ECS 455 Chapter 1

Introduction & Review

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Tuesday	**13:30-14:30**
Thursday	**13:30-14:30**

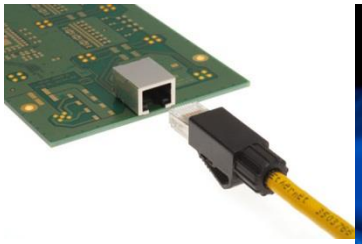
ECS 455 Chapter 1

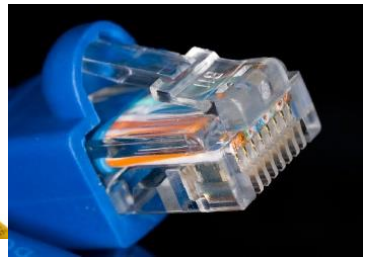
Introduction & Review

1.1 Mobile Communications

Wired Communication

- Cup-and-string communication





- POTS, Ethernet

Wireless communication

You have three unread messages…

Wireless communication

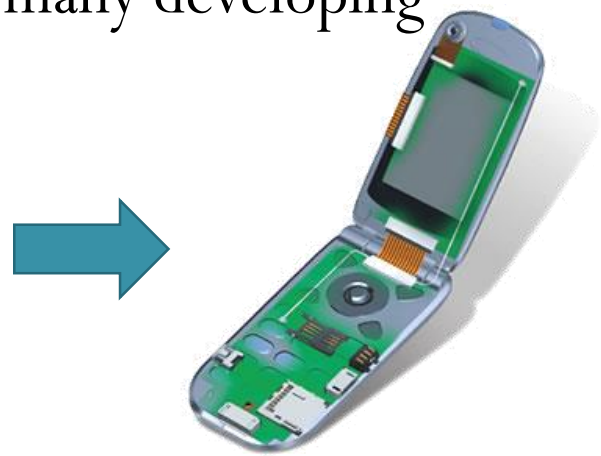
- Duncan Wilson's Cup Communicator

- Cellular Systems: 1G, 2G, 2.5G, 3G, 4G

- Wireless LAN Systems: WiFi (802.11a/b/g/n/ac)

Overview of Mobile Communications

- Wireless/mobile communications is the **fastest growing** segment of the communications industry.
- Cellular systems have experienced **exponential growth** over the last decade.
- Cellular phones have become a critical business tool and part of everyday life in most developed countries, and are rapidly replacing wireline (landline) systems in many developing countries.



Mobile?

- The term "mobile" has historically been used to classify all radio terminal that could be moved during operation.
- More recently,
  - use "**mobile**" to describe a radio terminal that is attached to a high speed mobile platform
    - e.g., a cellular telephone in a fast moving vehicle

  - use "**portable**" to describes a radio terminal that can be hand-held and used by someone at **walking speed**
    - e.g., a walkie-talkie or cordless telephone inside a home

[Rappaport, 2002, p 9]

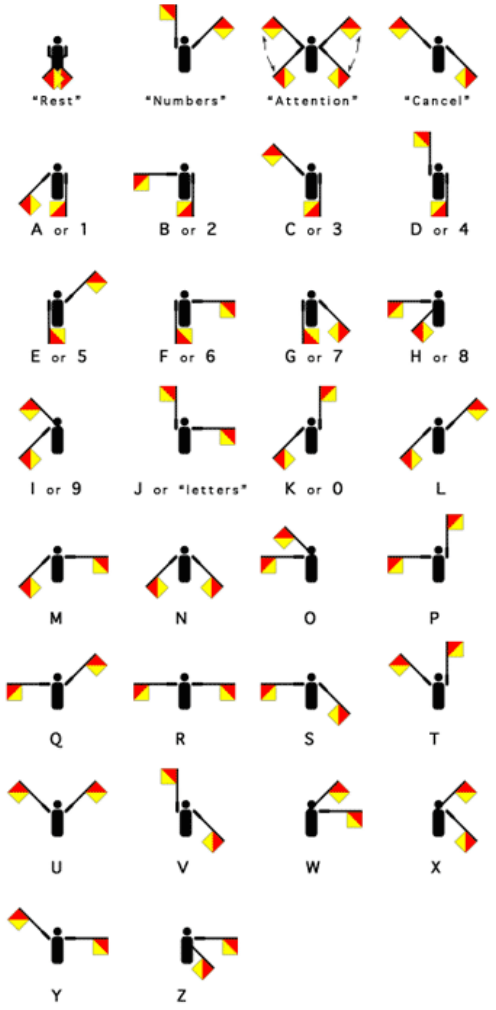
[Goldsmith, 2005, Section 1.1]

History (1)

- The first wireless networks were developed in the pre-industrial age.
- These systems transmitted information over **line-of-sight** distances (later extended by telescopes) using **smoke** signals, torch signaling, flashing mirrors, signal flares, or semaphore **flags**.

Semaphore


© Original Artist
Reproduction rights obtainable from
www.CartoonStock.com
'I think Lassie is trying to tell us something, ma.'


"Rest"
"Numbers"
"Attention"
"Cancel"
A or 1
B or 2
C or 3
D or 4
E or 5
F or 6
G or 7
H or 8
I or 9
J or "letters"
K or 0
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z

History: Radio

- Early communication networks were replaced first by the **telegraph network** (invented by Samuel **Morse** in 1838) and later by the telephone.
- In 1895, **Marconi** demonstrated the first radio transmission.
  - Very high transmission power (> 200 kW)

- Early radio systems transmitted **analog** signals.
- Today most radio systems transmit **digital** signals composed of binary bits.
- A digital radio can transmit a continuous bit stream or it can group the bits into packets.
- The latter type of radio is called a **packet radio** and is characterized by **bursty** transmissions

History: ALOHANET

- The first network based on packet radio, **ALOHANET**, was developed at the **University of Hawaii** in 1971.
- ALOHANET incorporated the first set of protocols for channel access and routing in packet radio systems, and many of the underlying principles in these protocols are still in use today.
- Lead to **Ethernet** and eventually wireless local area networks (**WLAN**).

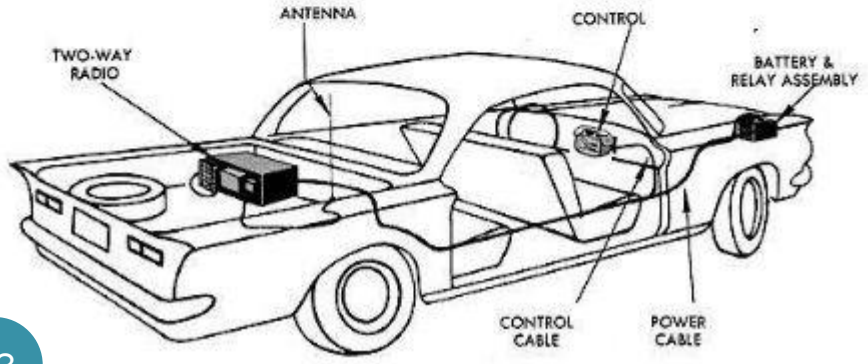
History: Pre-Cellular (1)

- The **most successful** application of wireless networking has been the **cellular telephone system**.
- 1915: Wireless voice transmission (wireless telephony) between New York and San Francisco was first established by AT&T.
- 1946: First public **mobile telephone** service was introduced in 25 cities across the US. The equipment was expensive at $2,000.
  - More than the price of a typical new car (at that time).

[Goldsmith, 2005, p 3]
[http://earlyradiohistory.us/1915ATT1.htm]

History: Pre-Cellular (2) Car Phone

Now—from your car—you can place or receive calls from any place in the world with General Electric's Simultaneous Duplex Mobile Telephone.



Typical GE DTO- Series Installation, Circa 1963

History: Pre-Cellular (3)

- These initial systems used a single **central transmitter** to cover an **entire** metropolitan **area**.
  - High-powered transmitter & Large tower
  - Inefficient!
  - FM push-to-talk
- 1976: (30 yrs after the introduction of the service in 1946),
  - the New York system (10M people) could only support 543 paying customers.
  - 3,700 on the waiting list
- The mobile units weighed about 10 kilograms and put out a steady 20-25 watts.
- The central transmitters that communicate with the mobile units broadcast 200 to 250 watts.

[Klemens, 2010, Chapter 3]

History: Pre-Cellular System (3.1)

- The central station could reliably communicate with the mobile units up to a radius of approximately 25 miles (50 km).

Colored area indicates the coverage area of the central transmitter in the corresponding region

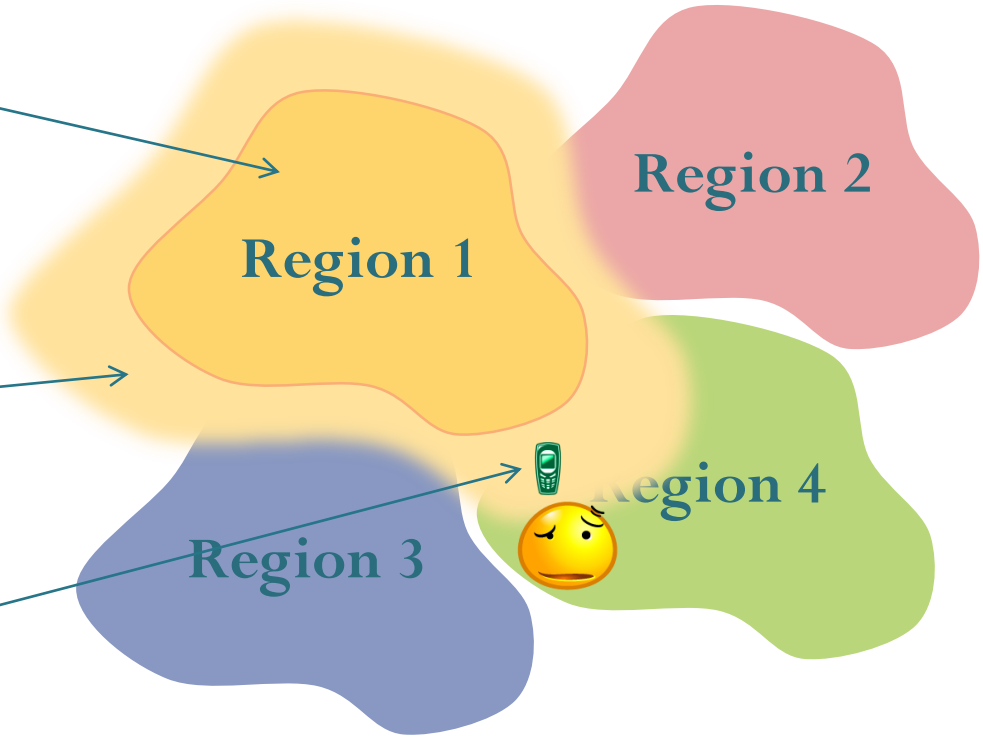
[Klemens, 2010, p 46]

History: Pre-Cellular System (3.2)

- Beyond that, up to a radius of 60 to 100 miles, the signal was too weak for consistent service, but strong enough to interfere with any other mobile radio system.

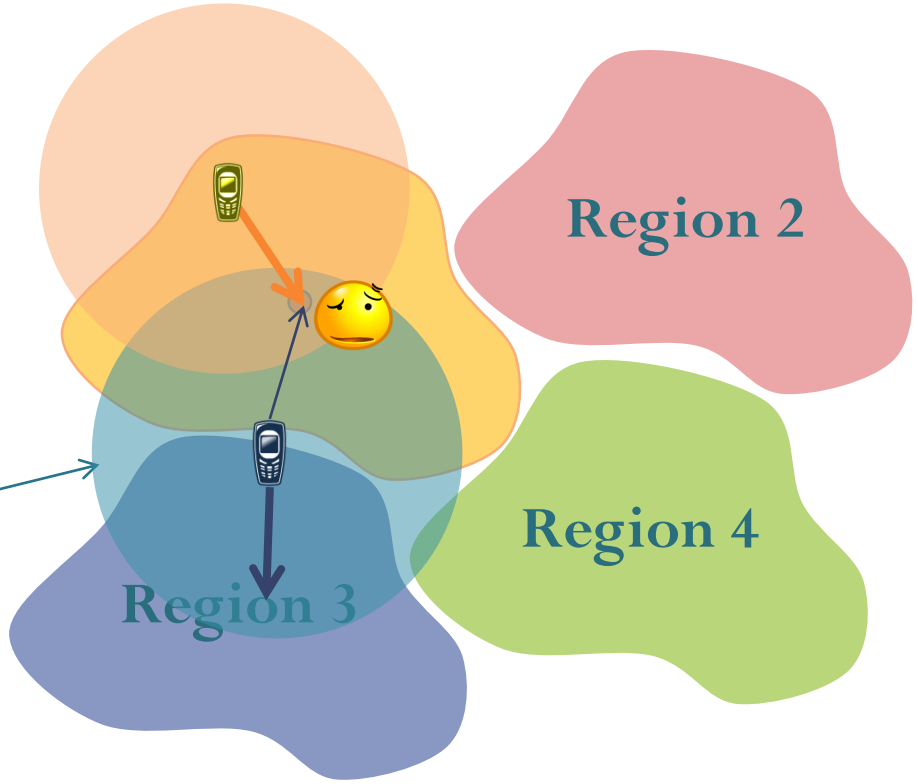
Downlink signal in this region is strong enough for communication

The signal in this region is ***not*** strong enough for communication but still impose significant ***interference*** on users in other regions



[Klemens, 2010, p 46]

History: Pre-Cellular System (3.3)



Uplink signals from user of a cell can reach the BS of a different region.

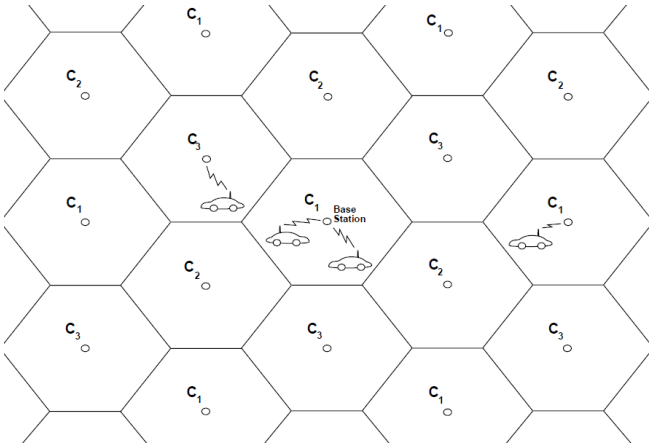
[Klemens, 2010, p 46]

History: Pre-Cellular System (3.4)

- Regions need to be well-separated!
- As a result, the central transmitters had to be at least 100 miles apart, leaving a 50 mile **blank space** between them.
- So a customer could use the sporadic and unreliable service only within the confines of one area.

History: 1G Cellular (1)

- A solution to this capacity problem emerged during the 50's and 60's when researchers at AT&T **Bell Lab**oratories developed the **cellular concept**.
- 1968: AT&T proposed the concept to the FCC
- Cellular systems exploit the fact that the power of a transmitted signal falls off with distance.
- Thus, two users can operate on the same frequency at spatially-separate locations with minimal interference between them.
  - Frequency reuse



History: 1G Cellular (2)

- **Japan** had the **world's first commercially available** cellular phone system.
  - (Japan's national monopoly telecoms operator/carrier) Nippon Telegraph and Telephone (NTT) created a cellular test system for Tokyo in 1975, with the result coming to market in 1979.

- The first trial in America of a complete, working cellular system was held in **Chicago** in the late 1970's.
- 1983: Advanced Mobile Phone System (**AMPS**)
  - First US cellular telephone system
  - Deployed in 1983 by Ameritech in Chicago, IL.
  - Worked well. (FM, FDMA)
  - May even have worked too well.
    - Its satisfactory performance lowered the demand for a better system, allowing Europe to take the lead by creating a digital cellular system first.

[http://communities-dominate.blogs.com/brands/2009/11/celebrating-30-years-of-mobile-phones-thank-you-ntt-of-japan.html]

History: 1G Cellular (3)

	U.S. and Canada (AMPS)	*U.K. (TACS)*	*Japan (NTT)*	*Nordic (NMT450)*	*Nordic (NMT900)*
Number of channels	2 × 416	2 × 500	2 × 500	180	1999
Cell radius (km)	2–20	2–20	2–20	1–40	.5–20
Cell repeat pattern (N)	7, 12	4, 7, 12, 21	9, 12	7, 12	9, 12
Cell receiver frequency (MHz)	825–845	890–915	860–885	453–457.5	890–915
Cell transmitter frequency (MHz)	870–890	935–960	915–940	463–467.5	935–960
Frequency sep. between receiver and transmitter (MHz)	45	45	55	10	45
Channel spacing	30	25	25	25	12.5
Cell-site transmitter power (W)	100	100	25	50	100
Mobile transmitter power (W)	3	7	5	15	6
Voice:					
Modulation	FM	FM	FM	PM	PM
Frequency deviation (kHz)	±12	±9.5	±5	±5	±5
Signalling:					
Modulation	FSK	FSK	FSK	FFSK	FFSK
Formatting	Bi-ø	Bi-ø	Bi-ø	NRZ	NRZ
Frequency deviation (kHz)	±8.0	±6.4	±4.5	±3.5	±3.5
Bit rate (Kbps)	10	8	.3	1.2	1.2

Old Cell Phone

Motorola's DynaTAC

First **commercially available** cell phone in 1983

Video Demo of 1G Phone

- A Tektronix CMD 80 cellular service monitor is used to simulate a cell tower.
- [1:11-7:00]

https://www.youtube.com/watch?v=GH_t2ZIX794

History: 2G Cellular

- The **first-generation (1G)** systems introduced in the 1980s were characterized by **analog speech transmission**.
- The **second generation** (**2G**) of cellular systems, first deployed in the early 1990's, were based on **digital** communications.
- The shift from analog to digital was driven by its higher capacity and the improved cost, speed, and power efficiency of digital hardware.
- 1991: US Digital Cellular (**USDC** – **IS-54** > IS-136)
  - Three times capacity of AMPS via digital modulation, speech coding, and TDMA
- While second generation cellular systems initially provided mainly **voice** services, these systems gradually evolved to support **data** services such as email, Internet access, and short messaging.

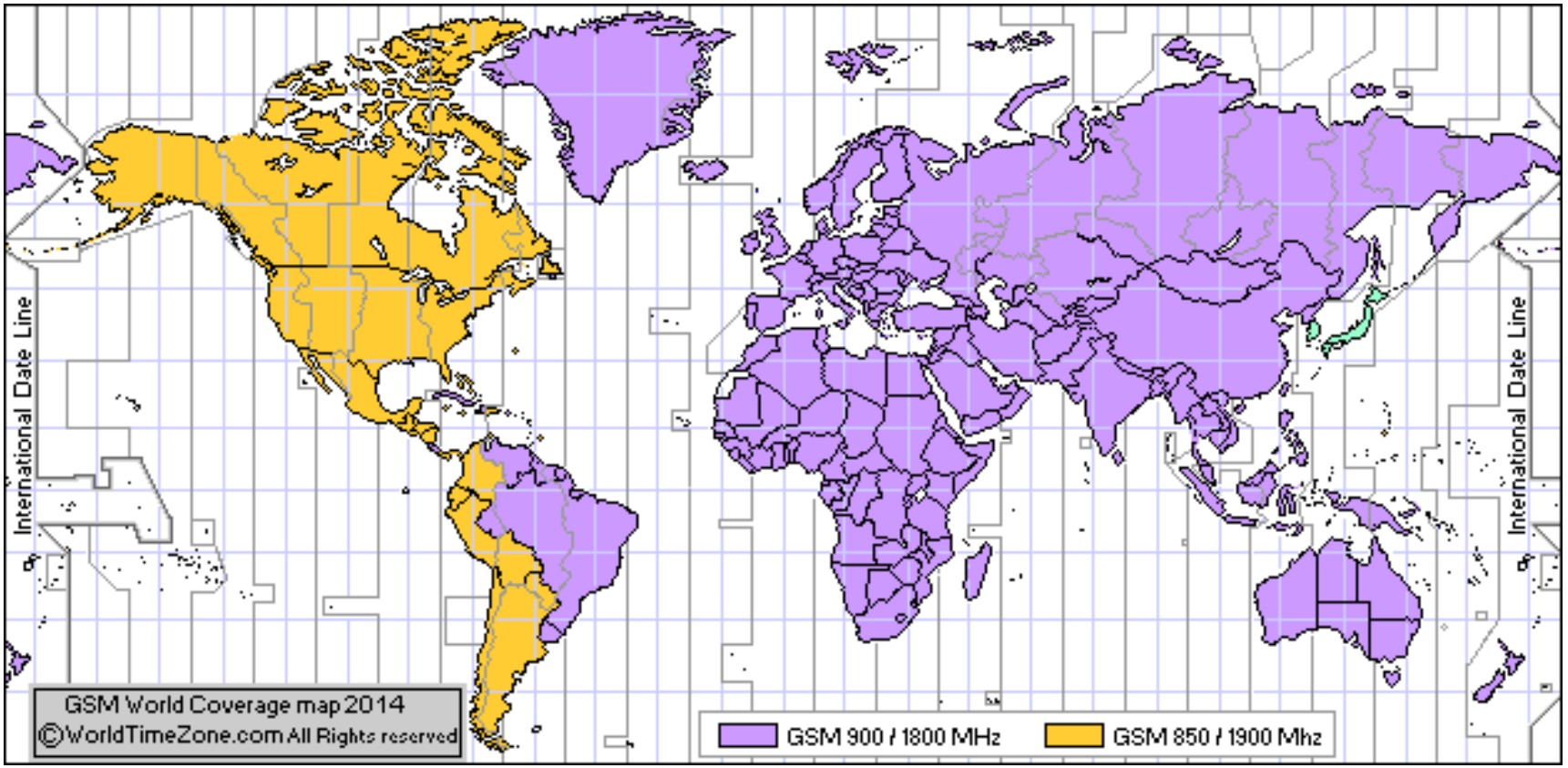
[Myung and Goodman, 2008]

Two important 2G systems

- **GSM** supports SMSs and user data at rates only up to **9.6 kb/s**.
  - Security features including (for example) the encryption of data and signaling messages on the path between the mobile phone and the BS.
  - Subscriber identity module (SIM)
    - A smart card
    - Contain the subscriber's personal details
    - Can be moved from one handset to another.

- **IS-95B** (**cdmaOne**) provides data rates in the range of **64 to 115 kb/s** in increments of 8 kb/s over a 1.25 MHz channel.
  - Each cell uses a carrier with a bandwidth of 1.25MHz, which is divided into 64 data and signalling channels by the use of orthogonal CDMA codes.

GSM World Coverage Map



[http://www.worldtimezone.com/gsm.html]

History (Thailand)

- 1G
  - 1986 (2529): NMT470 (TOT)
    - Nordic Mobile Telephone System @ 470MHz
  - AMPS (Advanced Mobile Phone System)
    - 1990 (2533): Cellular 900 (AIS)
    - Worldphone 800 (TAC)
- 2G: GSM (Global System for Mobile Communication)
  - 1994 (2537): GSM Advance @ 900 Mhz (AIS)
  - Worldphone 1800 (TAC)

CELLULAR 900 | DIGITAL GSM 1800 | 1-2-CALL | GSM advance

[http://3g.siamphone.com/articles/2009/3g/page.htm]

GSM Enhancement

[http://www.scriptdd.com/diary/windows_live_for_mobile.html]

- Want to deliver ***data*** as well as voice.
- **2.5G: General Packet Radio Service (GPRS)**
  - Provide connectivity to IP networks (Internet).
  - Each slot can handle up to **20 kb/s**. Each user may be allocated up to 8 slots
  - Data rates up to about **160 kb/s** per user are possible.
  - A single time slot may be shared by multiple users for transferring packet mode data.
- **2.75G: Enhanced Data Rates for GSM Evolution (EDGE)**
  - Support IP-based services in GSM at rates up to **384 kb/s**

2.5G: GPRS

- **General Packet Radio Service**
- The first commercial launches for GPRS took place in 2001.
- Construction of a **packet switched** core network, to run alongside the **circuit switched** network that was originally built for GSM.
  - "always on" connection that remains active as long as the phone is within range of the service.
- A single time slot may be shared by multiple users for transferring packet mode data.

2.5G: GPRS

- A good approximation for throughput in "average" conditions is 10 Kbps per time slot. [Korhonen, 2003]
- Especially suitable for non-real-time applications, such as e-mail and Web surfing.
- **Bursty data** is well handled with GPRS, as it can adjust the assigned resources according to current needs.
- Not well-suited for real-time applications
  - Resource allocation in GPRS is contention based
  - Cannot guarantee an absolute maximum delay.

2.75?G: EDGE

- **Enhanced Data Rates for GSM Evolution**
  - Originally this acronym stood for Enhanced Data rates for GSM Evolution, but now it translates into **Enhanced Data rates for Global Evolution**, as the EDGE idea can also be used in systems other than GSM [Korhonen, 2003]
- Higher modulation efficiency
  - **Eight-phase shift keying (8PSK)**
    - Can only be used effectively over a short distance.
    - For wide area coverage, the old GMSK (Gaussian minimum shift key) is still needed.
- Only requires a **software upgrade** to base stations
  - if the RF amplifiers can handle the non-constant envelope modulation with EDGE's relatively high peak-to-average power ratio (PAPR).
- EDGE is popular in North America, where the allocation of carrier frequencies has made it hard for GSM operators to upgrade to UMTS.

The Original iPhone

- 2007-2008
- Quad-band GSM/GPRS/EDGE (850, 900 1,800 1,900 MHz)

Motivation

Voice/SMS

~9.6Kbps

Mobile Narrow Band Internet

14.4~64Kbps

Low-QoS Mobile Multimedia Services

64~144Kbps

High-quality, Smooth and Low-delay Video, Voice, and Music Services

20~300Kbps

Mobile Broadband Internet Surfing

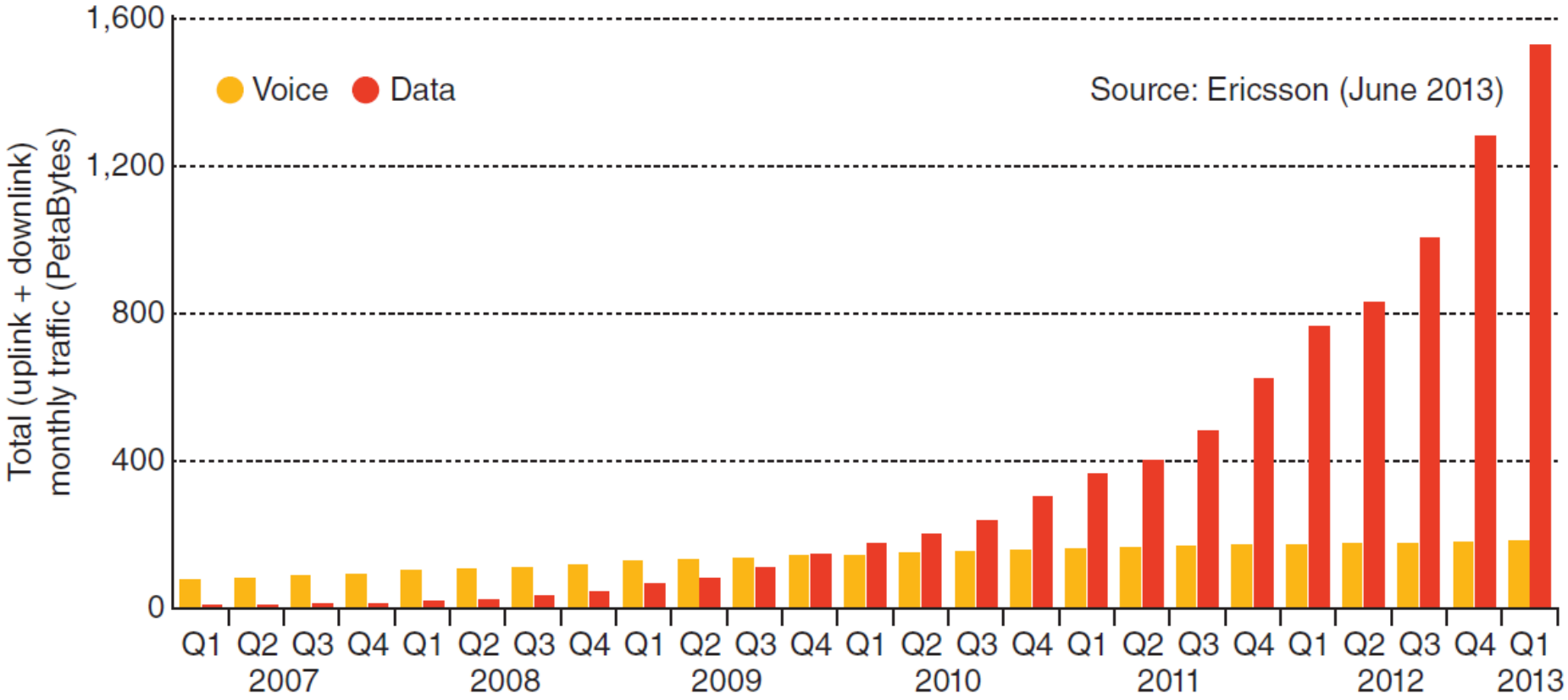
64~300Kbps

Abundant and High-quality New Mobile Services

300K~5Mbps

Worldwide voice vs. data traffic

- In mobile telecommunication networks



[Ericsson mobility report, June 2013]

The amount of data traffic increased by a factor of over 500.

3G

- Studies started even before the earliest 2G systems arrived on the market.
- International Mobile Telecommunications-2000 (**IMT-2000**)
  - A subgroup of the International Telecommunication Union (**ITU**)
  - Published a set of performance requirements of 3G (for both packet-switched and circuit-switched data):
    - A minimum data rate of 144 Kbps in the vehicular environment
    - A minimum data rate of 384 Kbps in the pedestrian environment
    - A minimum data rate of 2 Mbps in the fixed indoor and picocell environment
- There are several wireless standards and systems that qualify as third generation (3G) systems.
  - UMTS
  - CDMA2000

3GPP and 3GPP2

(Collaboration between groups of telecommunications associations (partners))

3rd Generation Partnership Project

3gpp.org

3gpp2.org

Scope

3G: IMT-2000

International Mobile Telecommunications systems

W-CDMA

CDMA2000

International Telecommunication Union

ITU-R

R = Radiocommunication Standardization Sector

The 3G technologies standardized by 3GPP are often referred to collectively as WCDMA.

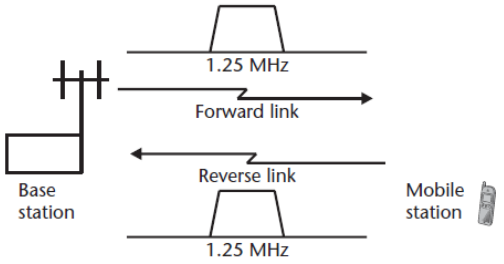
3GPP uses two other acronyms to describe its specifications:

UMTS (Universal Mobile Telecommunications System) applies to the entire cellular network contained in hundreds of 3GPP specifications; and

UTRAN (Universal Terrestrial Radio Access Network) refers to the collection of network elements, and their interfaces, used for transmission between mobile terminals and the network infrastructure.

cdma2000

- Another 3G mobile technology standard
- Multicarrier, direct-sequence CDMA FDD system.
- Backward-compatible with its previous 2G iteration IS-95 (cdmaOne).
- **CDMA2000 1X (IS-2000)**
  - also known as 1x and 1xRTT
  - 1x = Spreading Rate 1 = use the same chip rate of IS-95 (i.e., 1.2288 Mcps).
    - Same RF bandwidth as IS-95: a duplex pair of 1.25 MHz radio channels.
  - Core CDMA2000 wireless air interface standard.
  - Almost doubles the capacity of IS-95 by adding 64 more traffic channels to the forward link, orthogonal to (in quadrature with) the original set of 64.



UMTS

- **Universal Mobile Telecommunications System (UMTS)**
- The research activity on UMTS started in **Europe** at the beginning of the 1990s.
  - Even before the earliest 2G systems arrived on the market
- Designed to support wideband services with data rates up to **2Mbit/s**.
- Developed **from GSM**
  - Keep the core network more-or-less intact
  - Change the air interface to use **CDMA**
- Compatibility between UMTS and GSM:
  - Most UMTS mobiles also implement GSM, and the network can hand them over from a UMTS base station to a GSM one if they reach the edge of the UMTS coverage area.
  - However, network operators cannot implement the two systems in the same frequency band, so they are not fully compatible with each other.

Evolution of UMTS Specifications

Release	Functional freeze	Main UMTS feature of release
Rel-99	March 2000	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	December 2007	HSPA+ (64QAM downlink, MIMO, 16QAM uplink) LTE and SAE feasibility study

Also dubbed 3.5G, 3G+ or turbo 3G

3G	3GS	4	4S
In addition to prior: Tri-band 3.6 Mbps UMTS/HSDPA (850, 1900, 2100 MHz),[273]	In addition to prior: 7.2 Mbit/s HSDPA	In addition to prior: Penta-band UMTS/HSDPA (800, 850, 900, 1900, 2100 MHz),[112][274] 5.76 Mbit/s HSUPA *CDMA model:* Dual-band CDMA/EV-DO Rev. A (800, 1900 MHz)	In addition to prior: 14.4 Mbit/s HSDPA (marketed as 4G on AT&T), Dynamically switching dual antenna,[275] Combined GSM/CDMA World phone ability

HSPA

3.5G?

- **High Speed Packet Access (HSPA)** is a collection of two mobile telephony protocols
  - High Speed **Downlink** Packet Access (HSDPA) and
  - High Speed **Uplink** Packet Access (HSUPA)
- Extend and improve the performance of existing WCDMA/UMTS protocols.
- Current HSDPA deployments support down-link speeds of 1.8, 3.6, 7.2 and 14.0 Megabit/s.
- Many HSPA rollouts can be achieved by a **software upgrade** to existing 3G networks, giving HSPA a head start over WiMAX, which requires dedicated network infrastructure.

3.9G?

- There is also a further standard, **Evolved HSPA (HSPA+)**.

HSPA+

- HSPA+ provides data rates up to
  - 168 Megabits per second (Mbit/s) to the mobile device (downlink) and
  - 22 Mbit/s from the mobile device (uplink).
- Technically these are achieved through the use of MIMO and higher order modulation (64QAM) or combining multiple cells into one with a technique known as Dual-Cell HSDPA.
- The 168 Mbit/s and 22 Mbit/s represent theoretical peak speeds.
  - Only in very good radio conditions (very close to cell tower) or if the terminal and network both support either MIMO or Dual-Cell HSDPA
  - The actual speed for a user will be lower.
- Deliver significant battery life improvements and dramatically quicker wake-from-idle time – delivering a true always-on connection.

3G in Thailand: HSPA, HSPA+

- **Truemove H**: 850 MHz
  - Launched HSPA+ in September 2011
- **DTAC**: 850 MHz
  - Launched HSPA+ in September 2011
- **AIS**: 900 MHz
  - Launched HSPA+ in April 2011
- **TOT3G**: 2.1 GHz
- Different bands

[http://en.wikipedia.org/wiki/List_of_HSPA%2B_networks]

UMTS to LTE

(Collaboration between groups of telecommunications associations (partners))

3rd Generation Partnership Project

International Telecommunication Union

ITU-R

R = Radiocommunication Standardization Sector

Scope

International Mobile Telecommunications systems

3G: IMT-2000

UMTS (W-CDMA)

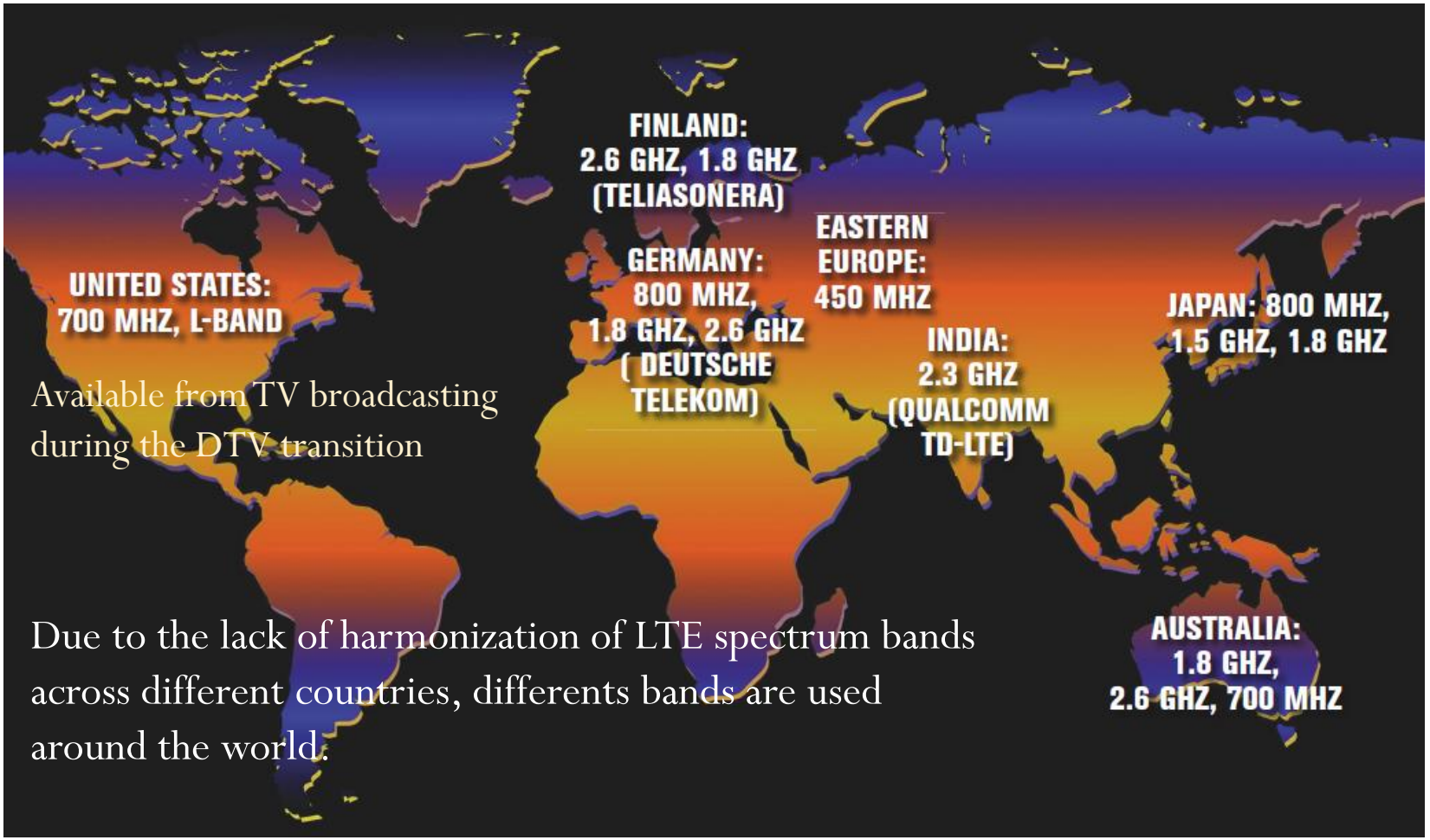
CDMA2000

IMT-Advanced

LTE-Advanced

Long Term Evolution

LTE Around the World (in the beginning)



Available from TV broadcasting during the DTV transition

Due to the lack of harmonization of LTE spectrum bands across different countries, differents bands are used around the world.

[Wireless Week Magazine, February 2011]
[http://www.hardwarezone.com.sg/feature-challenges-faced-operators-4g-lte-deployment]

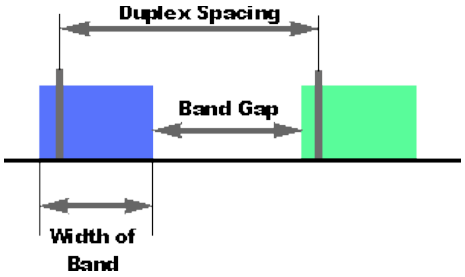
FDD and TDD LTE frequency bands

FDD LTE frequency band allocations

LTE BAND NUMBER	UPLINK (MHZ)	DOWNLINK (MHZ)	WIDTH OF BAND (MHZ)	DUPLEX SPACING (MHZ)	BAND GAP (MHZ)
1	1920 - 1980	2110 - 2170	60	190	130
2	1850 - 1910	1930 - 1990	60	80	20
3	1710 - 1785	1805 -1880	75	95	20
4	1710 - 1755	2110 - 2155	45	400	355
5	824 - 849	869 - 894	25	45	20
6	830 - 840	875 - 885	10	35	25
7	2500 - 2570	2620 - 2690	70	120	50
8	880 - 915	925 - 960	35	45	10
9	1749.9 - 1784.9	1844.9 - 1879.9	35	95	60
10	1710 - 1770	2110 - 2170	60	400	340
11	1427.9 - 1452.9	1475.9 - 1500.9	20	48	28
12	698 - 716	728 - 746	18	30	12
13	777 - 787	746 - 756	10	-31	41
14	788 - 798	758 - 768	10	-30	40
15	1900 - 1920	2600 - 2620	20	700	680
16	2010 - 2025	2585 - 2600	15	575	560
17	704 - 716	734 - 746	12	30	18
18	815 - 830	860 - 875	15	45	30
19	830 - 845	875 - 890	15	45	30
20	832 - 862	791 - 821	30	-41	71
21	1447.9 - 1462.9	1495.5 - 1510.9	15	48	33
22	3410 - 3500	3510 - 3600	90	100	10
23	2000 - 2020	2180 - 2200	20	180	160
24	1625.5 - 1660.5	1525 - 1559	34	-101.5	135.5
25	1850 - 1915	1930 - 1995	65	80	15

TDD LTE frequency band allocations

LTE BAND NUMBER	ALLOCATION (MHZ)	WIDTH OF BAND (MHZ)
33	1900 - 1920	20
34	2010 - 2025	15
35	1850 - 1910	60
36	1930 - 1990	60
37	1910 - 1930	20
38	2570 - 2620	50
39	1880 - 1920	40
40	2300 - 2400	100
41	2496 - 2690	194
42	3400 - 3600	200
43	3600 - 3800	200



[http://www.radio-electronics.com/info/cellulartelecomms/lte-long-term-evolution/lte-frequency-spectrum.php]

iPhone 5

- 2G
  - GSM 850 / 900 / 1800 / 1900 - GSM A1428
  - CDMA 800 / 1900 / 2100 - CDMA A1429
- 3G
  - HSDPA 850 / 900 / 1900 / 2100 - GSM A1428
  - CDMA2000 1xEV-DO - CDMA A1429
- 4G
  - LTE 700 MHz Class 17 / 1700 / 2100 - GSM A1428 or **LTE 850 / 1800 / 2100 – GSM A1429**
  - LTE 700 / 850 / 1800 / 1900 / 2100 - CDMA A1429

[http://www.apple.com/iphone/LTE/]

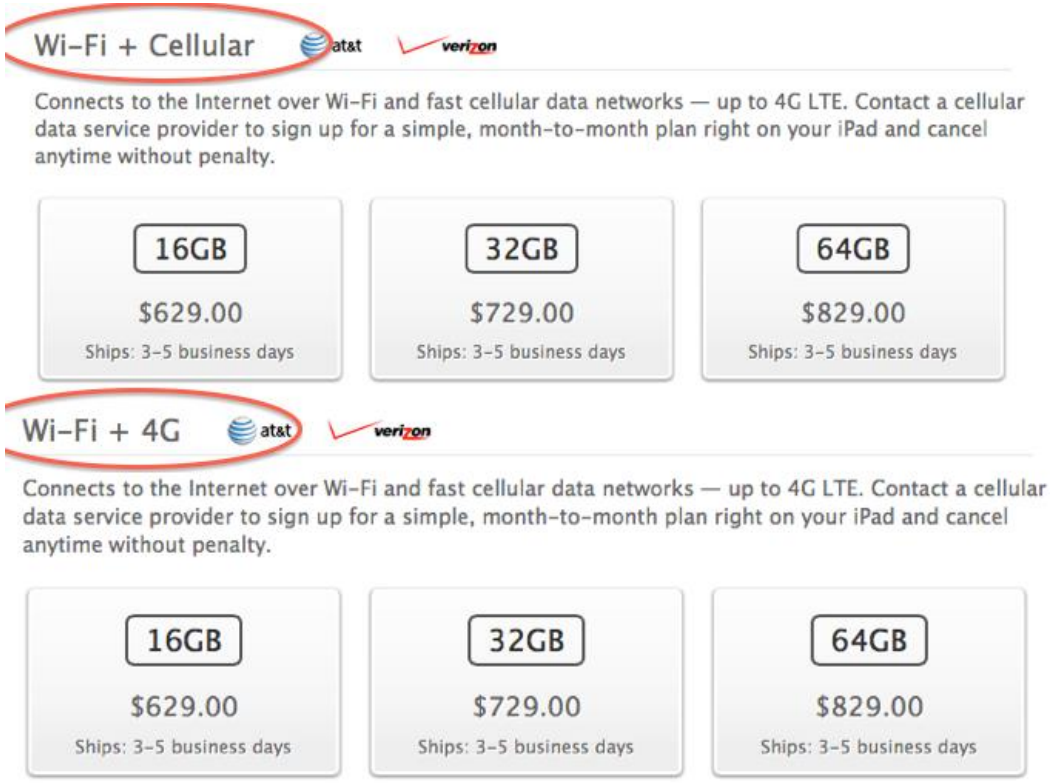
LTE on iPhone 5

Model Number[2]	LTE Band Support[3]	Country	Supported LTE Networks
Model A1428 (GSM model)	**4** (AWS) **17** (700b MHz)	United States	AT&T
		Canada	Bell (including Virgin) Rogers (including Fido) Telus (including Koodo)
Model A1429 (CDMA model)	**1** (2100 MHz) **3** (1800 MHz) **5** (850 MHz) **13** (700c MHz) **25** (1900 MHz)	United States	Sprint Verizon
		Japan	KDDI
Model A1429 (GSM model)	**1** (2100 MHz) **3** (1800 MHz) **5** (850 MHz)	Germany	Deutsche Telekom
		United Kingdom	EE
		Australia	Optus (including Virgin) Telstra
		Japan	Softbank
		Korea	SK Telecom KT
		Hong Kong	SmarTone
		Singapore	M1 SingTel

Not compatible with the 800MHz and 2.6GHz bands deployed across much of western Europe, including Spain, Italy and France. Instead, it works on the 1.8GHz band, which is still being used for voice calls by most operators in Europe.

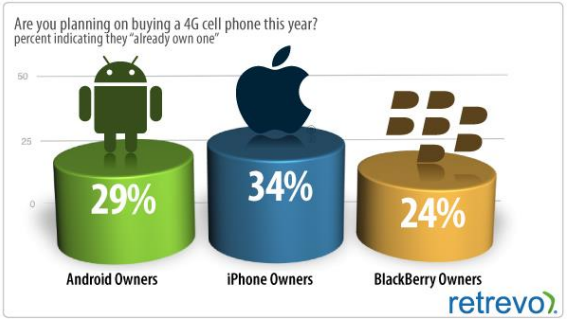
The New Ipad

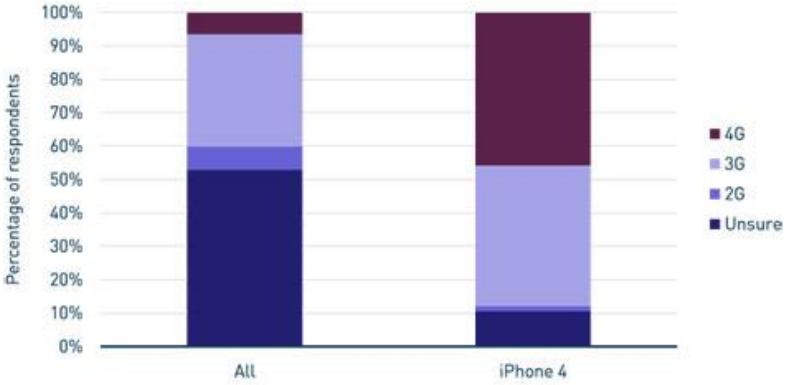
May 2012: Apple changes name of 'iPad WiFi + 4G' to 'iPad WiFi + Cellular' in many countries following international criticism



Important?

- July 2011: A survey by Retrevo found that (34% of) iPhone 4 owners actually believe that the "4" in their iPhone 4 stands for 4G
- Dec 2011: A survey from Analysys Mason showed that
  - 46 percent of iPhone 4 users believe that they already have 4G capability, even though they don't.
  - Over 50% of respondents were unsure as to their network technology.





[http://www.reuters.com/article/2012/09/14/us-apple-europe-spectrum-idUSBRE88D0NX20120914]
[http://www.retrevo.com/content/blog/2011/07/confusion-and-skepticism-may-impede-4g-adoption]
[http://www.pipelinepub.com/0112/OSS_BSS/Race-To-4G-1.php]
[http://www.analysysmason.com/About-Us/News/Insight/Insight_How_to_sell_4G_Dec2011/]

LTE on iPhones (sold in Thailand)

iPhone 6
Model A1586 (GSM)
Model A1586 (CDMA)

iPhone 6 Plus
Model A1524 (GSM)
Model A1524 (CDMA)

Upto 150Mbps download speed.

More LTE bands help you benefit from the growing number of roaming agreements around the world

1 (2100 MHz)
2 (1900 MHz)
3 (1800 MHz)
4 (AWS)
5 (850 MHz)
7 (2600 MHz)
8 (900 MHz)
13 (700c MHz)
17 (700b MHz)
18 (800 MHz)
19 (800 MHz)
20 (800 DD)
25 (1900 MHz)
26 (800 MHz)
28 (700 APT MHz)
29 (700 de MHz)
38 (TD 2600)
39 (TD 1900)
40 (TD 2300)
41 (TD 2500)

iPhone 5c
Model A1529

iPhone 5s
Model A1530

1 (2100 MHz)
2 (1900 MHz)
3 (1800 MHz)
5 (850 MHz)
7 (2600 MHz)
8 (900 MHz)
20 (800 DD)
38 (TD 2600)
39 (TD 1900)
40 (TD 2300)

iPhone 5
Model A1429
(GSM model)

1 (2100 MHz)
3 (1800 MHz)
5 (850 MHz)

[http://www.apple.com/iphone/LTE/]

Cellular Support in iPhone 6

Model A1586*
Model A1524*

CDMA EV-DO Rev. A and Rev. B (800, 1700/2100, 1900, 2100 MHz)

UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz)

TD-SCDMA 1900 (F), 2000 (A)

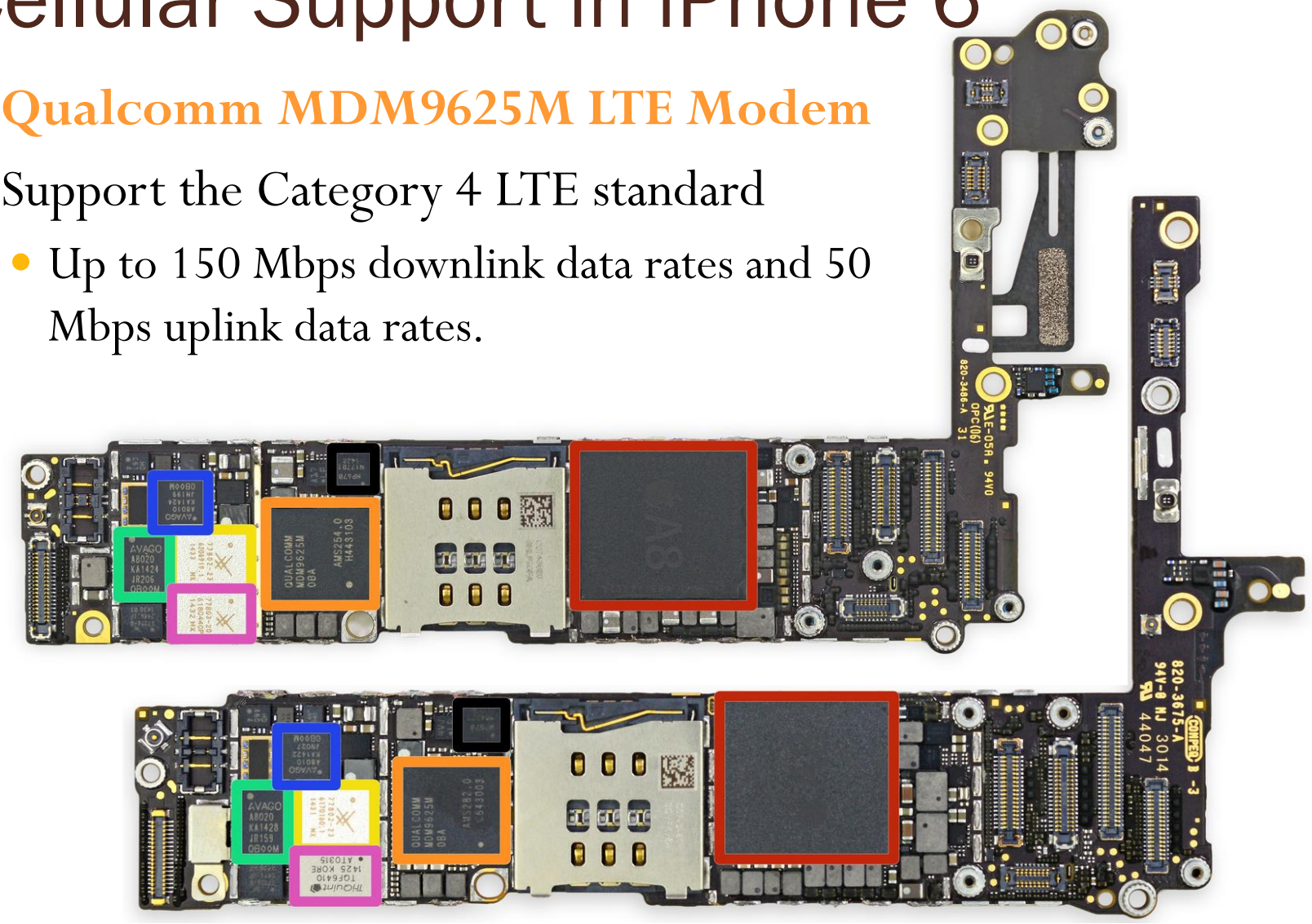
GSM/EDGE (850, 900, 1800, 1900 MHz)

FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 13, 17, 18, 19, 20, 25, 26, 28, 29)

TD-LTE (Bands 38, 39, 40, 41)

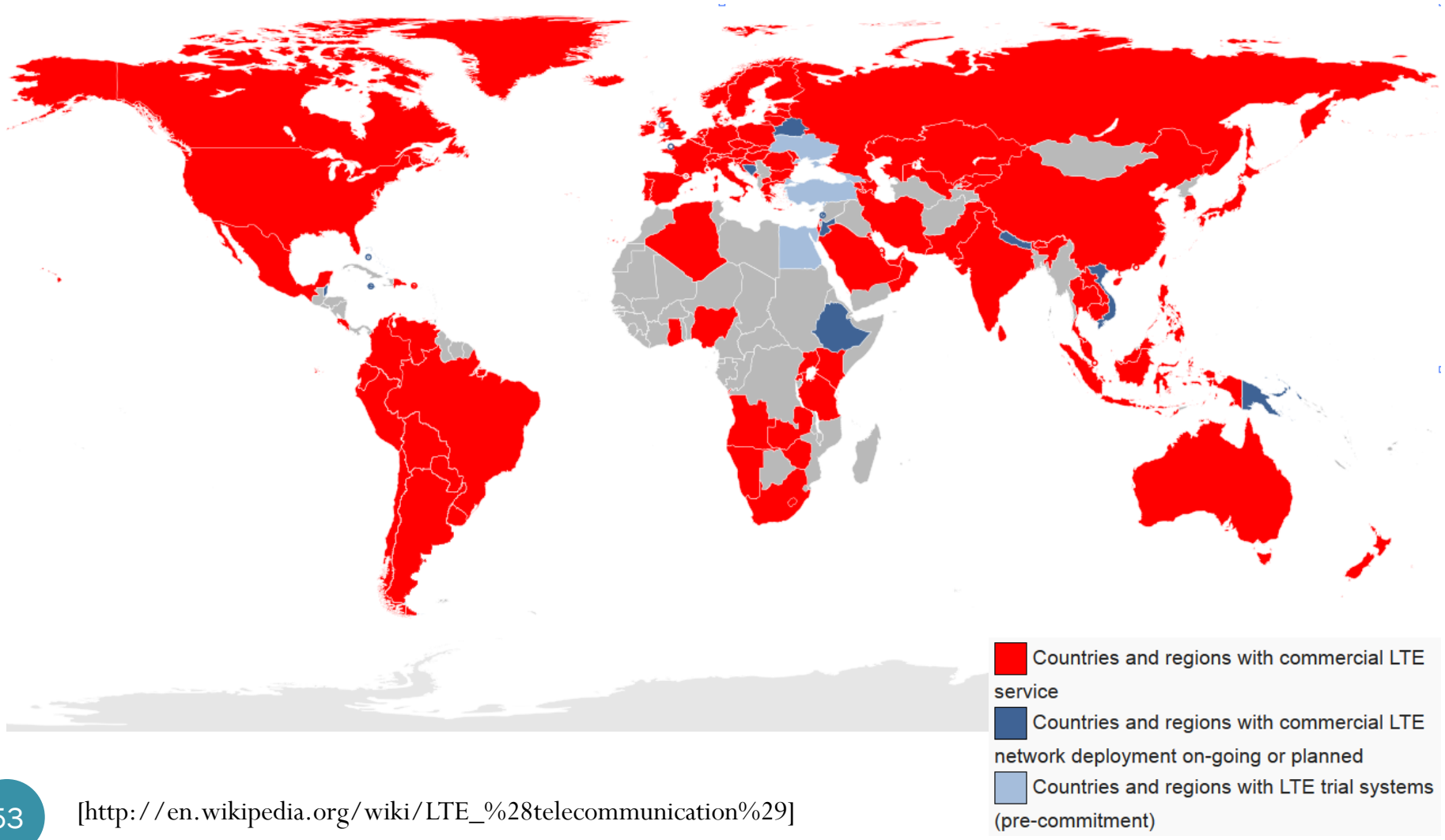
Cellular Support in iPhone 6

- **Qualcomm MDM9625M LTE Modem**
- Support the Category 4 LTE standard
  - Up to 150 Mbps downlink data rates and 50 Mbps uplink data rates.



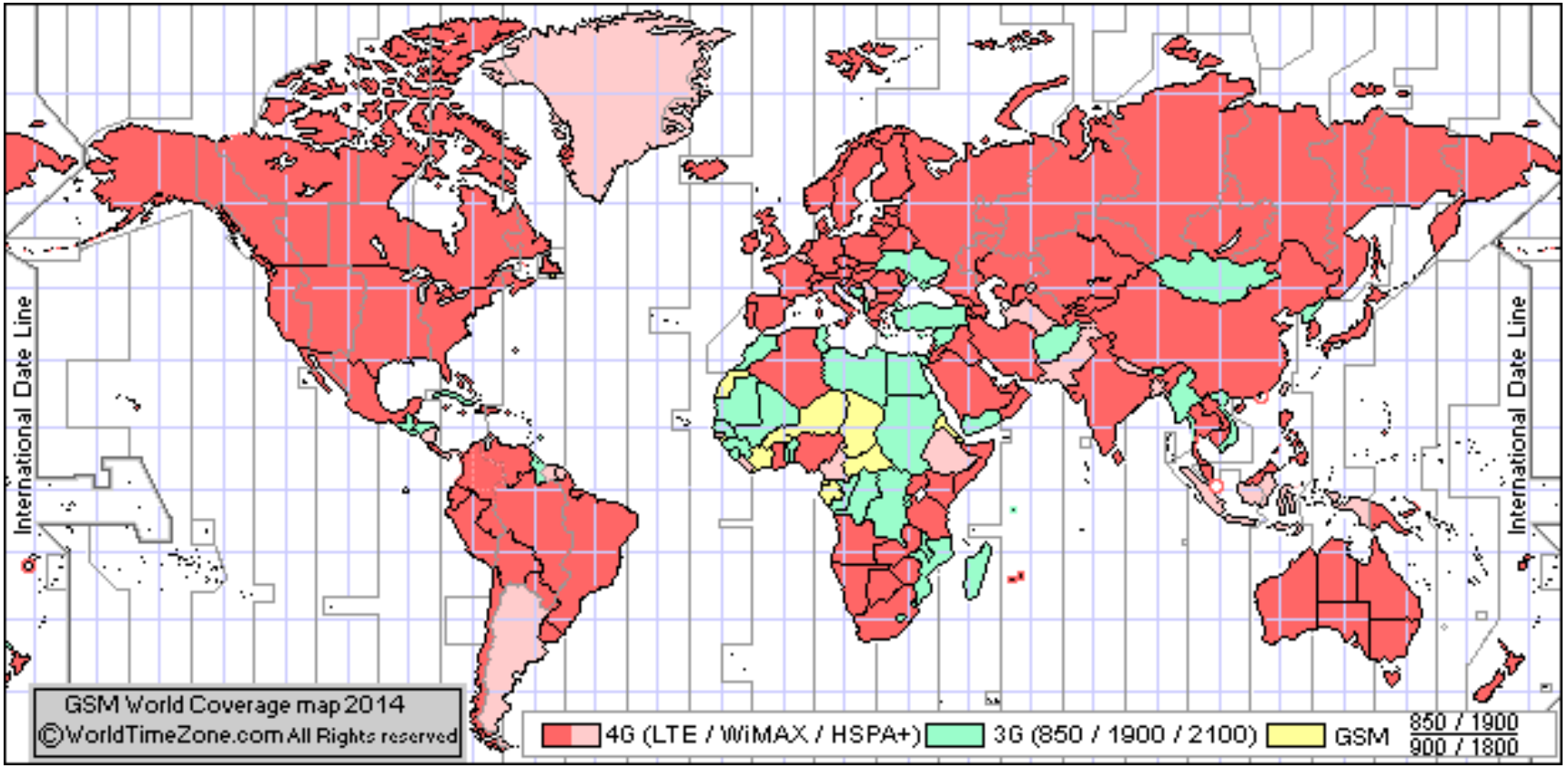
[https://www.ifixit.com/Teardown/iPhone+6+Plus+Teardown/29206]
[https://www.ifixit.com/Teardown/iPhone+6+Teardown/29213]

LTE Adoption (December 7, 2014)



[http://en.wikipedia.org/wiki/LTE_%28telecommunication%29]

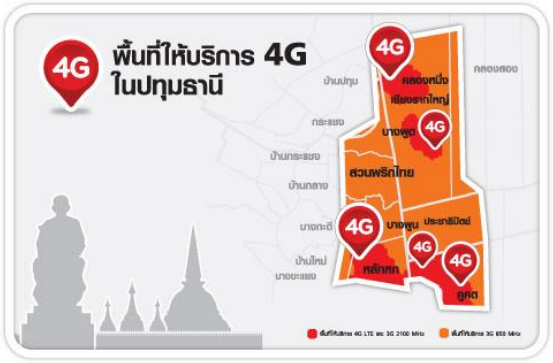
4G LTE World Coverage Map

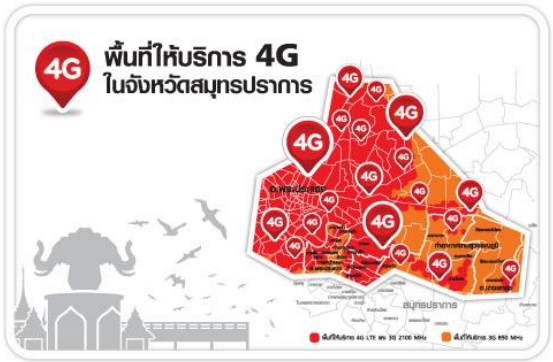


[http://www.worldtimezone.com/4g.html]

4G on True

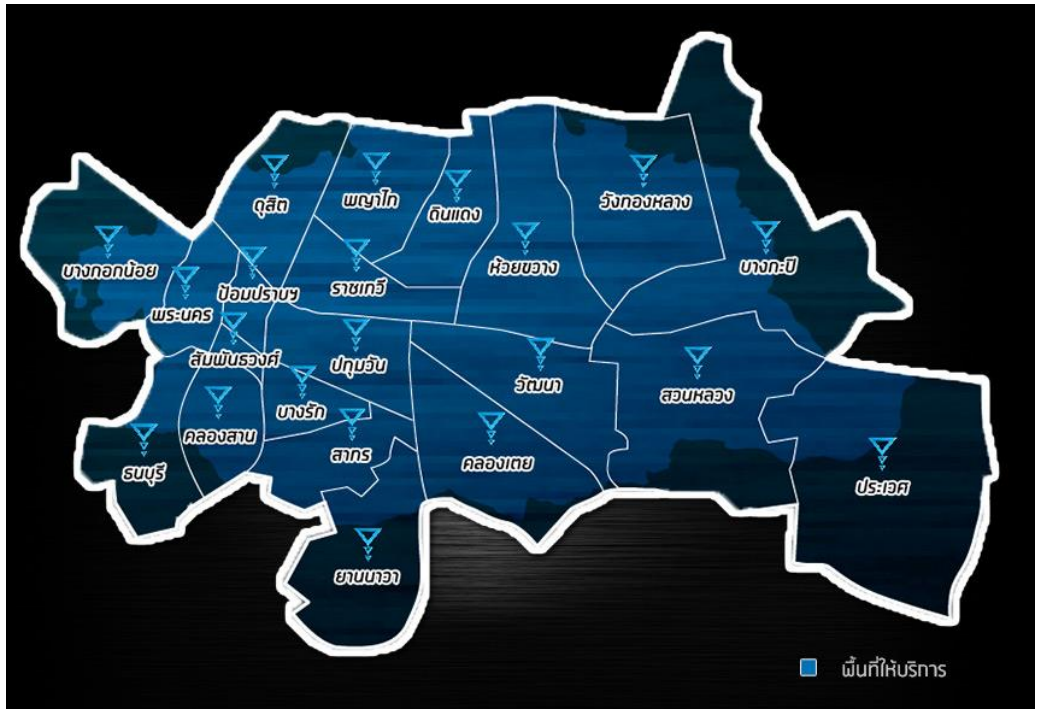
- 2100 MHz
- Launched in May 2013
- Currently, in central Bangkok and 14 provinces



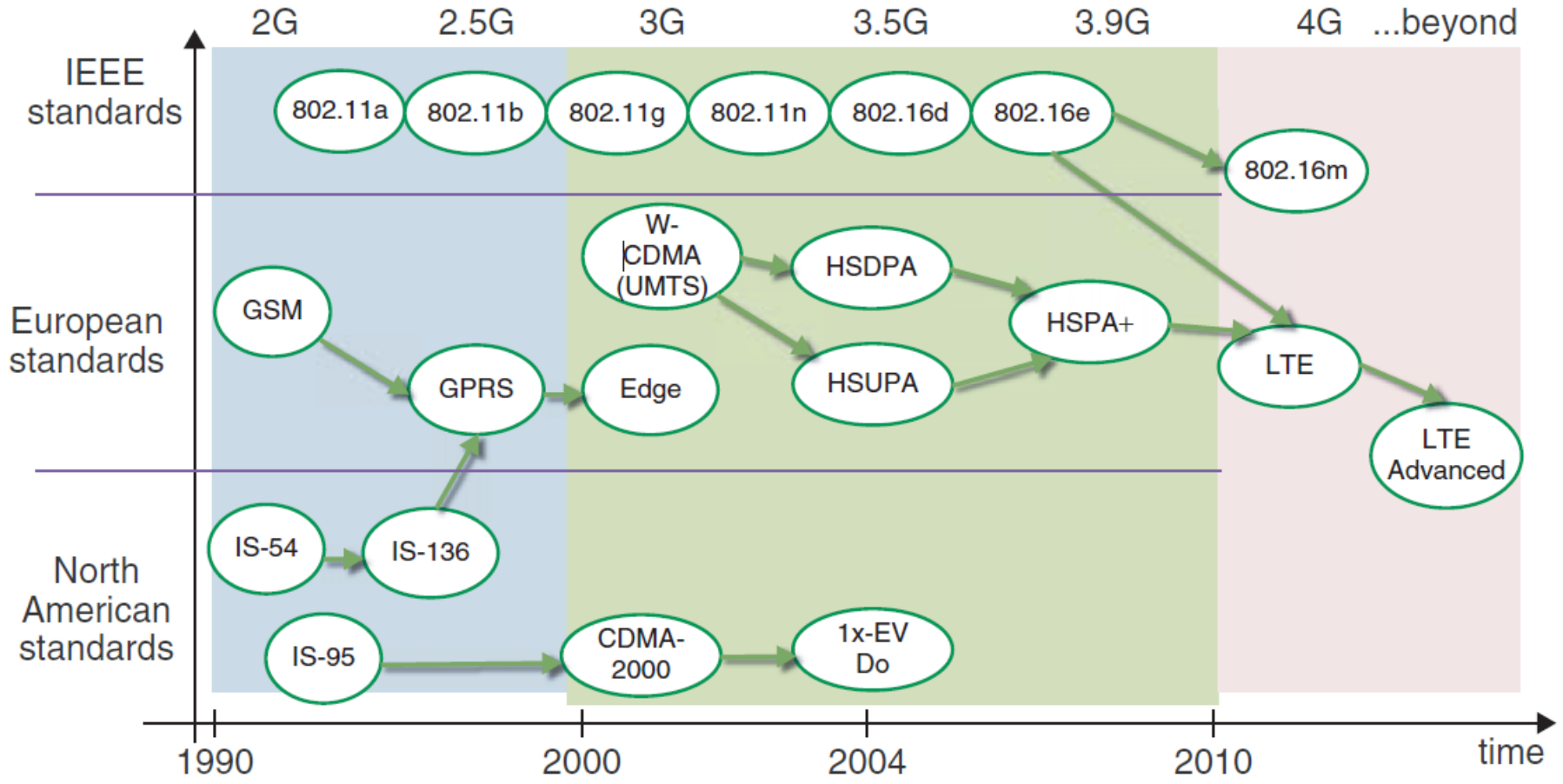


4G on DTAC

- TriNet (2100 MHz)



Evolution of wireless standards



[Zarrinkoub, 2014]

Evolution of iPhones

iPhone (1st generation)	3G	3GS	4	4S	5	5C	5S	6	6 Plus
									
Quad band GSM/GPRS/EDGE (850, 900, 1800, 1900 MHz)	In addition to prior: Tri-band 3.6 Mbps UMTS/HSDPA (850, 1900, 2100 MHz),[273]	In addition to prior: 7.2 Mbit/s HSDPA	In addition to prior: Penta-band UMTS/HSDPA (800, 850, 900, 1900, 2100 MHz),[112][274] 5.76 Mbit/s HSUPA *CDMA model:* Dual-band CDMA/EV-DO Rev. A (800, 1900 MHz)	In addition to prior: 14.4 Mbit/s HSDPA (marketed as 4G on AT&T), Dynamically switching dual antenna,[275] Combined GSM/CDMA World phone ability	In addition to prior: LTE, HSPA+ and DC-HSDPA			In addition to prior: LTE-Advanced[276]	
Mini-SIM			Micro-SIM		Nano-SIM				
Wi-Fi (802.11b/g) USB power adapter earphones with remote and mic	In addition to prior: Assisted GPS	In addition to prior: Voice control Digital compass Nike+ Volume controls on earphones	In addition to prior: Wi-Fi (802.11b/g/n) [802.11n on 2.4 GHz] 3-axis gyroscope Dual-mic noise suppression	In addition to prior: GLONASS support Siri voice assistant	In addition to prior: Wi-Fi (802.11a/b/g/n) [802.11n on 2.4 GHz and 5 GHz][277] Triple microphone noise suppression Revised iPod earpods		In addition to iPhone 5: Touch ID (finger-print scanner in home button)	In addition to prior: NFC Wi-Fi (802.11a/b/g/n/ac)	

[http://en.wikipedia.org/wiki/IPhone]

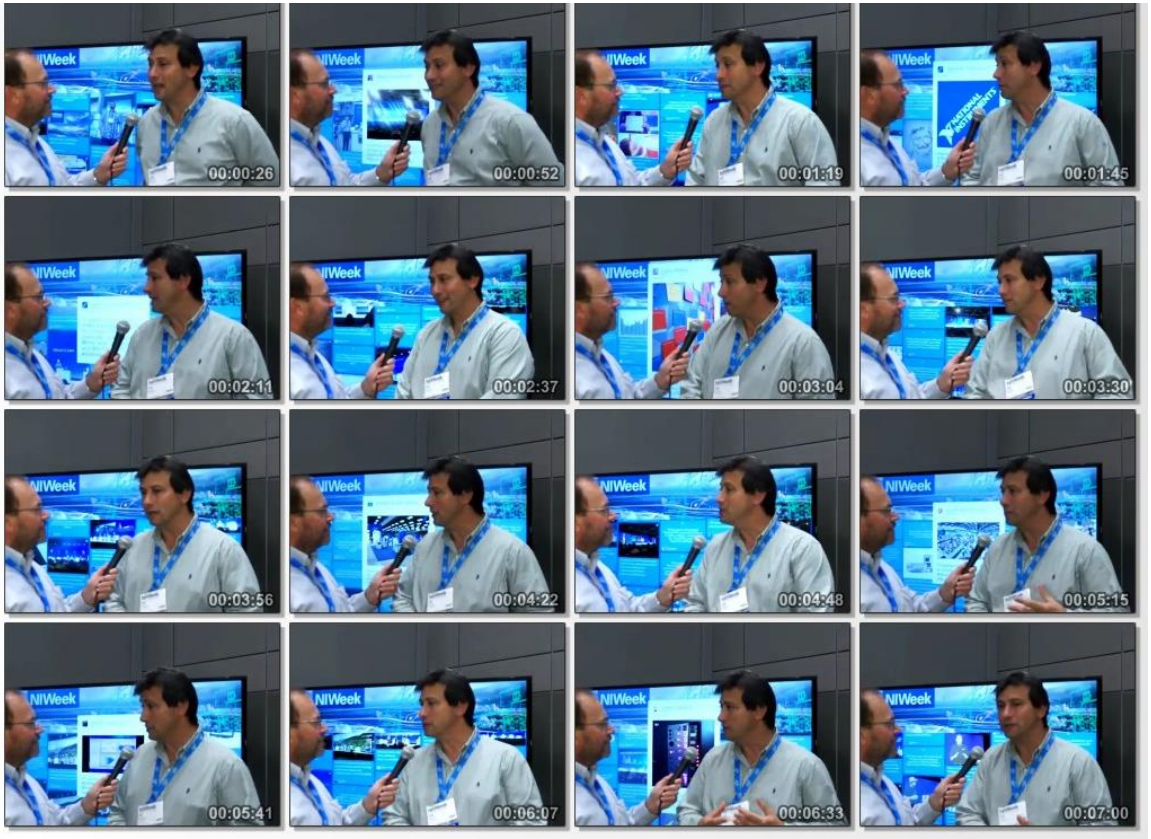
Peak data rates

Technology	Theoretical peak data rate (at low mobility)
GSM	9.6 kbps
IS-95	14.4 kbps
GPRS	171.2 kbps
EDGE	473 kbps
CDMA-2000 (1xRTT)	307 kbps
WCDMA (UMTS)	1.92 Mbps
HSDPA (Rel 5)	14 Mbps
CDMA-2000 (1x-EV-DO)	3.1 Mbps
HSPA+ (Rel 6)	84 Mbps
WiMAX (802.16e)	26 Mbps
LTE (Rel 8)	300 Mbps
WiMAX (802.16m)	303 Mbps
LTE-Advanced (Rel 10)	1 Gbps

[Zarrinkoub, 2014]

5G

- An interview with Ted Rappaport
- [0:00-1:54] and [4:33-END]



[https://www.youtube.com/watch?v=zskzsetSW1Y]