Lecture #1

University of Essex

Fundamentals on Computer Networks and Wireless Networks

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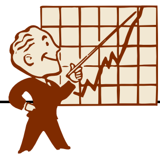
Agenda



- **Fundamentals of Computer Networks**
- Basics of Wireless Networks
  - PHY: Wireless Transmission
  - MAC: Medium Access Control
  - Cognitive Radio
- Q&A

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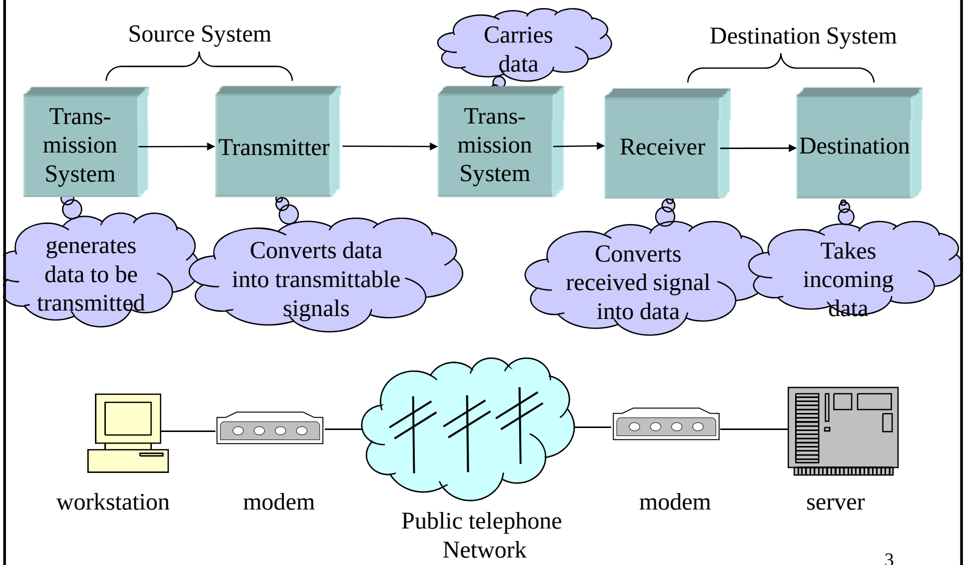
A General Communication Model



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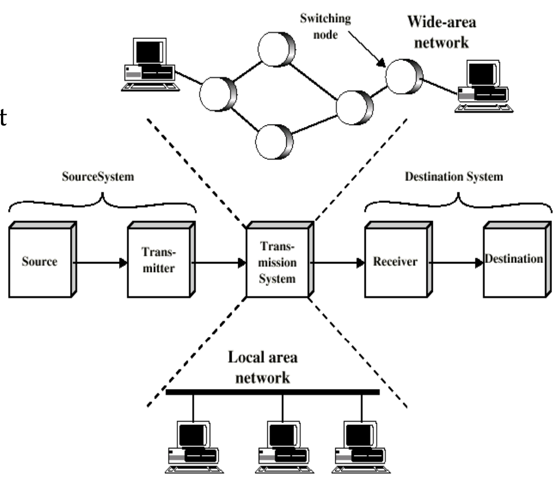
Networking

- **Point to point comm. not usually practical**
  - Devices are too far apart
  - Large set of devices would need impractical number of connections
- **Solution is a communications network**



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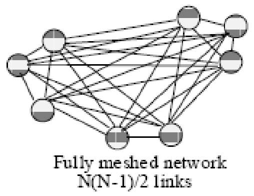
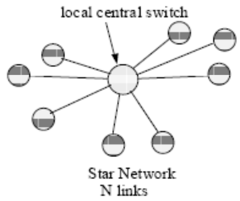
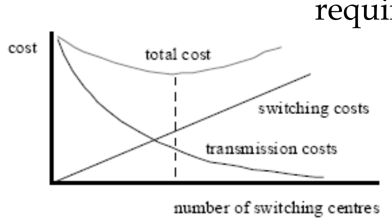
Transmission vs. Switching





requires many transmission links

Centralised switch network minimises transmission but requires complex switch

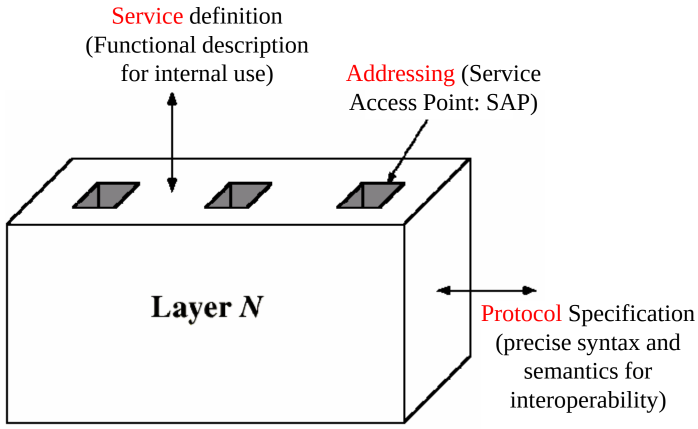


Trade off

ISO OSI (Open Systems Interconnection) Reference Model

Function	Layer	Scope	Scope
application-specific protocols	**7 application**	Application-oriented	End-to-end scope
data representation and encoding	**6 presentation**	Application-oriented	End-to-end scope
dialog and synchronisation	**5 session**	End-to-end	End-to-end scope
message transfer (and maybe error control, flow control, connection management)	**4 transport**	End-to-end	End-to-end scope
network routing and addressing (and maybe connection management)	**3 network**	Hop-by-hop	Global scope
data link control (framing, data transparency and maybe error control)	**2 data link**	Hop-by-hop	Local scope
mechanical, electrical and optical interface	**1 physical**	Hop-by-hop	Local scope

Layer Specific Standards



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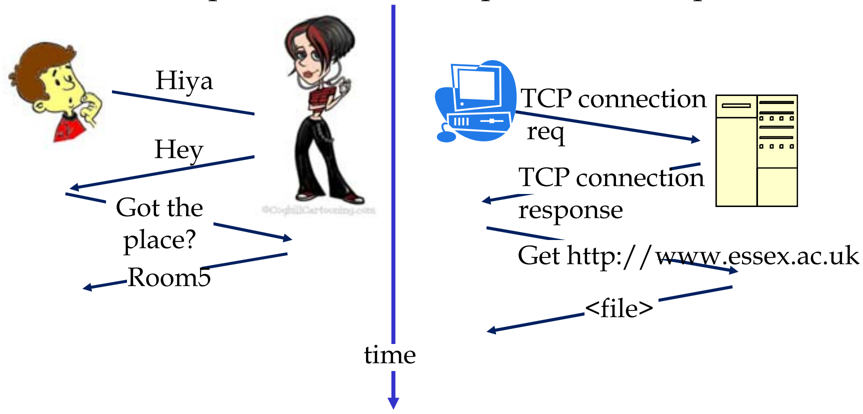
What's a protocol?

A human protocol and a computer network protocol



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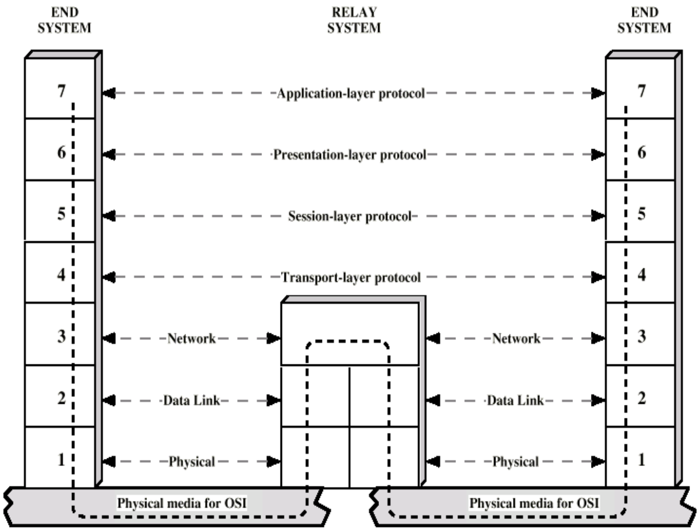
Protocols in OSI RM



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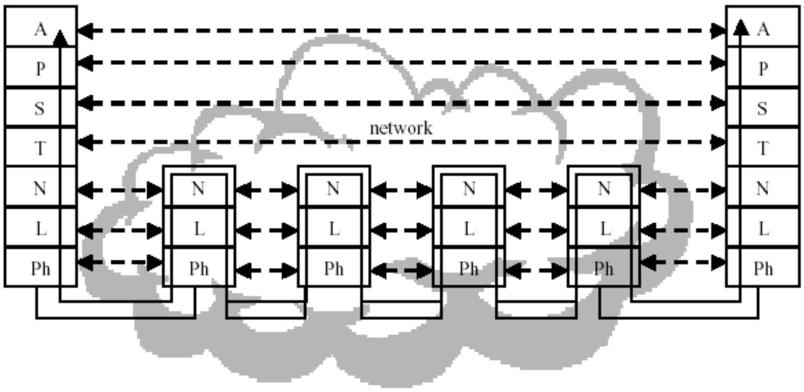
The Full ISO OSI RM



A application
P presentation
S session
T transport

N network
L (data) link
Ph physical

logical (peer-to-peer) communication
actual end-to-end message path

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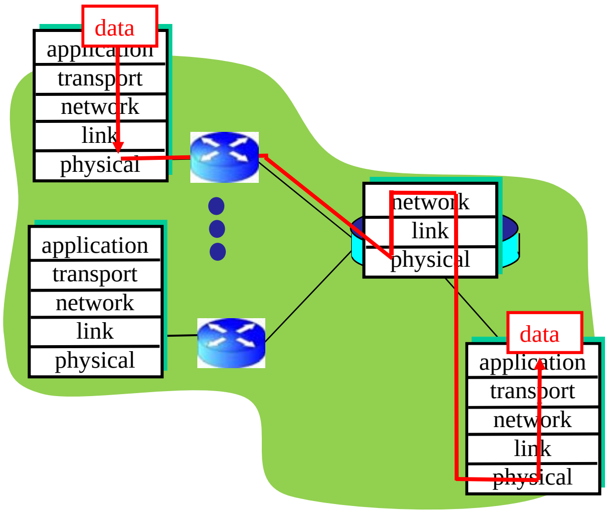
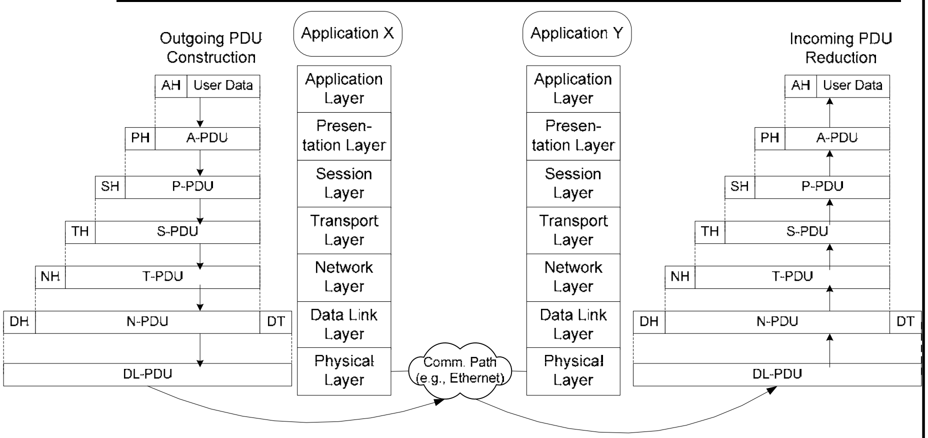
Layering: Physical Communication



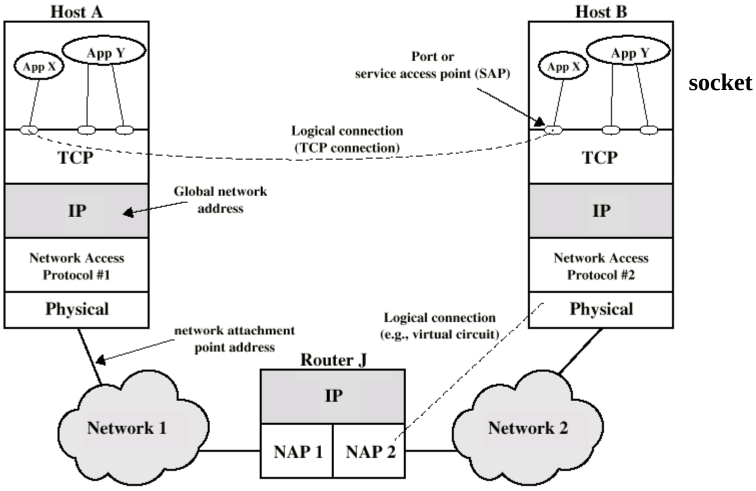
The OSI Environment



At Source: each layer takes data from above, adds header information to create new data unit, and then passes new data unit to layer below.

At Destination: the opposite operation

Addressing

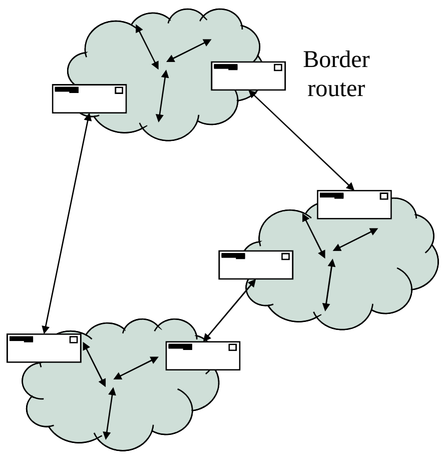


Unicast – broadcast - multicast

Network Structure

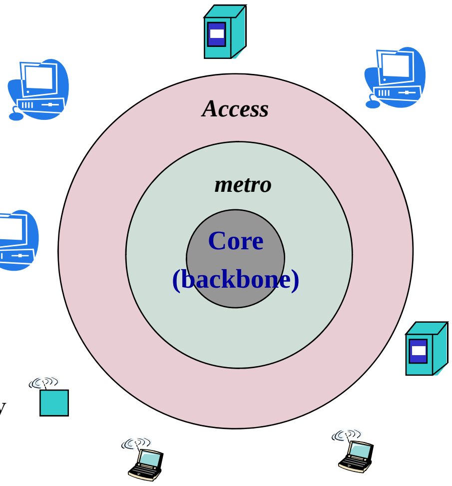
Administrative boundaries

- Autonomous system (AS):
  - intra-domain issues
  - internal policy
  - routing metric?
  - Routing protocols: RIPv2, OSPFv2
- Interconnection of ASs:
  - inter-domain issues
  - Interconnectivity information
  - Routing protocols: BGP
- Service Level Agreement/Specification
- Business Model



Network Structure : another view

- Access network:
  - With dedicated links
  - Low level of multiplexing
  - low volume of traffic
  - ISPs
  - **Broadband access: fixed, wireless**
- Distribution network: (transit)
  - interconnectivity at local level
  - low multiplexing
  - medium volume of traffic
  - Metropolitan Area Network
- Core network – backbone:
  - international/global interconnectivity
  - high volume of traffic
  - high multiplexing
- Network edge: applications and hosts



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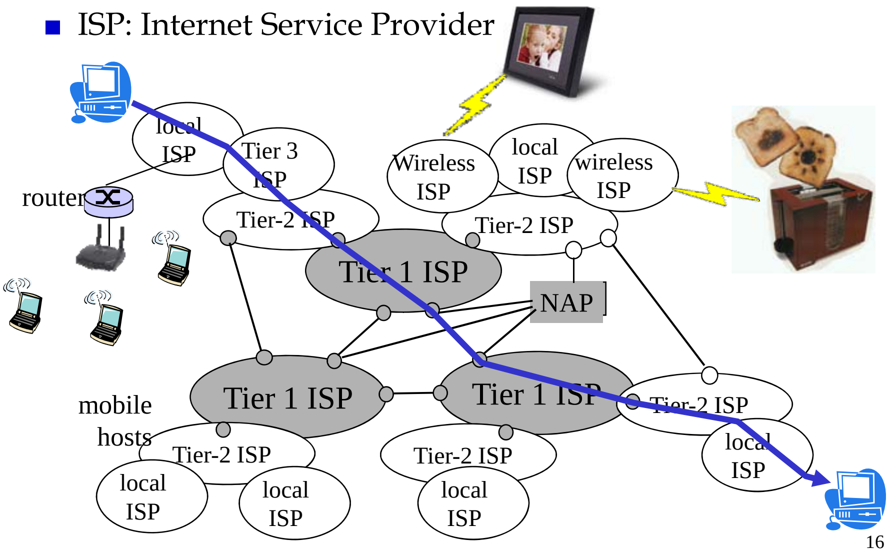
A packet passes through many networks!

- ISP: Internet Service Provider



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Agenda

- Fundamentals of Computer Networks
- Basics of Wireless Networks
  - PHY: Wireless Transmission
  - MAC: Medium Access Control
  - Cognitive Radio
- Q&A

Some slides here pay courtesy to J. Schiller, K. Guild & D. Hunter.

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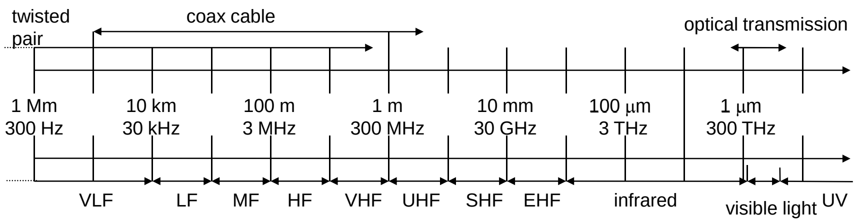
Frequencies for communication



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

- Frequency and wave length: $\lambda = c/f$
- wave length λ, speed of light $c \cong 3x10^8 m/s$, frequency f

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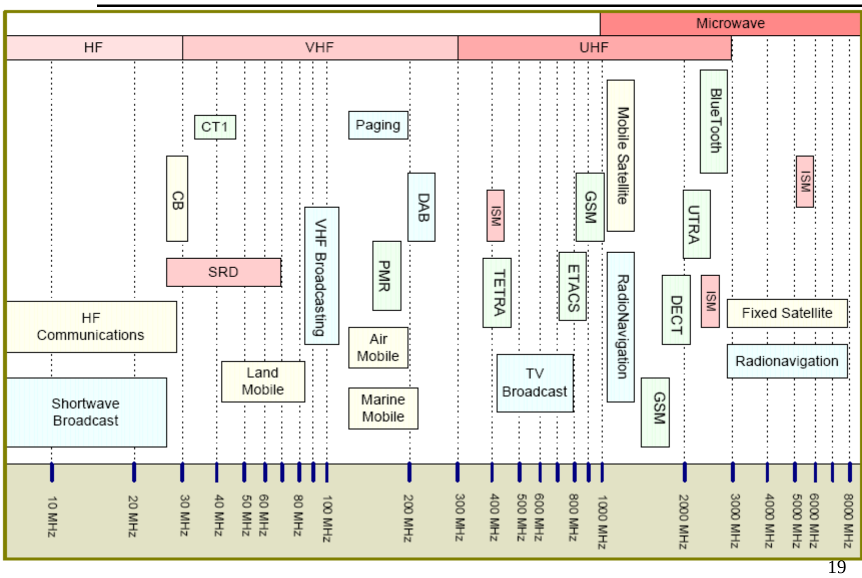
Radio Frequency Spectrum



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Frequencies for mobile communication

- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, focusing
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF spectrum
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - weather dependent fading, signal loss caused by heavy rainfall etc.

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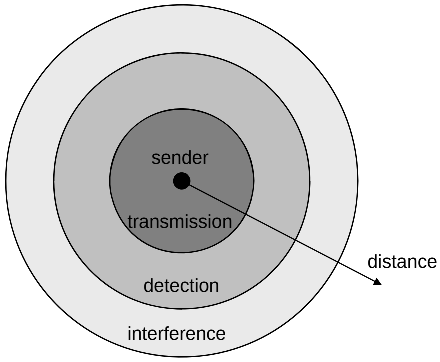
Signal propagation ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Receiving power proportional to $1/d^2$

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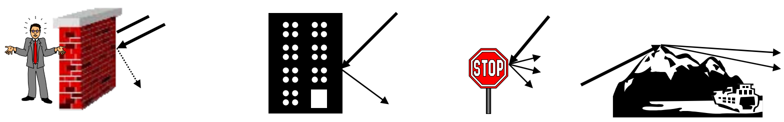
Signal propagation

- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$
  (d = distance between sender and receiver)
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - scattering at small obstacles
  - diffraction at edges



shadowing reflection scattering diffraction

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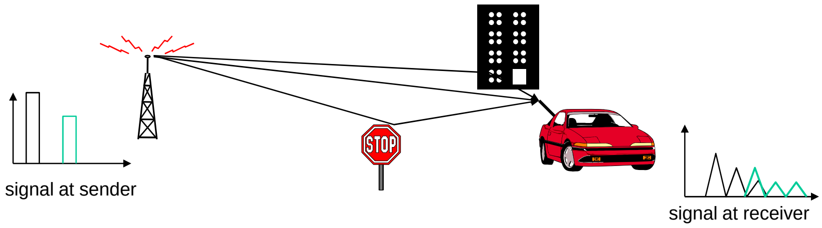
Multipath propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
  - interference with "neighbor" symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
  - distorted signal depending on the phases of the different parts

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Modulation

- Digital modulation
  - digital data is translated into an analog signal (baseband)
  - differences in spectral efficiency, power efficiency, robustness
- Analog modulation
  - shifts center frequency of baseband signal up to the radio carrier
- Motivation
  - smaller antennas (e.g., $\lambda/4$)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

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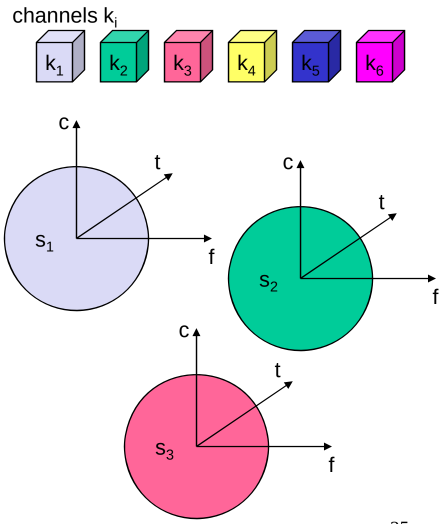
Multiplexing

- Goal: multiple use of a shared medium
- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)



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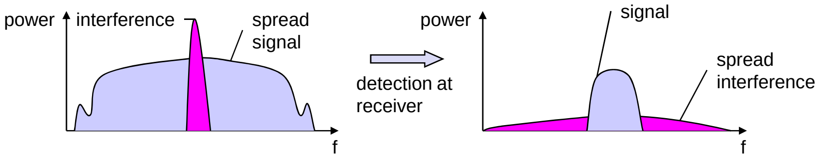
Spread spectrum technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
- protection against narrow band interference



protection against narrowband interference

- Side effects: coexistence of several signals without dynamic coordination

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Signal vs. Noise

- The signals at the input of a receiver can be small (< 1 uV).
- At this level thermal noise generated by the receiver electronics is significant.
  - A perfect receiver at room temperature would generate 4 x 10-21 W of noise per Hz of bandwidth.
  - Noise power is proportional to absolute temperature, cooling the receiver is nice.
  - Real receivers generate 2 –8 times more noise power than this in the active devices used to amplify the small signal.
- The receiver performance is characterised in terms of signal to noise ratio (SNR)

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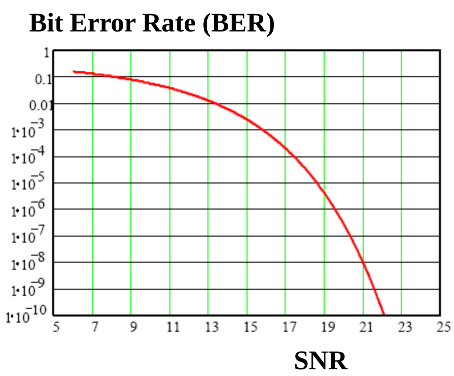
Bit Error Rate (BER)

- The receiver is trying to determine the sequence of bits that were sent by the transmitter.
- A low signal to noise ratio (SNR) means that there is a probability that the wrong decision will be made.
- Bit error rate (BER) characterises the performance of a receiver.
- The relationship between bit error rate and SNR depends on the modulation type.
- The signal to noise ratio needed for a particular minimum BER is termed the *power efficiency*.



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Payload Bit Error Rate

Payload	Acceptable BER
ADPCM Voice Channel	10^{-3}
GSM 13kb/s Compressed Voice	10^{-4}
MPEG Compressed Video	10^{-6}
File Transfer	10^{-12}

Leave it to upper layers

The physical radio layer cannot support these low error rates.

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An Mechanism to Reduce BER: ARQ

- ARQ: Automatic Repeat ReQuest: to repeat data that contains errors.
  - Terminal A sends a message to Terminal B.
  - Terminal B receives the packet with one or more errors.
  - Terminal B has the ability to detect that errors are present.
  - Terminal B sends a message to Terminal A requesting re-transmission.
  - Terminal A re-transmits the errored packet.
  - The new packet is received successfully.
- ARQ is only applicable when the channel error rate is very low.
  - If the probability of a bit error occurring in a packet is significant the system will be overwhelmed by repeat requests and throughput collapses.
- ARQ results in a throughput reduction even when there are no errors.
  - Terminal A has to idle while it waits for a repeat request from Terminal B.

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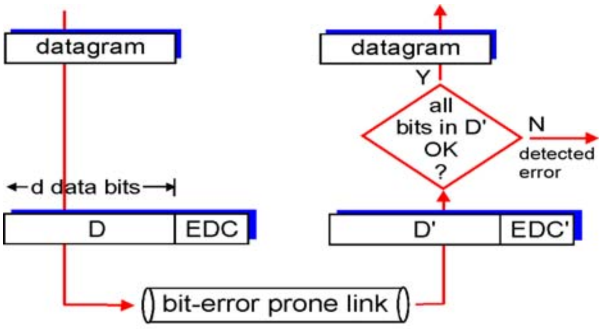
Error Detection

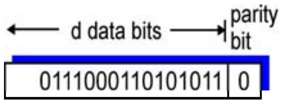
EDC= Error Detection and Correction bits (redundancy)
D = Data protected by error checking, may include header fields

- Error detection not 100% reliable!
  - protocol may miss some errors, but rarely
  - larger EDC field yields better detection and correction



Parity Checking

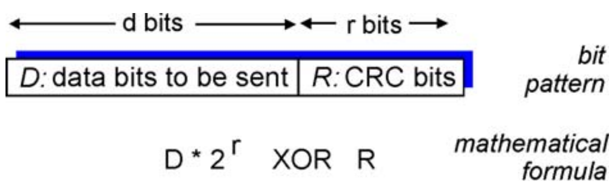
<u>Single Bit Parity:</u>
Detect single bit errors



- Single Bit Parity
  - If the sum of the bits in a packet is even, add an extra '0' to the packet.
  - If the sum of the bits in a packet is odd, add and extra '1' to the packet.
  - This will only detect a single bit error, if two bits are in error then it will fail.
- Radio channels can give rise to bursts of errors.
  - More complex error detection schemes are needed.
- Cyclic Redundancy Check (CRC) codes have become the standard way of solving the problem.

Cyclic Redundancy Check

- view data bits, *D*, as a binary number
- choose r+1 bit pattern (generator), *G*
- goal: choose r CRC bits, *R*, such that
  - <D,R> exactly divisible by G (modulo 2)
  - receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!
  - can detect all burst errors less than r+1 bits
- widely used in practice (ATM, HDCL)



CRC Example

Want:

$D \cdot 2^r$ XOR R = nG

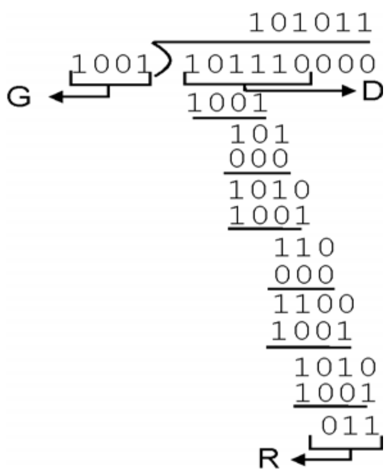
equivalently:

$D \cdot 2^r$ = nG XOR R

equivalently:

if we divide $D \cdot 2^r$ by G, we get remainder R

$$R = \text{remainder}\left[\frac{D \cdot 2^r}{G}\right]$$



Agenda

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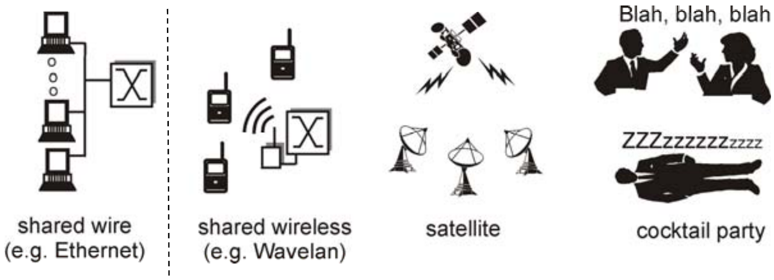
Multiple Access Links

Wireless is Broadcast in nature.



- single shared broadcast channel but two or more simultaneous transmissions by nodes → interference
  - only one node can send successfully at a time

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Multiple Access protocols

- Distributed algorithm that determines how nodes share channel, i.e., determine when a node can transmit
- Communication about channel sharing must use channel itself!
- What to look for in multiple access protocols?

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Ideal Multiple Access Protocol

Broadcast channel of rate R bps

1. When one node wants to transmit, it can send at rate R.
2. When M nodes want to transmit, each can send at average rate R/M
3. Fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. Simple

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Medium Access Control (MAC)

- MAC is concerned with controlling each terminal's access to the radio resource.
  - Prevention of collisions –blocking.
  - Fairness in allocating resource
- Quality of service (QoS): latency (delay), jitter, loss.
- Distinction between infrastructure networks and ad-hoc networks
  - Infrastructure networks can have a centralised view of the problem
    - Each terminal can be allocated its resource
    - The infrastructure is responsible for solving the MAC problem
  - Ad-hoc networks require distributed MAC
    - Each terminal has to be responsible for its own MAC

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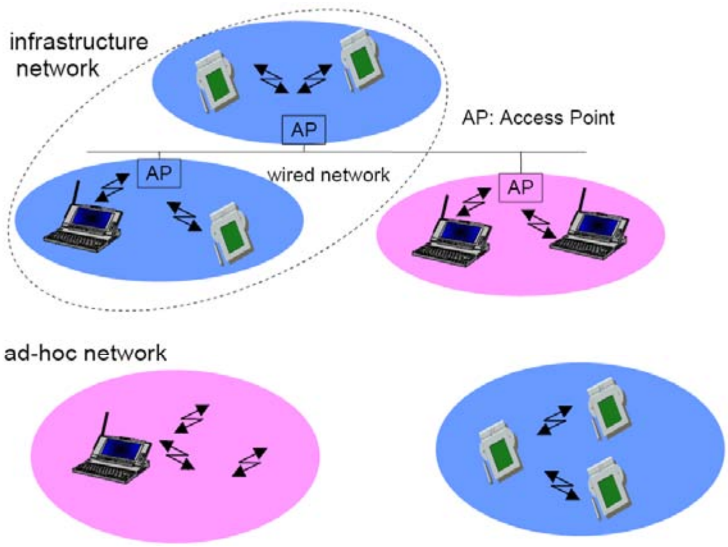
Basic Wireless Network Types



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MAC Protocols: a taxonomy

Three broad classes:

- Channel Partitioning
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use
- Random Access
  - channel not divided, allow collisions
  - "recover" from collisions
- "Taking turns"
  - tightly coordinate shared access to avoid collisions

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Channel Allocation

- Fixed Channel Allocation
  - Certain Channels are assigned to each cell.
  - Easy to implement but problems when traffic load changes
- Borrowing Channel Allocation
  - Neigbouring busy cells *borrow* channels from quiet ones
  - The borrowed channel may be being re-used in a neighbouring cell.
- Dynamic Channel Allocation
  - A brain dynamically allocates channels to cells depending on their load
  - Where is the brain??

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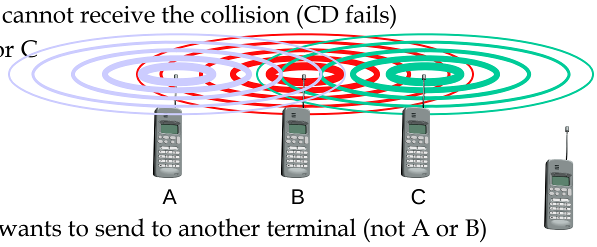
Can we apply media access methods from fixed networks?

- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Problems in wireless networks
  - signal strength decreases proportional to the square of the distance
  - the sender would apply CS and CD, but the collisions happen at the receiver
  - it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
  - furthermore, CS might not work if, e.g., a terminal is “hidden”

Hidden and exposed terminals

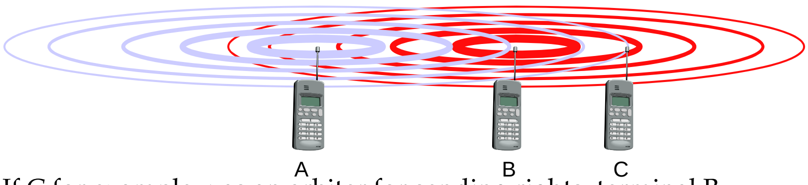
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a “free” medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is “hidden” for C



- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is “exposed” to B

Near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A's signal
  - C cannot receive A



- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks where transmitters share transmission frequencies and transmission time - precise power control needed!

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Access methods SDMA/FDMA/TDMA

- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- TDMA (Time Division Multiple Access)
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time

- The multiplexing schemes are now used to control medium access!

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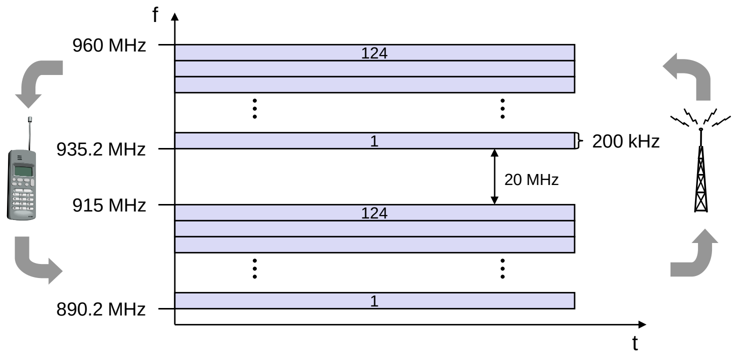
An FDD/FDMA Example - GSM



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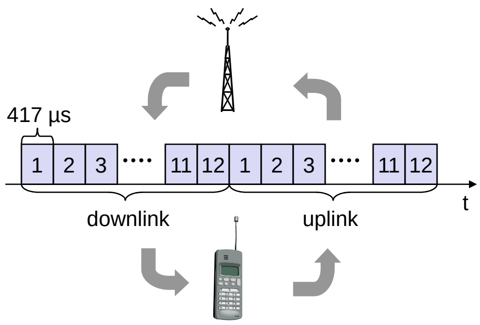
A TDD/TDMA Example: DECT

DECT: Digital Enhanced Cordless Telecommunications



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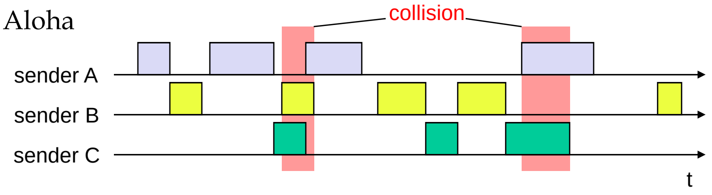
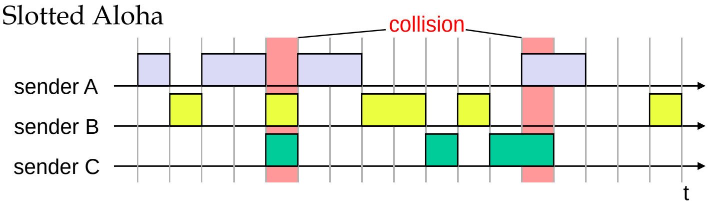
Aloha/slotted aloha

- Mechanism
  - random, distributed (no central arbiter), time-multiplex
  - Slotted Aloha additionally uses time-slots, sending must always start at slot boundaries
- Aloha



- Slotted Aloha



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DAMA - Demand Assigned Multiple Access

- Channel efficiency only 18% for Aloha, 36% for Slotted Aloha (assuming Poisson distribution for packet arrival and packet length)
- Reservation can increase efficiency to 80%
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite links
- Examples for reservation algorithms:
  - Explicit Reservation (Reservation-ALOHA)
  - Implicit Reservation (PRMA: Packet Reservation MA)

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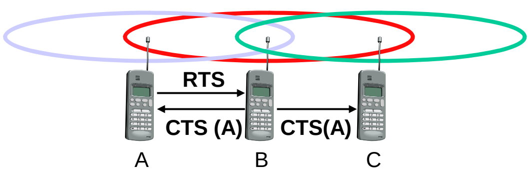
MACA - collision avoidance

- MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - RTS (request to send): a sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - CTS (clear to send): the receiver grants the right to send as soon as it is ready to receive
- Signaling packets contain
  - sender address
  - receiver address
  - packet size
- Variants of this method can be found in IEEE802.11 as DFWMAC (Distributed Foundation Wireless MAC)

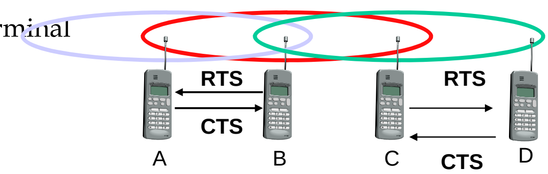
MACA examples: RTS/CTS

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B



- MACA avoids the problem of exposed terminals
  - B wants to send to A, and C

  wants to send to another terminal
  - now C does not have to wait because it cannot receive CTS from A



Polling mechanisms

- If one terminal can be heard by all others, this "central" terminal (a.k.a. base station) can poll all other terminals according to a certain scheme
- Example: Randomly Addressed Polling
  - base station signals readiness to all mobile terminals
  - terminals ready to send can now transmit a random number without collision with the help of CDMA or FDMA (the random number can be seen as dynamic address)
  - the base station now chooses one address for polling from the list of all random numbers (collision if two terminals choose the same address)
  - the base station acknowledges correct packets and continues polling the next terminal
  - this cycle starts again after polling all terminals of the list

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Access method CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
  - each sender has a unique random number, the sender XORs the signal with this random number
  - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function
- Disadvantages:
  - higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have the same strength at a receiver
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g. 2^{32}) compared to frequency space
  - forward error correction and encryption can be easily integrated

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Comparison SDMA/TDMA/FDMA/CDMA

Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km²	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	only in combination with TDMA, FDMA or CDMA useful	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA

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Source: IEEE Comm. Mag.

Wireless vs. Wired

- Wireless transmissions are far less robust than wired
  - Noise
    - If the link is too long the noise is bigger than the signal.
  - Interference
    - Our own, generated within the network
    - Other people using the radio spectrum
  - Mobility
- Wireless systems are inherently broadcast
  - We may talk about point to point comm but the signals still go everywhere
  - We have to engineer a multiple access scheme so that all terminals can share the available radio resource
- Radio spectrum is an expensive and scarce commodity -> **cognitive radio**?
- The radio channel is challenging - particularly indoors -> femto cell?

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Agenda

- Fundamentals of Computer Networks
- Basics of Wireless Networks
  - PHY: Wireless Transmission
  - MAC: Medium Access Control
  - Cognitive Radio
- Q&A

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Pondering on Spectrum Usage

The Ofcom Spectrum Vision

- **Spectrum should be free of technology, policy and usage constraints as far as possible**
- **It should be simple and transparent for licence holders to change the ownership and use of spectrum**
- **Rights of spectrum users should be clearly defined and users should feel comfortable that they will not be changed without good cause.**

Source: Ofcom

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Three possible ways of managing Spectrum

	Command & Control Zone	**Market Force Zone**	**Licence-exempt Zone**
Managed by:	Authorities: (No variations allowed, for ~100 years!)	Companies	nobody
Current percentage (UK)	94%	0%	6%
Future Trend:	↓	↑	↑
	The regulator cannot know as much as the market.	Trading existing spectrum between users	Key area for innovation but do we need more?

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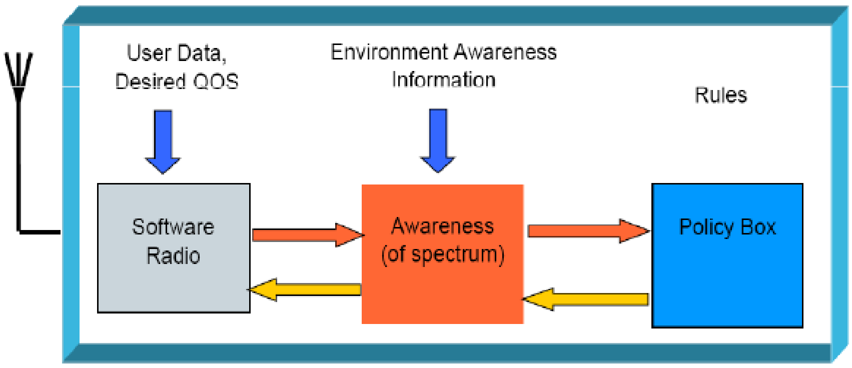
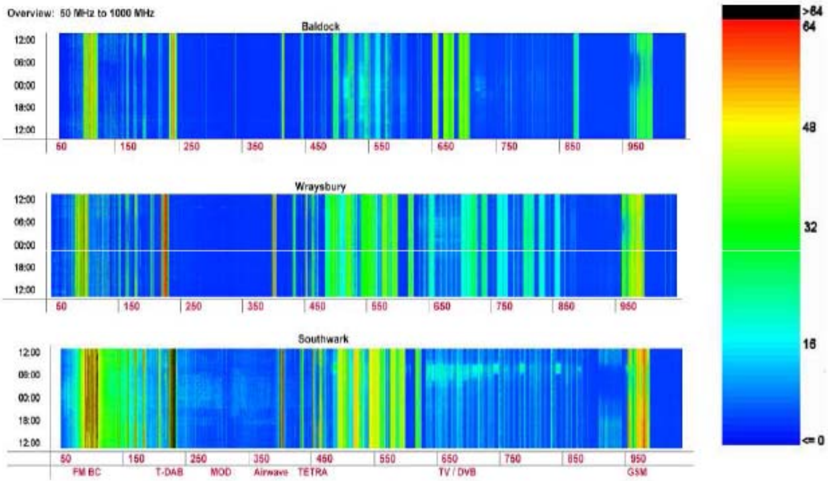
What is Cognitive Radio?

- *"… a radio that is aware of its surroundings and adapts intelligently…."* – Mitola 2000
- Primary users vs. secondary users



Source: Ofcom

A Spectrum Usage Test (London)



Source: Ofcom

Challenges of Cog. Radio

- Economics
  - Cost of CR devices over simpler delivery mechanism likely to be higher
  - Non-real time services for CR not as valuable
  - Depends on spectrum congestion and demand
- Hidden node / sharing issues
  - Ensure CRs do not interfere with each other
  - Making sure that they can exist with legacy users and other
- Cog. Radio devices
  - Controlling CRs to ensure they have the same spectrum picture
  - How will groups of CRs know what's going on?
  - Devices need to be aware of regulatory constraints
- Security and malicious use
  - The flexibility of CRs enables illegal transmissions
  - AAA

Where can I use Cog. Radio?

- licence-exempt (LE) bands: all right.
- and Licenced Bands!: not fair?! restricted to licensees?

- Non-time sensitive services, such as downloading could be most appropriate.
- But,
  - Emergency communications (with priority flag) ??
  - Broadband wireless services
  - Multimedia wireless networking

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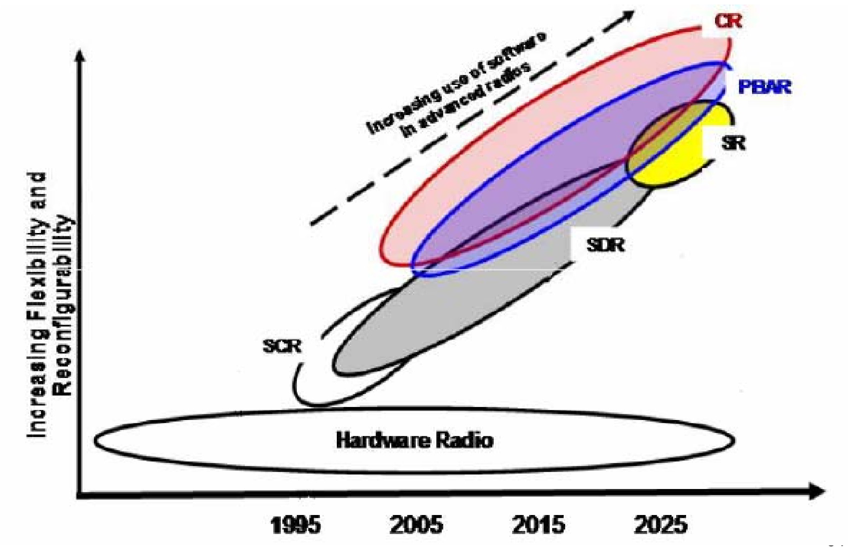
Conceptual Timeline (IEEE 1900)



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