DEPARTMENT OF ELECTRONIC &
ELECTRICAL ENGINEERING

UCL

Mobile Communications Systems (MCS)

2019

Mobile Communication Systems (MCS)

Schedule

Term 1- 2019/2020

Module Manager: Professor Izzat Darwazeh
G22 Pearson Building

Monday 7th Oct 2019		
14.00	Introduction and Basic Cellular Concepts	Professor Izzat Darwazeh
15.30	Discussion/break	
15.50	The Wireless Propagation Environment	
17.00	Discussion/Close	
Monday 14th Oct 2019		
14.00	Modulation techniques for wireless systems	Professor Izzat Darwazeh
15.30	Break	
15.50	Multiple Access Techniques	
17.00	Discussion/Close	
Monday 21 Oct 2019		
14.00	Introduction GSM system	Professor Izzat Darwazeh
15.30	Discussion/break	
15.50	GSM Physical Layer and signals	
17.00	Discussion/Close	
Monday 28 Oct 2019		
14.00	Coding for wireless systems-I	Dr Laura Toni
15.30	Discussion/break	
15.50	Coding for wireless systems-II	
17.00	Discussion/Close	
Monday 11 Nov 2019		
14.00 am	Mobile Systems Architecture	Dr Clive Poole
15.30am	Discussion/Break	
15.50am	Mobile Systems Operation	
17.00pm	Discussion/Close	
Monday 18 Nov 2019		
14.00 am	Third Generation systems and UMTS	Dr Ryan Grammenos
15.30am	Discussion/Break	
15.50am	UMTS Architecture and Operation	
17.00pm	Discussion/Close	
Monday 25 Nov 2019		
14.00 am	4th generation systems and LTE	Dr Clive Poole
15.30am	Discussion/Break	
15.50am	LTE operation	
17.00pm	Discussion/Close	
Monday 02 Dec 2019		
14.00	5th Generation Concepts	Professor Izzat Darwazeh
15.30	Break	
15.50	Advanced and Future Wireless Technologies	
17.00	Discussion/Close	

MCS workshop: Date to be set   Professor Izzat Darwazeh and Dr Clive Poole

Module Name: Mobile Communications Systems

Module Acronym: MCS

Module Manager: Professor Izzat Darwazeh

Course Summary:

This module considers the fundamentals of the mobile and wireless communications systems. The module starts with a detailed view of the wireless propagation channel, the wireless and cellular environments and the signals, coding, modulation and multiple access techniques used in wireless systems. We focus on the detailed implementation of two key mobile systems, namely; GSM and UMTS from the viewpoints of system architecture, the physical layer and system implementation and take a detailed look at the physical and logical channel implementation. The 2.5 and 3.5/3.75 Generations are also discussed with a description of HSCSD, GPRS, EDGE, HSDPA and HSUPA. Issues of network planning, mobile services and business are also considered in the module and non-mobile systems are introduced. 4th generation systems are covered, in the form of LTE and LTE advanced, at both the physical layers and network architectural aspects (the Evolved Packet Core). Students are also introduced to future concepts through looking at 5G proposals and some of the current research into possible 5G systems.

Intended Learning Outcomes

On completion of this course, students should be able to:

- know and understand the engineering principles of wireless transmission, cellular systems and the different cellular/mobile systems
- analyse and calculate the path loss, fading profiles and effects of multi-path propagation in various cellular environments (based on thorough understanding of the wireless channel)
- develop a thorough knowledge of system architecture, signal formats channel structure and services for GSM, UMTS and 4G/LTE systems.
- analyse error-correcting capabilities of different forward-error correcting schemes and justify the choice of particular schemes for given applications
- understand the standardisation processes of wireless systems and the different cellular generations and be familiar with the IP issues associated with the development of technologies and standards
- compare the different cellular generations and standards in terms of capabilities, technologies (core and wireless access/physical layer), services, cost, complexity and history

- make a learned guess at what is 'next step' in 5G cellular systems development on the basis of a thorough understanding of existing systems and of systems under development

Course Content

- **Introduction**

o Introduction and historical background
o The wireless and cellular environments
o The wireless propagation channel
o Modulation and multiple access techniques (analogue and digital, BPSK, QPSK and QAM, OFDM; TDMA, FDMA and CDMA)

- **GSM**

o System architecture
o The physical layer
o Logical and physical channels
o Data and services
o 2.5 G Basics (HSCSD, GPRS, EDGE, EGPRS)

- **UMTS**

o System architecture
o The physical layer
o Coding and channel allocation
o Network design
o 3.5 and 3.75 systems (HSDPA, HSUPA and HSPA)

- **4th generation systems and LTE**
- LTE system architecture and and evolved packet core (EPC)
- The LTE physical layer
- Beyond 4G and the move towards 5G systems

- **Other aspects and technologies**
- Mobile networks implementation and planning
- Standardization activities and standards structures

Assessment:

A two and half hour unseen written examination will be held under UCL MSc examination regulations at UCL.

Tutorials/Workshops:

A three hour tutorial will follow a week after the completion of the module.

UCL Electronic and Electrical Engineering

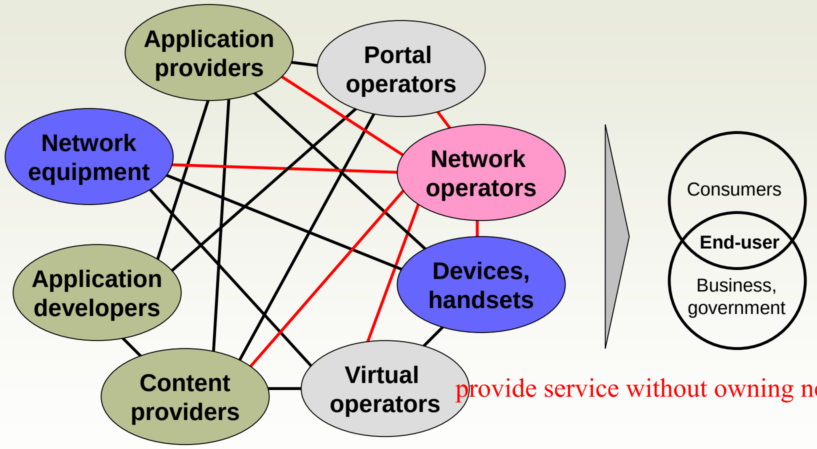
http://www.ee.ucl.ac.uk

Mobile Communications: An Introduction

Professor Izzat Darwazeh
Head of Communications and Information Systems Group
UCL
i.darwazeh@ucl.ac.uk

October 2018

Mobile is a complex business



provide service without owning network equipment

Source: www.lsa.umich.edu/comm/pohs/BauerPohsSlides.ppt

And varied in nature and applications

e-mail

SMS

voice

Multimedia messaging

Instant Messaging

Person to Person

Location services

Tele-metering

Browsing

Person to Machine

Machine to Machine

Parcel tracking

m-money

Games

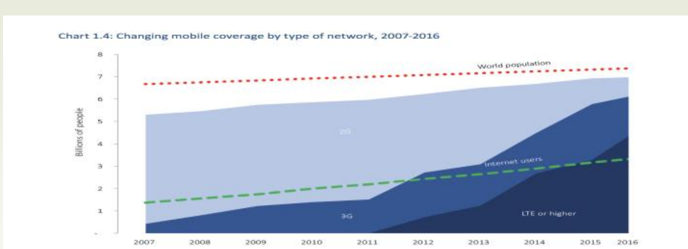
Ringtones

Info services

Health Monitoring

Remote data acquisition

Mobile and the Internet are the fastest developing fields of knowledge and engineering



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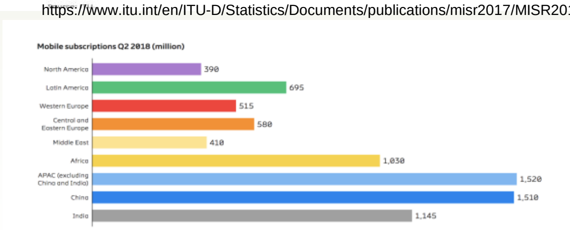
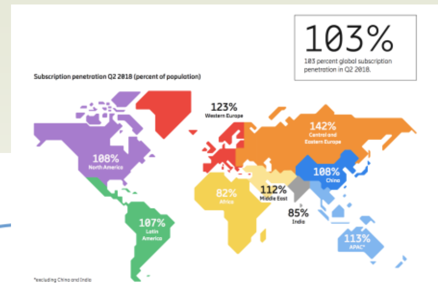
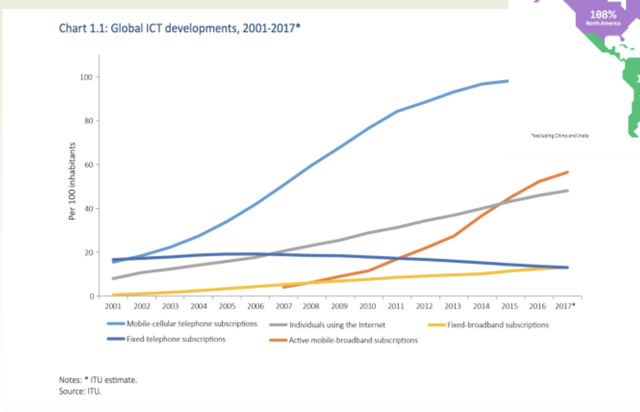


https://www.ericsson.com/assets/local/mobility-report/documents/2018/emr-q2-update-2018.pdf

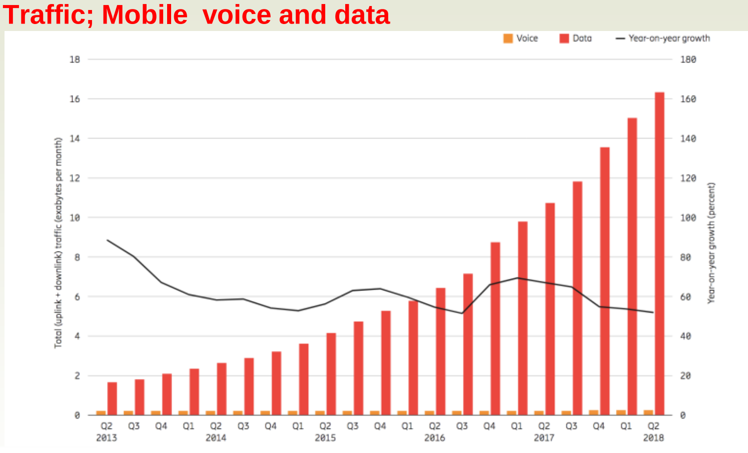
INTERNET and Mobile

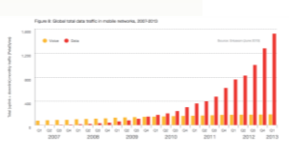


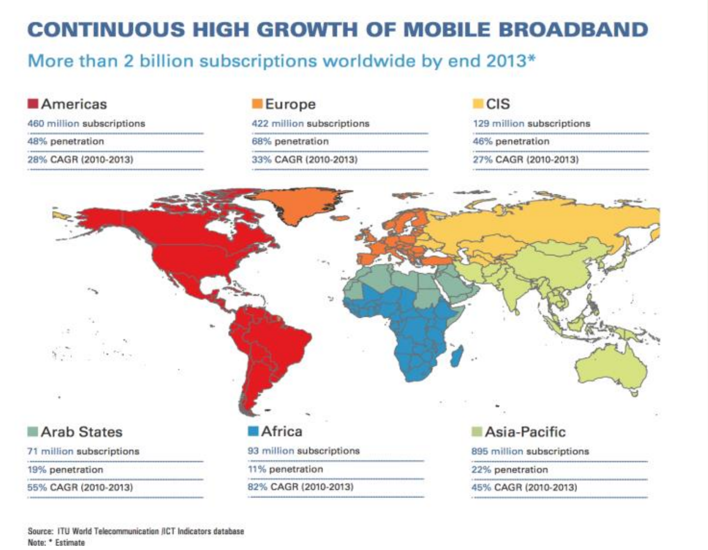


Converged Traffic; Mobile voice and data

Exa Byte =

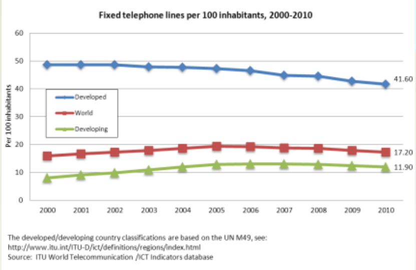


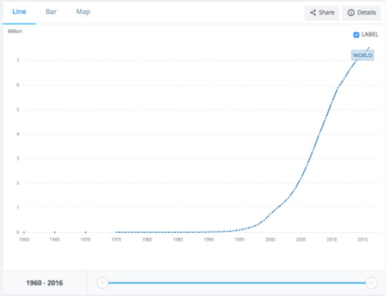


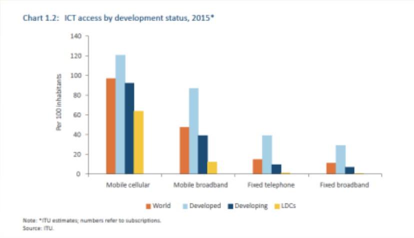


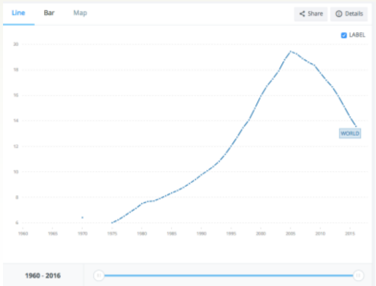
1.2 billion mobile phone lines in 2007

7.2 billion in 2015

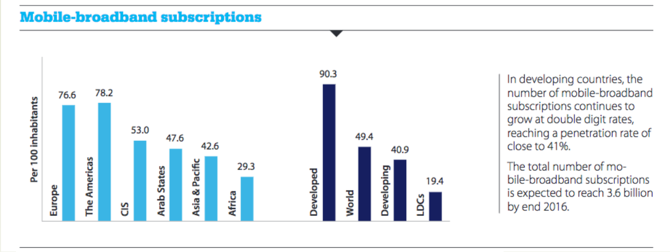


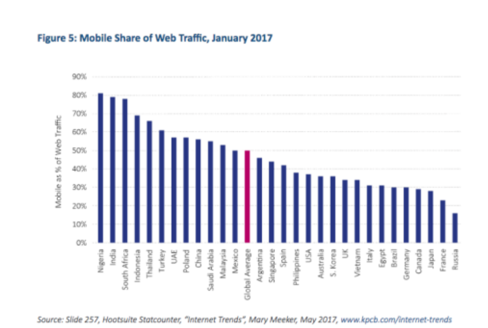






http://www.itu.int/ITU-D/ict/statistics/maps.html
https://data.worldbank.org/indicator/

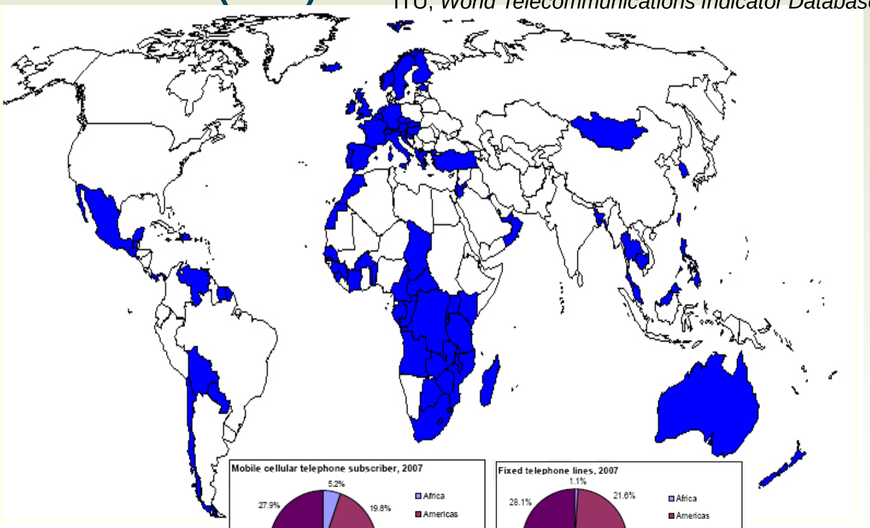


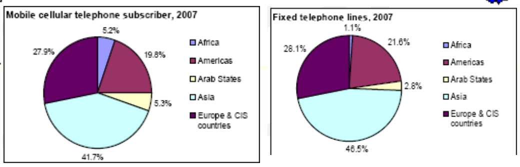


ITU Report "The State of Broadband-2017)
https://www.itu.int/pub/S-POL-BROADBAND.18-2017

Mobile > fixed (2001)

ITU, *World Telecommunications Indicator Database*



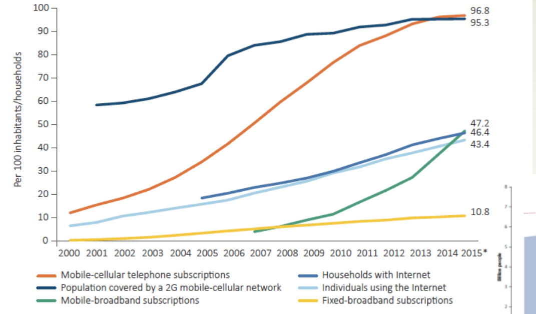


Unpredictable

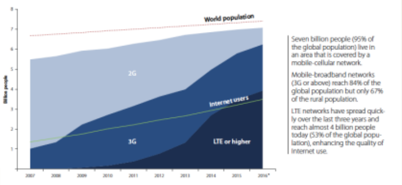
- Examples??

A changing business, difficult to predict!!

Chart 1.1: Global changes in major ICTs, 2000-2015*



Note: *ITU estimates.
Source: ITU.

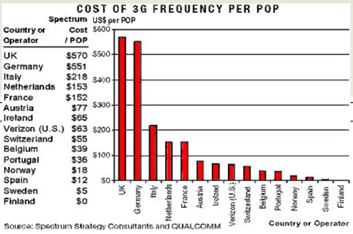


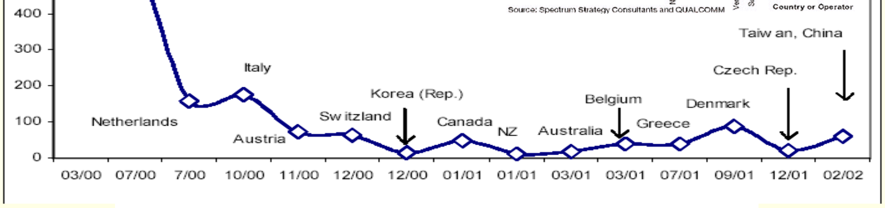
http://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2015/MISR2015-w5.pdf

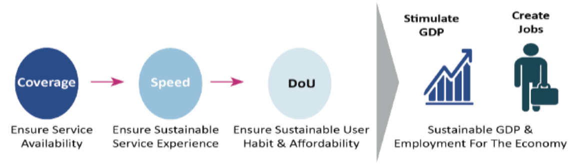
And an expensive/money making one!!
With socio-economic implications

3G spectrum auctions

www.umtsworld.com

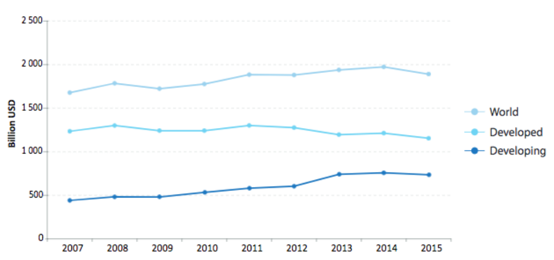






Source: Huawei. Note: DoU means Data of Usage.

Telecommunication revenues, world and by level of development



Source: ITU.

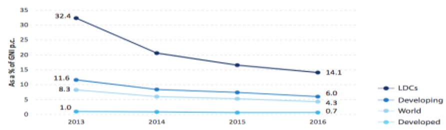
Global telecommunication revenues declined by 4% between 2014 and 2015, falling back to USD 1.9 trillion.

Developing countries saw a compound annual growth rate in telecommunication revenue of 6.6% in the period 2007-2015 whereas developed countries experienced a contraction of -0.8% during the same period.

Developing countries are home to 83% of the global population but generate only 39% of the world's telecommunication revenues.

MOBILE BROADBAND IS MORE AFFORDABLE THAN FIXED BROADBAND

Mobile broadband prices as a percentage of GNI per capita, 2016



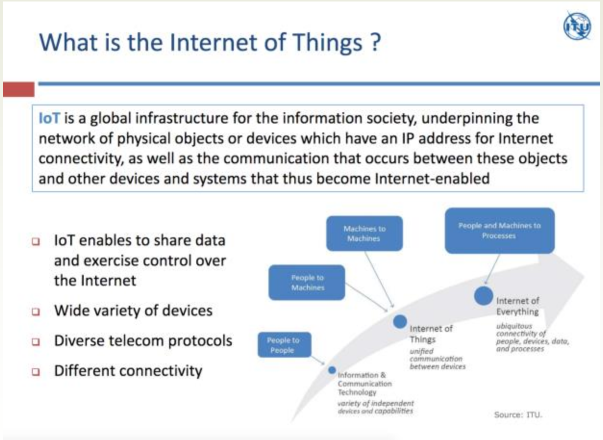
Mobile-broadband prices as a percentage of GNI per capita halved between 2013 and 2016 worldwide.

The steepest decrease ocurred in LDCs, where prices fell from 32.4 to 14.1% of GNI p.c.

Source: ITU.
Note: Based on simple averages including data for 136 countries. Prices are based on entry-level computer-based mobile-broadband plans with a minimum data allowance of 1 GB per month.

And an expanding one beyond predictable bounds

And from 10^6 to 10^9 to 10^{12} devices? IoT



What is the Internet of Things ?

IoT is a global infrastructure for the information society, underpinning the network of physical objects or devices which have an IP address for Internet connectivity, as well as the communication that occurs between these objects and other devices and systems that thus become Internet-enabled

- IoT enables to share data and exercise control over the Internet
- Wide variety of devices
- Diverse telecom protocols
- Different connectivity

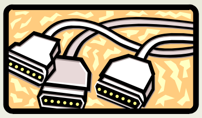
But, that is not what we'll be talking about……….

Instead…

Mobile Technologies

Mobility:

Wired vs Wireless Communication



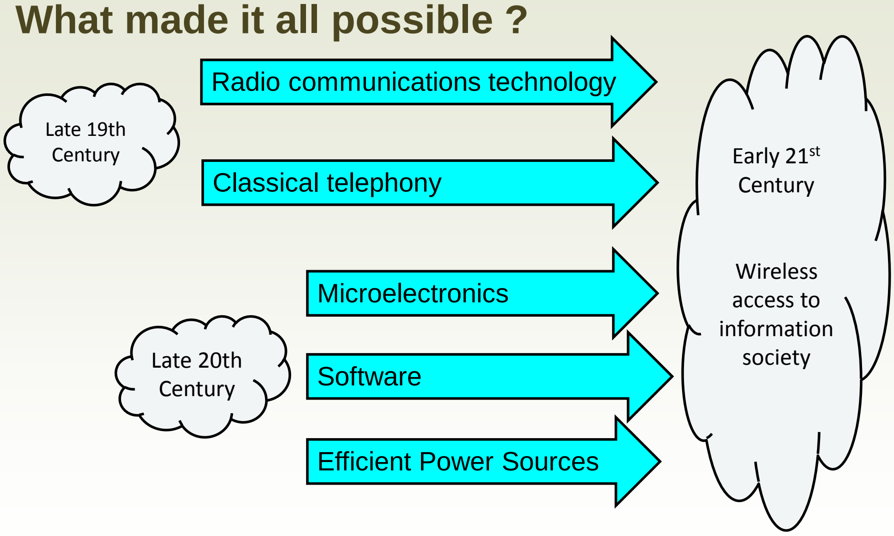
Wired	Wireless
Each wire is a separate “channel “	Only one “channel” shared by all users
Little or no interference from other users	Interference from other users is a major design issue
Low signal attenuation	High signal attenuation
Low channel distortion	High channel distortion
Little or no mobility	High mobility
Low complexity	Medium / high complexity

Agenda

- Some history
- Engineering concept (Cellular, the radio channel...etc)
- GSM and variants
- UMTS
- Non-Cellular wireless (tether-less) systems
- Design of Transmitters and receivers
- A system and business case

1876	Alexander Graham Bell invents the telephone.
1895	Guglielmo Marconi proves the feasibility of radio communications by sending and receiving the first radio signal.
1941	First two-way radio (Motorola) installed in a police car.
1946	The first commercial mobile radiotelephone service was introduced in USA.
1948	Invention of the transistor (Bell Labs)
1977	Experimental cellular systems launched in Chicago and the Washington, D.C.
1979	World’s first cellular system by NTT-Japan
1981	Nordic NMT-450 introduced in Sweden
1983	AMPS system begins commercial operation in Chicago.
1985	European TACS introduced in the UK
1990	First “2G” System (GSM) launched
2003	3G Systems rolled out
2009	First appearance of “4G” Systems (LTE by TeliaSonera and WiMax by Sprint)

What made it all possible ?



What made it possible?

Now, more than 1100 million mobile subscribers exist world wide. This has been possible due to major developments in the areas of:

- Electronics; VLSI, Low noise/low power/high frequency devices, filter technologies,DSP…
- Communication systems; for efficient modulation, coding, compression, security…
- Power sources; for small-long life batteries
- Software; for Signal processing and for system design and network management
- Radio techniques; for channel prediction and assessment techniques
- Telephony; digital telephony, Intelligent Network (IN) and signalling standards

Mobile Generations Summary

Generation	1G	2G	2.5G	3G	4G (LTE)
Design Began	1970	1980	1985	1990	2000
Roll-out	1984	1991	1999	2002	2010
Services	Analog voice, Synchronous data up to 9.6kbps	Digital voice, Short Message Service (SMS)	Packetized data	Broadband data up to 2Mbps	High speed, multimedia data, voice over IP
Standards	AMPS. TACS, NMT	TDMA, CDMA, GSM, PDC	GPRS, EDGE	WCDMA, CDMA2000	Single unified standard
Data Bandwidth	1.9 kbps	14.4 kbps	384 kbps	2 Mbps	1-100+ Mbps
Modulation Schemes	Analog FM	MSK, CDMA	MSK, 8-PSK, 16-QAM	W-CDMA, BPSK and QAM	BPSK, QPSK,16QAM and 64QAM
Multiple Access	FDMA	TDMA,CDMA	TDMA, CDMA	CDMA	OFDMA SC-FDMA
Core Network	PSTN	PSTN	PSTN, Packet network	Packet Network	All IP (Internet)

*Source : J. Ibrahim. 4g features. Bechtel Telecommunications Technical Journal, December 2002. (modified)_*

Designation	Description	Frequency Range
ELF	Extremely Low Frequency	3 to 30Hz
SLF	Super Low Frequency	30 to 300Hz
ULF	Ultra Low Frequency	300 to 3,000Hz
VLF	Very Low Frequency	3 to 30kHz
LF	Low Frequency	30 to 300kHz
MF	Medium Frequency	300 to 3,000kHz
HF	High Frequency	3 to 30MHz
VHF	Very High Frequency	30 to 300MHz
UHF	Ultra High Frequency	300 to 3,000MHz
SHF	Super High Frequency	3 to 30GHz
EHF	Extremely High Frequency	30 to 300GHz

Frequency Bands

Frequencies from 400MHz -1800MHz commonly used by present systems

Examples are:

- 450MHz for NMT
- 900 MHz band for AMPS
- 900MHz band for GSM
- 1800 MHz band for DCS 1800
- 1900 MHz band for PCS 1900 (US-GSM)
- 2000 MHz band for UMTS
- 2.4 GHz for WiFi (and higher)

All propagate at speed of light 300,000 km/s;

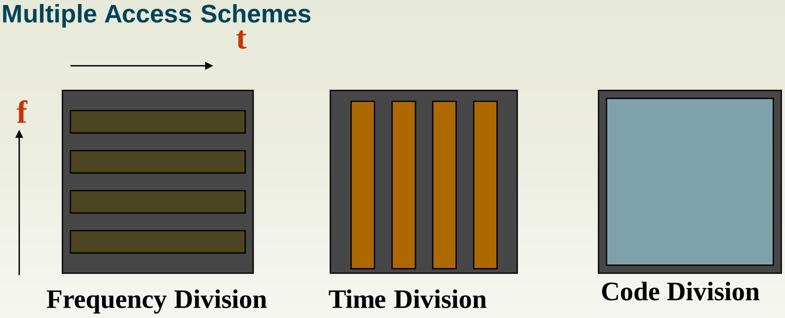
λ is 30 cm@ 1GHz

FDMA and TDMA

- FDMA (Frequency Division Multiple Access) involves dividing the available radio spectrum into channels (RF carriers) with one conversation occupying one (duplex) channel
- Good for analogue
- Bandwidth inefficient

- TDMA (Time Division Multiple Access)
- divides the radio carriers into an endlessly repeated sequence of time slots so that a radio carrier can carry a number of conversations at once
- The bandwidth per carrier must be increased to accommodate TDMA
- Needs complex synchronisation
- TDMA is Digital, used by GSM, DECT, PHP

One resource…Many users!
Multiple Access Schemes



- FDM - allocate frequencies throughout time (FDMA)
- TDM - allocate timeslots over frequency band (TDMA)
- CDM - spread each signal over time and frequency (CDMA)
- OFDMA- User allocation in time and frequency

What is special mobile?

- Cellular structure
  - Frequency re-use
  - Variable signal (service) quality
- Mobile operation
  - Variable location of users
  - Handover

Need special architectures

Deliver new services

Types of Mobility

Nomadic - Not active while in motion.

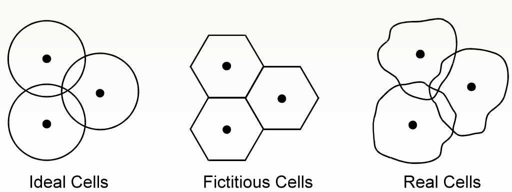
Cellular - Active while in motion.

Micro-Mobility – Small geographic area. Frequent and fast handoffs.

Macro-Mobility – Larger geographic area. Fewer handoffs.

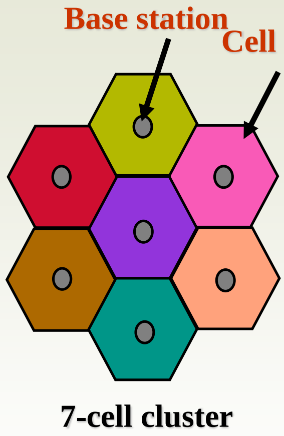
The Cellular Concept

- Frequency is a limited resource. In order to cover a large geographical area, with may users, with a limited frequency resource the area is divided into **cells**, with adjacent cells using different frequencies :
- This means that frequencies can be **re-used** in non-adjacent cells.
- This is an example of **Space Division Multiple Access (SDMA).**



Cellular Systems, GSM

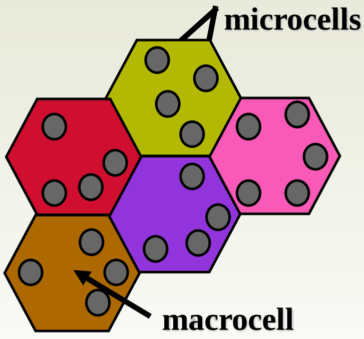
- Within a limited spectrum, main problem is ***Interference***
- Radio coverage of base-stations shown conceptually by hexagons
- One omni-directional antenna at each base station, or few when cell is sectorized
- This allows ***Frequency Reuse***
- Mobiles move within & between cells
- Base stations communicate simultaneously with any mobile
- Hand-off from one cell to another involves change of frequency
- Cell sizes vary: 1 to 35 km in diameter, with small cells employed to increase system capacity. ***WHY?***

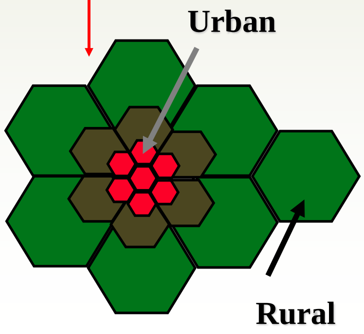


Compromise between cell size and capacity→Network Planning

Techniques to deal with capacity/size

- Cell Sectoring
- Cell Layering
- Cell splitting





Cell Splitting

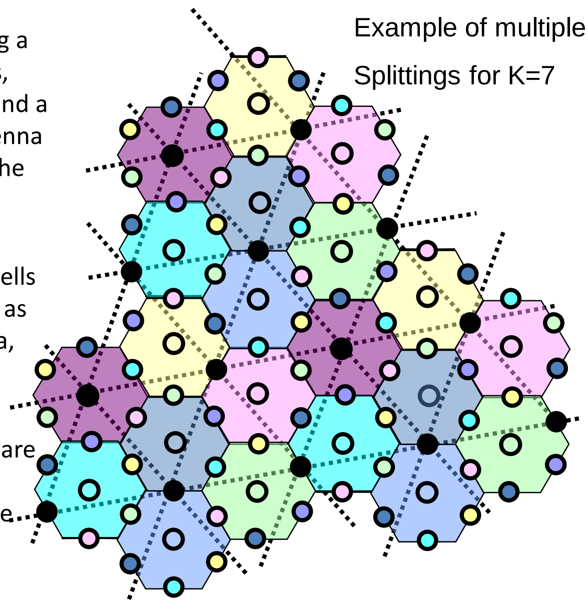
This is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power. The hexagonal pattern is preserved.

When the radius of the parent cells is halved then there are 4 times as many base stations per unit area, giving four times the capacity.

If only small areas of the region are to be "split", the new frequency assignments become much more complex.

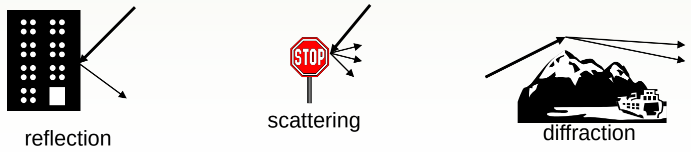
Example of multiple

Splittings for K=7



Signal Propagation

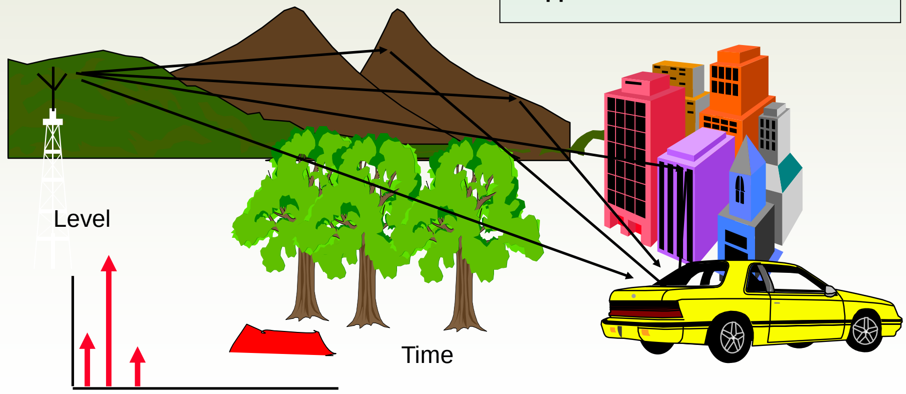
- **Reflection (large obstacles) :** occurs when a radio wave hits a surface with dimensions that are very large compared to the wavelength.
- **Scattering (small obstacles) :** occurs when the radio wave hits an object whose dimensions are on the order of a wavelength or less, and causes energy to be redirected in many directions.
- **Diffraction (edges) :** occurs at the edges of a large obstruction between the transmitter and receiver antennas. Secondary waves are generated behind the obstructing body which cause the original beam to "spread out". The diffraction effect reduces as the frequency gets higher. The higher the frequency the more the radio wave will start to behave like light.



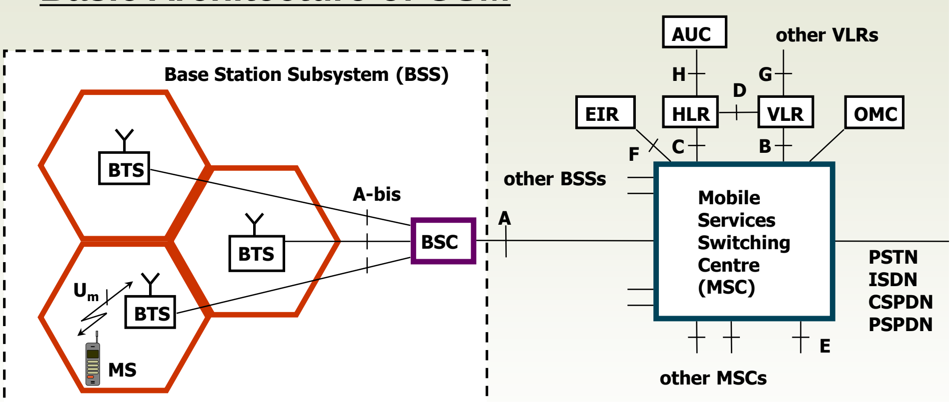
Multi-path propagation

Signal degrades due (mainly) to:

- **Multipath fading and spread**
- **Noise**
- **Multi-user / Access interference**
- **Doppler shift**

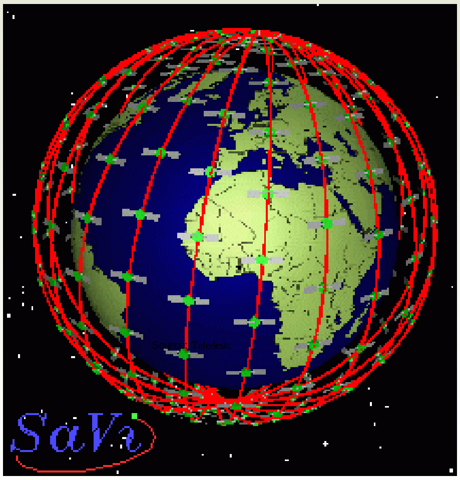


Basic Architecture of GSM

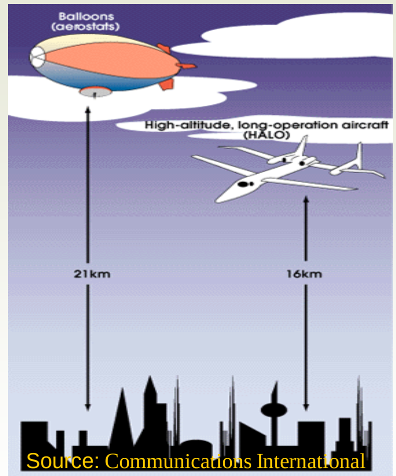


BTS: Base Transceiver Station
BSC: Base Station Controller
HLR: Home Location Register
VLR: Visited Location Register
OMC: Operation & Maintenance Centre
EIR: Equipment Identity Register
AUC: Authentication Centre

Space based Systems



Low Earth Orbit Systems



Stratospheric Platforms

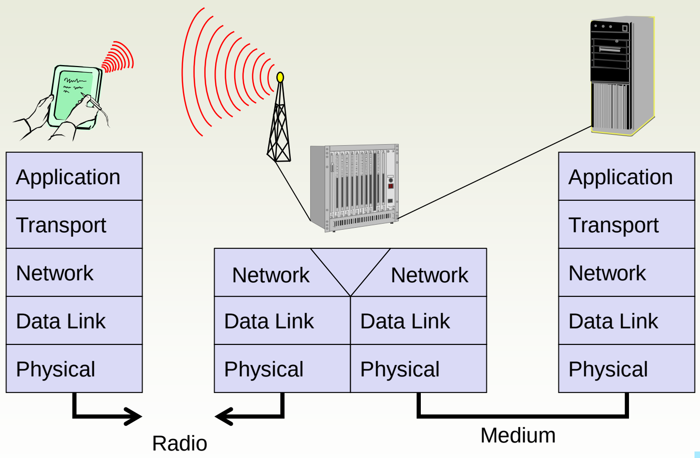
Terminal Evolution
Is it still a phone??

- Fashion item!!
- Video, audio, data, navigation…etc
- Multimode capability
  - GSM varieties/UMTS/Wifi/EDGE/LTE/BT..others
- Colour/touch screens
- Longr battery life
- More emphasis on software features
- A handheld computer with many facilities

LAN Standards

- IEEE 802®: Overview & Architecture
- IEEE 802.1™ Bridging & Management
- IEEE 802.2™: Logical Link Control
- IEEE 802.3™: CSMA/CD Access Method
- IEEE 802.4™: Token-Passing Bus Access Method
- IEEE 802.5™: Token Ring Access Method
- IEEE 802.6™: DQDB Access Method
- IEEE 802.7™: Broadband LAN
- IEEE 802.10™: Security
- IEEE 802.11™: Wireless LAN
- IEEE 802.12™: Demand Priority Access
- IEEE 802.15™: Wireless Personal Area Networks
- IEEE 802.16™: Broadband Wireless Metropolitan Area Networks

Simple reference model used in this course



Ref : Schiller p18

5 layer model : role of each layer

Application layer	service location new/adaptive applications multimedia
Transport layer	congestion/flow control quality of service
Network layer	addressing, routing device location hand-over
Data link layer	authentication media access/control multiplexing encryption
Physical layer	modulation interference attenuation Frequency

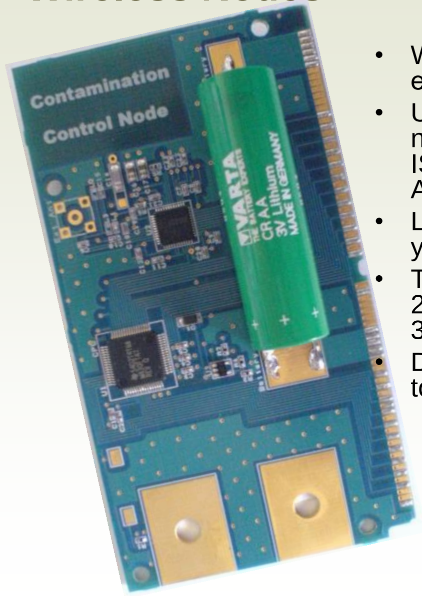
Ref : Schiller p19

Short range data connectivity

- WLANs offer the potential to remove wires from the office and desk
- Can use either infra-red optical systems or low-power radio systems
  - Bluetooth - Low-power radio system on a chip, up to 50Mb/s. 802.15.1.
  - WIGIG- 60 GHz with data rates up to 8 Gb/s. 802.11ad.

  - Other older technologies
  - UWB and High Data Rate WPAN –QoS and video
  - IrDA - infra-red data association

Wireless Nodes

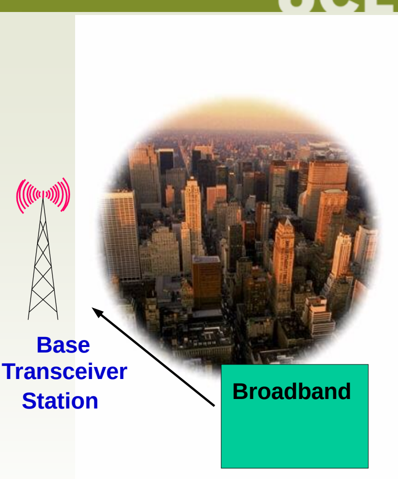


- Wireless communications are vital to enable 'invisible' remote sensing
- UCL has designed and built a wireless node and control software in the 2.4GHz ISM band for a Medical Monitoring Application
- Low Power Consumption – expected life >1 year
- The prototype design 110mm x 60mm x 20mm – expected to reduce to 60mm x 35mm x20mm
- Devices communication with a base-station to relay results to a graphical user interface

John Mitchell, Izzat Darwazeh, Duncan Bain

Fixed Wireless Access

- Fixed wireless access using the mm-wave band and digital carrier modulation can provide high capacity multi-service customer access - e.g. Local Multipoint Distribution Service (LMDS) operating around 28 GHz.
- 5G systems consider 28GHz and above for fixed wireless access with beam forming and steering



To summarise…

References

Several text books exist covering all aspects of MWC and wireless systems, for example:

- Mobile Communications by *J. Schiller* – Addison Wesley
- Wireless Communications by *T. Rappaport* – Prentice hall publishing
- The GSM system for Mobile Communications by Michel Mouly and Marie-Bernadette Pautet
- MobileRadio Networks by Bernard Walkw, Publisher Publisher John Wiley
- UMTS, The Fundamentals by Bernard Walkw, Publisher Publisher John Wiley
- WCDMA for UMTS by H. Holma and A. Toskala, Publisher John Wiley
- Wireless Digital Communications by K. Feher, Prentice hall publishing
- Digital Communications by John Proakis, Publisher McGraw-Hill
- The Mobile Propagation Channel by J. D. Parsons, Publisher John Wiley

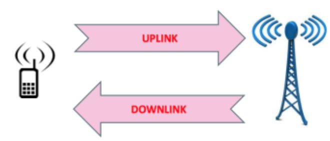
IEE Communications Journal
IEEE Communications Magazine
Also *Thousands* of internet resources. Specific system standards can be found on the ETSI, ITU, IEEE802 web sites and on the IEEE/explore site

http://www.gsmworld.com/
http://www.wi-fiplanet.com/
http://www.3gpp.org/
http://www.4g.co.uk/
http://www.wimaxforum.org/
http://www.zigbee.org/
http://www.uwbforum.org/
http://www.ieee802.org/

The Wireless Propagation Environment

Professor Izzat Darwazeh

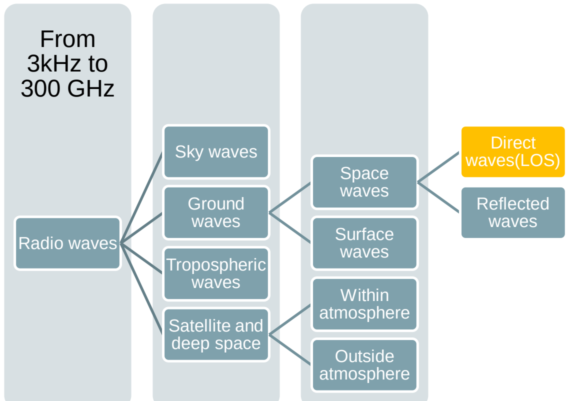
November 2018



The radio channel

- The propagation channel is the cause of many of the problems and limitations of radio systems
- Understanding of its properties is therefore key to the understanding of radio systems
- A line of sight (LOS) path between transmitter and receiver is the normal basis for radio transmission systems
- Some systems rely on ‘bending’ of the radio waves for ‘over the horizon’ communications, some on refraction from the ionosphere, some even on scattering from meteorites! – we’ll concentrate on the more ‘conventional’ systems

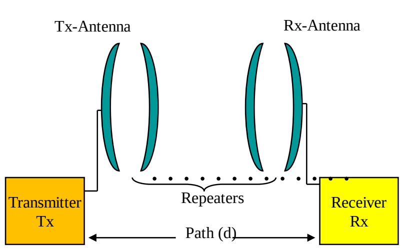
Radio propagation modes and frequencies



ELF <3kHz
VLF 3-30 kHz
LF 30-300 kHz
MF 300kHz-3 MHz
HF 3-30 MHz
VHF 30-300 MHz
UHF 300MHz-3GHz
SHF 3-30 GHz
EHF 30-300GHz
(mm-waves)
THz range >300 GHz

Wavelength = c/f; (1 GHz is ~30cm)

LOS microwave link



Repeaters may be used.
BT has 9000 microwave links for network edge and 1000 for its core network
1.4, 4, 5.8, 6, 18 and 38 GHz for 2 Mbit/s to different SDH delivery.
Some very long distances can work with no repeaters. How and why?

Effective isotropic radiated power (EIRP)

- Directional antennas mean that the power radiated is concentrated in the direction of the receiver
- This means that compared with an isotropic (omni-directional) radiator the transmitter has an apparently higher power
- The extent to which the antenna 'directs' the power is referred to as the antenna gain G
- The effective isotropic radiated power is then:

EIRP = Pt * G

G is not a "real" gain as the antenna is generally a passive device

Path loss

if the antenna is isotropic, there is no Gt. However, if it is directional, there is a Gt.
P is power

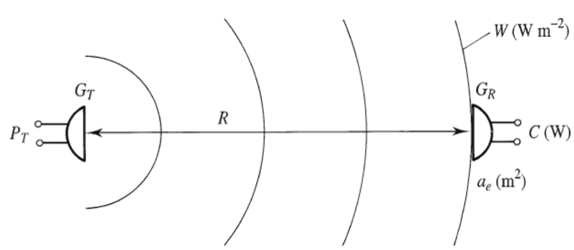
- Normally is the major source of loss (also called Free space loss or LOS)
- Due to the spatial separation between the TX and the RX
- In LOS case loss varies as $(\text{frequency})^2$ & $(\text{distance})^2$

the Gt 'gain' in the context of antenna does not mean that you get more power out than you put in , as would be the case fo r an amplifier. Antenna gain is simply measure of directivity. The higher gain, the more directional is the antenna

$$C = \frac{P_T}{4\pi R^2} G_T a_e$$

$$= \frac{P_T}{4\pi R^2} G_T \frac{\lambda^2}{4\pi} G_R$$

$$= P_T G_T \left(\frac{\lambda}{4\pi R}\right)^2 G_R \quad [\mathrm{W}]$$

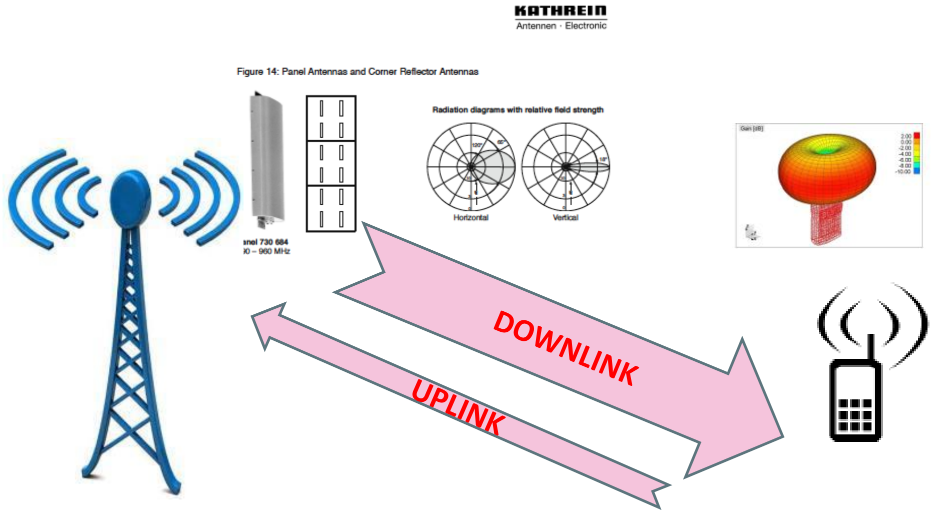


a_e= Antenna effective area
G= Antenna gain

$$L = \left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2$$

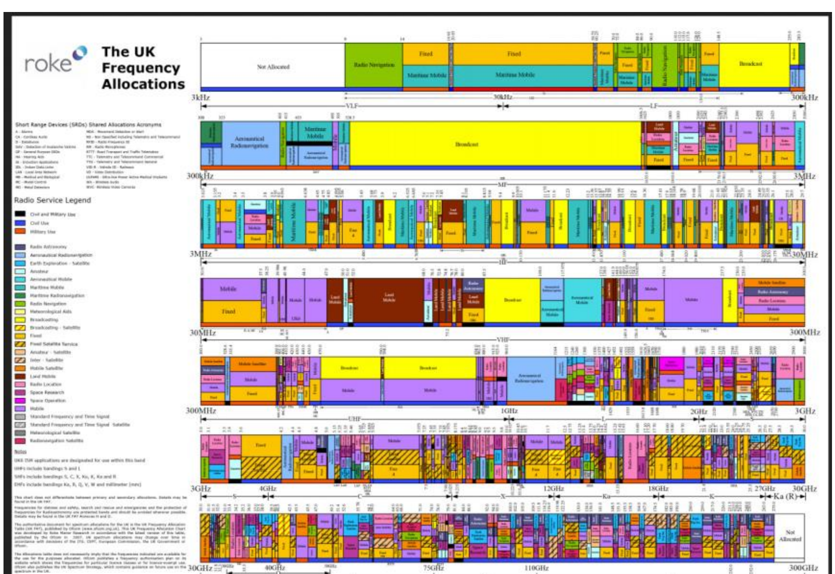
$$L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} d_{km} + 32.44$$

The Mobile Communications Channel



http://www.wipl-d.com/applications.php?cont=emc/mounted-antennas

Radio spectrum



dBm

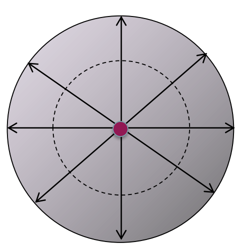
If we take one milliwatt as a reference (i.e. P_2) then we have a unit of absolute power called the “dBm”, which is defined as follows :

$$P_{dBm} = 10\log_{10}\left(\frac{P_1}{10^{-3}}\right)$$

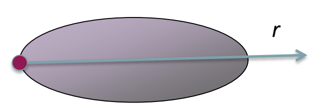
Where P_1 is in watts.

Power (mW)	Power (dBm)
1mW	0 dBm
5 µW	-23dBm
10µW	-20dBm
1 µW	-30dBm
1nW	-60dBm
1pW	-90dBm
1 kW	60 dBm

Antenna gain and directivity



isotropic antenna



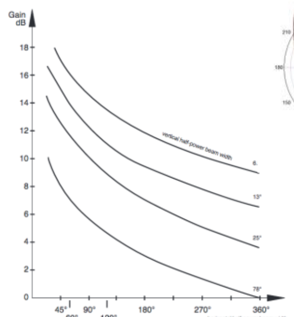
Directional antenna

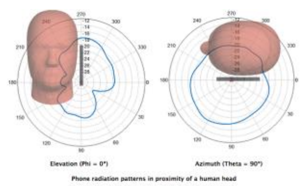
$$P_r = \frac{P_T}{4pr^2}$$

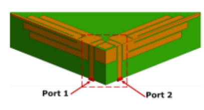
$$P_r = G\frac{P_T}{4pr^2}$$

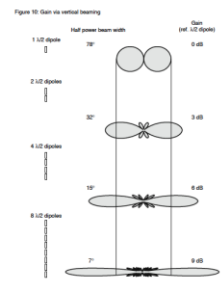
Typical Gain and Beam-width

Type of antenna	G_i [dB]
Isotropic	0
Dipole	2
Helix (10 turn)	14
Small dish	16
Large dish	45



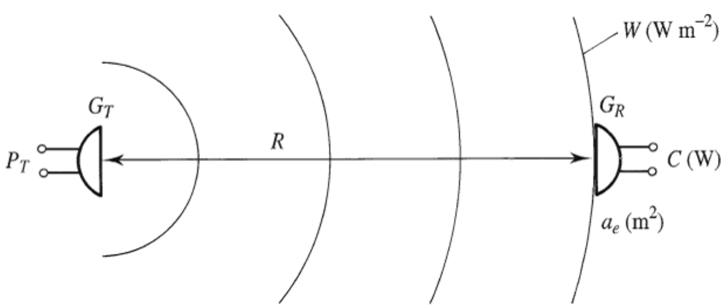






http://www.feko.info/applications/white-papers/design-and-optimisation-of-an-lte-mobile-phone-antenna

Path loss



Given two antennas, the power available at the output of the receiving antenna, P_r, is given by:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

Where G_t and G_r are the antenna gains (with respect to an isotropic radiator) of the transmitting and receiving antennas respectively, λ, is the wavelength, and R is the distance between the antennas.

Path loss

The path loss, being the ratio of transmitted power to received power, is defined as follows:

$$L = \frac{P_T}{C} = \frac{1}{G_T G_R}\left(\frac{4\pi R}{\lambda}\right)^2$$

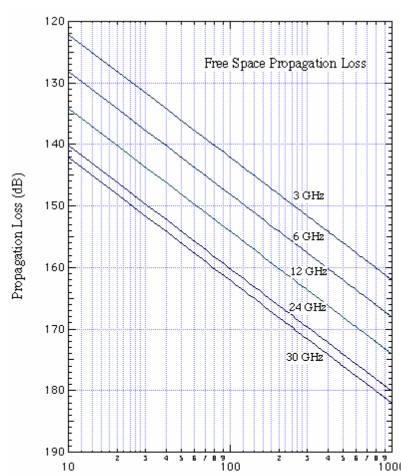
Replacing wavelength with frequency :

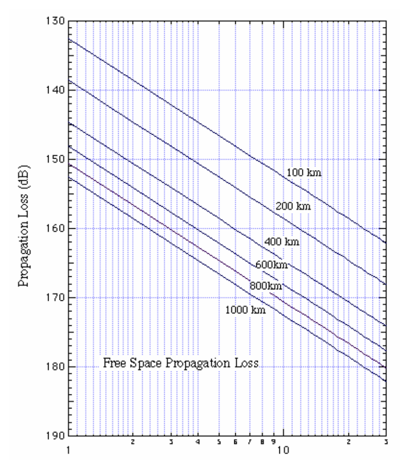
$$L = \frac{1}{G_T G_R}\left(\frac{4\pi R f}{c}\right)^2$$

If we assume both antenna are isotropic, i.e. Gt=GR=1, we can express the path loss equation in dB for convenience, as follows :

$$L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} R_{km} + 32.44$$

Path loss as a function of distance and frequency





Ref. JPL report 2005;

Estimation of Microwave Power Margin Losses Due to Earth's Atmosphere and Weather in the Frequency Range of 3–30 GHz

Link budget example calculation

Separation distance (R) = 500 m
Signal frequency (f) = 2 GHz
Transmitter power (Pt) = 1W (or 30dBm)
TX antenna gain (Gt) = 6 dB
RX antenna gain (Gr) = 2 dB
Total loss from assorted cables, connectors, etc. (Lx) = 0.5dB

First we calculate the free space path loss (also termed LOS):

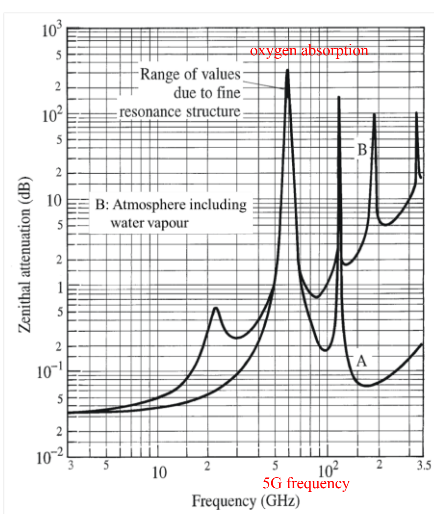
$$L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} R_{km} + 32.44$$

= 20 log (2000) + 20 log (0.5) + 32.33dB
= 66dB - 6dB +32.44dB = 92.44 dB

Total loss = LOS + other losses – (Gt –Gr) ~ 85 dB

Received signal power in dBm is 30 - 85 = -55 dBm = 3 nW

Effects of gaseous absorption

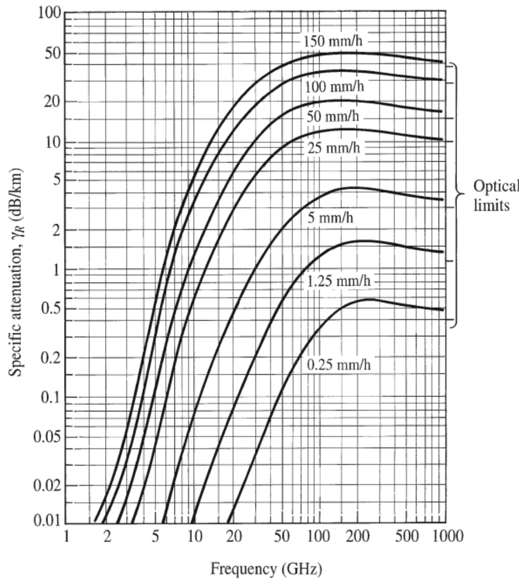


Reference atmosphere surface parameters:

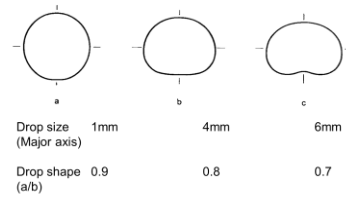
temperature	15 C
Pressure	1013 mb
water vapour	7.5 g/m^3

Specific attenuation due to rain

[After ITU-R, 1996]



Spherical raindrops assumed (therefore no polarisation dependence)



Cloud attenuation

- Liquid clouds
  - small, spherical, water droplets (0 – 10 µm radius)
  - Significant attenuation above 20 GHz
  - Attenuation proportional to total water content (g/m^3)
  - No cross polarisation
- Ice clouds
  - small needles and plates (sub-millimetre in size)
  - Attenuation (dominated by scattering rather than absorption) negligible below 100 GHz
  - Severe cross polarisation

Liquid cloud specific attenuation

Frequency (GHz)	Attenuation (dB/km)
5.0	0.023
10.7	0.106
15.4	0.217
23.8	0.507
31.4	0.859
90.0	4.74

- Clouds occur in many types
- Thicknesses from 100 m to several km
- Attenuation modest but may be present for large fractions of time - significant for low availability systems

[Extracted from Table 7.1, Brussaard, G & Watson, P A: Atmospheric modelling and millimetre wave propagation, Chapman Hall, 1995] (0 °C g/m^3)

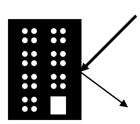
Scintillation

- Rapid fluctuation of signal amplitude and phase due to spatial and temporal variations in refractive index of atmosphere
- Fluctuation time scale - seconds to minutes
- Fluctuation amplitude - up to several decibels
- May result in signal enhancement as well as fades
- Most severe for low elevation-angle systems

Radio versus cable

- Radio transmission fundamentally involves $1/d^2$ reduction in signal strength due to ‘spreading/angular divergence’ of the radio waves
- Cable systems, on the other hand, involve an exponential reduction in signal strength with distance
- Exp(-d) is a much more rapid rate of decay than $1/d^2$ so in principle radio systems should ultimately be more capable of providing greater ‘single hop’ range than cable – although in practice that will depend n the attenuation factor of the cable for any given link
- Optical fibres have very low loss indeed (~0.2 dB/km) and in addition we have optical amplifiers available as a means of compensating for fibre loss, so that this ‘in principle’ ultimate advantage of radio over cable is not commonly applicable in practice

Radio Propagation mechanisms



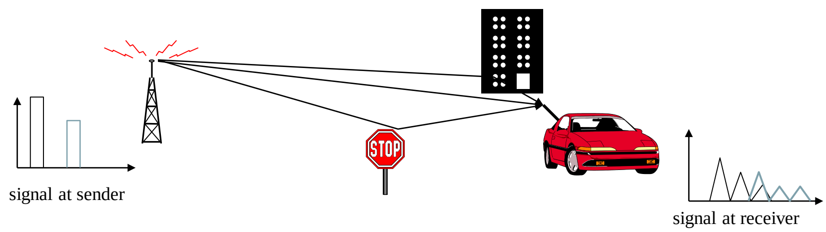
reflection

scattering

diffraction

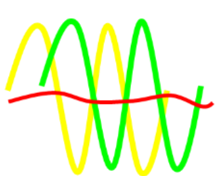
- **Reflection**
  - Propagation wave impinges on an object which is large as compared to wavelength (i.e the surface of the Earth, buildings, walls, etc.)
- **Diffraction**
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around the obstacle, even when LOS (line of sight) does not exist
- **Scattering**
  - Objects smaller than the wavelength of the propagation wave (i.e. foliage, street signs etc.)

Multipath Propagation



Multi-path propagation

- Multi-path propagation causes signals with different phases to add at the receiver
- This can be constructive or destructive - signal amplitude can go from maximum to minimum with a phase change of $\boldsymbol{\pi}$ /2
- Shadowing where there are obstructions between the TX and RX can occur and for access systems more complex arrangements relying on reflected paths are encountered.



handy point: 300 MHz wavelength is 1 metre
3GHz, wavelength is 10cm

signal 1 travels $\boldsymbol{\lambda}$/2 farther than Yellow to reach receiver. For 1 GHz, $\boldsymbol{\lambda}$=30cm.

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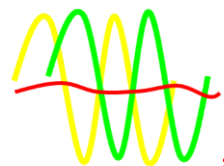
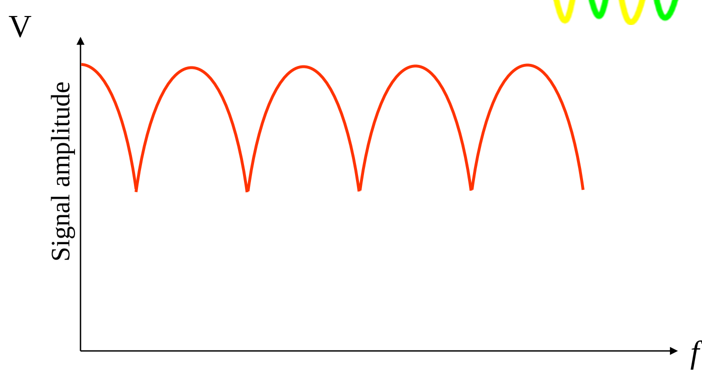
Frequency selective fading





Selective Fading or Selective Frequency Fading refers to multipath fading when the selected frequency component of the signal is affected. It means selected frequencies will have increased error and attenuation as compared to other frequency components of the same signal. This can be overcome by techniques such as OFDM which spreads the data across the frequency components of the signal to reduce data loss.

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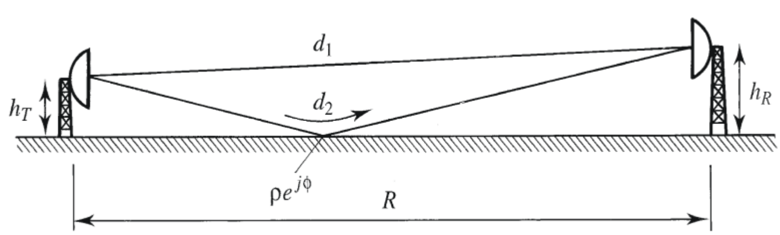
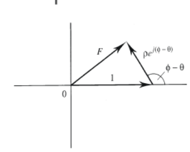
Two ray fading (Plane Earth Propagation)





Received free-space field strength modified by factor *F*:

$$F = 1 + \rho e^{j\phi} e^{-j2\pi\left(\frac{d_2 - d_1}{\lambda}\right)} \cong \frac{4\pi h_T h_R}{\lambda R} \quad \text{for small argument}$$

Received free-space carrier power modified by factor $|F|^2$

P is the reflection coefficient, for earth~1

$$\boxed{P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}}$$

When d>> h_t and h_r

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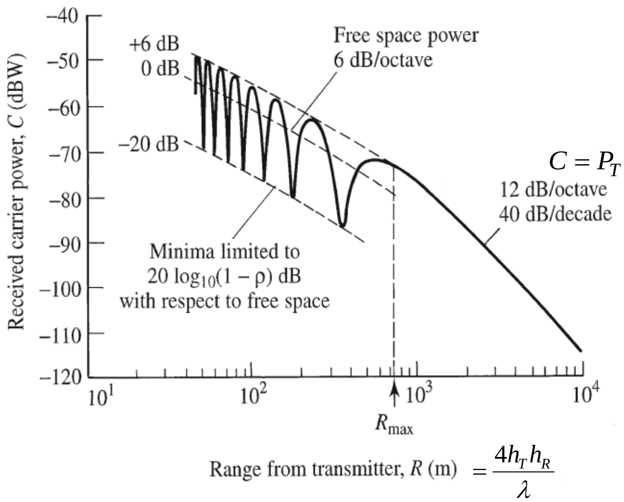
Plane-Earth propagation



For $R > R_{max}$:

$$C = P_T + G_T \underbrace{- 20\log_{10}\left(\frac{R^2}{h_T h_R}\right)}_{L_{PEPL}} + G_R$$

[Note the path loss is *subtracted*]

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Multipath Propagation; Positives and negatives!!

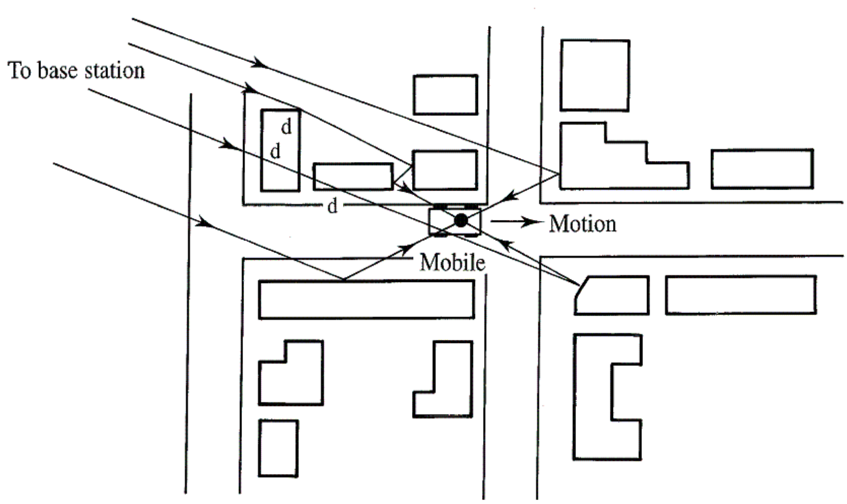
- Enables communication even when transmitter and receiver are not in “line of sight”. This allows radio waves effectively to go through obstacles by getting around them, thereby increasing the radio coverage area.
- Using sophisticated digital signal processing the multipath signals can be used to substantially increase the usable signal power at the receiver.

- Increased signal loss.
- Multiple copies of a signal may arrive at different phases. If phases add destructively, the signal level relative to noise declines, making detection more difficult.
- Intersymbol interference (ISI). One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit, causing interference at the receiver.

Channel and propagation models

- Channel model describes *what* happens
  - gives channel output for a particular input
  - black box
  - requires appropriate parameter (e.g. loss, fading, dispersion statistics)
- Propagation model describes *how* it happens
  - how signal gets from transmitter to receiver
  - how energy is redistributed in time and frequency
  - how the resulting fields 'satisfy' Maxwell's equations
  - can be used to obtain the parameters needed by channel models
- Measurement based (semi-emperical) models
  - Based on simple physical model (e.g. free-space path loss) plus a correction factor derived from measurements
  - If correction factor is simple offset in dB it is referred to as a clutter model and the offset is referred to as a clutter factor
  - Sensitive to changes in environment but probably less so than purely empirical model

Urban multipath propagation



Excess delays up to say 10 s for flat rural areas

d: denotes diffraction

Path loss - obstructed path

multipath means long distance, means more loss.

- Over a non-LOS path the path-loss exponent (α) becomes greater than 2 (e.g. cellular radio systems)
- Can now write the path loss expression as

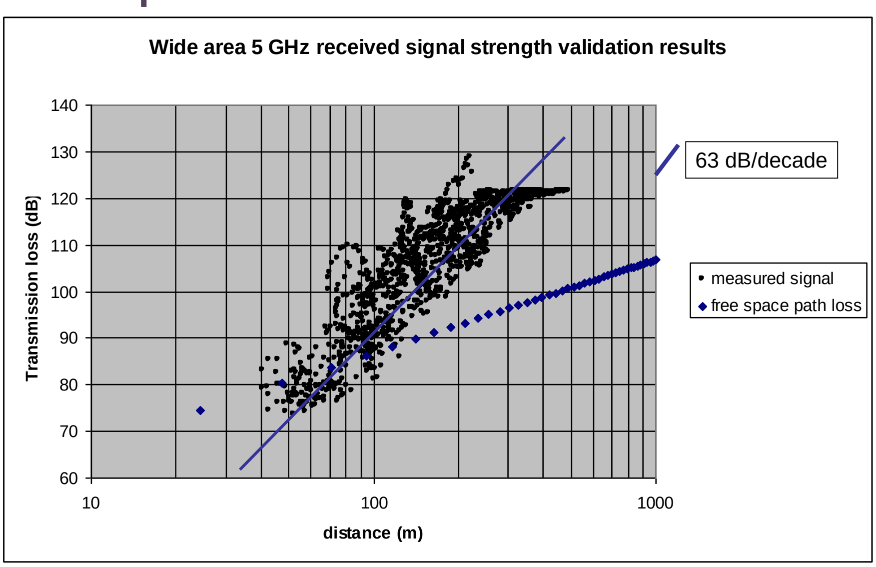
$$L_{dB} = 20\log_{10} f_{MHz} + 10\alpha \log_{10} d_{km} + 32.44$$

- Typical values for the loss exponent α are 3 to 5 in outdoor environments

Free-space	2
Large open rooms	2
Plane Earth (ideal reflection)	4
Urban macro-cells	2.7 – 3.5
Urban macro-cells, shadowed	3 – 5
Indoor, LOS	1.6 – 1.8
Indoor, Corridors	1.4-1.9
Indoor, NLOS (Obstructed path)	4 – 6
Indoor (factory, NLOS)	2 - 3

In door, there is a wall which contributes to enhance the power

Example



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Some specific path loss models

- Hata-Okumura [1]
  - Empirical macrocell model
- Ibrahim and Parsons [2]
  - Semi-empirical macrocell model
- Cost 231 [3]
  - Outdoor model (extension of Hata-Okumura)
  - Indoor (pico-cell) model
  - Building penetration model
- Walfish-Ikegami [4]
  - LOS mode is a simple modification of FSPL (loss ~ $1/R^{2.6}$)
  - NLOS mode supplements FSPL with a roof-to-street diffraction loss and a multiscreen diffraction loss

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Enhanced propagation models (Mobile systems)

typical handset require nW to mW signal strength

- Hata-Okumura model
- takes basic model described above and adds correction factors to accommodate effects such as antenna height, terrain, streets etc
  - based on extensive measurements in *urban* environments
  - corrections presented graphically
  - Hata enhanced the model by establishing empirical relationships to describe Okumura's graphical data
- Often taken as empirical 'reference' model
- Adopted with slight variations by ITU-R

$$L_{Ur,dB} = 69.55 + 26.16\log f_{MHz} - 13.82\log h_{TX} - a(h_{RX}) + (44.9 - 6.55\log h_{TX})\log d_{km}$$

Gives median path loss (L_{ur}) as a function of
frequency in MHz (f_{MHz})
height of the base station in m (h_{TX})
height of the mobile station in m (h_{RX})
range in km (d_{km})

Range of validity
$150 < f_{MHz} < 1500$ (MHz)
$30 < h_{TX} < 200$ (m)
$1 < h_{RX} < 10$ (m)
$1 < d < 20$ (km)

Modelling the radio channel

Hata established a convenient analytical formula based on Okumura's empirical results. The Hata formula was further extended, in the form of the so called "COST231-Hata" model, to support frequencies above the 1500 MHz unsupported by the original Hata formula.

The COST231-Hata model calculates the path loss LD in dB as follows

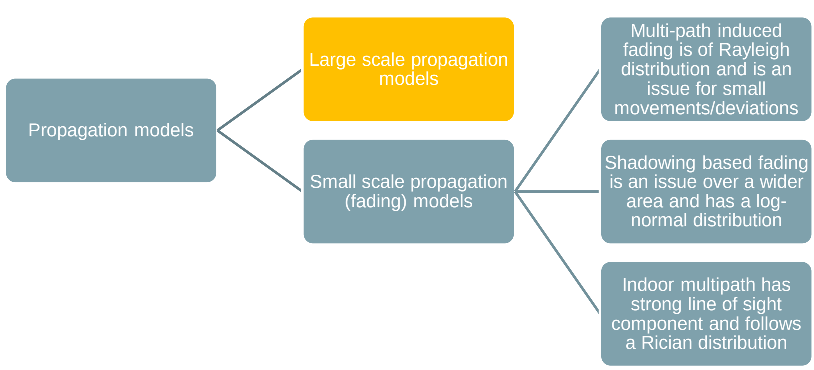
$$L_{dB} = 46.3 + 33.9 \log f_c - 13.82 \log h_t - \mathrm{a}(h_r) + \left(44.9 - 6.55 \log h_f\right) \log D$$

where fc is the carrier frequency in MHz, h_t is the base station antenna height in meters, h_r is the mobile terminal antenna height in meters, and D is the distance between the locations in km. In the formula a(hr) is given as follows :

$$\mathrm{a}(h_r) = (1.1 \ \log f_c - 0.7)h_c - (1.56 \ \log f_c - 0.8)$$

The COST231-Hata formula is applicable to cells with base station antennas above the average rooftop height of the surrounding buildings.

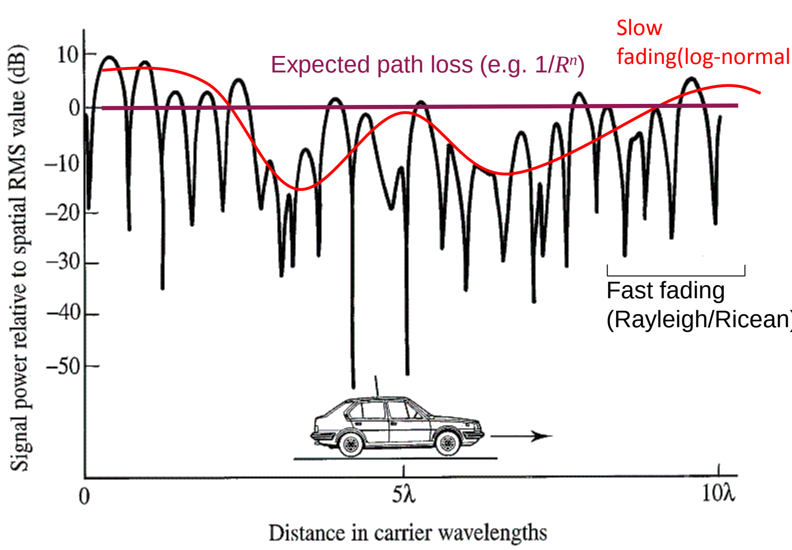
Fading



Fading effects of multipath propagation

- Spatial fading
  - Constructive and destructive interference between signals arising from multiple paths
  - Small-scale or fast fading
  - Importance of interleaving
- Temporal fading
  - Mobile terminal's motion through spatially varying field
  - Also movement of scatterers
- Frequency selective fading
  - Some frequencies will be faded more than others if signals are broadband

Typical multipath fading profile



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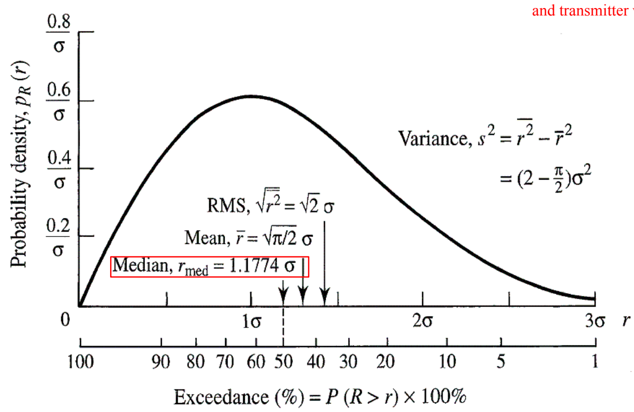
Rayleigh signal amplitude (many paths exist)

equalization can reduce the inter symbol interference

receiver need to estimate the channel so that equalization can work, and transmitter will know how much power has receiver obtained



$$p_R(r) = \begin{cases} \dfrac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, & \text{for } r \ge 0 \\ 0, & \text{for } r < 0 \end{cases}$$

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Ricean channel

- One path dominates
- Pdf of signal envelope is Ricean
- Rayleigh channel + one stronger (often LOS) signal
- Rice-factor, *k*, is defined by:

$$k = \frac{\text{Power of constant (LOS) component}}{\text{Power of random (Rayleigh) component}} = \frac{s^2}{2\sigma^2}$$

where *s* is amplitude of the constant component and σ is RMS amplitude of *either* inphase *or* quadrature part of the random component

Pdf of Ricean fading signal

$$p_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+s^2}{2\sigma^2}} I_0\left(\frac{rs}{\sigma^2}\right)$$

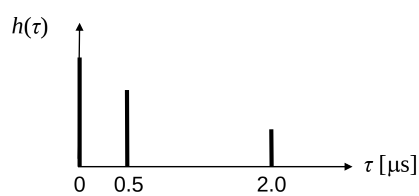
Zero order modified Bessel function of first kind

$$= \frac{2kr}{s^2} e^{-\frac{kr^2}{s^2}} e^{-k} I_0\left(\frac{2kr}{s}\right)$$

$$= \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} e^{-k} I_0\left(\frac{\sqrt{2k}\,r}{\sigma}\right)$$

Note: Ricean pdf tends to Rayleigh pdf as $s \sim 0$ (and $k \sim 0$)

Three-path example

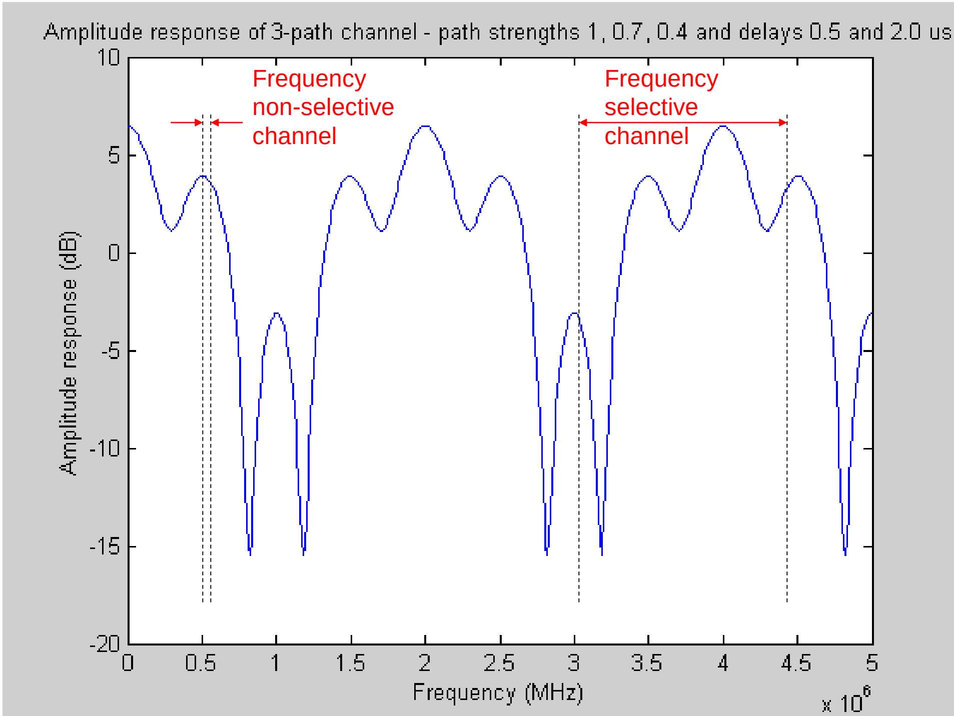


- Three ray channel with impulse response:

$$h(\tau) = 1 + 0.7\delta(\tau - 0.5\times10^{-6}) + 0.4\delta(\tau - 2.0\times10^{-6})$$

- Has the frequency response:

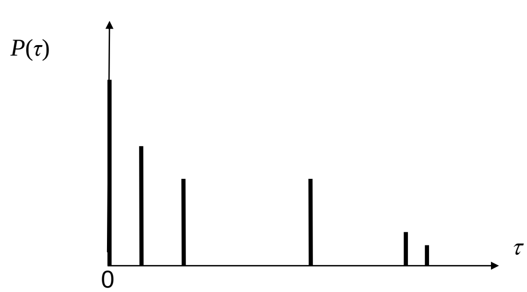
$$H(f) = 1 + 0.7e^{-j2\pi 0.5\times10^{-6} f} + 0.4e^{-j2\pi 2.0\times10^{-6} f}$$



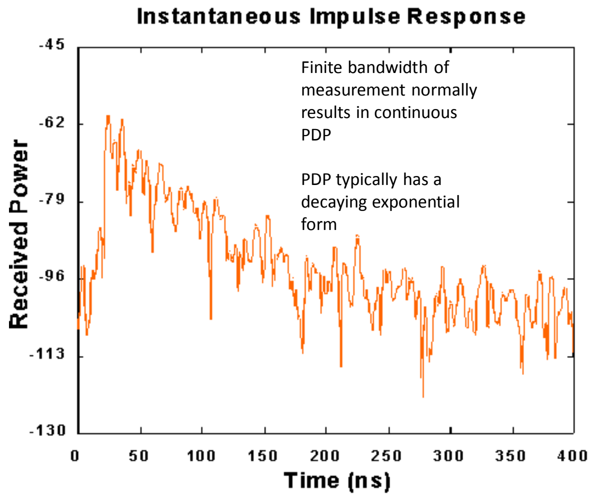
Power delay profile (PDP)

- Power received via the path with excess time delay τ_i is the value (height) of the discrete PDP component at t_i

$P(\tau)$ corresponds to $|h(\tau)|^2$



Example indoor PDP measurement



Typical RMS delay spreads

Environment	RMS delay spread (μs)
Indoor cell	10 – 50 ns
Satellite mobile	40 – 50 ns
Open area (rural)	< 0.2 μs
Suburban macrocell	< 1 μs
Urban macrocell	1 – 3 μs
Hilly macrocell	3 – 10 μs

6-tap outdoor urban model (COST 207) for 900 MHz

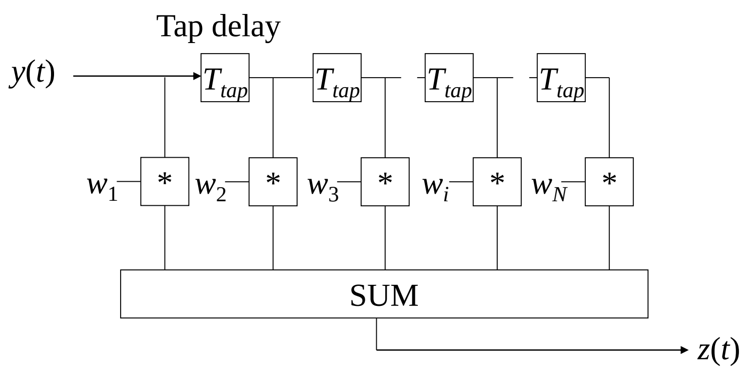
from COST 207 Management Committee: *Digital land mobile radio communications*, Final Report of COST Action 207, Office for Official Publications of the European Communities, 1989.

Tap no.	Delay (μs)	Average power level (dB)
1	0	-3
2	0.2	0
3	0.6	-2
4	1.6	-6
5	2.4	-8
6	5.0	-10

1. Short (direct) path assumed shadowed, therefore 2nd path is strongest
2. Uneven spacing of taps (can be realised in equal spacing implementation) by setting intermediate tap weights to zero
3. A more sophisticated version of this model uses 12 taps

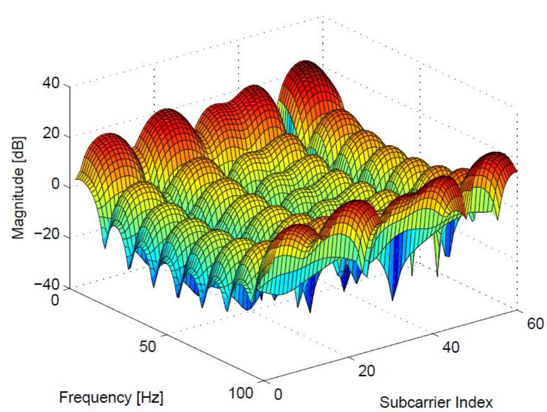
Generic wideband fading simulator

Finite impulse response linear transversal filter (FIR LTF)



In general complex weights, w_i, are time varying, $w_i(t)$

The mobile channel is time varying and frequency dependent



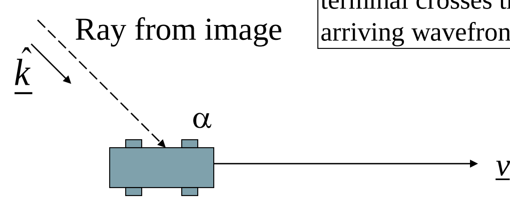
Doppler shift from obliquely incident ray

Doppler shift, f_D, can be thought of as the rate at which a mobile terminal crosses the arriving wavefronts

$$f_D = \frac{-\underline{v}\cdot\hat{\underline{k}}}{c} f_c$$

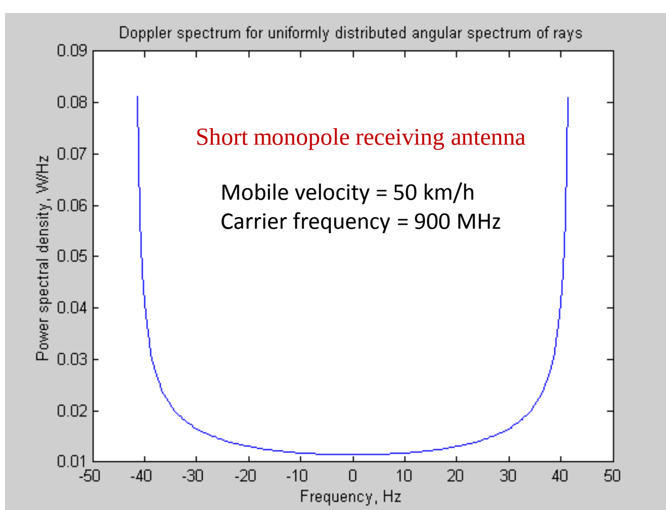
$$\frac{v\cos\alpha}{c} f_c$$

$$= \frac{v}{\lambda}\cos\alpha = f_m \cos\alpha$$



Note $\hat{\underline{k}}$ is the unit vector in the direction of the incident ray, $v = |\underline{v}|$ and f_m is the maximum possible Doppler shift

Doppler spectrum



Link budget calculation

- Using the path loss formula we can easily calculate the received signal strength at a receiver (in dBx)

$$P_{RX} = P_{TX} - L_{dB} + G_{TX} + G_{RX}$$

- The L is a sum of losses, LOS, atmospheric and fading
- For example, if we have a LOS path length of 2 km, a 10 W- 1 GHz transmitter, a TX antenna gain of 10 dB and a RX antenna gain of 0dB then the received power is -78 dBW (-48 dBm)

SNR calculations

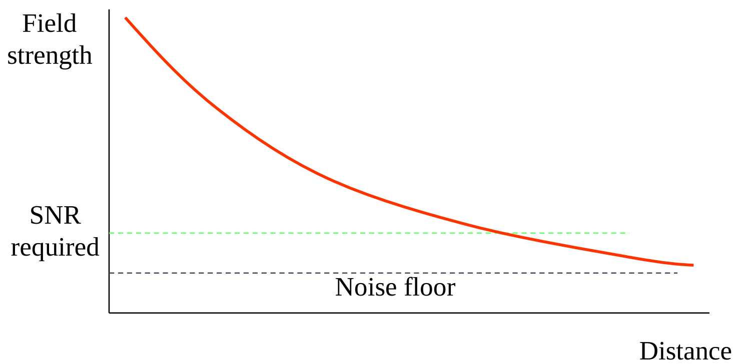
NF: noise figure

- It is relatively easy to extend the above to calculate a SNR at the receiver - this can then be used to predict BER for a digital system

$$SNR_{dB} = P_{RX} - NF_{dB} - 10\log_{10}(kTB)$$

- As an example, consider the above system where the power at the RX was -78 dBW, if the system had a bandwidth of 500 kHz and a NF of 5 dB the SNR would be 64 dB

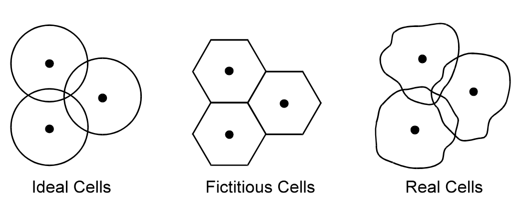
Noise limited service area



The Cellular Concept

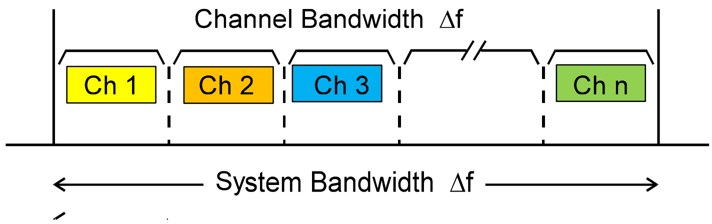
- Frequency is a limited resource. In order to cover a large geographical area, with may users, with a limited frequency resource the area is divided into **cells**, with adjacent cells using different frequencies :
- This means that frequencies can be **re-used** in non-adjacent cells.
- This is an example of **Space Division Multiple Access (SDMA).**

Cellular Antenna



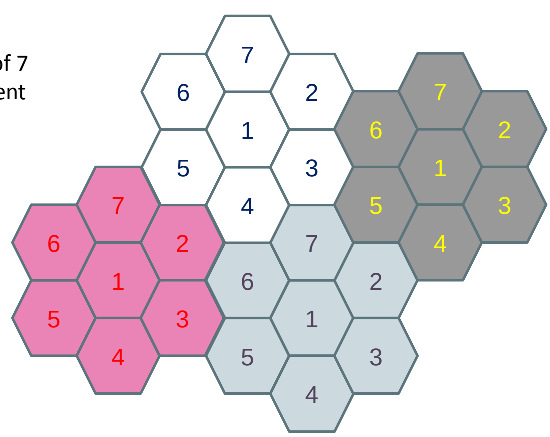
Frequency Reuse

- Each base station or cell is allocated a finite number, n_c, of frequency (or code) channels.
- Only a finite number, n, of frequency channels available in the system.
- The spectrum is partitioned into clusters of size $K = n / n_c$ with one cluster allocated per base station.
- Remember that this partitioning need not to be uniform



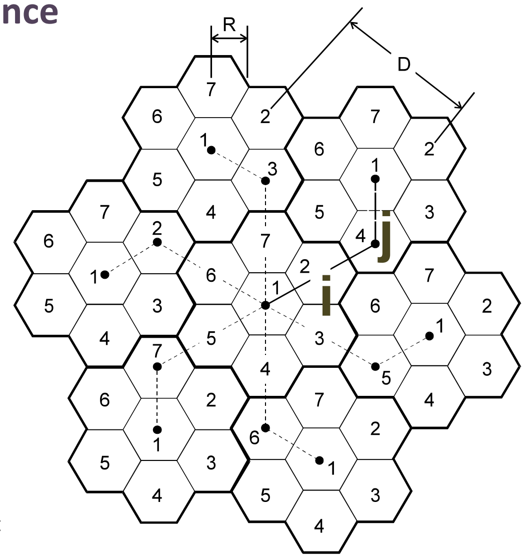
The Cellular Concept

Cellular system based on clusters of 7 hexagonal cells each using a different frequency band.



Frequency Re-use Distance

- In order to provide complete cellular coverage of an area it is necessary to re-use the clusters of frequency channels associated with base stations.
- Frequency re-use introduces the risk of co-channel interference between cells using the same frequencies. To keep co-channel interference low, base stations using the same frequencies must be separated by a minimum distance called the **frequency re-use distance** (D) as shown opposite.
- To find the nearest co-channel neighbour of a cell, move i cells along any chain of hexagons, turn 60º anti-clockwise and move j cells. There are at most 6 nearest co-channel cells.



Cell Cluster with K= 7

Frequency Re-Use Distance

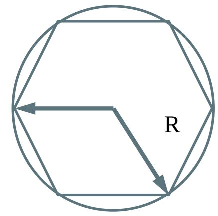
- The **frequency re-use distance**, D, is related to the **cluster size**, K.
- K is also called the **frequency re-use pattern** or the **cell repeat pattern**.
- K is specified in terms of the offset of the centre of a cluster from the centre of an adjacent cluster. For example, with K = 7 and if the centre cell is cell 1, then the next cell 1 is offset by i = 2 cell diameters to an intermediate cell and a further j = 1 cell diameter from that intermediate cell.

$$\boxed{K = i^2 + ij + j^2}$$

- Common cluster sizes are K = 4 (i = 2, j = 0) and K = 7 (i = 2, j = 1) for city centres and K = 12 (i = 2, j = 2) for rural areas.
- The ratio of reuse distance, D, to cell radius, R, is defined by :

$$\boxed{\frac{D}{R} = \sqrt{3K}}$$

Frequency Re-Use Distance



For a cell radius R, the frequency re-use distance D for an hexagonal cell, as a function of cluster size, plan is given by:

i \ j	0	1	2	3
0	0	1	4	9
1	1	3	7	13
2	4	7	12	19
3	9	13	19	27

Cluster Sizes K

K	D
3	3R
4	3.46R
7	4.58R
12	6R

Re-Use Distances

Example

If a total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to support full duplex voice, compute the number of channels available per cell if the system uses (a) 4-cell reuse, (B) 7-cell reuse and (c) 12-cell reuse.

Given:

Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz x 2 simplex channels = 50 kHz/duplex channel

Therefore, total available channels = 33,000/50 = 660 channels

(a) For K = 4 : Total number of channels available per cell n_c = 660/4 = 165 channels

(b) For K = 7 : Total number of channels available per cell n_c = 660/7 = 95 channels

(c) For K = 12 : Total number of channels available per cell n_c = 660/12 = 55 channels

(Note : Does not include control channels)

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Cell size implications and characterisation

- For a given number of channels being available, using smaller cells increases the total capacity of a system
- With smaller cells though, coping with a moving mobile becomes harder since handovers have to be done more frequently
- Large cells can be split into smaller micro- or pico-cells in areas where traffic demand is very high
- New systems use femtocells!!

Cell Type	Base Station/ Antenna Location	Cell Diameter
Macrocell	Above rooftop level	1-30km
Large cell (urban)	Above rooftop level	3-30km
Small cell (urban)	Above rooftop level	1-3km
Microcell	Below/at rooftop level	0.1-1km
Picocell	Below rooftop/in building	0.01-0.1km

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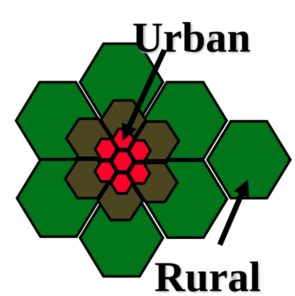
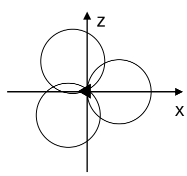
Improving Coverage and Capacity in Cellular Systems

- As demand for cellular services increases, the number of channels assigned to a cell eventually becomes insufficient. At this point cellular design techniques are required to provide more channels per unit coverage area.
- Invariably, these techniques stem from the capacity equation shown earlier and often involve procedures that reduce the cell size or attempt to reduce the amount of co-channel interference in the system and hence reduce the frequency reuse factor.
- Some of the main approaches used are:
  1. **Cell Splitting :** introduce smaller cells in an orderly manner based on existing cell plan.
  2. **Sectoring :** using directional antennas to control interference and frequency reuse
  3. **Microcell Zoning :** a special technique using microcells within a macrocell

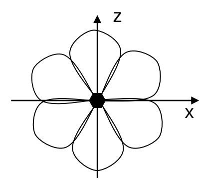


Sectorisation

- By using directional antennae on a base station, each pointing in different directions, it is possible to **sectorise** the base station so that several different cells are served from the same location.
- Typically these directional antennas have a beamwidth of 65 to 85 degrees. This increases the traffic capacity of the base station whilst not greatly increasing the interference caused to neighboring cells.
- Typically two antennas are used per sector, at spacing of ten or more wavelengths apart. This allows the operator to overcome the effects of fading due to physical phenomena such as multipath reception.



top view, 3 sector



top view, 6 sector

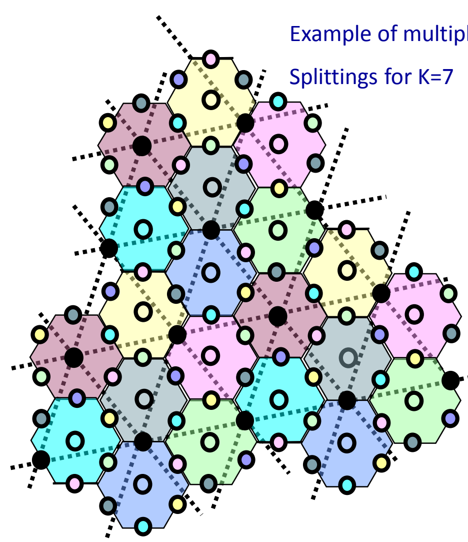
sectorized antennas

Cell Splitting

This is the process of subdividing a congested cell into smaller cells, each with its own base station and a corresponding reduction in antenna height and transmitter power. The hexagonal pattern is preserved.

When the radius of the parent cells is halved then there are 4 times as many base stations per unit area, giving four times the capacity.

If only small areas of the region are to be "split", the new frequency assignments become much more complex.



Example of multiple

Splittings for K=7

Adjacent Channel Interference

- Adjacent Channel Interference (ACI) is the interference which results from signals which are adjacent in frequency to the desired signal. ACI is caused by imperfect receiver filters which allow near-by frequencies to leak into the passband.
- One example of ACI, also known as the near-far effect, occurs when a mobile close to the base station is received with strong power while another mobile far from the base station is received with weak power. Spectral spill-over from the strong signal can drown the weak mobile signal.
- To avoid the near-far effect, cellular systems use **Power Control** at the serving base station.
- Up-link power control attempts to regulate each mobile's transmit power keeping it to the minimum to achieve required Quality of Service targets.

Summary

- Looked at the basic ideas behind radio propagation
- Seen how signal strength may vary and factors for such variation
- Looked at the causes and effects of fading
- Related propagation to cellular architectures and frequency reuse
- Calculation of link budget

MSc Telecommunications programmes

Mobile Communications Systems (MCS)

Mobile Communications Systems (MCS)

Modulation techniques for wireless systems

Dr Clive Poole
Principal Teaching Fellow - University College London

Monday 29th October 2018

Lecture outline

- **Part 1 : Systems, signals and noise**
  - Generic radio communications system.
  - Introduction to signals and noise.
- **Part 2 : Basic Modulation Schemes**
  - The need for modulation.
  - Single carrier digital modulation (ASK, FSK, PSK).
- **Part 3 : Higher Modulation Schemes**
  - Quadrature amplitude modulation (QAM).
  - Multi carrier modulation schemes.

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Part 1 : Systems, signals and noise

3

Analog versus Digital Communications

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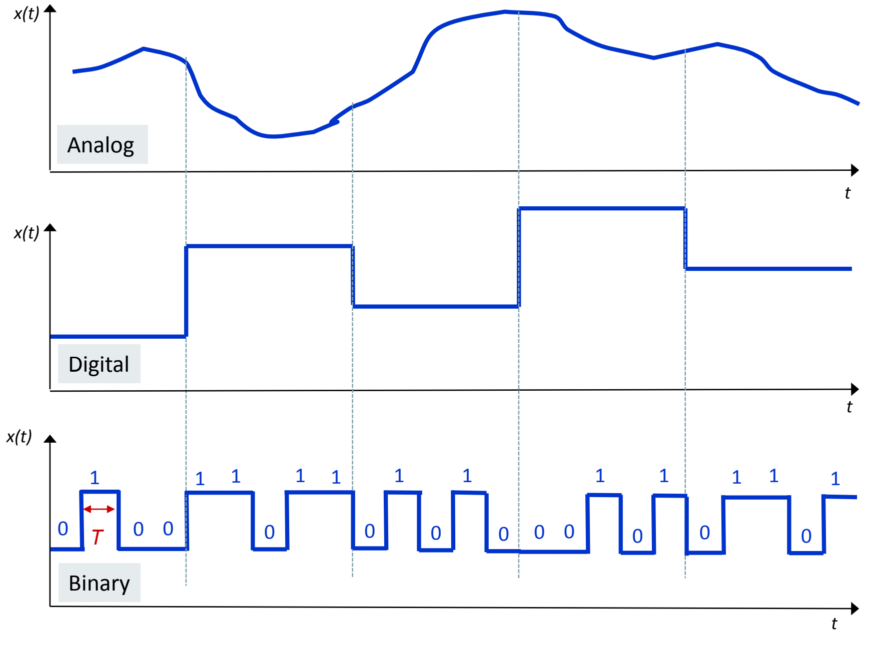
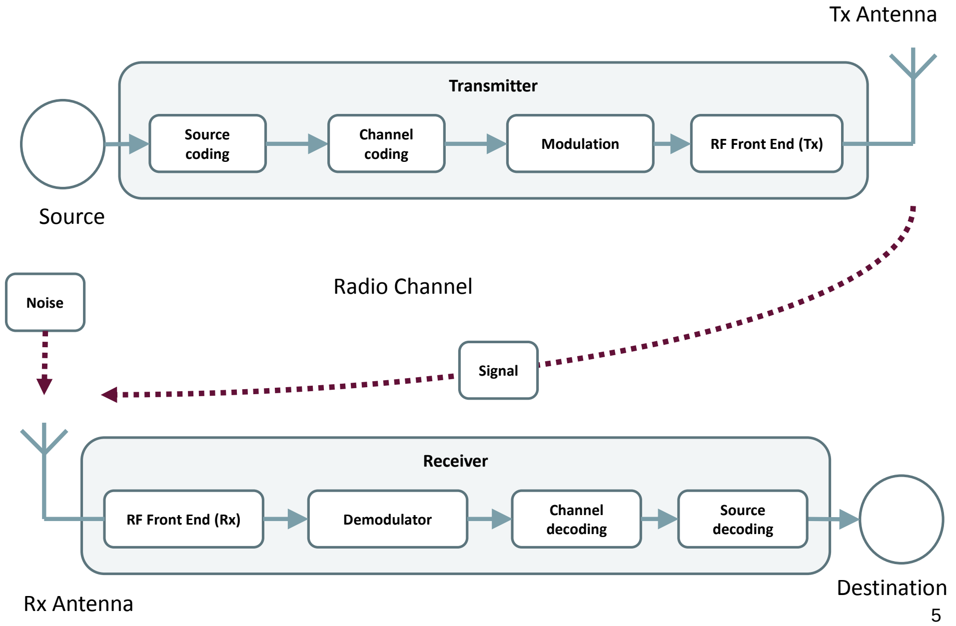


Generic digital radio communications system

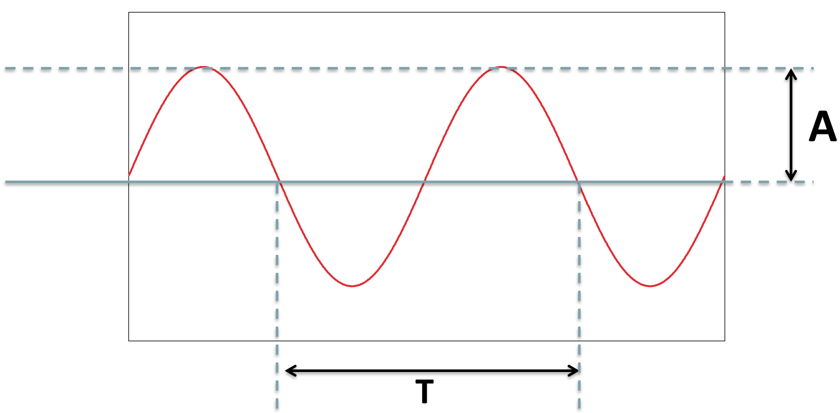


5

Signals

$$v(t) = A\cos(\omega t + \phi)$$

Amplitude Frequency Phase

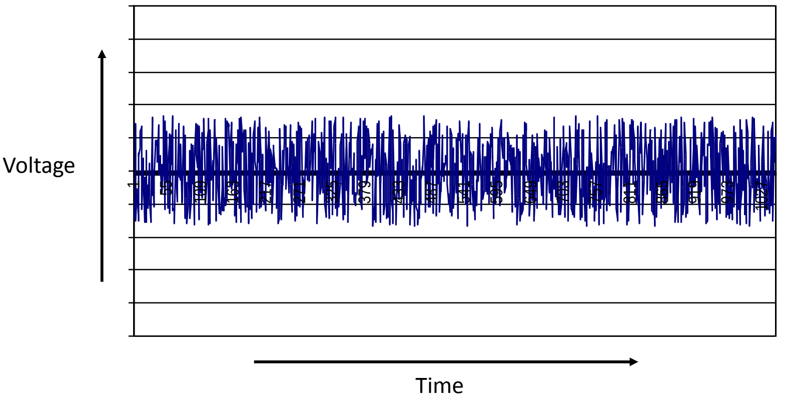


Typical Thermal Noise waveform

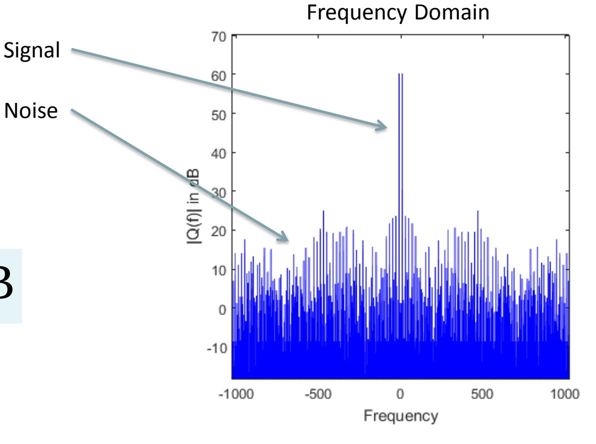
$$v_n = \sqrt{4k_B TRB}$$

$$N_o = k_B TB$$

- k_B Boltzmann's constant 1.3807×10^{-23} [J/K]
- T is absolute temperature [K]
- R is the resistance of the circuit [Ω]
- B is the measurement bandwidth [Hz]



Noise power spectral density

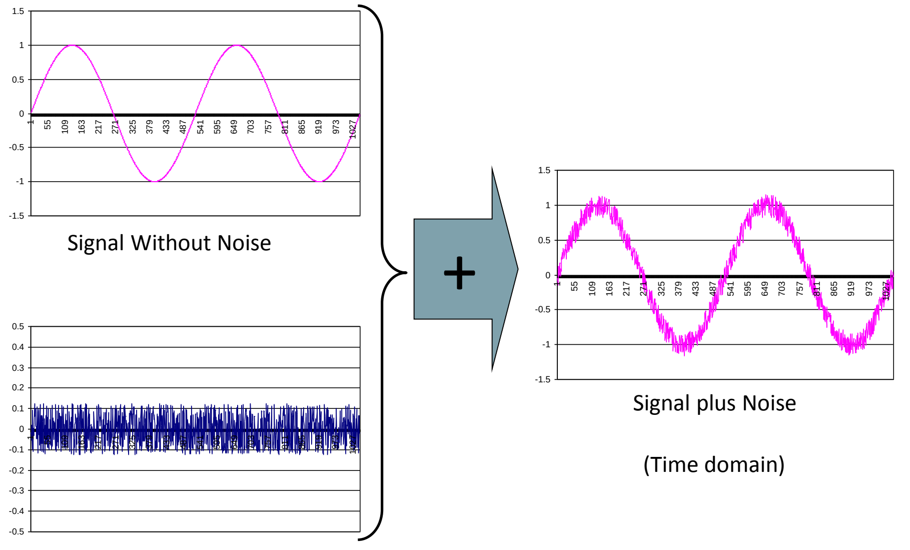


$$N_o = k_B TB$$

$$N_{o(dB)} = 10\log(k_B) + 10\log(T) + 10\log(B)$$

$$= 10\log(T) + 10\log(B) - 228.6 \text{ dBW}$$

Signal plus noise



Signal Without Noise

Noise

Signal plus Noise

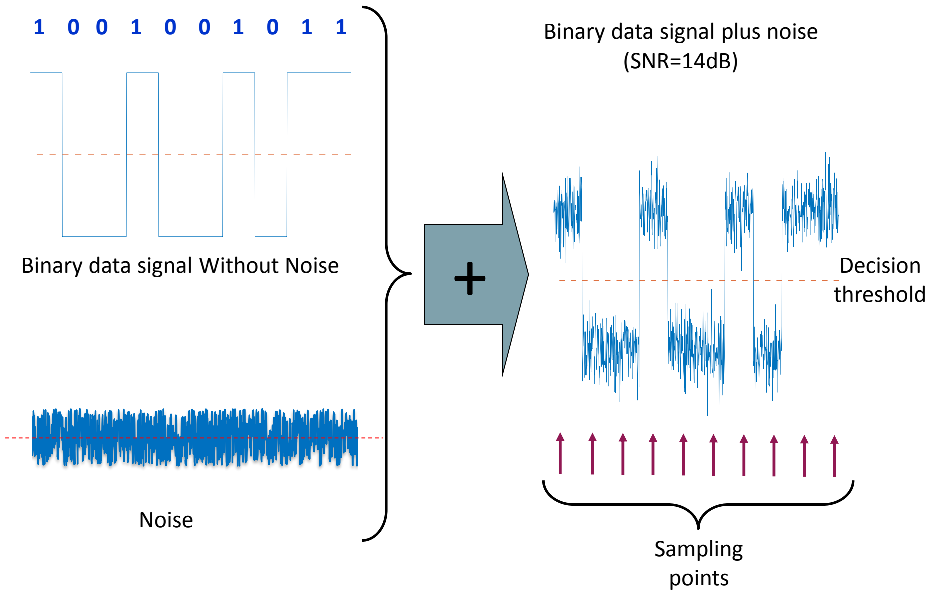
(Time domain)

Signal to Noise ratio

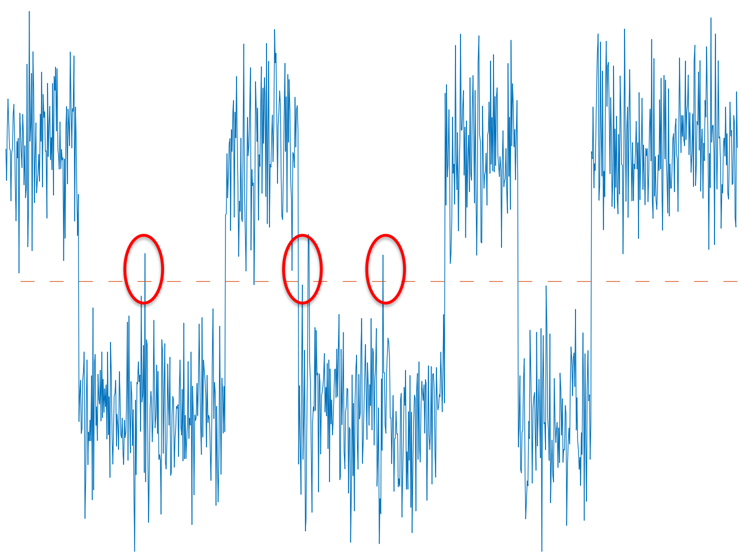
- We need a way to quantify the amount of noise that we are dealing with, by relating the noise power to the signal power.
- The commonly used metric is the signal-to-noise ratio, or SNR, which is a ratio of ‘signal (wanted) power’-to-‘noise (unwanted) power’ expressed in decibels.
- The formula for calculating SNR is shown here, where Ps is the signal power and Pn is the Noise power. The lower the signal to noise ratio the more ‘noisy’ our signal will be and the more difficult it will be to recover the information from it.

$$SNR_{dB} = 10\log\left(\frac{P_s}{P_n}\right)$$

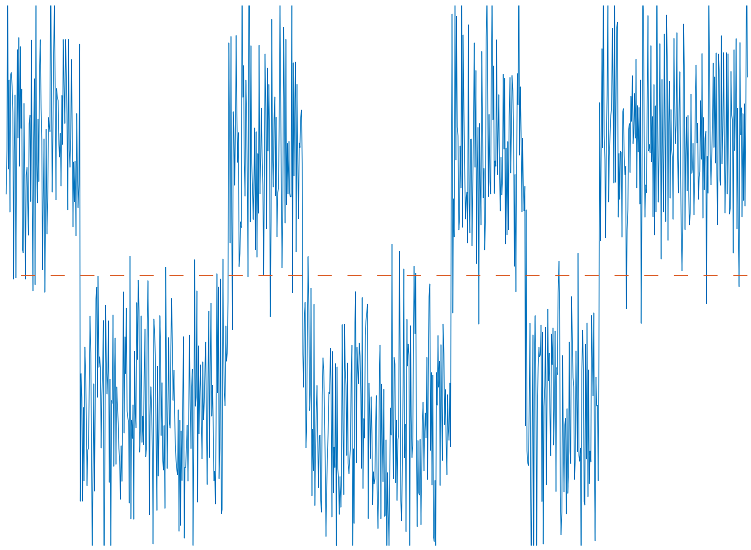
Noise in data signals



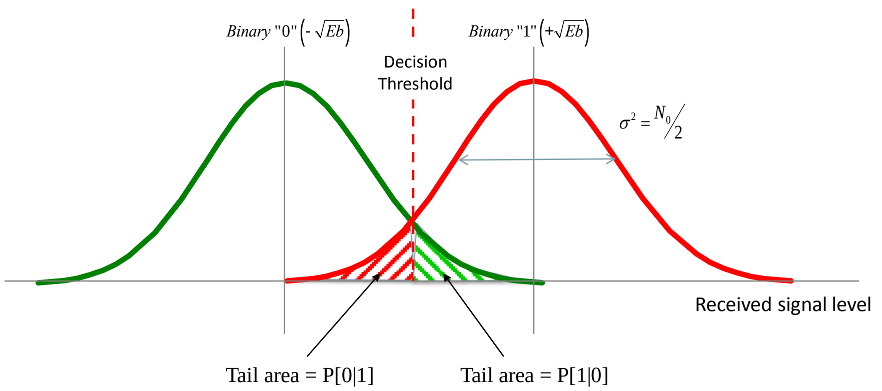
Data signal with noise (SNR=11dB)



Data signal with noise (SNR=8dB)



Bit Error Rate (BER)

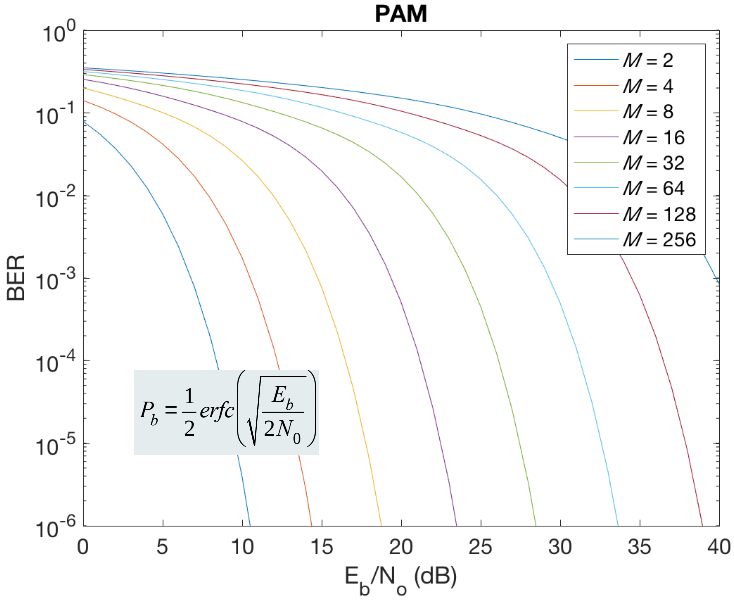


$$BER = \frac{(P[0\,|\,1] + P[1\,|\,0])}{2}$$

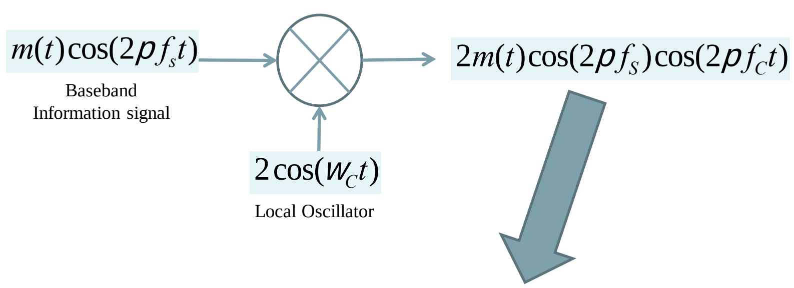
$$P_b = \frac{1}{2}\, erfc\left(\sqrt{\frac{E_b}{2N_0}}\right)$$

Where :
P[0|1] is the probability of a 0 being erroneously detected as a 1.
P[1|0] is the probability of a 1 being erroneously detected as a 0.

BER curves



Frequency Translation



$$2m(t)\cos(2\pi f_S)\cos(2\pi f_C t) = m(t)\cos[2\pi(f_C - f_S)t] + m(t)\cos[2\pi(f_C + f_S)t]$$

Lower sideband

Upper sideband

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Channel Capacity

The Shannon's capacity limit tells us how many bits can be transmitted per second without errors over a channel of bandwidth B Hz, when the signal power is limited to S Watts and is exposed to N Watts of Gaussian White (uncorrelated) Noise that is added to the signal.

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

$$C = 3.32\,B\log_{10}\left(1+\frac{S}{N}\right)$$

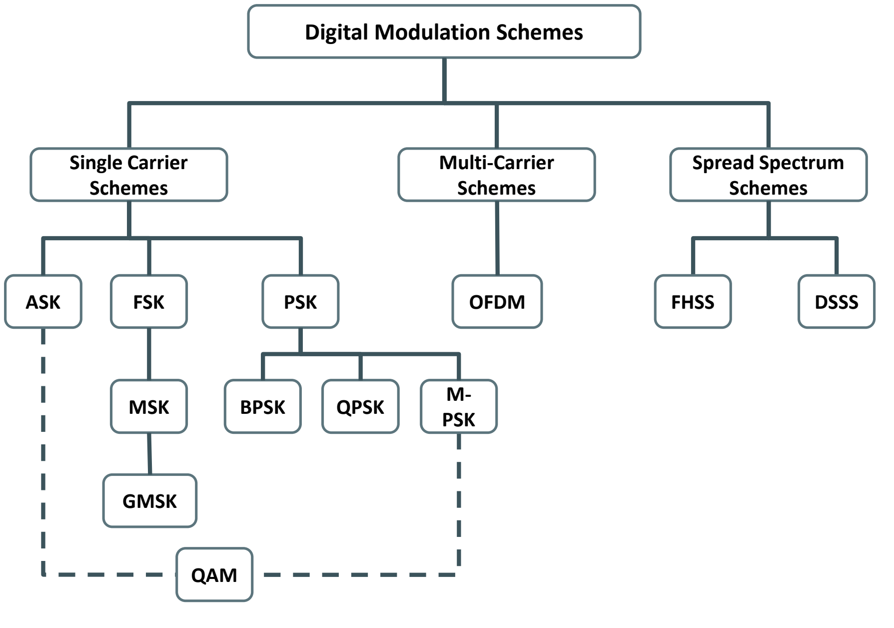
where :
C = Channel information capacity (bps)
B = bandwidth (hertz)
S /N = signal-to-noise power ratio (numerical, not dB)

Part 2 : Basic Modulation Schemes

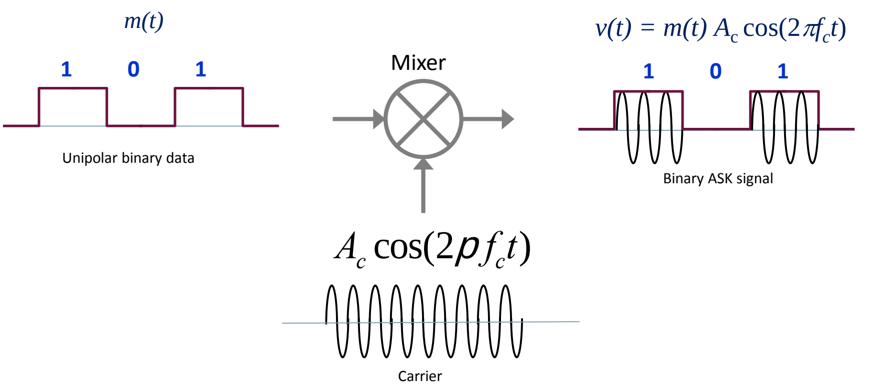
Modulation Schemes

- **Analogue modulation schemes**
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)
- **Digital modulation schemes**
  - Amplitude Shift Keying (ASK)
  - Phase Shift Keying (PSK)
  - Frequency Shift Keying (FSK)
  - Gaussian Minimum Shift Keying (GMSK)
  - Quadrature Phase Shift Keying (QPSK)
  - Quadrature Amplitude Modulation (QAM)
  - Orthogonal Frequency Division Modulation (OFDM)
  - Spread spectrum schemes

Digital Modulation Scheme Hierarchy

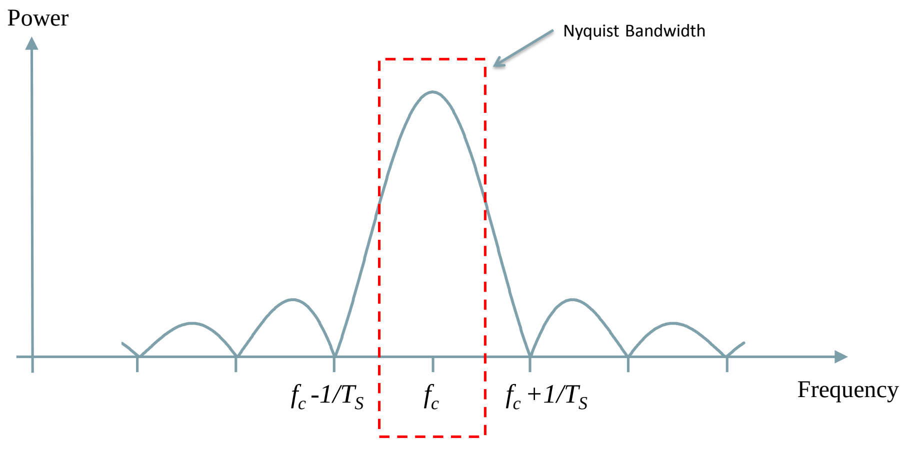


Amplitude Shift Keying (ASK)



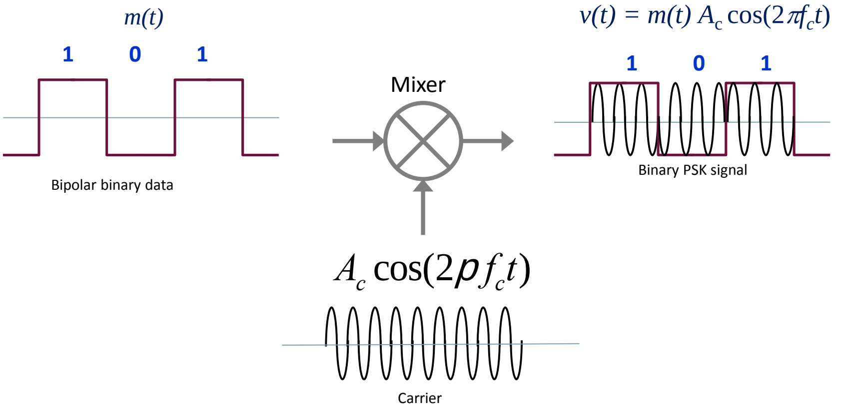
$$v(t) = \begin{cases} A_c \cos(2 p f_c t) & symbol\ "1" \\ 0 & symbol\ "0" \end{cases}$$

Bandwidth of ASK



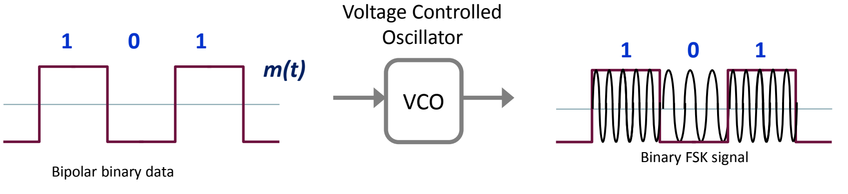
$$Nyquist\ Bandwidth\ (ASK) = \frac{1}{T_S}$$

Phase Shift Keying (PSK)



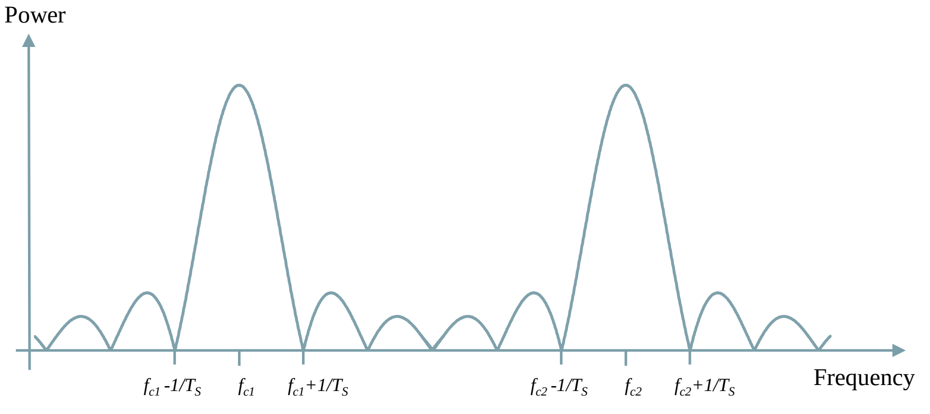
$$v(t)=\begin{cases} A_c\cos(2\pi f_c t) & symbol\ "1" \\ A_c\cos(2\pi f_c t+\pi) & symbol\ "0" \end{cases}$$

Frequency Shift Keying (FSK)

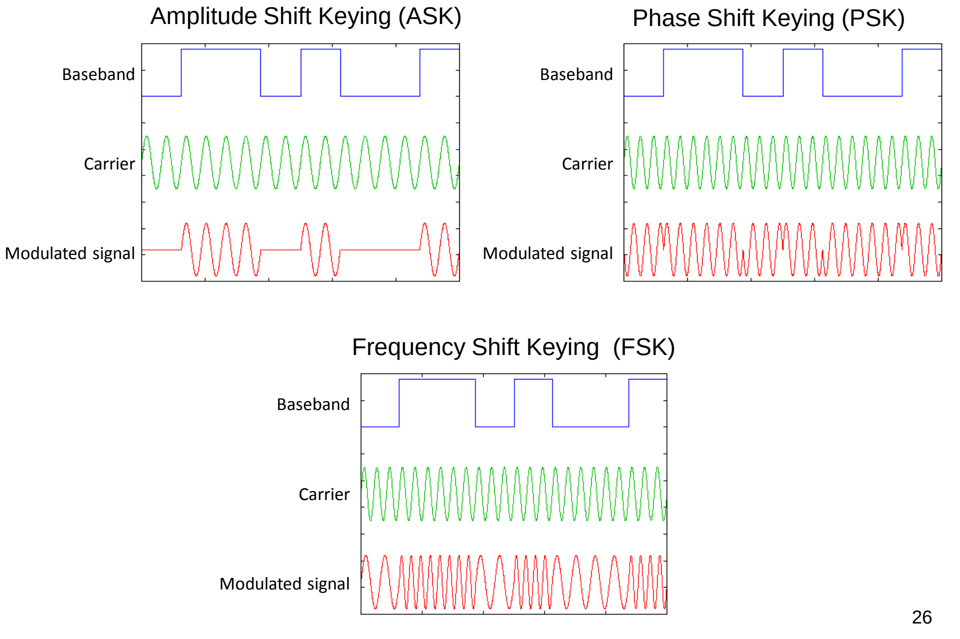


$$v(t)=\begin{cases} A_c\cos(2\pi f_{c1} t) & symbol\ "1" \\ A_c\cos(2\pi f_{c2} t) & symbol\ "0" \end{cases}$$

Binary FSK Spectrum



Summary of Basic Modulation Schemes



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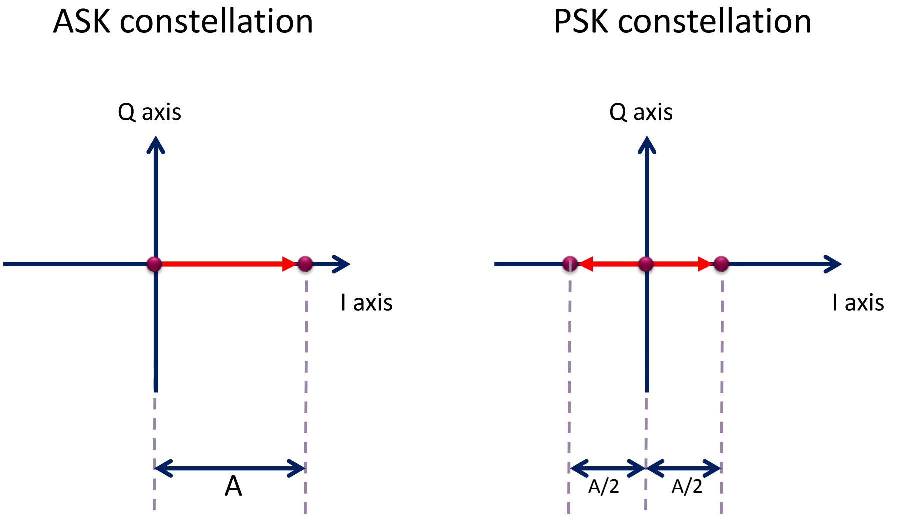
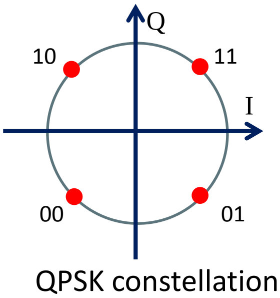
Constellation Diagrams



When M=4 : QPSK

- Consider the case when we have four symbols, represented by four different carrier phases all having the same amplitude. This is referred to as **Quadrature Phase-Shift Keying**, or **QPSK**.
- We can now encode two bits per **symbol**, which gives us twice the bit rate as BPSK for the same channel symbol rate. This means that QPSK is twice the **bandwidth efficiency** of BPSK. Each two-bit combination is referred to as a **dibit,** and the carrier phase used to represent each dibit is shown in the table here.

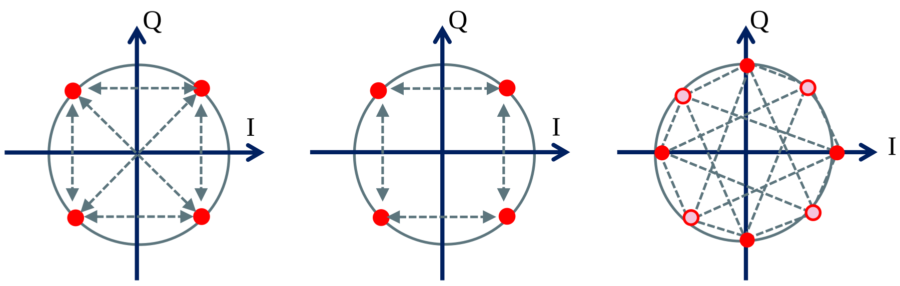
DiBit	Phase offset
00	-135^o
01	-45^o
11	45^o
10	135^o



QPSK constellation

Varieties of QPSK

- In conventional QPSK the transition from one constellation point to the other passes through the origin of the constellation diagram. This means that there will be a 180 degree phase transition in the time domain waveform: a problem in practical communication system design as it requires expensive linear amplification to prevent distortion of the signal.
- In **offset QPSK** the phase transitions are limited to 90 degrees by offsetting the timing of the odd and even bits by one bit-period, or half a symbol-period. This ensures that the in-phase and quadrature components will never change at the same time.
- In **π/4 QPSK** two identical constellations are rotated by 45 degrees, or π by 4 radians, with respect to one another. This has the effect of reducing the phase transitions between symbols to a maximum of 135 degrees. Note that the phase transitions never pass through the origin, meaning that there are never any 180 degree phase transitions in the π/4 QPSK waveform.



Conventional QPSK   Offset QPSK   π/4 QPSK

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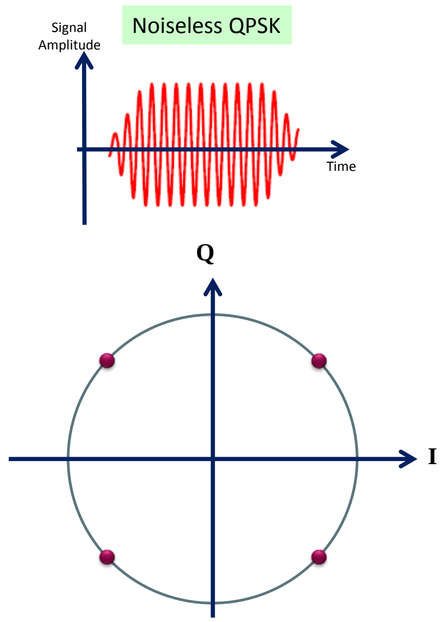
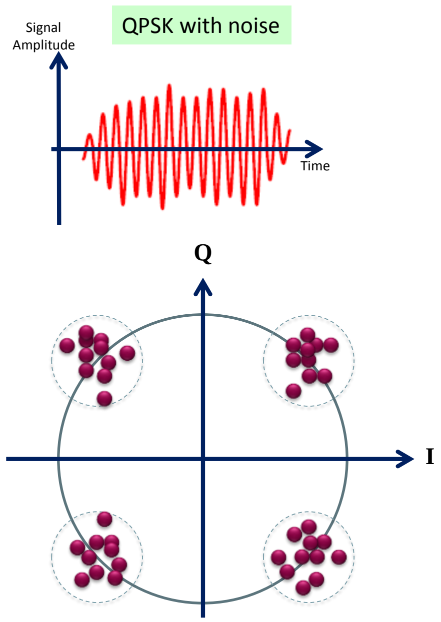
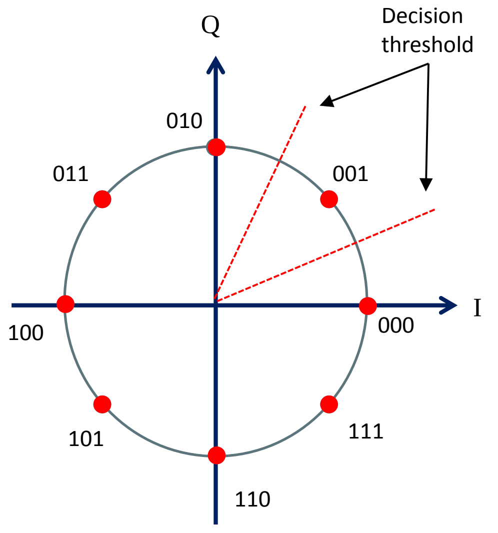
Effect of noise on QPSK



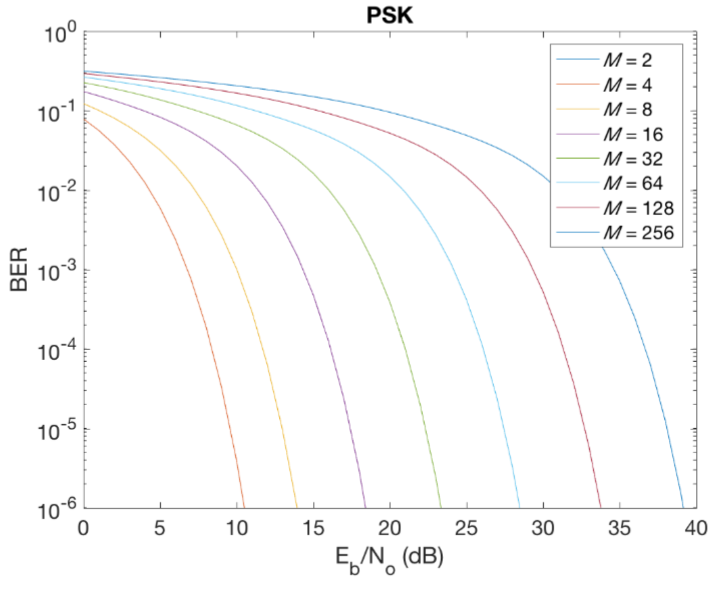


8-PSK Constellation

TriBit	Phase offset
000	0°
001	45°
010	90°
011	135°
100	135°
101	-135°
110	-45°
111	45°



BER performance of PSK



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UCL

Exercise:

- If the required binary bit rate is 1,500 bits per second, what will be the **symbol rate** if we use **QPSK**?
- What would it be if we use **8-PSK**?

UCL

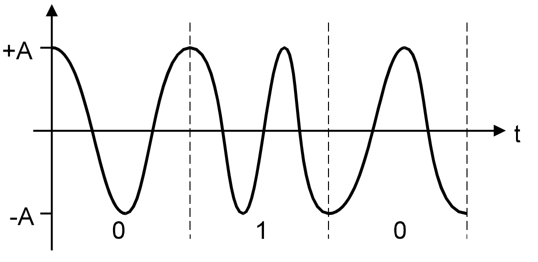
Exercise - Solution

- 1,500 bit/s
- QPSK: 4 levels gives 2 bits per symbol
- = **750** symbols per second.

- 8-PSK: 8 levels will give 3 bits per symbol
- = **500** symbols per second.

Minimum Shift Keying (MSK)

- MSK is a type of continuous-phase frequency-shift keying that was designed to limit the excessive bandwidth of conventional FSK.
- When looking at a plot of a signal using MSK modulation, it can be seen that the modulating data signal changes the frequency of the signal and there are no phase discontinuities.
- In MSK the frequency separation between the two tones is $\Delta f=1/(2T_b)$, which is the minimum frequency separation necessary to ensure orthogonality between the two tones over the signalling interval of length $T_{b.}$
- The power efficiency of MSK is similar to the power efficiency of BPSK, but the bandwidth efficiency of MSK is twice the bandwidth efficiency of BPSK.



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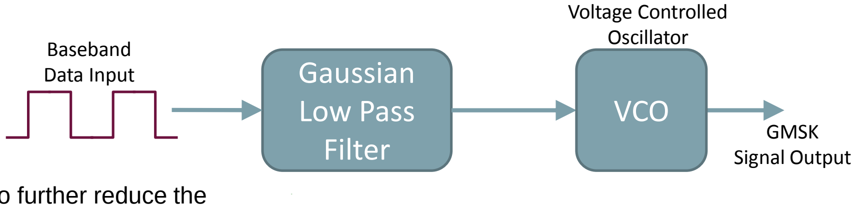
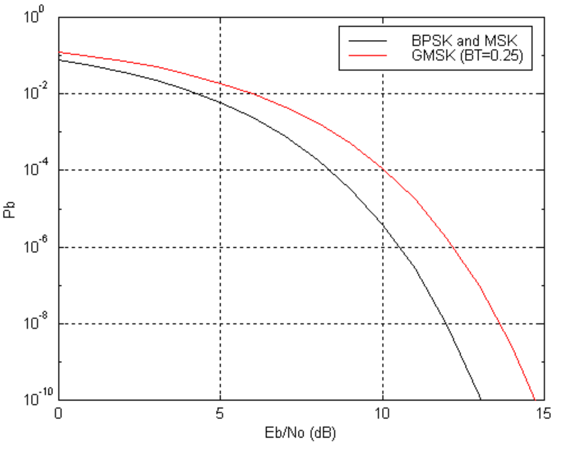
Gaussian Minimum Shift Keying (GMSK)



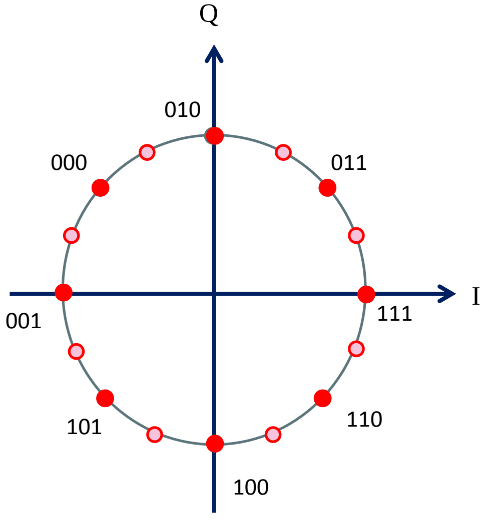
To further reduce the sidelobes of MSK is to constrain the rate of change of frequency by shaping the baseband data waveform. **Gaussian Minimum Shift Keying**, or **GMSK** uses a Gaussian filter to further increase spectral efficiency.

It is for this reason that GMSK was chosen as the modulation scheme for use in the **GSM** system.



Practical application of GMSK and PSK : EDGE

- EDGE: “Enhanced Data rates for GSM Evolution”.
- EDGE employs both GMSK as well as 8-PSK modulation to achieve a theoretical maximum data rate of 59.2kbps per timeslot, which equates to **473.6 kbit/s** for eight timeslots.
- Although the 8 PSK has three times the spectral efficiency of GMSK, The frequency spectrum occupied by 8-PSK and GMSK in EDGE is the same, illustrating the advantage of multi-level modulation.
- EDGE 8-PSK uses a 3 pi/8 version of PSK, in other words two constellation sets offset by 3 pi/8 in order to limit phase transitions, following the same principle as pi/4 PSK.



EDGE Data rates

Modulation and Coding Scheme	Modulation format	Throughput per timeslot	Theoretical max throughput (8 timeslots)
MCS-1	GMSK	8.8 kbps	70.4 kbps
MCS-2	GMSK	11.2 kbps	89.6 kbps
MCS-3	GMSK	14.8 kbps	118.4 kbps
MCS-4	GMSK	17.6 kbps	140.8 kbps
MCS-5	8-PSK	22.4 kbps	179.2 kbps
MCS-6	8-PSK	29.6 kbps	236.8 kbps
MCS-7	8-PSK	44.8 kbps	358.4 kbps
MCS-8	8-PSK	54.4 kbps	435.2 kbps
MCS-9	8-PSK	59.2 kbps	473.6 kbps

Part 3 : Higher Modulation Schemes

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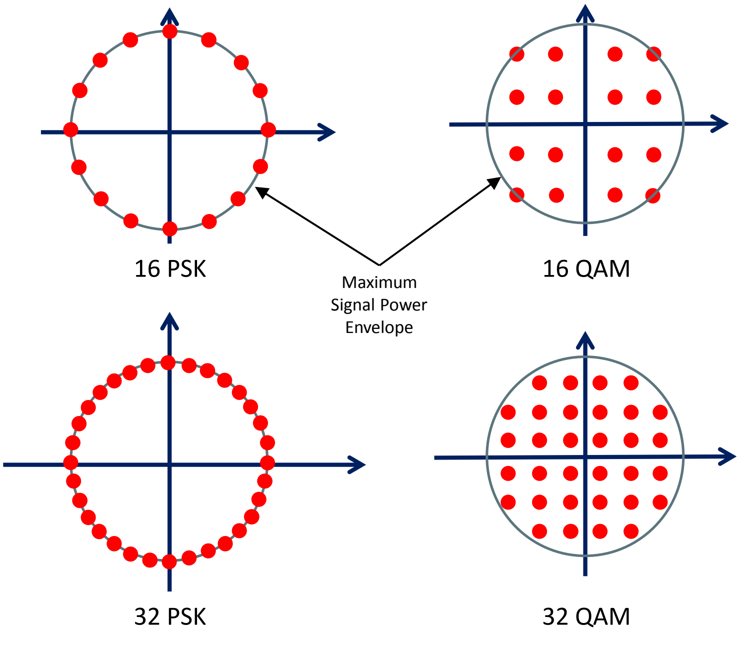
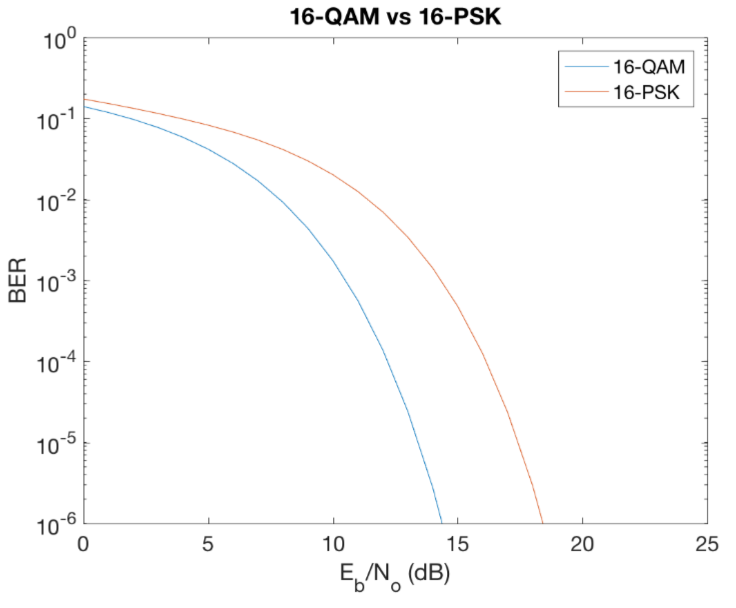
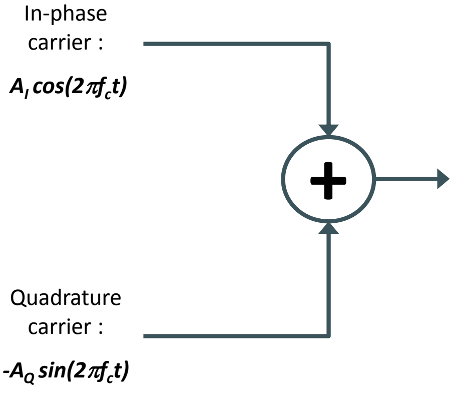
Phase plus Amplitude Modulation



BER for 16-QAM versus 16-PSK



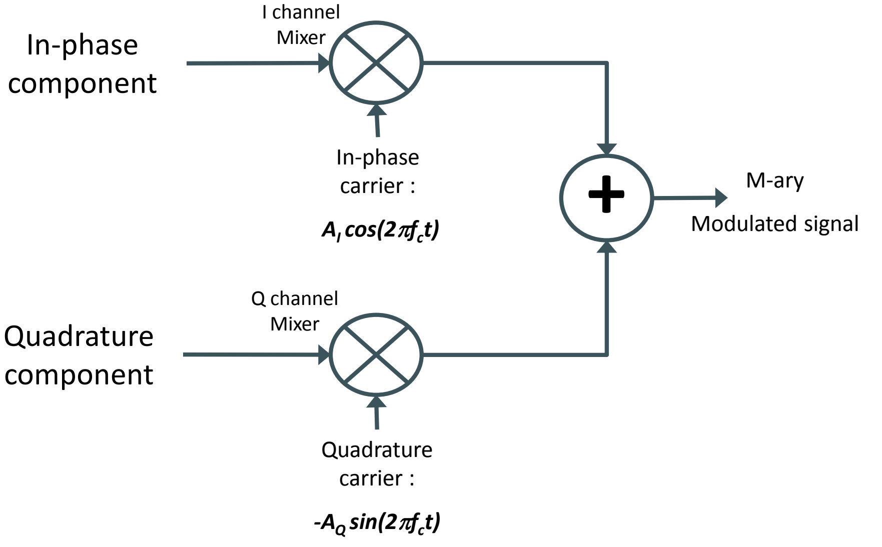
Generation of M-ary Digital Signals



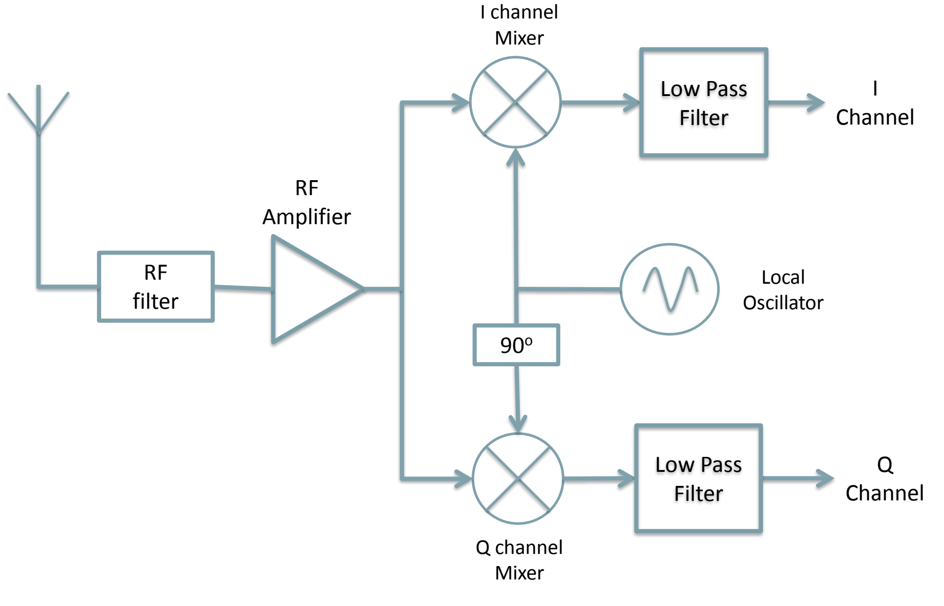
$$A_I \cos(2\pi f_c t) - A_Q \sin(2\pi f_c t)$$

$$= A_C \cos(2\pi f_c t + \phi)$$

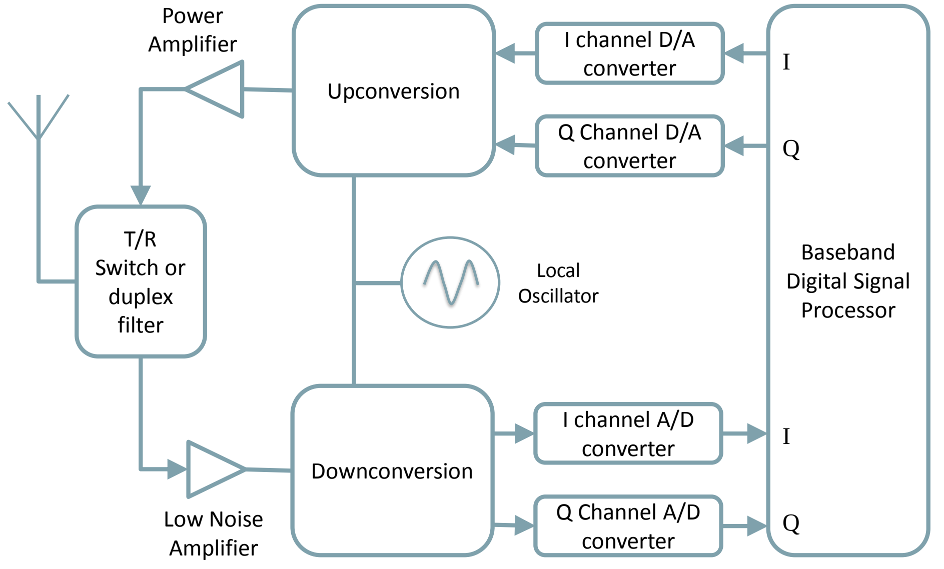
Generation of M-ary Digital Signals



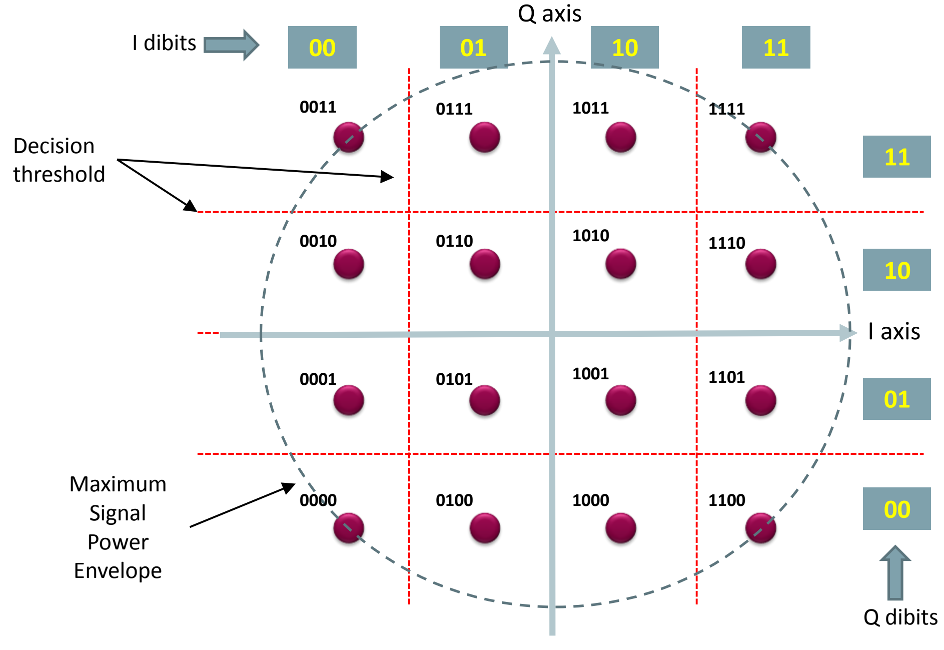
Direct Conversion (Zero IF) architecture



Generic mobile transceiver

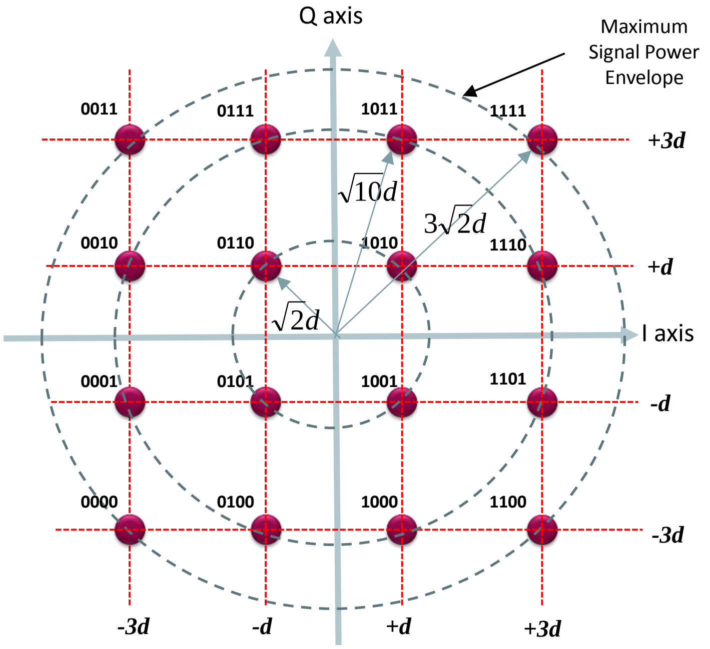


16-QAM constellation diagram



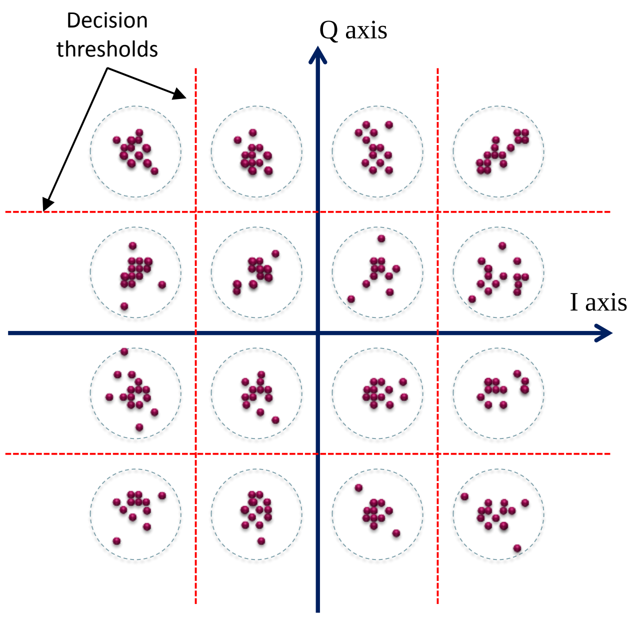
16-QAM average signal power

Symbol	r
0000	$3\sqrt{2}d$
0001	$\sqrt{10}d$
0010	$\sqrt{10}d$
0011	$3\sqrt{2}d$
0100	$\sqrt{10}d$
0101	$\sqrt{2}d$
0110	$\sqrt{2}d$
0111	$\sqrt{10}d$
1000	$\sqrt{10}d$
1001	$\sqrt{2}d$
1010	$\sqrt{2}d$
1011	$\sqrt{10}d$
1100	$3\sqrt{2}d$
1101	$\sqrt{10}d$
1110	$\sqrt{10}d$
1111	$3\sqrt{2}d$



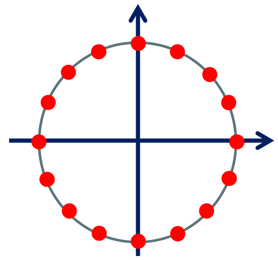
Effect of noise in QAM

- Noise will cause the constellation point for a given received symbol to be different from the one transmitted.
- Errors will occur when the received constellation point is closer to a different constellation point than to the point that was transmitted.
- The symbol error rate can be approximated by computing the probability that the noise voltage exceeds the distance to the decision threshold.

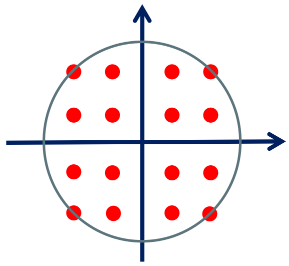


Application of QAM : Evolved EDGE

Modulation and Coding Scheme (MCS)	EDGE / Evolved EDGE	
	Type of modulation	Throughput (4 timeslots)
MCS-1	GMSK	35.2 kbps
MCS-2	GMSK	44.8 kbps
MCS-3	GMSK	59.2 kbps
MCS-4	GMSK	70.4 kbps
MCS-5	8-PSK	89.6 kbps
MCS-6	8-PSK	118.4 kbps
MCS-7	8-PSK	179.2 kbps
MCS-8	8-PSK	217.6 kbps
MCS-9	8-PSK	236.8 kbps
MCS-10	16-QAM with turbo codes	268.8 kbps
MCS-11	16-QAM uncoded	326.4 kbps

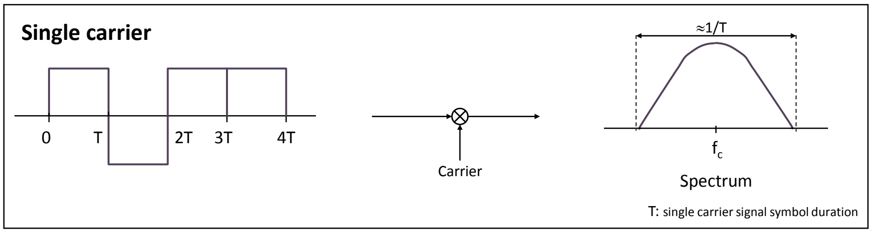


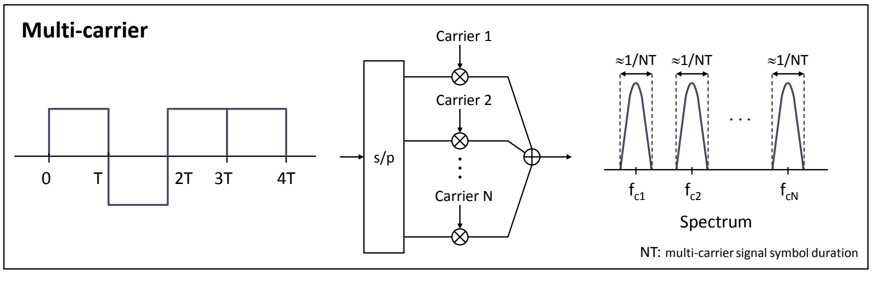
16 PSK



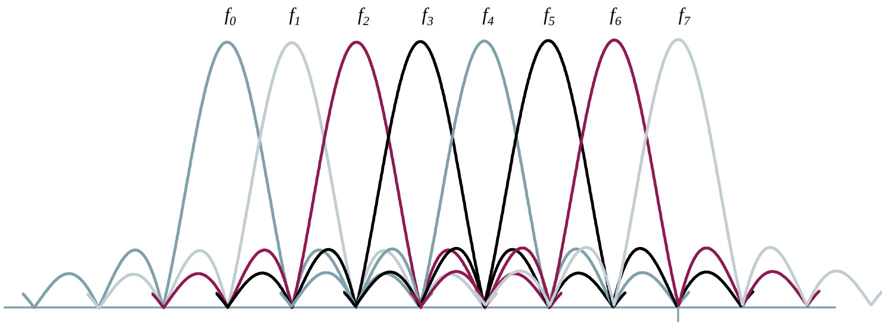
16 QAM

Multi-carrier Modulation



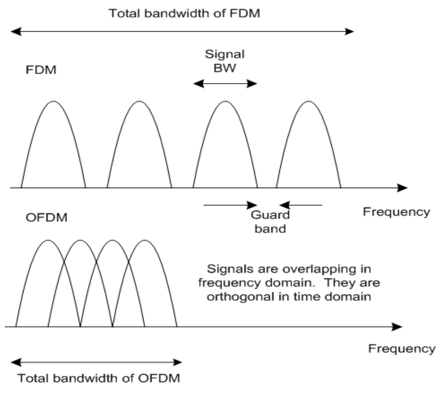


Orthogonal Frequency Division Multiplexing (OFDM)

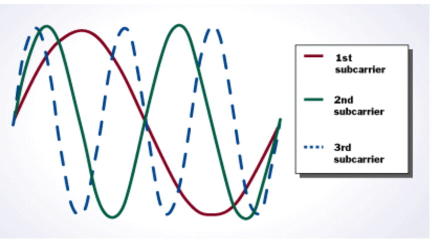


FDM versus OFDM

Frequency Domain



Time Domain



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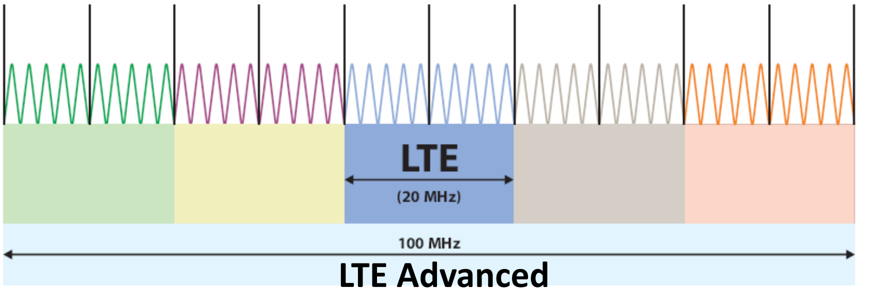
OFDM Example - 802.11 a/g

- Uses OFDM with 52 sub-carrier (4 of which are pilot tones) in a 20MHz bandwidth to provide a maximum of 54MBit/s
- Each tone is modulated with up to 64-QAM
- Forward error correction is also used which reduces the total bandwidth available (this will be covered later)

Data Rate	Modulation	Coding
6	BPSK	½
9	BPSK	¾
12	QPSK	½
18	QPSK	¾
24	16-QAM	½
36	16QAM	¾
48	64-QAM	2/3
54	64-QAM	½

Application of OFDM : LTE and LTE-Advanced

Channel Bandwidth	Subcarriers (downlink)	Subcarriers (uplink)
1.4 MHz	73	72
3 MHz	181	180
5 MHz	301	300
10 MHz	601	600
15 MHz	901	900
20 MHz	1201	1200



Summary of modulation schemes used in Mobile

Modulation scheme	Application in Mobile
FSK	AMPS/TACS (1G)
GMSK	GSM (2G)
GMSK, 8-PSK	EDGE (2.75G)
16-QAM	Evolved EDGE (2.75G)
16/64 QAM	HSPA (3.5G)
QPSK, QAM over OFDM	LTE (4G)

L DEPARTMENT OF ELECTRONIC AND ELECRICAL ENGINEERING
INTEGRATED GRADUATE DEVELOPMENT PROGRAMME
MSc Telecommunications; Internet Engineering; Wireless and Optical Communications

GSM Architecture and signals

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University College London

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November 2018

Contents

- Background to GSM
- Bearer vs Tele services
- GSM System Architecture
- Channels, physical and logical
- GSM radio Interface

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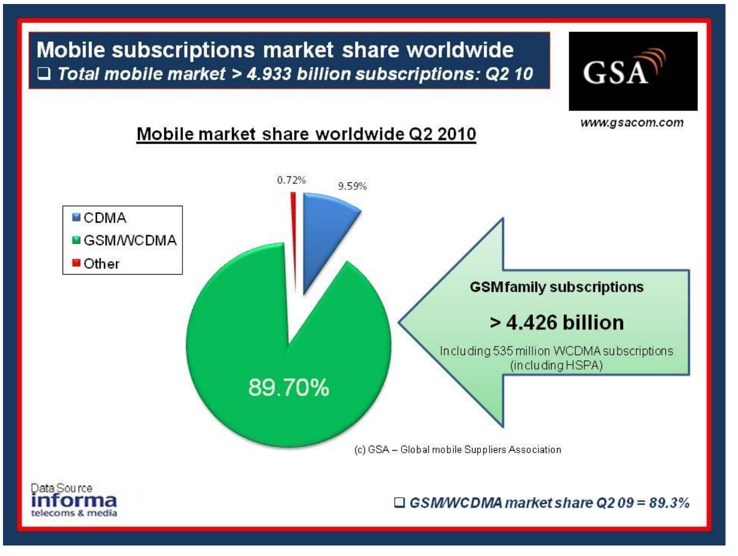
Background to GSM

- GSM was originally the acronym for “Groupe Spéciale Mobile” (circa 1982). Later changed to “Global System for Mobile Communication”
- CEPT initiated work on GSM in 1982, ETSI issued the standards in 1990
- Pan-European standard (ETSI, European Telecommunications Standardization Institute)
- Conceived as a digital system, based on circuit switched telephony, primarily for voice, fax and SMS. IP Data services were later “bolted on” in the form of GPRS.
- Designed to enable seamless roaming within Europe (major distinction with previous analog systems).
- GSM is now the primary mobile standard in the world with more than 400 operators in more than 130 countries and nearly 4 billion subscribers worldwide.

These lectures are in two parts:

- **Part 1: General system introduction**
  - GSM basics
  - Services
  - Architecture,
  - Components
  - Signals and channels
  - Transmission
- **Part 2: Operation (as a network):**
  - Numbering
  - Location management
  - Call processes
  - Handover
  - SMS
  - Roaming
- **GPRS and EDGE will be covered with the 3G/UMTS material**

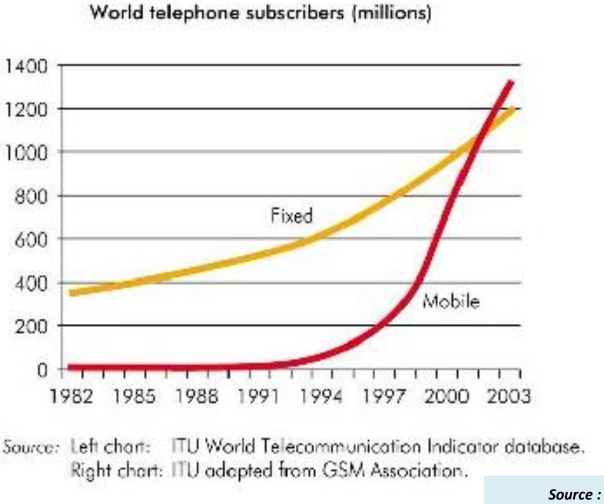
Mobile subscriber growth : Africa



Ref : http://www.gsacom.com/news/statistics.php4

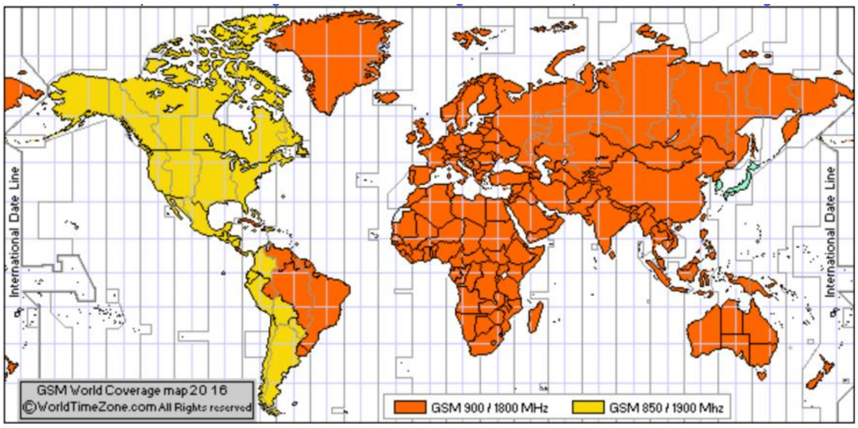
Subscriber Growth

Total world mobile subscribers overtook total fixed line subscribers around 2002



Source : **ITU website**

Worldwide map of GSM coverage (2016)



GSM (Groupe Special Mobile) - Global System for Mobile communications - most popular standard for mobile phones in the world.
GSM 900 / GSM 1800 MHz are used in most parts of the world: Europe, Asia, Australia, Middle East, Africa.
GSM 850 / GSM 1900 MHz are used in the United States, Canada, Mexico and most countries of S. America.

source :http://www.worldtimezone.com/gsm.html

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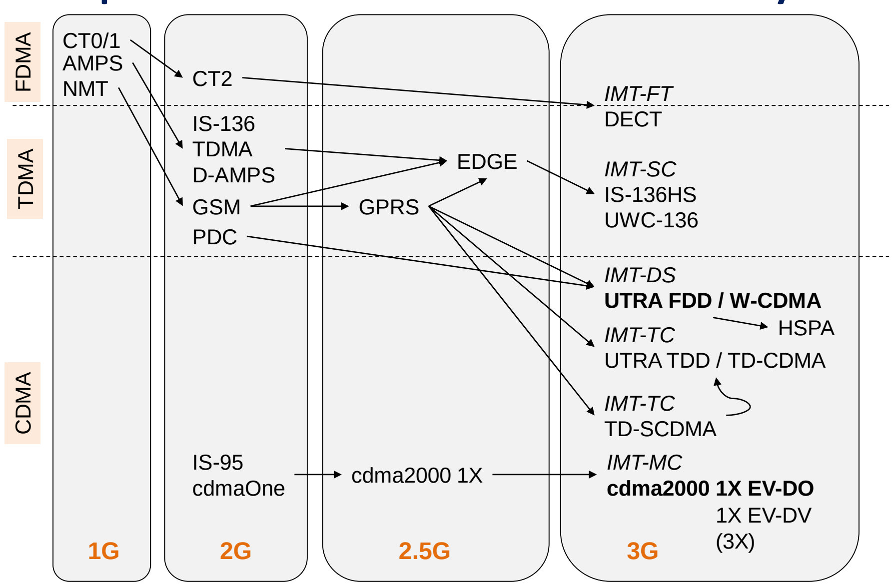
Development of mobile telecommunication systems



Ref : Schiller, p95

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Evolutionary stages of Mobile Communications

Generation	Era	Features
1G	1970	Analogue voice
2G	1980	Digital voice
2.5G	1985	Packet data add-on to 2G
3G	1990	Integrated voice/data/video
4G (LTE)	2000	All IP mobile network

GSM Standards (ETSI)

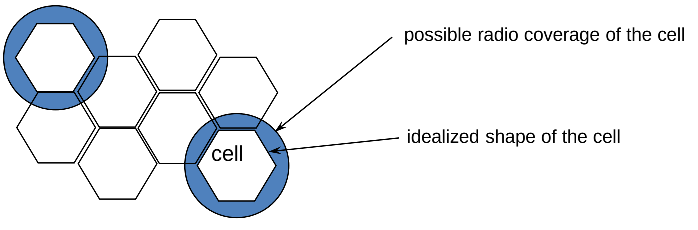
GSM Standard

Series	Specifications area
01	General
02	Service aspects
03	Network aspects
04	MS-BS interface and protocol
05	Physical layer and radio path
06	Speech coding specification
07	Terminal adapter for MS
08	BS-MSC interface
09	Network internetworking
10	Service internetworking
11	Equipment and type approval specification
12	Operation and maintenance

- Divided into 12 series
- Standardization efforts coordinated by ETSI
- www.etsi.org
- Specifications available online – free of charge
- Standardization and public availability of specification - one of fundamental factors of GSM success

GSM is a cellular network

segmentation of the area into cells

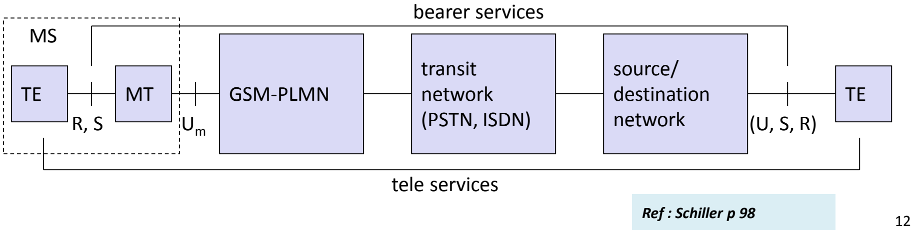


- use of several carrier frequencies
- not the same frequency in adjoining cells
- cell sizes vary from some 100 m up to 35 km depending on user density, geography, transceiver power etc.
- hexagonal shape of cells is idealized (cells overlap, shapes depend on geography)
- if a mobile user changes cells handover of the connection to the neighbor cell

Ref : Schiller

GSM Mobile Service Domains

- **Bearer Services**
  - telecommunication services that are used to transfer user data and control signals between two pieces of equipment.
- **Telematic Services**
  - telecommunication services providing the complete capability, including terminal equipment functions, for communication between users according to protocols established by agreement between network operators.
- **Supplementary Services**
  - Services provided on top of teleservices or bearer services, and include features such as caller identification, call forwarding, call waiting, multi-party conversations, and barring of outgoing (international) calls, among others. Services



Ref : Schiller p 98

Bearer Services

- Telecommunication services to transfer data between access points
- Specification of services up to the terminal interface (OSI layers 1-3)
- Different data rates for voice and data (original standard)
  - data service (circuit switched)
    - synchronous: 2.4, 4.8 or 9.6 kbit/s
    - asynchronous: 300 - 1200 bit/s
  - data service (packet switched)
    - synchronous: 2.4, 4.8 or 9.6 kbit/s
    - asynchronous: 300 - 9600 bit/s
- GSM data has now been largely superseded by GPRS.

Ref : Schiller p 98

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Tele Services I

- Telecommunication services that enable voice communication via mobile phones
- All these basic services have to obey cellular functions, security measurements etc.
- Offered services
  - **Mobile telephony**
    primary goal of GSM was to enable mobile telephony offering the traditional bandwidth of 3.1 kHz
  - **Emergency number**
    common number throughout Europe (112); mandatory for all service providers; free of charge; connection with the highest priority (preemption of other connections possible)
  - **Multinumbering**
    several ISDN phone numbers per user possible

Ref : Schiller p 98

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Tele Services II

- Additional services
  - Non-Voice-Teleservices
    - group 3 fax
    - voice mailbox (implemented in the fixed network supporting the mobile terminals)
    - electronic mail (MHS, Message Handling System, implemented in the fixed network)
    - Short Message Service (SMS)
      alphanumeric data transmission to/from the mobile terminal (160 characters) using the signaling channel, thus allowing simultaneous use of basic services and SMS (almost ignored in the beginning now the most successful add-on!)

Ref : Schiller p 98

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Supplementary services

- Services in addition to the basic services, cannot be offered stand-alone
- Similar to ISDN services besides lower bandwidth due to the radio link
- May differ between different service providers, countries and protocol versions
- Important services
  - identification: forwarding of caller number
  - suppression of number forwarding
  - automatic call-back
  - conferencing with up to 7 participants
  - locking of the mobile terminal (incoming or outgoing calls)
  - ...

Ref : Schiller p 98

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GSM frequency bands (examples)

Type	Channels	Uplink [MHz]	Downlink [MHz]
GSM 850	128-251	824-849	869-894
GSM 900 classical extended	0-124, 955-1023 124 channels +49 channels	876-915 890-915 880-915	921-960 935-960 925-960
GSM 1800	512-885	1710-1785	1805-1880
GSM 1900	512-810	1850-1910	1930-1990
GSM-R exclusive	955-1024, 0-124 69 channels	876-915 876-880	921-960 921-925

- Additionally: GSM 400 (also named GSM 450 or GSM 480 at 450-458/460-468 or 479-486/489-496 MHz)
- Please note: frequency ranges may vary depending on the country!
- Channels at the lower/upper edge of a frequency band are typically not used

Ref : Schiller

GSM System Architecture

Architecture of the GSM system

GSM is a type of PLMN (Public Land Mobile Network)

A GSM network can be divided into 3 subsystems :

- **RSS (radio subsystem):** covers all radio aspects
- **NSS (network and switching subsystem):** call forwarding, handover, switching
- **OSS (operation subsystem):** management of the network

Different GSM networks around the world are connected together via the terrestrial networks :

- **PSTN :** Public Switched Telephone Network
- **PDN :** Public Data Network (e.g. "the internet")

Ref : Schiller

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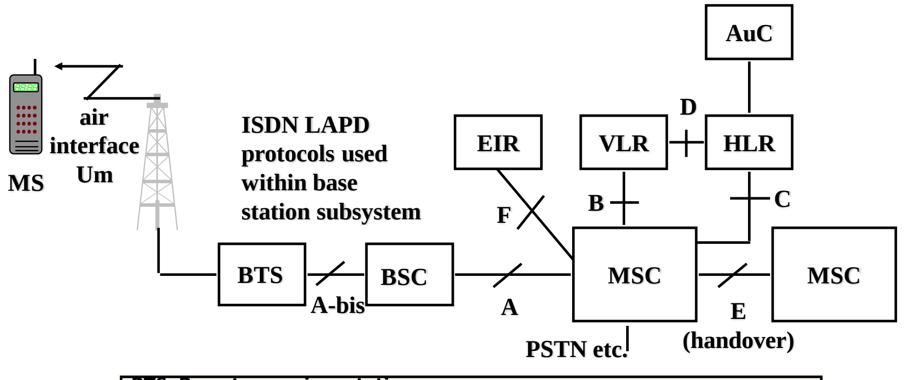
GSM Mobile network architecture- reference points



BTS=Base transceiver station	EIR=Equipment identity register
BSC=Base station controller	VLR=Visitor location register
MSC=Mobile switching centre	AuC=Authentication centre

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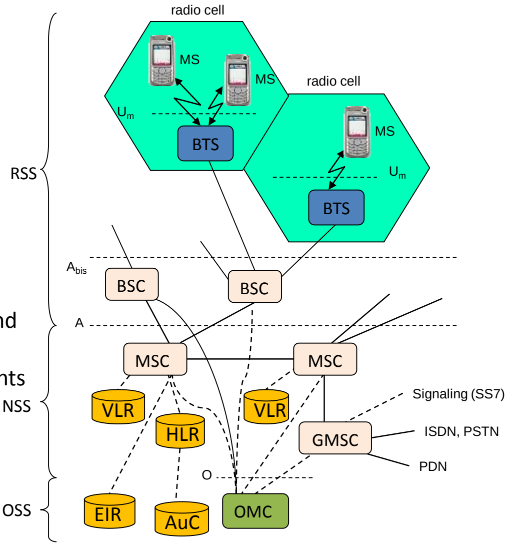
GSM: Components, Interfaces, Databases

Components
- MS= Mobile Station
- BTS=Base Transceiver Station
- BSC=Base Station Controller
- MSC=Mobile Switching Centre
- GMSC=Gateway MSC
- OMC=Operation & Maintenance Centre

Interfaces
- A interface : links MSC and BSC
- Abis interface : links BSC and BTS
- Um interface : radio link between BTS and MS
- O interface : connects OMC to all elements

Databases
- HLR=Home Location Register
- VLR=Visitor Location register
- EIR=Equipment Identity Register
- AuC=Authentication Centre



Ref : Schiller, p101

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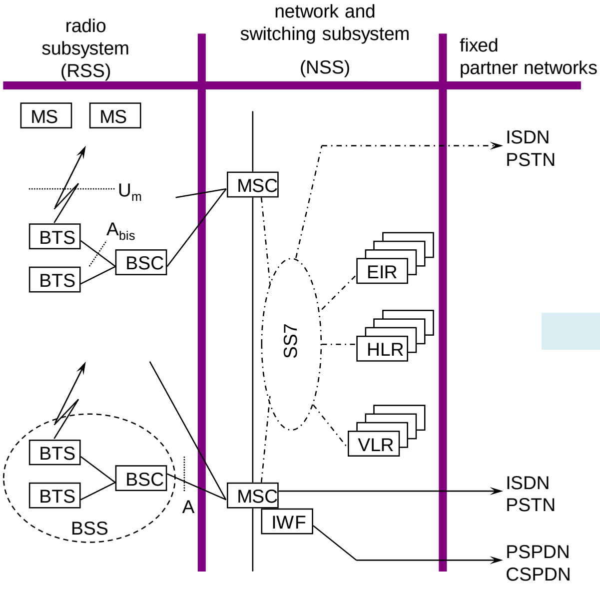
GSM: system architecture



Ref : Schiller

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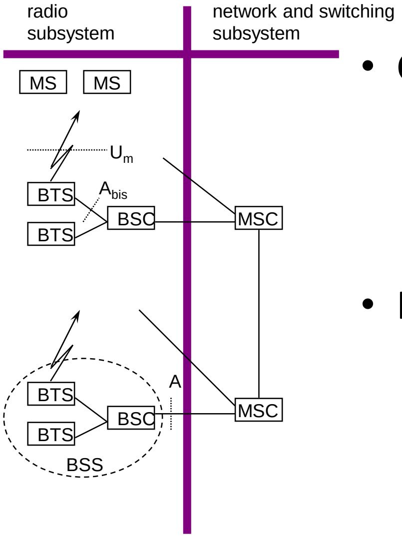
System architecture: radio subsystem



- Components
  - *MS* (Mobile Station)
  - *BSS* (Base Station Subsystem): consisting of
    - *BTS* (Base Transceiver Station): sender and receiver
    - *BSC* (Base Station Controller): controlling several transceivers
- Interfaces
  - U_m : radio interface
  - A_{bis} : standardized, open interface with 16 kbit/s user channels
  - *A*: standardized, open interface with 64 kbit/s user channels

Ref : Schiller

Radio subsystem

- The Radio Subsystem (RSS) comprises the cellular mobile network up to the switching centers
- Components
  - Base Station Subsystem (BSS):
    - **Base Transceiver Station (BTS):** radio components including sender, receiver, antenna - if directed antennas are used one BTS can cover several cells
    - **Base Station Controller (BSC):** switching between BTSs, controlling BTSs, managing of network resources, mapping of radio channels (U_m) onto terrestrial channels (A interface)
    - **BSS** = BSC + sum(BTS) + interconnection
  - Mobile Stations (MS)

Ref : Schiller

GSM interfaces

Abis Interface
- Interface between BTS and BSC
- Non-standardised interface, manufacturers follow certain guidelines
- Based on transmission of data on a PCM 30 interface (2.048Mb/s transmission rate partitioned into 32 channels of 64 kb/s each)
- Voice compression can pack between 4 and 8 voice channels into single PCM 30 channel

A Interface
- Interface between BSS and MSC
- Standardised interface allows mixing of equipment from different manufacturers
- A-Interface at physical level consists of two parts
  - First part between BSS and TRAU, transmission payload is still compressed
  - Second part between TRAU and MSC A-Interface at higher layers depends on SS7 MTP and
- SCCP to carry BSSA

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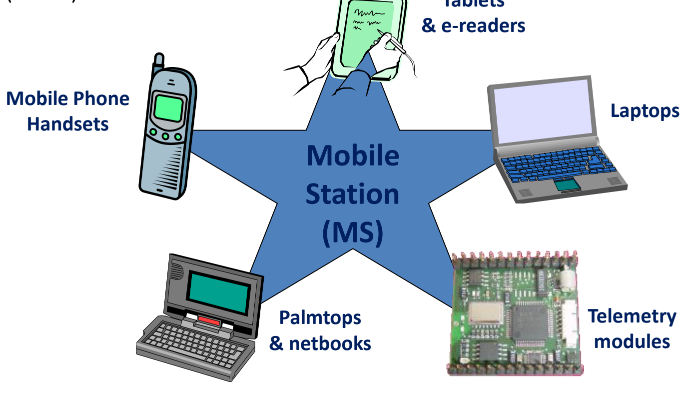
The Mobile Station (MS)

- An MS is any fixed or mobile device which can be used to access the GSM network.
- Five RF power levels are defined : 20W, 8W, 5W, 2W and 0.8W
- RF power can be reduced in 2 dB steps down to 20 mW
- BTS measures power and signals MS to change power in 2 dB steps every 13 TDMA frames (60 ms)



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Mobile Station (MS) vs SIM

- Every MS is uniquely identified by an IMEI (International Mobile Equipment Identity). One function of the IMEI is to verify the identity of the MS in the event of loss, theft or fraud.
- The subscriber is uniquely identified by the Subscriber Identity Module (SIM) which is inserted into the MS, but can be removed and inserted into a different MS.
- **MSISDN - *Mobile Subscriber ISDN Number*** is the number called by a party that wishes to contact the subscriber (the “phone number”).
- **IMSI - *International Mobile Subscriber Identity*** identifies a subscriber inside the mobile network
- **TMSI - *Temporary MSI*** used to enhance security
- Billing and routing done on the basis of the subscriber not the equipment - using the SIM to identify the subscriber

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Function of the MS

1. Voice and data transmission
   – digitising, encoding, error protecting, encrypting and modulation as well as inverse
2. Frequency and time synchronisation
   – MS tunes to a certain TDMA slot specified by the BSC
3. Monitoring signal strength and quality from surrounding cells
   – BER of synchronisation sequence of signals from <7 cells measured and communicated to BSC – contributes to handover calculations
4. Provision of location updates
   – periodic or forced - allows paging a MS in the correct LA
5. Equalisation of multipath distortions
   – adjusted every frame
6. Display of short messages (SMS)
7. Timing advance
   – calculated by BTS and required advance sent to MS

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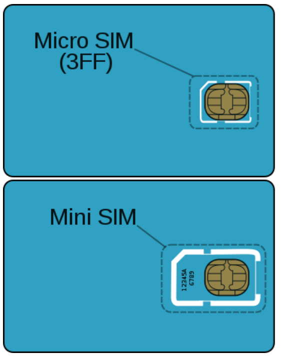
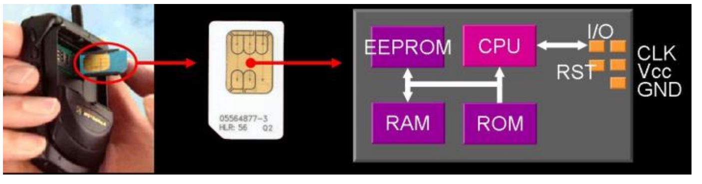
Subscriber Identification Module (SIM)

- The SIM is a smart card which is inserted into the MS
- The SIM contains a single chip computer with it's own Operating System, File System, applications etc.
- Smart Card contains security keys, network identifiers (IMSI, MSISDN) and algorithms
- SIM security is protected by PIN
- SIM can be moved from one MS to another.
- SIM applications can be written with SIM Toolkit





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BTS vs BSC

- **Functions of the BTS :**
  - Radio transmission and reception
  - Wireless channel encryption
  - Conversion between wired and wireless signals
  - Frequency Hopping
  - There is very little "intelligence" in the BTS
- **Functions of the BSC :**
  - Controls several BTS
  - Locates the MS (paging)
  - Controls handovers
  - Translates GSM 13-Kbps voice to standard 64-Kbps format
  - Operation and maintenance functions of the BSS

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BTS vs BSC : summary

Function	BTS	BSC
Management of radio channels		√
Frequency hopping	√	√
Management of Terrestrial channels		√
Mapping of terrestrial channels onto radio channels		√
Channel coding and decoding	√	
Rate adaption	√	
Encryption and decryption	√	√
Paging	√	√
Uplink signal measurement	√	
Traffic measurement		√
Authentication		√
Location registry, location update		√
Handover management		√

Ref : Schiller p103

Mobile Switching Centre (MSC)

- The MSC is a critical central component of the network
- MSC is basically a high performance telephony switch, which handles functions specific to mobile subscribers :
  - Registration
  - Authentication
  - Handover management
  - Billing (generation of CDR files)
- A Gateway MSC (GMSC) handles interconnection with other networks (PSTN, ISDN etc.)

GSM Databases

HLR : "Home Location Register"

- database of all users registered on that network (one HLR per network)
- Stores current location of the subscriber
- Regularly updated when MS changes location

VLR : "Visitor Location Register"

- A database of all users and roamers in the geographic area.
- Stores TMSIs and MSRNs
- Caches the HLR

EIR : "Equipment Identity Register"

Stores the IMEI numbers for all MS on the network

AuC : "Authentication Centre"

Stores the authentication keys used for authorizing the subscriber access to the associated GSM PLMN.

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Visitor Location Register (VLR)

- The VLR temporarily stores information about the mobile stations that are active in the geographic area for which the VLR is responsible.
- The HLR, VLR, and AuC comprise the management databases that support roaming (including international roaming) in the GSM network.
- There is a VLR associated with each MSC in the network.
- Having a local cache of HLR data in the VLR avoids frequent HLR database updates and long distance signalling of the user information, allowing faster access to subscriber information.

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Role of the VLR in Roaming

- When a new subscriber roams into a location area, the VLR copies subscriber information from the home network HLR to its local database.
- The VLR is responsible for allocating a **Mobile Station Roaming Number (MSRN)** and **Temporary Mobile Subscriber Identity (TMSI)** to visiting roamers, when required to route incoming (MT) calls.

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HLR and VLR Roaming Brief

- Together the HLR and VLR support roaming in a GSM network.
- VLR activated when a new subscriber roams into a location area.
  - Stores information about MSs active in that area.
- Subscriber information copied from home HLR to location VLR.
  - Reduces long distance signalling of user information.
  - Allows faster access to subscriber information.
  - Prevents frequent HLR database updates.
- VLR allocates two numbers to route incoming calls:
  - A Mobile Station Roaming Number (MSRN)
  - A Temporary Mobile Subscriber Identity (TMSI)

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GSM location Hierarchy

- **GSM service area**
  - Combination of all member countries where a GSM MS can be served
- **PLMN service area**
  - Can be several within a country - links from a PLMN and other PLMN, PSTN or ISDN network done through gateway MSCs which are national or international transit exchanges
- **MSC service area**
  - MS in one MSC service area at a time and details held in VLR
- **Location area (LA)**
  - MS can move within the LA without updating its location in the VLR
- **Cell**
  - Smallest unit of location in a GSM network. MS can be in only located in one cell at a time.

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Other network elements : TRAU

- TRAU = Transcoder Rate Adaptor Unit
- Transcoding is the process of making the digitised voice signal compatible with standard PSTN 2 Mbit/s connections (E1).
- Combines 4 13 kbit/s speech or 3.6/6/12 kbit/s data and multiplexes these up to 64 kbit/s
- Synchronising data is added to each stream to raise the rate to 16 kbit/s before multiplexing
- The TRAU can be at the BTS, BSC or MSC location but is functionally a part of the BSS

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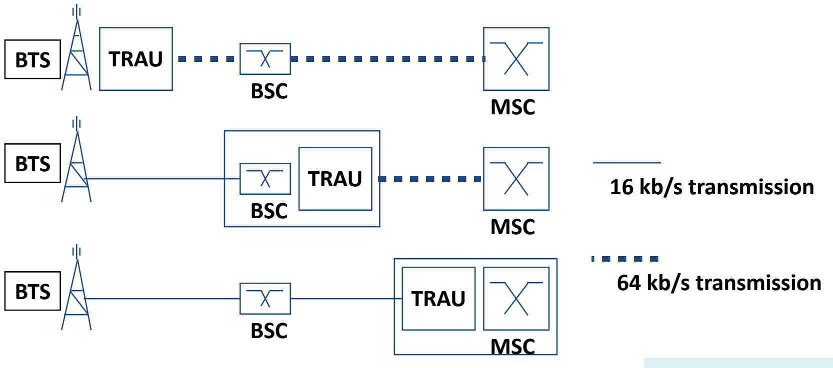
Other network elements : TRAU

- The TRAU provides for conversion from GSM to ‘conventional’ digital telephony signal rates.
- The TRAU may be variously positioned in the network, as indicated below



Ref : I. Darwazeh

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Other network elements : Echo canceller

- Total GSM round-trip delay (encoding, decoding and signal processing) is about 180 ms)
- Reflection at the 4-wire to 2-wire hybrid would be annoying for the MS user (although it is not a problem for a PSTN user)
- The echo canceller at the interface between the MSC and the PSTN reduces the effects of this echo

Ref : I. Darwazeh

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Location Management in GSM

- In order for international roaming to work, the location of the MS must be known to the network (HLR) at all times. A mobile will update its location to it's HLR when it detects a change in location area.
- Areas of national networks are divided into location areas each with a unique **Location Area Identity (LAI)** broadcast on the BCCH.
- Each location area has a mobile switching centre (MSC) with a Home Location Register (HLR) and a Visitor Location Register (VLR).

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Location Update

Location updating is carried out via the fixed network using the following procedure:

1. The VLR issues a **Mobile Subscriber Roaming Number (MSRN**) to be associated with the actual mobile identity (i.e. the **International Mobile Subscriber Identity – IMSI**) over the radio path.
2. Both the IMSI and MSRN are conveyed to the subscriber's HLR over the fixed SS7 network.
3. Information on the subscriber's user-profile is conveyed from the subscriber's HLR to the VLR.
4. The HLR now contains the subscriber's telephone number, the mobile's IMSI and the MSRN that points to the mobile's actual location.

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GSM radio Interface

GSM Radio Interface (U_m)

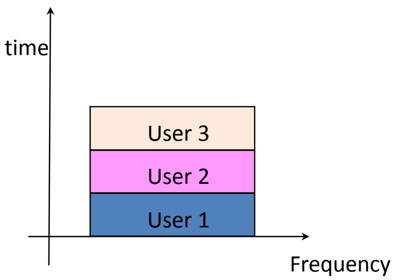
The GSM radio interface (Um) employs examples of the following :

- **SDMA :** Cellular structure assigning an MS to a BTS
- **FDD :** Separate frequencies for uplink and downlink
- **FDMA :** Available frequency resource is divided into separate channels (e.g GSM900 has 124 channels, each 200kHz wide)
- **TDMA :** Each frequency channel is divided into time **frames** that repeat every 4.615ms. TDMA frames are further divided into 8 **time slots** of 576.9μS duration.

Data is transmitted in **bursts**. Each burst consists of 148 bits and lasts for 546.5μS. The remaining 30.4μS is used as **guard space** to avoid overlap with other bursts.

Each **physical channel** has a raw data rate of 33.8kbps. Therefore, each radio carrier is capable of transmitting approximately 270kbps

Time Division Multiple Access (TDMA)



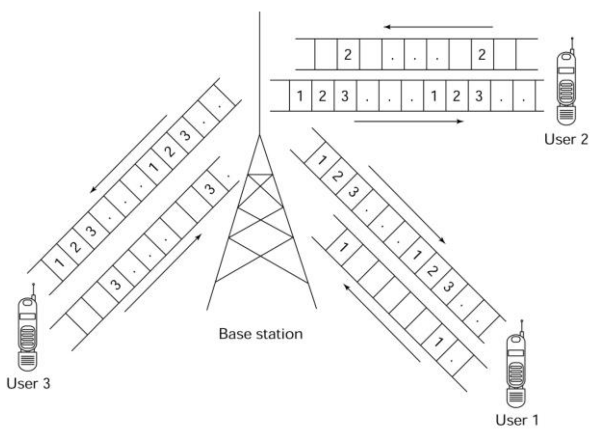
GSM adopts TDMA/FDMA mode
channel width: 200KHz
each channel has 8 timeslots

Concept:

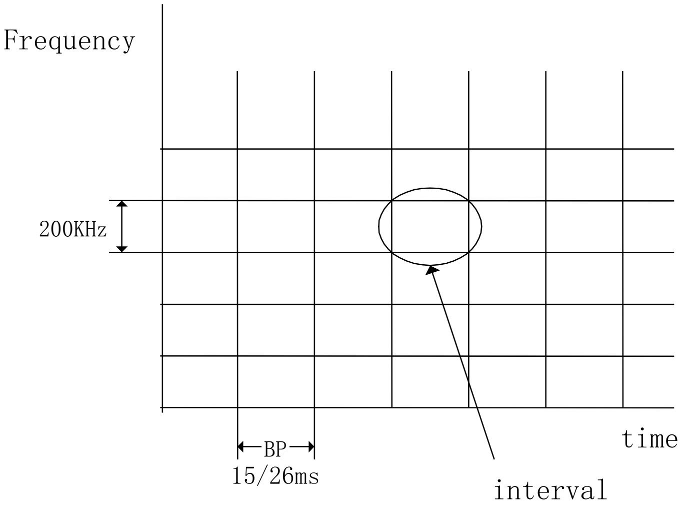
channel is composed of a series of timeslots of periodicity. Different signal energies are distributed into different timeslots. The adjacent channel interference is restricted by connection choosing from time to time. So the useful signal is passed only in the specified timeslot.

TDMA principle

- GSM uses TDMA within each carrier
- Each user occupies the entire carrier one *time slot* pr. *time frame*
  - 8 slots per frame

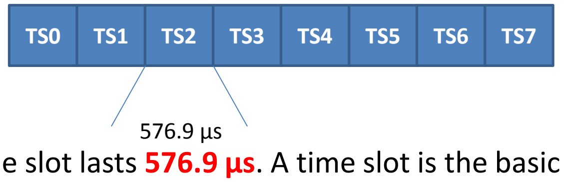


GSM Timeslot and Frame structure



GSM Radio Interface : TDMA

- Each frequency is divided up into 8 **time slots**, numbered 0 to 7.



- Each time slot lasts **576.9 µs**. A time slot is the basic radio resource used to facilitate communication between the MS and the BTS
- Time slots are constructed into **frames**, each lasting **4.615ms** (8 time slots plus guard spaces)
- One **physical channel** consists of a single time slot, repeated every frame (i.e. repeated every 4.615ms).
- Therefore, basic data rate of a single physical channel = 148/4.615ms = 32kbps

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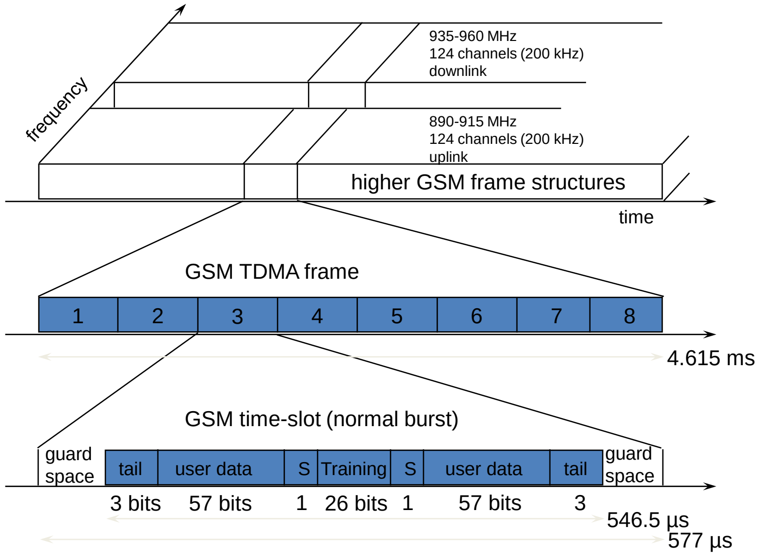
GSM Radio Interface : TDMA/FDMA



Ref : Schiller, p109

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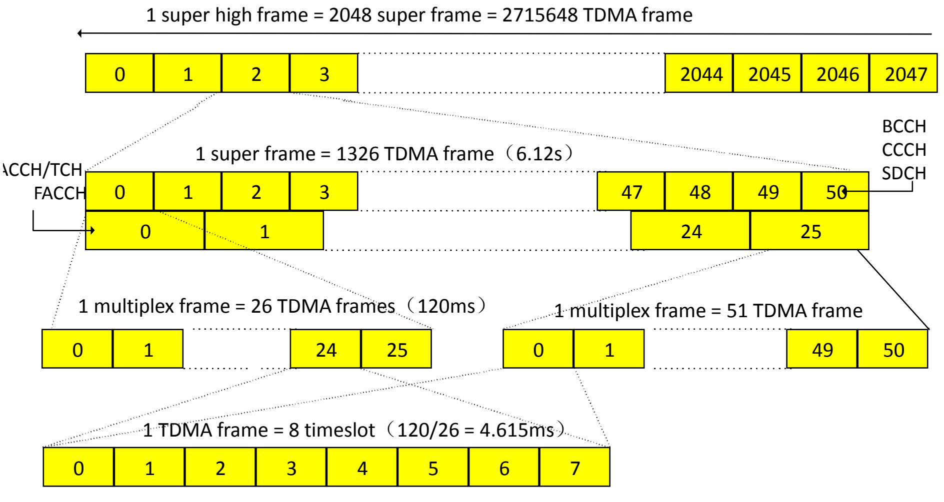
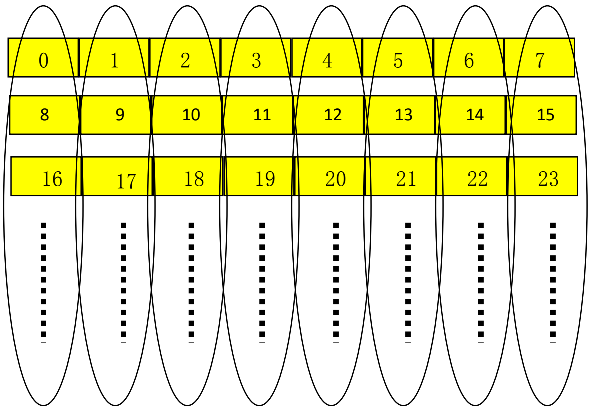
Timeslot and Frame structue

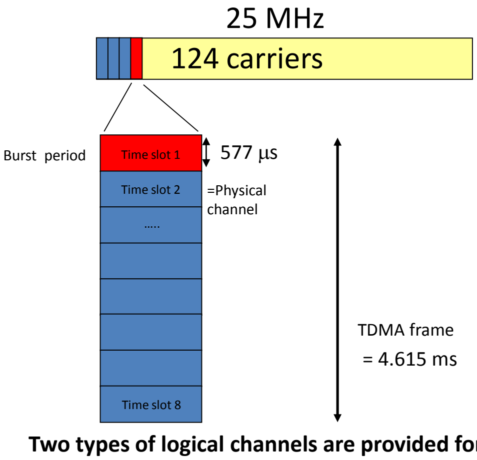


Physical Channel



- The physical channel adopts FDMA and TDMA technologies.
- In the time domain, a specified channel occupies the same timeslots in each TDMA frame, so it can be identified by the timeslot number and frame number.

GSM Channel structure



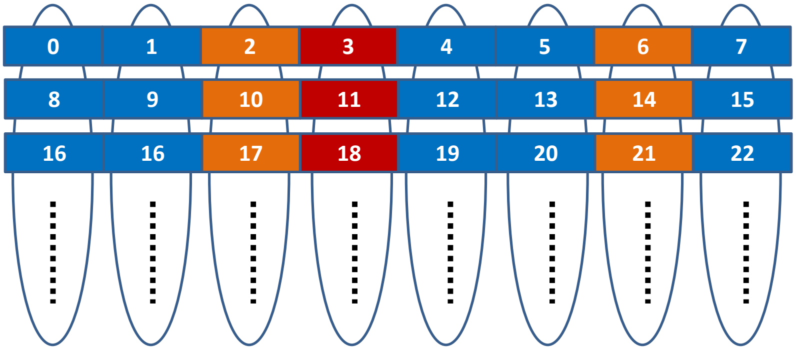
Logical channels are built up of physical channels

Two types of logical channels are provided for in GSM :

1. **Traffic Channels (TCH)**
   - Transmit voice and data
2. **Control Channels (CCH)**
   - transmit the signaling and synchronous data between BTS and MS.

Logical vs Physical Channels

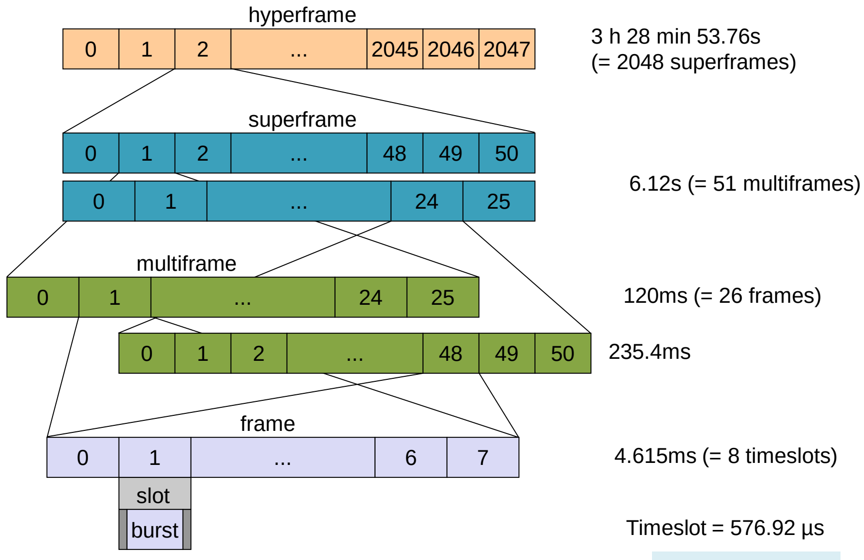
- The physical medium is divided into 8*124 duplex channels (previous slide). These **physical channels** are mapped into **Logical channels**.
- A specified logical channel occupies repeated timeslots in each TDMA frame. e.g. timeslot 3,11,18 etc.
- For logical channels requiring higher data rates, multiple physical channels may be used for the same logical channel, e.g. 2,6,10,14,17,21.



Logical channels and frame hierarchy

- **Multiframes** are frames that are grouped or linked together to perform specific functions.
- Multiframes in the GSM system use established schedules for specific purposes, such as coordinating with frequency hopping patterns.
- Multiframes used in the GSM system include the 26 traffic multiframe, 51 control multiframe, superframe, and hyperframe.

GSM hierarchy of frames



Ref : Schiller, p109

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Superframe and Hyperframe

Superframe

- A superframe is a multiframe sequence that combines the period of a 51 multiframe with 26 multiframes (6.12 seconds).
- The use of the superframe time period allows all mobile devices to scan all the different time frame types at least once.

Hyperframe

- A hyperframe is a multiframe sequence that is composed of 2048 superframes, and is the largest time interval in the GSM system (3 hours, 28 minutes, 53 seconds).
- Every time slot during a hyperframe has a sequential number (represented by an 11 bit counter) that is composed of a frame number and a time slot number. This counter allows the hyperframe to synchronize frequency hopping sequence, encryption processes for voice privacy of subscribers' conversations.

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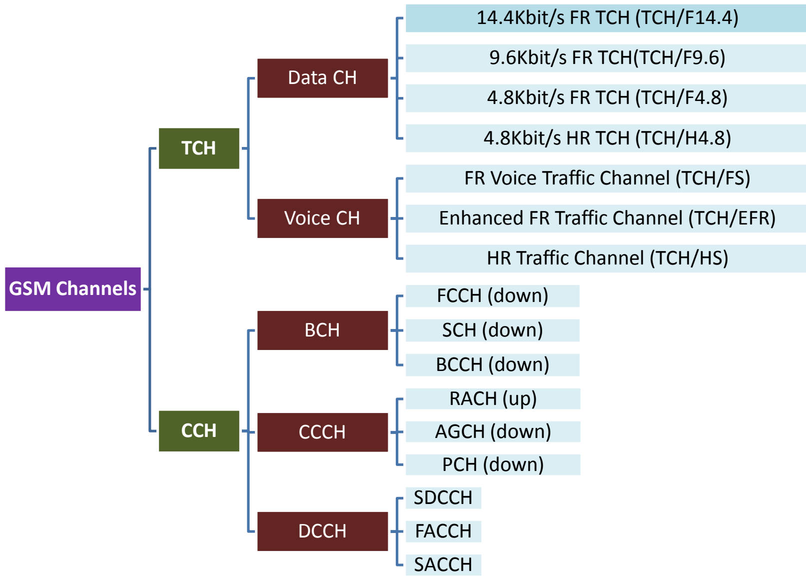
GSM Logical Channel Hierarchy



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Traffic Channels (TCH)

- GSM uses a TCH to transmit user data (e.g., voice, fax). Two basic categories of TCHs have been defined, :
  - <u>**full-rate TCH (T CH/F)**</u>
  - <u>**full-rate TCH (T CH/H)**</u>
- With the voice codecs available at the beginning of the GSM standardization, 13 kbit/s were required, whereas the remaining capacity of the TCH/F (22.8 kbit/s) was used for error correction (TCH/FS).
- Improved codes allow for better voice coding and can use a TCH/H. Using these TCH/Hs doubles the capacity of the GSM system for voice transmission. Speech quality decreases with the use of TCH/Hs, however, and many operators try to avoid using them.
- The standard codecs for voice are called full rate (FR, 13 kbit/s) and half rate (HR, 5.6 kbit/s). A newer codec, enhanced full rate (EFR), provides better voice quality than FR as long as the transmission error rate is low. The generated data rate is only 12.2 kbit/s.

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Broadcast channels (BCH)

The BCH channels are used, by the base station, to provide the mobile station with the sufficient information it needs to synchronize with the network. There are 3 subchannels of the BCH as follows :

- **Broadcast Control Channel (BCCH) :**A BTS uses this channel to signal information to all MSs within a cell. information transmitted in this channel is, e.g., the cell identifier, options available within this cell (frequency hopping), and frequencies available inside the cell and in neighboring cells.
- **Synchronization Channel (SCH) :** Supplies the mobile station with the training sequence needed in order to demodulate the information transmitted by the base station
- **Frequency-Correction Channel (FCCH) :** Supplies the mobile station with the frequency reference of the system in order to synchronize it with the network

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Common Control Channel (CCCH)

All information regarding connection setup between MS and BS is exchanged via the CCCH. The subchannels of the CCCH are as follows :

- **Paging CHannel (PCH) :** The BTS uses the paging channel (PCH) for paging the appropriate MS in order to set up a mobile terminated (MT) call.
- **Random Access Channel (RACH) :** If an MS wants to set up a call, it uses the random access channel (RACH) to send data to the BTS. The RACH implements multiple access (all MSs within a cell may access this channel) using slotted Aloha. This is where a collision may occur with other MSs in a GSM system.
- **Access Grant CHannel (AGCH) :** The BTS uses the access grant channel (AGCH) to signal an MS that it can use a TCll or SDCCH for further connection setup.

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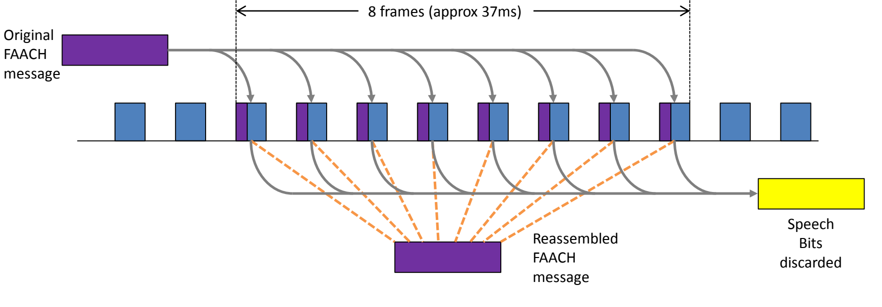
Dedicated Control Channel (DCCH)

While the previous channels have all been unidirectional, the following channels are bidirectional.

- As long as an MS has not established a TCH with the BTS, it uses the **Stand-alone Dedicated Control CHannel (SDCCH)** with a low data rate (782 bit/s) for signaling. This can comprise authentication, registration or other data needed for setting up a TCH.
- Each TCH and SDCCH has a **Slow Associated Dedicated Control CHannel (SACCH)** associated with it, which is used to exchange system information, such as the channel quality and signal power level.
- Finally, if more signaling information needs to be transmitted and a TCH already exists, GSM uses a **Fast Associated dedicated Control CHannel (FACCH).** The FACCH uses the time slots which are otherwise used by the TCH. This is necessary in the case of handovers where BTS and MS have to exchange larger amounts of data in less time.

Fast Associated Control Channel Signaling

- The GSM **Fast Associated Control Channel** (FACCH) is transmitted by "stealing" speech frames and replacing them with control information.
- The FACCH message is divided and transmitted over 8 sequential channel bursts and the speech information that would normally be transmitted is discarded.
- When received, the FACCH message is reassembled into its original message structure.
- Since the proportion of speech data stolen and discarded is small, the effect on voice quality is not noticable.



Mapping of Physical Channels in GSM

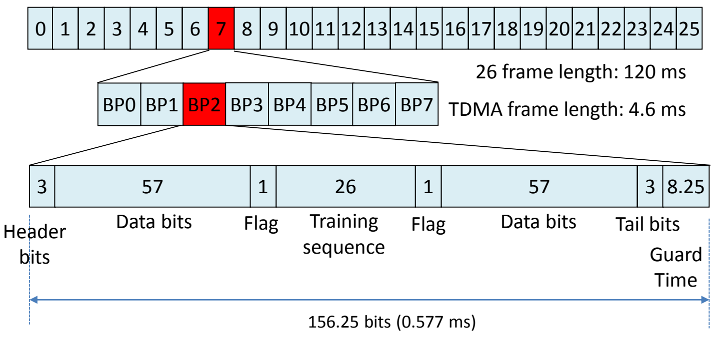
There are 5 types of burst that can occupy a timeslot:

(1) Normal burst (148 bits + 8.25 guard bits).
(2) Frequency correction Burst (148 bits + 8.25 guard bits).
(3) Synchronisation burst (148 bits + 8.25 guard bits).
(4) Random access burst (88 bits + 68.25 guard bits).
(5) Idle burst

- A normal burst consists of 148 bits transmitted at 270.833 kb/s: 114 bits are available for data transmission, 26 bits are used for the equaliser training sequence, 3 Head and 3 Tail bits ensure equalisation of data bits close to the burst edges.
- A guard time of 8.25 bits is added at the end of each burst to prevent transmitted bursts from different mobiles overlapping., as a result of their differing distances from the base station.
- Two stealing flags (SF) indicate that a TCH has been stolen for signalling purposes.
- If slow frequency hopping is implemented then the frequency is changed between bursts using those frequency channels available in the serving cell.

GSM Normal Burst

- logical channels are mapped onto the basic TDMA frame structure below and the recurrence of one particular timeslot on each frame constitutes one physical channel.
- The GSM normal burst is used for the standard communications between the base station and the Mobile Stations, and is used to carry both TCH and CCH data.



GSM Normal Burst

- ***3 tail bits:*** These tail bits at the start of the GSM burst give time for the transmitter to ramp up its power
- ***57 data bits:*** This block of data is used to carry information, and most often contains the digitised voice data although on occasions it may be replaced with signalling information in the form of the Fast Associated Control CHannel (FACCH). The type of data is indicated by the flag that follows the data field
- ***1 bit flag (steal bi):*** This bit within the GSM burst indicates the type of data in the previous field.
- ***26 bits training sequence:*** This training sequence is used as a timing reference and for equalisation. There is a total of eight different bit sequences that may be used, each 26 bits long. The same sequence is used in each GSM slot, but nearby base stations using the same radio frequency channels will use different ones, and this enables the mobile to differentiate between the various cells using the same frequency.
- ***1 bit flag*** Again this flag indicates the type of data in the data field.
- ***57 data bits*** Again, this block of data within the GSM burst is used for carrying data.
- ***3 tail bits*** These final bits within the GSM burst are used to enable the transmitter power to ramp down. They are often called final tail bits, or just tail bits.
- ***8.25 bits guard time*** At the end of the GSM burst there is a guard period. This is introduced to prevent transmitted bursts from different mobiles overlapping, as a result of their differing distances from the base station.

GSM Synchronisation Burst

The Synchronisation burst provides synchronisation for all the Mobile Stations on the network :

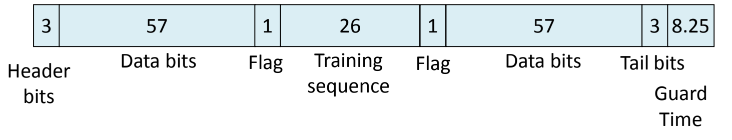
- 3 tail bits: Again, these tail bits at the start of the GSM burst give time for the transmitter to ramp up its power
- 39 bits of information:
- 64 bits of a Long Training Sequence:
- 39 bits Information:
- 3 tail bits Again these are to enable the transmitter power to ramp down.
- 8.25 bits guard time: to act as a guard interval.

3	57	1	26	1	57	3	8.25
Header bits	Data bits	Flag	Training sequence	Flag	Data bits	Tail bits	Guard Time

GSM Frequency Correction Burst

The Frequency correction burst essentially consists of a constant frequency carrier with no phase alteration (data is all zeros)

- 3 tail bits: Again, these tail bits at the start of the GSM burst give time for the transmitter to ramp up its power.
- 142 bits all set to zero:
- 3 tail bits Again these are to enable the transmitter power to ramp down.
- 8.25 bits guard time: to act as a guard interval



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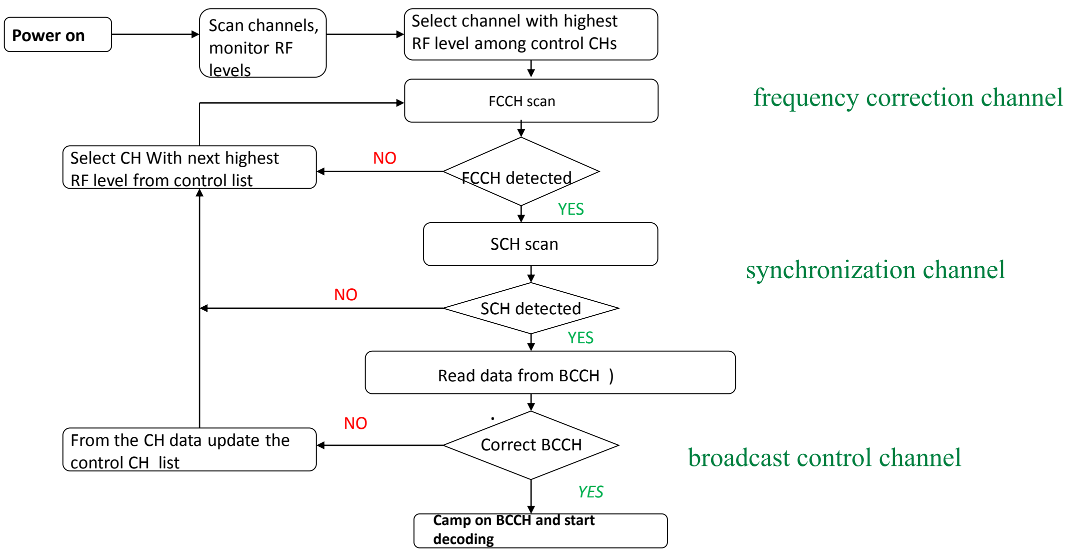
GSM Random Access Burst

The GSM random access burst is used when accessing the network and it is shortened in terms of the data carried, having a much longer guard period.

This GSM burst structure is used to ensure that it fits in the time slot regardless of any severe timing problems that may exist. Once the mobile has accessed the network and timing has been aligned, then there is no requirement for the long guard period.

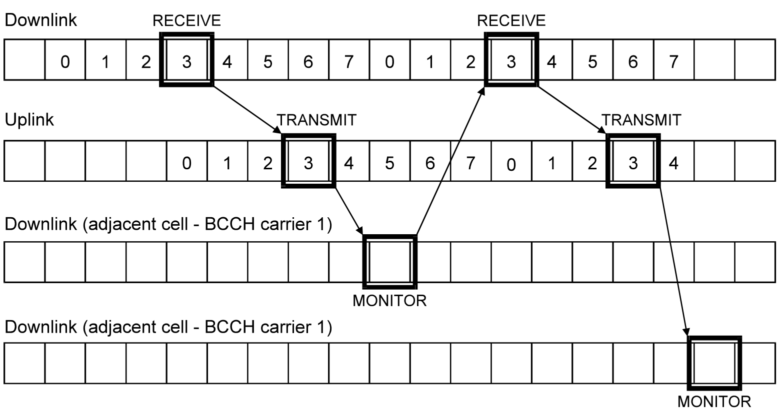
- ***7 tail bits:*** The increased number of tail bits is included to provide additional margin when accessing the network.
- ***41 training bits:***
- ***36 data bits:***
- ***3 tail bits*** Again these are to enable the transmitter power to ramp down.
- ***69.25 bits guard time:*** The additional guard time, filling the remaining time of the GSM burst provides for large timing differences

Example of use of bursts: registration



Mapping of Physical Channels in GSM

The basic TDMA frame applies to both uplink and downlink. However, the slot numbers are staggered by three slots so that the mobile does not transmit and receive at the same time.



GSM Slots and Scanning Structure

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Mapping of Logical Channels in GSM

Five different cases of mapping logical channels onto one physical channel are used in GSM as follows:

1. One full-rate TCH and its SACCH.
2. Two half-rate TCHs (HTCH) and their SACCH.
3. BCCH and CCCH.
4. Eight SDCCH.
5. Four SDCCH, one BCCH and one CCCH (this for lower capacity than case (3)).

In order to achieve these mappings two multiframe formats are used:

- **Multiframe Format (1) :**
  - » 26 TDM frames for the TCH/SACCH cases (1) and (2)
- **Multiframe Format (2) :**
  - » 51 TDM frames for cases (3), (4) and (5).

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Channel Assignment inside cells

- **Small capacity cell with only 1 TRX**

  TN0: FCCH+SCH+CCCH+BCCH+SDCCH/4(0,_,3)+SACCH/C4(0,_,3);

  TN1-7: TCH/F+FACCH/F+SACCH/TF

- **The medium-size cell with 4 TRXs**

  1TN0 group: FCCH+SCH+BCCH+CCCH;

  2 SDCCH/8(0,_,7)+SACCH/C8(0,_,7);

  29 TCH/F+FACCH/F+SACCH/TF

- **Large-size cell with 12 TRXs**

  1 TN0 group: FCCH+SCH+BCCH+CCCH;

  1 TN2 group, 1 TN4 group and 1 TN6 group: BCCH+CCCH;

  5 SDCCH/8(0,_,7)+SACCH/C8(0,_,7);

  87 TCH/F+FACCH/F+SACCH/TF

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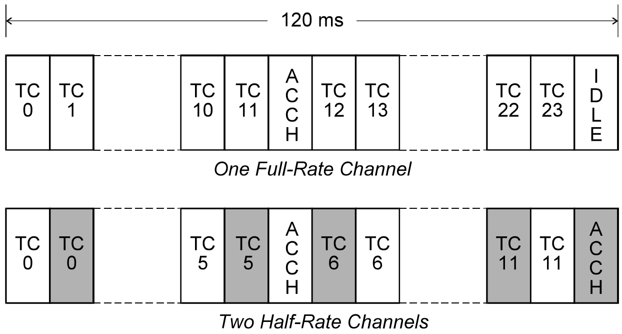
Mapping of TCH and SACCH



Full- and Half-Rate Channels

In the diagram TC0 denotes a normal burst of 0.577 ms (associated with a TDMA frame) on a physical channel. TC1 denotes the next burst occurring 4.615 ms later on the same physical channel and so on. The multiframe duration equals $\underline{26 \times 4.615 \text{ ms} = 120 \text{ ms}}$.

Mapping of TCH and SACCH

The gross bit rate per TCH is derived as follows:

Data bits per normal burst = 114 bits

Normal bursts per 120 ms Multiframe = 24

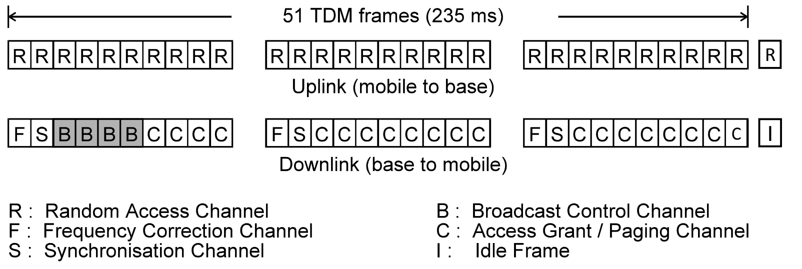
Gross Bit Rate = 24 x 114 / 0.12 = $\underline{22.8 \text{ kb/s}}$

SACCH uses 114 bits per 120 ms = $\underline{950 \text{ b/s}}$

For the HTCH, two half-rate channels share one physical channel and the SACCH associated with the second HTCH occupies the idle frame. Hence, each HTCH occupies 12 frames with a gross bit rate of 11.4 kb/s while each SACCH uses 950 b/s.

The FACCH uses the TCH as indicated by the stealing flags.

Mapping of BCCH and CCCH

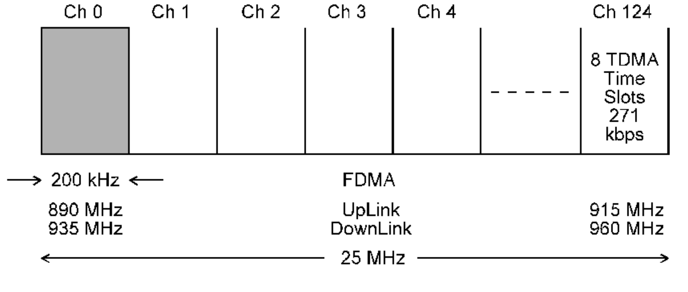


Multiframe Structure

This multiframe format is carried by timeslot 0 on one of the allocated carriers in the serving cell called the BCCH carrier. On the uplink the mobile can use any one of the 51 frames in timeslot 0 to access the network. On the downlink the 51 frames are grouped into 5 sets of 10 frames (the 51st slot is idle).

GSM Radio Interface : FDMA

- GSM uses Frequency Division Duplexing (FDMA) to separate the uplink and downlinks.
- FDD requires two distinct frequency bands; 890MHz to 915MHz for the uplink (MS to BTS) and 935MHz to 960MHz for the downlink (BTS to MS).
- Channel separation is 200kHz, meaning that there are 125 channels in each of the above frequency bands.
- Each cell can have 1 to 15 pairs of carriers and each carrier is time multiplexed into 8 slots. A physical channel therefore consists of a carrier frequency **and** a timeslot.



Absolute Radio Frequency Channel Number (ARFCN)

- Each uplink/downlink pair is assigned a number called the **Absolute Radio Frequency Channel Number (ARFCN).**
- The uplink and downlink frequencies each have a bandwidth of 200 kHz. The uplink and downlink have a specific *offset* that varies for each band. The offset is the frequency separation of the uplink from the downlink.
- Every time the ARFCN is incremented, the uplink increases by 200 kHz and the downlink also increases by 200 kHz.
- An ARFCN has an allowed bandwidth of 200 kHz, which corresponds exactly to the carrier separation.
- The frequency of the ARFCN refers to its **centre** frequency. For example, if an ARFCN has a frequency of 914.80 MHz, then it occupies the frequency space from 914.7 MHz to 914.9 MHz (200 kHz total).

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ARFCN for various GSM standards

	GSM 450	EGSM 450	GSM 850	GSM 900	EGSM 900	GSM 1800	GSM 1900
Uplink Frequency Range	450 to 458 MHz	478 to 486 MHz	824 to 849 MHz	890 to 915 MHz	880 to 915 MHz	1710 to 1785 MHz	1850 to 1910 MHz
Downlink Frequency Range	460 to 468 MHz	488 to 496 MHz	869 to 894 MHz	935 to 960 MHz	925 to 960 MHz	1850 to 1880 MHz	1930 to 1990 MHz
ARFCN	259 - 293	306 - 340	128 - 251	1 - 124	0 – 124, 975 - 1023	512 - 885	512 - 810
Offset	10MHz	10MHz	45MHz	45MHz	45MHz	95MHz	80MHz

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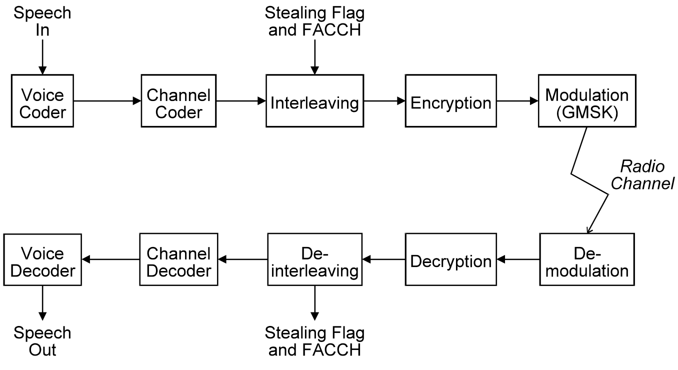
GSM Coding and Modulation



Coding and Decoding in GSM

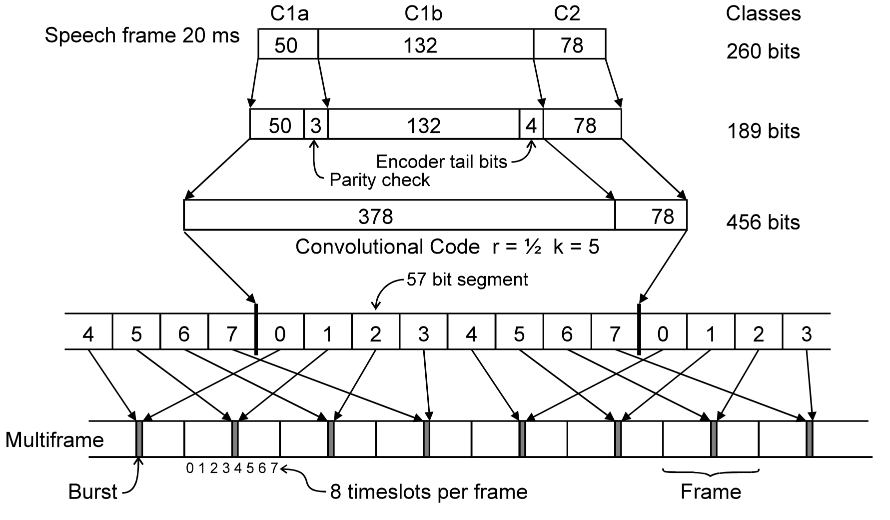
The various stages of coding and decoding in a GSM TCH are shown above. The speech codec operates at 13 kb/s since speech is encoded into 260 bit frames of 20 ms duration. Each 260 bit frame is then channel encoded using block and convolutional codes to give a 456 bit frame.

Discontinuous Transmission and Reception

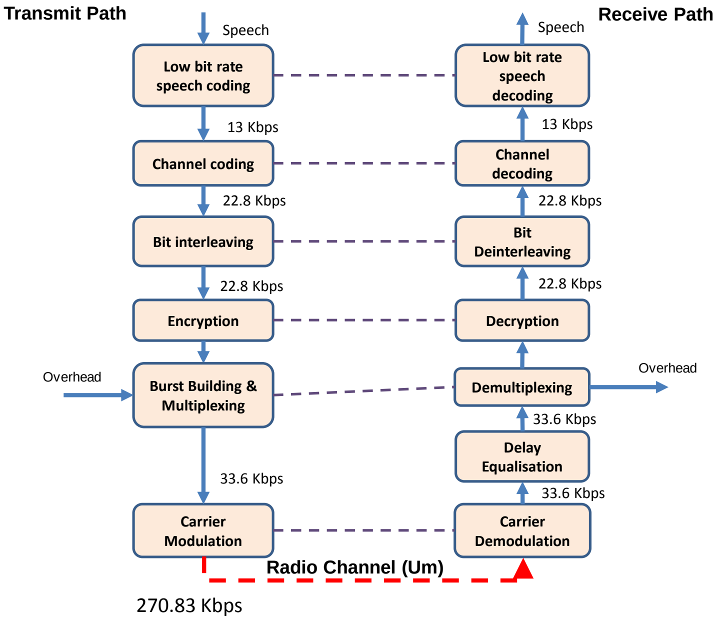
– An average speech activity of just 44% means that a voice activity detector (VAD) can be used to suppress TCH transmission during silent periods.
– This reduces the level of co-channel interference by 3 dB on average and prolongs battery life.
– The silent periods are filled with low level comfort noise to remove the impression that the link has been disconnected.
– Since the mobile need only listen to a subset of all paging frames, then in the remaining time it can switch to stand-by-mode, thereby conserving power. This process is called discontinuous reception.

GSM Coding and Modulation (contd.)

The 456 bit frame is subdivided into 8 x 57 bit blocks which are interleaved to a depth of 8. The process of channel coding and interleaving is shown below.



GSM Speech Path



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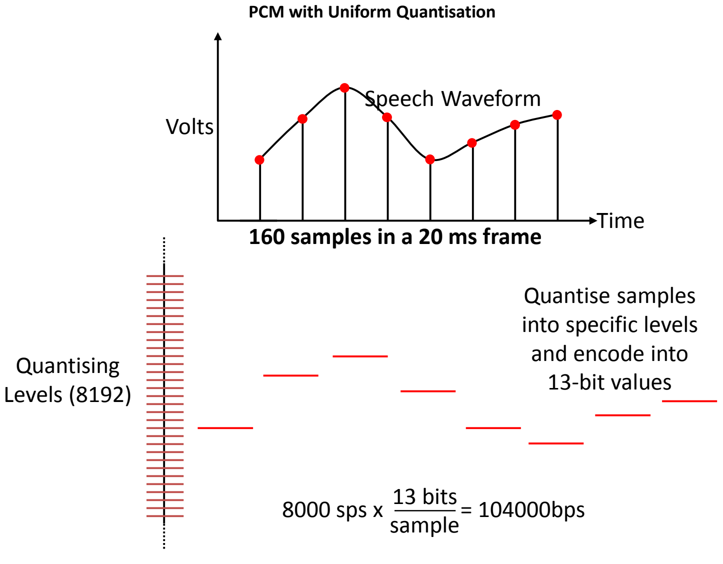
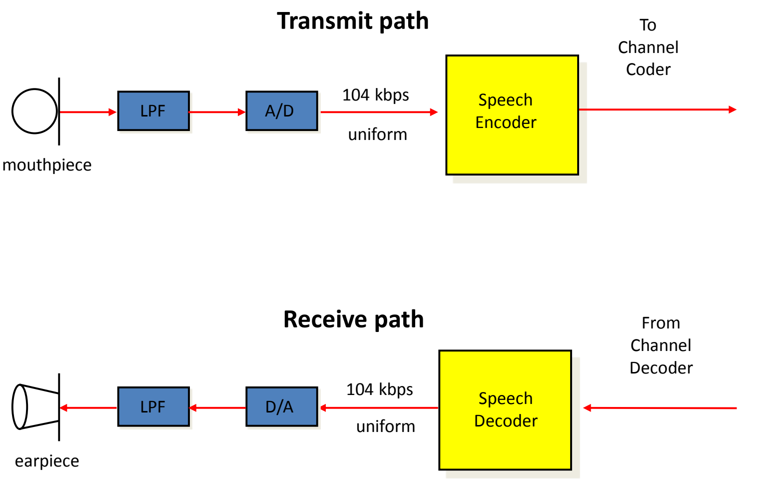
Speech Coding at Mobile Side

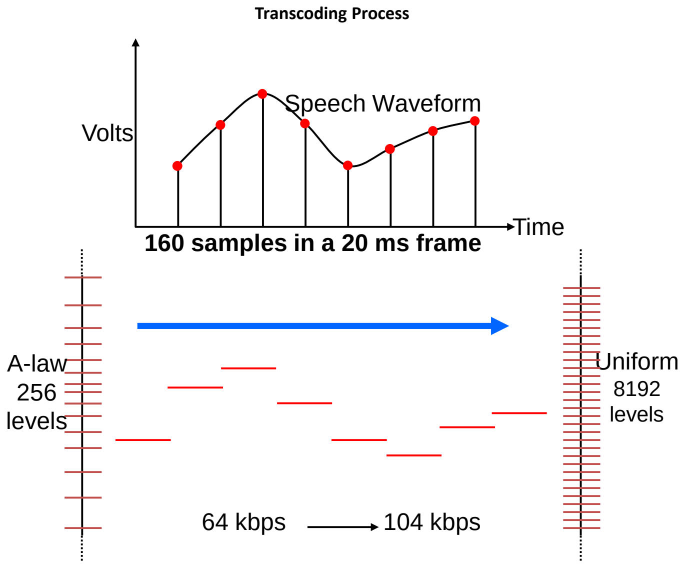


$$8000 \text{ sps} \times \frac{13 \text{ bits}}{\text{sample}} = 104000\text{bps}$$

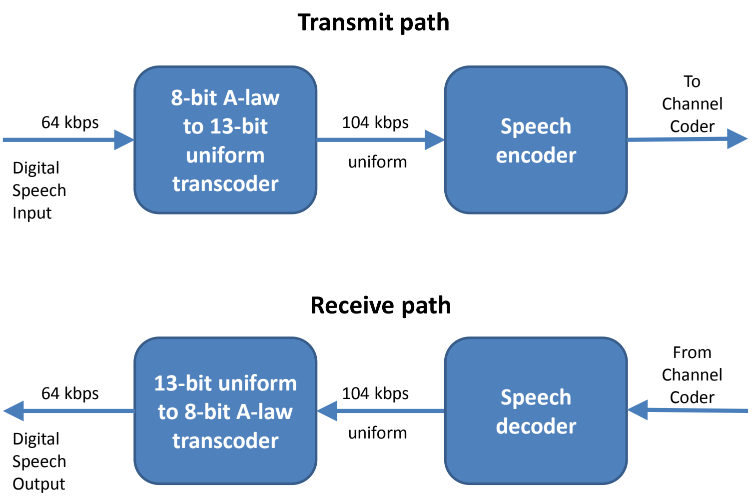
GSM Speech Processing : MS side



GSM Speech Coding at Network Side



GSM Speech Processing : Network side



GSM Channel Coding

GSM Channel Coding Uses Several procedures:

Block Coding

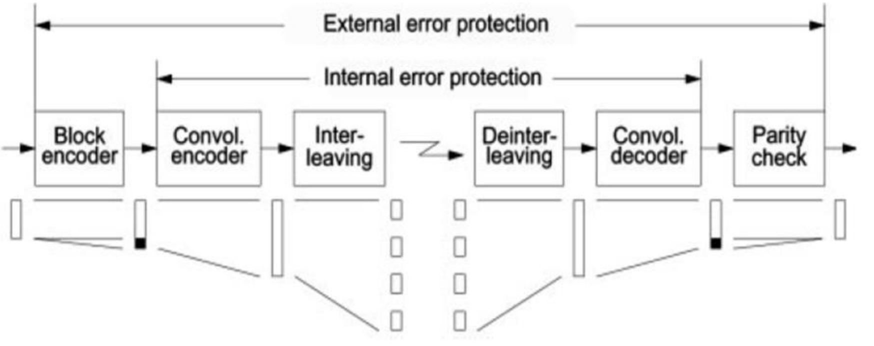
generates parity bits for error detection.

Convolution Coding

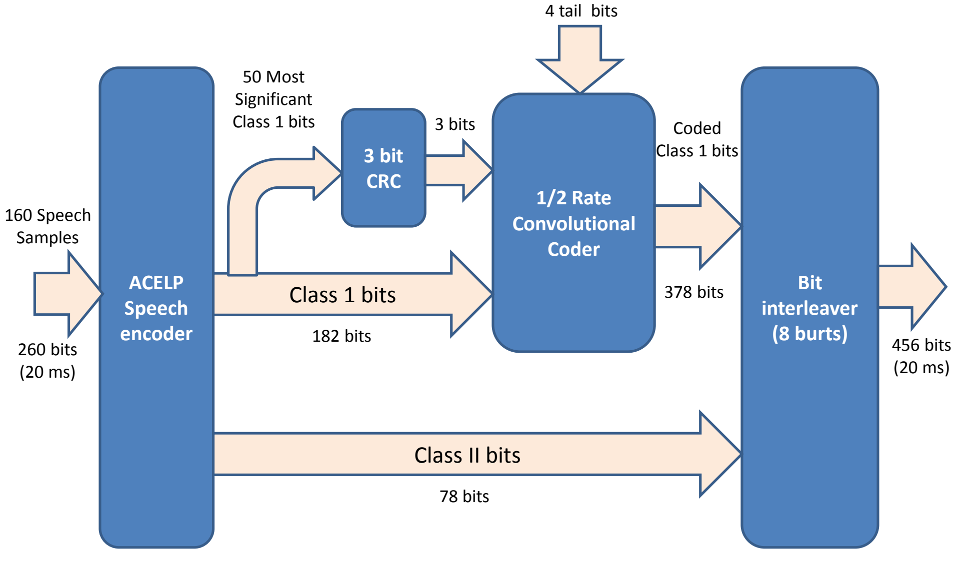
generates redundancy for error Correction.

Interleaving

Interleaving of data over several blocks reduces the damage done by burst error



Channel Coding for Full-rate Speech in GSM



Coding in GSM

For Full Rate Speech 260 bits are transmitted in 20ms equalling a transmission rate of 13 kbps and encoded in blocks according to respective importance to the of speech **intelligibility.**

Class 1a

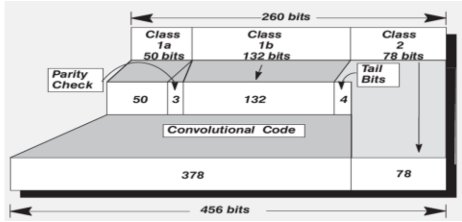
- 50 class 1a bits.
- 3 parity bits are generated on these bits.
- These are most important bits.

Class 1b

- 132 class 1b bits.
- Not parity checked
- 4 tail bits are added to this class.

Class 2

- 78 bits least important
- Not protected at all.



Channel type	Abbr.	Block distance (ms)	Bits per block			Convol. code rate	Encoded bits per block	Inter-leaver depth
			Data	Parity	Tail			
TCH, full rate, speech	TCH/FS	20	260				456	8
Class I			182	3	4	1/2	378	
Class II			78	0	0	–	78	
TCH, half rate, speech	TCH/HS	20	112				228	4
Class I			95	3	6	104/211	211	
Class II			17	0	0	–	17	
TCH, full rate, 14.4 kbit/s	TCH/F14.4	20	290	0	4	294/456	456	19
TCH, full rate, 9.6 kbit/s	TCH/F9.6	5	4 × 60	0	4	244/456	456	19
TCH, full rate, 4.8 kbit/s	TCH/F4.8	10	60	0	16	1/3	228	19
TCH, half rate, 4.8 kbit/s	TCH/H4.8	10	4 × 60	0	4	244/456	456	19
TCH, full rate, 2.4 kbit/s	TCH/F2.4	10	2 × 36	0	4	1/6	456	8
TCH, half rate, 2.4 kbit/s	TCH/H2.4	10	2 × 36	0	4	1/3	228	19
FACCH, full rate	FACCH/F	20	184	40	4	1/2	456	8
FACCH, half rate	FACCH/H	40	184	40	4	1/2	456	6
SDCCH, SACCH			184	40	4	1/2	456	4
BCCH, NCH, AGCH, PCH		235	184	40	4	1/2	456	4
RACH		235	8	6	4	1/2	36	1
SCH			25	10	4	1/2	78	1
CBCH		235	184	40	4	1/2	456	4

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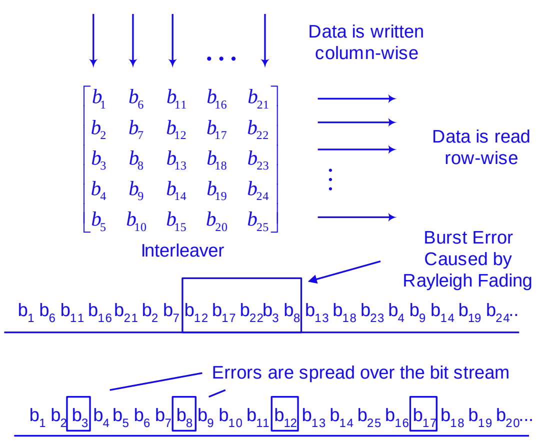
Interleaving

- In mobile communications, the errors are "bursty"
- Optimal performance from ECC is obtained for uniform error distribution
- Interleaving increases the performance of ECC in mobile environment



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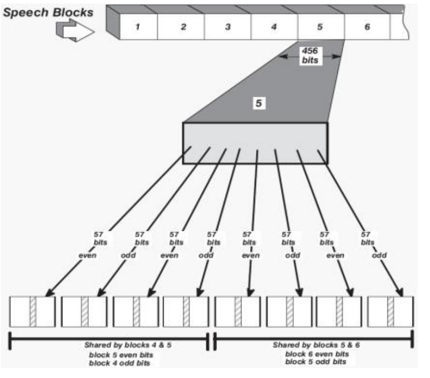
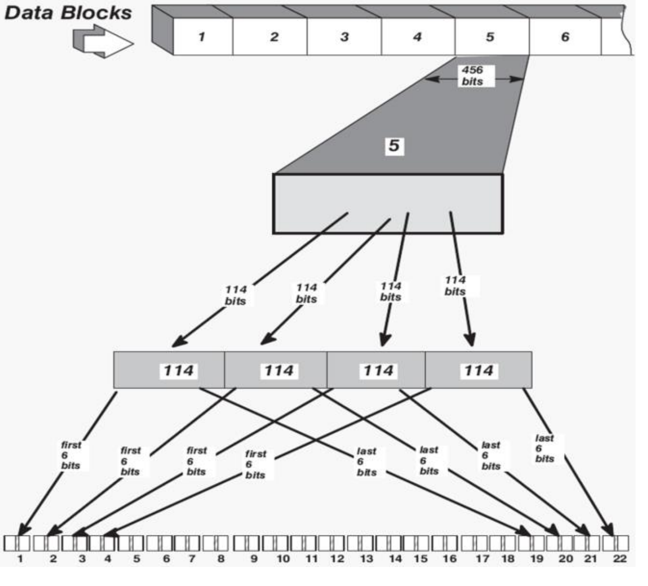
After channel encoding, the next step is to build its *bit stream* into bursts to be transmitted within TDMA frame structure.
Interleaving ***spreads*** the content of one traffic block across several TDMA timeslots.

Interleaving depths/typed used:
Speech – 8 blocks/ Diagonal
Control – 4 blocks/Rectangular
Data – 22 blocks/Hybrid

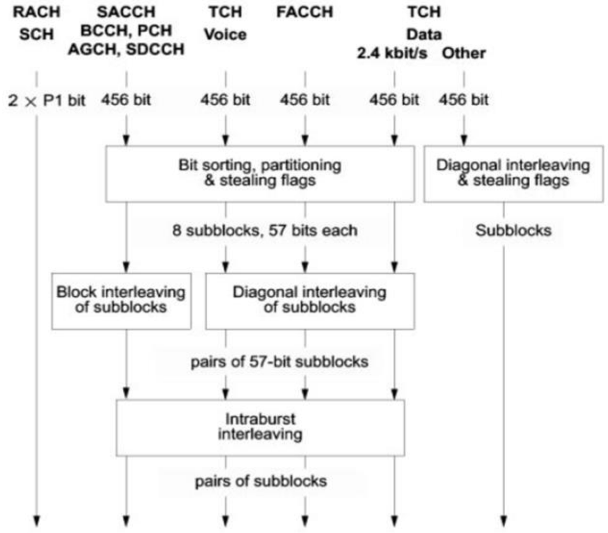


Hybrid Interleaving

- Data channels encoded previously to 456 bits are divided into blocks of four 114 bit each. These blocks are then interleaved together.
- The first 6 bits from the first block are placed in the first burst, the 2nd 6 from block in the 2nd burst and so on. Each 114 bits will be spread across 19 bursts and total 456 across 22 bursts.



Interleaving processes



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Discontinuous Transmission and Reception

– An average speech activity of just 44% means that a **Voice Activity Detector (VAD)** can be used to suppress TCH transmission during silent periods.
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– The silent periods are filled with low level comfort noise to remove the impression that the link has been disconnected.
– Since the mobile need only listen to a subset of all paging frames, then in the remaining time it can switch to stand-by-mode, thereby conserving power. This process is called discontinuous reception.

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GSM AMR codec

- **Adaptive Multi-rate (AMR)** codec is now the most widely used GSM codec.
- The AMR codec was adopted by 3GPP in October 1988 and it is now widely used for both GSM and circuit switched UMTS / WCDMA voice calls.
- The AMR codec provides a variety of options for one of eight different bit rates as described in the table below.
- The bit rates are based on frames that are 20 millisceonds long and contain 160 samples.
- **Discontinuous transmission** is employed so that when there is no speech activity the transmission is cut. Additionally **Voice Activity Detection (VAD)** is used to indicate when there is only background noise and no speech. To provide audio feedback to indicate to the user that the connection is still present, a **Comfort Noise Generator (CNG)** is used to provide some background noise, even when no speech data is being transmitted. This is added locally at the receiver.

Mode	Bit Rate (kbps)	Full/Half rate
AMR 12.2	12.2	FR
AMR 10.2	10.2	FR
AMR 7.95	7.95	FR / HR
AMR 7.40	7.4	FR / HR
AMR 6.70	6.7	FR / HR
AMR 5.90	5.9	FR / HR
AMR 5.15	5.15	FR / HR
AMR 4.75	4.75	FR / HR

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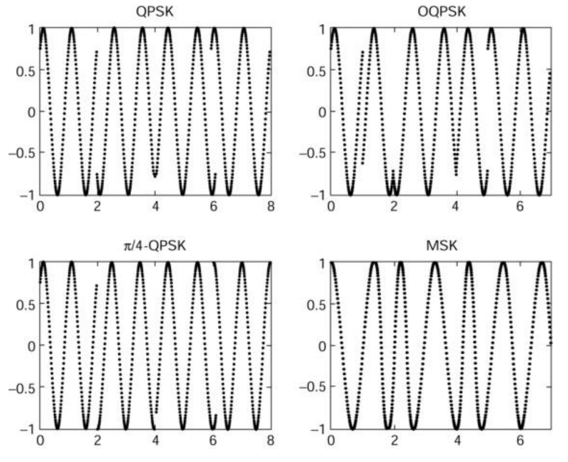
Modulation

- Considerations upon choosing modulations scheme:
  - Spectrum efficiency
  - Out of band emission (rapid drop off desired to limit adjacent channel interference)
  - Constant envelope desired for low cost amplifiers, e.g. in handheld equipment
- Always a trade off
- In GSM: GMSK – Gaussian Minimum Shift Keying is used

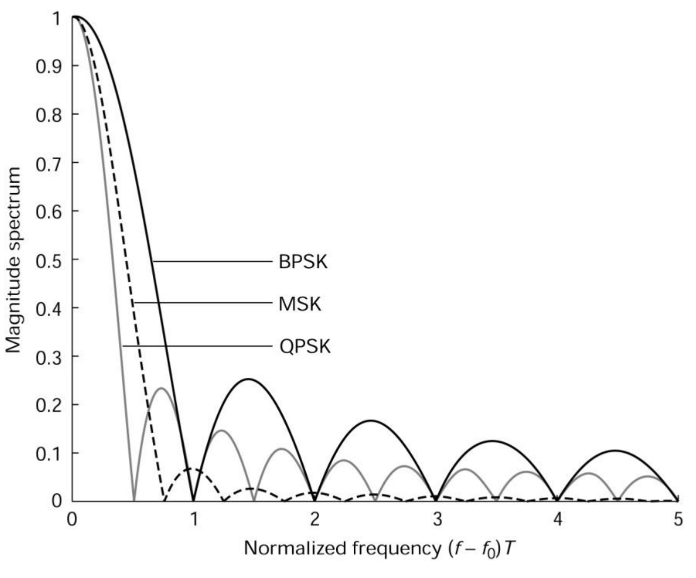
GMSK Modulation

- MSK can be considered as a development of QPSK but without the abrupt discontinuities at phase transitions.
- MSK is an example of continuous phase modulation
- The constant amplitude envelope of MSK results in relatively low sidelobes



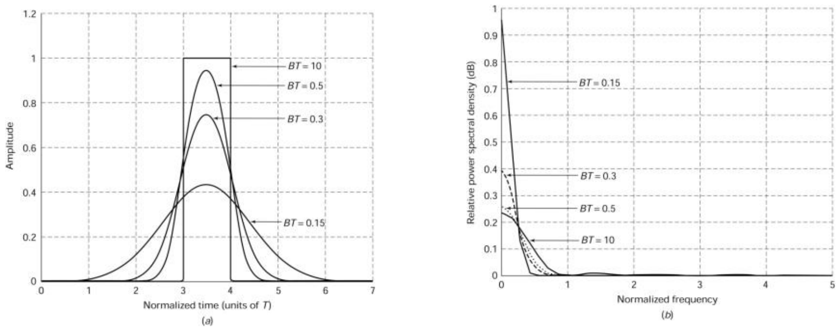
GMSK Modulation

Spectrum of MSK, QPSK and BPSK



GMSK Modulation

- GMSK further reduces sidelobes by using a Gaussian filter
  - Cost: introduces inter-symbol-interference (ISI)
- Figures show time and frequency response
  - GSM uses BT = 0.3



Gaussian Minimum Shift Keying (GMSK)

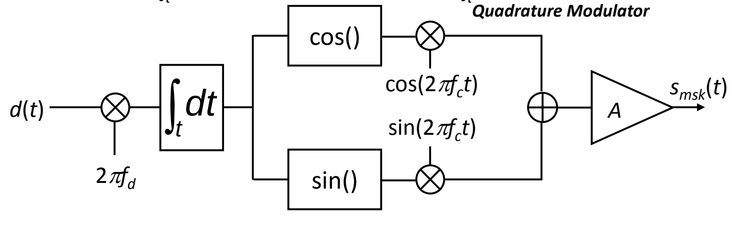
To appreciate GMSK we must first consider Minimum Shift Keying (MSK) implemented using quadrature modulation. MSK is a special form of binary frequency shift keying (FSK) using a frequency deviation $f_d = 1/4T$, where T is the bit duration.

$$s_{msk}(t) = A\cos\left(2\pi f_c t - \int_t 2\pi f_d d(t)dt\right)$$

where data $d(t) = \pm 1$ for $0 \le t \le T$

$$s_{msk}(t) = A\cos\left(\int_t 2\pi f_d d(t)dt\right)\cos(2\pi f_c t) + A\sin\left(\int_t d2\pi f_d d(t)dt\right)\sin(2\pi f_c t)$$

Quadrature Modulator

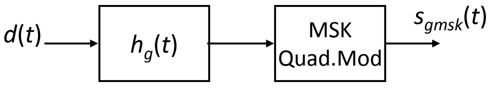


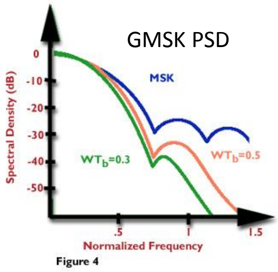
$$s_{msk}(t) = A\cos\left(\pm\frac{\pi t}{2T}\right)\cos(2\pi f_c t) + A\sin\left(\pm\frac{\pi t}{2T}\right)\sin(2\pi f_c t)$$

$$\text{Modulation index} = \frac{2 f_d}{R_b} = \frac{2(1/4\text{T})}{1/\text{T}} = 0.5$$

Gaussian Minimum Shift Keying (Contd.)

To obtain GMSK, the data $d(t)$ is pre-filtered by a Gaussian shaped filter:

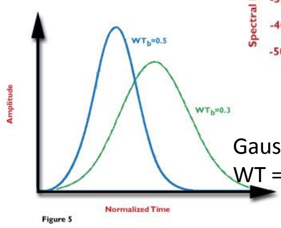




where $h_g(t) = \dfrac{\sqrt{\pi}}{\alpha}\exp\left(-\left[\dfrac{\pi t}{\alpha}\right]^2\right)$

$H_g(f) = \exp\left(-\alpha^2 f^2\right)$

and $\alpha = \dfrac{\sqrt{\ln 2}}{\sqrt{2}B} = \dfrac{0.5887}{B}$



Gaussian Pulse Shape
WT = BT!

In GSM the BT = 0.3, which defines B for a given T and hence α.

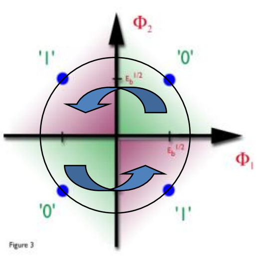
The bit error rate of GMSK is given by: $P_e = Q\left(\sqrt{\dfrac{2\gamma E_b}{N_o}}\right)$

where γ = 0.68 for BT = 0.25 and indicates the degradation in BER due to the ISI introduced by the Gaussian filter.

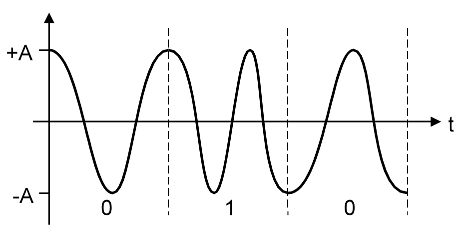
Gaussian Minimum Shift Keying (contd.)

GMSK is an example of a constant amplitude, continuous phase modulation scheme which is characterised by:

1) Bandwidth efficient;
2) Low out-of-band sidelobes;
3) Low distortion and spectral regrowth in presence of PA non-linearity.



GMSK Constellation



GMSK Waveform

The purpose of Gaussian filtering is to reduce the out of band sidelobe energy caused by the sudden change in carrier frequency associated with bit transitions. The presence of the Gaussian filter constrains the rate of change of frequency at a bit transition as shown in the above diagram. The GMSK waveform as well as showing constant amplitude and continuous phase also shows smoothed frequency changes.

Security in GSM

The security functions in GSM include:

(1) Authentication of the user.
(2) Radio Path Encryption.
(3) User Identity Protection (prevents disclosure of location).

GSM Architecture and signals

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- Original data services in GSM
- Introduction to GPRS
- GPRS network elements & protocols
- GPRS Roaming
- EDGE

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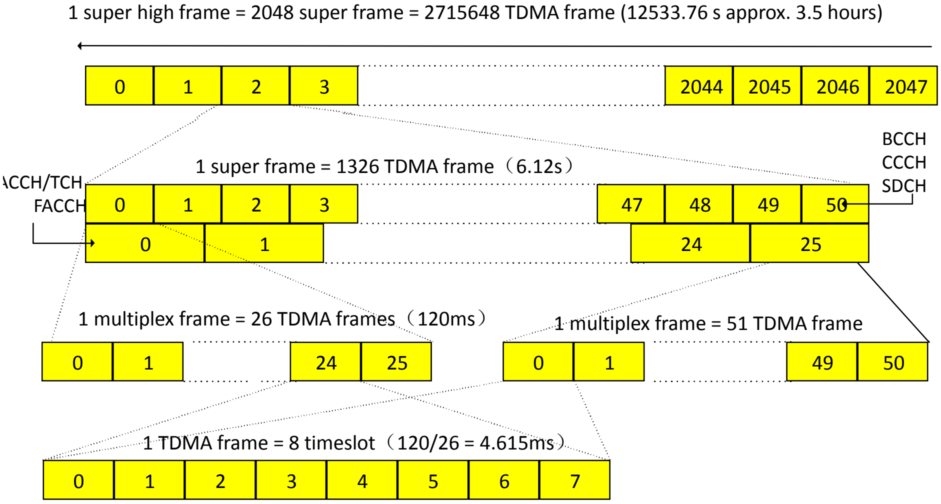
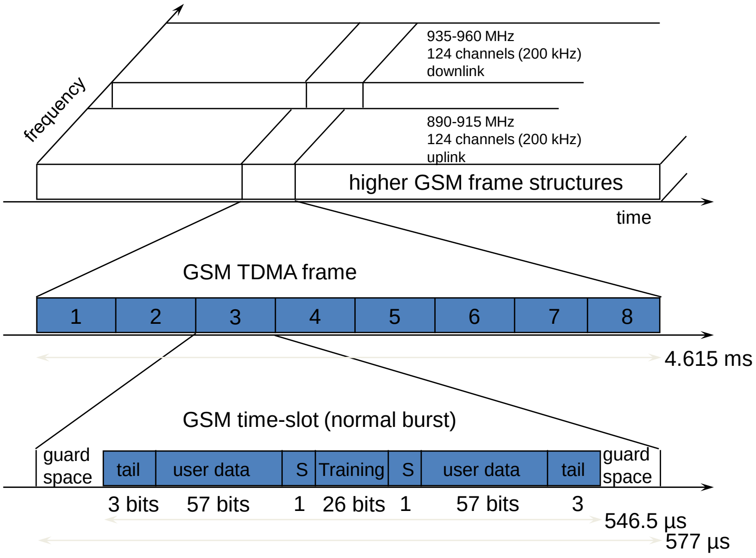
2.5G enhancements

- The GSM system, as defined in the original specification, is referred to as 2G (second generation mobile system)
- 2G networks were built mainly for voice services, short messages and relatively slow data transmission.
- In order to meet the demand for higher data rates on 2G systems prior to the arrival of 3G, a number of enhancements were introduced which have been collectively come to be referred to as “2.5G”.
- These enhancements include :
  - High-Speed Circuit-Switched Data (HSCSD)
  - General Packet Radio Service (GPRS)
  - Enhanced Data rates for GSM Evolution (EDGE)

Timeslot and Frame structue



GSM Radio Interface : TDMA/FDMA



Ref : Schiller, p109

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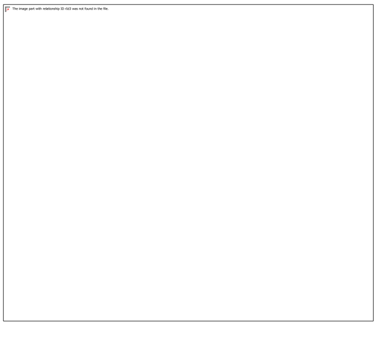
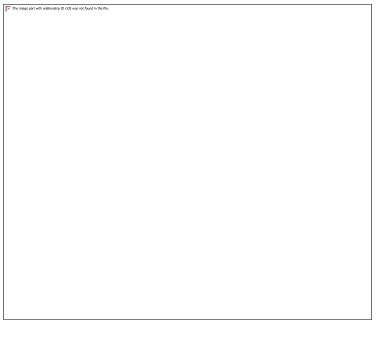
GMSK Modulation

- GMSK further reduces sidelobes by using a Gaussian filter
  - Cost: introduces inter-symbol-interference (ISI)
- Figures show time and frequency response
  - GSM uses BT = 0.3
  - GM total rate 271 kbit/s
  - Spectral Efficiency 1.3 bits/s/Hz





Original Data Services in GSM

- GSM data transmission standardized with only 9.6 kbit/s
  - advanced coding allows 14.4 kbit/s
  - not enough for Internet and multimedia applications
- HSCSD (High-Speed Circuit Switched Data)
  - bundling of several time-slots to get higher AIUR (Air Interface User Rate)(e.g., 57.6 kbit/s using 4 slots, 14.4 each)
  - advantage: ready to use, constant quality, simple
  - disadvantage: data channels are blocked for voice transmission

HSCSD: Pros and Cons

Pros :

- HSCSD offers four times higher bandwidth than the original GSM data service.
- HSCSD requires minor network upgrades only. No new network elements are required. Capital investment is about a fifth of the one for GPRS.
- HSCSD charging principles are well introduced in the network and well accepted by customers.
- HSCSD has a well defined QoS.

Cons :

- HSCSD is still circuit switched, i.e. the network load is not as efficiently handled as with GPRS and thus an always on service is hard to deliver.
- channels blocked for voice transmission whilst used for data.

Comparison of data transfer speed (in Kbps)

56K dial up	GSM	HSCSD (Max speed)	GPRS (Max speed)	GPRS (Realistic speed)
56k	9.6k	56k	171. 2k	43k to 56k

General Packet Radio Service : GPRS

- GPRS is a packet-switching extension to GSM networks. Information sent on a GPRS network is split into separate "packets" before it is transmitted and reassembled at the receiving end.
- The GPRS network acts in parallel with the GSM network, providing packet switched connections to the external networks.
- GPRS can provide an instant connection where information can be sent and received immediately. Unlike a GSM only network where the user has to "dial up" and wait for a connection to be established, GPRS allows users to be "always connected" to the network.
- Theoretically, a GPRS connection can provide a data transmission speed of up to 171.2Kbps (approximately three times that of a fixed-line 56K dial-up) if all eight time slots are used.

GPRS Evolution

- GPRS was orginally standardized by the Specialised Mobile Group (SMG) within ETSI.
- GPRS first introduced as "Release 97" in 1997.
- Last ETSI SMG specification for GPRS was "Release 99" in 2000. Thereafter, responsibility for GPRS specifications passed to 3GPP.
- Most significant ETSI SMG standards releases are as follows :

Version	Released	Description
Release 96	1997 Q1	GSM Features, 14.4 kbit/s User Data Rate,
Release 97	1998 Q1	GSM Features, GPRS Introduced
Release 98	1998	GSM Features, AMR, EDGE, GPRS for PCS1900
Release 99	2000 Q1	Specified the first UMTS 3G networks, incorporating a CDMA air interface

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Introduction to 3GPP

- **3GPP** is a collaboration agreement established in 1998 between several standards organisations.
- In 2000 the specification work of GSM radio was moved from ETSI SMG to 3GPP. This means that Rel'99 was the last release of the GSM/EDGE standard that was specified in ETSI SMG and thereafter, all specifications related to GSM radio access network were moved under 3GPP responsibility with new specification numbers.
- 3GPP specifications are based on evolved GSM specifications.
- 3GPP standardization encompasses Radio, Core Network and Service architecture.

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GPRS Services Offered

GPRS makes the following services possible:

- "Always on" internet access
- Multimedia messaging service (MMS)
- Push to talk over cellular (PoC)
- Mobile Instant messaging
- Internet applications for smart devices through the wireless application protocol (WAP)

GPRS Device Classes

Devices supporting GPRS are divided into three classes:

- **Class A devices -** Can be connected to GPRS service and GSM service (voice, SMS), using both at the same time.
- **Class B devices -** Can be connected to GPRS service and GSM service (voice, SMS), but using only one or the other at a given time. During GSM service (voice call or SMS), GPRS service is suspended, and then resumed automatically after the GSM service (voice call or SMS) has concluded. Most GPRS mobile devices are Class B.
- **Class C devices -** Are connected to either GPRS service or GSM service (voice, SMS). Must be switched manually between one or the other service.

A true Class A device may be required to transmit on two different frequencies at the same time, and thus will need two radios. To get around this requirement, a GPRS mobile may implement the dual transfer mode (DTM) feature.

A DTM-capable mobile may use simultaneous voice and packet data, with the network coordinating to ensure that it is not required to transmit on two different frequencies at the same time. Such mobiles are considered pseudo-Class A, sometimes referred to as "simple class A".

GPRS user data rates and Coding Schemes

- The GSM system allocates between 1 and 8 timeslots within a TDMA frame for GPRS data.
- Timeslots are allocated on demand, not in a fixed, pre-determined manner.
- Uplink and downlink are allocated separately.
- The system chooses the **Coding Scheme** (CS) depending on the current error rate. CS-4 provides no error correction capabilities.

Coding scheme	1 slot	2 slots	3 slots	4 slots	5 slots	6 slots	7 slots	8 slots
CS-1	9.05	18.1	27.15	36.2	45.25	54.3	63.35	72.4
CS-2	13.4	26.8	40.2	53.6	67	80.4	93.8	107.2
CS-3	15.6	31.2	46.8	62.4	78	93.6	109.2	124.8
CS-4	21.4	42.8	64.2	85.6	107	128.4	149.8	171.2

Ref : Schiller, p 125

GPRS device classes 1 to 12

- These classes describe the data bandwidth supported by the device.
- The basic unit of bandwidth in GPRS is the channel. Each channel can transmit **8 to 12 kbps** of data with the data coding scheme used today by most networks (i.e. CS1 and CS2).
- Depending on their class, a device can use up to 5 channels simultaneously (the limit is 4 for a single direction: you can have 4 channels used in download and 1 upload but not 5 channels for upload and 0 for download).

Class	Dynamic Allocation	Download channels	Upload channels	Max Active Channels	Combinations
1	No	1	1	2	(1+1)
2	No	2	1	3	(2+1)
3	Yes	2	2	3	(2+1) (1+2)
4	No	3	1	4	(3+1)
5	No	2	2	4	(2+2)
6	Yes	3	2	4	(3+1) (2+2)
7	Yes	3	3	4	(3+1) (2+2) …
8	No	4	1	5	(4+1)
9	No	3	2	5	(3+2)
10	Yes	4	2	5	(4+1) (3+2)
11	Yes	4	3	5	(4+1) (3+2) …
12	Yes	4	4	5	(4+1) (3+2) …

GPRS network architecture

- GPRS assumes an underlying GSM infrastructure.
- The MS, BSS, MSC/VLR and HLR in the GSM network all need to be modified for GPRS (e.g. HLR is enhanced with GPRS subscriber info.)
- In addition, two new physical nodes must be added to a GSM network :
  - **SGSN** = "**Serving GPRS Support Node**" : supports the MSC for localization, billing and security
  - **GGSN** = "**Gateway GPRS Support Node**" : gateway to the packet data network – usually the Internet

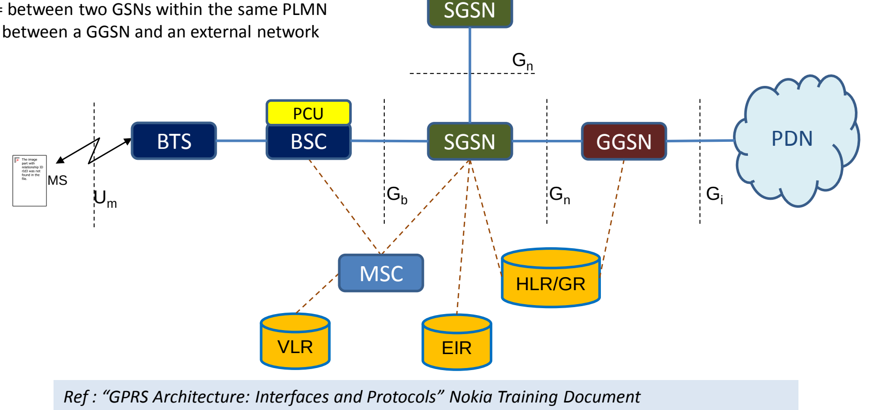
GPRS Architecture and Interfaces

New network Nodes :

- SGSN = "Serving GPRS Support Node" : supports the MSC for localization, billing and security
- GGSN = "Gateway GPRS Support Node" : gateway to the packet data network – usually the Internet
- GR = "GPRS Register" : supports the HLR. Used for user address mapping
- PCU = "Packet Control Unit" : provides physical and logical data interface to the BSC for packet data traffic

New Interfaces :

- Um = Radio interface between the MS and the GPRS network
- Gb = Frame relay interface between a SGSN and a BSS
- Gn = between two GSNs within the same PLMN
- Gi = between a GGSN and an external network



Ref : "GPRS Architecture: Interfaces and Protocols" Nokia Training Document

Serving GSN (SGSN)

The SGSN is the most important element of the GPRS network. The SGSN in the GPRS network is equivalent to the MSC in the GSM network. There must at least one SGSN in an GPRS network. There is a coverage area associated with a SGSN. As the network expands and the number of subscribers increases, there may be more than one SGSN in a network. The SGSN has the following functions:

- Protocol conversion (for example IP to FR)
- Ciphering of GPRS data between the MS and SGSN
- Data compression is used to minimise the size of transmitted data units
- Authentication of GPRS users
- Mobility management as the subscriber moves from one area to another, and possibly one SGSN to another
- Routing of data to the relevant GGSN when a connection to an external network is required
- Interaction with the NSS (that is, MSC/VLR, HLR, EIR) via the SS7 network in order to retrieve subscription information
- Collection of charging data pertaining to the use of GPRS users
- Traffic statistics collections for network management purposes.

Ref : "GPRS Architecture: Interfaces and Protocols" Nokia Training Document

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Gateway GSN (GGSN)

The GGSN is the gateway to external networks. Every connection to a fixed external data network has to go through a GGSN. The GGSN acts as the anchor point in a GPRS data connection even when the subscriber moves to another SGSN during roaming. The GGSN may accept connection request from SGSN that is in another PLMN. Hence, the concept of coverage area does not apply to GGSN. There are usually two or more GGSNs in a network for redundancy purposes, and they back up each other up in case of failure. The functions of a GGSN are given below:

- Routing mobile-destined packets coming from external networks to the relevant SGSN
- Routing packets originating from a mobile to the correct external network
- Interfaces to external IP networks and deals with security issues
- Collects charging data and traffic statistics
- Allocates dynamic or static IP addresses to mobiles either by itself or with the help of a DHCP or a RADIUS server
- Involved in the establishment of tunnels with the SGSN and with other external networks and VPN.

Ref : "GPRS Architecture: Interfaces and Protocols" Nokia Training Document

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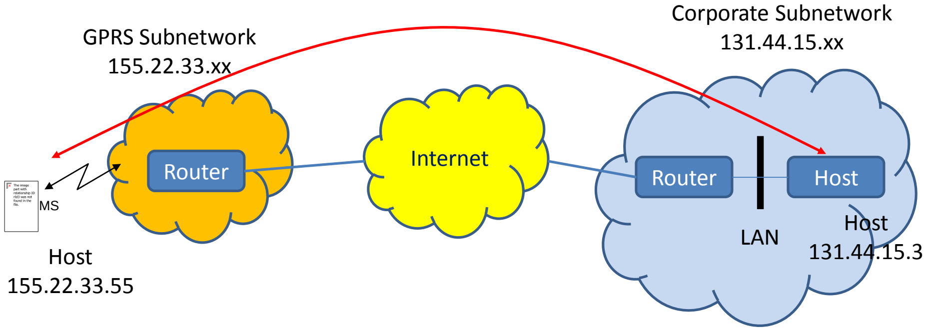
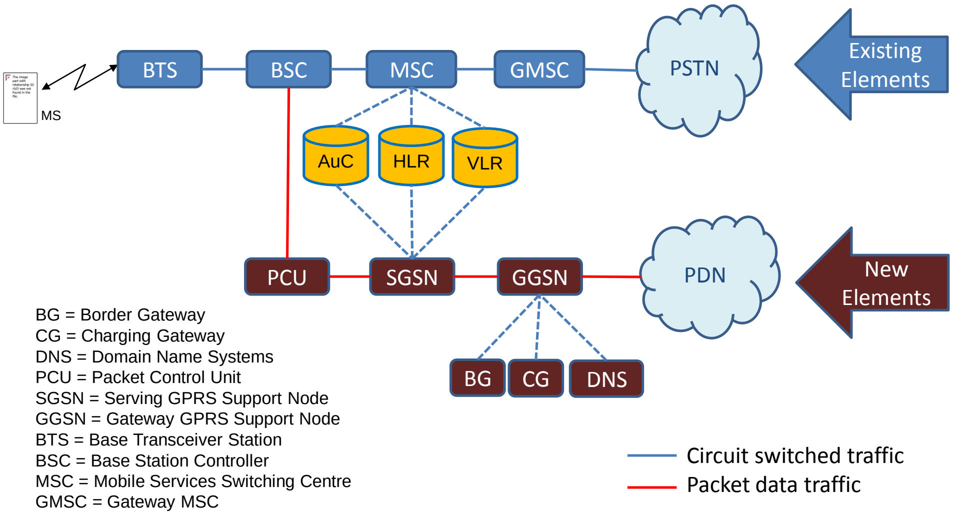
GGSN operation

From the external network's point of view, the GGSN is simply a router to an IP sub-network. This is shown below. When the GGSN receives data addressed to a specific user in the mobile network, it first checks if the address is active. If it is, the GGSN forwards the data to the SGSN serving the mobile. If the address is inactive, the data is discarded. The GGSN also routes mobile originated packets to the correct external network.



Ref : "GPRS Architecture: Interfaces and Protocols" Nokia Training Document

Existing and new GPRS Network Elements



GPRS Radio Interface

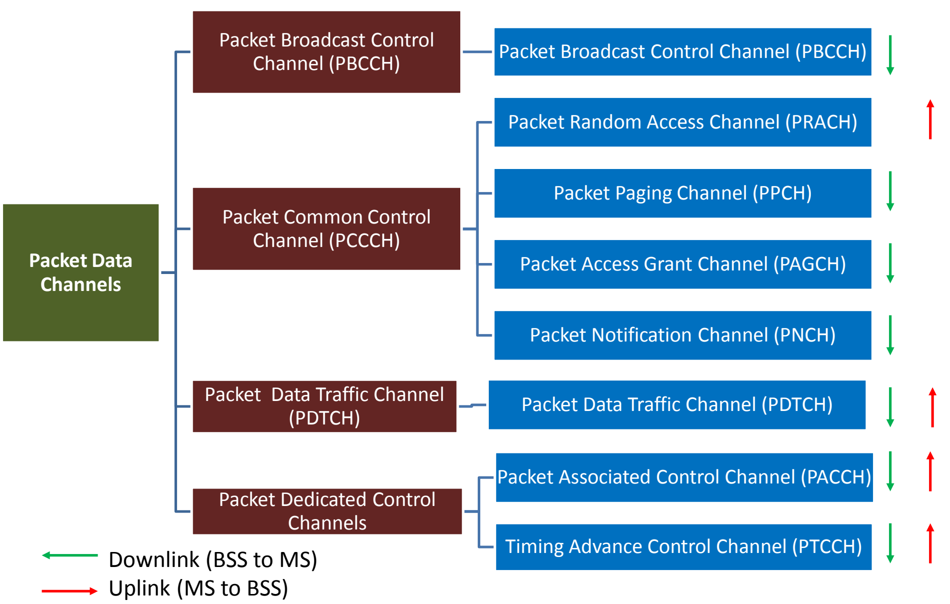
Logical channels:

- packet common control channels (PCCCH)
  - packet random access channel (PRACH)
  - packet paging channel (PAGCH)
  - packet access grant channel (PAGCH)
  - packet notification channel (PNCH)
- packet broadcast control channel (PBCCH)
- packet data traffic channel (PDTCH)
  - data rates 9.05 to 21.4 kbps, depending on channel coding
- packet associated control channel (PACCH)

Physical channels:

- PDTCH is mapped to one physical channel
- dynamic or permanent channel allocation for GPRS possible
- if no PCCCH possible, MSs park on CCCH (common control channel)

GPRS Logical Channel Hierarchy



GPRS Attach/Detach

- In order to use GPRS services, an MS must first make its presence known to the network by performing a **GPRS attach**. This makes the MS available for SMS over GPRS and SMS over IMS, paging via the SGSN, and notification of incoming packet data. If the UE is already PS-attached due to an attach via E-UTRAN it makes its presence known to an SGSN by a **Routing Area Update**.
- In order to send and receive packet data by means of GPRS services, the MS must activate the Packet Data Protocol context that it wants to use. This operation makes the MS known in the corresponding P-GW/GGSN, and interworking with data networks can commence.
- User data are transferred transparently between the MS and the packet data networks with a method known as **encapsulation** and **tunnelling**: data packets are equipped with GPRS-specific protocol information and transferred between the MS and the P-GW/GGSN. This transparent transfer method lessens the requirement for the PLMN to interpret external data protocols, and it enables easy introduction of additional interworking protocols in the future.

GPRS PDP Context

- The PDP Context has a **record of parameters**, which consists of all the required information for establishing an end-to-end connection.
  - PDP Type (usually IP v4)
  - address of the MS (normally the IP address), which allows mapping of PDP address to GSM address
  - QoS profile request (QoS parameters requested by user)
  - QoS profile negotiated (QoS parameters negotiated by network)
  - Authentication type (PAP or CHAP)
  - DNS type (Dynamic DNS or Static DNS)
- The PDP Context is mainly designed for two purposes for the terminal :
  - PDP Context is designed to allocate a **Packet Data Protocol** (PDP) address, either IP version 4 or IP version 6 type of address, to the mobile terminal.
  - PDP Context is used to make a logical connection with QoS profiles, the set of QoS attributes negotiated for and utilized by one PDP context, through the GPRS/UMTS network.

GPRS: Pros and Cons

Pros :

- GPRS offers four times higher bandwidth than the traditional GSM data service.
- GPRS offers optimal network resource usage and optimized mobile Internet access by introducing the packet switched principle into GSM.
- GPRS allows operators to address the mass market with an always on data service.

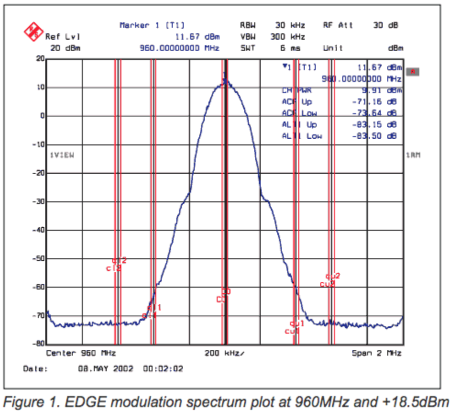
Cons:

- Due to the IP character the GPRS QoS can not be guaranteed.
- GPRS requires major network upgrades and totally new network elements. GPRS is expensive.
- Charging principles of GPRS are unclear and thus appropriate interfaces to the billing systems do not exist.

EDGE

GMSK Modulation

- GMSK further reduces sidelobes by using a Gaussian filter
  - Cost: introduces inter-symbol-interference (ISI)
- Figures show time and frequency response
  - GSM uses BT = 0.3
  - GM total rate 271 kbit/s
  - Spectral Efficiency 1.3 bits/s/Hz



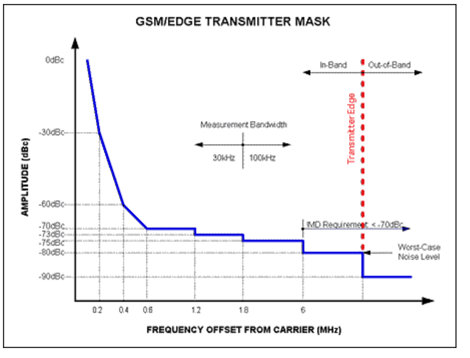
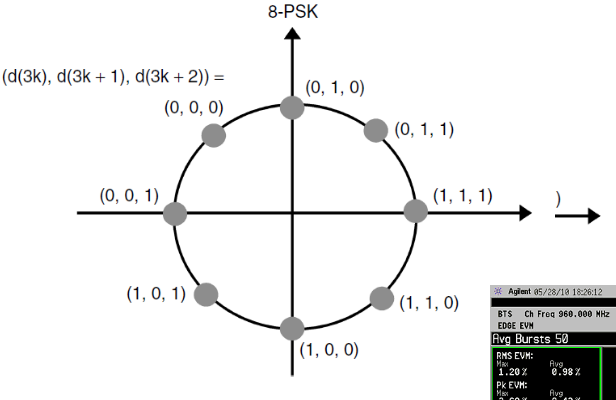
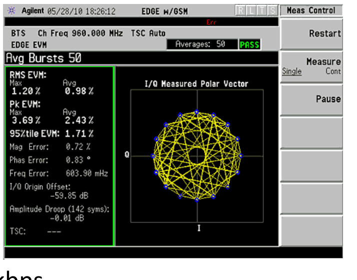


Figure 1. EDGE modulation spectrum plot at 960MHz and +18.5dBm P_{OUT}.

https://www.maximintegrated.com/en/app-notes/index.mvp/id/1829





- 1 symbol = 3 bits
- Therefore, bit rate = 3 x Symbol rate
- Symbol rate = 270,833 ksps, Bit rate = 812,5 kbps

EDGE: Enhanced Data rates for GSM Evolution

- EDGE is an advance on GPRS which uses GMSK (Same as GSM), as well as 8-PSK for higher data rates.
- EDGE requires software and some hardware upgrade to BSS and MS
- EDGE uses 9 air interface formats, known as multiple Modulation and Coding Schemes (MCS) autonomously and rapidly selectable for each time slot or user. Controlled by a feedback loop for maximum throughput with an acceptable outage performance.
- Using all 8 slots, EDGE can reach a maximum of 547 Kbps per user. In practice around 384 Kbps per user per carrier.
- Due to the small incremental cost of including EDGE capability in GSM network deployment, virtually all new GSM infrastructure deployments are also EDGE-capable and nearly all new GSM handsets are also EDGE compatible.

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EDGE Benefits

- EDGE is a relatively straightforward, cost-effective network upgrade for most GSM operators.
- EDGE deployments usually require only software and additional channel cards for the existing GSM-GPRS network infrastructure.
- EDGE does not require operators to acquire additional spectrum. It can be deployed in most widely used frequency bands, including 850, 900, 1800 and 1900 MHz.
- The ability to deploy EDGE in its existing spectrum means that an operator can launch 3G type services quickly, in more markets and at a lower cost than technologies that require new spectrum.

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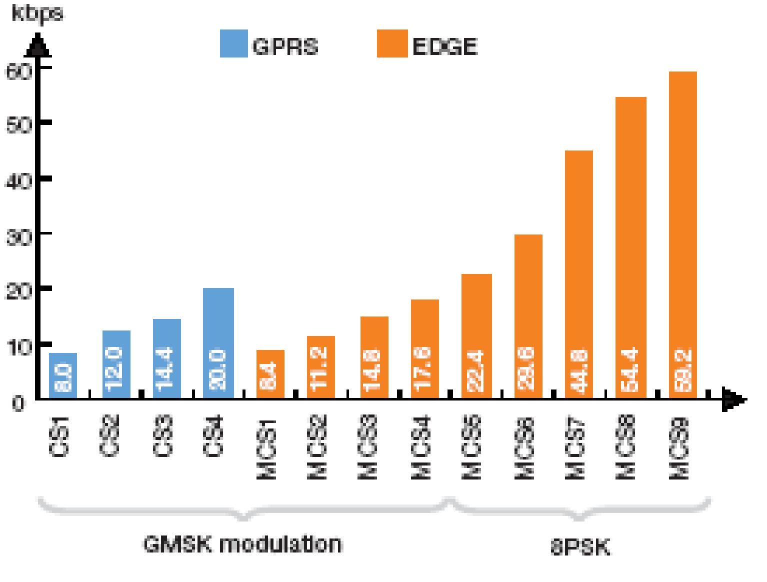
EDGE Data rates

Modulation and Coding Scheme	Modulation	Throughput per time slot
MCS-1	GMSK	8.8kbps
MCS-2	GMSK	11.2kbps
MCS-3	GMSK	14.8kbps
MCS-4	GMSK	17.6kbps
MCS-5	8-PSK	22.4kbps
MCS-6	8-PSK	29.6kbps
MCS-7	8-PSK	44.8kbps
MCS-8	8-PSK	54.4kbps
MCS-9	8-PSK	59.2kbps

EDGE Data rates



Evolved EDGE

- Evolved EDGE is a further enhancement of EDGE, employing an even higher modulation scheme (16 Quadrature Amplitude Modulation or "16-QAM") and a new set of modulation/coding schemes that increases maximum throughput per timeslot by 38 percent.
- Evolved EDGE allows reception on two distinct radio channels to increase the number of simultaneous timeslots.
- A type 2-enhanced EDGE device (which can simultaneously transmit and receive) will be able to receive up to 16 timeslots in two radio channels as well as transmit on up to eight timeslots in one radio channel
- Reduced Transmission Time Interval (TTI) to reduce overall latency.
- Downlink diversity reception of the same radio channel to increase the robustness in interference and improve the receiver sensitivity.
- Sensitivity gains of 3 dB and a decrease in required C/I of up to 18 dB for a single co-channel interferer are shown in simulations

Evolved EDGE Data rates

Modulation and Coding Scheme (MCS)	Current EDGE		Evolved EDGE	
	Type of modulation	Throughput - 4 slots	Type of modulation	16-QAM EDGE Enhancement throughput - 4 slots
MCS-1	GMSK	35.2kbps	GMSK	35.2kbps
MCS-2	GMSK	44.8kbps	GMSK	44.8kbps
MCS-3	GMSK	59.2kbps	GMSK	59.2kbps
MCS-4	GMSK	70.4kbps	GMSK	70.4kbps
MCS-5	8-PSK	89.6kbps	8-PSK	89.6kbps
MCS-6	8-PSK	118.4kbps	8-PSK	118.4kbps
MCS-7	8-PSK	179.2kbps	8-PSK	179.2kbps
MCS-8	8-PSK	217.6kbps	8-PSK	217.6kbps
MCS-9	8-PSK	236.8kbps	8-PSK	236.8kbps
MCS-10	N/A	N/A	16-QAM with turbo codes	268.8kbps
MCS-11	N/A	N/A	16-QAM uncoded	326.4kbps

MSc Telecommunications programmes

Mobile Communications Systems (MCS)

UCL

Mobile Communications Systems (MCS)

GSM System Operation

Dr Clive Poole
Principal Teaching Fellow - University College London
E-mail : c.poole@ucl.ac.uk

Tuesday 30th October, 2018

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UCL

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- MO and MT call setup
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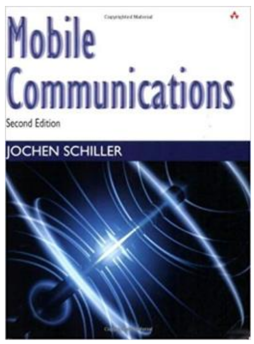
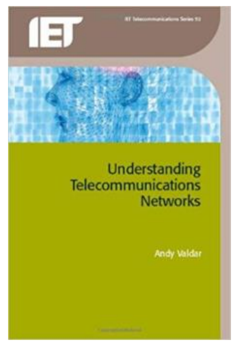
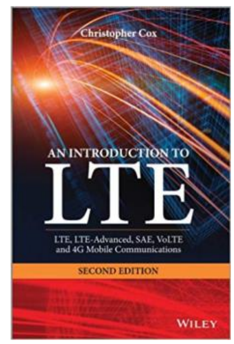
2

Suggested reference texts

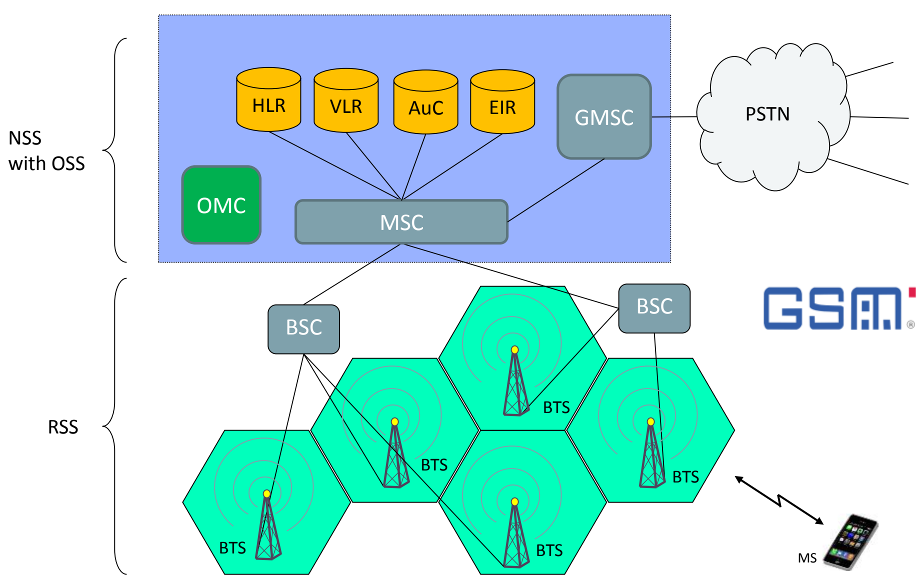






3

Recap : GSM Network Overview



4

GSM Numbering : IMSI

International Mobile Subscriber Identification number (IMSI)

IMSI = MCC + MNC + MSIN

E.212 numbering format

- MCC = Mobile Country Code (3 digits, e.g. 635 for Rwanda)
- MNC = Mobile Network Code (2 digits, e.g. 10 for MTN, 12 for Rwandatel)
- MSIN = Mobile Subscriber Identity Number (≤10 digits)

- The IMSI is a unique identification associated with each GSM and UMTS mobile phone user.
- IMSI is stored as a 64 bit field in the SIM inside the phone and is sent by the phone to the network, where it is stored in the HLR.
- IMSI is based on the ITU-T E.212 numbering plan and cannot be used for routing a circuit-switched call (exchanges or switching centers do not understand such numbers).

5

GSM Numbering : MSISDN

Mobile Subscriber ISDN Number（MSISDN）

MSISDN = CC + NDC + SN

E.164 numbering format

- CC = Country Code (1-3 digits, e.g 250 for Rwanda)
- NDC = National Destination Code (1-3 digits)
- SN = Subscriber Number

- The MSISDN is the number uniquely identifying a subscriber in a GSM or a UMTS mobile network. The MSISDN is basically the “telephone number” of the SIM card in a mobile/cellular phone.
- Mobile station ISDN (MSISDN) numbers are based on the ITU-T E.164 numbering plan and can therefore be used for routing a circuit-switched call.
- When the calling (PSTN or PLMN) user dials an MSISDN number, the call is routed to the gateway MSC (GMSC) located in the home network of the called (mobile) user.

6

GSM Numbering : IMEI

International Mobile Equipment Identification code (IMEI)

IMEI = **TAC** + **FAC** + **SNR** + **SP**

- TAC=model ratification code, 6 digits
- FAC=factory assembling code, 2 digits
- SNR=sequence code, 6 digits
- SP=reserved, 1 digit

- The IMEI uniquely identifies every Mobile Station
- The IMEI is a decimal number of 15 digits.
- The IMEI is programmed into the MS at the factory and is not changed throughout the live of the equipment.

7

GSM Numbering : MSRN

Mobile Subscriber Roaming Number (MSRN)

MSRN = **CC** + **NDC** + **TN**

E.164 numbering format

CC = Country Code (1-3 digits)
NDC = National Destination Code (1-3 digits)
TN = Temporary Number

- The MSRN is temporarily allocated to the subscriber by the VLR according to the request by the HLR when this subscriber is called.
- The MSRN is a temporary number which is only used for call set-up then immediately released to be assigned to other subscriber.
- MSRN are also based on the ITU-T E.164 numbering plan and is in the same format as the MSISDN.

8

GSM Numbering : TMSI

Temporarily Mobile Subscriber Identification Number (TMSI)

- The TMSI is a 32-bit number (4 octets) that is temporarily assigned to a **MS** by the **VLR** and is used to ensure security of the **IMSI** by substituting for the IMSI in over the air communication .
- The TMSI It is designed to protect the privacy of the subscriber and prevent the IMSI from being discovered.
- The VLR will assign the TMSI to a MS when it registers in that **Location Area**.
- The network may also require the VLR to assign a new TMSI to a MS periodically or even every time it completes a transaction.
- The TMSI is stored on the **SIM** card.
- The TMSI is always assigned when in cipher mode. (traffic is encrypted).
- The TMSI is the same format as the IMSI

9

GSM Numbering : LAI

Location area Identity (LAI)

LAI = MCC | MNC | LAC

E.212 numbering format

MCC = Mobile Country Code (3 digits)
MNC = Mobile Network Code (2 digits)
LAC = Location Area Code (≤10 digits)

The location area identity (LAI) points to a location area belonging to a certain MSC/VLR. This identity must be stored in the HLR so that mobile terminated calls can be routed to the correct serving MSC/VLR.

10

Location Management in GSM

GSM provides international roaming that relies on the mobile's location being known to the network. Areas of national networks are divided into Location Areas each with a unique identity broadcast on the BCCH. A mobile will update its location with the network when it detects a change in location area.

Each location area has an MSC containing a HLR and a VLR.

- The HLR is a database of all mobiles normally resident in that location area.
- The VLR is a database of all mobiles not normally resident but visiting that location area.

Location updating is carried out via the fixed network using the following procedure:

The VLR issues a Mobile Subscriber Roaming Number (MSRN) to be associated with the actual mobile identity (i.e. the International Mobile Subscriber Identity – IMSI) over the radio path.

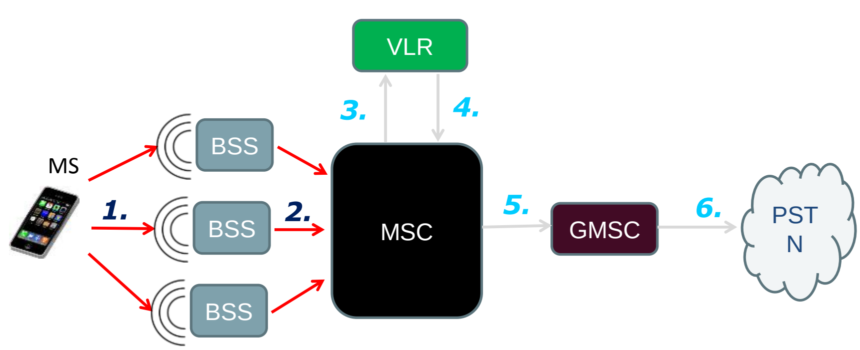
Both the IMSI and MSRN are conveyed to the mobile's HLR over the fixed network. Information on the mobile's user-profile is conveyed from the mobile's HLR to the VLR. The HLR now contains the subscriber's telephone number, the mobile's IMSI and the MSRN that points to the mobile's actual location.

Ref : Schiller p119

11

Mobile Originated Call – Steps 1 & 2

- Step 1 : The MS transmits a request for a new connection to the BSS
- Step 2 : The BSS passes the request to the MSC.

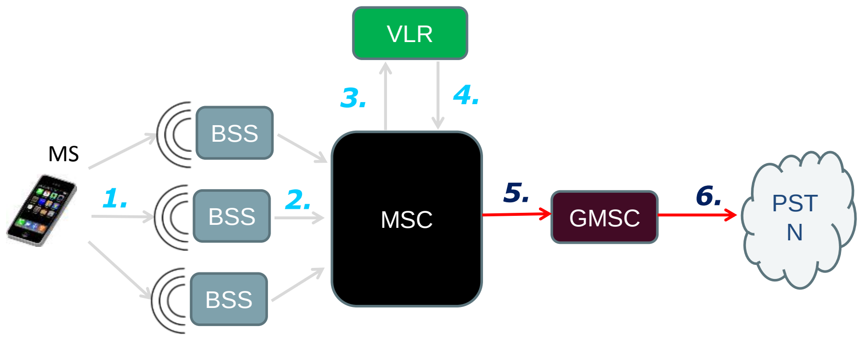


Ref : Schiller p115

12

Mobile Originated Call – Steps 5 & 6

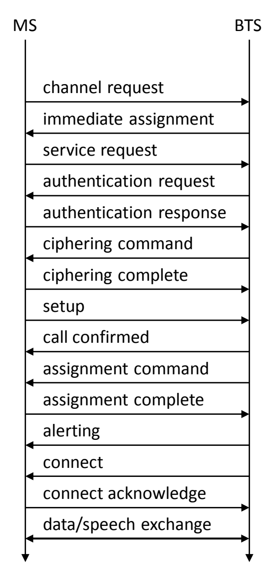
- Step 5 : the MSC instructs the GMSC to set up the call.
- Step 6 : the GMSC routes the call through the PSTN



Ref : Schiller p115

Summary of MOC messaging

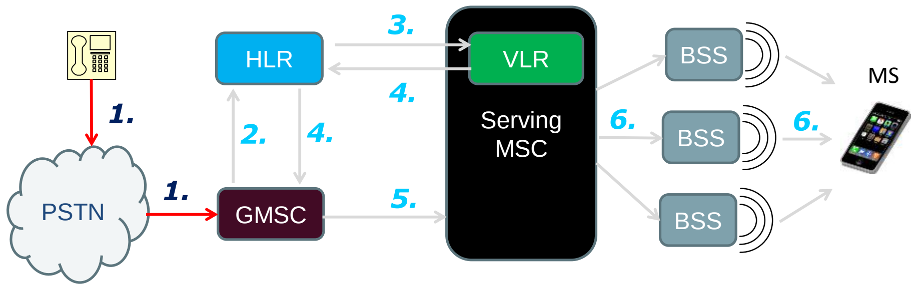
- **Ciphering** is a security procedure designed to protect the subscriber identity and data, and is an optional procedure in GSM.
- When ciphering is active, all information exchanged between the mobile and the network on the dedicated radio channels is **encrypted**.
- The key previously set between the network and the MS is used to encipher and to decipher the encrypted information that is sent over the air.



Ref : Schiller p116

Mobile Terminated Call – Step 1

- The calling party dials the MSISDN of the target mobile subscriber from either a land line or a mobile.
- The call is routed through the PSTN to the GMSC in the home network of the called mobile user using this MSISDN and standard SS7/ISUP signalling.



Ref : Schiller p115

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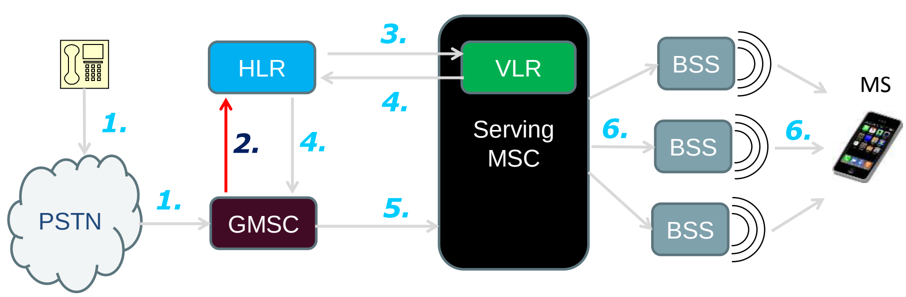
Mobile Terminated Call – Step 2

- The GMSC interrogates the HLR of the called mobile user.
- This SS7/MAP signalling message contains the MSISDN number which points to the mobile user record in the HLR database.
- The HLR record contains the IMSI, LAI where the subscriber is roaming, etc.



Ref : Schiller p115

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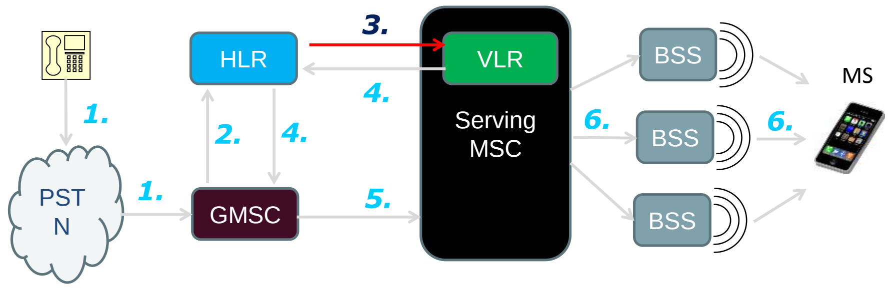
Mobile Terminated Call – Step 3

- Using global title translation (GTT), the HLR translates the IMSI and LAI information into the signalling **point code** of the serving MSC/VLR, which may be in a foreign network (Roaming).
- The HLR sends the SS7/MAP request "Provide roaming number" (i.e. provide an MSRN) to the VLR.



Ref : Schiller p115

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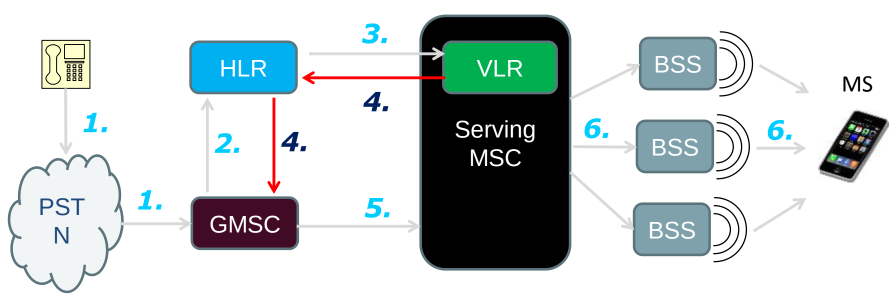
Mobile Terminated Call – Step 4

- The VLR generates an MSRN for this subscriber from the pool of available MSRNs and sends this MSRN back to the GMSC via SS7/MAP signalling.



Ref : Schiller p115

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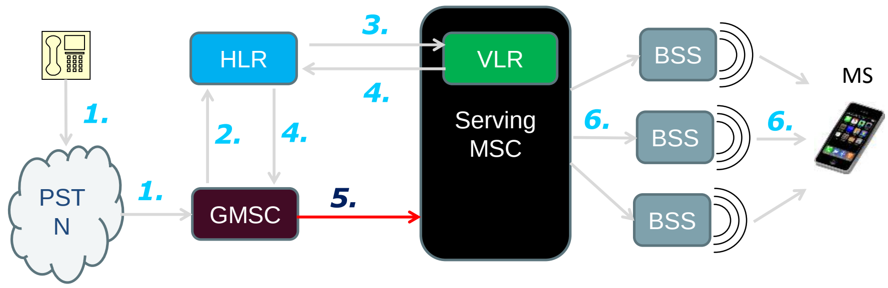
Mobile Terminated Call – Step 5

- Using the MSRN number and standard SS7/ISUP signalling, the call is routed to the serving MSC.
- The subscriber could be roaming, so serving the MSC/VLR may be located anywhere the world.
- There may be several intermediate switching centres in between the GMSC and the Serving MSC.



Ref : Schiller p115

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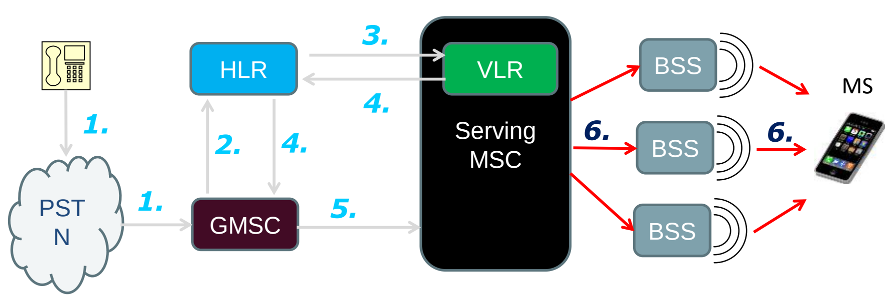
Mobile Terminated Call – Step 6

- MSC/VLR starts **paging** within the location area (LA) in which the called mobile user is located, using TMSI for identification.
- Only the mobile user with the corresponding TMSI responds to the paging via the random access channel (RACH).
- Once the MS has been identified, the call is connected over the air via the TCH



Ref : Schiller p115

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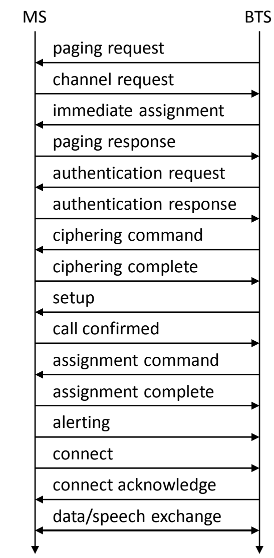
Summary of MTC messaging



Ref : Schiller p116

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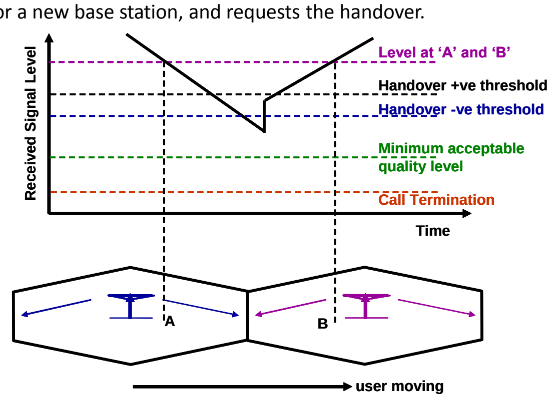
Handover

- Handover is the process of transferring a call from one base station to another as the user moves and the received signal quality deteriorates.
- Handovers should be fast (so overlaps of areas of cells can be minimised); reliable (dropped calls are more frustrating than blocked calls - some channels can be reserved for handovers); infrequent (minimise system resources required)
- 1G systems measured signal strength of users with poor reception at current base station. The mobile did not participate in handoff at all. 2G & 3G systems use **"mobile assisted handover" (MAHO):** the mobile looks for a new base station, and requests the handover.

Note the slight hysteresis in threshold levels: this prevents too many handovers.



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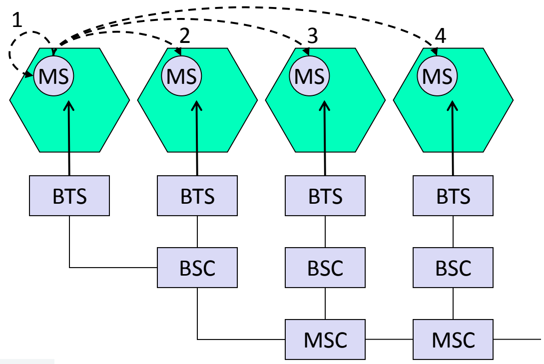
Types of GSM handover

There are 4 types of handover :

1. **Intra-cell handover :** Within a cell, narrow-band interference could make transmission as a certain frequency impossible. The BSC could then decide to change the carrier frequency.
2. **Inter-cell, intra-BSC handover :** This is a typical handover scenario. The MS moves from one cell to another but stays within the same BSC. Handover is controlled by the BSC.
3. **Inter-BSC, intra-MSC handover :** When the MS moves out of one BSC area into another. Handover is controlled by the MSC
4. **Inter MSC handover :** A handover between two cells belonging to different MSCs



Ref : Schiller p119

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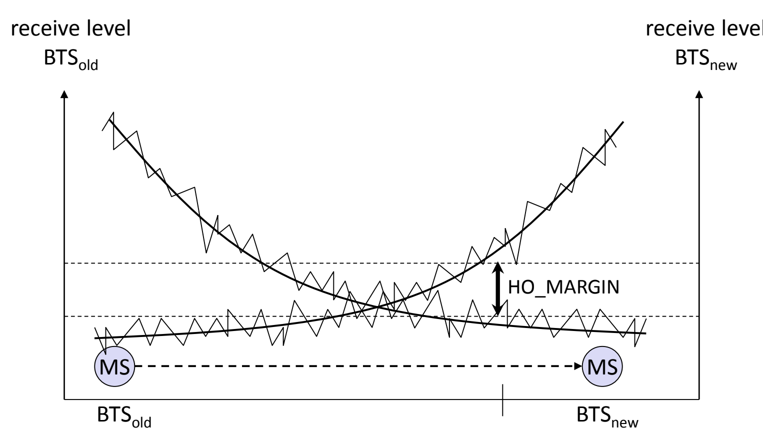
Handover decision

Handover occurs when the received signal strength at the MS received from the “old” BTS falls below a defined threshold, and the received signal from a “new” BTS exceeds it by a defined margin.



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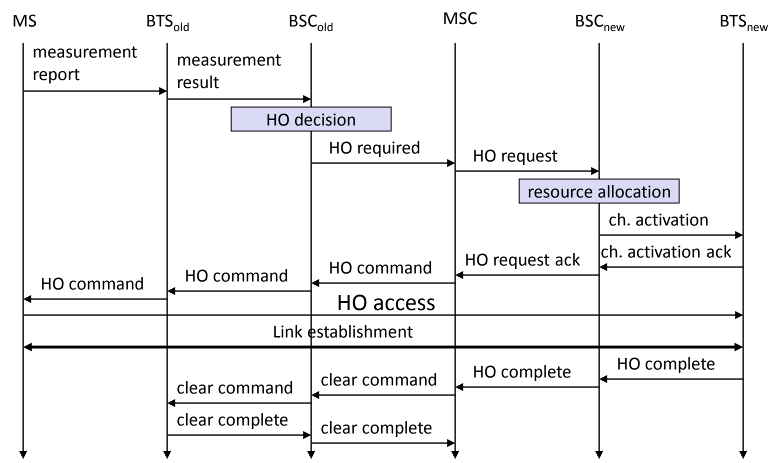
Handover procedure



Ref : Schiller p119

Mobile Speech coding

- Traditionally fixed line telephony uses conventional Pulse Code modulation (PCM) :
  - Speech bandwidth : 3.4kHz
  - Sampling rate : 8,000 samples / second.
  - Sample size : 8 bits
  - Therefore, aggregate bit rate = 8 x 8,000 = **64k bits/second**
- PCM is not suitable for mobile telephony. A much higher bandwidth efficiency is required.
- To achieve higher bandwidth efficiency in voice transmission, an **Audio Codec** or **Vocoder** is used to compress/decompress the voice signal.
- Modern audio codecs use a technique known as **linear prediction**, which involves constructing a mathematical model of the human vocal tract.

Mobile voice codec algorithms

UCL

- **Code Excited Linear Prediction (CELP) :** The most widely used codec algorithms and the basis of other voice codecs including ACELP, RCELP, VSELP, etc. The main principle behind the CELP codec is that is uses a principle known as "**Analysis by Synthesis**" wherein encoding is performed by perceptually optimising the decoded signal in a closed loop system.
- **Algebraic Code Excited Linear Prediction (ACELP) :** A development of the CELP model. However the ACELP codec codebooks have a specific algebraic structure as indicated by the name.
- **Vector Sum Excitation Linear Prediction codec (VSELP) :** One of the major drawbacks of the VSELP codec is its limited ability to code non-speech sounds. This means that it performs poorly in the presence of noise. As a result this voice codec is not now as widely used, other newer speech codecs being preferred and offering far superior performance.

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Mobile Speech coding standards

UCL

Mobile System	Speech coding Algorithm	Bitrate
GSM (Full rate)	RPE-LTP	13 kbps
GSM (Half rate)	VSELP	5.6 kbps
GSM (Enhanced full rate)	ACELP	12.2 kbps
UMTS (AMR)	ACELP	12.2 to 4.75 kbps

Compare the above with standard PCM : 64k bps

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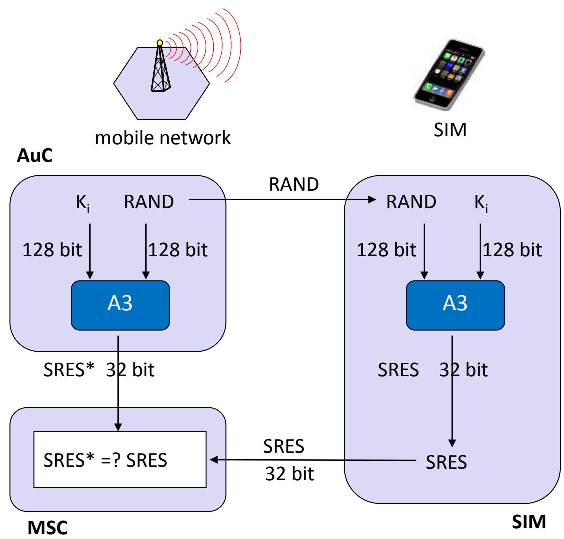
GSM authentication

- Each SIM contains a secret key **Ki** unknown to the user but known by the network and stored in the mobile's HLR record.
- To authenticate a user, the network generates and sends a random number, **RAND,** to the mobile which then uses Ki and RAND as input parameters to a secret algorithm **A3** that generates a response, **SRES,** which is returned to the network.
- The network also generates SRES in the mobile's HLR using Ki , RAND and A3.
- If both SRESs are the same then the mobile is accepted.
- While the computation of SRES from Ki and RAND is straight-forward, the computation of Ki from RAND and SRES is not.



K_i: individual subscriber authentication key

SRES: signed response

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GSM Roaming

- International roaming, i.e. the facility for the subscriber to take their GSM handset to another country and use it on another network, without having to change SIMs, was one of the core requirements of the original GSM specifications.
- International roaming was the key differentiator between GSM and the earlier 1G (analogue) systems
- The necessary conditions for roaming are :
  1. A handset which can receive and send on the frequencies used by the GSM network in the country you are visiting.
  2. A roaming agreement between your operator and the one you wish to connect to in the country you are visiting
  3. Roaming function enabled on your phone (may depend on you tariff plan).

30

GSM Roaming

- When the mobile device is turned on or is transferred via a handover to a new network, the new (**visited**) network recognises that the handset is not registered as one of its own subscribers, and then attempts to identify the home network from the IMSI (which is stored in the SIM).
- If there is no roaming agreement between the two networks, the visited network denies service.
- If roaming is allowed, the **visited** network contacts the **home** network HLR over the SS7 network and copies the subscriber profile from the home network HLR to the visited network VLR.
- The visited network begins to maintain a temporary subscriber record for the device in the VLR. Likewise, the home network updates its information to record the location of the subscriber on the visited network, so that any information sent to that device can be correctly routed.

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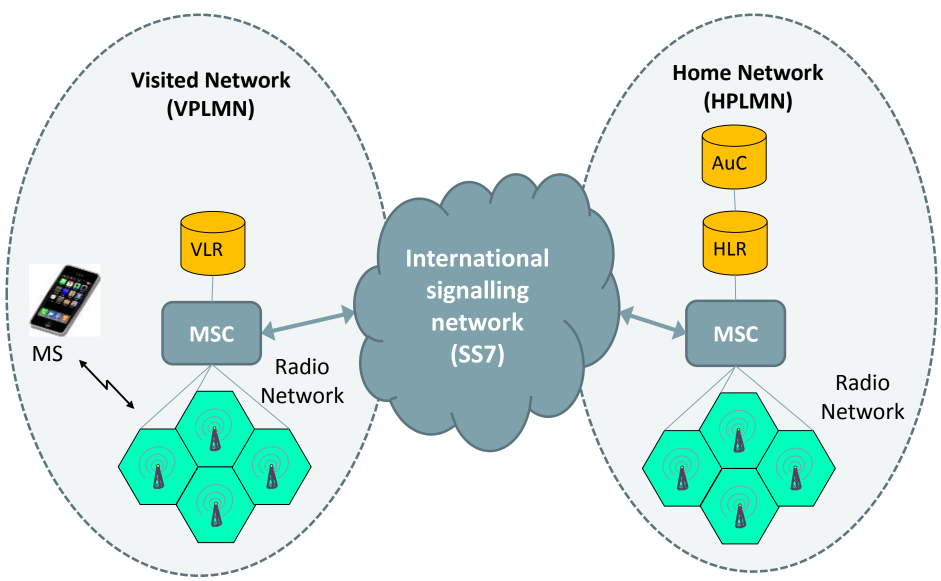
GSM Roaming



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GSM Roaming : MT calls

- When someone calls a roaming subscriber, the call is routed on the MSISDN to the home network GMSC.
- The home network HLR records indicate that the subscriber is roaming. The HLR record also contains the exact location (LAI) of the subscriber, which has been continuously updated every time the MS has moved from on BTS to another.
- The VLR assigns a Mobile Station Roaming Number (MSRN) to the roaming subscriber which is a unique virtual number to which incoming calls can be routed. Once the incoming call is established, the MSRN is released back into the pool and can be re-used.

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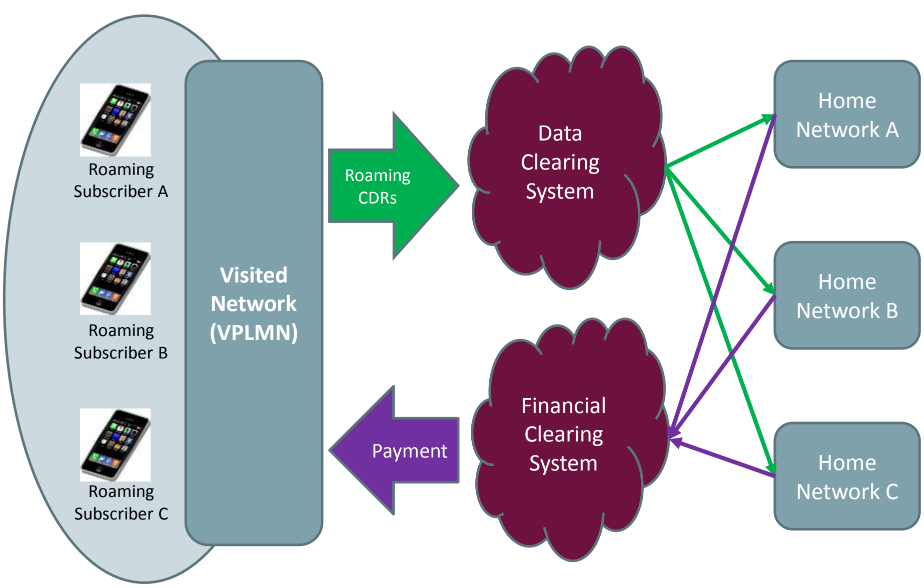
GSM Roaming billing



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GSM Roaming : billing

- The retail charge for all traffic generated by a roaming subscriber (MO or MT) whilst they are on the visited network will appear on their monthly (?) bill which is issued by their home network. This normally appears on the subscribers bill as "roaming charges".
- How does the home network know how much usage there has been when the subscriber was roaming?
- The visited network MSC generates **Call Detail Records (CDRs)** for all the MS on their network, including roamers.
- Every day, the visited network sends it's CDR files to a **Data Clearing House** which sorts the CDRs according to home network ID (MNC code) which is contained in the IMSI.
- The Data Clearing House collates the CDRs according to home network ID, rates them according to **Inter-Operator Tariff (IOT)** and sends them off to the relevant parties.
- At the end of the month (?) the various home networks settle the wholesale cost of their roaming subscribers usage on the various visited networks, according to the rated CDRs they have received through Data Clearing. Payment is done through a **Financial Clearing House**.
- The Financial Clearing House collates all the payments from the various home networks and delivers them to the correct visited network.

UCL DEPARTMENT OF ELECTRONIC AND ELECRICAL ENGINEERING
INTEGRATED GRADUATE DEVELOPMENT PROGRAMME
MSC TELECOMMUNICATIONS

Coding Techniques for Wireless Systems

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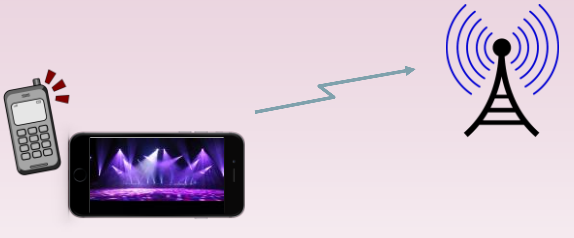
Why do we need coding?



- Speech and video needs to be compressed (limited network resources for large volume of data)
- Compressed bitstream needs to be protected against errors (wireless channel might introduce error in the transmitted bitstream)

Requirements for Speech/Video Transcoding

- Speech: many options available to convert analogue signals into a digital representation
- For a wireless channel there are extra considerations
- Minimisation of the channel bandwidth
- Good quality under ‘good’ radio conditions

3

How can we limit the bandwidth and maintain quality?

source encoding

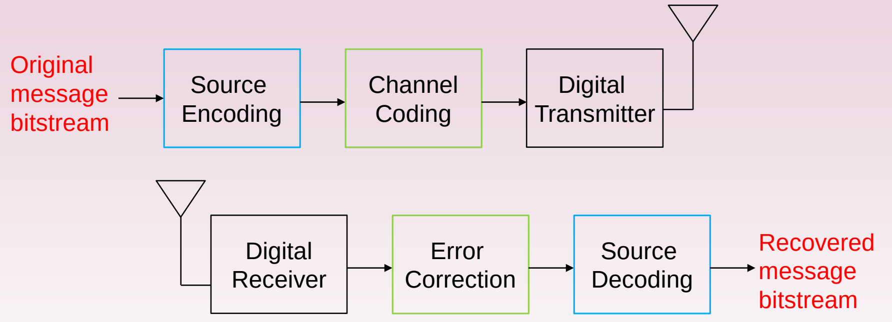
- To limit the bandwidth we can:
  - Use the redundancy inherent in human speech to compress the data
  - Recognise that although a full-duplex type of link is required, each channel will have periods of inactivity

channel coding

- To maintain quality we can:
  - Include error checking and error correction

4

Source Encoding vs Channel Coding



Source encoding: reduce the redundancy → represent the source with fewest bits such that best source recovery from compressed data is possible

Channel coding: increase the redundancy → represent the compressed message with more bits to increase such that reliability against error

Introduction

- **Part 1: Source Coding**
  - Requirement for Speech Coding
  - Digital Speech
  - GSM RPE-LPC arrangement
  - Image/Video Coding
- **Part 2: Channel Coding**
  - Error Control coding requirements
  - Error Control principles and techniques (overview)
  - Application to GSM networks

Source Encoding

Source Encoding

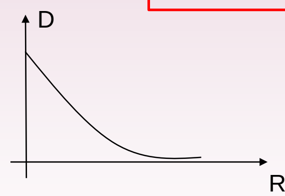
Lossless

Lossy

Speech and Video coding

Shannon's first theorem (1948)

Coding rate R greater than the source entropy



Source recovered with a distortion D (function of the coding rate)

Introduction

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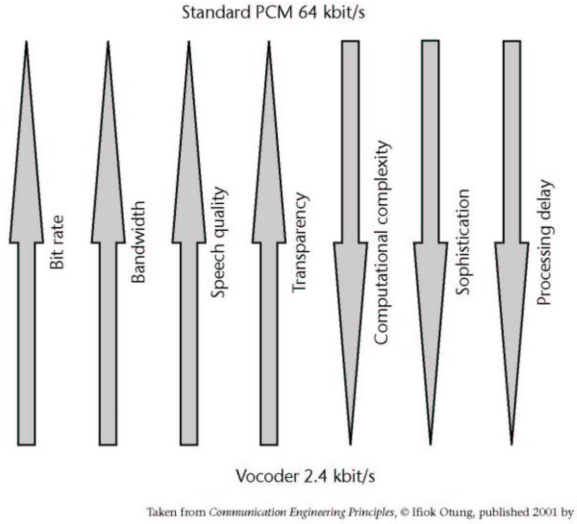
Digital Speech

- Pulse Code Modulation (PCM)
  - 64 kb/s companded for telephony (A-law and μ-law)
- Adaptive Differential Pulse Code Modulation (ADPCM)
  - 32 kb/s ITU-T standard for telephony
- Various ‘compressed’ speech arrangements:
  - Sub-band, pitch predictive ADPCM, Adaptive Predictive Coder, Adaptive Transform Coder, Vocoder (voice excited, channel, formant), Linear Predictive Coefficient
  - The GSM speech coder employs regular pulse excitation (RPE), long term prediction(LTP) and linear prediction coding (LPC) and is commonly referred to a RPE-LPC
- A Transcoder provides for conversion and rate adaptation between GSM speech and digital PCM speech in the main (fixed) network

9

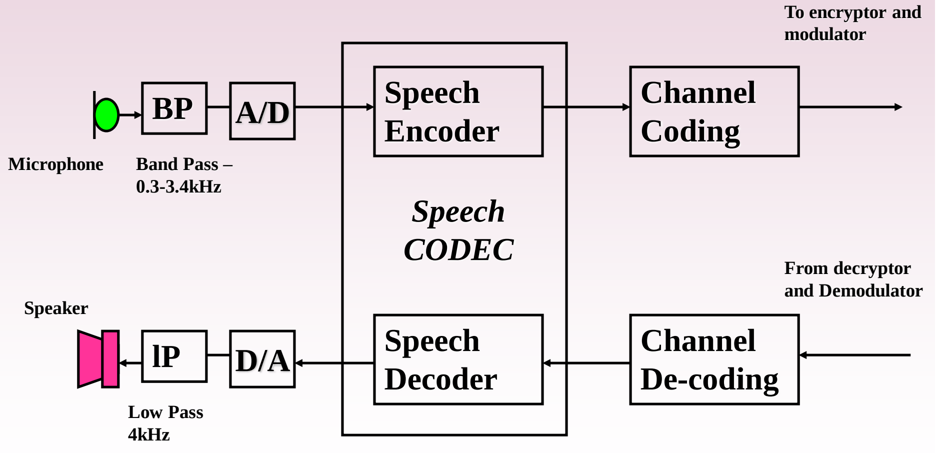
Trade-offs in speech coding



Taken from *Communication Engineering Principles*, © Ifiok Otung, published 2001 by Palgrave

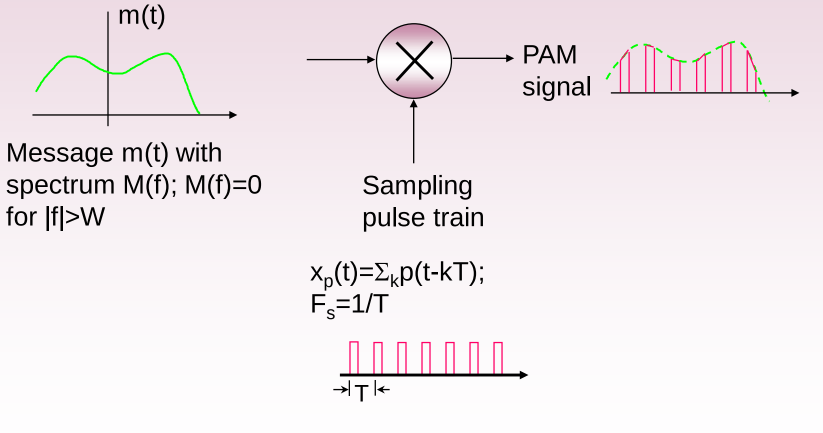
10

How does the whole process work?



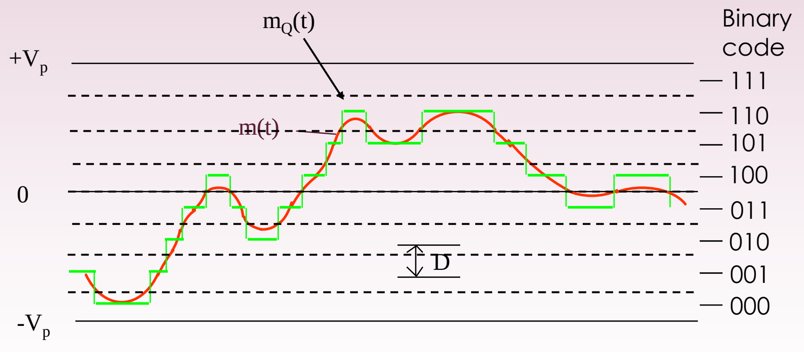
11

Sampling - the time domain



12

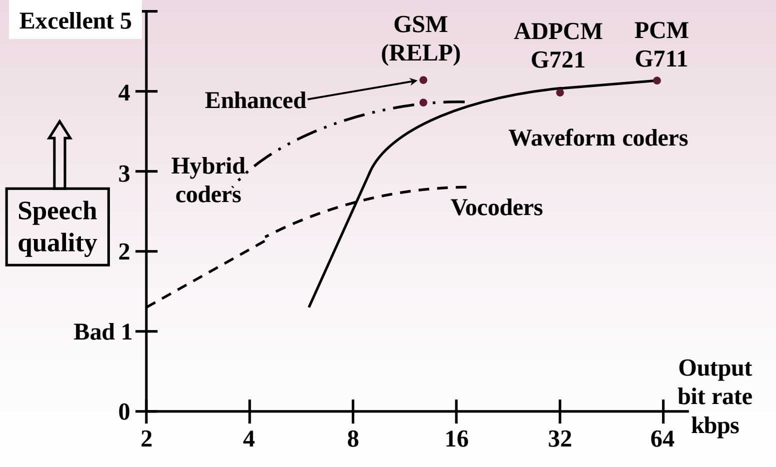
Quantisation and Coding



GSM Speech coding

- GSM is slightly different to normal ‘wired’ PCM
- The PAM signal is quantised by 13 bits $=2^{13}=8,192$ quantisation levels
- This gives a data rate of 8,000 x 13=104 kb/s
- This is too high, the coder must do something to significantly reduce this rate
- The GSM speech coder employs regular pulse excitation (RPE), long term prediction(LTP) and linear prediction coding (LPC) and is commonly referred to a RPE-LPC

Speech Quality versus Bit Rate

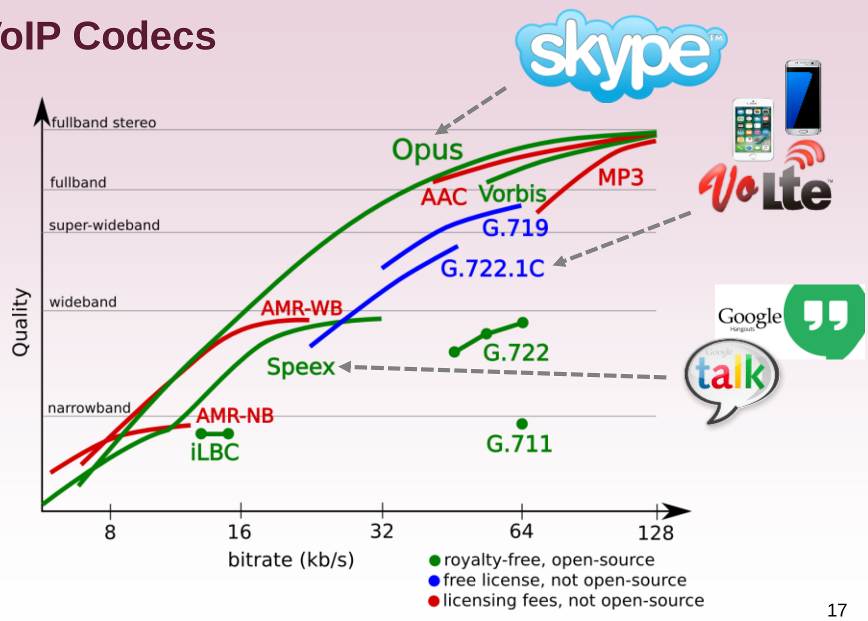


VoIP Codecs

Codec	Algorithm	Bit Rate (Kbps)
ITU G.711	PCM (Pulse Code Modulation)	64
ITU G.723	Multi-rate Coder	5.3 and **6.4**
ITU G.726	ADPCM (Adaptive Differential Pulse Code Modulation)	16, 24, 32, and 40
ITU G.727	Variable-Rate ADPCM	16-40
ITU G.728	LD-CELP (Low-Delay Code Excited Linear Prediction)	16
ITU G.729	CS-ACELP (Conjugate Structure Algebraic-Code Excited Linear Prediction)	8 and **6.3**
ILBC	Internet Low Bitrate Codec	13.33 and 15.20
GSM - Full Rate	RPE-LTP (Regular Pulse Excitation Long-Term Prediction)	13
GSM - Enhanced Full Rate	ACELP (Algebraic Code Excited Linear Prediction)	12.2
GSM - Half Rate	CELP-VSELP (Code Excited Linear Prediction - Vector Sum Excited Linear Prediction)	11.4
ITU G.722	SBADPCM (Sub-Band Adaptive Differential Pulse Code Modulation)	48, 56 and 64
Speex	CELP (Code Excited Linear Prediction)	2.15-44.2
AMR-WB (ITU G.722.1)	ACELP (Adaptove Code Excited Linear Prediction)	6.6-23.85

Broadband codecs

VoIP Codecs



Required Bandwidth

- Typically the range of human hearing is from 20Hz up to a maximum of 20kHz
- However, different types of signals have different requirements
- Music

22kHz – 16bit   12kHz – 16bit   5.5kHz – 16bit   4kHz – 16bit

- Telephony

16kHz – 8bit   4kHz – 8bit

Speech Coding

- But if we use this on music which does not follow the same patterns as speech then the result is slightly different.

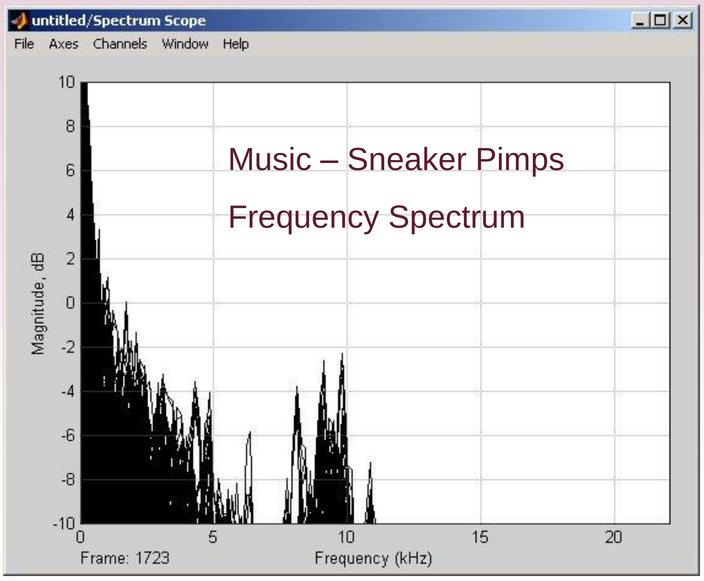
Music Clip CD quality 44.1kHz sampling
2035kbytes total file

Music Clip PCM 8kHz sampling
210kbytes total file

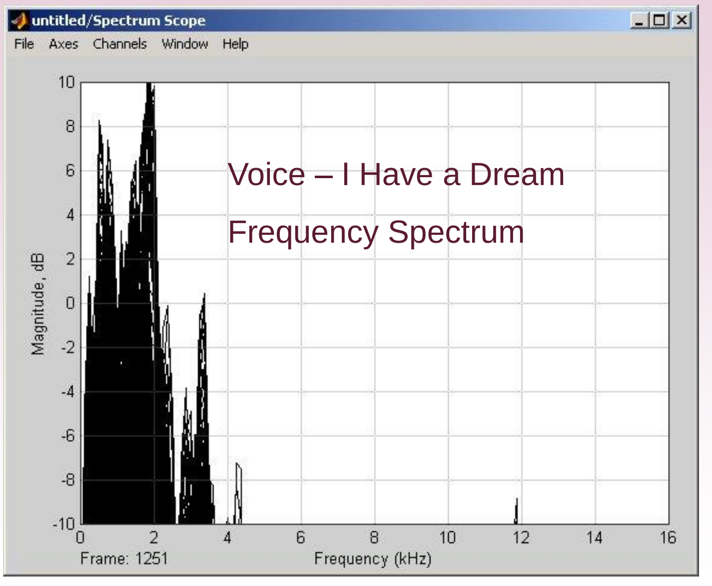
Music Clip ADPCM 8kHz sampling
56kbytes total file

Music Clip GSM 6.1 Encoding 8kHz sampling
1kb/s - 22kbytes total file

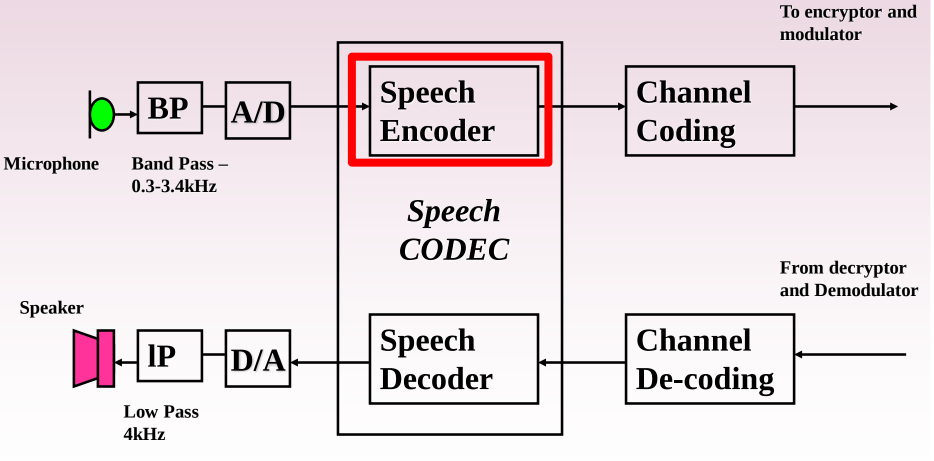
Why?



Why?



How does the whole process work?



GSM SPEECH CODING AND SPEAKER RECOGNITION

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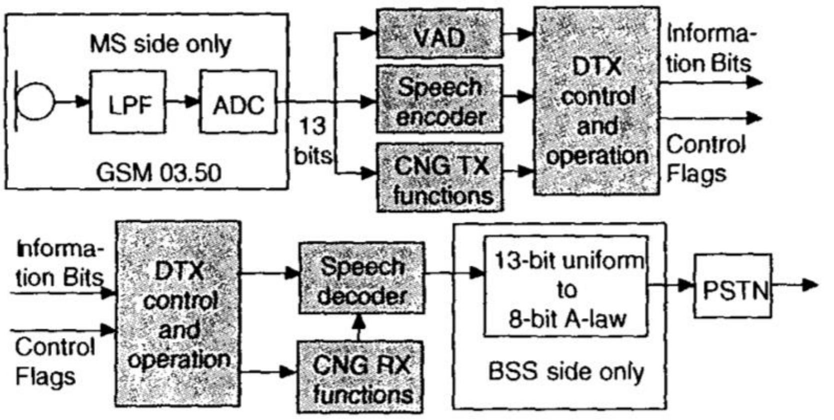
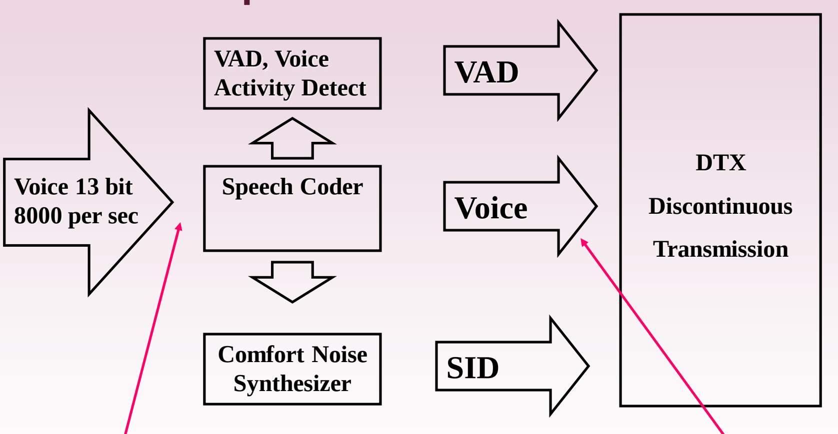
laurent.besacier@imag.fr , sara.grassi@imt.unine.ch



UCL

GSM Speech Codec



Blocks of 160 Samples of 13 bits every 20ms

260 bit blocks at rate of 13 kb/s, i.e. 1:8 compression

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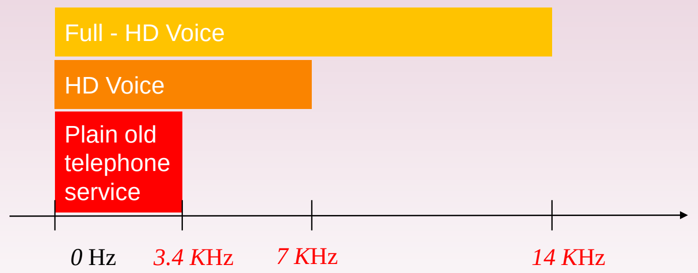
Discontinuous Transmission

- GSM provides for discontinuous transmission - the DXT mode (In the US literature the term variable bit rate is sometimes used)
- It aims to increase system efficiency by decreasing the interference level as a result of inhibiting radio transmission when not required
- DXT is an optional alternative
- It involves some degradation of quality, especially when used twice for a call between two GSM users
- It can be effected by the network on a per-call basis

DTX - cont'd

- The goal is to encode at 13kbit/s when speech is present and otherwise at a much reduced rate of around 500bit/s
- This low rate is sufficient to encode the background (comfort noise), regenerated for the listener to give reassurance that the connection remains
- It corresponds to decreased effective radio transmission since active speech flow is one 260 bit frame every 20 ms and inactive speech flow is one 260 bit frame every 480 ms

What's Next? Full-HD Voice



Human voice transmits audio between 75 Hz and 14 kHz. Full-HD will cover the entire range of human hearing.

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Introduction

- **Part 1: Source Coding**
  - Requirement for Speech Coding
  - Digital Speech
  - GSM RPE-LPC arrangement
  - Image/Video Coding
- **Part 2: Channel Coding**
  - Error Control coding requirements
  - Error Control principles and techniques (overview)
  - Application to GSM networks

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Image/Video compression

"Since it's digital, there's no generation loss"

WRONG!

– All image/video compressions are lossy
– If generations are made by compress/decompress, then losses can be ugly

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Image Compression - JPEG

Compress (avoid redundancy) in the spatial domain

Compression level "low"
Compression ratio 1:16
6 % of original file size
No visible image quality degradation

Compression level "high"
Compression ratio 1:96
1 % of original file size
Image quality clearly degraded

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Video Compression

Spatial vs. temporal compression

- spatial → intra-frame, just image compression
- temporal → inter-frame (based on motion compensation)

⇩

Two kinds of frames

- key frames: spatial compression only
- difference frames: spatial and temporal (relative to some other frame)

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Temporal Compression

- Two ways to deal with moving material
  - reuse the background in multiple frames
  - move the foreground actor across the scene
  - in practice, these are the same thing (why?)

- MPEG (Moving Picture Experts Group) uses motion compensation
  - attempts to find nearby areas with similar pixel patterns
  - 16x16 “macroblocks” plus motion vectors describing how they shift
  - not trying for perfect representation

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MPEG sequencing

- Three types of pictures (frames)
  - **I-picture**: intra-frame compression only
  - **P-picture**: predicted, difference from earlier I
    - 3:1 compression
  - **B-picture**: bidirectional prediction
    - based on earlier I/P, later I/P
    - 4.5:1 compression, but reconstruction is complex
- Group of pictures
  - begins with I-picture
  - IBBPBBPBB is a common pattern

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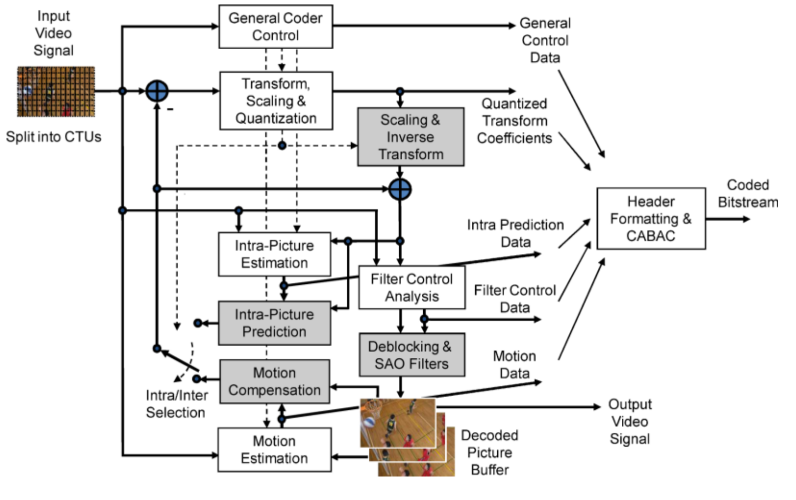
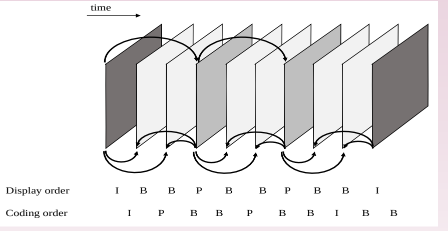
HEVC Coding Structure

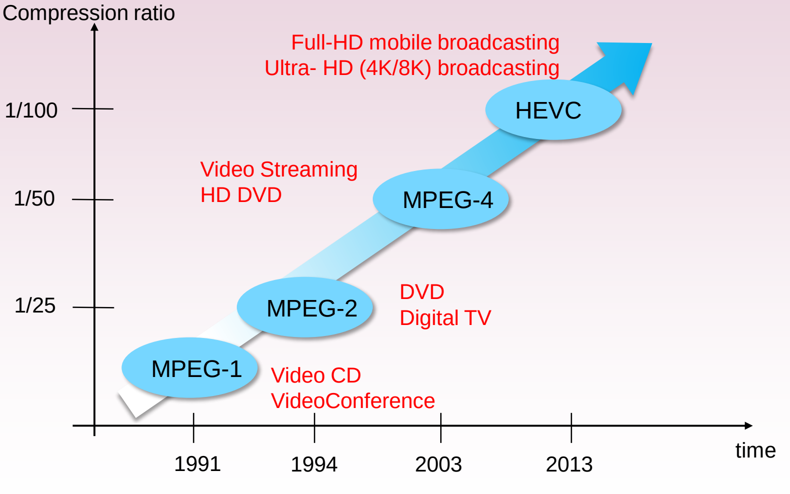


Display vs. Coding ordering



- Display order is the order in which the images should be shown
  – requires decoder to buffer B pictures
- Coding order
  – requires buffering of 2 I/P images
  – first series has unusual order to bootstrap process

History of Video Compression Standards



Competing Codecs

- VP8/VP9,
- AV1
- MPEG/ITU HEVC/H.265

- use scalar or vector quantization
- use temporal compression
- highly asymmetric
- 4K full-HD videos
- Compression up to 50% compared to previous codecs

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Competing Codecs

- VP8/VP9,
- AV1
- MPEG/ITU HEVC/H.265

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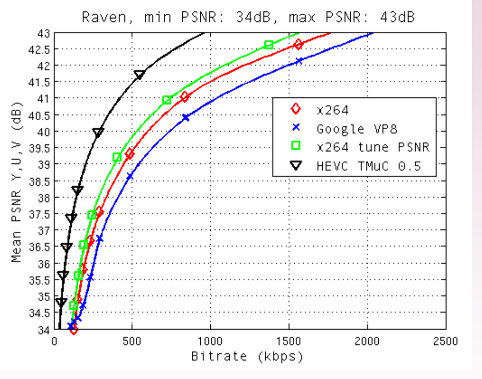
Performance comparison



"Rate-distortion performance of contemporary video codecs: Comparison of Google/WebM VP8, AVC/H. 264, and HEVC TMuC", E Ohwovoriole and Y Andreopoulos - LENS Symp., London, 2010.
http://www.ee.ucl.ac.uk/~iandreop/OHWOVORIOLE_LCS_2010_H264_VP8_HEVC_comparison.pdf

Raw Bandwidth

Raw Bandwidth = color depths * W * L * refresh frequency

Resolution (WxL)	24bit@25fps	8bit@25fps	8bit@15fps	8bit@5fps
4K (3840x2160)	5 Gbit/s	1.6 Gbit/s	995 Mbit/s	331 Mbit/s
HDTV (1920x1080)	1.3 Gbit/s	414 Mbit/s	248 Mbit/s	83 Mbit/s
VGA (640x480)	184 Mbit/s	61 Mbit/s	36 Mbit/s	12 Mbit/s
SCIF (704x576)	240 Mbit/s	80 Mbit/s	48 Mbit/s	16 Mbit/s
CIF (352x288)	60 Mbit/s	60 Mbit/s	12 Mbit/s	4 Mbit/s
QCIF (176x144)	12 Mbit/s	12 Mbit/s	3 Mbit/s	1 Mbit/s

- Uncompressed video is **BIG**
- A DVD would hold max 5 secs of uncompressed video at 1920x1080 resolution
- 6 MHz channel for transmission therefore maximum possible bitrate is 18 Mb/sec
- Requires compression of 83:1

Future Video Applications

Immersive Communications
(holoportation, from Microsoft)

Virtual Reality,
360 Videos

Telepresence
(from Cisco)

Speech/Audio/Video Coding Summary

- Requirements for Coding of each Source
- Speech Coding Principle
- Discontinuous Transmission
- GSM Speech Coding
  - RPE-LPC
  - Enhanced Full Rate
- Different Video Coding Formats, motion compensation

UCL DEPARTMENT OF ELECTRONIC AND ELECRICAL ENGINEERING
INTEGRATED GRADUATE DEVELOPMENT PROGRAMME
MSC TELECOMMUNICATIONS

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Wireless Channel Coding

UCL

Introduction

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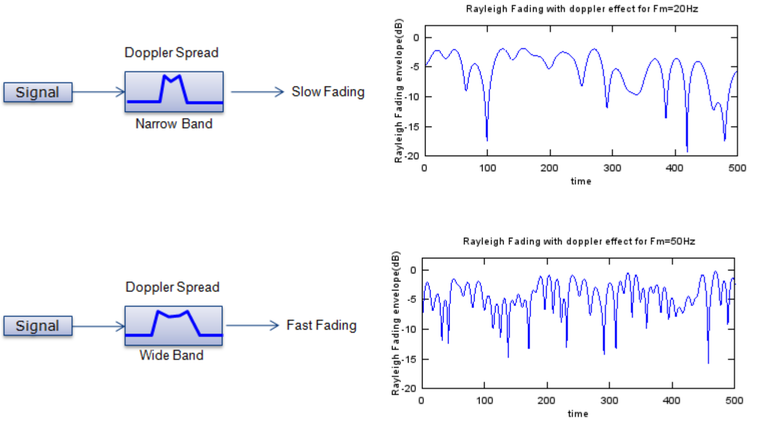
Need for error control

- Mobile radio channel characterised by marked variability due to propagation effects and interference
  - Propagation in outdoor environments: urban, suburban, rural
  - Propagation into buildings; Propagation within buildings
- Path loss and fading considerations
  - Even over small distances radio signals can experience large variations in level of 30 to 40 dB
  - Interference limits scope for increasing signal power to overcome these effects
- Error control provides for reliable, power efficient operation of the radio systems

Fast vs Slow Fading



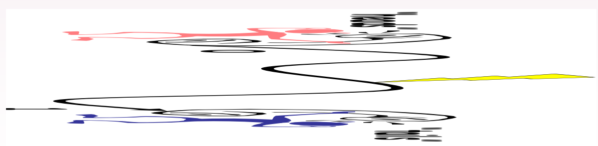
Need for error control


0 - heads   1 - tails

1 bit perfectly encodes the information..

… but is it robust enough?

message “0” sent → **during transmission a** **single-bit error occurs** → message “1” received (different information conveyed)



The information needs to be protected!

Error control coding

- Add redundant bits to a message so that errors can be detected and corrected
- Rate of a code is a measure of redundancy = ratio of message bits to total bits
- May be effected on fixed length data blocks (block codes) or on a continuous data stream (convolutional codes)
- Error control power related to redundancy and block length

Coding Implementation

- Most systems use a combination of techniques, with the combination depending on the type of data being transmitted
- **Block Codes** provide parity bits for error detection
- **Convolution Codes** generate redundancy needed for error correction in GSM
- UMTS allows for the use of **Turbo codes** as well

We will now review Error Coding Principles

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Block code examples

- Hamming (7,4) single error correcting code has block length= 7; *k*=4 data bits per word; 3 check bits per word; rate *R*=4/7
- BCH (15,7) is a double error correcting code; *n*=15, *k*=7, R=7/15
- RS(255, 239) has 255 symbols per block with each symbol represented by 8 bits (finite field of degree 256); Block length is this 2040 bits with 1912 data bits; R=239/255

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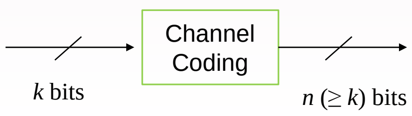
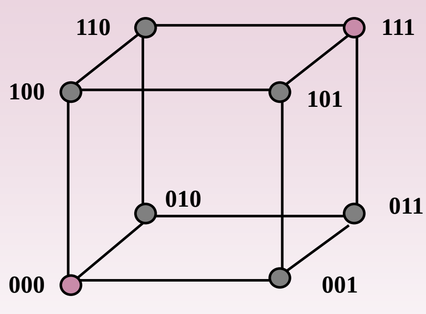
Hamming Distance

- Hamming distance
  - the number of symbol positions in which two code words vary is denoted the Hamming distance, d
  - e.g 1001 and 1000 are separated by Hamming distance 1, while 1001 and 0110 are separated by distance 4
- Redundancy
  - binary words of length *n* carrying only *k* information bits contain redundancy which, if properly structured can provide for error detection and correction in an (*n*,*k*) code
- Rate
  - The ratio *k*/*n* is the code rate



Hamming Distance



- 3-bit binary words arranged in 3-dimensional space on a cube
- minimum Hamming distance between words is 1
- 000 and 111 have Hamming distance 3 and represent an ECC
- Code rate is 1/3, single errors can be corrected

Parity Checks

Information bits	Parity bits

- We can add a parity bit to a word to ensure it has a defined parity - 1110 has odd parity (odd number of 1's)
- A single error will then disturb the parity and can thus be detected, this is the basis of error detection coding
- By introducing parity bits applied across subsets of the information bit positions it is possible to both detect and correct errors - the basis of error correction codes (ECCs)
- The parity bits are sometimes mixed in with the information bits rather than attached at the end of the codeword

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Array Parity EDC code

row checks

0	1	0	0	0
1	1	0	0	1
0	1	0	1	1
1	1	1	0	0
1	1	0	0	1

column checks

check on row and column checks

- Odd parity is applied to rows and columns
- A single error may be detected and corrected (EDC)

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Hamming (7,4) code

- 7-bit codewords: 4 information bits plus 3 check (parity) bits
- With 4 information bits there are $2^4=16$ possible codewords
- 3 equations define the check bits
- $d1,d2,d3,d4$:$c1,c2,c3$ define data and check bits
- Non-zero syndrome [S] defines location of error

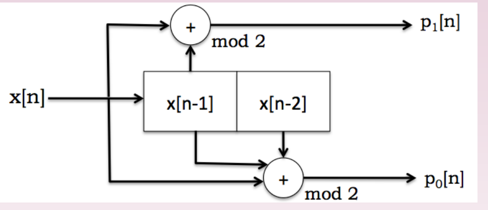
$$
\begin{aligned}
&[c1, c2, d1, c3, d2, d3, d4] \\
&c1 = d1 \oplus d2 \oplus d4 \\
&c2 = d1 \oplus d3 \oplus d4 \\
&c3 = d2 \oplus d3 \oplus d4
\end{aligned}
$$

$$
[S] = \begin{cases} s1 = c3 \oplus d2 \oplus d3 \oplus d4 \\ s2 = c2 \oplus d1 \oplus d3 \oplus d4 \\ s3 = c1 \oplus d1 \oplus d2 \oplus d4 \end{cases}
$$

Multiple error correction

- Hamming distance determines the error correcting properties
- Distance of two allows single error detection, distance three allows single error correction
- Distance to 2t+1 allows up to t errors to be corrected - a t-error correcting code
- An (n,k) code has length n implying 2^n possible binary words of length n and 2^k codewords, giving distance up to (n-k) and 2^{n-k} binary words which are not allowed code words
- Hamming codes have $n=2^c-1$ and $k=2^c-1-c$ for any integer c

Convolutional Codes

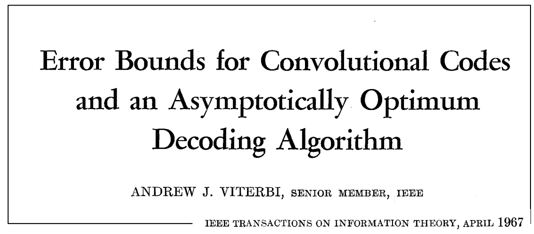


- Like the block codes, they involve the transmission of parity bits that are computed from message bits
- Unlike block codes, the sender does not send the message bits followed by the parity bits; in a convolutional code, the sender *sends only the parity bits*.
- The encoder uses a *sliding window* to calculate r > 1 parity bits by mixing or current and preceding digits on a continuous basis

Convolutional Codes

- Used in a variety of systems including today's popular wireless standards (such as 802.11) and in satellite communications.
- Tend to be relatively low rate, such as 1/2, 3/4
- Punctured convolutional codes can have higher rates: 7/8 would be a high rate (although some very high rate codes have been devised recently - at the cost of implementation complexity)

Convolutional Decoding – Viterbi Algorithm



Error Bounds for Convolutional Codes and an Asymptotically Optimum Decoding Algorithm

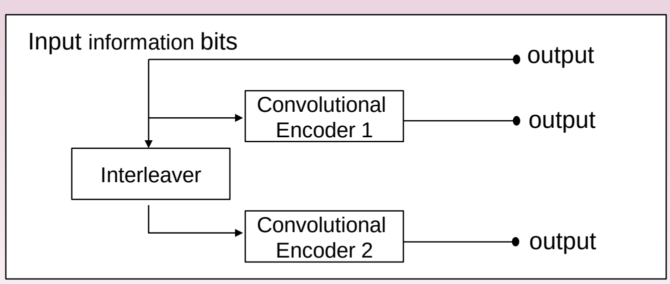
ANDREW J. VITERBI, SENIOR MEMBER, IEEE

IEEE TRANSACTIONS ON INFORMATION THEORY, APRIL 1967

Decoding is generally realised using the Viterbi algorithm - or reduced state Viterbi decoders

To recover the *mathematically most likely* message from among the set of all possible transmitted messages.

Turbo Codes



- Formed as parallel concatenated convolutional codes
- Turbo decoders use a pair of SISO (Soft Input Soft Output) decoders

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Turbo Codes

- Relatively new invention (circa 1993)
- Can perform very closely to Shannon's theoretical channel limit
- Adopted in 3G/4G mobile communications and in satellite communications
- UTRAN uses a parallel concatenated convolutional code (PCCC), which is two convolutional encoders in parallel separated by an interleaver

Error Control in GSM

- Channel coding
  - Improves transmission quality when interference, multipath fading and Doppler shift are encountered
  - The bit/frame/word error rates are reduced, but throughput is also reduced
- Interleaving
  - Interleaving scrambles and 'spreads in time' a sequence of bits prior to transmitting the.
  - Bursts of errors occurring in transmission thus affect adjacent 'channel' bits, corresponding to widely separated 'message' bits
  - De-interleaving at the receiver puts back the message bits back again and separates

Interleaving

- Interleaving is intended to de-correlate the relative positions of the bits respectively in the code words and in the modulated radio bursts
- Useful because bit errors tend to occur consecutively, both due to statistics of radio transmission and because of intersymbol interference introduced by modulation processes and circuits
- Interleaving involves spreading *b* bits of a code into *n* bursts so as to change the proximity relations between bits
- The larger the value of *n* the better the transmission performance but the longer the transmission delay - hence a compromise is required
- Several interleaving schemes are used in GSM, depending on channel usage

Interleaving - continued

- Simple arithmetic relations between *b* and *n* and the number of bits per burst (4x114 in GSM) reduces complexity
- Example - for a code word of *b*=456 = 4x114 bits we could adopt:
- 4 parts of 114 bits, each filling up a whole burst
- 8 parts of 57 bits, each filling half a burst
- GSM also uses a markedly more complex interleaving scheme for 9.6kbit/s data based on an arrangement involving 76 parts of 6 bits each using one 19th of a burst, referred to as "19 bursts interleaving" (although since 19 does not divide 456 it is actually effected on 22 bursts!)

GSM Error Control

- Four types of error control code are used in GSM:
- Convolutional (L,k) to correct random errors . The code rate R= k/L with GSM using variously R=1/2, 1/3 and 1/6
- Fire codes (224, 184) used as a block code to detect and correct a single burst of errors
- Parity check codes used for error detection
- Concatenation codes with a convolutional inner code and 'fire' outer code [(224, 184) Fire Code and R=1/2 convolutional code]

Error Control Summary

- Error Control coding requirements
- Error Control principles and techniques (overview)
- Application to GSM networks

Web References

- 3G Latest
  http://www.umts-forum.org/
- GSM Information
  http://www.gsmworld.com/
- Fraunhofer Full-HD Voice
  http://www.full-hd-voice.com/
- MPEG Information
  http://www.chiariglione.org/mpeg/
- Speech Coding
  http://www-mobile.ecs.soton.ac.uk/speech_codecs/
- Netflix TechBlog
  http://techblog.netflix.com/search/label/encoding

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ELEC0102 – Mobile Communications Systems (MCS) [previously referred to as ELECGT19]

3G / UMTS

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Senior Teaching Fellow
Department of Electronic and Electrical Engineering
University College London

Autumn 2018

Outline

- **Part 1: UMTS Basics**
  - History and standardisation
  - System architecture
- **Part 2: UMTS Radio Interface**
  - Frequency bands and duplexing
  - Channel structure and mapping
  - Spreading, modulation, multiplexing and coding
- **Part 3: UMTS Physical Layer Procedures**
  - Cell search and synchronisation
  - Radio link establishment
  - Power control
  - Handover

PART 1: UMTS BASICS

Part 1: UMTS Basics – History and Standardisation

Third Generation (3G) Standards

- Goals for a 3G system defined by ITU in late 1990's.
  - ITU: International Telecommunication Union.
- Referred to as IMT-2000 by the ITU.
  - IMT: International Mobile Telecommunications
- Key differentiator from GSM was support of multimedia services.
- Eventually multiple, different 3G systems made up IMT-2000.
  - Not a single standard.
- Development now led by 3GPP.
  - 3GPP: Third Generation Partnership Project.

    http://www.3gpp.org/about-3gpp/partners
- UMTS is part of 3G family of systems (IMT-2000).
  - A separate standard within the 3G standards.

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3GPP Standards (Releases)

3GPP RELEASES		
3GPP RELEASE	RELEASE DATE	DETAILS
Phase 1	1992	Basic GSM
Phase 2	1995	GSM features including EFR Codec
Release 96	Q1 1997	GSM Updates, 14.4 kbps user data
Release 97	Q1 1998	GSM additional features, GPRS
Release 98	Q1 1999	GSM additional features, GPRS for PCS 1900, AMR, EDGE
Release 99	Q1 2000	3G UMTS incorporating WCDMA radio access
Release 4	Q2 2001	UMTS all-IP Core Network
Release 5	Q1 2002	IMS and HSDPA
Release 6	Q4 2004	HSUPA, MBMS, IMS enhancements, Push to Talk over Cellular, operation with WLAN
Release 7	Q4 2007	Improvements in QoS & latency, VoIP, HSPA+, NFC integration, EDGE Evolution

Source: Radio Electronics, http://www.radio-electronics.com/info/cellulartelecomms/3gpp/standards-releases.php

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3GPP Standards (Releases) – Continued

Release 8	Q4 2008	Introduction of LTE, SAE, OFDMA, MIMO, Dual Cell HSDPA
Release 9	Q4 2009	WiMAX / LTE / UMTS interoperability, Dual Cell HSDPA with MIMO, Dual Cell HSUPA, LTE HeNB
Release 10	Q1 2011	LTE-Advanced, Backwards compatibility with Release 8 (LTE), Multi-Cell HSDPA
Release 11	Q3 2012	Heterogeneous networks (HetNet), Coordinated Multipoint (CoMP), In device Coexistence (IDC), Advanced IP interconnection of Services,
Release 12	March 2015	Enhanced Small Cells operation, Carrier Aggregation (2 uplink carriers, 3 downlink carriers, FDD/TDD carrier aggregation), MIMO (3D channel modelling, elevation beamforming, massive MIMO), MTC - UE Cat 0 introduced, D2D communication, eMBMS enhancements.
Release 13	Scheduled for March 2016	LTE-U / LTE-LAA, LTE-M, Elevation beamforming / Full Dimension MIMO, Indoor positioning, LTE-M Cat 1.4MHz & Cat 200kHz introduced
Release 14	Mid 2017	Elements on road to 5G
Release 15	End 2018	5G Phase 1 specification
Release 16	2020	5G Phase 2 specification

Source: Radio Electronics, https://www.radio-electronics.com/info/cellulartelecomms/3gpp/standards-releases.php

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Universal Mobile Telecommunication System (UMTS)

- European answer to IMT-2000.
  - Standardized in 3GPP (Release 99).
- Largely based on GSM standard and (commonly) uses WCDMA.
  - WCDMA: Wideband Code Division Multiple Access.
- Packet-based transmission of data with rates up to 2 Mbps.
- Key goals:
  - Higher data capacity.
  - Better speech quality.
  - Multimedia services and application.
  - IP interconnectivity.
  - Consistent service environment even when roaming.

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3G vs UMTS vs WCDMA

- WCDMA refers to the radio access technology.
- UMTS refers to the complete 3G system.
  - Encompassing the radio access technology (WCDMA) and the core network.
- 3G describes the standards for systems fulfilling IMT-2000.

3G standard	First release	Mainly used in :	Standards body	Radio interface / modulation scheme
UMTS	2001	Europe, Japan, China	3GPP	W-CDMA (TDS-CDMA in China)
CDMA2000	2001	North America, South Korea	3GPP2	CDMA

TDS-CDMA: Time Division Synchronous – Code Division Multiple Access

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Moving from GSM to UMTS

- Main difference between GSM and UMTS is the use of W-CDMA.
  - Modulation on the air interface.
- UMTS Terrestrial Radio Access Network (UTRAN) includes:
  - Radio Network Controller (RNC) .
  - Radio base stations, referred to in the standards as “Node B”.
- UMTS RNC and Node B, is similar to the GSM BSC and BTS.
- A new reference point, I_{ur}, is added between RNCs.
  - For macro diversity soft handover.
- RNC has a "general purpose" I_u interface to connect to the CN.
  - CN: Core Network.

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Part 1: UMTS Basics – System Architecture

UMTS Terminology

Nomenclature :

MS / UE = Mobile Station / User Equipment

UTRAN = UMTS Terrestrial Radio Access Network

CN = Core Network

Uu = Radio interface which connects the UE to the UTRAN (similar to ‘Um‘ in GSM)

Iu = Interface which connects the UTRAN to the CN (similar to ‘A‘ interface in GSM)

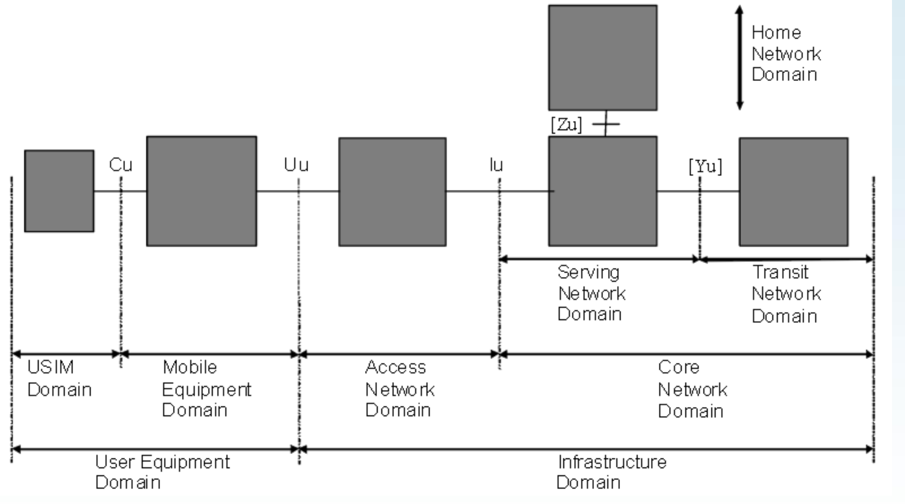
RNC = Radio Network Controller

RNS = Radio Network Subsystem

Iub = Connects the Node B and the RNC (similar to Abis in GSM)

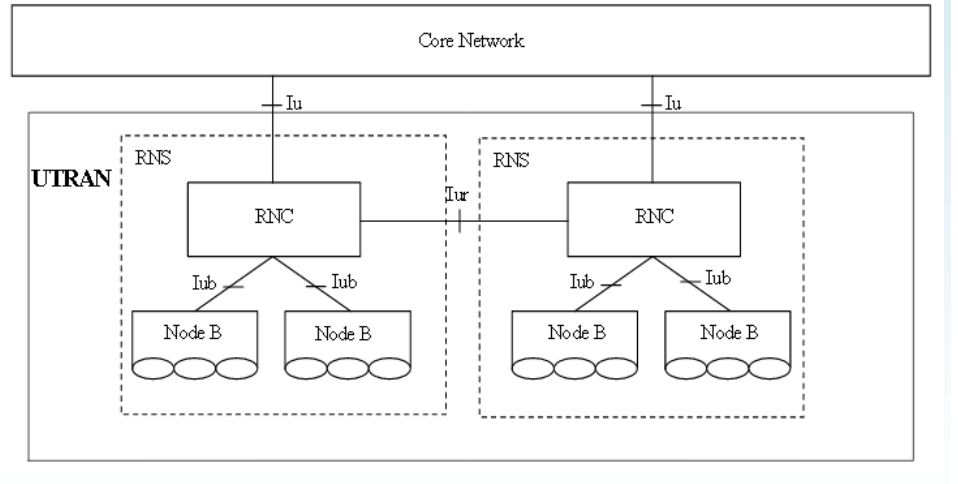
Iur = Allows RNCs to communicate between them

UMTS Architecture – Top Level



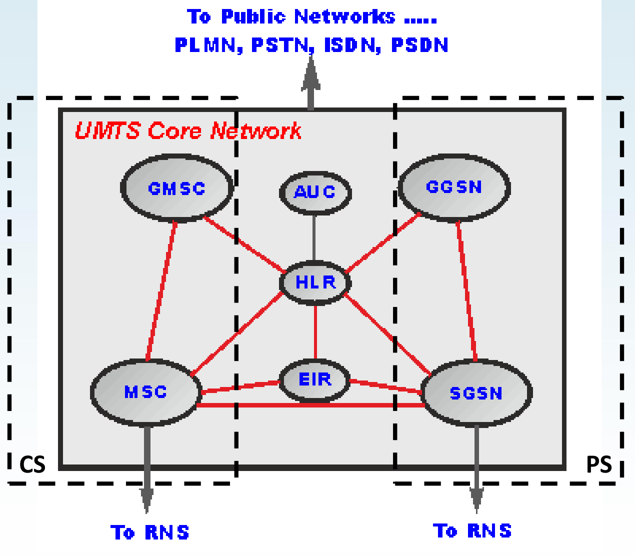
Source: http://www.etsi.org/deliver/etsi_ts/123100_123199/123101/13.00.00_60/ts_123101v130000p.pdf

UMTS Architecture – UTRAN



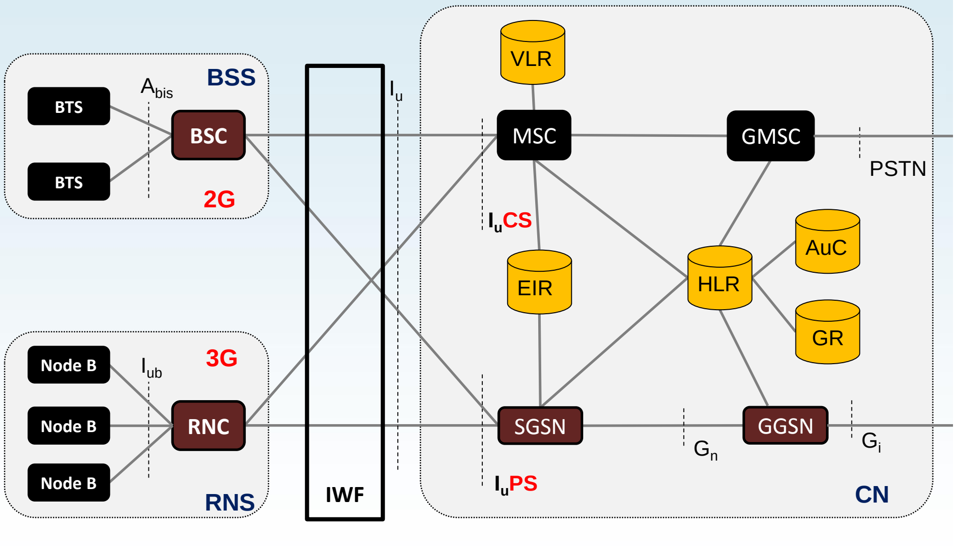
Source: http://www.etsi.org/deliver/etsi_ts/125400_125499/125401/04.02.00_60/ts_125401v040200p.pdf

UMTS Architecture – Core Network (CN)



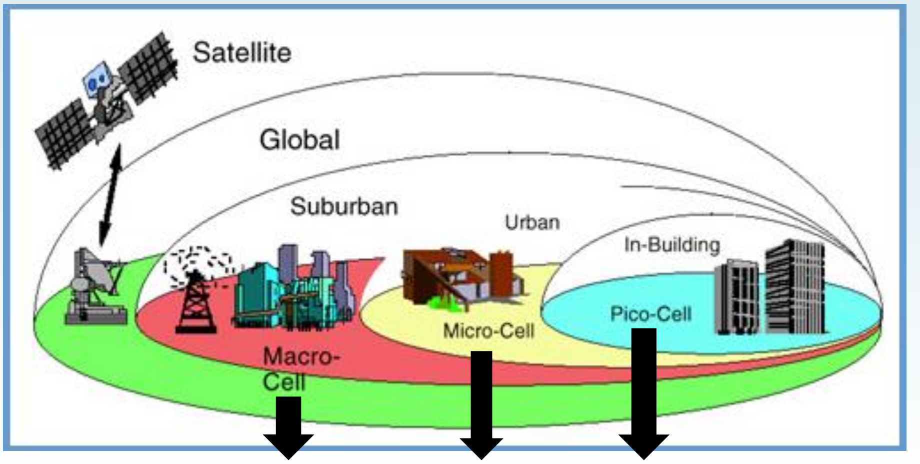
Source: Radio Electronics, Network Architecture

UMTS Architecture – UTRAN and CN



Source: Schiller, page 152

UMTS Coverage Areas



Source: https://cordis.europa.eu/infowin/acts/rus/impacts/mobile.htm

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UMTS Services

1. **Bearer services**
   - Different QoS for maximum transfer delay, delay variation and BER.
   - Offered data rate targets are:
     - 144 kbits/s satellite and rural outdoor.
     - 384 kbits/s urban outdoor.
     - 2048 kbits/s indoor and low range outdoor.

2. **Network services**
   - Have different QoS classes for four types of traffic:
     - Conversational class (voice, video telephony, video gaming).
     - Streaming class (multimedia, video on demand, webcast).
     - Interactive class (web browsing, network gaming, database access).
     - Background class (email, SMS, downloading).

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PART 2: UMTS RADIO INTERFACE

Part 2: UMTS Radio Interface – Frequency Band and Duplexing

UMTS Air Interface Parameters

KEY SPECIFICATIONS FOR UTRAN OPERATION FOR FDD & TDD		
PARAMETER	UTRA FDD	UTRA TDD
Multiple access method	CDMA	TDMA, CDMA
Channel spacing	5 MHz	5 MHz (and 1.6MHz for TD-SCDMA)
Carrier chip rate	3.84 Mcps	3.84 Mcps
Spreading factors	4 .. 512	1 .. 16
Time slot structure	15 slots / frame	15 / 14 slots / frame
Frame length (ms)	10	10
Multirate concept	Multicode, and OVSF[1]	Multicode, multislot and OVSF[1]
Burst types	N/A	(1) traffic bursts (2) random access burst (3) synchronisation burst
Detection	Coherent based on pilot symbols	Coherent based on mid-amble
Dedicated channel power control	Fast closed loop 1500 Hz rate	Uplink: open loop 100 Hz or 200 Hz rate Downlink: closed loop max 800 Hz rate

UMTS uses frequencies from 1,900 to 2,025 MHz for the uplink and from 2,110 to 2,200 MHz for the downlink

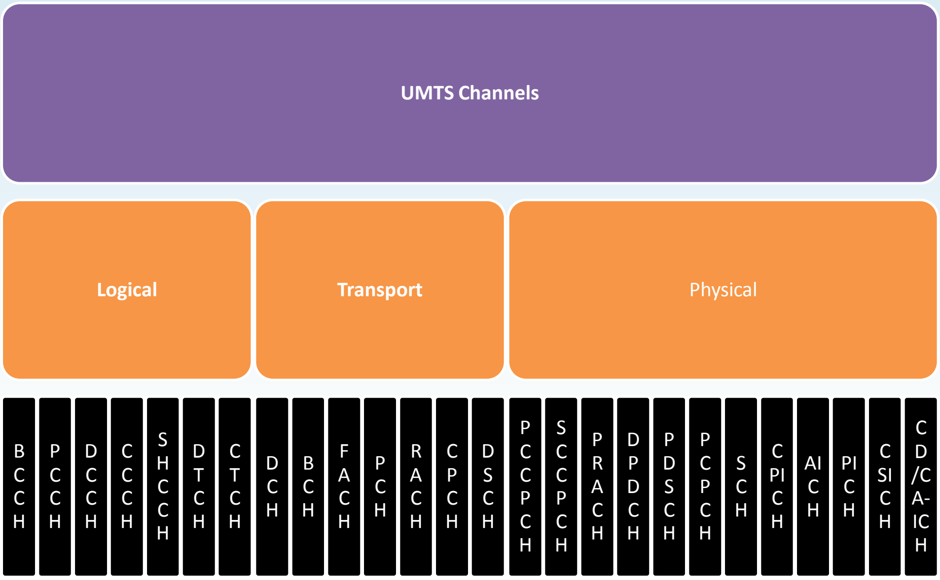
Source: Radio Electronics, UTRA/UTRAN

UMTS Duplexing

- UMTS has two types of duplex protocol defined.
- Frequency Division Duplexing (FDD)
  - Used in paired frequency bands
  - Targeted at outdoor applications
- Time Division Duplexing (TDD)
  - Used in unpaired bands
  - Targeted mainly at indoor WLAN-like applications

Part 2: UMTS Radio Interface – Channel Structure and Mapping

UMTS Channel Hierarchy



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UMTS Logical Channels

Seven logical channels are used to transmit different types of data

Downlink

- Broadcast Control Channel (BCCH)
- Paging Control Channel (PCCH)
- Common Traffic Channel (CTCH)

Bi-directional

- Common Control Channel (CCCH)
- Dedicated Control Channel (DCCH)
- Dedicated Traffic Channel (DTCH)
- Shared Channel Control Channel (SHCCH)

UMTS Transport Channels

Logical channels are mapped onto (seven) Transport channels via MAC layer

Uplink

- Random Access Channel (RACH)
- Common Packet Channel (CPCH)

Downlink

- Broadcast Transport Channel (BCH)
- Paging Channel (PCH)
- Forward Access Channel (FACH)
- Downlink Shared Channel (DSCH)

Bi-directional

- Dedicated Transport Channel (DCH)

UMTS Physical Channels

Transport channels are then mapped onto 13 physical channels

Uplink

- Physical Random Access Channel (PRACH)
- Physical Common Packet Channel (PCPCH)

Downlink

- Primary Common Control Physical Channel (P-CCPCH)
- Secondary Common Control Physical Channel (S-CCPCH)
- Synchronization Channel (SCH)
- Common Pilot Channel (CPICH)
- Physical Downlink Shared Channel (PDSCH)
- Acquisition Indication Channel (AICH)
- Page Indication Channel (PICH)
- Common Packet Channel Status Indication Channel (CSICH)
- Collision Detection/Channel Assignment Indication Channel (CD/CA-ICH)

Bi-directional

- Dedicated Physical Data Channel (DPDCH)
- Dedicated Physical Control Channel (DPCCH)
- Coded Composite Traffic Channel (CCTrCH): Combination of DPDCH and DPCCH

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Dedicated Physical Channel

- Data and control channels are transmitted in the uplink.
  - At the same time using dual channel modulation (I- and Q- multiplexing)
- Control elements include:
  - **Pilot bits**: For channel estimation and equalization
  - **Transmit Power Control (TPC) bits**: To change transmission power
  - **Feed Back Information (FBI) bits**: Feedback the antenna weights to Node-B
  - **Transport Format Combination Indicator (TFCI) bits**: Determine the structure of the data that are transmitted over the DPDCH

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Part 2: UMTS Radio Interface – Spreading, Modulation, Multiplexing and Coding

Spreading and Multiple Access in UMTS

- Wideband-CDMA (WCDMA) was chosen for UMTS.
- WCDMA uses Code Division Multiple Access (CDMA).
- CDMA employs Direct Sequence Spread Spectrum (DSSS).
  - Message is multiplied by a code sequence before modulating the carrier.
  - Message is recovered by correlating received signal with code sequence.
  - The remaining interference and noise are spread.
- CDMA uses codes to separate different users.

Spreading Factors and Operations

- Spreading is applied to the physical channels in two steps:
  - **Channelisation**: Transforms slow data sequence into fast chip sequence.
  - **Scrambling**: A scrambling code is applied to the spread signal.
- Spreading Factor (SF) : The number of chips per data symbol.
  - Also referred to as **processing gain** expressed in decibels (dB).
- Channelisation codes lead to bandwidth expansion.
- Good codes have two key characteristics:
  - Sharp autocorrelation: For good robustness against multipath fading.
  - Zero cross-correlation: To mitigate interference between users.
- UMTS uses codes of various families:
  - Orthogonal Variable Spreading Factor (OVSF) codes.
  - Kasami and Gold codes.

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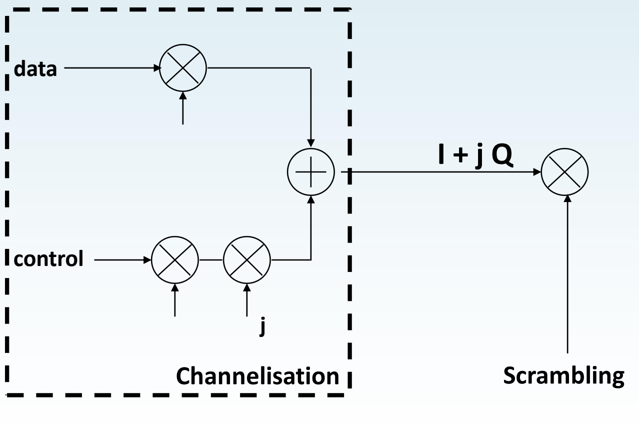
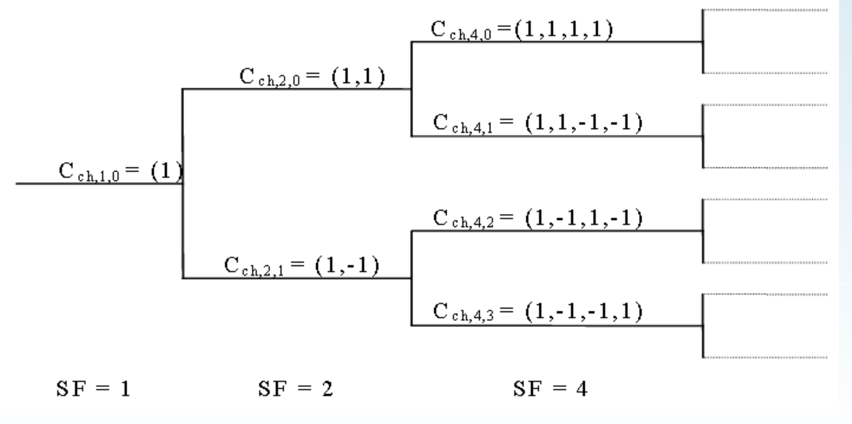
Channelisation and Scrambling



Channelisation Codes for Spreading



Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125213/12.00.00_60/ts_125213v120000p.pdf

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Scrambling Codes for Separation

Scrambling codes are repeated for every 10 ms radio frame.

Uplink data and control channels are scrambled by 2^{24} of either:

- Long codes from a set of Gold sequences of 38400 chips.

OR

- Short codes from the family of periodically extended S(2) codes.

Downlink: 2^{18} –1 scrambling codes can be generated.

- Only 8192 of these scrambling codes are used.
- Scrambling codes are divided into 512 sets:
  – One primary scrambling code.
  – 16 secondary scrambling codes.
- These are segments of a different set of the Gold sequences.

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Channel Coding in UMTS

Type of TrCH	Coding scheme	Coding rate
BCH	Convolutional coding	1/2
PCH		
RACH		
CPCH, DCH, DSCH, FACH		1/3, 1/2
	Turbo coding	1/3

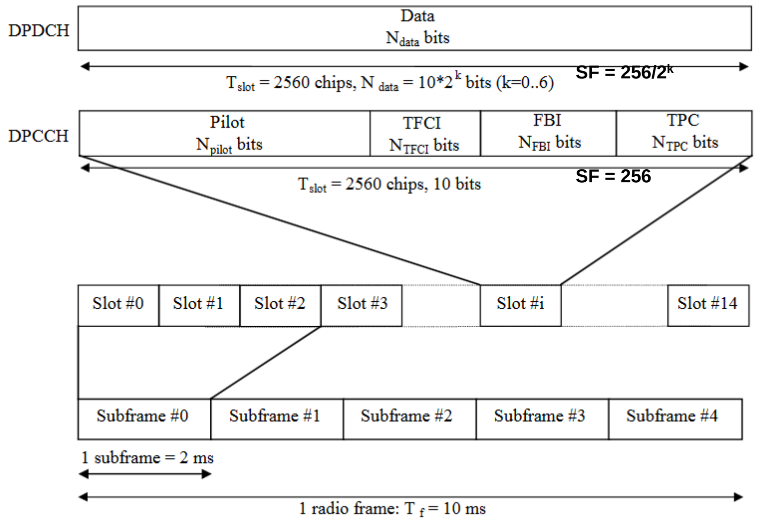
Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125212/05.01.00_60/ts_125212v050100p.pdf

Speech Coding in UMTS

Bit 8…Bit 1 CoID	Codec_Type	Name
0000.0000	GSM Full Rate (13.0 kBit/s)	GSM FR
0000.0001	GSM Half Rate (5.6 kBit/s)	GSM HR
0000.0010	GSM Enhanced Full Rate (12.2 kBit/s)	GSM EFR
0000.0011	Full Rate Adaptive Multi-Rate	FR AMR
0000.0100	Half Rate Adaptive Multi-Rate	HR AMR
0000.0101	UMTS Adaptive Multi-Rate	UMTS AMR
0000.0110	UMTS Adaptive Multi-Rate 2	UMTS AMR 2
0000.0111	TDMA Enhanced Full Rate (7.4 kBit/s)	TDMA EFR
0000.1000	PDC Enhanced Full Rate (6.7 kBit/s)	PDC EFR
other codes	reserved for future use.	

Source: http://www.etsi.org/deliver/etsi_ts/126100_126199/126103/04.01.00_60/ts_126103v040100p.pdf

UMTS FDD uplink frame structure



FBI: Feedback Information

TPC: Transmit Power Control

TFCI: Transport Format Combination Indicator

DPCCH: Dedicated Physical Control Channel

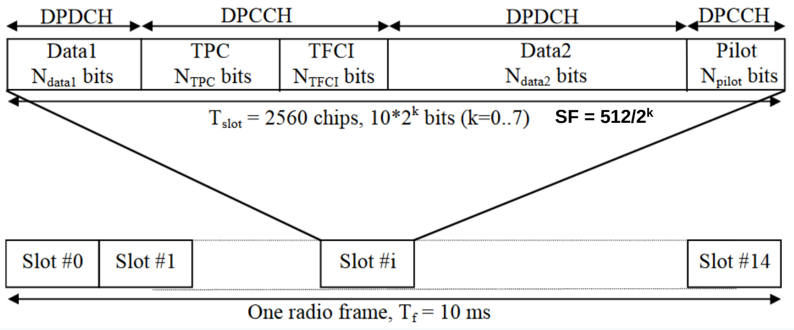
DPDCH: Dedicated Physical Data Channel

DPCH: Dedicated Physical Channel

Slot structure NOT for user separation but for synchronisation of periodic functions

Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125211/08.07.00_60/ts_125211v080700p.pdf

UMTS FDD downlink frame structure



FBI: Feedback Information

TPC: Transmit Power Control

TFCI: Transport Format Combination Indicator

DPCCH: Dedicated Physical Control Channel

DPDCH: Dedicated Physical Data Channel

DPCH: Dedicated Physical Channel

Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125211/08.07.00_60/ts_125211v080700p.pdf

Multiplexing, channel coding and interleaving

The following processes take place to offer transport services over the radio link:

- CRC attachment (to each transport block).
- Concatenation and segmentation.
- Channel coding.
- Frame equalisation.
- Rate matching.
- Insertion of discontinuous transmission (DTX).
- Interleaving.
- Frame segmentation.
- Multiplexing (of transport channels).
- Physical channel segmentation.
- Mapping to physical channels.

Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125212/11.06.00_60/ts_125212v110600p.pdf

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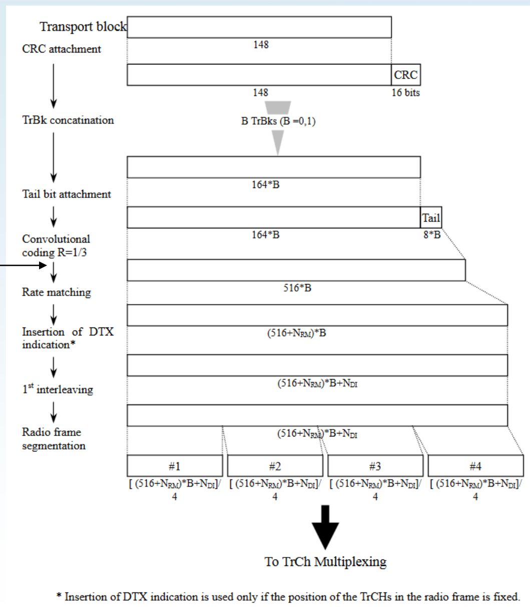
Example for DCCH: 3.4 kbps data

Frame equalisation

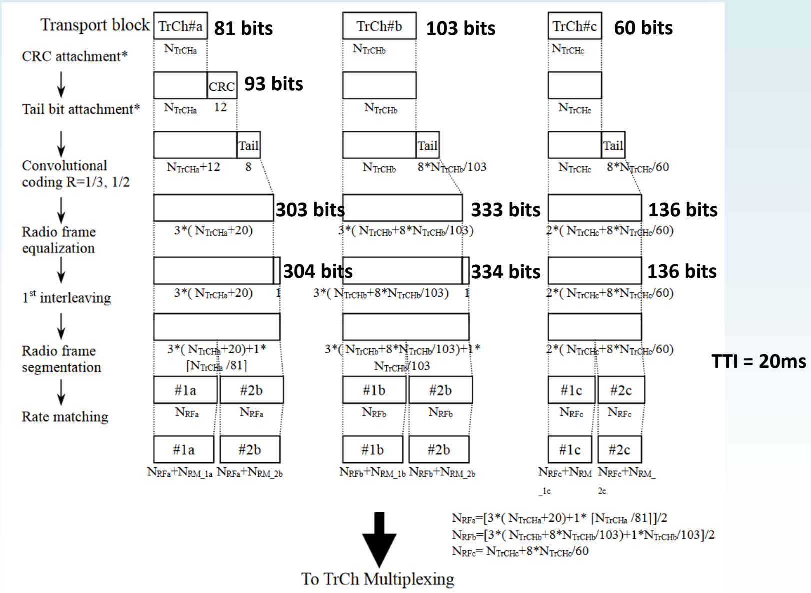


TTI = 40ms

Source: http://www.etsi.org/deliver/etsi_tr/125900_125999/125944/04.01.00_60/tr_125944v040100p.pdf

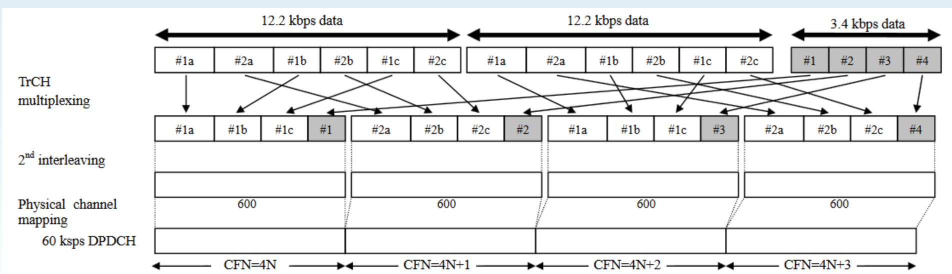
40

Example for AMR Speech: 12.2 kbps



Source: http://www.etsi.org/deliver/etsi_tr/125900_125999/125944/04.01.00_60/tr_125944v040100p.pdf 41

Multiplexing different types of data

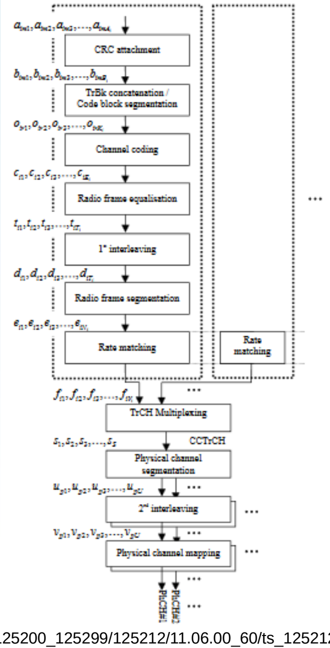


CFN: Connection Frame Number

Example of multiplexing 12.2 kbps data (AMR) with 3.4 kbps data (DCCH)

Source: http://www.etsi.org/deliver/etsi_tr/125900_125999/125944/04.01.00_60/tr_125944v040100p.pdf 42

Coding and multiplexing of uplink channels



Source: http://www.etsi.org/deliver/etsi_ts/125200_125299/125212/11.06.00_60/ts_125212v110600p.pdf

UMTS Air Interface Parameters

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PARAMETER	UTRA FDD	UTRA TDD
Multiple access method	CDMA	TDMA, CDMA
Channel spacing	5 MHz	5 MHz (and 1.6MHz for TD-SCDMA)
Carrier chip rate	3.84 Mcps	3.84 Mcps
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Time slot structure	15 slots / frame	15 / 14 slots / frame
Frame length (ms)	10	10
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UMTS uses frequencies from 1,900 to 2,025 MHz for the uplink and from 2,110 to 2,200 MHz for the downlink

Source: Radio Electronics, UTRA/UTRAN

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WCDMA versus GSM Air Interface

	W-CDMA	GSM
Carrier Spacing	5MHz	200kHz
Frequency reuse factor	1	1-18
Power control frequency	1500Hz	2Hz or lower
Quality control	Radio resource management algorithms	Network planning (frequency planning)
Frequency diversity	5MHz bandwidth gives multipath diversity with Rake receiver	Frequency hopping
Packet data	Load-based packet scheduling	Time slot based scheduling with GPRS
Downlink transmit diversity	Supported for improving downlink capacity	Not supported by the standard, but can be applied

Source: https://telecomstudy18.blogspot.co.uk/2015/09/differences-between-wcdma-and-second.html

PART 3: UMTS PHYSICAL LAYER PROCEDURES

Physical Layer Procedures

- Cell Search and Synchronisation
- Radio Link Establishment
- Power Control
- Handover

Part 3: UMTS Physical Layer Procedures – Cell Search and Synchronisation

Cell Search and Synchronisation

Goal: Search for cell with strongest signal and synchronise to it.

Steps:

1. Slot synchronisation.
2. Frame synchronisation and code-group identification.
3. Scrambling-code identification.

Part 3: UMTS Physical Layer Procedures – Radio Link Establishment

Radio Link Establishment

Goal: Establish a connection between the UE and the network.

Steps:

1. Synchronise to the network.
2. Read the broadcast channel.
3. Select preamble spreading code.
4. Select message scrambling code.
5. Calculate uplink transmission power.
6. Transmit message if ACK received, else increase transmit power.
7. If access grant message not received, repeat procedure.

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Part 3: UMTS Physical Layer Procedures – Power Control

Power Control in UMTS

- Soft Capacity
- Near-Far Effect
- Power Control
  - Inner / Outer.
  - Open / Closed.
  - Uplink / Downlink.

Soft Capacity

- TDMA / FDMA:
  - Number of users limited by number of timeslots / channels.
- CDMA:
  - Number of users limited by interference (soft capacity).
  - Increasing power leads to increased interference (in and between cells).
- Limit on capacity:
  - Signal to interference ratio (SIR) becomes too high.
  - No more power at NodeB to serve more users.
  - No more codes to assign to users (rare situation).

Near-Far Effect

- In CDMA systems, all users transmit their signals simultaneously.
- Imperfect orthogonality limits interference mitigation.
- Near-far effect:
  - Users close to NodeB may drown users at cell edge.
  - Users at cell edge may not be heard due to high interference.
- Tight power control procedures required.

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Inner and Outer Loop Control

- Inner loop:
  - Adjust NodeB transmission power to maintain SIR at given target.
- Outer loop:
  - Estimate connection quality using BER and FER.
  - Adjust target SIR used by inner loop control.

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Open Loop Control

- Used:
  - During initial power settings.
  - When a feedback channel is not available.
- Measure average received power of CCPCH.
- Calculate path loss from the receiving signal.
- Obtain estimate of required transmission power.

Closed Loop Control

- Used with inner and outer loops to provide fast power control.
- Transmission power is updated every 667 μs.
  - Designed to be faster than Rayleigh fading at high mobile speeds.
- Maintains UE and NodeB power levels at a minimum.
- Adjusts UE and NodeB power levels based on signal quality.

Downlink and Uplink Closed Loop Control

- Downlink:
  - Closed loop control to maintain good SNR.
  - UE measures SNR and requests power increase / decrease accordingly.
  - Request sent via TPC commands to the NodeB.
  - Ttransmission power of all other channels adjusted accordingly.
- Uplink:
  - NodeB estimates received signal power and sends TPC commands to UE.
  - UE adjusts transmission power accordingly.

Part 3: UMTS Physical Layer Procedures – Handover

Handover Causes and Strategies

Causes:

- Signal quality and measurements
- Change of service
- Directed retry
- Traffic load
- Pre-emption

Strategies:

- Intra / Inter-frequency Handover
- Inter-system (or Inter-RAT) Handover
- Hard / Soft / Softer Handover

Handover Scenarios

- **Intra-frequency**: Uses soft handover.
  - UE moves between NodeBs on the same carrier frequency.
- **Inter-frequency**: Uses hard handover.
  - UE moves between cells on different carrier frequencies.
  - UE switches between modes, for example, from TDD to FDD.
  - No capacity on existing channel so UE moves to a new channel.
- **Inter-system (or Inter-RAT)**: Uses hard handover.
  - UE moves between different networks (or RATs).
  - Handover managed by different MSCs.

Handover Types

- **Hard**: Used in TDMA/FDMA systems, such as GSM.
  - Switching happens at specific point in time.
  - Existing connection terminated before new connection is established.
  - Measurements taken using two receivers or using compressed mode.
- **Soft**: Introduced in CDMA networks, such as UMTS.
  - UE always maintains at least one active link to RAN.
  - Can be performed on the same carrier frequency only (FDD mode).
- **Softer**: Special case of soft handover.
  - UE is in overlapping coverage of two sectors of the same NodeB.
  - UE connected concurrently to both sectors via separate interfaces.

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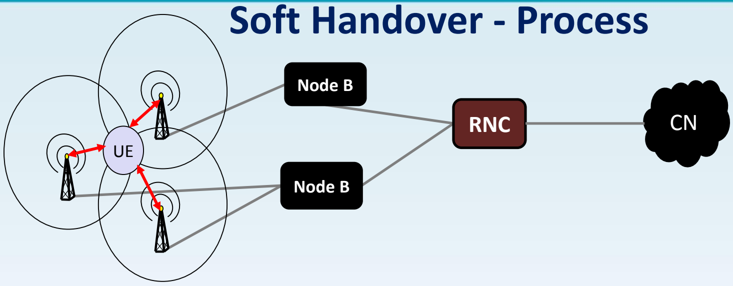
Soft Handover - Process



- Less power -> Less Interference -> **More Capacity**.
- Occurs when UE is in **overlapping coverage** of two NodeBs.
- **Downlink**: Streams combined via MRC* using RAKE receiver.
  - Different scrambling codes applied to different RAKE fingers.
- **Uplink**: Streams routed to RNC for selection combining.

Source: Schiller, page 154

***MRC = Maximal Ratio Combining**

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Soft Handover - Measurements

- UE **synchronises** to more than one cells.
- UE continuously **monitors** signals:
  - In active cells (to which UE has established a connection).
  - In neighbouring cells (to which UE is not connected to).
  - By measuring the RSSI on the CPICH.
- UE **changes** cells:
  - Neighbouring cells with sufficient RSSI* added to active set.
  - UE waits until summed signal strength exceeds upper threshold.
  - Remaining cells are then removed from active set.

***RSSI = Received Signal Strength Indicator**

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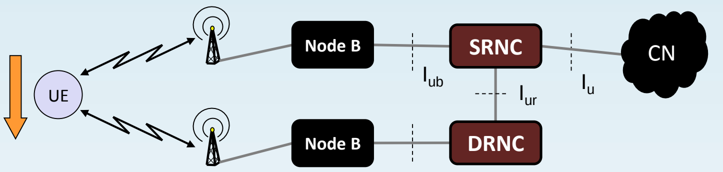
Soft Handover and Macro Diversity



- **Soft handover**: Same frequency assigned to different cells.
- **Macro diversity**: Multicast data via multiple physical channels.
  - Provides robustness against multipath fading.
  - Enables users at the cell edge to be better served.
  - Downlink: UE receives data from different cells at the same time.
  - Uplink: Data from UE received by multiple NodeBs at the same time.

Source: Schiller, page 155

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- Ian Poole, 3G UMTS / WCDMA Basics Tutorial, Radio-Electronics.com, Available: http://www.radio-electronics.com/info/cellulartelecomms/umts/umts_wcdma_tutorial.php

MSc Telecommunications programmes

Mobile Communications Systems (MCS)

UCL

Mobile Communications Systems (MCS)

4th Generation Mobile - LTE

Dr Clive Poole
Principal Teaching Fellow - University College London

Thursday 1st November 2018

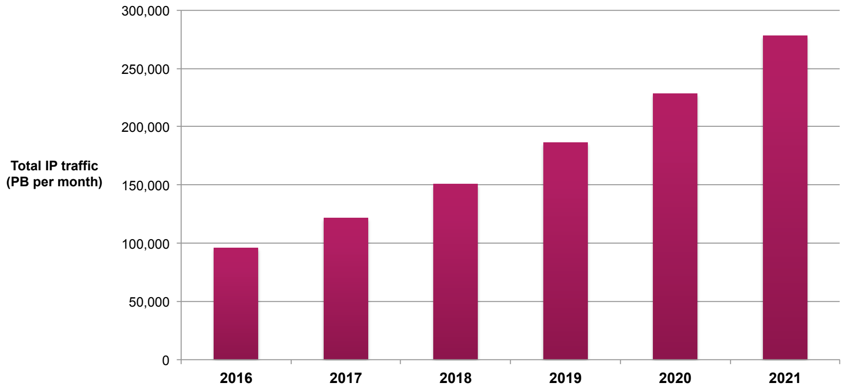
Outline

- **Part 1: Long Term Evolution**
  - Motivations for Long Term Evolution (LTE)
  - Services
  - System architecture
- **Part 2: LTE Radio Link**
  - Multiple access
  - Channel structure and mapping
  - Modulation and coding
- **Part 3: Beyond LTE**
  - Signalling protocol structure
  - Radio resources management
  - Mobility management
  - Connection management

Part 1 : Long Term Evolution

Wireless data forecast

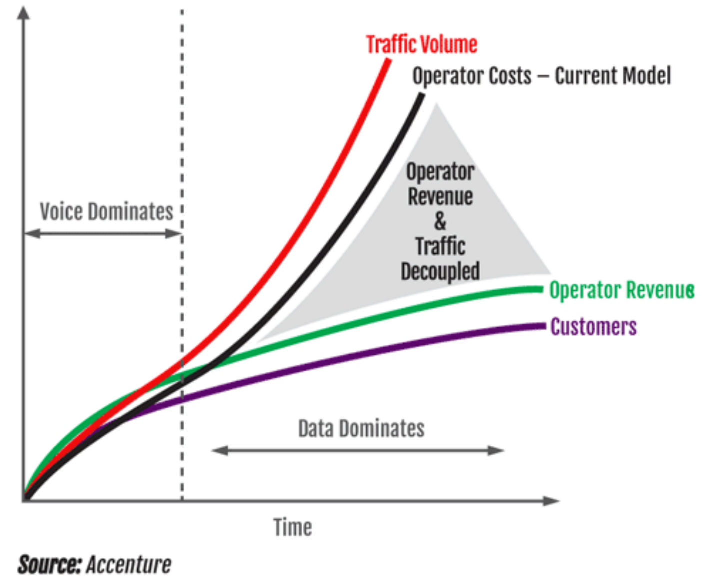
- Cisco forecasts that CAGR for worldwide mobile data traffic from 2016 to 2021 will be 24%, reaching close to 300 Exabytes per month by 2021.
- 1 Exabyte = 10^{18} Bytes or 1,000 Petabytes (PB) or 200 million DVDs.
- 5 Exabytes = "a transcript of all the words ever spoken"



Source : https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.html#_Toc484813982

4

Traffic-Revenue Decoupling



Source : Lee Joon Seong/Accenture : http://www.telecomasia.net/content/big-money-big-data

5

Motivations for Long Term Evolution (LTE)

1. **Need to cater for higher data rates**
   – New air interface employing recent advances in spectrally efficient modulation.
   – Greater flexibility in spectrum usage.
2. **Need to cater for higher data volumes**
   – Need to evolve UMTS towards a data-centric network based on Packet Data end-to-end.
3. **Need for offer more variety and quality of services**
   – Different levels of QoS according to type of service.
   – Dramatically lower latency.
   – "Always-on" experience.
   – Improved power management in the Mobile Station (MS)
4. **Need for cheaper infrastructure**
   – Reduced number of network elements.
   – Use of more generic hardware.

6

3GPP introduction

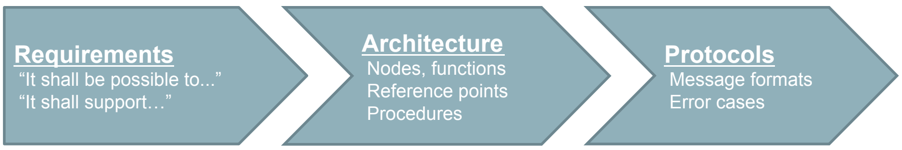
- 3rd Generation Partnership Project
  - a collaboration between groups of telecommunications associations, known as the **Organizational Partners**.
  - Organisational Partners include GSMA, ETSI, CCSA.
  - Established in 1998 to define UMTS (3G)
  - Today also works on LTE and access-independent IMS
- 3GPP standardizes systems
  - Architecture, protocols
- Works by way of "releases"

A GLOBAL INITIATIVE

7

3GPP mode of operation

Stage 1 **Stage 2** **Stage 3**



E.g., 22-series specs E.g., 23-series specs E.g., 29-series specs

Specification numbering example:

3GPP TS 23.401 V11.2.0

TS=Technical Specification (normative)
TR=Technical Report (info only)

Spec. number

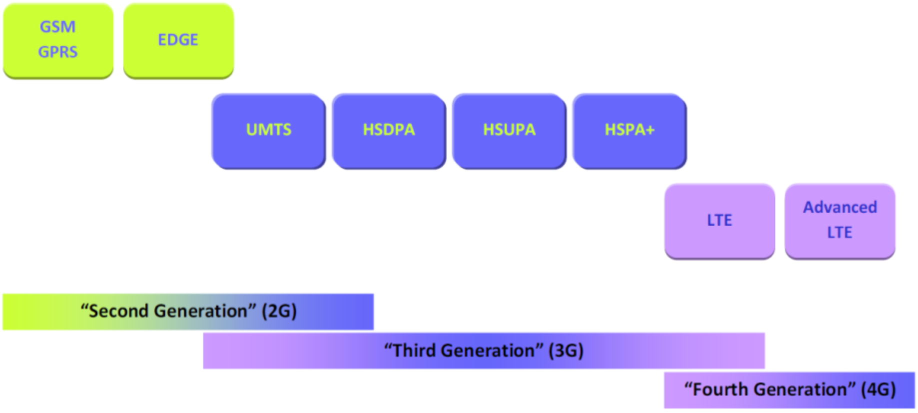
Release
- Consistent set of specs per release
- New release every 1-2 years

Updated after a meeting

http://www.3gpp.org/specification-numbering

8

3GPP Standards Evolution



Source : "LTE in a Nutshell : System Overview" © 2010 Telesystem Innovations Inc.

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3GPP documents relating to LTE

- http://www.3gpp.org/specification-numbering
  - Pointers to the series of specifications
  - Architecture documents in 23-series
- Main LTE architecture references
  - 23.002 – Overall architecture reference
  - 23.401 – Evolved Packet Core with LTE access, GTP-based core
  - 23.060 – 2G/3G access, and integration to Evolved Packet Core
  - 23.402 – Non-3GPP access, and PMIP-based core

10

Key 3GPP LTE Standards Releases

Release No.	Date	Content
Release 8	2008 Q4	First LTE release. All-IP Network (SAE). New OFDMA, FDE and MIMO based radio interface, not backwards compatible with previous CDMA interfaces. Dual-Cell HSDPA.
Release 10	2011 Q1	Introduced "LTE Advanced" : Multi-Cell HSDPA (4 carriers).
Release 11	2012 Q3	Introduced Heterogeneous networks (HetNet).
Release 12	2015 Q2	Introduced Device to Device communication (D2D) and the integration of WiFi in to mobile operator's offerings.
Release 13	2016 Q2	Enhancements for operation of LTE in unlicensed spectrum, Carrier Aggregation, Machine-Type Communications (MTC), Beamforming and MIMO.
Release 15	2017 Q4	Introduces the first set of 5G standards.

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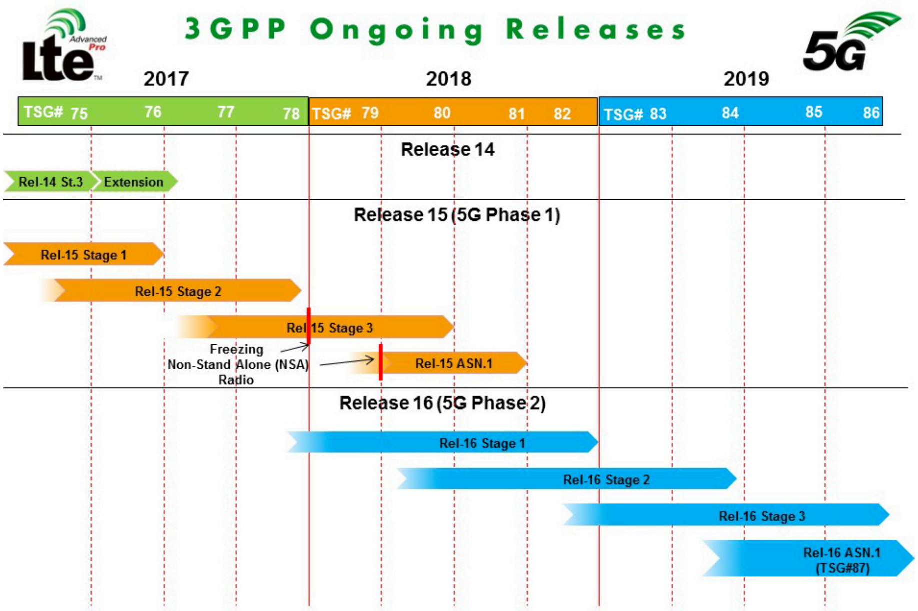
3GPP LTE Standards Releases



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"4G" versus "LTE"

- The 4G standard was defined by the International Telecommunications Union-Radio (ITU-R) in March 2008. According to the ITU definition of 4G, the peak download speed should be 100Mbps for high mobility devices and 1Gbps for stationary devices.
- Since that time the term "4G" has come to be used as a blanket term for all mobile data technologies that exceed typical 3G speeds.
- LTE, or "Long Term Evolution" describes a technology path, based on GSM/EDGE and UMTS/HSPA network technologies, and evolving towards the achievement of 4G speeds.
- The standards defining LTE are the responsibility of the 3GPP (3rd Generation Partnership Project) and embodied in its Release 8 document series, with minor enhancements described in Release 9.
- Most LTE networks today doesn't achieve the 100Mbps required for 4G, but they are, nonetheless, usually referred to as "4G" or "4G LTE" by the marketing departments of mobile operators.

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Key 4G/LTE Performance Requirements

- **Data Rate :**
  - Instantaneous downlink peak data rate of 100Mbit/s in a 20MHz downlink bandwidth (i.e. 5 bit/s/Hz)
  - Instantaneous uplink peak data rate of 50Mbit/s in a 20MHz uplink bandwidth (i.e. 2.5 bit/s/Hz)
- **Latency**
  - Less than 5 ms in unload condition (i.e., single user with single data stream) for small IP packet.
- **Cell range :**
  - 5 km - optimal size
  - 30km sizes with reasonable performance
  - up to 100 km cell sizes supported with acceptable performance

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Latency

In packet networks, latency is defined as the amount of time it takes for a data packet to get from one designated point to another.

Network latency is a combination of:

1. **Propagation / Transmission delay:** The delay in traversing the medium itself from point A to point B, which depends on the type of medium (optical fiber, wireless etc.). In wireless systems the signal travels at the speed of light, so the delay will be **3.3nS per meter**. In optical fiber the speed is lower and depends on the square root of the refractive index.
2. **Router and other processing delays:** Each gateway node takes time to examine and possibly change the header in a packet. This introduces a processing delay.
3. **Buffering and storage delays:** Packets may be subject to buffering at intermediate devices such as switches and bridges, where they are stored for a short time until a following resource becomes available.

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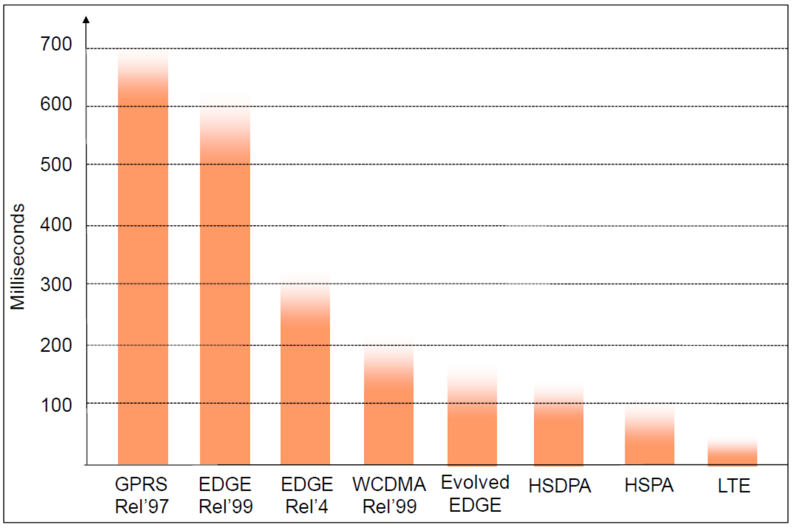
Continuous improvements in Latency



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LTE - key themes

- **Technology Evolution**
  - Migration from circuit switching to packet switching for all services.
  - All IP network, end-to-end.
  - Availability of low cost computing power – generic hardware.
  - Low cost digital signal processing makes complex modulation possible – greater spectrum utilisation.
- **Network delayering**
  - Separation of application layers from the transport layers.
  - Simplified network architecture with fewer "boxes"
  - Services decoupled from underlying networks, and can be sold separately.

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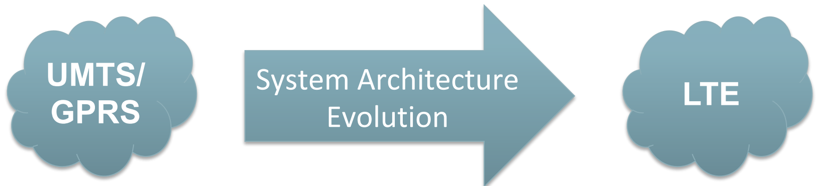
System Architecture Evolution (SAE)



System Architecture Evolution (**SAE**) refers to the evolution of the GPRS Core Network to accommodate LTE.

The main principles and objectives of the LTE-SAE architecture include :

- A common anchor point and gateway (**GW**) node for all access technologies.
- IP-based protocols on all interfaces.
- Simplified network architecture.
- All IP network : all services (including voice) are delivered via Packet Switched domain
- Support mobility between heterogeneous radio access technologies, including legacy systems such as GSM/GPRS, but also non-3GPP systems (say WiFi/ WiMax)

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Control plane and User plane

A key feature of the SAE is a flat, all-IP architecture with separation of **Control Plane** and **User Plane** traffic, as shown here. A plane is an abstraction that helps in the understanding the design and operation of an LTE network.

The user plane carries the network user traffic, whereas the control plane carries signalling traffic. Under the user plane, the application creates data packets that are processed by protocols such as TCP, UDP and IP. Under the control plane, something called the Radio Resource Control (RRC) protocol generates signalling messages that are exchanged between the base station and the mobile. In both cases, the information is processed by the Packet Data Convergence Protocol (PDCP), the Radio Link Control (RLC) protocol and the Medium Access Control (MAC) protocol, before being passed to the physical layer for transmission.

The requirements of control plane and user plane are different. The control plane requires lower throughput but higher signal integrity, whereas user plane requires higher throughput but signal integrity is less important.

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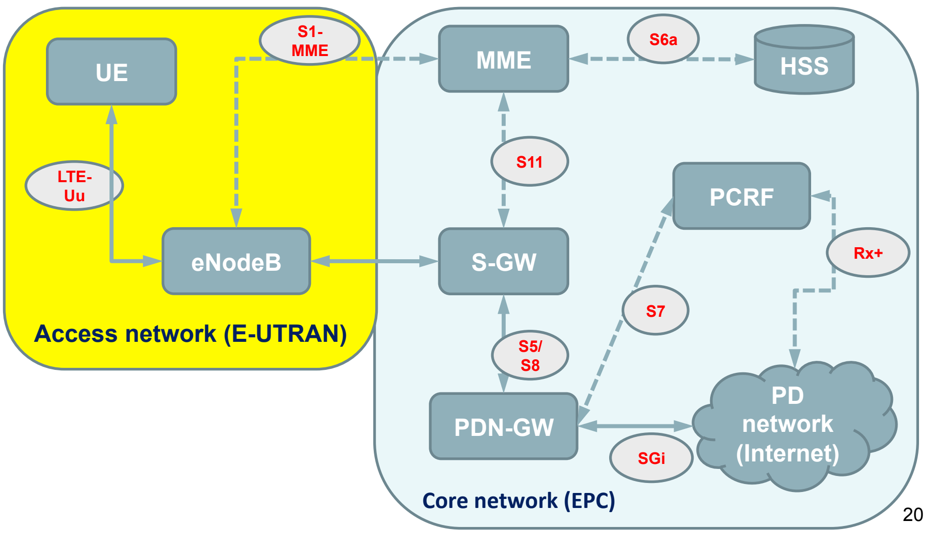
LTE Network Architecture

- The LTE network consists of an Evolved Universal Terrestrial Radio Access Network (**E-UTRAN**) and an Evolved Packet Core (**EPC**).
- The various network entities are connected via specific interfaces.



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LTE Access network (E-UTRAN)

- The Access Network comprises the **eNodeBs** which are interconnected through an interface called X2, and to the EPC through the S1 interface (S1-MME to the MME and S1-U to the S-GW). The protocols between the eNodeB and the UE are known as **Access Stratum (AS)** protocols. The X2 interface is used to transfer the UE context between eNodeBs to support mobility function.
- The eNodeB is responsible for radio-related functions such as **Radio Resource Management (RRM)** which include admission control, mobility control, scheduling and dynamic resource allocation to the UE in both uplink and downlink; security by encrypting user data; and other functions to ensure efficient use of the radio interface such as IP packet header compression.
- By placing all radio control functions in the eNodeB, LTE increases efficiency and reduces latency. It increases the resiliency of the network by eliminating the need for a central controller for such functions as in prior 3GPP technologies.

Adapted from : "LTE in a Nutshell : System Overview" © 2010 Telesystem Innovations Inc.

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eNode B

- eNodeB are the wireless access points into the network.
- eNodeB support all Layer 1 and Layer 2 features associated to the E-UTRAN OFDM physical interface, and they are directly connected to network routers.
- Under LTE there is no more intermediate controlling node (i.e. BSC in 2G or RNC in 3G/ RNC) which means simplified network operation and better performance over the radio interface.
- The termination of Layer 2 protocols in eNodeB rather than in the RNC helps to decrease data-transmission latency.

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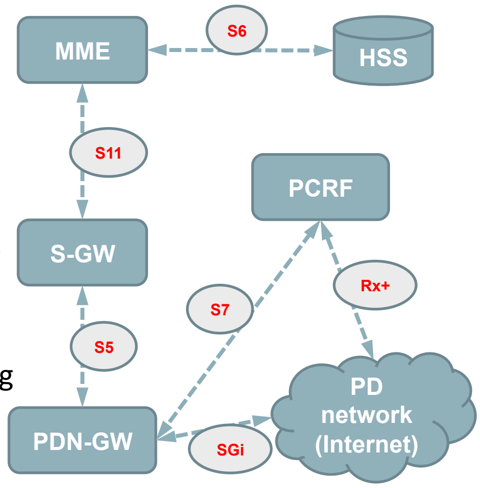
Evolved Packet Core (EPC)

The EPC (Evolved Packet Core) is composed of several functional entities:

- The **MME** (Mobility Management Entity)
- The **HSS** (Home Subscriber Server)
- The Serving Gateway (**S-GW**).
- The Packet Data Network Gateway (**PDN-GW**).
- The **PCRF** (Policy and Charging Rules Function) Server.



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Serving Gateway (S-GW)

- The Serving GW is the termination point of the packet data interface towards E-UTRAN.
- When terminals move across eNodeB in E-UTRAN, the Serving GW serves as a mobility anchor for other 3GPP technologies (e.g. 2G/GSM and 3G/UMTS).
- serves as the local mobility anchor for data bearers (service flows) and retains information about the bearers when the UE is in idle mode.
- The S-GW performs some administrative functions in the visited network such as collecting charging information (e.g. volume of sent and received user data).

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PDN Gateway (P-GW)

- The PDN gateway is the termination point of the packet data interface towards the Packet Data Network.
- Responsible for allocation of IP address to the UE, QoS enforcement and flow-based charging according to PCRF rules.
- The P-GW filters downlink user IP packets into different bearers depending on QoS classification.
- As an anchor point for sessions towards the external Packet Data Networks, the PDN GW also supports **Policy Enforcement features** (which apply operator-defined rules for resource allocation and usage) as well as packet filtering (like deep packet inspection for virus signature detection) and evolved charging support (like per URL charging).

Mobility Management Entity (MME)

The MME is in charge of all the Control plane functions related to subscriber and session management. From that perspective, the MME supports the following:

- **Security procedures** – this relates to end-user authentication as well as initiation and negotiation of ciphering and integrity protection algorithms.
- **Terminal-to-network session handling** – this relates to all the signalling procedures used to set up Packet Data context and negotiate associated parameters like the Quality of Service.
- **Idle terminal location management** – this relates to the tracking area update process used in order for the network to be able to join terminals in case of incoming sessions.

The MME is linked through the S6 interface to the HSS which supports the database containing all the user subscription information.

Home Subscriber Server (HSS)

The HSS (Home Subscriber Server) is the concatenation of the **HLR** and the **AuC** – two functions being already present in 2G/GSM and 3G/UMTS networks. The HLR part of the HSS is responsible for storing and updating the database containing all the user subscription information, including but not limited to :

- **User identification and addressing** – this corresponds to the IMSI (International Mobile Subscriber Identity) and MSISDN (Mobile Subscriber ISDN Number) or mobile telephone number.
- **User profile information** – this includes service subscription states and user-subscribed Quality of Service information (such as maximum allowed bit rate or allowed traffic class).

The AuC part of the HSS is responsible for generating security information from user identity keys. This security information is provided to the HLR and further communicated to other entities in the network. Security information is mainly used for:

- Mutual network-terminal authentication.
- Radio path ciphering and integrity protection, to ensure data and signalling transmitted between the network and the terminal is neither eavesdropped nor altered.

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Part 2 : The LTE Radio Link

Spectral efficiency trends in the air interface

1900's
Switch the source on and off (non-coherent)

1950's
Modulate the frequency/phase of the source (coherent)

1980's
Spread spectrum (coherent)

1990's
Modulate the phase and amplitude of the source simultaneously (coherent)

Present
Split available bandwidth into subcarriers and modulate each one separately (coherent)

Oldest - Simplest

Newest - Most complex

Modulation scheme	FSK	GMSK	8-PSK	WCDMA	OFDM	QAM + OFDM	16/64 QAM	OFDM
Bandwidth efficiency (BPS/Hz)	**0.45**	**0.52**	**1.35**	**2.50**	**3.00**	**7.00**	**8.00**	**16.00**
Mobile generation	1G (AMPS)	2G (GSM)	2.75G (EDGE)	3G	WiFi (802.11 a/g)	WiFi (802.11n)	3.5G (HSDPA)	4G (LTE)

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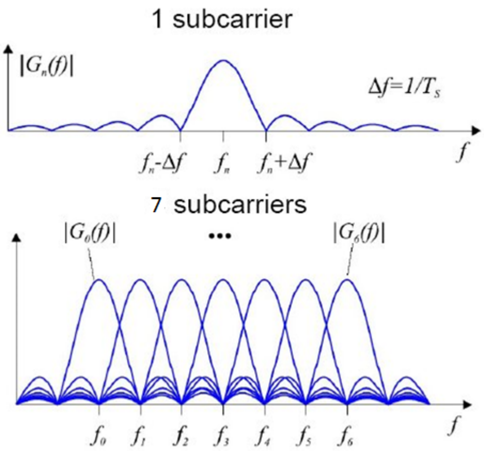
LTE-Downlink air interface (OFDM)

- The principle of the OFDMA is based on the use of narrow, orthogonal subcarriers
- In LTE the OFDMA sub-carrier spacing is **15KHz** regardless of the total transmission bandwidth.
- Within the LTE OFDM signal each subcarrier is modulated using one of the following formats:
  - QPSK (2 bits per symbol)
  - 16QAM (4 bits per symbol)
  - 64QAM (6 bits per symbol)



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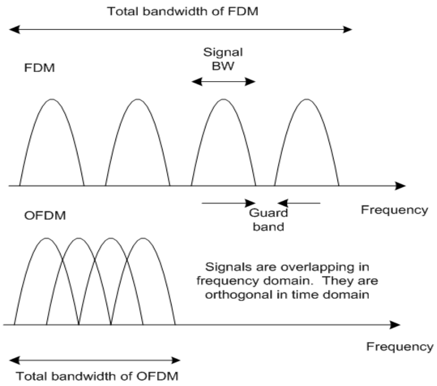
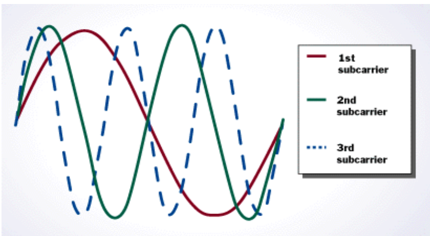
FDM versus OFDM

- OFDM minimizes separation between carriers
- In the **frequency domain**, orthogonality means that the carrier spacing is **Δf=1/T**, where T is the symbol duration.
- In the **time domain**, orthogonal means that the symbol interval is an integer number of full cycles for all carriers.
- In the LTE standard, carrier spacing is **15KHz** and the symbol duration is **66.67µs**.

Note: it is the orthogonality between carriers in time domain that allows optimum spacing in frequency domain.



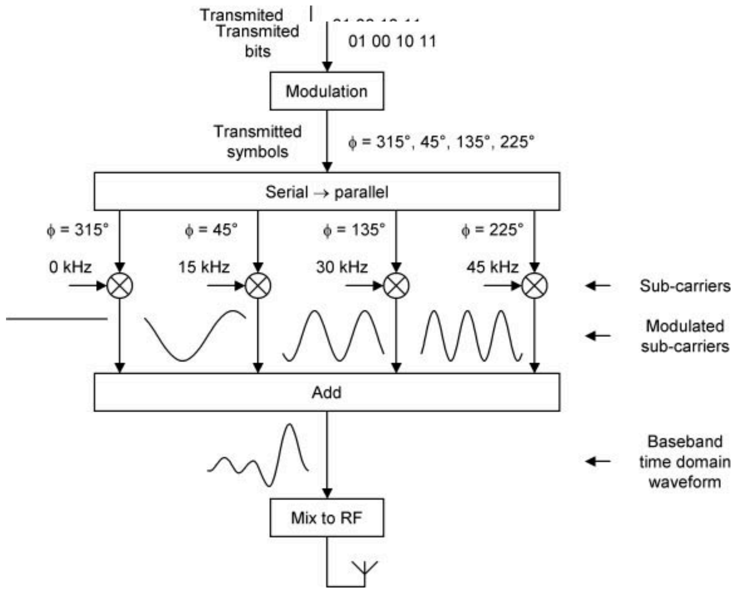


Self assessment question 6.3 :

Which one of the following signals is orthogonal to a subcarrier of frequency 15KHz?

a)	20KHz
b)	200KHz
c)	300KHz
d)	100KHz

Conceptual OFDM transmitter (4 subcarriers)



Source : *Christopher Cox "An introduction to LTE", John Wiley & Sons Ltd, 2012*

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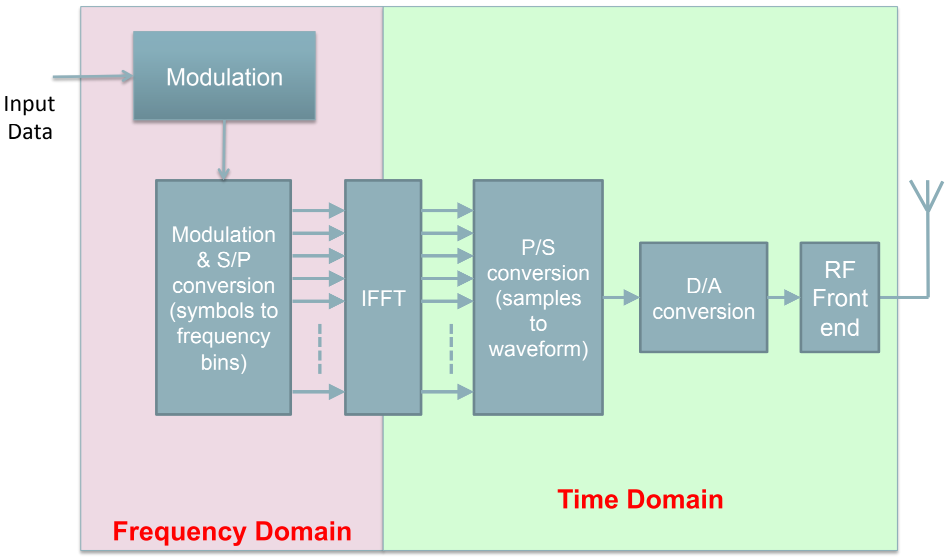
Practical OFDM Transmitter



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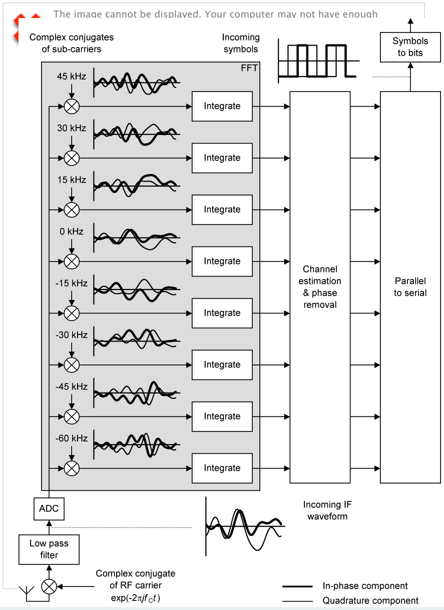
Conceptual OFDM Receiver



Source : *Christopher Cox "An introduction to LTE", John Wiley & Sons Ltd, 2012*

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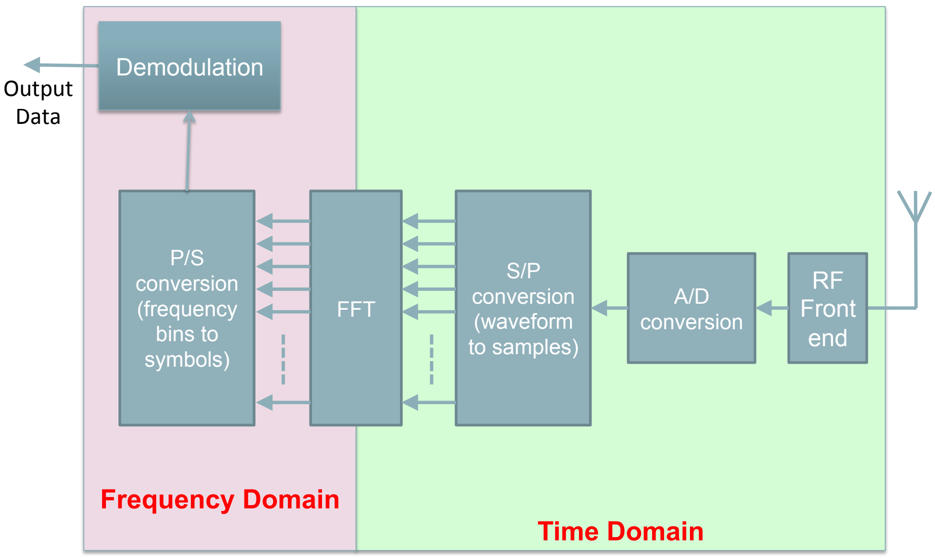
Practical OFDM Receiver



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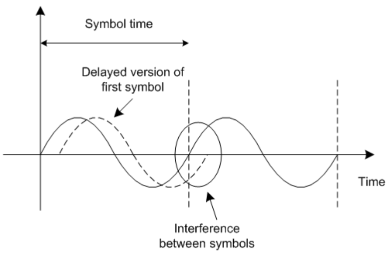
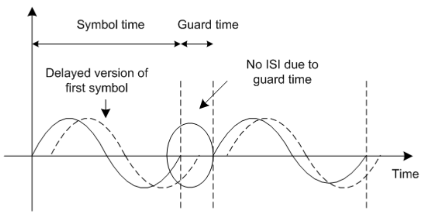
Guard interval

- The duration of the OFDM symbol is chosen to be much longer than the multi-path delay spread (typically 4 to 7μs in urban areas).
- Long symbols imply low rate on individual OFDM carriers.
- In a multipath environment long symbol minimizes the effect of channel delay spread.
- To make sure that there is no Inter Symbol Interference (ISI) between OFDM symbols a **guard interval** is inserted.



OFDM symbols without guard time



OFDM symbols with guard time

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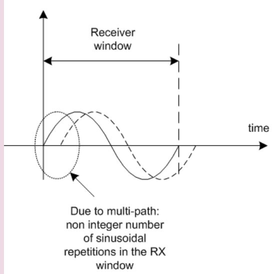
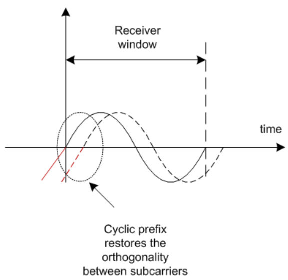
Cyclic prefix

- Inserting a guard time reduces ISI between OFDM symbols.
- Multipath propagation conditions degrade orthogonality between carriers within an OFDMS symbol.
- To regain the orthogonality between subcarriers a **cyclic prefix** (CP) is used. The duration of the cyclic prefix should be greater than the duration of the multipath delay spread.
- The cyclic prefix fills in the guard time between the OFDM symbols and is generated by copying the beginning part of the main body of the OFDMA symbol and inserting it back at the and of the symbol.
- Inserting the cyclic prefix, rather than just leaving an "empty" guard band, creates a smooth transition between the guard band and the following symbol.

There are two choices of Cyclic prefix:

1. The standard ('short") cyclic prefix is 4.69μs. This enables the system to accommodate path variations of up to 1.4 km. This is used in urban environments.
2. A long cyclic prefix of 16.67μs is available. This enables the system to accommodate path variations of up to 5 km. This is used in rural environments.





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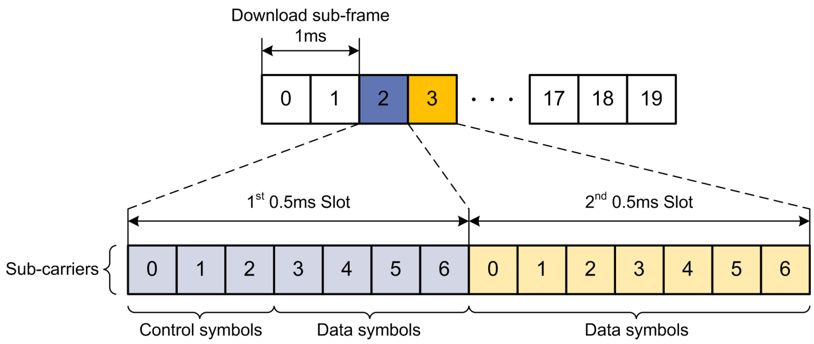
LTE Downlink

- The duration of the LTE system frame is **10 ms,** consisting of ten 1ms sub-frames with two slots each.
- Within one slot, six or seven OFDM symbols are transmitted, depending on the cyclic prefix used (to be explained).



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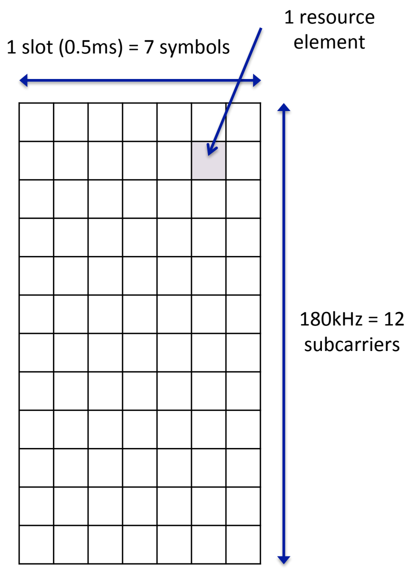
LTE Resource block

- Under LTE, information is organised in terms of both time and frequency, using a two dimensional **resource grid**.
- A **resource bloc** is shown here. The resource block is built from of a number of **resource elements**.
- Each resource element spans one symbol in time by one subcarrier in frequency.
- In the frequency domain one resource block occupies 12 sub carriers, i.e. 12 * 15khz = 180 Khz.
- In the time domain, the same resource block occupies one slot which is half of a subframe (0.5ms).
- For the normal cyclic prefix (shown here) there are 7 symbols per timeslot. If the extended cyclic prefix is used there are 6 symbols per timeslot.
- The allocation of LTE physical resource blocks (PRBs) is handled by a scheduling function at the 3GPP base station (eNodeB).



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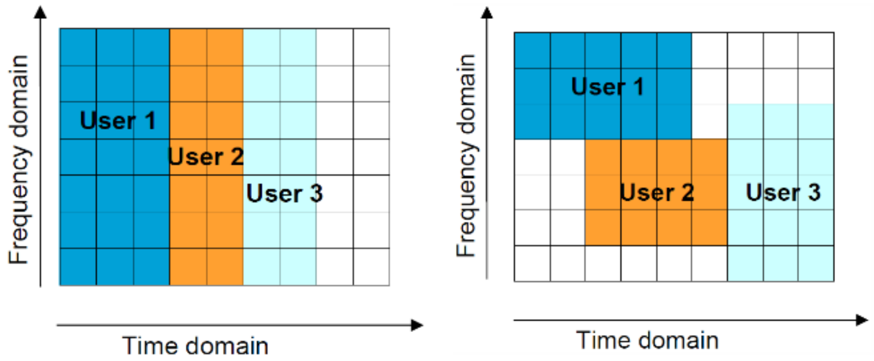
OFDM vs OFDMA

- Under classical **OFDM**, each user is able to use the full frequency range for a predetermined time.
- Under **OFDMA**, the subcarriers are dynamically allocated to multiple users at any given time.

- OFDM allocates users in time domain only
- OFDMA allocates users in time and frequency domain



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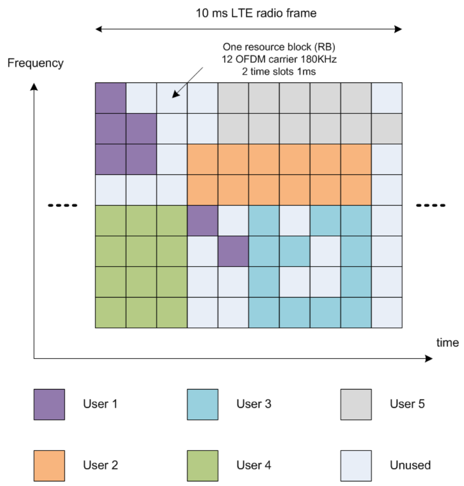
OFDMA time-frequency scheduling

- The minimum allocateable resource in LTE is **Resource Block (RB) pair**
- A resource block pair is 12 carriers wide in frequency domain and lasts for two time slots (1ms)
- Depending on the length of cyclic prefix RB pair may contain 14 or 12 OFDM symbols.
- Physical channels (PHY) consist of certain number of allocated RB pairs.
- Overhead channels typically occupy a predetermined location in time frequency domain.
- Within a RB different AMC scheme may be used.
- Allocation of the radio block is carried out by scheduler at eNode B.



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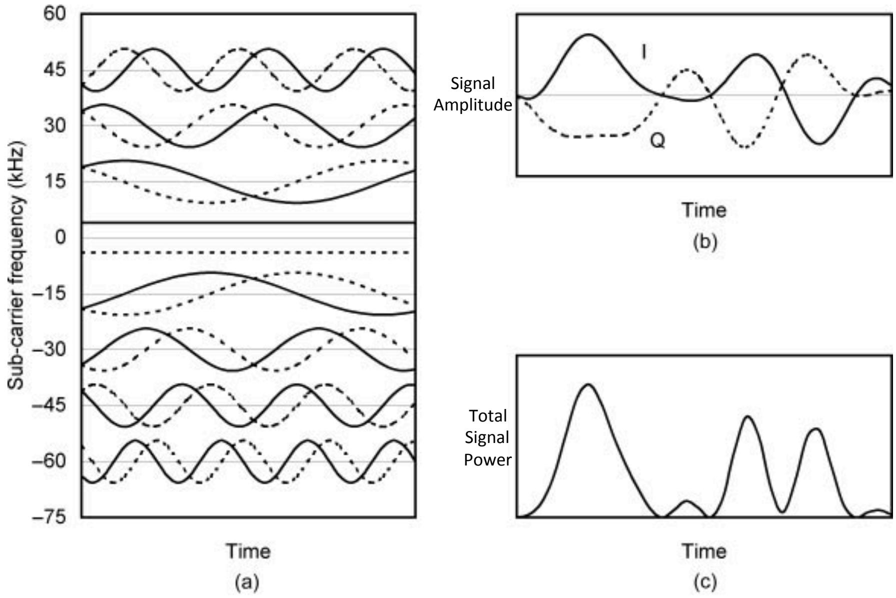
Power variations with OFDM/OFDMA



Source : *Christopher Cox, "An introduction to LTE", John Wiley & Sons Ltd, 2012*

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LTE Uplink

- The uplink also uses a variant of OFDMA known as Single Carrier Frequency Division Multiple Access (SC-FDMA).
- The mobile station (MS) faces different challenges from the fixed infrastructure, most notably in terms of the limited power resource available from the battery. Hence, power efficiency of radio blocks is of far greater significance at the MS.
- The OFDM signal is characterized by a high value of **peak power to average power ratio (PAPR)**, which implies the need for a high degree of linearity in the power amplifier and a decrease in the average power of emitted signal as compared to signals for which the PAPR is insignificant.
- SC-FDMA overcomes this by "spreading" each data symbol over multiple subcarriers, SC-FDMA offers **spreading gain** or **frequency diversity gain** in a frequency selective channel. Thus, SC-FDMA can be viewed as frequency-spread OFDM or DFT-spread OFDM.

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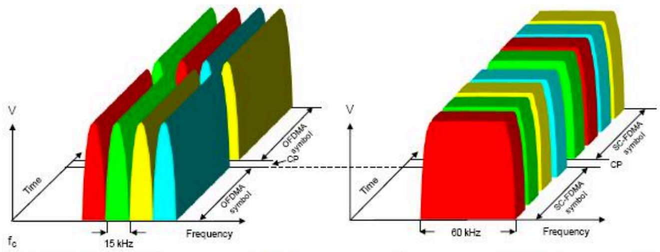
LTE Uplink (SC-FDMA)

- Single Carrier FDMA (SC-FDMA) is a variation of OFDMA which facilitates reduced PAPR on the LTE uplink.
- Whereas OFDMA transmits, for example, four QPSK data symbols in parallel, one per each subcarrier, SC-FDMA transmits the four QPSK data symbols in series at four times the symbol rate, with each data symbol occupying the full N x 15 kHz bandwidth.
- Visually, the OFDMA signal is clearly multi-carrier and the SC-FDMA signal looks more like single-carrier, which explains the “SC” in its name.



Transmission scheme	OFDMA		SC-FDMA	
Analysis bandwidth	15 kHz	Signal BW (M x 15 kHz)	15 kHz	Signal BW (M x 15 kHz)
Peak to average power ratio (PAR)	Same as data symbol	High PAR (Gaussian)	< data symbol (not meaningful)	Same as data symbol
Observable IQ constellation	Same as data symbol at 66.7 µs rate	Not meaningful (Gaussian)	< data symbol (not meaningful)	. Same as data symbol at M X 66.7 µs rate

The reason for using SC-FDMA rather than OFDM in the uplink is low to **Peak to Average Power Ratio** (PAPR). This leads to Improved battery life and less stringent requirements in the transceiver circuitry.

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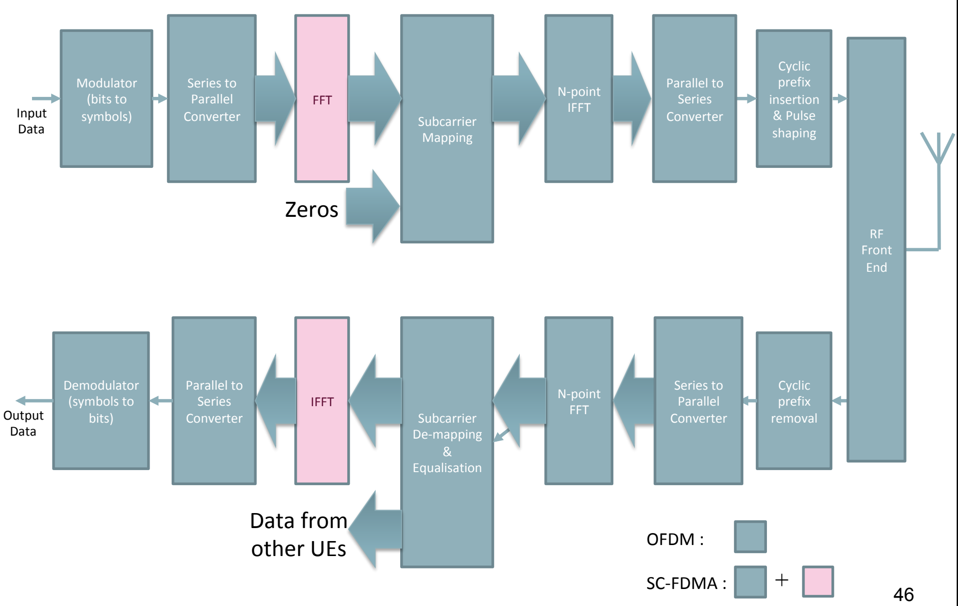
LTE Uplink transceiver implementation



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Self assessment question 6.5:

The uplink in LTE uses a modified version of OFDM, called SC-FDMA, for the following reason:

a)	To conserve battery power
b)	To reduce the PAPR thereby simplifying the design of the transmitter power amplifier.
c)	To conserve bandwidth
d)	To reduce inter-symbol interference

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Hierarchical Channel Structure in LTE

- In order to efficiently support various QoS classes of service, LTE adopts a hierarchical channel structure. There are three different channel types, as follows:
  1. logical channels
  2. transport channels
  3. physical channels
- Each channel type is associated with a **Service Access Point (SAP)** between different layers. These channels are used by the lower layers of the protocol stack to provide services to the higher layers.
- The radio interface protocol architecture and the SAPs between different layers are shown in Figure below.
- Physical channels are the actual implementation of transport channels over the radio interface.
- Logical channels provide services at the SAP between MAC and RLC layers, while transport channels provide services at the SAP between MAC and PHY layers.

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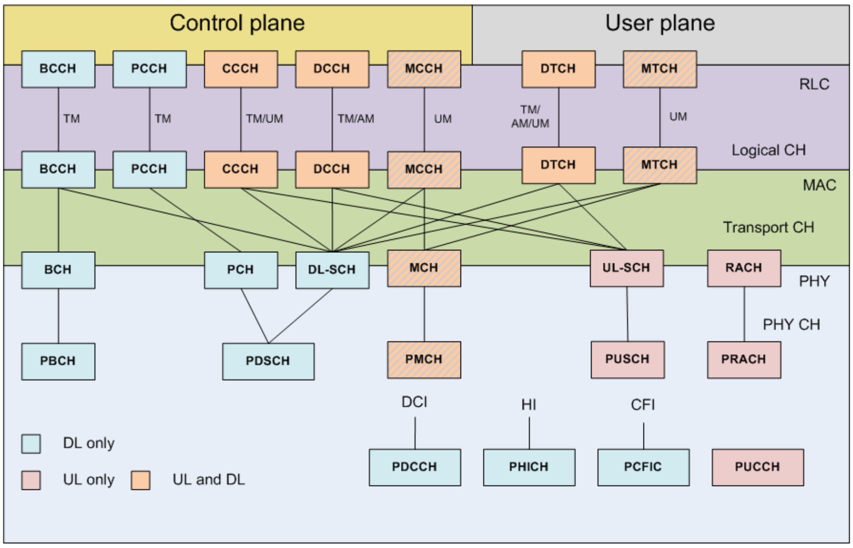
LTE Channel Architecture



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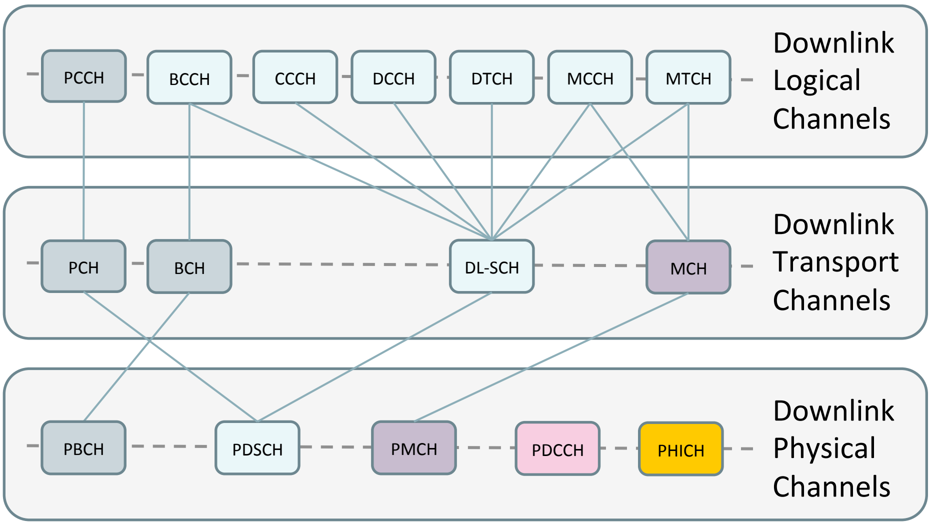
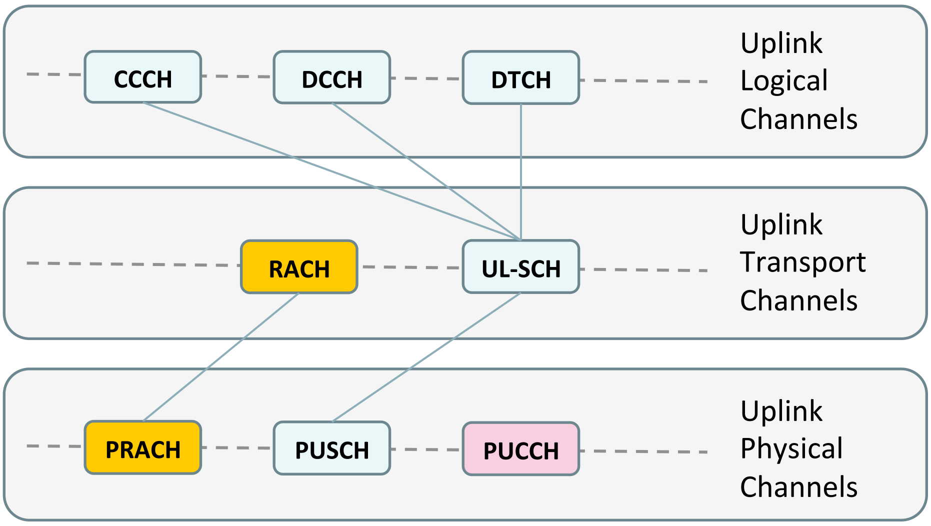
LTE Downlink channels



50

LTE Uplink and bi-directional channels



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LTE Downlink Logical Channels

Paging Control Channel (PCCH)

- A downlink channel that transfers paging information and system information change notifications.
- This channel is used for paging when the network does not know the location cell of the UE.

Broadcast Control Channel (BCCH)

- A downlink channel for broadcasting system control information.

Common Control Channel (CCCH)

- Channel for transmitting control information between UEs and network.
- This channel is used for UEs having no RRC connection with the network.

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LTE Downlink Logical Channels

Dedicated Control Channel (DCCH)
- A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network.
- Used by UEs having an RRC connection.

Dedicated Traffic Channel (DTCH)
- A point-to-point channel, dedicated to one UE, for the transfer of user information.
- A DTCH can exist in both uplink and downlink.

Multicast Control Channel (MCCH)
- A point-to-multipoint downlink channel used for transmitting MBMS control information from the network to the UE, for one or several MTCHs.
- This channel is only used by UEs that receive MBMS.

Multicast Traffic Channel (MTCH)
- A point-to-multipoint downlink channel for transmitting traffic data from the network to the UE.
- This channel is only used by UEs that receive MBMS.

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LTE Downlink Transport Channel

Paging Channel (PCH)
- Supports UE discontinuous reception (DRX) to enable UE power saving
- Broadcasts in the entire coverage area of the cell;
- Mapped to physical resources which can be used dynamically also for traffic/other control channels.

Broadcast Channel (BCH)
- Fixed, pre-defined transport format
- Broadcast in the entire coverage area of the cell

Multicast Channel (MCH)
- Broadcasts in the entire coverage area of the cell;
- Supports MBSFN combining of MBMS transmission on multiple cells;
- Supports semi-static resource allocation e.g. with a time frame of a long cyclic prefix.

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LTE Downlink Transport Channel

Downlink Shared Channel (DL-SCH)

- Supports Hybrid ARQ
- Supports dynamic link adaptation by varying the modulation, coding and transmit power
- Optionally supports broadcast in the entire cell;
- Optionally supports beam forming
- Supports both dynamic and semi-static resource allocation
- Supports UE discontinuous reception (DRX) to enable UE power saving
- Supports MBMS transmission

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LTE Downlink Physical Channels

Physical Downlink Shared Channel (PDSCH)

- Carries the DL-SCH and PCH
- QPSK, 16-QAM, and 64-QAM Modulation

Physical Downlink Control Channel (PDCCH)

- Informs the UE about the resource allocation of PCH and DL-SCH, and Hybrid ARQ information related to DL-SCH
- Carries the uplink scheduling grant
- QPSK Modulation

Physical Hybrid ARQ Indicator Channel (PHICH)

- Carries Hybrid ARQ ACK/NAKs in response to uplink transmissions.
- QPSK Modulation

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Part 3 : Beyond LTE

Voice over LTE

LTE has been conceived as an IP only network. How best to transport voice traffic over such a network ?

- **Voice over LTE (VoLTE)**
  - IP multimedia subsystem (IMS) with voice calls carried over packet
- **Circuit Switched Fall Back (CSFB)**
  - Calls are passed to existing MSC and carried over legacy circuits.
- **Simultaneous Voice and LTE (SVLTE)**
  - Handset works simultaneously in LTE and CS modes for data and voice respectively.
  - Relies on special handsets – power hungry.
- **Over the Top (OTT) services**
  - Skype, Vonage, etc
  - No Quality of Service, inefficient codecs

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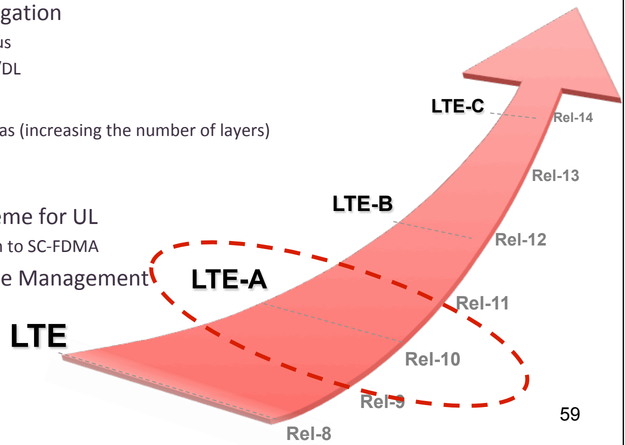
LTE Evolution – "LTE-Advanced"

Emerging technologies for LTE-Advanced

- Multi-hop transmission (Relay)
- Multi-cell cooperation (CoMP: Cooperative Multipoint Tx/Rx)
- Interference management in heterogeneous cell overlay

Enhancements from LTE Rel-8/9

- Bandwidth/spectrum aggregation
  - Contiguous and non-contiguous
  - Control channel design for UL/DL
- MIMO enhancement
  - Extended utilization of antennas (increasing the number of layers)
  - UL SU-MIMO
  - Enhanced UL/DL MU-MIMO
- Hybrid multiple access scheme for UL
  - Clustered SC-FDMA in addition to SC-FDMA
- DL/UL Inter-cell Interference Management



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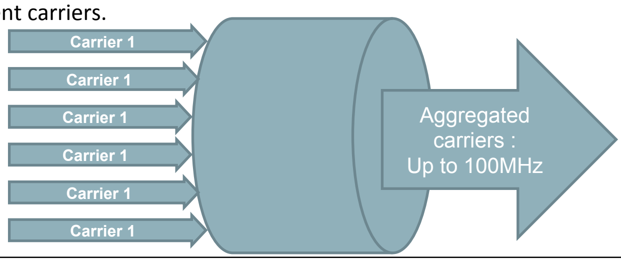
LTE Evolution – Carrier aggregation

- The obvious way to increase capacity in the LTE air interface is to add more bandwidth. Since it is important to keep backward compatibility with LTE R8 and R9 (i.e. non-LTE Advanced) mobiles, it was decided to provision the increase in bandwidth in LTE-Advanced by combining legacy R8/R9 carriers.
- The maximum bandwidth allocated for an LTE R8/R9 carrier is 20 MHz. **Carrier Aggregation (CA)** is allowed under LTE Advanced to increase the available bandwidth by combining carriers together.
- Each aggregated carrier is referred to as a component carrier. The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five component carriers can be aggregated. The maximum bandwidth available under CA is therefore100 MHz.
- The number of aggregated carriers can be different in the uplink and downlink, provided that the number of uplink component carriers is never larger than the number of downlink component carriers.



LTE Evolution – Carrier aggregation

- The easiest way to arrange carrier aggregation is to use contiguous component carriers within the same operating frequency band (as defined for LTE). This is called **Intra-Band Contiguous CA**.
- This might not always be possible depending on frequency allocation.
- For non-contiguous CA there are two categories :
- **Intra-band non-contiguous CA** : the component carriers belong to the same operating frequency band, but are separated by a frequency gap.
- **Inter-band non-contiguous CA** : the component carriers belong to different operating frequency bands.

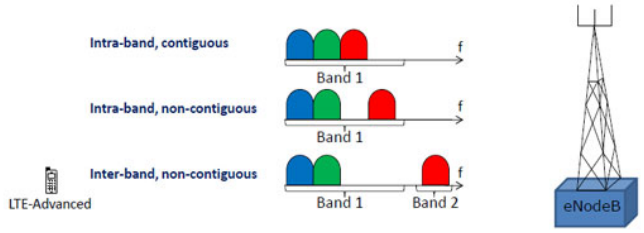
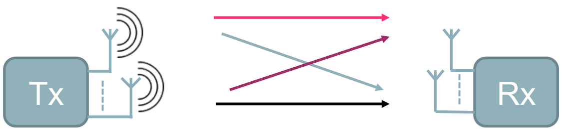
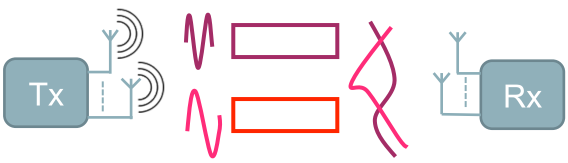


Image source : http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced

LTE Evolution – MIMO support



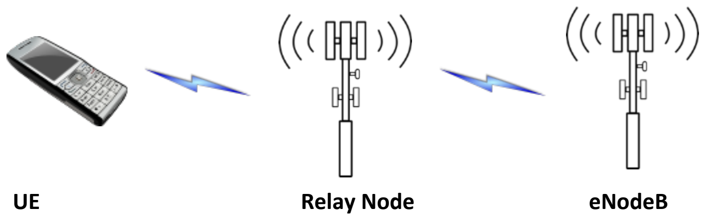
Spatial Diversity ➡ Resistance to interference



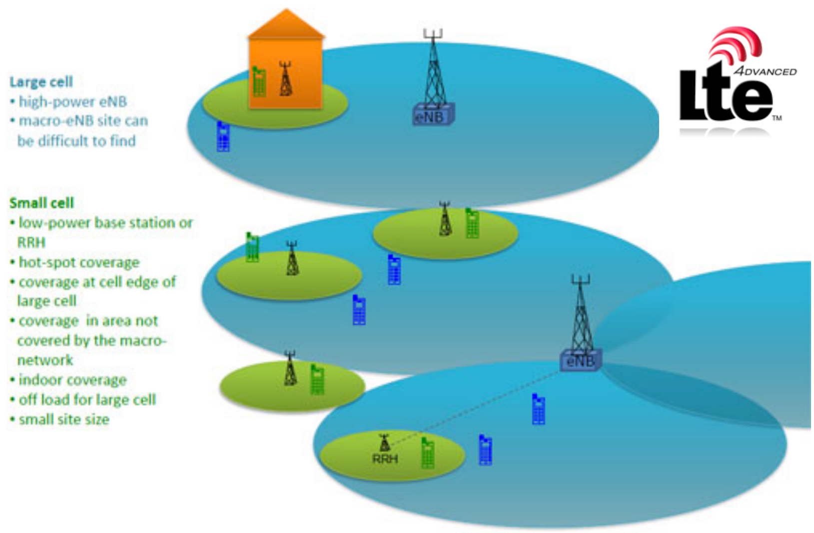
Spatial Multiplexing ➡ Increased data rate

LTE Evolution – Relaying

- LTE-Advanced introduces the concept of **Relay Nodes (RNs)** to extend network coverage and density.
- An LTE Relay Node is a piece of fixed infrastructure that is resembles a low power base station, but without the backhaul connection. The purpose of the relays is to pick up communications between a User Equipment (UE) and the base station, thereby allowing multihop communication.
- The Relay Node is connected to the **Donor eNodeB** (DeNB) via a radio interface, Un, which is a modification of the E-UTRAN air interface Uu. Hence in the Donor cell the radio resources are shared between UEs served directly by the DeNB and the Relay Nodes.



LTE Evolution–Heterogeneous network support



Source : http://www.3gpp.org/hetnet

Summary - LTE vs. LTE-Advanced

Technology	LTE	LTE--A
Peak data rate Down Link (DL)	150 Mbps	1 Gbps
Peak data rate Up Link (UL)	75 Mbps	500 Mbps
Transmission bandwidth DL	20MHz	100 MHz
Transmission bandwidth UL	20MHz	40 MHz (requirements as defined by ITU)
Mobility	Optimized for low speeds(<15 km/hr) High Performance At speeds up to 120 km/hr Maintain Links at speeds up to 350 km/hr	Same as that in LTE
Coverage	Full performance up to 5 km	a) Same as LTE requirement b) Should be optimized or deployment in local areas/micro cell environments.
Scalable Band Widths	1.3,3, 5, 10, and 20 MHz	Up to 20–100 MHz
Capacity	200 active users per cell in 5 MHz.	3 times higher than that in LTE

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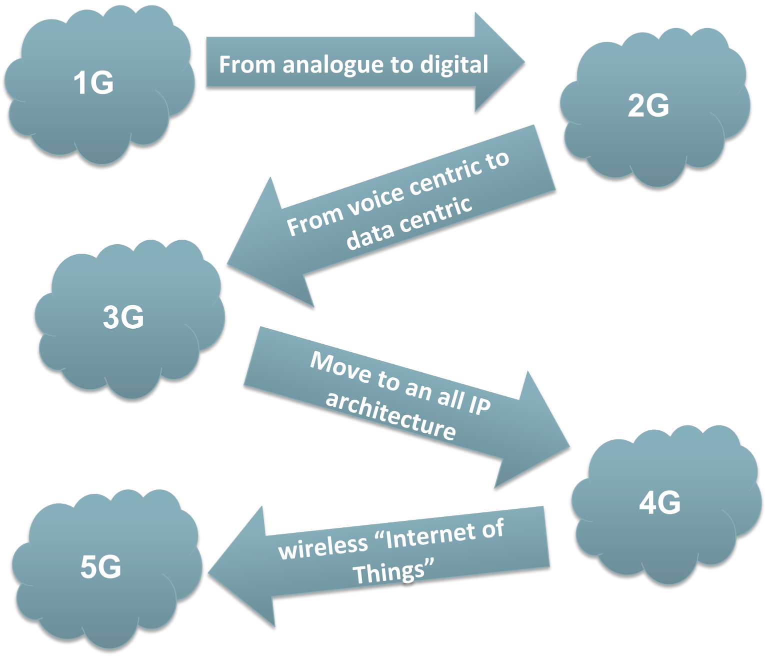
Paradigm shifts in mobile technology



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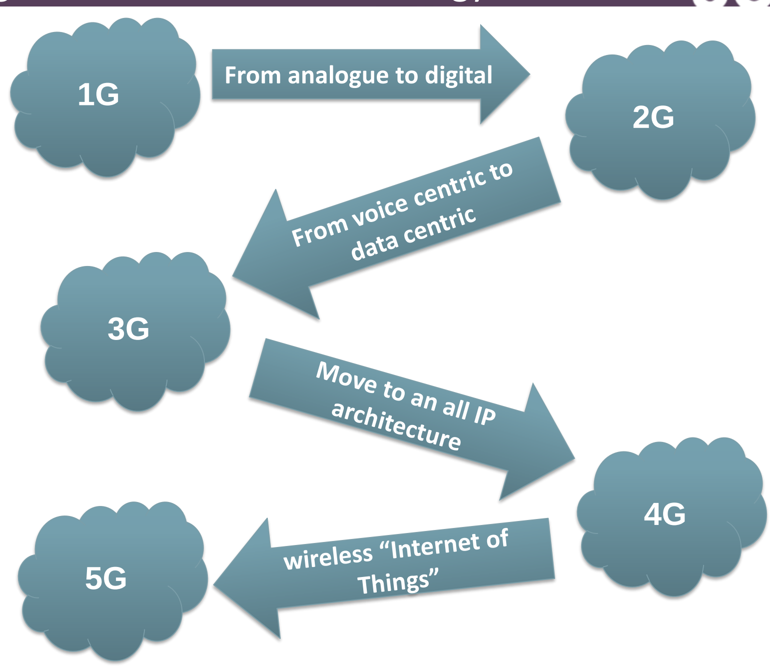
Mobile Communications Systems (MCS)

5G Concepts and New Technologies

Professor Izzat Darwazeh

November 2018

Paradigm shifts in mobile technology



2

Requirements for 5G

Higher capacity

- Larger volumes of data per user, larger number of users/devices
- multi-Gbps mobile access, >10 Gbps backhaul,
- MIMO and smart antennas
- more spectrum, dense access points distribution (small cells).

Higher flexibility

- easy deployment of capacity where/when it is needed.
- Wireless backhaul, self-organizing network.

Green radios

- Low power consumption per bit transmitted
- mmW radios, directive antennas, short distance links

Low EM exposure

- lower EM field density (lower Tx power), focused radiation

3

The "big three" 5G technologies:

1. **Extreme densification** and offloading to improve the area spectral efficiency. Put differently, more active nodes per unit area and per Hz.
2. **Increased bandwidth** primarily by moving toward and into mmWave spectrum but also by making better use of WiFi's unlicensed spectrum in the 5-GHz band.
3. **Increased spectrum efficiency** primarily through advances in MIMO, to support more bits/s/Hz per node.
4. **Increased spectrum efficiency** New signal formats (non-orthogonal and/or filtered) with higher bit/s/Hz

Source : Andrews, J. G. "What will 5G be?" IEEE Journal on selected areas in Communication, VOL. 32, NO. 6, June 2014

4

5GPP Standardisation Initiatives

5G standardization or definition effort has been started by various different organizations:

1. ITU
2. 5G-PPP - European ICT industry and the European Commission
3. METIS - European Commission initiative
4. Advanced Wireless Research Initiative (AWRI) - US National Science Foundation (NSF)
5. IMT2020 – Chinese Government initiative.
6. UK Ofcom regulator
7. Association of Radio Industries and Businesses (ARIB) - Japan

5

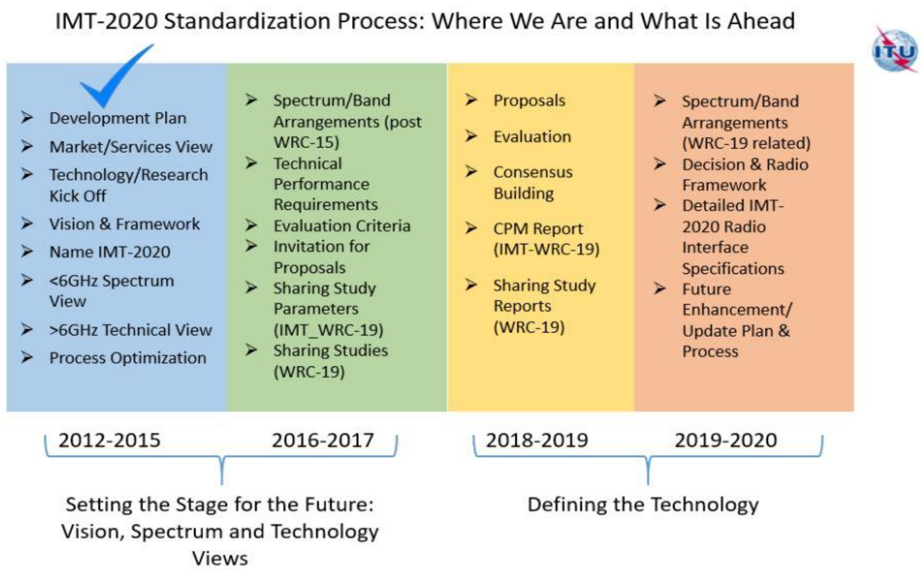
Possible 5G features :

Even though 5G is not yet even defined, we can speculate about some possible features of a 5G-based telecommunications network :

1. Much higher peak download and upload speeds : between 1 and 10Gbps
2. Much greater number of connected devices : 10 times to 100 times current networks
3. Pervasive networks : The user can simultaneously be connected to several wireless access technologies and seamlessly move between them
4. User centric network concept instead of operator-centric (as in 3G) or service-centric (as in 4G)
5. Low latency: (5 to 8ms), even 1ms?
6. High reliability : 99.999%
7. Use of internet protocol version 6 (IPv6) throughout.
8. “Internet of Things” and wearable devices.

6

ITU 5G Initiatives



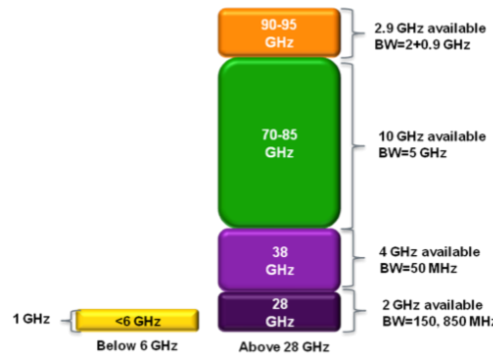
http://www.rcrwireless.com/20160719/internet-of-things/5g-standards-process-tag31-tag99

Spectrum Utilisation

- For 5G the focus is on improving **spectrum utilisation,** which is defined as bits per second per Hertz per unit area, rather than spectrum efficiency (defined as bits second per Hertz).
- Improvements in spectral efficiency are constrained by background noise, meaning that improvements through coding and modulation design become more difficult and less effective (the 'Shannon Limit').
- On the other hand, new technological approaches, such as massive MIMO, super-dense meshed cells and 'phantom cells' can substantially improve spectrum utilisation.

5G Spectrum options

- A large amount of additional spectrum, both below and above 6 GHz, will be needed to meet the capacity targets for 5G beyond 2020.
- Available spectrum below 6 GHz is limited and there are practical limits to how much small cells can shrink to efficiently use the limited spectrum.
- 56-62, 71-76 GHz and 81-86 GHz are good candidate bands for deploying 5G local area networks because of the availability of over 10 GHz of bandwidth.



Source : http://networks.nokia.com/zh/news-events/insight-newsletter/articles/5g-ultra-wideband-enhanced-local-area-systems-at-millimeter-wave#sthash.MJhdOrRt.dpuf

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Moving to mmWave spectrum

Why ?

- Current usable spectrum is already full. The milimetre wave (above 30GHz) and even the Terahertz region (above 300GHz) is essentially unpopulated territory.
- Greater bandwidths available at higher frequencies : in the THz region there is **30 times greater** bandwidth available than the *entire* radio spectrum currently allocated.
- New services can be launched quickly without disrupting existing allocated services.

Challenges :

- Expensive transmitters and receivers (but costs are falling due to higher integration).
- "line of sight" propagation characteristics : coverage challenges.
- Reduced penetrating power : absorption by buildings, human bodies etc.
- Atmospheric absorption peaks : H_2O around 27GHz and 180GHz, O_2 around 60GHz etc.

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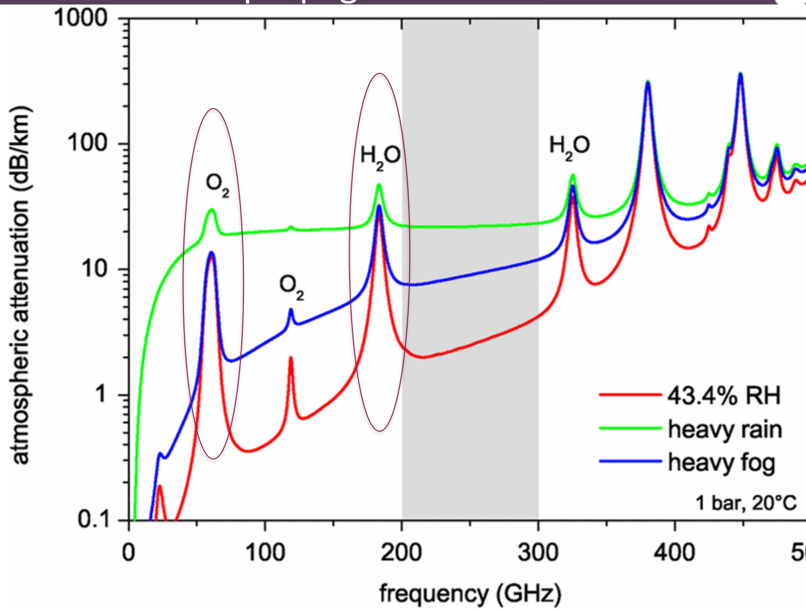
Millimeter wave propagation issues



Note O_2 and H_2O absorption peaks at 60GHz and 120GHz

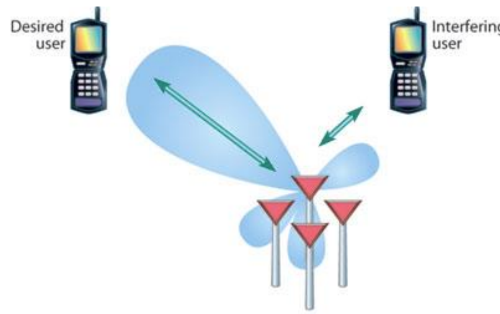
Millimeter wave properties

- Millimeter waves exhibit "line-of-sight" properties, i.e. they can be blocked by solid objects such as buildings.
- Free space loss and atmospheric absorption are higher for millimeter waves, limiting propagation to a few kilometers. This can be an advantage, however, in densely packed cellular communications networks as it aids frequency reuse.
- Other ”quasi-optical" propagation characteristics of millimeter wave are :
  - They can be reflected and focused by small metal surfaces such as cars, and diffracted by building edges.
  - Surfaces appear "rougher" at shorter wavelengths so there is increased reflection and scattering.
  - Doppler shift is more be significant, even at pedestrian speeds.
  - Increased absorption by the human body.

Source : Prof. Theodore S.Rappaport, NYU Wireless, Polytechnic Institute of New York University (NYU-Poly)

Steerable antennas and Beamforming

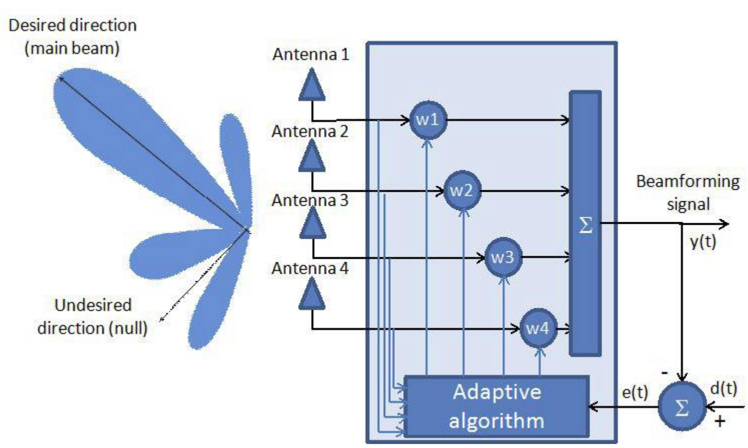
- Beamforming or **spatial filtering**, is achieved by combining elements in a **phased array** in such a way that signals at particular angles experience constructive interference while others experience destructive interference. This enables the RF power to be focussed into a narrow beam.



- 5G can exploit smart antenna systems, with more focus being placed on pointing in the direction of maximum signal levels using multiple beams (for simplicity, first ignore interference).

Source : Prof. Theodore S.Rappaport, NYU Wireless, Polytechnic Institute of New York University (NYU-Poly) 13

Beamforming architecture

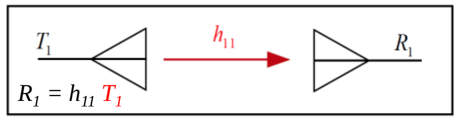


Beamforming is computationally intensive and is only now becoming economically viable in consumer applications because of very high levels of integration of RF front-end circuitry.

Source : Prof. Theodore S.Rappaport, NYU Wireless, Polytechnic Institute of New York University (NYU-Poly) 14

Multiple In Multiple Out (MIMO)

- Parallel communications; more than one transmit antenna and more than one receive antenna
- Can transmit at the same frequency
- Signals will be reflected and delayed due to multipath
- Several paths exist between each tx antenna and each receive antenna
- Multipath is exploited in MIMO
- Spatial diversity
- Space Time Coding (Alamouti)

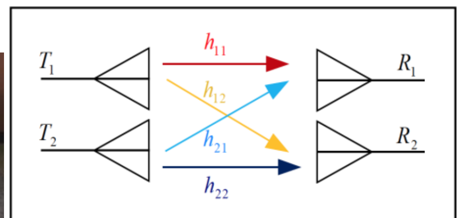


SISO Channel

$R_1 = h_{11}\ T_1 + h_{21}\ T_2$

$R_2 = h_{12}\ T_1 + h_{22}\ T_2$

Massive MIMO



MIMO Channel

http://complextoreal.com/wp-content/uploads/2013/01/mimo.pdf

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Prototype 5G handset

- Samsung's 5G wireless prototype contains a beamforming antenna consisting of an adaptive array of 16 antennas arranged around the outside of the handset case.
- Each antenna has it's own millimeter-wave radio transceiver.
- Individual antenna outputs are driven by phase shifters to create a focused beam.

http://spectrum.ieee.org/telecom/wireless/smart-antennas-could-open-up-new-spectrum-for-5g

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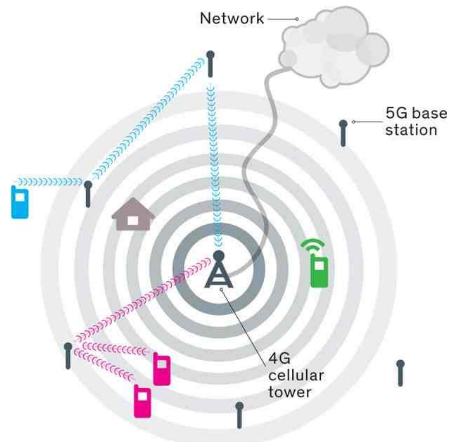
5G mobile radio schemes

- Each handset is equipped with a steerable mm-wave antenna.
- Phones at the edge of a 5G cell [blue] use steerable mm-wave beams to route signals around obstacles.
- Because the beams don't interfere, few phones could use the same frequencies [pink] without interference.
- Phones near the 5G tower could connect directly to it [green].



http://spectrum.ieee.org/telecom/wireless/millimeter-waves-may-be-the-future-of-5g-phones/?

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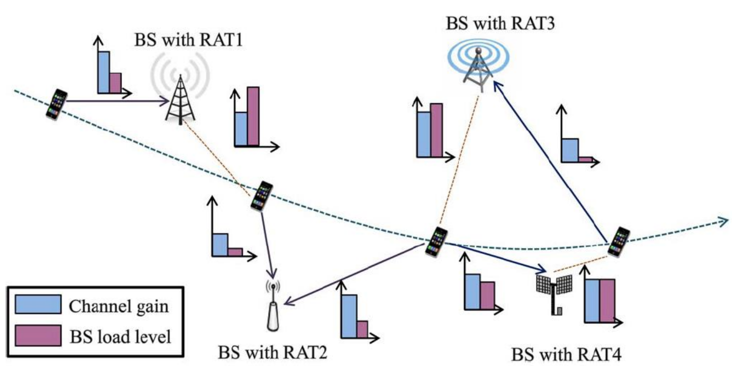
5G RAN - Heterogeneous networks

A key feature of 5G will be the use of "**heterogeneous networks**" involving increased integration between different RATs, with a typical 5G-enabled device having radios capable of supporting not only a potentially new 5G standard (e.g., at mmWave frequencies), but also 3G, numerous releases of 4G LTE including possibly LTE-Unlicensed and several types of WiFi.



Source : Andrews, J. G. "What will 5G be?" IEEE Journal on selected areas in Communication, VOL. 32, NO. 6, June 2014

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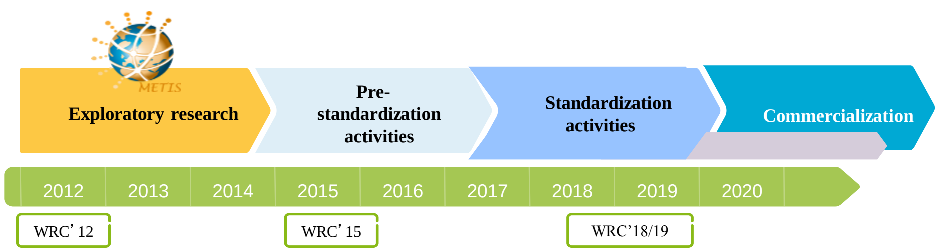
METIS

- METIS is an Integrated Project set up by the European Commission.
- METIS stands for for "Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society."
- The European Commission has committed €50 million ($69 million) in research grants to develop 5G technology by 2020. Nearly one-third of that total has gone to the METIS.



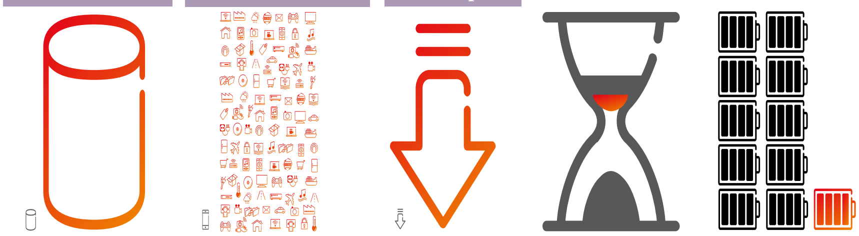
Source : METIS 19

METIS members

Source : METIS 20

METIS Technical Objectives

1000x data volume	50/500 B devices	Up to 10Gbps	Few ms E2E	10 years



1000x	10-100x	10-100x	5x	10x
higher mobile data volumes	higher number of connected devices	typical end-user data rates	lower latency	longer battery life for low-power devices

Source : METIS

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METIS 5G Requirements

Requirement	Target
Data rates	1-10Gbps (resp.100s of Mbps)
Capacity	36TB/month/user (resp. 500 GB)
Spectrum	Higher frequencies & flexibility
Energy	~10% of today's consumption
Latency reduction	~ 1ms (e.g. tactile internet)
D2D capabilities	NSPS, ITS, resilience, …
Reliability	99.999% within time budget
Coverage	>20 dB of LTE (e.g. sensors)
Battery	~10 years
Devices per area	300.000 per access node

Ultra-dense networks

Ultra Reliable Comm.

Massive Machines

Source : METIS

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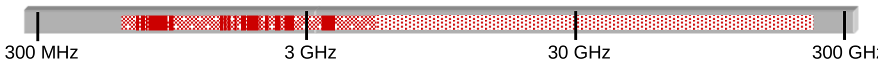
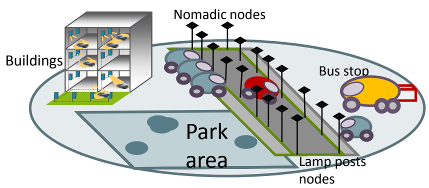
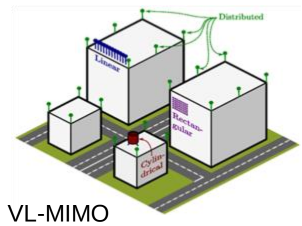
Key 5G Technology Components



New spectrum bands and access methods

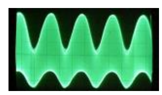


Dense and moving networks
Multi-hop wireless backhaul

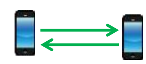


VL-MIMO
Massive multi-antenna systems

Context-aware interference and mobility management



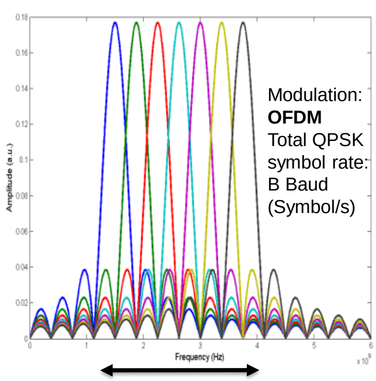
Air interfaces for new applications and reduced signaling



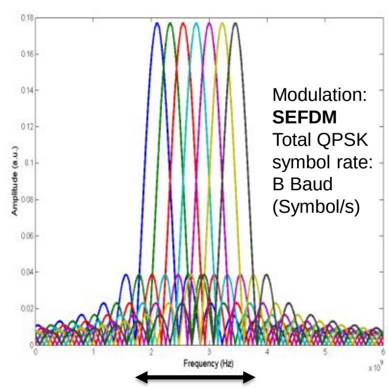
Mobile
Device-to-device

Source : METIS

Spectrally Efficient FDM: Bandwidth Saving vs. ICI



Bandwidth ≈ B Hz
No ICI



Bandwidth ≈ α·B Hz, 0<α<1
With ICI

- Multiple subcarrier modulation format
- Enables tunable bandwidth "compression"
- Think of OFDM but with less than orthogonal subcarrier spacing

UCL

SEFDM based radio

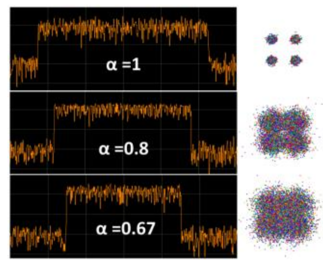
✓OFDM modulation (like MB-OFDM or OFDM) is an excellent candidate for radio over fiber comms due to its immunity to the dispersive optical/wireless channels, its high spectral efficiency, and its compatibility with already developed pre-standards.

✓**What about further reducing sub-carrier spacing i.e. increasing spectral efficiency?**

☺Spectral efficiency equals 2/α

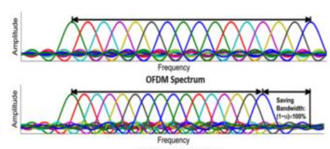
☹Non-orthogonally spaced sub-carriers induce ICI

☹When a standard detector is used the signal cannot be recovered

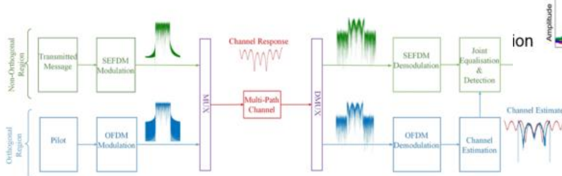


UCL

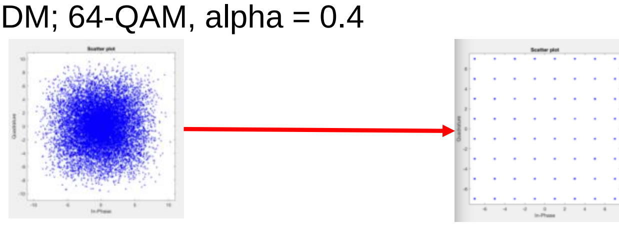
Recovery of information from of severely distorted signals



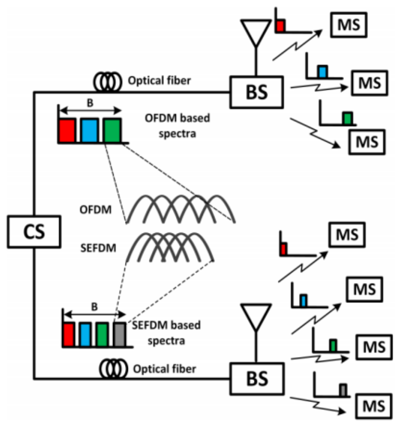
ion



- SEFDM; 64-QAM, alpha = 0.4

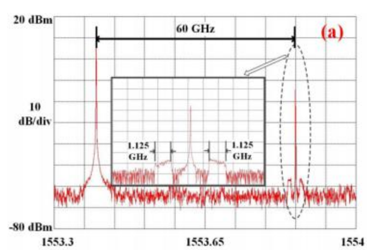


UCL scenario of the mm-wave SEFDM

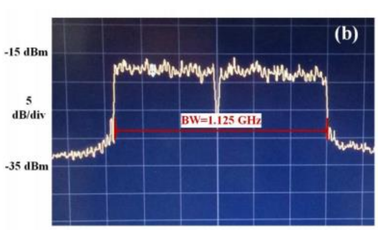


- CS indicates central station
- BS indicates base station
- MS indicates mobile station.

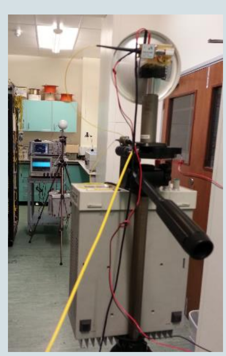
Indoor 60 GHz millimeter-wave signal transmission



Spec-A

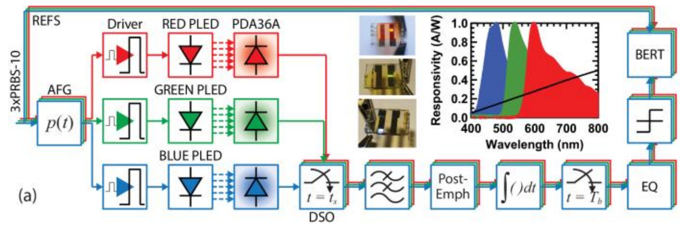


Spec-B

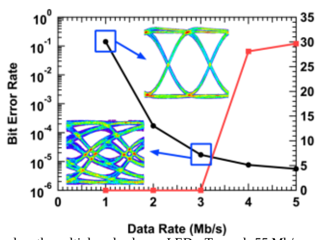


- 60 GHz parabolic antennas have 30 dBi gain; and 3 dB beamwidth of 3.1◦are employed.
- A 30 dB gain high power amplifier (HPA) at the transmitter and a 30 dB gain low noise amplifier (LNA) at the receiver.
- Transmission distances from few cm to 3 metres.

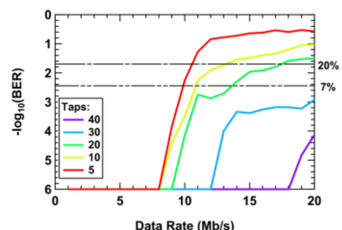
Use of Visible Light Communications (VLC)



Performance **without** ML:

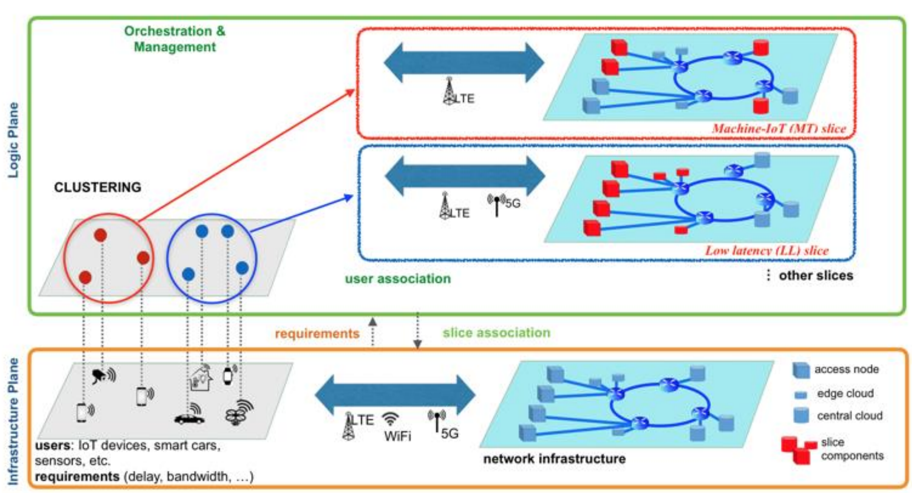


Performance **with** ML:



Haigh, P. A. et al., Wavelength-multiplexed polymer LEDs: Towards 55 Mb/s organic visible light communications, *IEEE Journal on Selected Areas in Communications, IEEE*, **2015**, *33*, 1819-1828

Network Slicing



Machine Learning

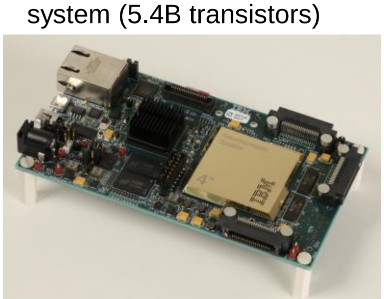
Enabling machines to **learn** without explicit programming rules
Based on many technologies (eg. neural networks, deep learning, NLP),
Use of existing structured or unstructured information to make new decisions.

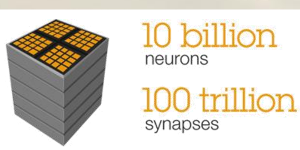
Different Questions to Address

Question	Task	Type
• Is this a cat or a dog?	Classification	SUPERVISED LEARNING
• What's the weather like tomorrow?	Prediction	SUPERVISED LEARNING
• Can we cluster the electorate?	Clustering	UNSUPERVISED LEARNING
• Which direction should I take next?	Taking actions	REINFORCEMENT LEARNING

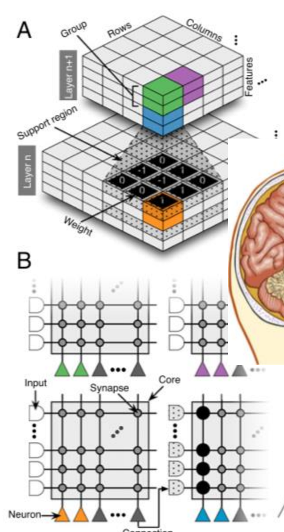
Electronic neurons; a reality

- IBM integrated neurosynaptic system (5.4B transistors)

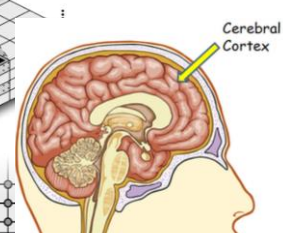




http://researcher.watson.ibm.com/researcher/files/au1-sharrer/IBM_truenorth_chip_heroshot.jpg



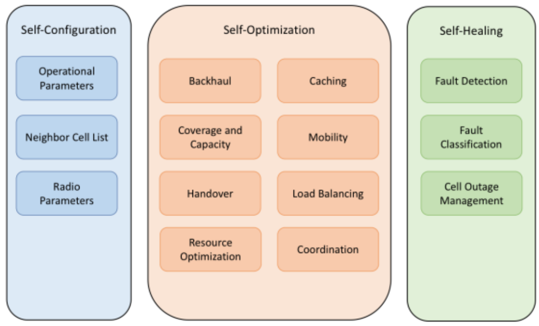
16 billion neurons



Steven K. Esser, et al., Convolutional networks for fast, energy-efficient neuromorphic computing, PNAS 2016 113 (41) 11441-11446; published ahead print September 20, 2016, doi:10.1073/pnas.1604850113

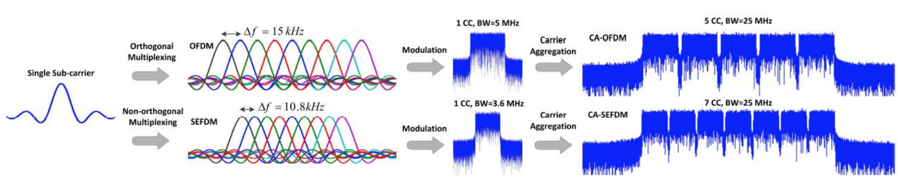
Machine Learning in Communications

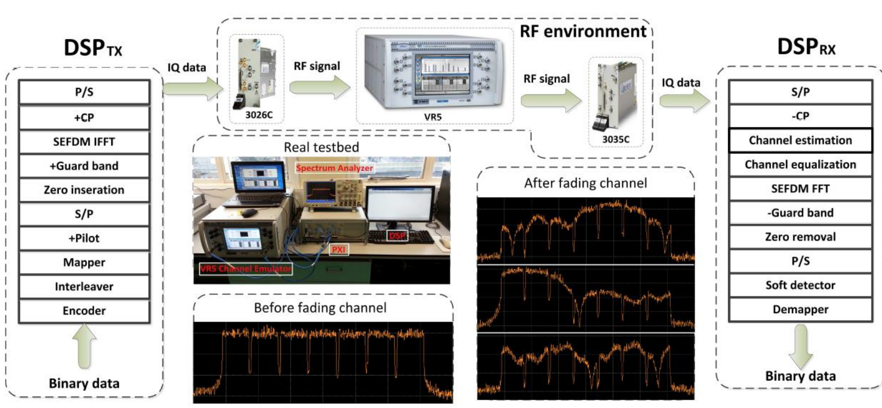
Use by operators, designers of all layers and technologies



Klaine, Paulo Valente, et al. "A Survey of Machine Learning Techniques Applied to Self Organizing Cellular Networks." *IEEE Communications Surveys & Tutorials* (2017).

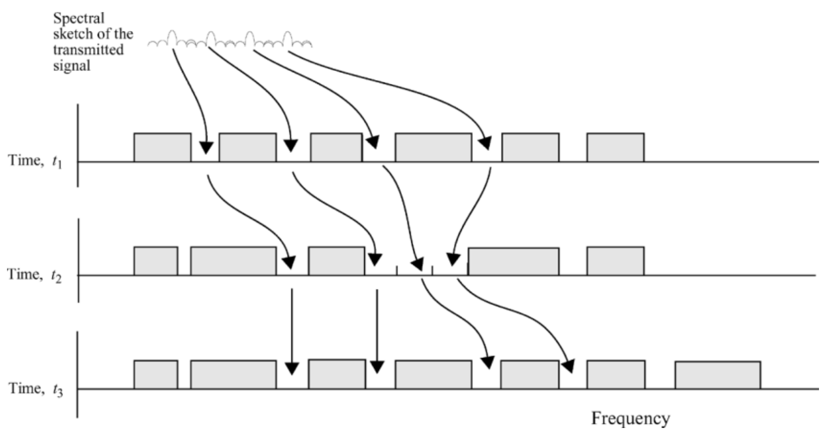
UCL SEFDM with Carrier Aggregation





Cognitive Radio

- A cognitive radio hops into available "whitespace" and then hops out again when a higher priority carrier shows up.
- Using OFDM, individual subcarriers can hop independently of each other.



Source : Haykin "Cognitive Radio: Brain-Empowered Wireless Communications" IEEE Journal on selected areas in communications, Vol. 23, No. 2, February 2005
Reference: Kit Wong -UCL

35

The "Tactile internet"

- The remote control and direction of real and virtual objects in real time.
- Requires high data throughput and a round-trip delay from terminals through the network back to terminals of around 1 ms.

- Has the potential to change how humans communicate and operate around the world.
- Will revolutionise such areas as health care, mobility, education, manufacturing etc.

Device-to-Device (D2D) Communications

Potential D2D applications include:
1. Proximity-based services where devices detect their proximity and subsequently trigger different services (such as social applications triggered by user proximity, advertisements, local exchange of information
2. Smart communication between vehicles, etc.).
3. Public safety support, where devices provide at least local connectivity even in case of damage to the radio infrastructure.

Proximity-based social networking, gaming, …

Advertisements for by-passers

Public Safety

Traffic control/safety "Intelligent Traffic System" (ITS)

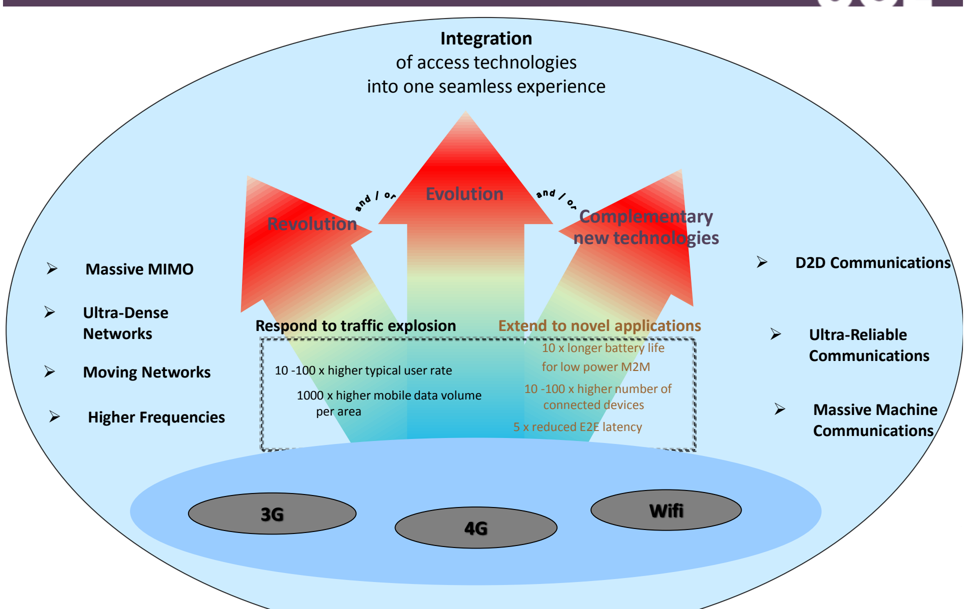
Device-to-Device (D2D) Communication

- Direct D2D communication allows direct communication between mobile devices and exchange data packets between devices locally.
- **Motivation**
  - **End user benefits:** Reduced power consumption; Increased throughput; Discovery of geographically close activities;
  - **Operator benefits:** Increased spectrum efficiency; Extended coverage; Growing number of devices to be connected in the future; Internet of Things

Source : METIS

What other new technologies?

METIS 5G Future vision



Source : METIS

Summary

- The next generation of cellular systems (5G) will need to address the exponential growth in demand (connected devices plus data capacity).
- 5G will involve the exploitation of entirely new areas of technology, not just extensions of the existing technologies :
  - More efficient use of spectrum with new modulation schemes.
  - Cognitive radio and D2D communications
  - Opening up new spectrum in mm-wave and possibly THz regions.
  - Multiple, steerable antennas : MIMO.
- Around the world, current academic research is focused in the above areas.

5G References

1. 5G: What is it? – Ericsson : www.ericsson.com/res/docs/2014/5g-what-is-it.pdf
2. 5G: What is it for? – Ericsson :www.ericsson.com/res/docs/2014/5g-what-is-it-for.pdf
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4. 5G radio architecture : http://fp7-semafour.eu/media/cms_page_media/9/SEMAFOUR_2014_RAScluster%20White%20paper.pdf
5. A. Osseiran et al, Scenarios for the 5G Mobile and Wireless Communications: the Vision of the METIS Project, IEEE Comm. Mag., May, 2014 https://www.metis2020.com/documents/publications/
6. Andrews, J.G. “what will 5G be?” IEEE Journal on selected areas in communications, Vol. 32, No. 6, June 2014

Mobile Communications Systems (MCS)

29^{th} October – 2^{nd} November 2018

Course Evaluation

Please provide feedback by circling the number on the scale:

5 = Excellent, 4 = Very Good, 3 = Good, 2 = Fair, 1 = Poor/Inadequate

1.	General achievement of your objectives and expectations for this module			1 2 3 4 5
2.	Course material (visual aids etc)			1 2 3 4 5
3.	Instructors' knowledge of the subject			1 2 3 4 5
4.	Difficulty of the material	Too difficult	Just right	Too simple
5.	Pace of teaching	Too fast	Just right	Too slow

6. Did you learn new material in this module? If yes, what?

7. What were the most useful aspects?

8. Do you have suggestions for improvements?

Please provide feedback on the individual presenters using the same scale.

Izzat Darwazeh	A. Knowledge of subject	1 2 3 4 5
	B. Presentation style	1 2 3 4 5
Clive Poole	A. Knowledge of subject	1 2 3 4 5
	B. Presentation style	1 2 3 4 5
Ryan Grammenos	A. Knowledge of subject	1 2 3 4 5
	B. Presentation style	1 2 3 4 5
Laura Toni	A. Knowledge of subject	1 2 3 4 5
	B. Presentation style	1 2 3 4 5

Add any other comments here:

Please indicate by ticking whether you are:	CPD (Module Only)	[ ]
	IGDP (MSc)	[ ]
	Full-time MSc	[ ]

Name (Optional): ______________________________

Thank you for completing this form