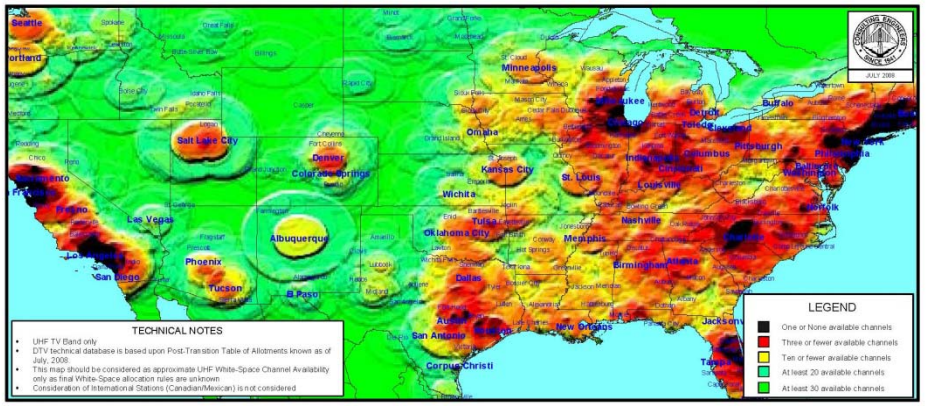
APPROXIMATE WHITE-SPACE UHF BAND CHANNEL AVAILABILITY
BASED UPON FULL-SERVICE POST-TRANSITION BROADCAST STATION ALLOCATION PROTECTION
ALLOCATION PROTECTION TO LOW POWERED TELEVISION/TV TRANSLATORS/CLASS A STATIONS ARE NOT CONSIDERED FOR THIS STUDY

- Available Channels By Class
  - 54-60 MHz FIXED <-> FIXED ONLY
  - 76-88 MHz FIXED <-> FIXED ONLY
  - 174-216 MHz FIXED <-> FIXED ONLY
  - 470-512 MHz FIXED <-> FIXED ONLY
  - 512-608 MHz ALL TVBD
  - 614-698 MHz ALL TVBD
  - Not within 20 km of border
  - Not 608-614 (adjacent to chan 37) in 13 metros (LMR conflict)
- Limited spectrum in urban areas
- Prototypes submitted pre-regs from multiple vendors
  - —Motorola, Microsoft, Adaptrum, Phillips…
- Proposals to be database administrators from 9 companies
  - —Google, Northrup, KeyBridge, SpectrumBridge…
  - —Some coordination in TVWS Database Group

Available Channels

- IMPORTANT:
  - Ignores International Borders
  - From Pre-FCC Regs Study
- Less important: UHF only (Channels 22-51)
- Portable color coding
  - Black cells less than 5 channels available
  - Red cells between 5 to 10 channels available
  - Blue cells between 10 to 15 channels available
  - Green cells between 15 to 20 channels available
  - Blank cells more than 20 channels available

Fixed



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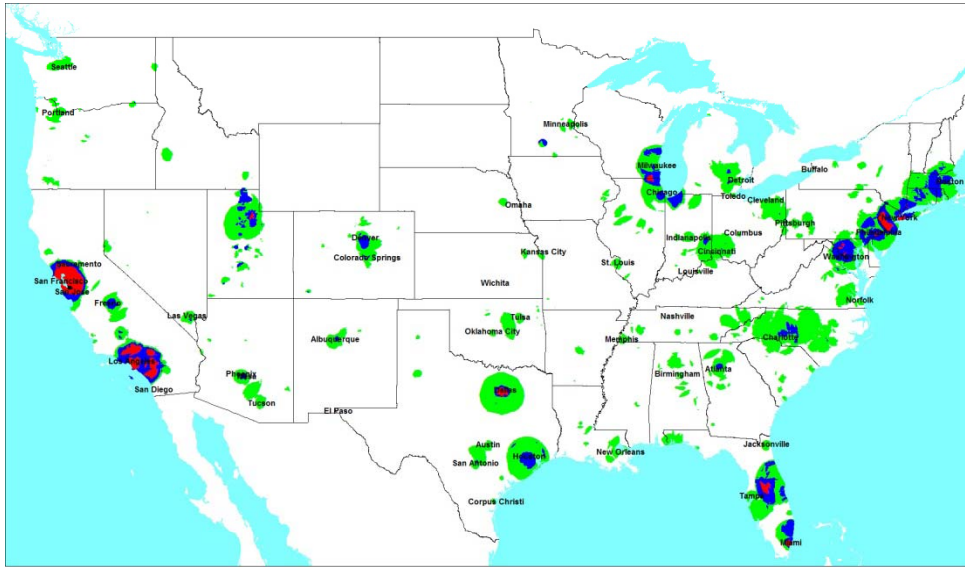
du Treil, Lundin & Rackley, Inc Sarasota, Florida



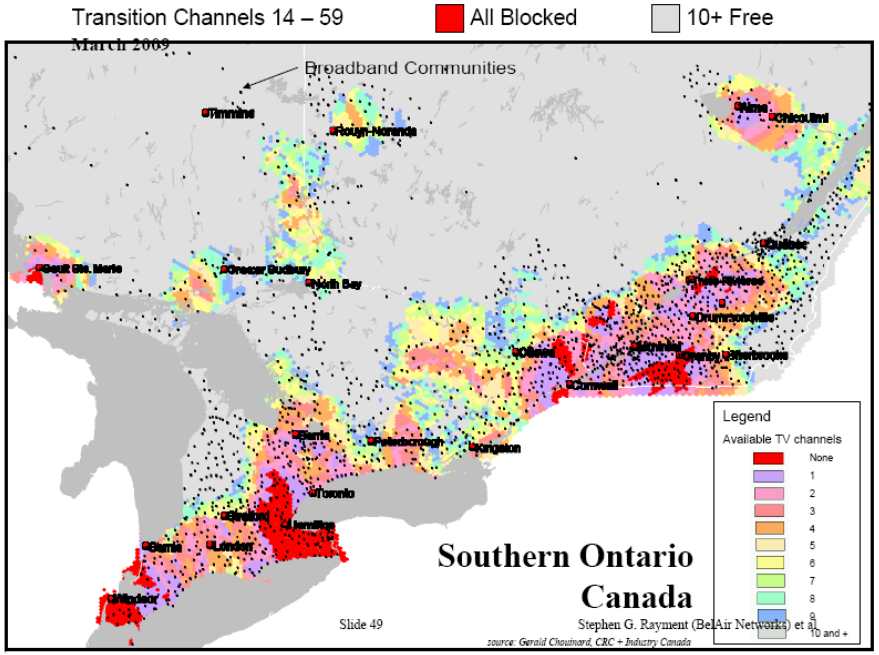
Portable

Source: https://mentor.ieee.org/802.22/dcn/08/22-08-0311-00-0002-preliminary-white-space-allocation-availability.ppt

White Space Canada

- Canada
  - Interim Guidelines (06)
    - http://www.ic.gc.ca/epic/site/smt-gst.nsf/en/sf08739e.html
  - High power, licensed, intended for fixed (point to multipoint) systems, up to 500 W, Vertically polarized (TV services are horizontally polarised)
  - Not CR
    - *"Sites and services including spectrum are individually planned and coordinated around TV services"*
  - 3/09 licenses issued, no services yet

- Channel Availability in Ontario



Source: http://www.ieee802.org/802_tutorials/2009-03/2009-03-10%20TV%20Whitespace%20Tutorial%20r0.pdf

VERY Limited in Urban areas

White Space UK (OFCOM)

- http://www.ofcom.org.uk/consult/condocs/cognitive/statement/

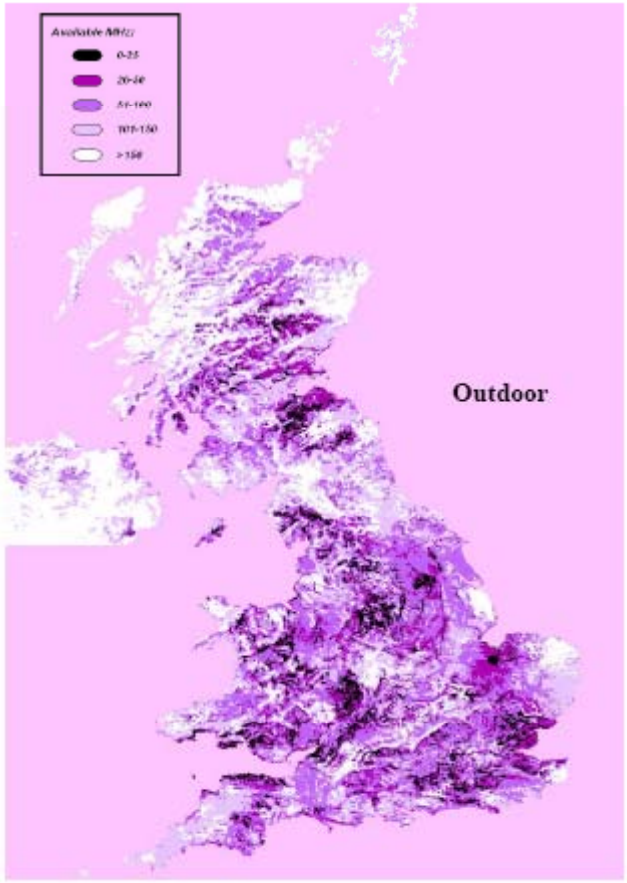
Table 1. Key parameters for detection	
Cognitive parameter	Value
Sensitivity assuming a 0 dBi antenna	-120 dBm in 8 MHz channel (DTT) -126 dBm in 200 kHz channel (wireless microphones)
Transmit power	4 dBm (adjacent channels) to 17 dBm
Transmit-power control	Required
Bandwidth	Unlimited
Out-of-band performance	< -46 dBm
Time between sensing	< 1 second

1.12 Table 2 sets out the key parameters for geolocation that we are able to conclude upon at this point.

Table 2. Key parameters for geolocation	
Cognitive parameter	Value
Locational accuracy	Nominally 100 metres
Transmit power	As specified by the database
Transmit-power control	Required
Bandwidth	Unlimited
Out-of-band performance	< -46 dBm

- Considering Geolocation / database requirements / processes
  - Responses by Feb 9, 2010
  - http://www.ofcom.org.uk/consult/condocs/cogaccess/

Outdoor Availability



VERY Limited in Urban areas
(not as bad indoor)

Source: http://www.ieee802.org/802_tutorials/2009-03/2009-03-10%20TV%20Whitespace%20Tutorial%20r0.pdf

CR-Related Items from Broadband Plan

- TVWS
  - Move expeditiously to complete
  - High power fixed rural
- TV-> Mobile
  - Some TV bands appears to be going to cellular (impact on TVWS?)
    - At least 120 MHz
  - "Voluntary"
- Satellite
  - Enhance movement to mix terrestrial / satellite in Mobile Satellite Spectrum (MSS).
- D-block public/private still of interest (pushing LTE)
- Other
  - Encourage R&D
  - Easier experimental licensing
- Spectrum Monitoring
  - Create a "dashboard"
  - Augment with utilization info
    - Release annually
- Opportunistic Use
  - Encourage
  - < 10 years new contiguous nationwide band
  - Encourage secondary markets
- Federal Squeeze
  - AWS 20 MHz
  - Look for more opportunities to repurpose
  - Start charging fees to users of government spectrum.

http://www.broadband.gov/download-plan/

Commercial Cognitive Radio Efforts

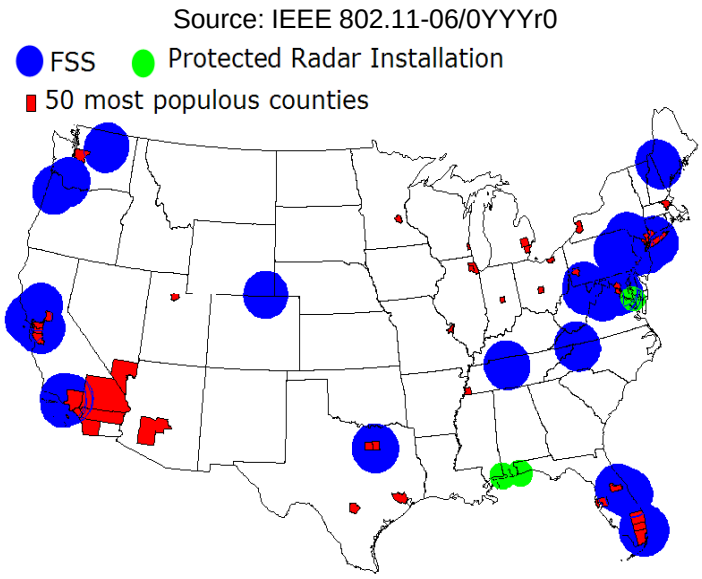
- PHY / MAC Protocols
  - TVWS
    - 802.22 (CR for rural)
    - 802.16h (CR WiMAX)
    - 802.11af (WhiteFi)
    - CogNeA
  - Other bands
    - 802.11h
    - 802.11y
- Supporting Standards
  - 1900
  - WinnForum MLM
  - 802.19.1
  - 802.21
  - Self-organizing networks

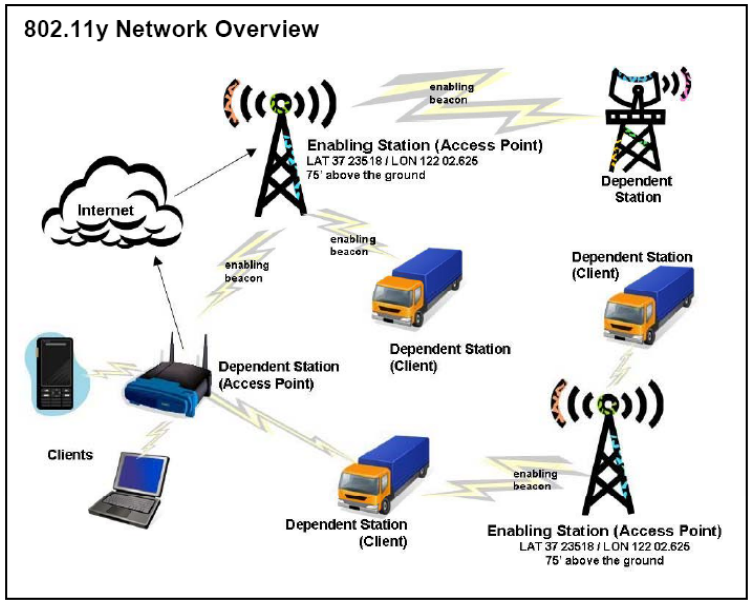
802.11h – Unintentionally Cognitive

- Dynamic Frequency Selection (DFS)
  - Avoid radars
    - Listens and discontinues use of a channel if a radar is present
  - Uniform channel utilization
- Transmit Power Control (TPC)
  - Interference reduction
  - Range control
  - Power consumption Savings
  - Bounded by local regulatory conditions

802.11y

- Ports 802.11a to 3.65 GHz – 3.7 GHz (US Only)
  - FCC opened up band in July 2005
  - Completed 2008
- Intended to provide rural broadband access
- Basis for 802.11af
- Incumbents
  - Band previously reserved for fixed satellite service (FSS) and radar installations – including offshore
  - Must protect 3650 MHz (radar)
  - Not permitted within 80km of inband government radar
  - Specialized requirements near Mexico/Canada and other incumbent users
- Key features:
  - Database of existing devices
    - Access nodes register at http://wireless.fcc.gov/uls
    - Must check for existing devices at same site
  - "Light" licensing
    - Right to transmit, but not protected
  - Automatic policy recognition
    - Varies by channel location
  - Tiered policy enforcement
    - Enabling – determines operating regs
    - Dependent – follows instructions



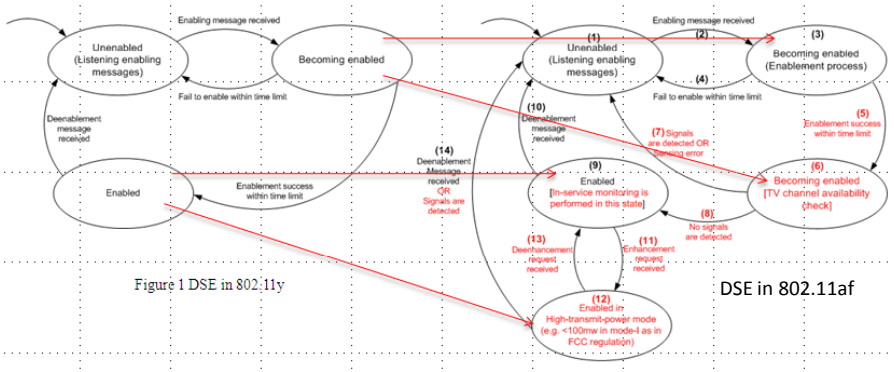


WiFi Alliance, "A New Regulatory and Technical Environment for Wireless Broadband: A Primer on the IEEE 802.11y Amendment,"

802.11af

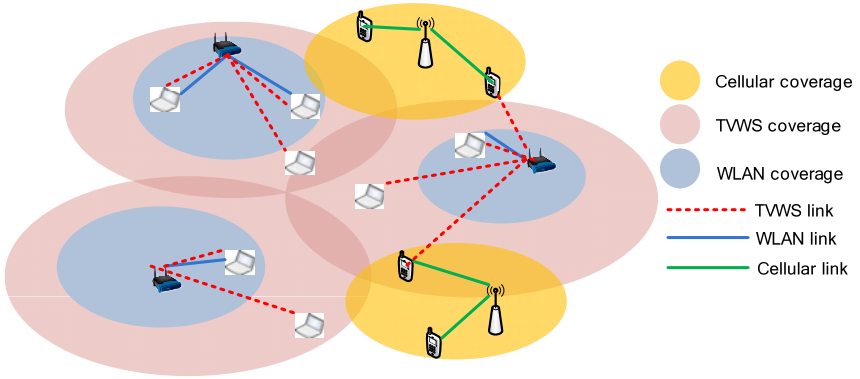
- Builds on 802.11y
  - DFS, TPC, quiet periods, policy enabling
  - Hope to be done in two years
  - Maybe only 15 pages…
  - Started in January 2010
- Considering non-contiguous channels
  - Not in other TVWS proposals
- Multiband support
- Looking for techniques to speed up channel sensing
- Sharing MAP information

Building on 802.11y (Engagement State machine)



IEEE 802.11-10/0261r0

Multi-band Concept



IEEE 802.11-10/0263r3

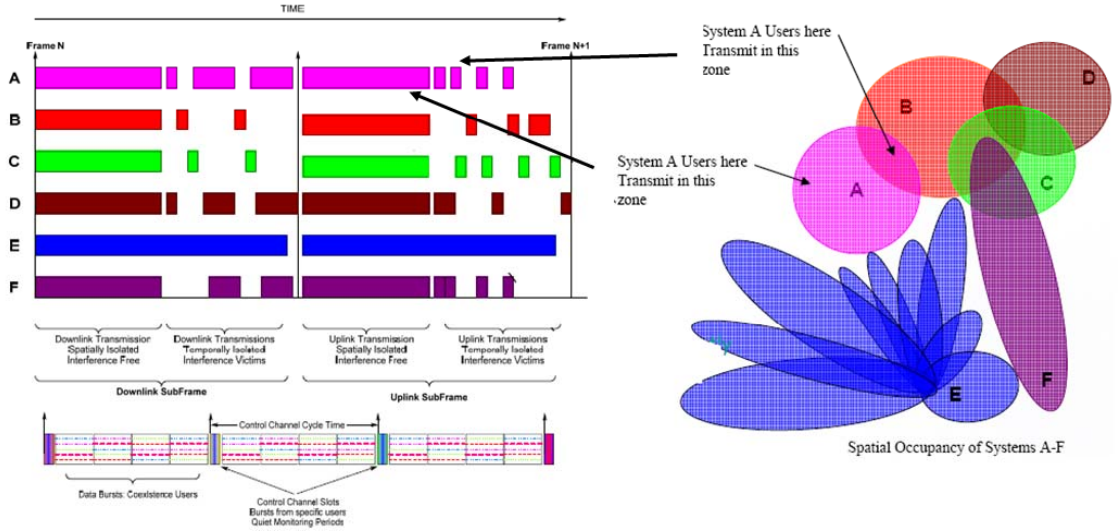
802.16h

- Started as WiMAX for unlicensed
  - Focus on 3.65 GHz
- Migrated to TVWS
- Draft 15(!) March 2010
- Improved Coexistence Mechanisms for License-Exempt Operation
- Explicitly, a cognitive radio standard
- Incorporates many of the hot topics in cognitive radio
  - Token based negotiation
  - Interference avoidance
  - Network collaboration
  - RRM databases
- Coexistence with non 802.16h systems
  - Regular quiet times for other systems to transmit
- Location-aware, time-aware scheduling to allow non-interfering parallel transmissions, and sequential transmissions of transmissions that would interferer
  - Also in 802.22

Cognitive Techniques in 802.16h

non-collaborative mechanism	*(CXCC:) dynamic frequency selection (DFS) *6.4.2.2*
	*(CXCC:) GPS timing recovery (GPS/UTC) *15.2.1*
	Extended quiet periods (EQP) *6.4.3.3*
	Adaptive EQP *6.4.3.4*
	Listen before talk *6.4.3.5*
	Uncoordinated Coexistence Protocol (UCP) *6.4.2.4*
collaborative mechanism	IP network message (CXP message) *15.5.2*
	coexistence proxy (CXPRX) *15.1.6*
	*(CXCC:) coexistence signaling (CSI/ radio signature) *15.3.1*
	*(CXCC:) coexistence messaging (CMI/CCD) *15.3.2*
	sub frame sharing (master sub frame) *15.4.2*
	channel reallocation (ACS) *15.4.1*
	Subframe Reallocation (ASFA) *15.4.2.2*
	credit token *15.4.2.5*

From: M. Goldhamer, "Main concepts of IEEE P802.16h / D1," Document Number: IEEE C802.16h-06/121r1, November 13-16, 2006.

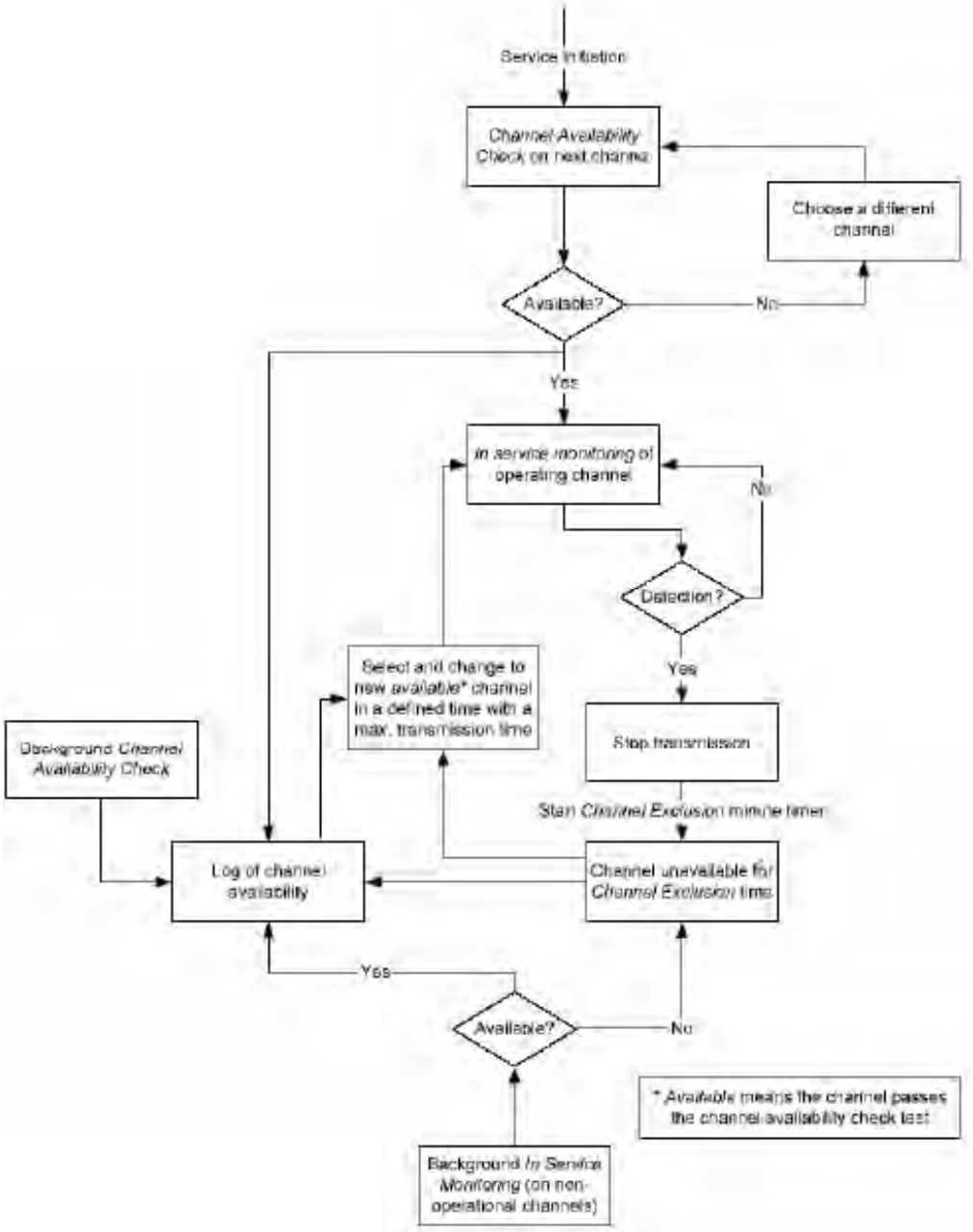


General Cognitive Radio Policies in 802.16h

- Must detect and avoid radar and other higher priority systems
- All BS synchronized to a GPS clock
- All BS maintain a radio environment map (not their name)
- BS form an interference community to resolve interference differences
- All BS attempt to find unoccupied channels first before negotiating for free spectrum
  - Separation in frequency, then separation in time

DFS in 802.16h

- Adds a generic algorithm for performing Dynamic Frequency Selection in license exempt bands
- Moves systems onto unoccupied channels based on observations



Generic DFS Operation Figure h1
(fuzziness in original)

Adaptive Channel Selection

- Used when BS turns on
- First – attempt to find a vacant channel
  - Passive scan
  - Candidate Channel Determination
  - Messaging with Neighbors
- Second – attempt to coordinate for an exclusive channel
- If unable to find an empty channel, then BS attempts to join the interference community on the channel it detected the least interference

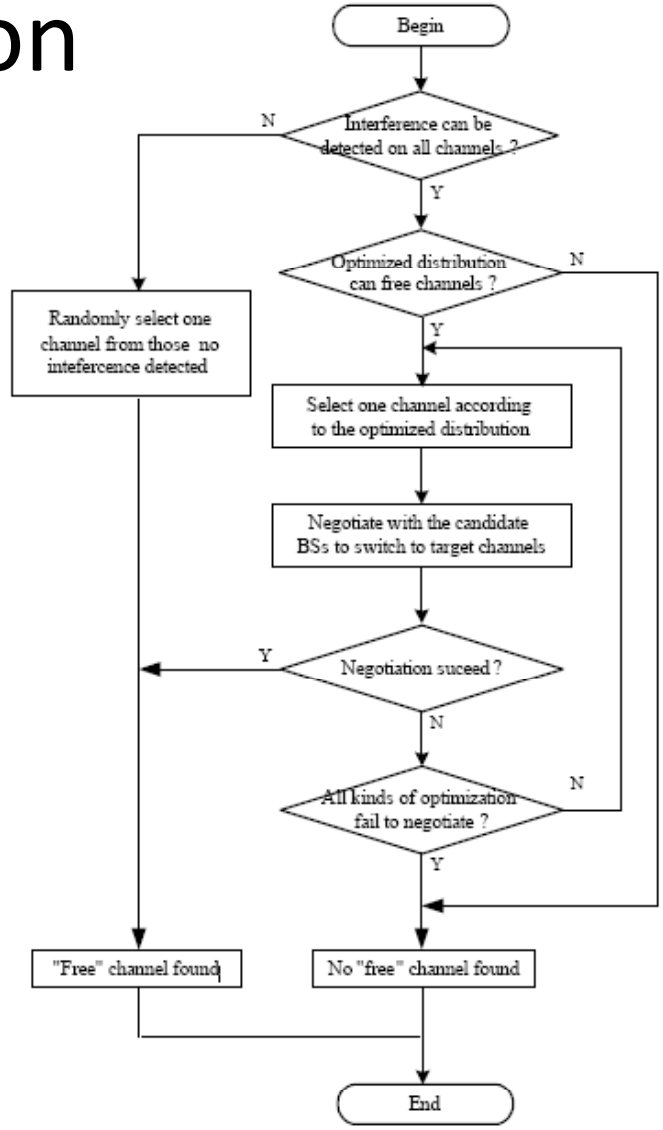
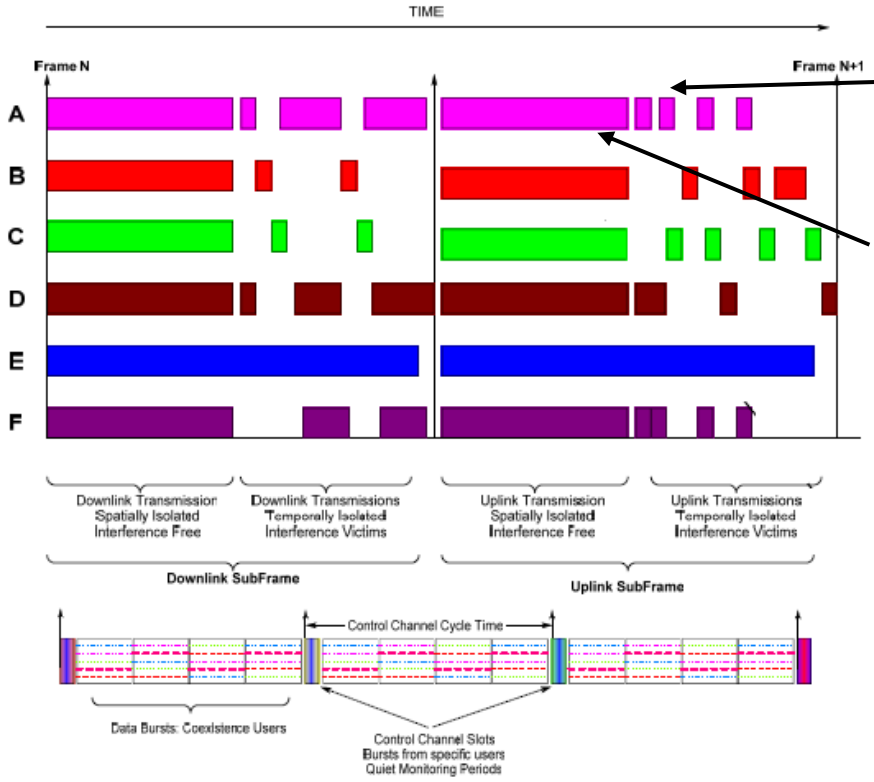
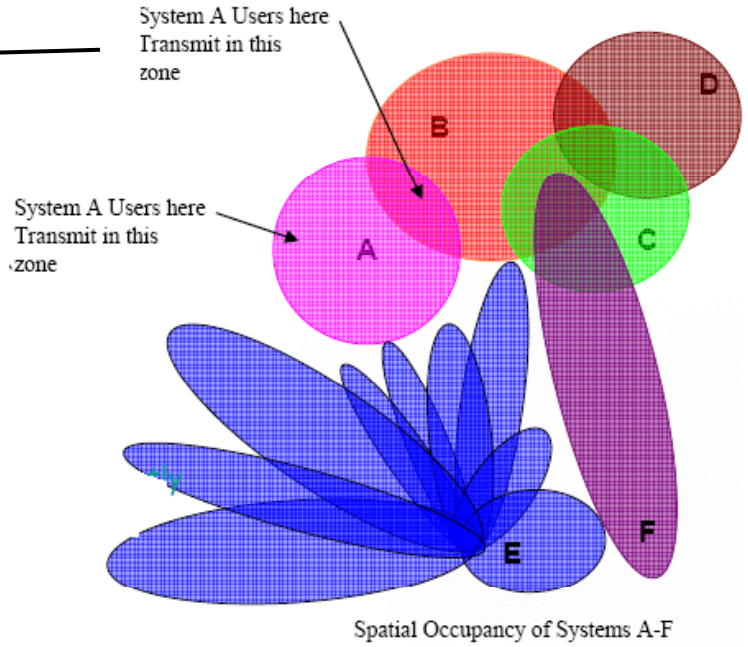


Figure h37: IEEE 802.16h-06/010 Draft IEEE Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems Amendment for Improved Coexistence Mechanisms for License-Exempt Operation, 2006-03-29

Scheduling in 802.16h

- Coordinate on times to deconflict users
  - "Interference free" operation
  - Fractional Time Reuse (my term)
  - Requires significant coordination and information awareness



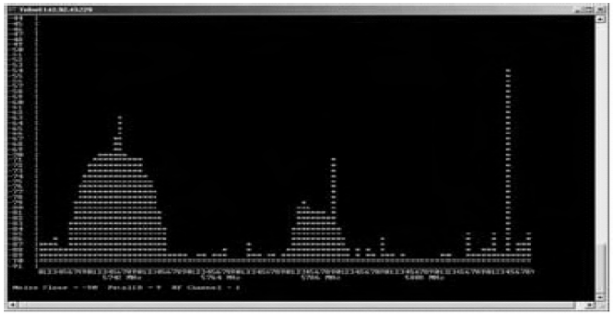


Spatial Occupancy of Systems A-F

Modified from CRC pub.

Discovery

- BS / Interference Group Schedules Quiet Periods in DL-MAP to detect PU
- SS report back interference levels, IDs, and possibly PSDs

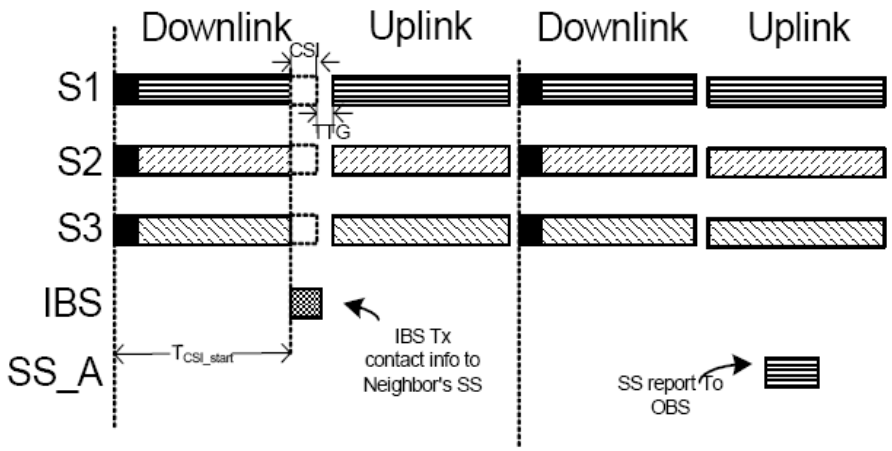


- Databases maintained of interferers and detected devices

- Leverage BS database to
  - determine locations
  - estimate likely interference levels
  - Form initial interference groups
- IP connection generally assumed
- Non IP enabled (“backhaul-less”) systems are slaved to systems with backhaul
  - Communicate over air via various signaling protocols

Coexistence Signaling Interval

- Coexistence Signaling Interval
  - Scheduled every N frames
  - Initialization and over the air
  - BS<->BS via SS via CT-CXP
- Transmit BS Identifiers when no BS interference server exists

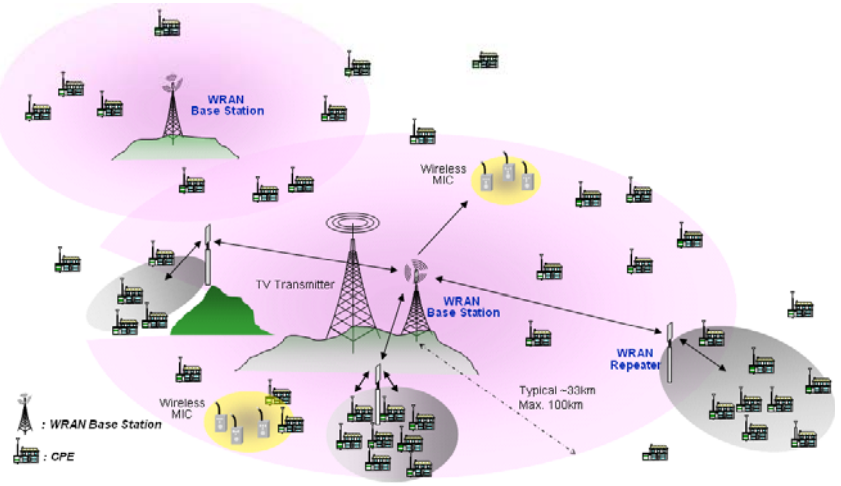


Collaboration

- BS can request interfering systems to back off transmit power
- Master BS can assign transmit timings
  - Intended to support up to 3 systems (Goldhammer)
- Slave BS in an interference community can “bid” for interference free times via tokens.
- Master BS can advertise spectrum for “rent” to other Master BS
  - Bid by tokens
- Collaboration supported via Base Station Identification Servers, messages, and RRM databases
- Interferer identification by finding power, angle of arrival, and spectral density of OFDM/OFDMA preambles
- Every BS maintains a database or RRM information which can be queried by other BS
  - This can also be hosted remotely
- Updates neighbors when adapting channels
- Broadcasts information on initialization during initial coexistence signaling interval (ICSI)

802.22

- Wireless Regional Area Networks (WRAN)
  - First standard to enter TVWS
  - Aimed at bringing broadband access in rural and remote areas
  - Takes advantage of better propagation characteristics at VHF and low-UHF
  - Takes advantage of unused TV channels that exist in these sparsely populated areas
- Status
  - Resolving comments
  - Still developing
  - Likely done shortly after final FCC regs
- 802.22.1
  - Enhanced interference protection
  - Particularly for mics
- 802.22.2
  - Best practices for deployment



Features of 802.22

- Data Rates 5 Mbps – 70 Mbps
- Point-to-multipoint TDD/FDD
- DFS, TPC
- Adaptive Modulation
  - QPSK, 16, 64-QAM, Spread QPSK
- OFDMA on uplink and downlink
- Use multiple contiguous TV channels when available
- Fractional channels (adapting around microphones)
- Space Time Block Codes
- Beam Forming
  - No feedback for TDD (assumes channel reciprocity)

•802.16-like ranging

•802.16 MAC plus the following

–Multiple channel support

–Coexistence

- Incumbents
- BS synchronization
- Dynamic resource sharing

–Clustering support

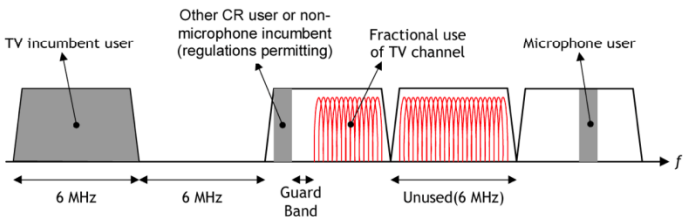
–Signal detection/classification routines

•Security based on 802.16e security

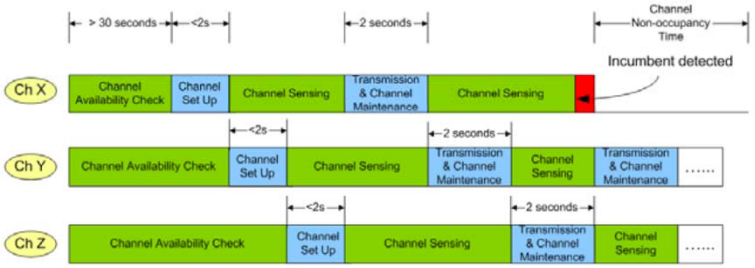
•Collaborative sensing

•Techniques in 802.22 will be extended to other standards and to other bands around the world

Channel Bonding



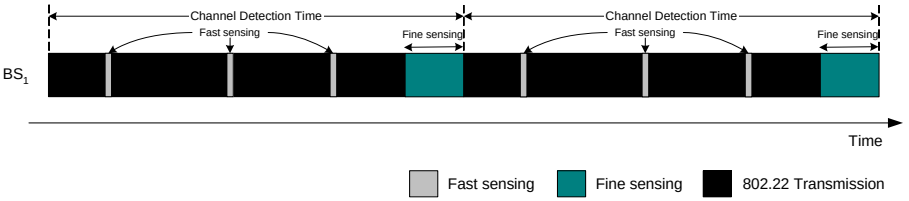
Frequency Switching



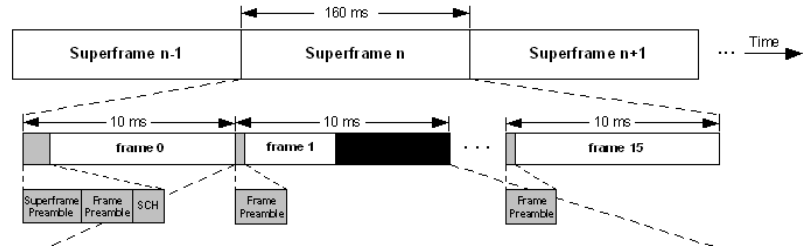
802.22 Sensing and Quiet Periods

- WIDE variety of algorithms proposed
  - Includes microphone beacon
  - Most leverage signal properties
- Bulk measurements from SU
- Variable quiet period methods + opportunistic quiet periods
- Hopping when extra channels available

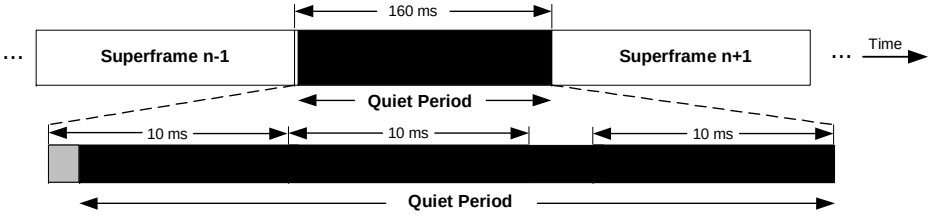
Variable Resolution



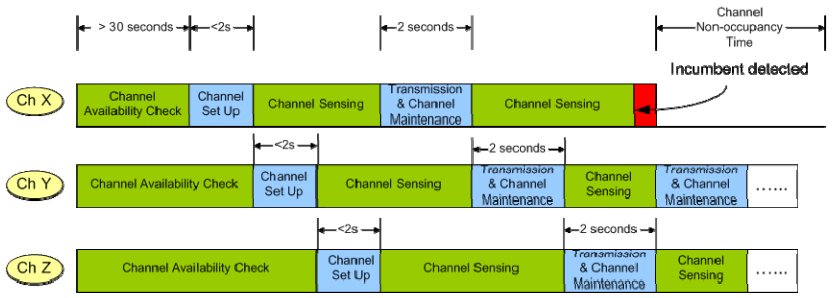
Frame quiet period (5.1 ms)



Superframe quiet period; up to 168 ms

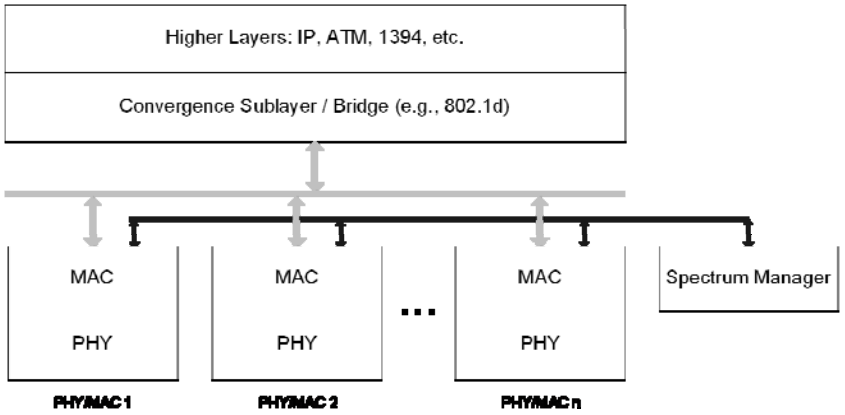


Hopping across channels

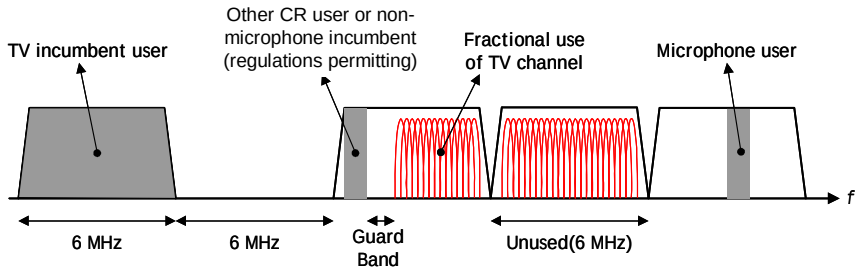


802.22 MAC Features

- Bandwidth
  - Channel Bonding
    - Assumes contiguous channels
  - Fractional BW Use
    - Again contiguous channels
  - Managed by SM
    - E.g., R. Wu, IEEE 802.22-09/113r0 TV WhiteSpace Manager, June 2009



Fractional BW Use



Channel Management

① The channel becomes useless as incumbent service appears.

② Incumbent service releases the channel and its quality is good, then it is classified as a member of candidate set.

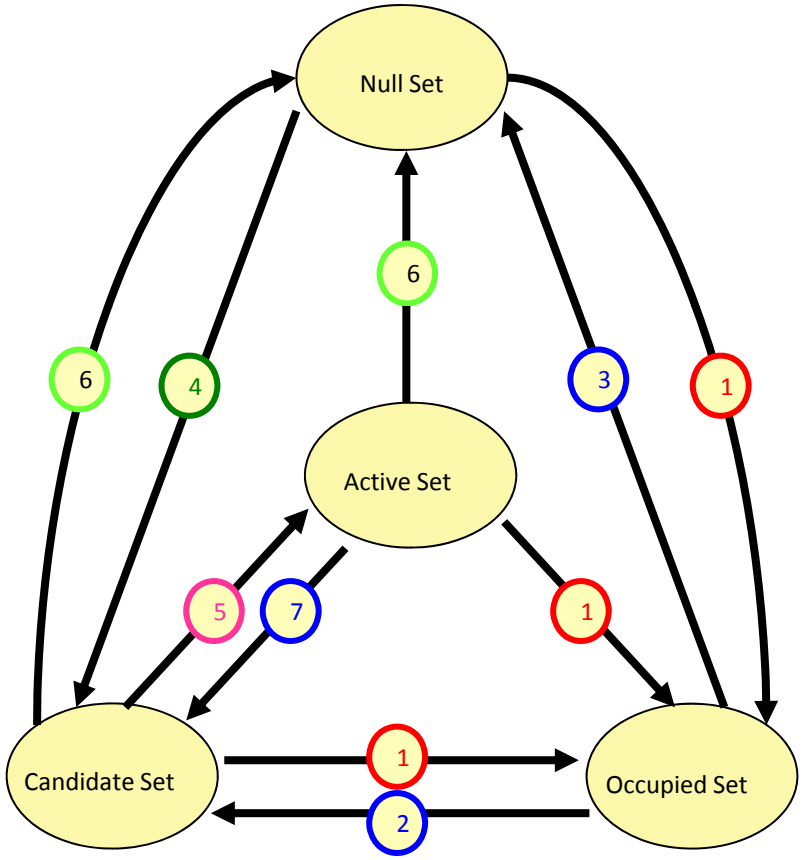
③ Incumbent service releases the channel and its quality is poor, then it is classified as a member of null set.

④ If the channel quality is better than an existing member of the candidate set, then it replaces the member of candidate set.

⑤ The channel becomes active as quality goes above a given threshold.

⑥ The channel is classified as a member of null set as quality goes below a given threshold.

⑦ The channel is released due to the finish of its usage.



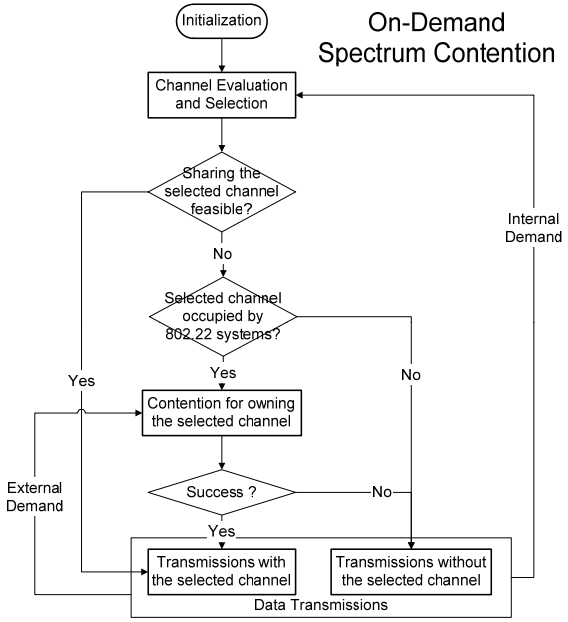
SLIDE FROM: Woo-Jae Kim, IEEE 802.22 WRAN PHY/MAC proposals (Draft 0.1), May, 2007

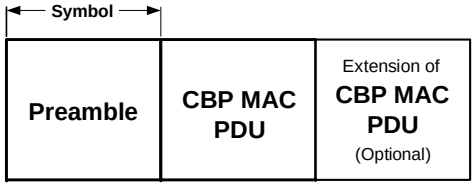
802.22 Rendezvous / Channel Adaptation

- Maintain backup channel list
  - Disjoint to minimize simultaneous impairment
- On detection
  - Choose *c* from candidate list
  - Wait a random time to ensure operation
    - If collision then begin again with longer random time period
    - Else start operating
- Not entirely certain what subscribers are doing

Contention / Coexistence

- Variable contention strategies
  - Tries to backoff power first
    - Minimum SNR
  - Can rent spectrum exchange tokens
    - Both sides bid (request and holder)
- Inter-BS communication / negotiation
  - Over-the-air and Via Backhaul
  - Contention number exchange and comparison
- Coexistence beacon
  - Transmitted during the self-coexistence windows at the end of some frames by the BS and/or some designated CPE
  - Monitored by BSs and other CPEs from same and different cells on same channel or different channel for future channel switching
  - Signals IP address of BS and CPE **<u>every 15 min</u>**. as asked by R&O

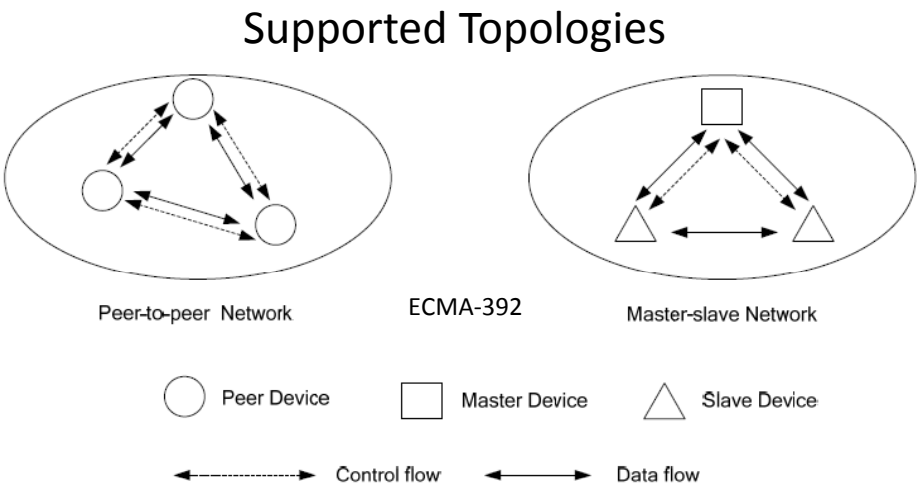


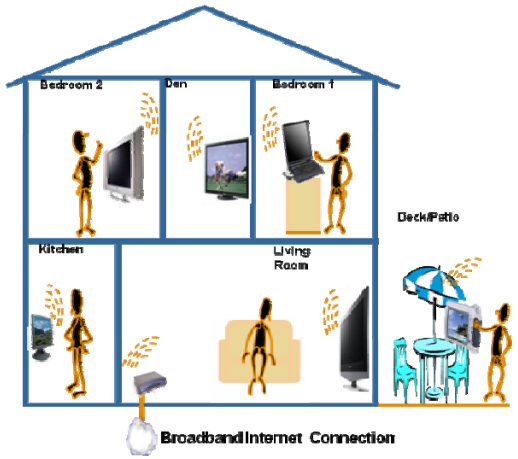


Coexistence Beacon Protocol (CBP) burst

CogNeA

- Industry Alliance formed in 2007
  - http://www.cognea.org/
    - looks like a bad blog, but that's the website
  - BT, Cambridge Consultants, ETRI, Philips, Samsung Electro-Mechanics, MaxLinear, Georgia Electronic Design Center (GEDC) at Georgia Institute of Technology and Motorola
- Use cases more focused on internet and whole-home networks
- Approved draft
  - http://www.ecma-international.org/publications/standards/Ecma-392.htm
  - PHY/MAC
  - Bluetooth-like
- Features:
  - DFS, TPC, scheduled quiet periods, beacons, geo-location, sensing





Ecma/TC48-TG1/2009/017

CogNeA PHY

- QoS Support:
  - Background, best effort, vide, and voice
- 128-point FFT OFDM
- Single TVWS channel
- Gray coded QPSK, 16-,64-QAM
- Reed-Solomon (245,255) and Convolutional Encoding
- Soft (combined) retransmission with interleaver variation
- Multiple antenna support (2)
  - No STBC

TABLE 1 LINK MARGIN

Parameter	Value	Value
Data Rate	4.75 Mbps	23.74 Mbps
Average transmit power	20 dBm	20 dBm
Total path loss (600 MHz)	88 dB (at 1000 m)	68 dB (at 100 m)
Received power/bit	-68 dBm	-48 dBm
Total noise power/bit (with 6 dB Noise Figure)	-101.20 dBm	-94.25 dBm
Required E_b/N_o (BER of 1.0e-6)	3.1 dB	12.52
Fading margin	10 dB	10 dB
Implementation & other losses	14 dB	14 dB
Link Margin	6.09 dB	9.74 dB

TABLE 2 OFDM PARAMETERS

TV channel bandwidth (MHz)	6	7	8
Total number of subcarriers, NFFT	128		
Number of guard subcarriers, NG (L,DC,R)	26 (13,1,12)		
Number of used subcarriers, NT=ND+NP	102		
Number of data subcarriers, ND	98		
Number of pilot subcarriers, N_P	4		
Sampling frequency (MHz)	48/7	8	64/7
FFT period, T_{FFT} (us)	18.667	16	14
Subcarrier spacing, ΔF (KHz)	53.571	62.5	71.429
Signal bandwidth (MHz)	5.518	6.438	7.357

http://www.ecma-international.org/publications/files/drafts/tc48-tg1-2009-132.p

CogNeA MAC (1/2)

- Fine (normal) and Fast TPC (adjacent incumbent)
- Rendezvous
  - Backup channel with same settings
  - Master, peer, or timeout initiated
- Network merging
  - Cuts down on inter-network collisions
  - Coordinates quiet periods
- Beaconing
  - Control information
    - Channel information, slot reservations, quiet periods, device discovery, channel evacuation
  - Merges beacons with networks merge

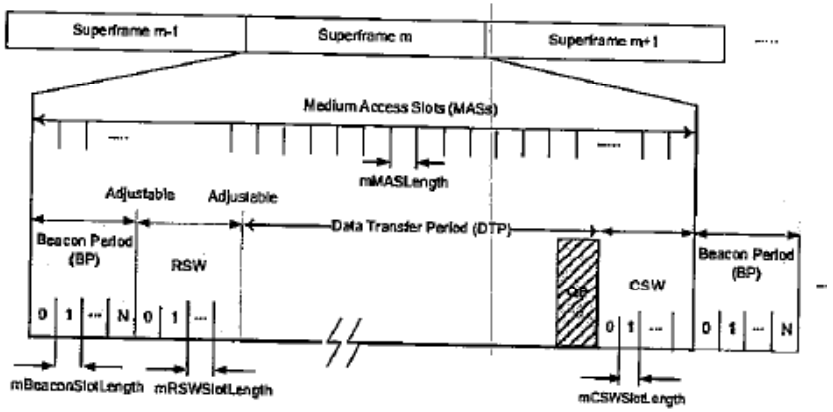
TABLE 4 FEATURES TO SUPPORT KEY FUNCTIONALITIES

Functionality	Features
Network formation	Peer to peer, master-to-slave, mesh
Beaconing	Scalable multi-device beaconing
Channel access	High efficient reservation access with overlay support of prioritized contention access
Frame processing	Frame aggregation and burst transmission with block ACK
Spectrum sensing	Synchronized Quiet Period and Extended Quiet Zone
Self-coexistence	Full interoperability between different device types. Support channel reservation and QP schedule across neighboring networks.
Spectrum agility	Proactive channel selection, fast channel evacuation and connection re-establishment
TPC	Wide-range TPC based on link quality and incumbent status
Device discovery	Auto discovery
Power management	Traffic indication MAP, Hibernate and sleep modes

http://www.ecma-international.org/publications/files/drafts/tc48-tg1-2009-132.pdf

CogNeA MAC (2/2)

- Channel Access
  - Allocation of Medium Access Slots (MAS)
  - Reservation, Prioritized Contention Access
  - Reserve via beacon
    - Shared when merged
  - TIM field indicates to target receivers presence of buffered data to reduce power



Priority	User Priority	802.1D Designation	AC	Designation (Informative)
Lowest	1	BK	AC_BK	Background
	2	-	AC_BK	Background
	0	BE	AC_BE	Best effort
	3	EE	AC_BE	Best effort
	4	CL	AC_VI	Video
	5	VI	AC_VI	Video
	6	VO	AC_VO	Voice
Highest	7	NC	AC_VO	Voice

http://www.ecma-international.org/publications/files/drafts/tc48-tg1-2009-132.pdf

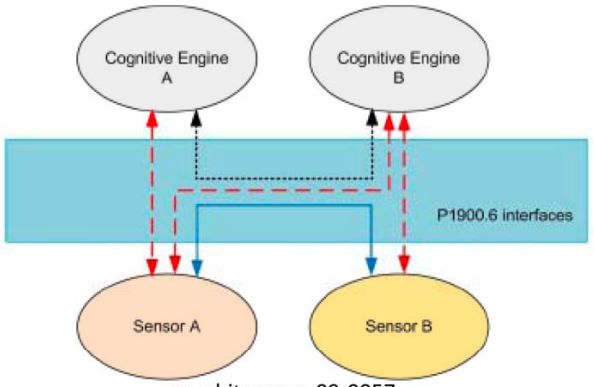
Reservation Type	Description
Alien BP	Prevents transmission during MASs occupied by an alien BP.
Hard	Provides exclusive access to the medium for the reservation owner and target; unused time should be released for PCA
Soft	Permits PCA, but the reservation owner has preferential access.
Private	Provides exclusive access to the medium for the reservation owner and target. Channel access methods and frame exchange sequences are out of scope of this specification; unused time should be released for PCA.
PCA	Reserves time for PCA. No device has preferential access.

IEEE 1900 (SCC41)

- IEEE 1900 (aka Standards Coordinating Committee 41 – Dynamic Spectrum Access Networks)
  - http://www.scc41.org/
  - 1900.1 – Terminology and Concepts
  - 1900.2 - Recommended Practice for Interference and Coexistence Analysis
    - Approved
    - http://crtwireless.com/blog/2008/04/02/19002-approved/
  - 1900.3 – Conformance Evaluation for SDR modules
  - 1900.4 – Architectural Building Blocks
    - network resource managers
    - device resource managers
    - the information to be exchanged between the building blocks
  - 1900.5 – Policy Languages
  - 1900.6 – Spectrum Sensing
    - Information exchange
    - Went to ballot in April

	1900.1	1900.2	1900.3	1900.4	1900.5	1900.6
PAR Approved	3/04/05	03/20/05	12/05/07	12/06/06	03/28/08	9/26/08
Initial Ballot - Open	9/07/07	07/02/07	Pending Withdrawal	9/08/08		
Initial Ballot – Close	10/07/07	08/03/07		10/08/08		
1st Recirc – Close	4/17/08	10/24/07		10/26/08		
2nd Recirc - Close		01/01/08		11/22/08		
RevCom Approval	4/10/08	1/08/08		1/19/09		
SASB Approval	6/12/08	3/28/08		1/29/09		
Published	9/26/08	7/29/08		2/27/09		

sg-whitespace-09-0057



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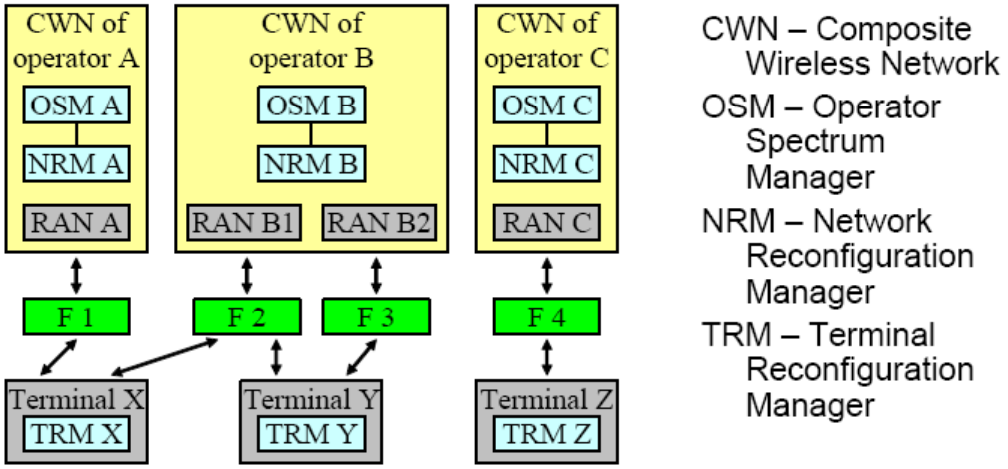
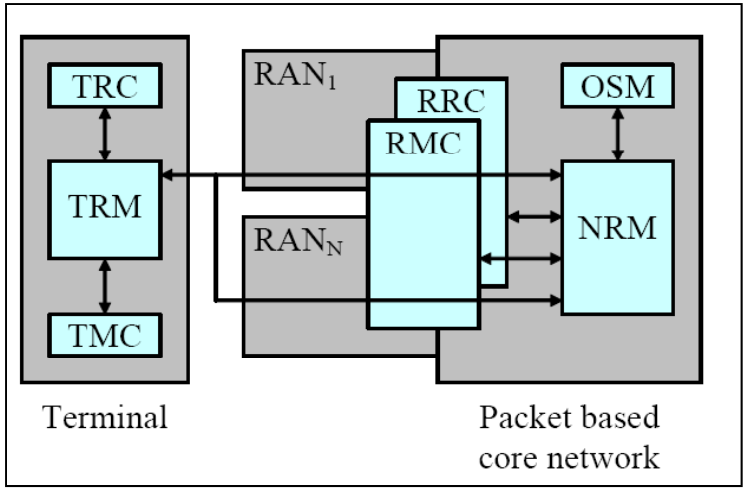
1900.4 (Architecture)

- Published Feb 2009
- Material
  - system and functional requirements
  - system and functional architecture
  - information model
  - generic procedures
  - use cases
  - deployment examples
- Architecture
  - Managers / controllers on terminal and network
  - Measurement collectors
  - Spectrum manager on network
  - Well suited for cellular apps

Use Cases



http://grouper.ieee.org/groups/scc41/4/IEEE-1900.4-Overview-2009-01-07.pdf



http://grouper.ieee.org/groups/scc41/4/IEEE-1900.4-Overview-2009-01-07.pdf

1900.5: Policy Languages

Document Outline

1 Overview
1.1 Scope
1.2 Purpose
1.3 Document Overview
2 Normative References
3 Definitions
4 Use Cases
4.1 Network Reachback
4.2 Opportunistic Spectrum Environment [XG & TV whitespace]
4.3 Licensed Spectrum Environment [P1900.4]
5 Policy System Architecture Requirements
5.1 General Architecture Requirements
5.2 Policy Management Requirements
5.3 Requirements Related to Data Handling
5.4 Requirements for Access Control Policies
6 Policy Language and Ontology Requirements
6.1 Language Expressiveness
6.2 Reasoning

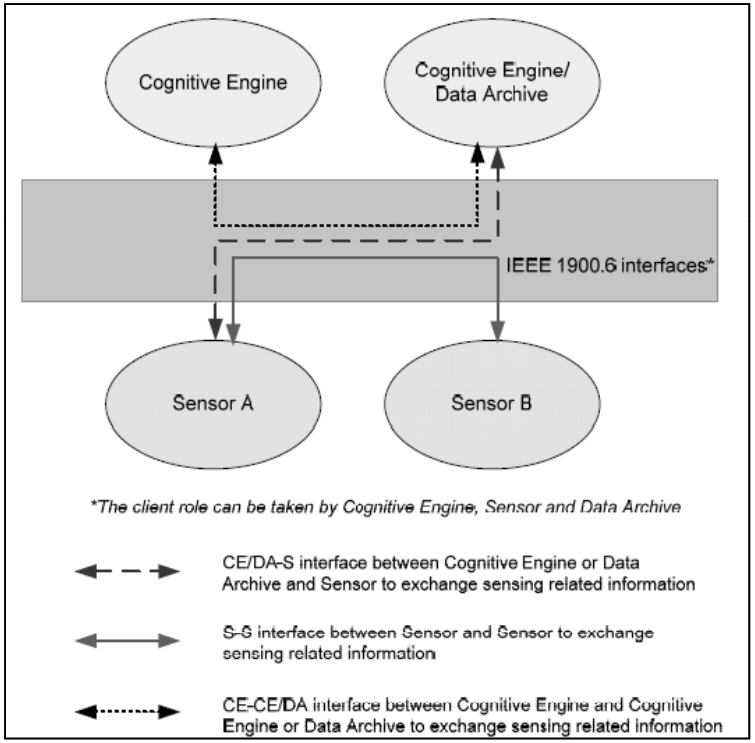
- Scope:
  - set of policy languages,
  - relation to policy architectures
  - In DySPAN like networks
- Subgroups
  - Policy Architecture Ad Hoc
  - Policy Language Ad Hoc
  - Use Case Analysis Ad Hoc
- System Engineering Documents (SEDs) on
  - Policy Architecture, Policy Language, and Definitions.
- Completion later this year?
- Current Focus on policy engines and compliance

M. Kokar, J. Hoffmeyer, "IEEE Standards Coordinating Committee 41 Dynamic Spectrum Access Networks," Briefing to SDR Forum Modeling Language for Mobility Work Group,14 September 2009

1900.6

- Standard for sharing sensing information
- First Ballot

This standard defines the information exchange between spectrum sensors and their clients in radio communication systems. The logical interface and supporting data structures used for information exchange are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client.

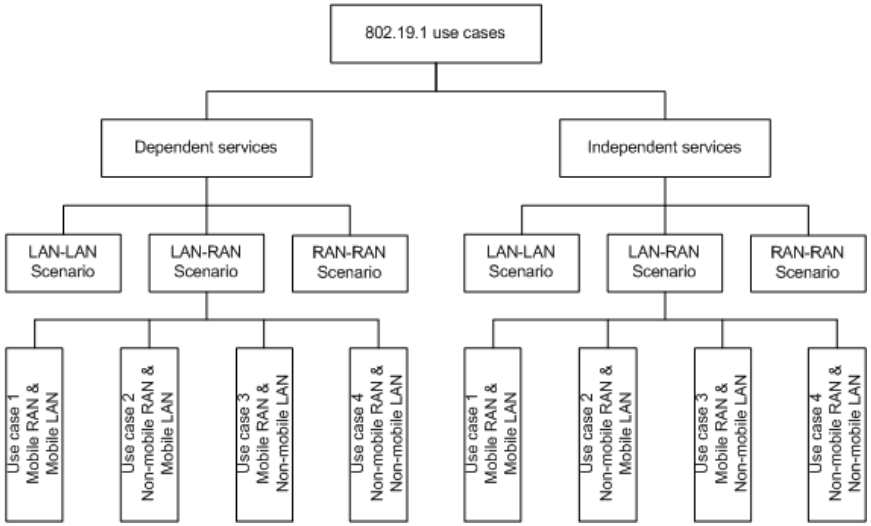


1900.6 Draft 1

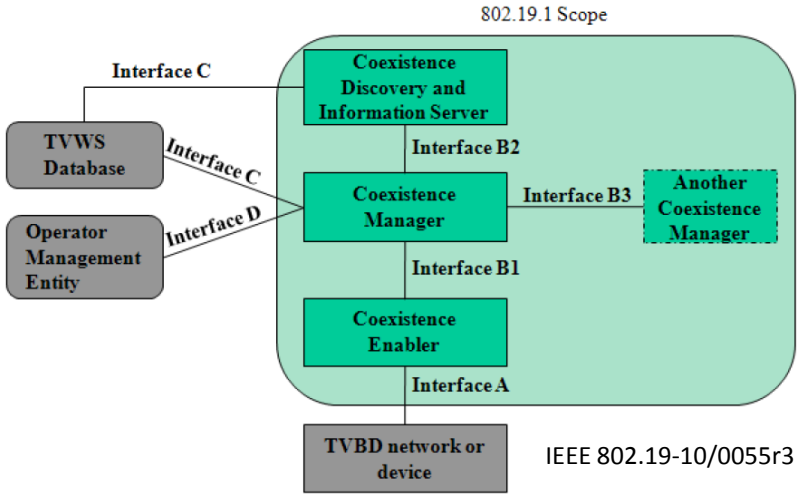
- Mix of soft / hard measurements

802.19.1 (TVWS Coexistence)

- Coexistence mechanisms for heterogeneous networks in TVWS
- Device discovery
- Manage coexistence info
  - Database, shared info
- Support reconfiguration requests
- Automate analysis of info
- Make coexistence decisions
- Support multiple topologies



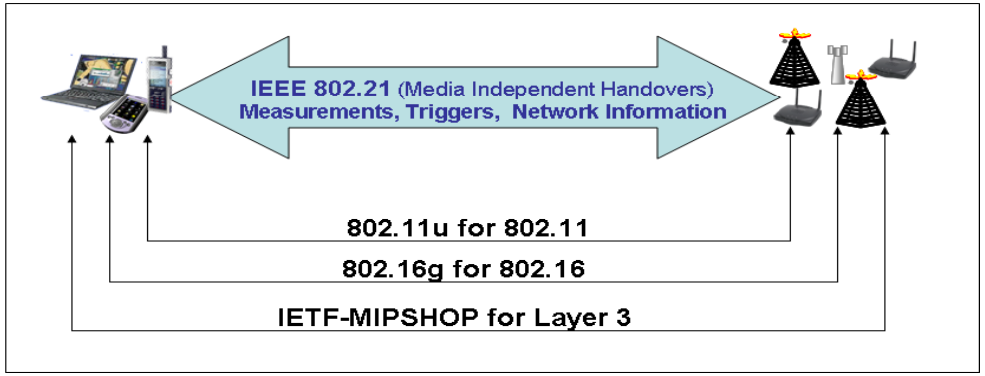
IEEE 802.19 DCN 19-10-0008-01-0000

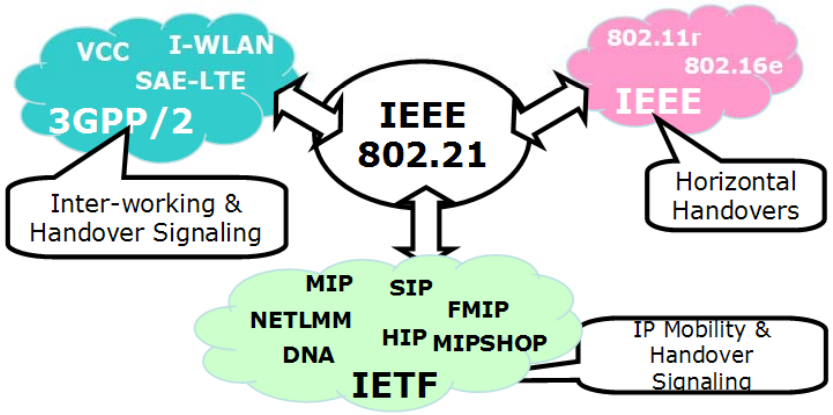


IEEE 802.19-10/0055r3

802.21 (Media Independent Handoffs)

- Key Services
  - Triggers (state change, predictive, network initiated)
  - Network Information (services, maps, list of available networks)
  - Handover commands (client or network initiated, vertical handoffs)
- Published January 2009
- Follow on (mostly study groups)
  - Mobile Broadcast Handoffs (e.g., Digital Video Broadcasting, MediaFLO, Digital Multimedia Broadcast)
  - Inter-network handoff Security
  - Multi-radio power
  - Deployment Scenarios,
  - Emergency Services





V. Gupta, "IEEE 802.21 MEDIA INDEPENDENT HANDOVER," IEEE 802.21 session #15 July 17, 2006

http://www.ieee802.org/802_tutorials/july06/802 21-IEEE-Tutorial.ppt

Self Organizing Networks

- Objective:
  - Reduce operating expenses by minimizing
  - Better support for multi-tiered heterogeneous networks
- Standardized by 3GPP (WCDMA, LTE) and Next Generation Mobile Networks
- Features
  - Automatically extend, change, configure and optimize the
  - network coverage, capacity, cell size, topology, and frequency allocation and bandwidth,
  - based on changes in interference, signal strength, location, traffic pattern, and other environmental criteria.
- The first release of SON (3GPP Release 8)
  - automatic inventory, automatic software download, Automatic Neighbor Relation, Automatic Physical Cell ID (PCI) assignment
- Second release of SON (3GPP Release 9)
  - Coverage & Capacity Optimization, Mobility optimization, RACH optimization, and Load Balancing Optimization.
- Similar effort in 802.16m

USE CASES

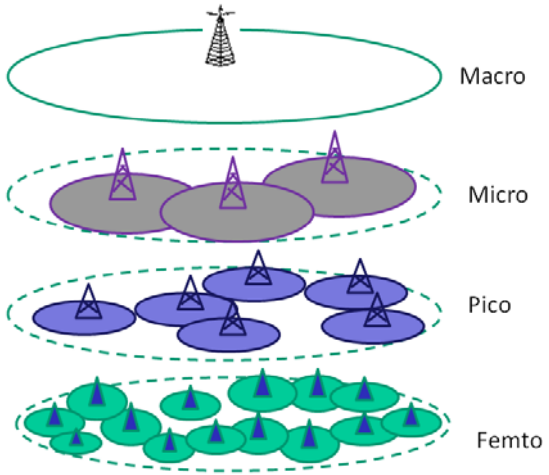
Planning
Planning of eNodeB
Planning of eNodeB Radio parameters
Planning of eNodeB Transport parameters
Planning of eNodeB data alignment

Optimization
Support of centralized optimization entity
Neighbor list optimization
Interference control
Handover parameter optimization
QoS parameter optimization
Load Balancing
Home eNodeB optimization
RACH load optimization

Deployment
Hardware installation
eNodeB/network authentication
O&M Secure tunnel setup
Automatic inventory
Automatic Software download to eNB
Transmission setup
Radio parameter setup
Self Test

Maintenance
Hardware/capacity extension
Automated NEM upgrade
Cell/Service outage detection and compensation
Real-Time Performance management
Information correlation for fault management
Subscriber and equipment trace
Outage compensation for higher level network elements
Fast recovery of unstable NEM system
Mitigation of outage of units

"The Benefits of SON in LTE: Self-Optimizing and Self-Organizing Networks," *3G Americas*, December 2009. Available online: http://www.3gamericas.org/documents/2009_%203GA_LTE_SON_white_paper_12_15_09_Final.pdf



Implementation Issues

- Many different architectures [Amana_10]
- Many different metrics [Zhao_09]
- Interaction between choice of processes in an architecture [Zhao_09]
- Greater sophistication implies increasing complexity [Kokar_06]
  - Generally nonlinearly

			Scenario 1	Scenario 2
Observation	Parameters	O	*Interference at access point from other access points*	*Interference seen by clients*
		A	Frequency (channel)	Frequency (channel)
		D	Lowest interference channel	Lowest interference channel
		G	Minimize interference	Minimize interference
		C	Tent city	Tent city
	Result		Converges to near-optimal frequency reuse pattern [48]	Enters an infinite loop with probability 1 as network scales [51]
Actions	Parameters	O	SINR at cluster head	SINR at cluster head
		A	*Frequency*	*Power*
		D	Maximize goal	Maximize goal
		G	Maximize SINR	Maximize SINR
		C	Isolated cluster	Isolated cluster
	Result		Network tends to converge to low interference states	Network tends to converge to self-jamming states
Decisions	Parameters	O	Collisions	Collisions
		A	Transmission times	Transmission times
		D	*Collaborate on times*	*Noncollaboratively choose times*
		G	Maximize collisions	Maximize collisions
		C	Isolated cluster	Isolated cluster
	Result		Rapid convergence to minimal interference state, adjustable to different user priorities	Slow (if at all) convergence, throughput as low as ALOHA $(1/e)$
Goals	Parameters	O	SINR at cluster head	SINR at cluster head
		A	Power	Power
		D	Maximize goal	Maximize goal
		G	*Target SINR*	*Maximize SINR*
		C	Isolated cluster	Isolated cluster
	Result		If target SINR is feasible, converges to target SINR [78]	Network tends to converge to self-jamming states
Context	Parameters	O	SINR at cluster head	SINR at cluster head
		A	Power	Power
		D	Punish (jam) radios deviating from target SINR	Punish (jam) radios deviating from target SINR
		G	Target SINR	Target SINR
		C	*Isolated cluster*	*Isolated cluster with a jammer*
	Result		Network overcomes defection problems for significant improvement in performance [41]	Network self-jams as it "punishes" the jammer

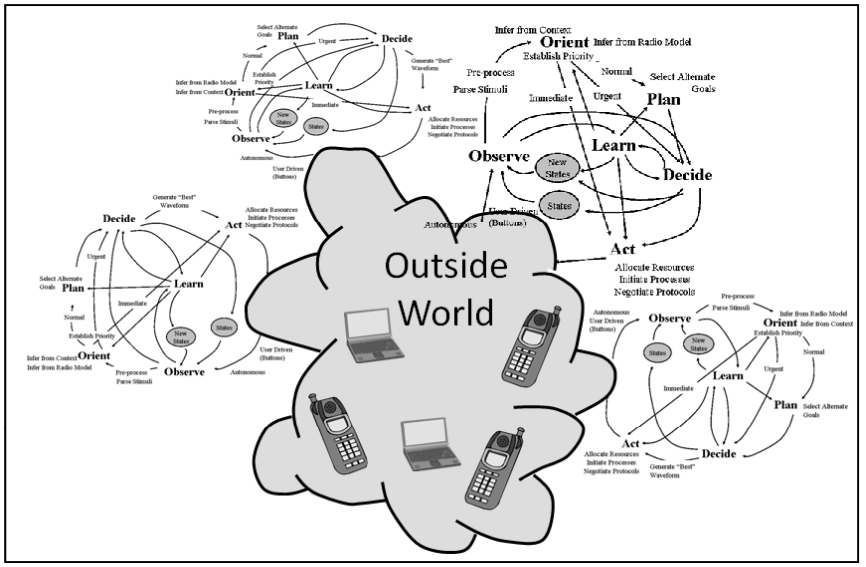
[Zhao_09]

[Kokar_06]

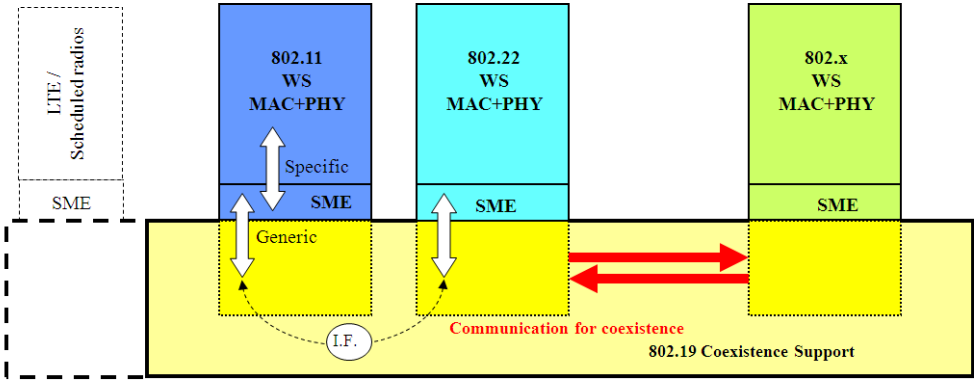
Language	Features	Reasoning	Complexity
XTM	Higher order relationships	None	$O(N)$
RDF	Binary Relationships	None	$O(N)$
RDFS	RDF plus subclass, subproperty, domain, and range	Subsumption	$O(N^m)$
OWL Lite	RDFS plus some class constructors; no crossing of metalevels	Limited form of description logic	$O(e^N)$
OWL-DL	All class constructors; no crossing of metalevels	General description logic	$<\infty$
OWL Full	No restrictions	Limited form of first order predicate logic	**unbounded**

Coexistence Issues

- Multiple co-deployed CRs interact in ways that SDRs did not
- Coexistence issues:
  - Self-coexistence
  - External coexistence
    - Spectrum sharing
    - Timing (sensing, decisions)
    - Share information
- Being examined for 802 TVWS in 802.19.1



[Neel_06]



[Kasslin_10]

Security Issues

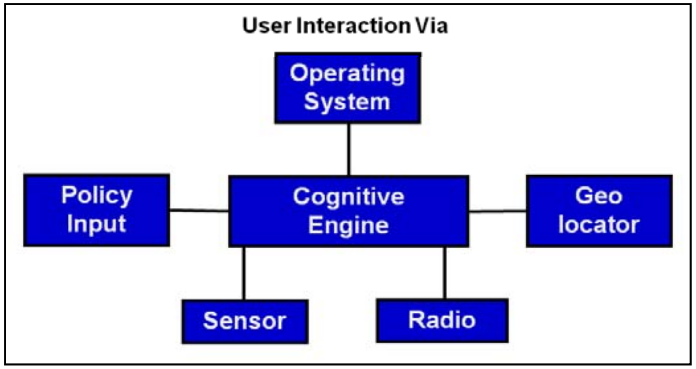
[Clancy_08]

- Primary user emulation attacks where characteristics of a primary user are spoofed to impact the behavior of secondary cognitive radios
- Belief manipulation attacks wherein the learning phases of CRs are subverted to train the systems to operate in undesirable states, e.g., by jamming the "correct" choices and leaving the "wrong" choices unmolested
- A "cognitive radio virus" wherein cooperative learning or shared software allows a single compromised radio to propagate problems across a network

- Spectrum sensing data falsification in the context of cooperative sensing of primary users [Chen_08a]
- Quiet period jamming [Bian_08] which reduces the ability of a secondary system to sense a primary system
- Replay sensing attacks [Bian_08]
- False coexistence information such as requesting excessive bandwidth or manipulating the beacon in 802.22 [Bian_08]
- Honeypot attacks that lead users to vulnerable states by selectively jamming good states [Newman_09]
- Chaff point attacks that mis-train signal classifiers [Newman_09]

Attacker …	Bea-con	Geo+ DB	Detect Sense
injects policies that prevent CR communication on specific primary channels.	■	■	
injects policies that deny CR communication on all primary channels.	■	■	
injects policies that allow CR communication on specific primary channels.	■	■	
injects policies that induce CR communication on all primary channels.	■	■	
emulates primary user on all primary channels.			■
emulates primary user on specific primary channels.			■
masks primary user on specific occupied primary channels.			■
blocks location information		■	
jams at spectrum handoff.	■	■	■
blocks access to networked sensor information.			■
blocks access to policies.	■	■	
induces receiver errors on specific licensed channel			■
induces receiver errors on multiple licensed channels.			■

[Brown_08]



Implementation / Coexistence References

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- [Kasslin_10] M. Kasslin, P. Ruuska, "Coexistence Architecture of 802.19.1," *IEEE 802.19-10/0013r0*, January 2010.
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Security References

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FCC Regs on White Space

From Appendix B: “Final Rules” FCC-08-260A, Nov 14, 2008

Device Glossary

(d) Fixed Device. A TVBD that transmits and/or receives radiocommunication signals at a specified fixed location. Fixed TVBDs may operate as part of a system, transmitting to one or more fixed TVBDs or to personal/portable TVBDs.

(l) Personal/portable Device. A TVBD that transmits and/or receives radiocommunication signals while in motion or at unspecified locations.

(f) Master Device. A TVBD operating in *Master Mode*.

(g) Master Mode. An operating mode in which the TVBD has the capability to transmit without receiving an enabling signal. The TVBD is able to select a channel itself and initiate a network by sending enabling signals to other devices. A network always has at least one device operating in master mode.

(b) Client Device. A TVBD operating in *Client Mode*.

(c) Client Mode. An operating mode in which the transmissions of the TVBD, including frequencies of operation, are under control of the *Master Device*. A device in client mode is not able to initiate a

(h) Mode I Operation. Operation of a personal/portable TVBD operating only on the *Available Channel* identified by either the fixed TVBD or Mode II TVBD that enables its operation. Mode I operation does not require use of a *Geo-location* capability or access to the *TV bands database* and requires operation in *Client Mode*.

(i) Mode II Operation. Operation of a personal/portable TVBD whereby the device determines the *Available Channels* at its location using its own *Geo-location* and *TV bands database* access capabilities. Devices operating in Mode II may function as *Master Devices*.

General Operation Information

- Available Channels By Class
  - 54-60 MHz FIXED <-> FIXED ONLY
  - 76-88 MHz FIXED <-> FIXED ONLY
  - 174-216 MHz FIXED <-> FIXED ONLY
  - 470-512 MHz FIXED <-> FIXED ONLY
  - 512-608 MHz ALL TVBD
  - 614-698 MHz ALL TVBD
  - Not within 20 km of border
  - Not 608-614 (adjacent to chan 37) in 13 metros (LMR conflict)
- Normal Operation
  - Fixed / Mode II Consult database + IA
  - Mode 1 As specified by Fixed / Mode II

Power Limits

- Fixed: < 1 W / channel
  - No more than 6 dBi effective directional gain
- Personal / Portable:
  - < 100 mW
- Sensing only:
  - “Devices authorized under this section must demonstrate with **an extremely high degree of confidence** that they will not cause harmful interference to incumbent radio services.”
  - Exact measurements undefined
  - 50 mW max power

Interference Avoidance Mechanisms

- Protected services: DRV, translator / booster stations, PLMR / CMRS, offshore radio telephone, cable head-ends, *Authorized* Mics (hard to tell what is authorized)

Geolocation Requirements

- General Requirements
  - +/- 50m accuracy
  - Portables re-establish location at each power-on
  - Fixed / Mode II must access database first ("over the Internet")
  - Recheck database each day
  - Mode I gets data from Master device

- Exclusion zones

Antenna Height of Unlicensed Device	Required Separation (km) From Digital or Analog TV (Full Service or Low Power) Protected Contour	
	Co-channel	Adjacent Channel
Less than 3 meters	6.0 km	0.1 km
3 – Less than 10 meters	8.0 km	0.1 km
10 – 30 meters	14.4 km	0.74 km

Type of station	Protected contour		
	Channel	Contour (dBu)	Propagation curve
Analog: Class A TV, LPTV, translator and booster	Low VHF (2-6)	47	F(50,50)
	High VHF (7-13)	56	F(50,50)
	UHF (14-69)	64	F(50,50)
Digital: Full service TV, Class A TV, LPTV, translator and booster	Low VHF (2-6)	28	F(50,90)
	High VHF (7-13)	36	F(50,90)
	UHF (14-51)	41	F(50,90)

  - Canada:
    - 32 km (all bands)
  - Mexico:
    - 40 km (UHF)
    - 60 km (VHF)
  - 2.4 km of specified radio telescope location

Sensing Requirements

- Sensing: (referenced to omni)
  - ATSC: -114 dBm (over 6 MHz)
  - NTSC – 114 dBm (over 6 MHz)
  - Mic: -114 dBm (200 kHz)
  - Initially verify clear for at least 30 s
  - Verify still clear every 60 s
  - Vacation time (post-detect): 2 s
  - Clients must inform masters of detected PUs

Other Regs

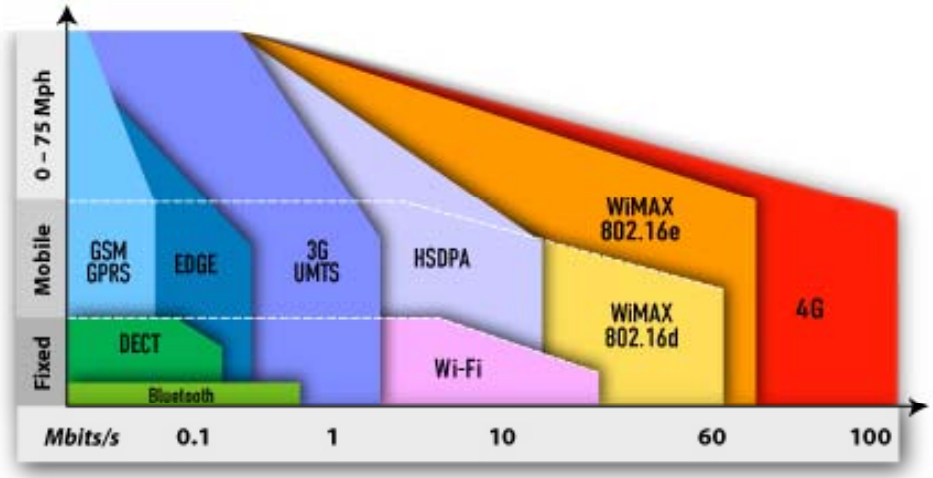
- Must use transmit power control to limit “operating power to the minimum necessary for successful communication”
- Fixed/Mode II devices must register with database and provide identifying and contact information
  - Fixed also transmit this info
- Antennas
  - Fixed
    - RX >= 10 m above ground
    - TX <= 30 m above ground
  - Personal / Portable
    - Antennas must be permanent

Summary

- Numerous emerging commercial CR standards to exploit TV White Space opportunities
- TV White Space is (continually) Near
  - PHY / MAC protocols in final drafts
  - 9 Geolocation Database Management Proposals submitted
  - Numerous prototypes
- Also driven by increasing complexity of wireless ecosystem and reducing management costs
  - Self-organizing networks
- Protocols build on one another
  - Initially just TPC, DFS (already deployed)
  - Now collaborative techniques, dynamic policy, shared databases…
  - Future will be increasingly sophisticated
- Supporting standards being developed (some done)
  - Information sharing, policy languages, architectural pieces, coexistence, media-independent handoffs, whitespace database
- Unsupported Speculation
  - Downbanded LTE and WiFi will eventually crush the other standards
  - Maybe a role for TVWS Zigbee
  - 802.16h / 802.22 in backhaul
  - Converge to databases for PU coexistence, sensing + other techniques for SU<-> SU coexistence

Presentation Overview

Emerging Standards



http://www.wisoa.net/members_logos/mobile_internet-big.jpg

CRT
Cognitive Radio Technologies

Wireless LANs

802.11

802.11 Alphabet Soup

Jun	1997	802.11	2 Mbps ISM
Sep	1999	802.11a	54 Mbps UNII
Sep	1999	802.11b	11 Mbps ISM
Oct	2001	802.11d	global roaming
Jun	2003	802.11f	interoperability
Jun	2003	802.11g	54 Mbps ISM
Oct	2003	802.11h	spectrum management
Jun	2004	802.11i	security
Oct	2004	802.11j	Japanese spectrum
Sep	2005	802.11e	real time QoS
May	2008	802.11k	RRM measurements
May	**2008**	**802.11r**	**fast roaming**
Nov	**2008**	**802.11y**	**US 3.65 GHz**
Sep	2009	802.11w	packet security
Sep	**2009**	**802.11n**	**100 Mbps**
Jun	**2010**	**802.11p**	**vehicular (5.9)**
Sep	2010	802.11u	external networks
Sep	2010	802.11v	network management
Sep	2010	802.11z	direct link setup
Jun	**2011**	**802.11s**	**mesh networks**
Oct	2011	802.11aa	video transport streams
Dec	**2012**	**802.11ac**	**very high throughput < 6GHz**
Dec	**2012**	**802.11ad**	**very high throughput 60GHz**
Dec	2012	802.11ae	mgmt packet prioritization
Dec	**2012**	**802.11af**	**WhiteFi**

Past dates are standards approval/publication dates.

Future dates from 802.11 working group timelines.

Letters are working group (WG) designations assigned alphabetically as groups created.

No WG/ WG document

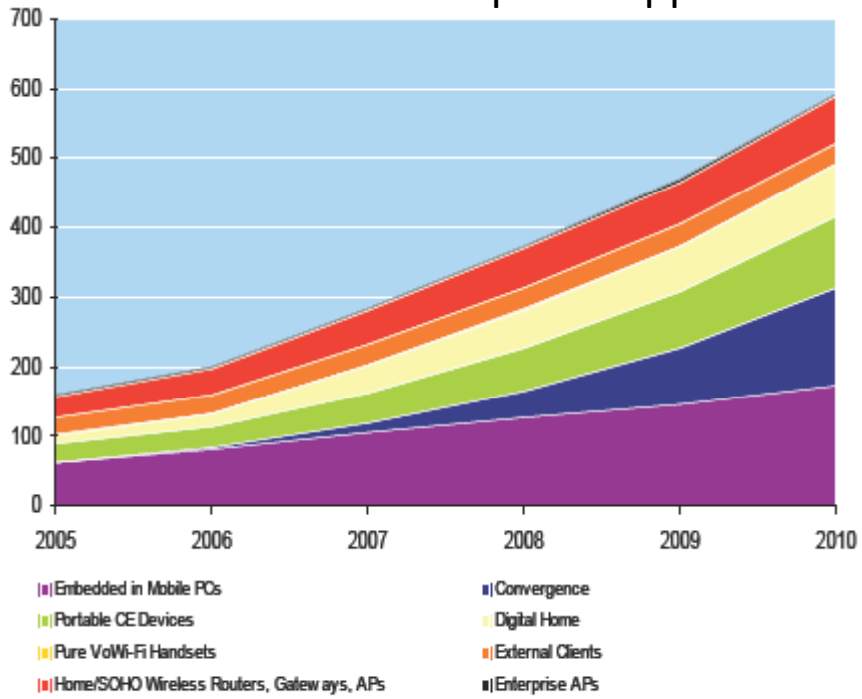
- 802.11c MAC Bridging
  - incorporated into 802.1d
- 802.11l “typologically unsound”
- 802.11m doc maintenance
- 802.11o “typologically unsound”
- 802.11q too close to 802.1q
- 802.11x generic 802.11 standard
- 802.11t (test) became 802.11.2

http://www.ieee802.org/11/Reports/802.11_Timelines.htm

WiFi Alliance

- Industrial consortium that promotes 802.11
  - www.wi-fi.org
- Certifies interoperability between vendors' products
- Certifies consistency with standards
- Fills in the gap when 802.11 standards process too slow (draft n)
- WiFi success owes significant debt to WiFi Alliance
- Line between 802.11 standards community and WiFi Alliance has gotten very blurry
- Certifications
  - 802.11a/b/g/n WiFi
  - 802.11e Wireless Multimedia
  - EAP (authentication)
  - (Optional) Wi-Fi Protected Setup
  - (Optional) Wi-Fi Multimedia
  - (Optional) WMM Power Save
  - (Optional / Mandatory) Wi-Fi in handsets

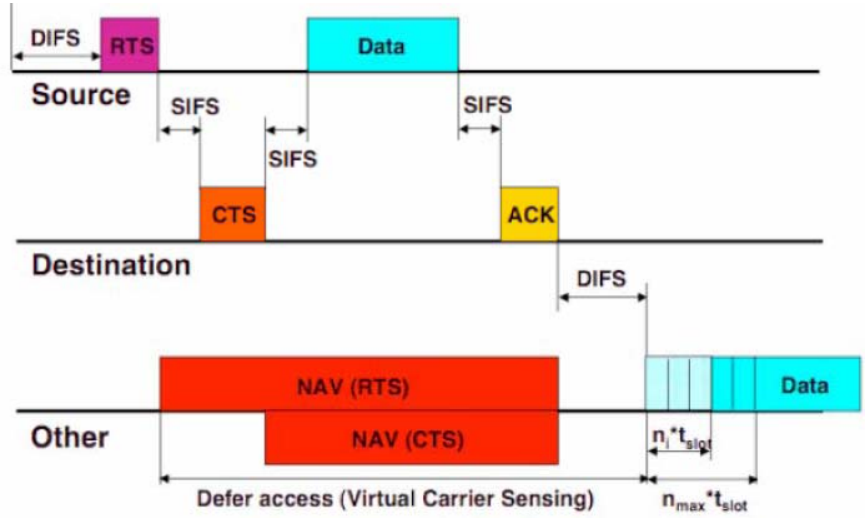
Millions of WiFi Chipset Shipped



Wi-Fi Alliance, Introducing Wi-Fi Protected Setup™, *January 3, 2007*

Distributed Coordination Function (DCF)

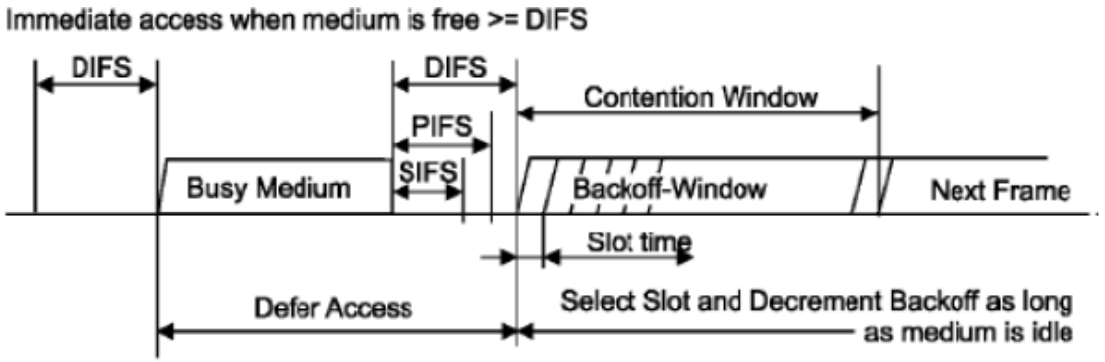
- Intended to combat “hidden nodes” in an uncoordinated network and generate fair access to channel
- Basic components:
  - After waiting DIFS after last detected transmission, source sends Request to Send (RTS)
  - Destination replies with Clear to Send (if OK)
  - Data is then transferred and ACKed
  - If an error occurs (e.g., collision), then station has to wait for DIFS + random backoff.
    - Random backoff grows with # of collisions

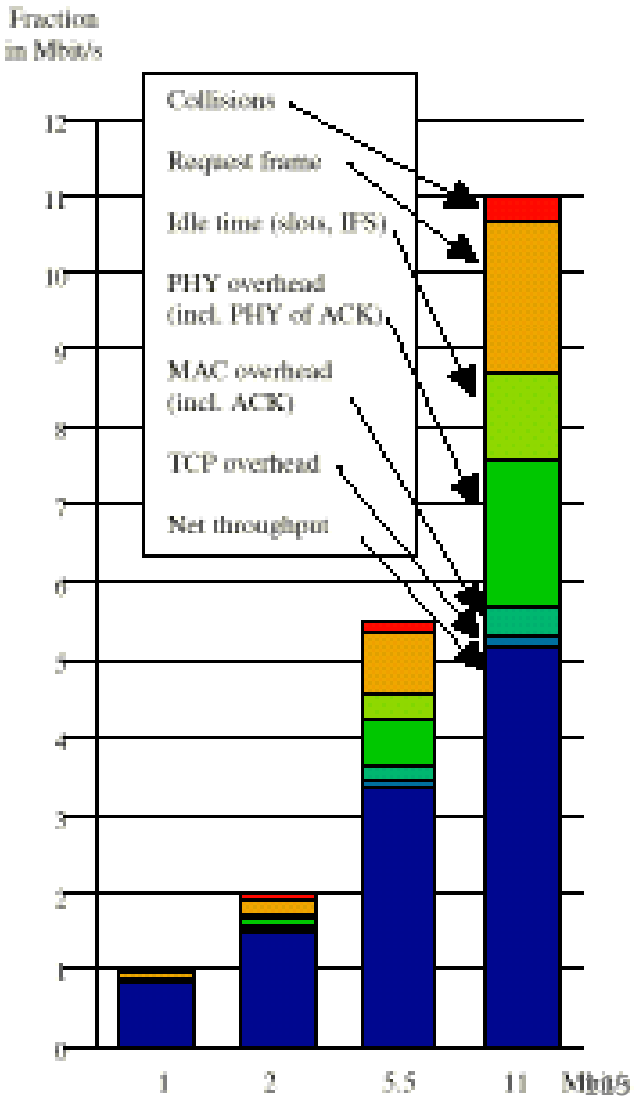


- Network allocation vector
  - Acts as virtual carrier sense
  - Duration given in RTS/CTS fields
- DIFS = DCF Interframe Space
- SIFS = Short Interframe Space

802.11 overhead

- Significant overhead involved in 802.11
  - RTS/CTS/ACK SIFS
  - TCP, IP, MAC framing
  - Real throughput is rarely come close to PHY raw rate



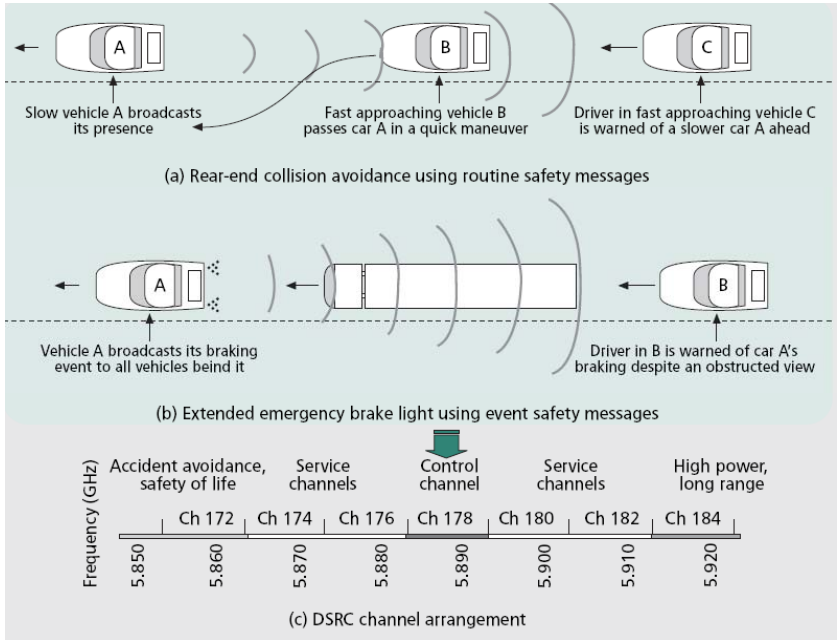


http://www.cs.tut.fi/kurssit/TLT-6556/Slides/Lecture4.pdf

wireless.ictp.trieste.it/school_2002/lectures/ermanno/**System_Performance.ppt**

802.11p Operation

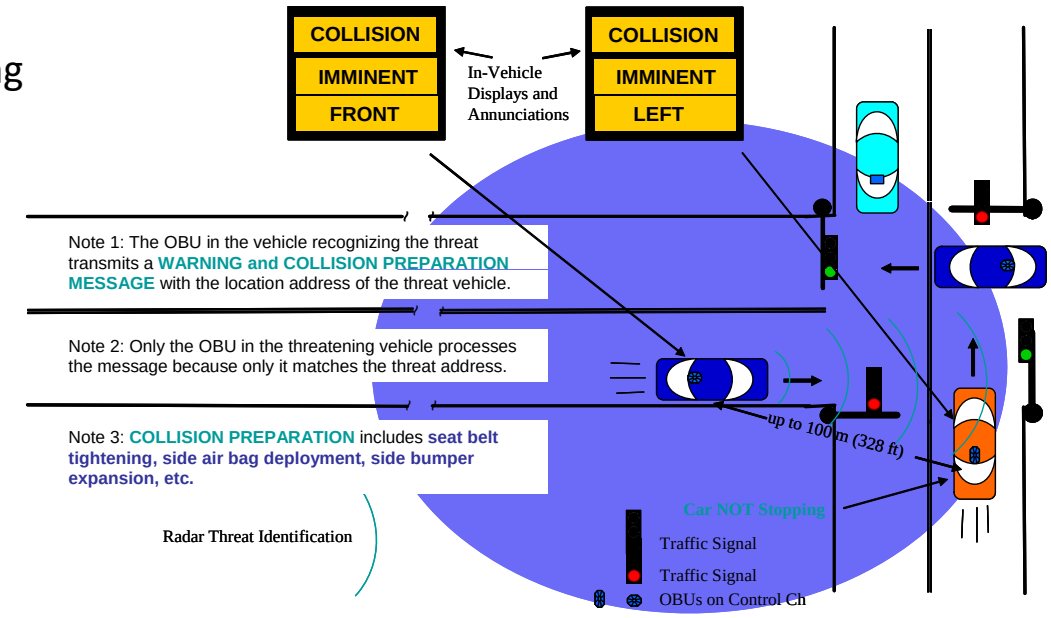
- "Dedicated Short Range Communications" (DSRC)
  - Started in IEEE 1609, spun into 802.11p
  - Aka (WAVE) Wireless Access for Vehicular Environment
- IEEE 802.11a adjusted for low overhead operations
  - 54 Mbps, <50 ms latency
  - 5.850 to 5.925GHz band
- Spectrum divided into 7 bands
  - 178 is control (safety)
  - 2 edge channels are reserved for future
  - The rest are service channels (not application specific)
- Mix of roadside-to-vehicle and vehicle-to-vehicle communications
- Questions on business model
  - http://www.rita.dot.gov/press_room/press_releases/index.html



D. Jiang, V. Taliwal, A. Meier, W. Holfelder, R. Herrtwich, "Design of 5.9 ghz dsrc-based vehicular safety communication," IEEE Wireless Comm, Oct 06, pp. 36-43

802.11p Applications

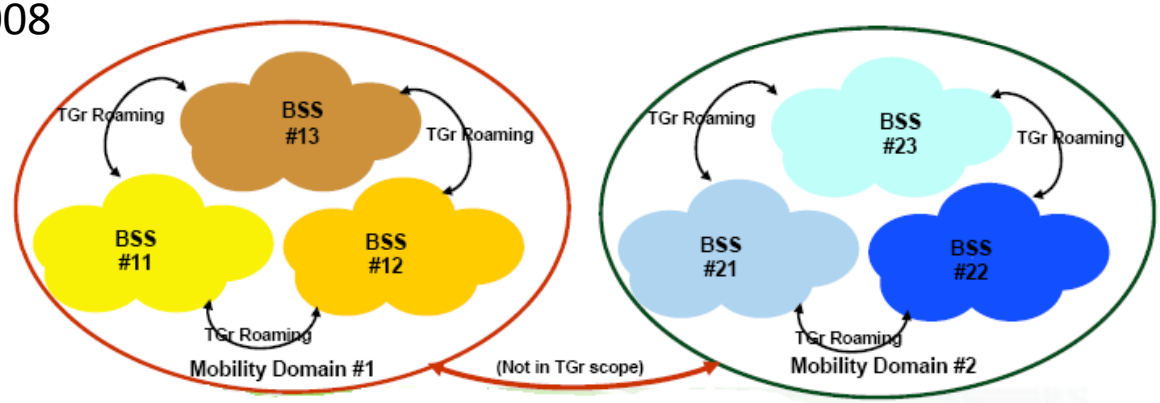
- Emergency warning system for vehicles
- Cooperative Adaptive Cruise Control
- Cooperative Forward Collision Warning
- Intersection collision avoidance
- Approaching emergency vehicle warning (Blue Waves)
- Vehicle safety inspection
- Transit or emergency vehicle signal priority
- Electronic parking payments
- Commercial vehicle clearance and safety inspections
- In-vehicle signing
- Rollover warning
- Probe data collection
- Highway-rail intersection warning



From: IEEE 802.11- 04/ 0121r0, Available: http://www.npstc.org/meetings/Cash%20WAVE%20Information%20for%205.9%20GHz%20061404.pdf

802.11r overview

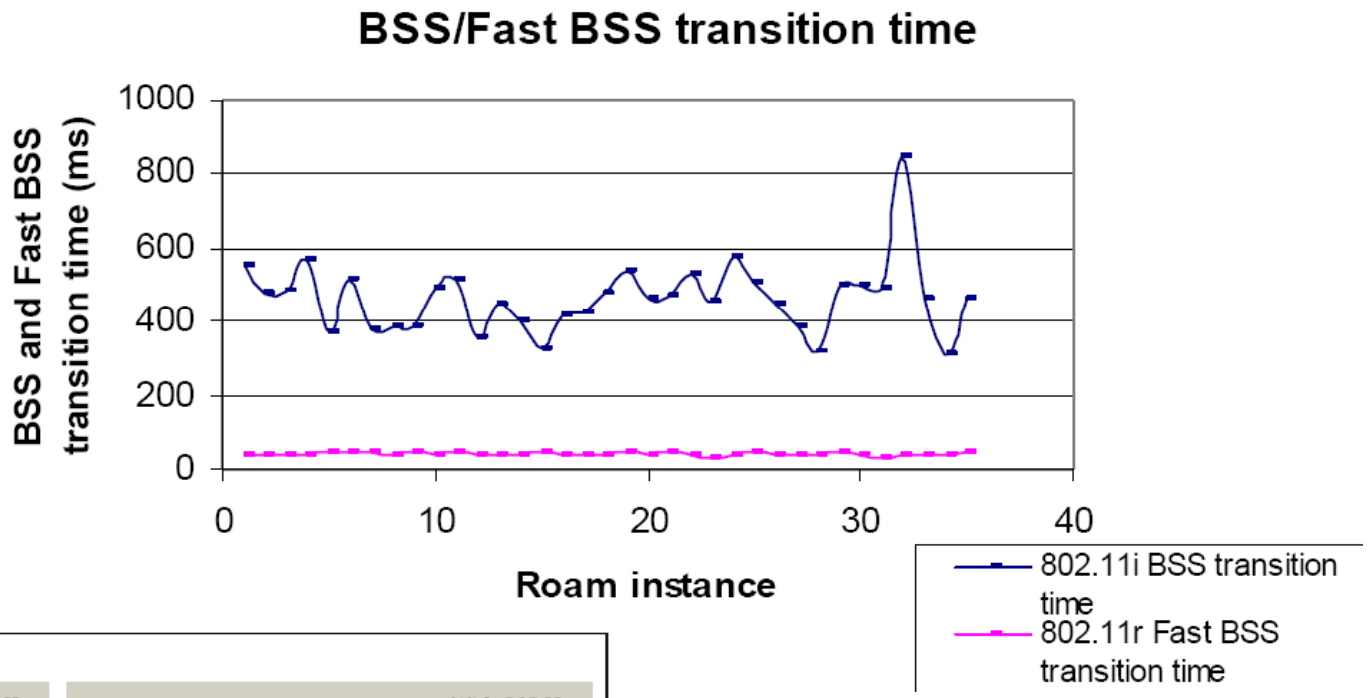
- Fast BSS Roaming/Transition within IEEE WLAN networks
  - Preserve security with handovers <50ms
- Fast BSS Roaming is possible only within a certain area called the mobility domain (MD), inter-MD cases are not covered
  - Mobility Domain (MD): Set of BSS grouped together with the same 48bit MD Identifier
  - FT functionality seeks to provide handover performance for RT services
- Key Issues
  - Resource Reservations
  - Security
- Collapsed 5 step process down to 3
  - Scanning – active or passive for other APs in the area
  - Authentication with a (one or more) target AP
  - Re-association to establish connection at target AP
- Released 2008

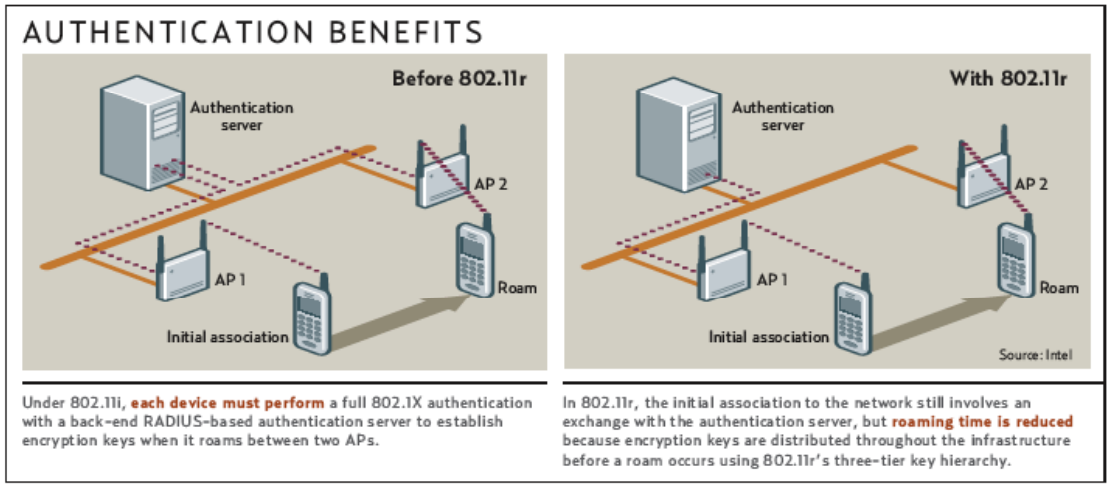


http://www.cs.tut.fi/kurssit/TLT-6556/Slides/Lecture4.pdf

802.11r - Reduction in Roaming Time

S. Bangolae, C. Bell, E.Qi, "Performance study of fast BSS transition using IEEE 802.11r," International Conference On Communications And Mobile Computing, 2006

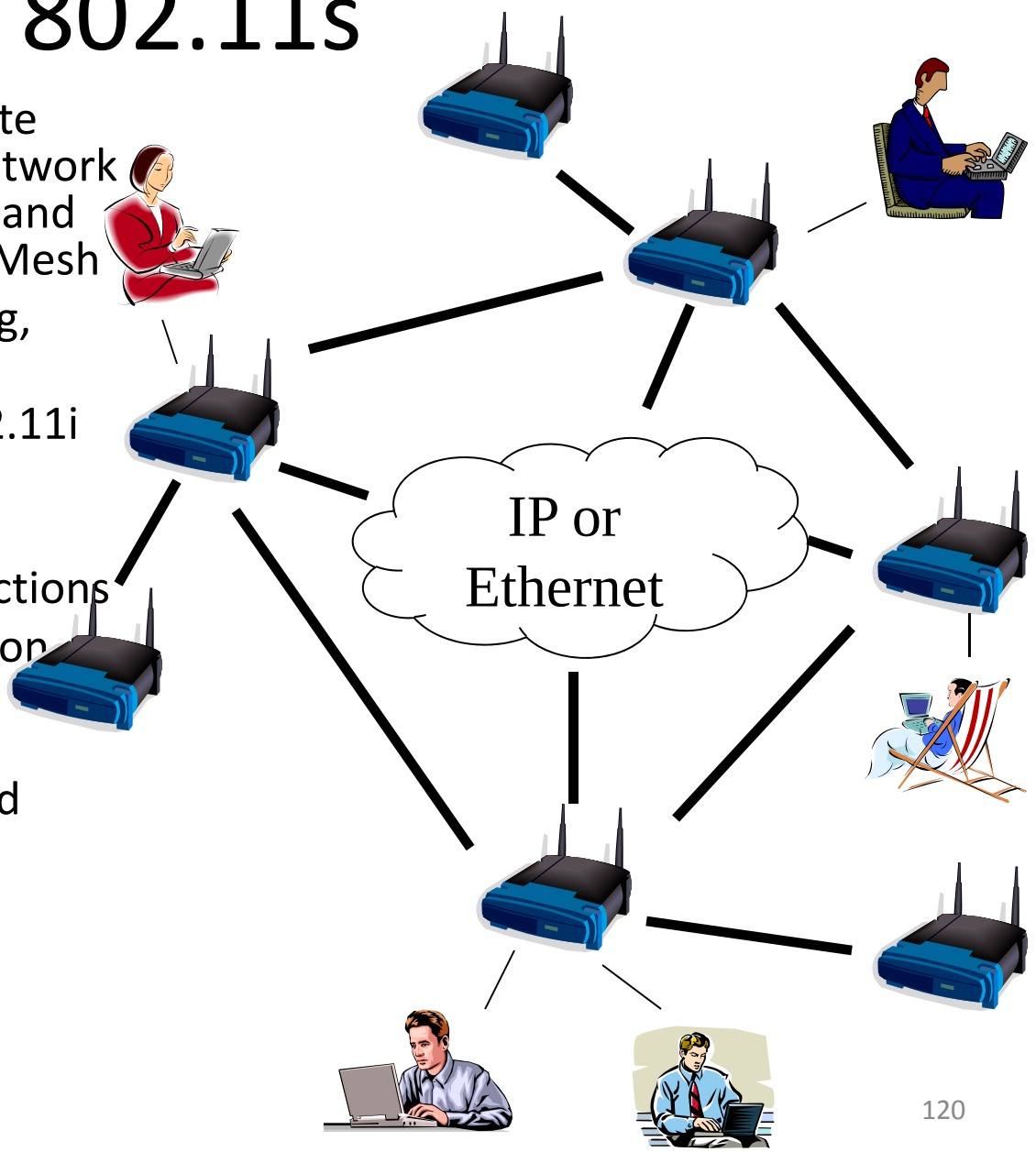




http://www.networkcomputing.com/gallery/2007/0416/0416ttb.jhtml;jsessionid=0CK4ZKR20HC5QQSNDLPCKHSCJUNN2JVN

802.11s

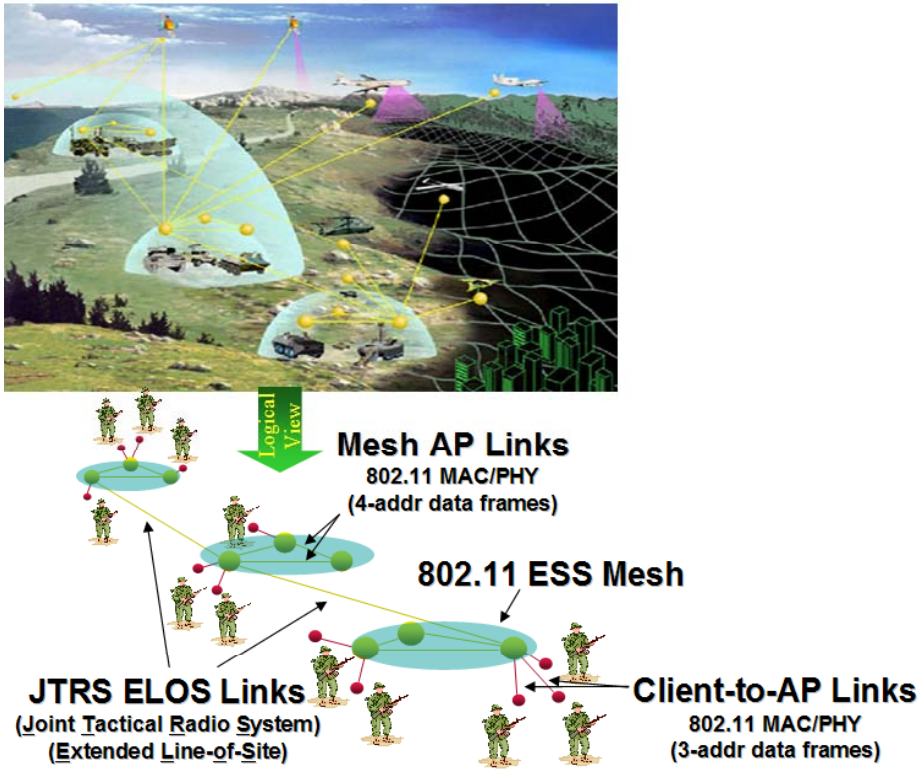
- Modify 802.11 MAC to create dynamic self-configuring network of access points (AP) called and Extended Service Set (ESS) Mesh
- Automatic topology learning, dynamic path selection
- Single administrator for 802.11i (authentication)
- Support up to 32 AP
- Support higher layer connections
- Allow alternate path selection metrics
- Extend network merely by introducing access point and configuring SSID



http://standards.ieee.org/board/nes/projects/802-11s.pdf

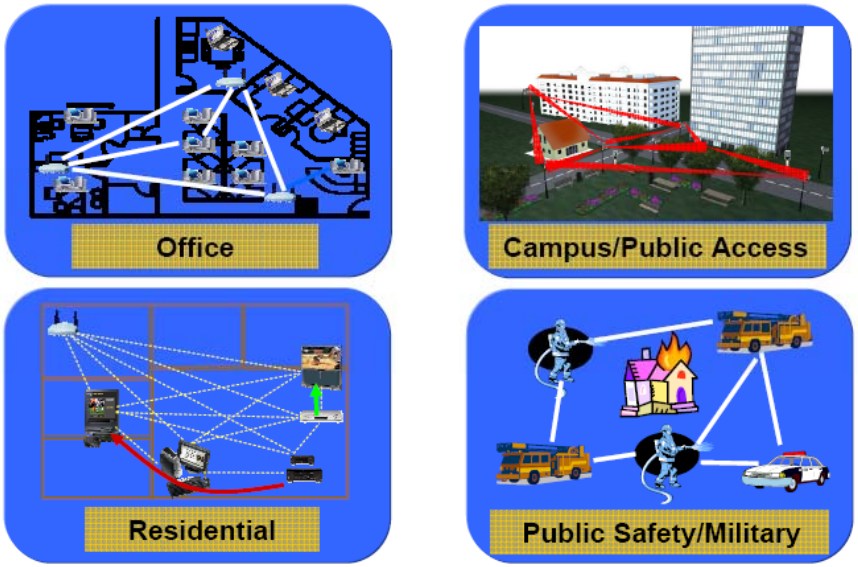
802.11s

- Key Technologies
  - Topology Formation
  - Internetworking
  - Routing
  - Security



- Open 802.11s (Linux)
  - http://www.open80211s.org/
- Numerous WiFi mesh products
  - http://www.cs.wustl.edu/~jain/cse574-06/ftp/j_jmesh/sld019.htm

Deployment Scenarios

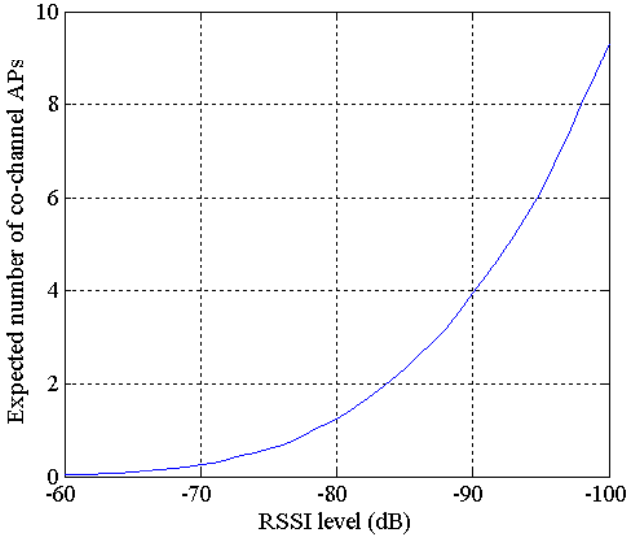


J. Hauser, D. Shyy, M. Green, MCTSSA 802.11s Military Usage Case

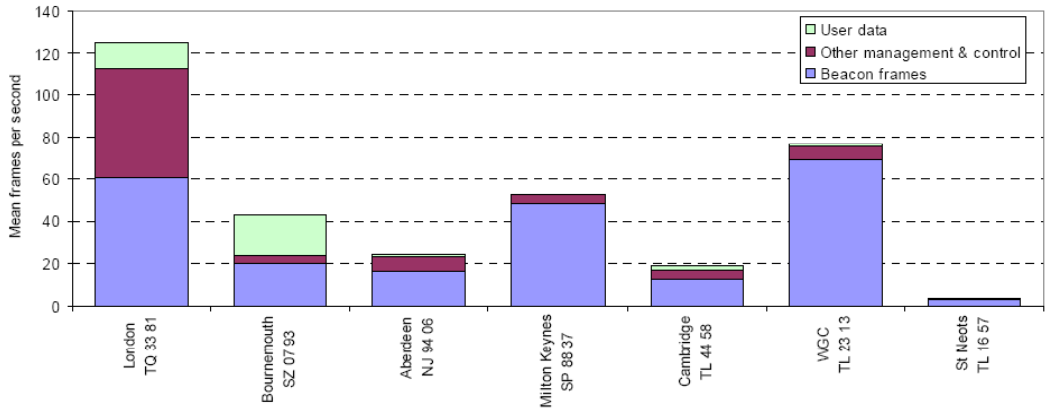
http://ieee802.org/802_tutorials/nov06/802.11s_Tutorial_r5.pdf

Too much 2.4 GHz Interference

- WiFi is very popular -> Very crowded spectrum
- Ofcom sponsored study (http://www.ofcom.org.uk/research/technology/research/exempt/wifi/wfiutilisation.pdf)
  - Generally more interference from other impolite devices
  - Cities have more congestion
  - 802.11a Cisco study (802.11-08/1440r0)
  - Expect AP-AP collisions in urban deployments



802.11-08/1440r



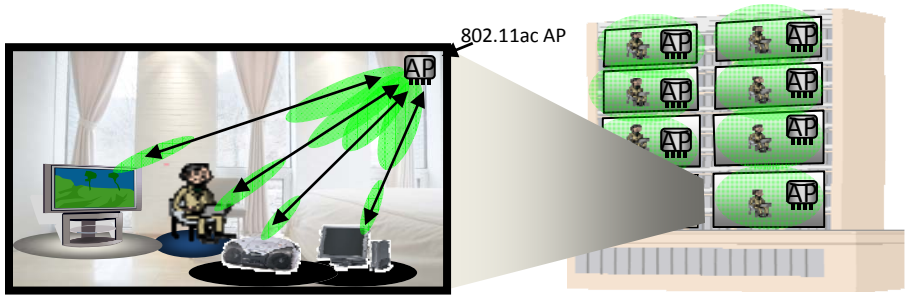
Mass Consulting Ltd., "Estimating the Utilisation of Key Licence-Exempt Spectrum Bands," April 2009. Available online: http://www.ofcom.org.uk/research/technology/research/exempt/wifi/wfiutilisation.pdf

802.11aa

- Expectation of interference means degradation of performance
  - Potentially quite bad for video, voice over WiFi
- 802.11aa PAR Goals (doc.: IEEE 802.11-07/1972r14):
  - “Graceful degradation of audio video streams when there is insufficient channel capacity, by enabling packet discarding without any requirement for deep packet inspection,
  - Increased robustness in overlapping BSS environments, without the requirement for a centralised management entity,
  - Intra-Access Category prioritization of transport streams by modifying EDCA timing and parameter selection without any requirement for deep packet inspection,
  - Improved link reliability and low jitter characteristics for multicast/broadcast audio video streams,
  - Interworking with relevant 802.1AVB mechanisms” (Audio / Video Bridging)
- 802.11-08/0764r1
  - “There are many ways in which audio video data is streamed over IP networks
  - Some methods lend themselves to selective packet discarding, some do not
  - Probably the best pragmatic approach is some simple signalling per UDP packet and let the application decide when it can provide discard hints.”
- 802.11-08/0818r0
  - Managed contention access
  - Modify framing / coordination function to reduce contention
- Considering
  - broadcast / multicast
  - Distributed network management
  - Extending 802.11s mechanisms

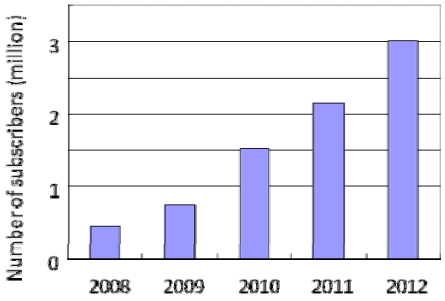
802.11ac

- Very High throughput < 6 GHz
- Target Application:
  - Streaming IPTV (and video in general)
  - VoIP, smart phones
- Requirements (IEEE 802.11-08/1285r):
  - 15 bps/Hz
  - 500 Mbps / 40 MHz – single link
  - 1 Gbps / 40 MHz – multi-station
- Key tech appears to be Spatial Division Multiple Access
  - And **A LOT** of antennas



802.11-09/0630r1

3 million IPTV subscribers in Japan in 3 years



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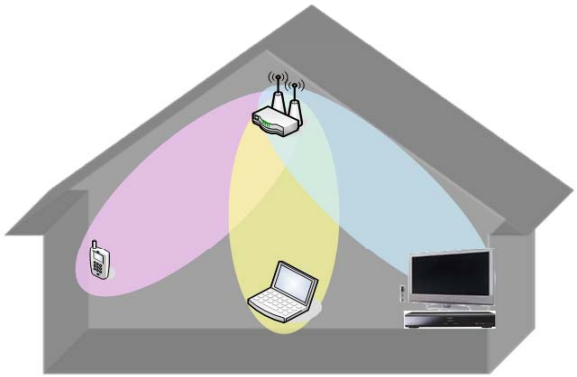
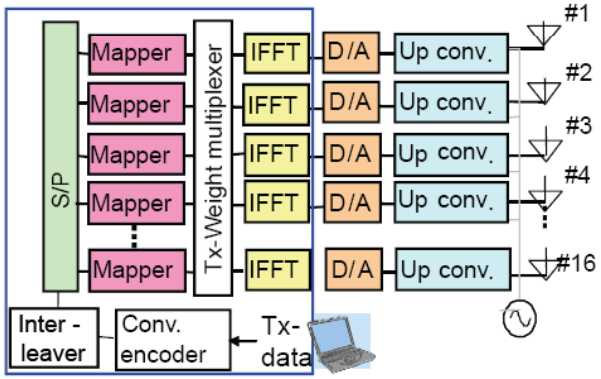
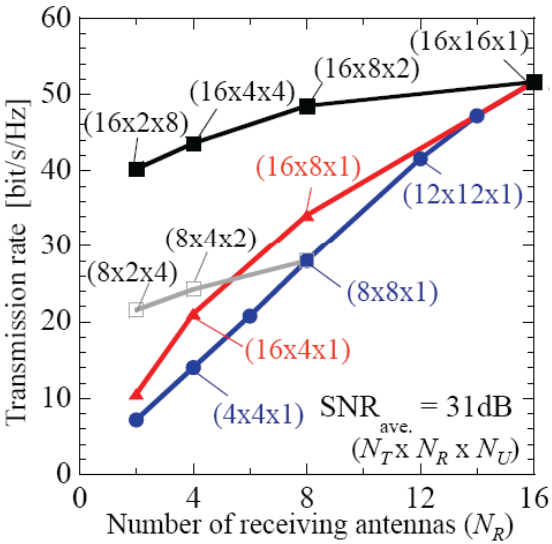


802.11-09-0532-00-00ac

Up to 42.8 bps/Hz with 16 antennas



802.11-09/0303r1



802.11-09/0303r1

Move To 60 GHz Unlicensed

- 2001, FCC designated 57-64 GHz as unlicensed
  - Similar around the globe
  - Avoid the interference

More bandwidth => More throughput

	Channel Bandwidth	Effective Transmit Power	Max possible data rate
UWB	520 MHz	0.4 mW	80 Mbps
802.11n	40 MHz	160 mW	1,100 Mbps
60 GHz	2,500 MHz	8,000 mW	25,000 Mbps

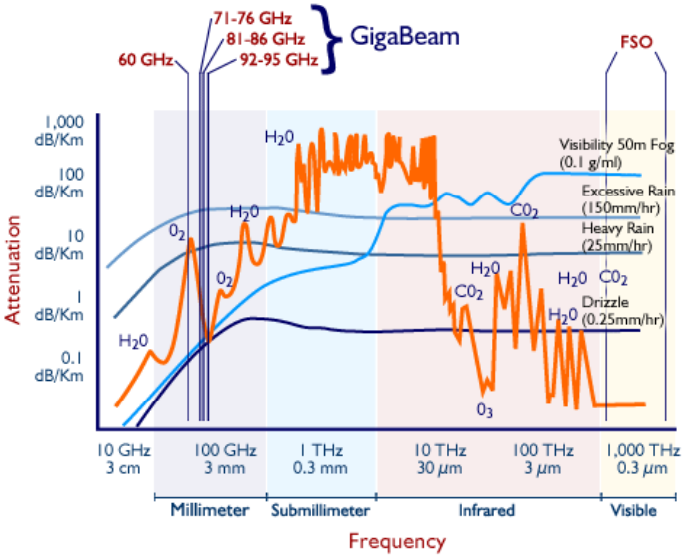
http://www.gigabeam.com/technology.cfm

More antenna gain (same size)

Frequency	99.9% Beam Width
2.4 GHz	117 degrees
24 GHz	12 degrees
60 GHz	4.7 degrees

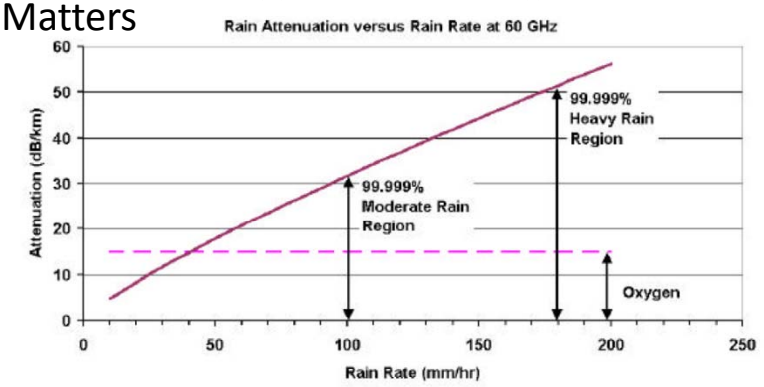
Shorter Propagation

Strong O2 Absorption



http://www.gigabeam.com/technology.cfm

Rain Matters



http://wireless.fcc.gov/outreach/2004broadbandforum/comments/YDI_benefits60GHz.pdf

802.11ad

- Requirements
  - IEEE 802.11-08/1285r0
  - > 1 Gbps @ 10 m
  - Seamless handoffs between 2.4/5 GHz and 60 GHz
    - 3 Gbps ~ uncompressed 1080p
- Known Issues
  - Coexistence with 802.15.3c (60 GHz version)

Req number	Parameter	Value	Description
Req04	Rate	3 Gbps	Uncompressed video, 1080p (RGB): 1920x1080 pixels, 24bits/pixels,60frames/s
Req05	Packet loss rate (8Kbyte payload)	1e-8	
Req06	Delay	2 ms	

- "Done"
  - Published draft at wigig.org with adopter program
  - Alliance of all major players
  - Used as common draft in 802
    - https://mentor.ieee.org/802.11/dcn/10/11-10-0432-02-00ad-cp-presentation.ppt
    - https://mentor.ieee.org/802.11/dcn/10/11-10-0433-02-00ad-cp-specification.docx
    - Sept/10 session, approve creation of D1.0 and go into WG letter ballot
  - http://wirelessgigabitalliance.org/news/wigig-alliance-publishes-multi-gigabit-wireless-specification-and-launches-adopter-program/
  - Probably ends Amimon
  - SiBeam to do WiGig
    - http://www.eetasia.com/ART_8800606508_499488_NT_da2689da.HTM

Major 802.11ad Amendments

Item	This complete proposal	Subclause of 802.11-10/433r2
Network architecture	Infra-BSS, IBSS, PBSS	5.2
Scheduled access	Scheduled Service Periods	9.23.6
Contention access	EDCA tuned for directional access	9.2
Dynamic allocation of resources	(Re-)allocation of channel time with support to P2P and directionality	9.23.7, 9.23.8, 9.23.9
Power save	Non-AP STA and PCP power save	11.2.3
Security mechanism	GCMP	8
Measurements	Amendments to 802.11k to support directionality	11.33
PHY	SC and OFDM, with common preamble	21
Beamforming	Unified and flexible beamforming scheme	9.25
Fast session transfer	Multi-band operation across 2.4GHz, 5GHz and 60GHz	11.34
Coexistence	Provides coexistence with other 60GHz systems	11.35

IEEE 802.11-10/0432r2

Also uses LDPC as main error correction.

Others in the Market

- WHDI (Amimon) – variant of 802.11
  - 3Gbps (including uncompressed 1080p) in a 40MHz @ 5 GHz
  - http://www.whdi.org/Technology/
- WirelessHD (SiBeam)
  - 4 Gbps @ 60 GHz (4 channels)
  - OFDM + beamforming + (a bunch of 802.11-like services)
  - Spec: http://www.wirelesshd.org/pdfs/WirelessHD_Full_Overview_071009.pdf
- WiGig
  - Website: http://wirelessgigabitalliance.org/
  - Big players
    - Atheros, Dell, LG, Samsung, Microsoft, Nokia, Panasonic
  - Spec out end of 2010
    - http://www.multichannel.com/article/277089-Wireless_HD_Delivery_Race_Heats_Up.php

Technology	Est. Max. Speed	Operating Frequency	Max. Resolution	Est. Range (feet)
802.11n	540 Mbps	2.4 or 5 GHz	1080p (compressed)	300
UWB/Tzero	480 Mbps	3.1 to 10.6 GHz	1080p (compressed)	30
WirelessHD	3 Gbps	3.1 to 4.8 GHz	1080p	25
WHDI	3 Gbps	5 GHz	1080p	100
WiHD	4 Gbps	60 GHz	1080p	32

http://www.hometheatermag.com/hookmeup/607hook/

WiFi on the Plane

- Idle hands are a good source of revenue
  - 12-15% of customers pay for it on a plane
  - $7.95 smart phone,
  - $9.95 normal, < 3 hrs
  - $12.95 normal > 3 hrs
  - http://www.broadbandreports.com/shownews/1215-Use-InFlight-WiFi-102611
- Boeing / Connexion
  - Satellite based connection to plane
  - Launched in 2004, shut down in 2006 – citing no market
  - Still provides services to US Gov planes
    - http://www.boeing.com/news/releases/2007/q3/070814a_nr.html
  - 800 lbs, 2 weeks to install, $1,000,000 / plane
- Row44
  - Satellite based (leased from Hughes)
  - Planned for use by Southwest, Alaska, Norwegian Shuttle
  - 2 nights to install (use in day), 150 pounds
  - http://www.row44.com/

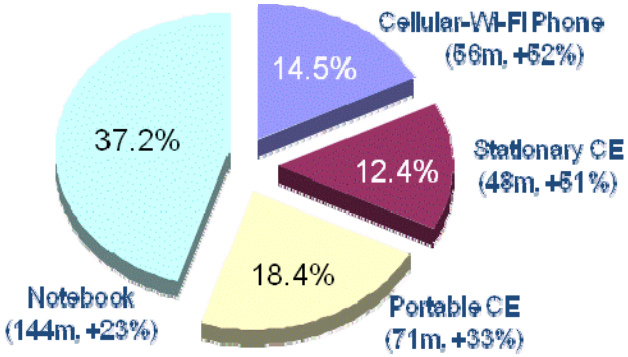
Aircell Coverage Area

http://www.aircell.com/index.php?option=com_content&task=view&id=312&Itemid=1

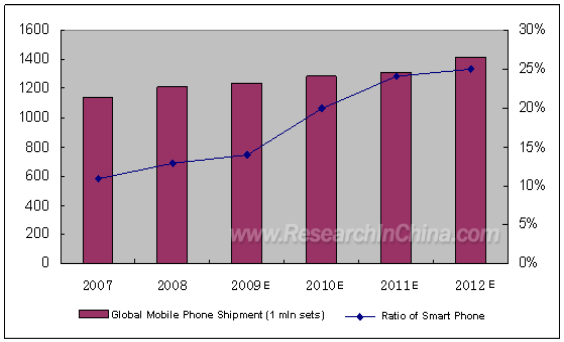
- Aircell (GoGo)
  - EVDO-based ground network
  - 1,000 planes by end of 2009
    - Delta, AirTrans. NorthWest, United, American, Air Canada,
    - Virgin (28)
  - $100,000 / plane, 1 day turnaround

WiFi on Smart Phones

- Statistics
  - 802.11-09-0453r00ac
  - 2008 - 56 M (~44%)
  - 2011- 300M
  - 2014 – 520M (90%)



WiFi chip shipments of 2008



http://ipod.about.com/od/iphoneinterfacegallery/ig/iPhone-Gallery--Settings/iPhone-WiFi-Settings.htm

- Cellular Providers Establishing WiFi Relationships for free service
  - AT&T + Qwest (May 09)
    - http://blogs.wsj.com/digits/2009/05/06/qwest-unveils-wi-fi-deal-with-att/
  - AT&T buys WayPort (Nov 08)
    - http://online.wsj.com/article/SB122598801123705301.html
  - Verizon with Boingo
    - http://wifinetnews.com/archives/2009/05/verizon_broadband_subscribers_get_free_wi-fi.html
  - T-Mobile
    - https://content.hotspot.t-mobile.com/AssetProcess.asp?asset=com.default.main.001
  - Sprint-Nextel – no longer odd man out
    - http://www1.sprintpcs.com/explore/ueContent.jsp?scTopic=pcsWiFiAccessFromSprint

WiFi in … Bluetooth?

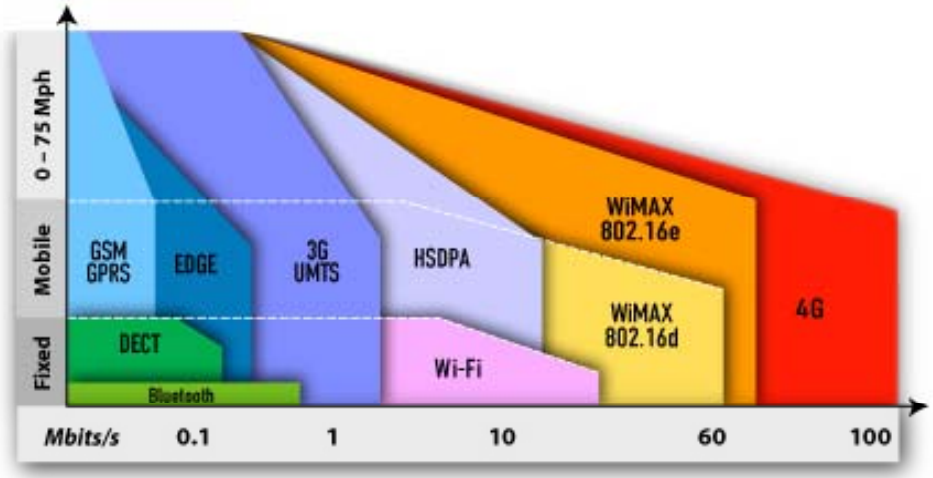
- Bluetooth 3.0 Highspeed is 802.11n
  - http://www.wi-fiplanet.com/news/article.php/3816556
- Some Bluetooth advocates say that this is no concession as WiFi is not just 802.11

WLAN Summary

- VERY Popular
- 802.11n slow to finalize standard
  - WiFi Alliance certifying to Draft 2.0
  - Looks to be finally completed
- Most activities directed towards expanding markets
  - Better support for voice
  - Vehicular networks
  - Other spectrum opportunities
    - 802.11j, 802.11h (later)
  - Mesh networks (802.11s)
  - Interoperability with cellular (later)
- Significant overhead in baseline
- Significant interference and congestion in 2.4 GHz band
- Showing up in lots of other devices
  - Bluetooth 3.0, Cell phones, cameras (even memory sticks!)
- Personally expect WiFi to win White Spaces too

Presentation Overview

Emerging Standards



http://www.wisoa.net/members_logos/mobile_internet-big.jpg

CRT
Cognitive Radio Technologies

Wireless Personal Area Networks

Industry and Open Standards

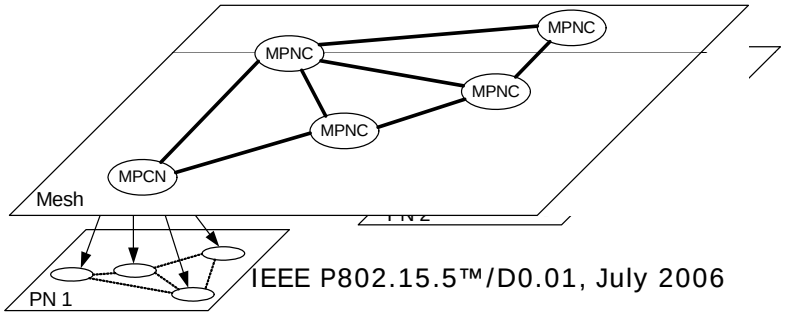
802.15 Standards

802.15.1	April 2002	Bluetooth/WPAN
802.15.2	Oct 2003	Coexistence
802.15.3	Jun 2003	High data rate
~~802.15.3a~~		~~UWB (high rate)~~
802.15.3b		Doc Maintenance
802.15.3c	May 2008	mm-wave PHY
802.15.4	May 2003	zigbee (PHY/MAC)
802.15.4a	March 2007	UWB (low rate)
802.15.4b	Sep 2006	Updates 802.15.4 document
802.15.4c	Jan 2009	Chinese WPAN PHY
802.15.4d	Mar 2009	950 MHz in Japan
802.15.4e		MAC for 802.15.4c
TG4e		WPAN Enhancements
TG4f	2010 ?	RFID
TG4g	PAR Approved	Smart Utility Neighborhood
TG5	March 2009	WPAN Mesh
TG6		Body Area Networks
TG7		Visible Light Communication
SGpsc		Personal Space Comm
Sgmban		Medical body area network
Iglecim		Low Energy Critical Infrastructure
IGThz		Terahertz interest group (300 GHz+)
WNG		Wireless Next Generation

- Proprietary / Industry
  - Zigbee (on 802.15.4)
    - Zigbee Pro
  - Bluetooth (originally)
  - WiBree
  - WiMedia
  - Z-Wave
  - En-Ocean
  - Insteon
  - Keer
  - TransferJet

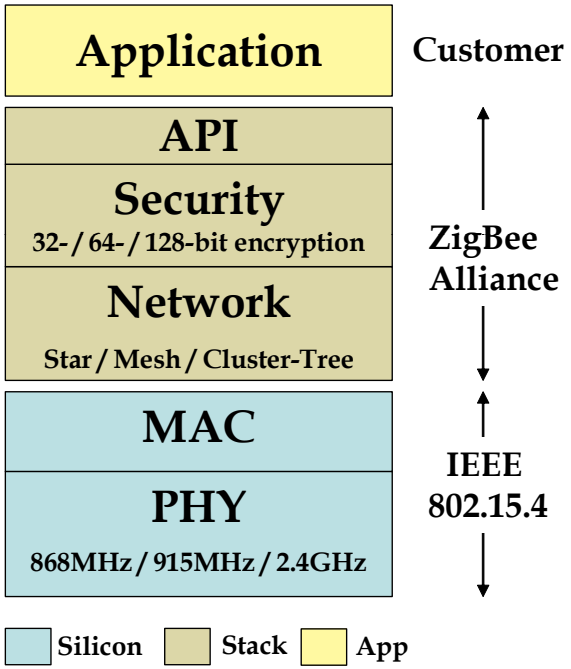
Emerging 802.15 Standards

- 802.15.4c (China)
  - –779-787 MHz band
  - –Two PHY Modulations: MPSK PHY and O-QPSK
  - –Considering OFDM, beamforming
- 802.15.4d (Japan)
- 802.15.5e
  - –Enhanced MAC for Industrial applications
  - –Modified MAC for 802.15.4c changes
- 802.15.5
  - –Mesh networking
- Terahertz study group
  - –300 GHz -> 3 THz
  - –http://www.ieee802.org/15/pub/IGthz.html
- TG6 – Body Area Networks
  - –http://www.ieee802.org/15/pub/TG6.html
  - –Just starting
- Visible Light Interest Group
  - –http://www.ieee802.org/15/pub/IGvlc.html



ZigBee

Standard
http://www.zigbee.org/en/spec_download/download_request.asp



Source: http://www.zigbee.org/en/resources/

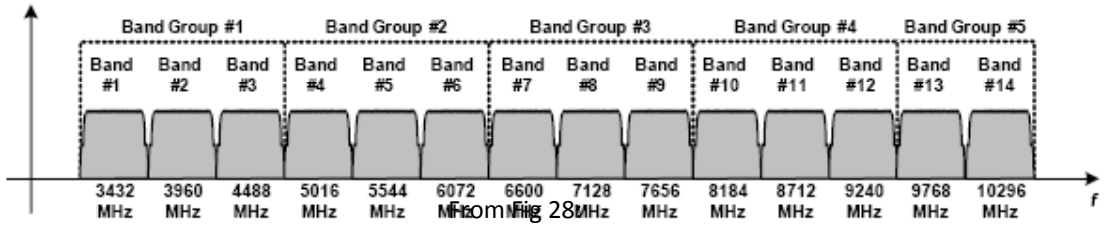
- Open source implementations
- Open-ZB
  - http://www.open-zb.net/
- Meshnetics Open-MAC
  - http://www.meshnetics.com/opensource/mac/

ZigBee Alliance

  - the software
  - Network, Security & Application layers
  - Brand management
- IEEE 802.15.4
  - "the hardware"
  - Physical & Media Access Control layers
- PHY
  - 868MHz/915MHz, 2.4 GHz
  - Band specific modulations
  - 20-250 kbps
- MAC
  - CSMA-CA channel access
  - Support for ad-hoc networks
- Zigbee Pro (Industrial grade)
  - Network Scalability
  - Fragmentation
  - Frequency Agility
  - Automated Device Address Management
  - Group Addressing
  - Centralized Data Collection
  - Wireless Commissioning

WiMedia

- Industry alliance from MBOA 802.15.3a
- Standardized for US in Dec 2005 in ECMA-368 and 369
  - http://www.ecma-international.org/publications/standards/Ecma-368.htm
  - ECMA used specifically to avoid 802 standardization problems
- PHY
  - Multiband OFDM QPSK
  - 53.3, 80, 106.7, 160, 200, 320, 400, 480 Mbps nominal data rates
  - Range of 10 m indoor
  - Data can be interleaved across 3 bands, 7 defined patterns (channels)
  - Mandatory support for band group 1
- MAC
  - Peer to Peer, Ad-hoc
  - AES 128
  - Support for Dynamic Chann
  - Ranging via propagation de
  - Bluetooth-like information discovery

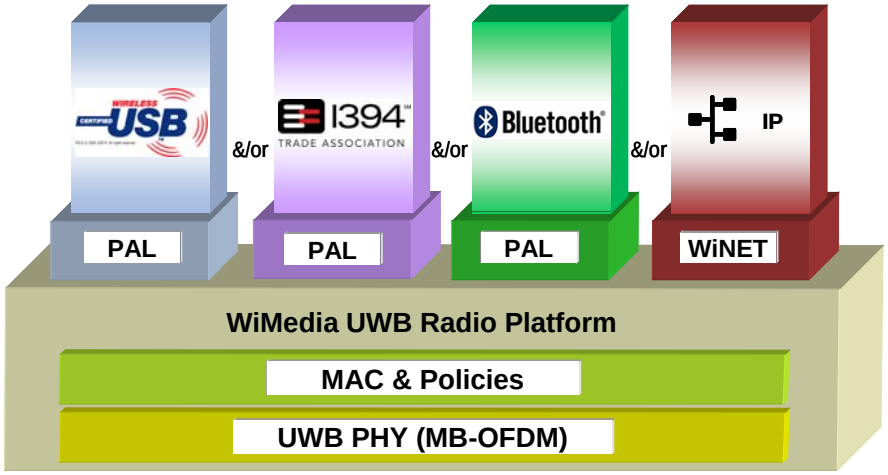


From Fig 28

WiMedia Implementations

- Primarily marketed as cable replacement
- Wireless USB out in Dec 2006
  - –Hub-spoke model
  - –Mandatory support for band group 1
  - –Mandatory rates of 53.3, 106.7, 200 Mbps
  - –Initial Belkin device didn't live up to the hype
    - Data rate of 6.35 Mbits/s
    - Reportedly not to WiMedia spec
    - http://www.eetimes.com/news/latest/showArticle.jhtml?articleID=196602148
    - Now certified
      - –http://www.wimedia.org/imwp/idms/popups/pop_download.asp?contentID=11961

From: http://www.wimedia.org/en/events/documents/02WiMedia_Overview_CES2006.ppt



PAL: Protocol Adaptation Layer

- Bluetooth 3.0 devices in 2008
  - – http://gizmodo.com/gadgets/wireless/nextgen-bluetooth-30-on-the-way-179684.php
- Wireless Firewire and IP also supported over WiMedia standard

- Status
  - Will merge with Bluetooth SIG this year (2009) as ultra low power Bluetooth.
  - Nokia sponsored initiative announced Oct 2006
  - Specification work is currently being evaluated, targeted for availability second quarter 2007
- Public data: (from wibree.com (no more) and http://www.theregister.co.uk/2006/10/06/wibree_analysis/)
  - 2.4 GHz ISM band
  - Range 10 meters
  - 1 Mbps data rate
  - Targets low power/low cost market
  - From http://www.computerworld.com.au/index.php/id;992123146;fp;4;fpid;18
    - Up to 8 devices Master/Slave
    - Turns off frequency hopping
    - Expects different technology to serve as backbone between masters
    - Expects to share resources with full Bluetooth
- Many reports mentioned WiBree as a competitor to Bluetooth
  - Brought into Bluetooth fold as low power alternative
  - "Bluetooth Low Energy"
  - https://www.bluetooth.org/About/bluetooth_sig.htm#Bluetooth%20Wireless%20Technology
  - Now a competitor to Zigbee

Z-Wave

- Originally Zensys proprietary
  - http://www.zen-sys.com/
- Industry standard “Z-wave”
  - http://www.z-wave.com
- Low power alternative to Zigbee
- PHY
  - 9.6 kbps or 40 kbps
  - GFSK
  - 100 ft range
- 900 MHz ISM
- http://www.z-wavealliance.com/
- http://en.wikipedia.org/wiki/Z-Wave

Z-Wave Alliance

http://www.z-wave.com/modules/AboutZ-Wave/?id=21&chk=4ed024468cb3d7f9095aa54227ea197a

DASH7

- Standards
  -ISO 18000-7
- DASH7 Alliance
  - http://www.dash7.org/
  - Previously a military technique.
- PHY
  - 27.77 kbps up to 250 kbps
  - Up to 2 km
- 433 MHz ISM, global available.
- Multi-year battery life.
- http://wapedia.mobi/en/DASH7
- http://en.wikipedia.org/wiki/DASH7

Comparison with Zigbee

http://www.dash7.org/index.php?option=com_content&view=article&id=11&Itemid=13

Near Field Communication

- Standards
  -ISO/IEC 14443
- NFC Forum
  - http://www.nfc-forum.org/
  - Consumer electronics.
- PHY
  - 424 kBd
  - ASK
  - p2p
- 13.56 MHz
- http://en.wikipedia.org/wiki/Near_Field_Communication
- http://wiki.forum.nokia.com/index.php/NFC

More 60 GHz Standards

- Standards
  -ISO/IEC 13156
  - High rate 60 GHz PHY, MAC and HDMI PAL
- Industry standard
  - ECMA387 by EUWB
  - Dec. 2008.
- PHY
  - Type A (SCBT/OFDM)/Type B/Type C devices.
  - DBPSK/DQPSK,UEP-QPSK/OOK,4ASK
  - 1.008 Gbps-4.032 Gbps/3.175 Gbps/3.2 Gbps
  - 56-77 GHz band
- http://www.ecma-international.org/publications/standards/Ecma-387.htm

Other Proprietary Standards

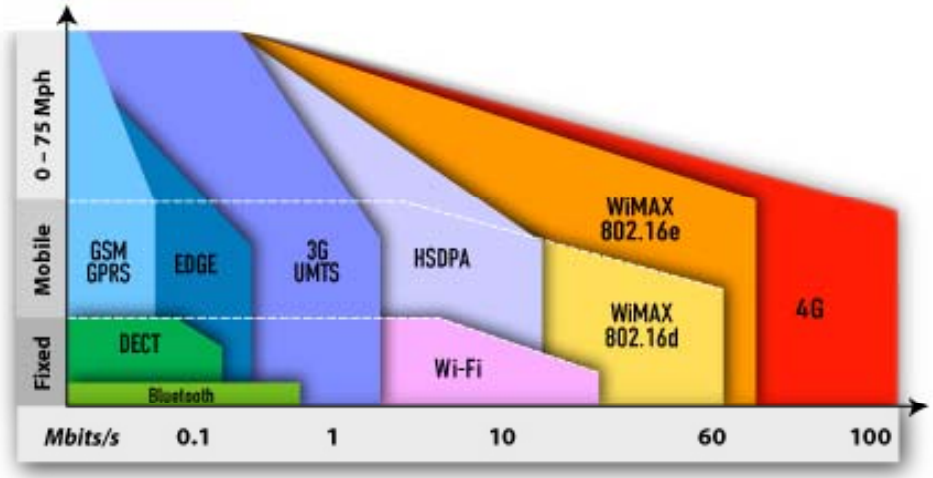
- TransferJet (Sony)
  - –Features
    - http://www.sony.net/SonyInfo/News/Press/200801/08-002E/index.html
    - Electric induction field coupling
    - 3 cm range
    - 4.48 GHz center frequency
    - 560 Mbps (Max) 375 Mbps (effective)
      - – Adaptive modulation
    - "Touch & Get: transfer by touching devices together
    - Some registration security
  - –Demonstrated shortly after announced
    - http://www.engadget.com/2008/01/06/video-sonys-transferjet-gets-demonstrated/
- Kleer
  - – http://www.kleer.com
  - – Proprietary low power RF for audio / video
- En-Ocean
  - – http://www.enocean.com/en/
  - – Best known as energy scavengers
  - – Runs a proprietary wireless mesh protocol
- Insteon
  - – Mixes power line comm with RF comm
  - – Industry Alliance (15 manufacturers)
    - http://www.insteon.net/alliance-about.html
    - Wireless Valley is a member
  - – Open source http://www.efundies.com/

WPAN Summary

- Greater reliance on industry standards than other classes of waveforms
  - Seems to work more smoothly
  - Bluetooth, WiMedia, Z-wave, ECMA387
- Bifurcation into low power devices (e.g., Zigbee, Wibree) and high-throughput devices
- Impulse UWB as a WPAN appears dead
- Heavy emphasis on mesh networks
- Possible trend to mix protocols at different mesh levels
- Cooperation between Zigbee Alliance and Demand Response and Smart Grid (DRSG) coalition.
- Niche markets a good thing for this class

Presentation Overview

Emerging Standards



http://www.wisoa.net/members_logos/mobile_internet-big.jpg

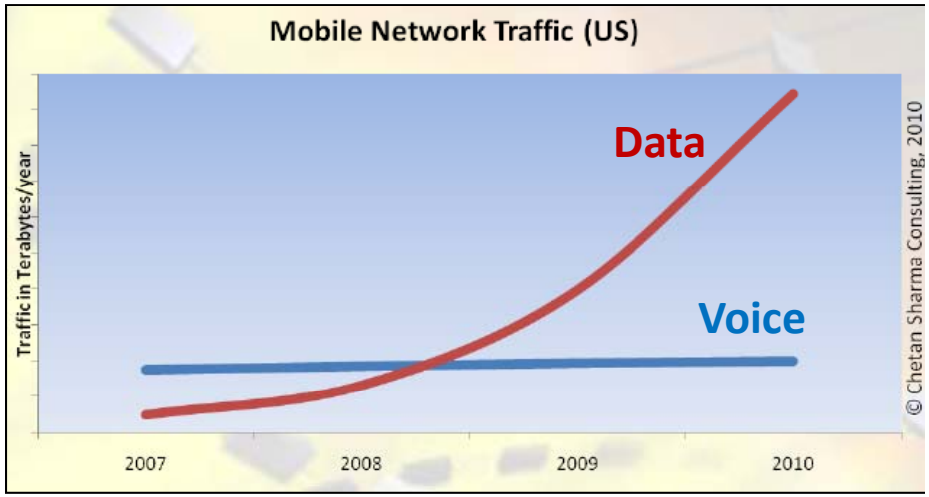
CRT
Cognitive Radio Technologies

Conclusions and Future Trends

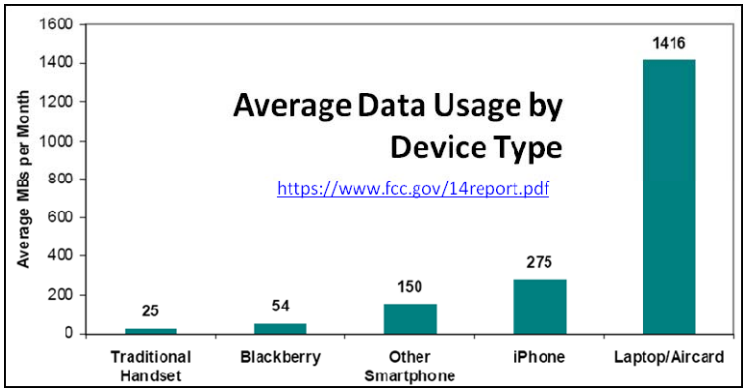
Major changes underway in cellular market

- Apps > Network
  - Skype, Kindle, Smart Grid
  - Changing the way we use the network
    - More indoors
    - Landlines? We don't need no stinking landlines
- Expect Android to win, Symbian and RIM to lose, and Apple to make A LOT of money
  - Microsoft already lost
- Data usage is exploding but revenues are flat
- Business models changing
  - It's 5:00. Do you know what your service plan is?
  - Expect to see more creative deployment plans

iPhone versus the Android Army

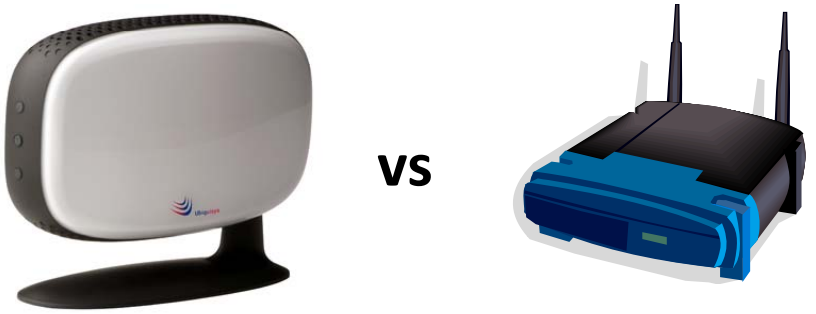


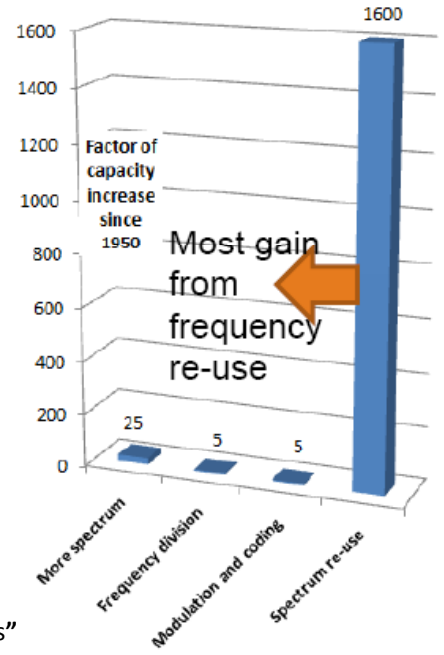
http://www.chetansharma.com/usmarketupdateq12010.htm



Need for Capacity and Spectrum is Pushing Development

- Smaller cells will happen
  - Femto, WiFi, or WiGiG?
- Higher frequencies
  - 60 GHz (802.15.3c, WiGiG)
  - Terahertz
  - Trades a capacity problem for a coverage problem which creates an access problem
- Both smaller and higher
  - Optical LED
    - Laser comm logical limit to capacity?

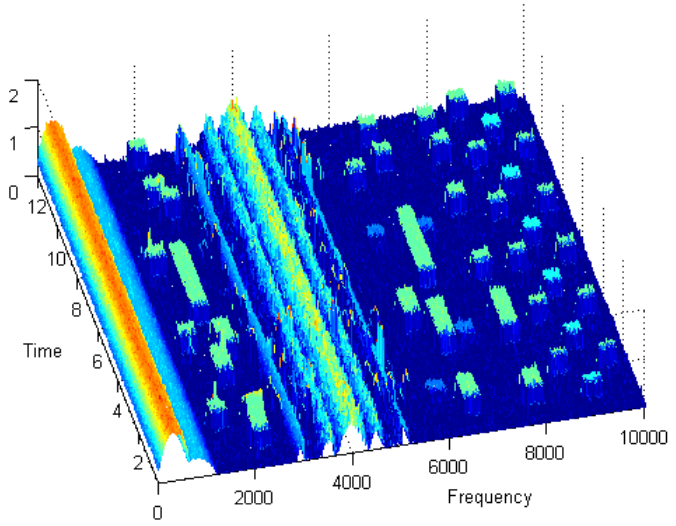




Rupert **Baines, "The Best** That LTE Can Be**:** Why LTE Needs Femtocells**"**

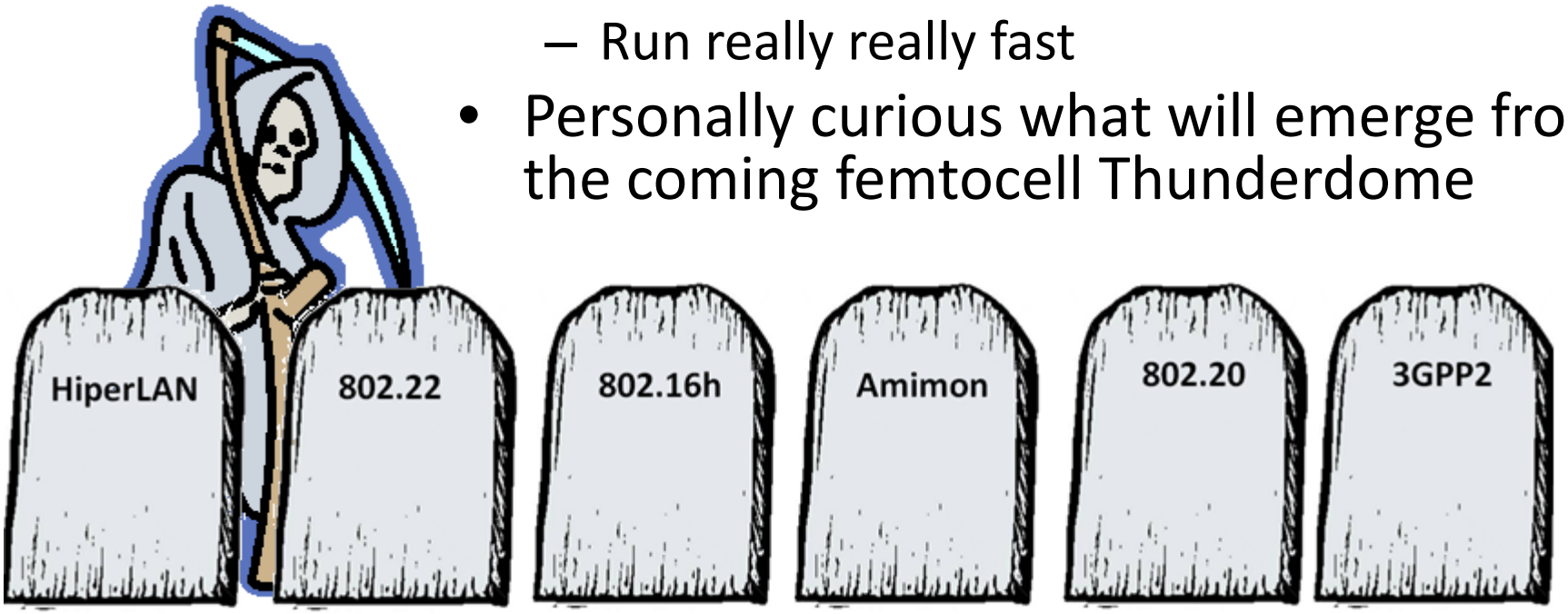
CR is everywhere and nowhere

- TVWS / DSA
  - Regulatory hangups have been bad
  - Not certain any of the current standards will endure
    - Other than 802.11af
  - LTE and WiFi will enter and end it
- Elsewhere
  - Femtocells, SON, 802.16m, LTE-Advanced
  - Increasing presence in cellular to reuse own spectrum
- Applications become “just software” or “adaptive”
  - Implicitly questionable current value of learning…
  - May change
- Depends on what your definition of “is” is



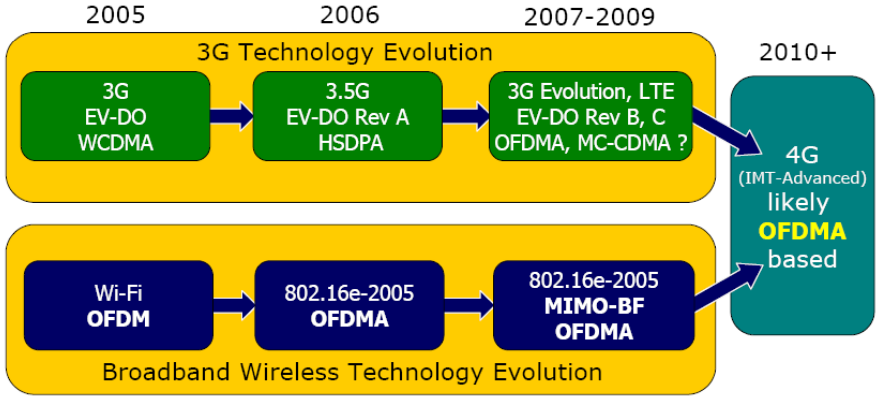
The WiFi and 3GPP Massacre

- If your business model requires widescale coverage and is not using 3GPP or WiFi, you should rethink it.
  - Ok for niche markets – see WPANs
  - Rule even applies to China.
- One theoretical escape clause
  - Run really really fast
- Personally curious what will emerge from the coming femtocell Thunderdome



Breeding Successful Technologies

- Mobile WiMAX similar to LTE
  - Transition of technologies can significantly extend useful lifetime of deployments
    - Enhanced EDGE
    - WCDMA + MIMO may steal LTE's market
  - 802.11n predates mobile WiMAX
- 802.22 techniques opening up legacy spectrum for other standards
  - White Space Coalition
  - 802.16m
- Other convergences
  - Flat, IP-core network
  - Support for heterogeneous nets
  - Apps on
- Standards can expect to continue to evolve even post-deployment
  - Need for SDR
- Is LDPC next breakout technique?
  - 802.11ad, an option in many standards



Source: http://www.wimaxforum.org/technology/downloads/ WiMAX_and_ IMT_2000.pdf

Major Technology Trends and Drivers

- Femtocells
  - Greater capacity + frequency reuse + movement indoors
- Cognitive radio
  - Reuse spectrum + better interference management
  - Access more spectrum
- Self-organizing networks
  - Lower cost + CR reasons + femtocells
- mm-Wave standards
  - Expensive spectrum + greater capacity + frequency reuse

Useful Websites (News, Promotional, Forums, Standards)

WLAN
- www.wi-fi.org
- www.wi-fiplanet.com/
- http://grouper.ieee.org/groups/802/11/

802.15
- www.bluetooth.com
- https://www.bluetooth.org/
- www.wimedia.org
- http://www.zigbee.org/en/
- http://www.uwbforum.org/
- www.wibree.org
- http://www.multibandofdm.org/
- http://grouper.ieee.org/groups/802/15/

802.16
- www.wimaxforum.org
- http://wimaxxed.com
- http://wimax.com
- http://grouper.ieee.org/groups/802/16/

3GPP Family
- www.gsmworld.com
- www.umtsworld.com
- www.gsacom.com
- www.3gpp.org
- http://www.tdscdma-forum.org/

3GPP2 Family
- www.cdg.org
- www.3gpp2.org

802.20
- http://grouper.ieee.org/groups/802/20/

802.21
- http://www.ieee802.org/21/
- www.umatechnology.org

802.22
- http://grouper.ieee.org/groups/802/22/

E^2R "Requirements and scenario definition," Available online: http://e2r.motlabs.com/Deliverables/E2R_WP4_D4.1_040725.pdf

Take Aways (1/2)

- High data rate systems migrating to OFDM + Antenna Array Processing PHY
  - OFDM – WiMedia, 802.11a,g, 802.16, 802.20, 802.22, UMB, LTE
  - OFDM + MIMO – 802.11n, 802.16e, 802.20, UMB, LTE
- More responsive/adaptive resource management (early cognitive radio)
  - Multiple QoS levels – 802.11e; 802.16e; 802.20; UMB, LTE, EVDO,
  - Dynamic channel selection – WiMedia; 802.11h,y; 802.16h; 802.22
  - Distributed sensing – 802.22
- Coexistence given increasing interest
  - Vertical handoffs – 802.21, 802.11u
  - Legacy systems – 802.22, 802.11h,y, 802.16h
- New bands opening up for old techs
  - 802.15.4d, 802.11j,p,y

Take-Always (2/2)

- Some spectral harmonization
  - 5 GHz for WiMAX
- China less of a push for own standards
  - 802.15.4c, TD-SCDMA, TD-SOFDMA
- Emergence of Advanced Networking
  - 802.11s, 802.15.5, 802.16j
- Increasing # of technologies
  - Legacy systems not quickly fading and large # of new ones
- Convergence on AES for security
  - 802.11i, WiMedia, Mobile WiMAX
- Convergence on all IP Backbone
  - Mobile WiMAX, UMB, LTE
- Importance of apps, smart phones and handling massive amounts of data