Mobile Networks 101

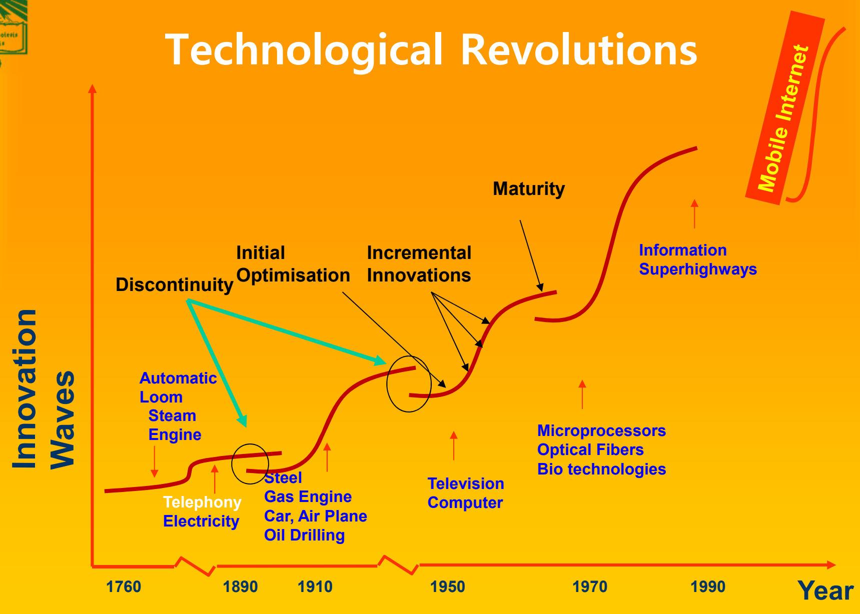
***Aula da Cadeira* Comunicações Móveis**

Rui Luis A. Aguiar

The communication network

Trends and history

Technological Revolutions



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The weight of time

The beauty of networking effects

Everybody uses it

The ugliness of networking effects

Now everybody uses it…

Society takes time

- **Business**
- **People habits**
- **Technology interoperation**

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How networks evolve?

- Real life evolution is complicated
  - Depends on real life – technologies, business, society, relationships, laws, …
- Users are shaping communication networks
  - Networks are no longer a business/technology binomial, but strongly depend on users acceptance of (or requirements for) change
  - "Killer ideas" are often unpredictable
- Legacy is a major issue
  - Large networks cannot be changed instantaneously
  - Mobile is particularly lenient in this aspect (why?)

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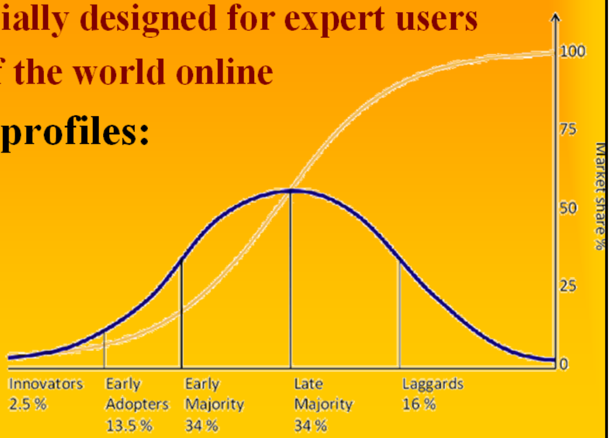
The user

- Internet is being challenged by its own success
  - Internet initially designed for expert users
  - Now 30% of the world online
- Users follow profiles:
  - Techs
  - Business
  - Teens
  - "World"
  - "Oldies"



Source: Rogers

Trends in communications

- Current telecommunication industry has been the result of different trends in the last 40 years:
  - The saturation of the telephone market, at the end of the 80ies
  - The coming of age of the data world, in the early 90ies
  - The pervasiveness of mobility, in the mid 90ies.

Note: many upcoming slides with statistics are dated around 2010, when 3G was established in Western Europe, and we were moving to 4G.

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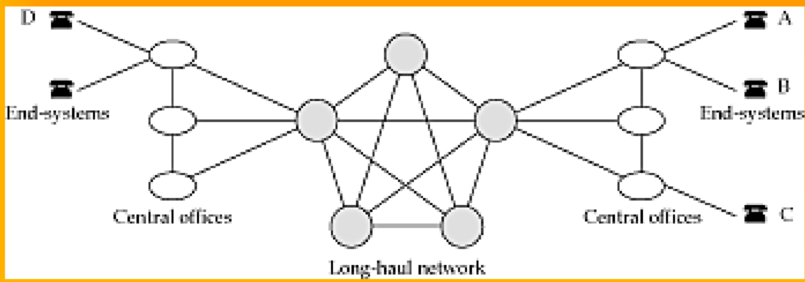
The communication network

The phone network

Telephone System



- Uses switched circuits (virtuals...)
- Access via low bandwidth circuits
- "out-of-band" call establishment using signaling system based in packets (SS7)
- Channels between switching exchanges carry multiple calls
  - Multiplexing (analogue or digital)

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Public telephony (PSTN): history

- 1876 invention of the phone
- 1915 first transcontinental connection (NY–SF)
- 1920's first automatic switching exchanges
- 1956 transatlantic cable TAT-1 (35 linhas)
- 1962 digital transmission (T1)
- 1974 Internet: voice over packets
- 1977 digital switching exchange
- 1980s Signaling System #7 (out-of-band)
- 1988 RDIS (ISDN Blue Book)
- 1990s Intelligent Networks
- (1990s ATM)
- 2000 local bundle liberalization (Europe)

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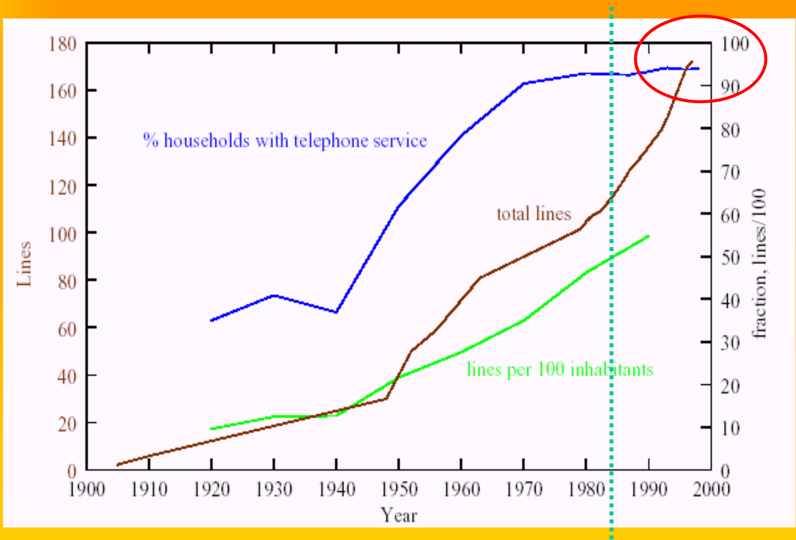
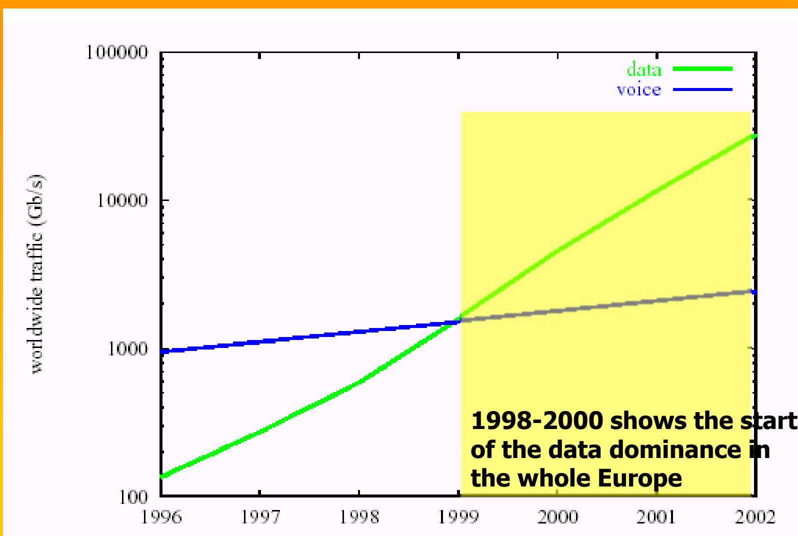
Phone service in US



AT&T Divestitude

Evolution: Voice vs Data



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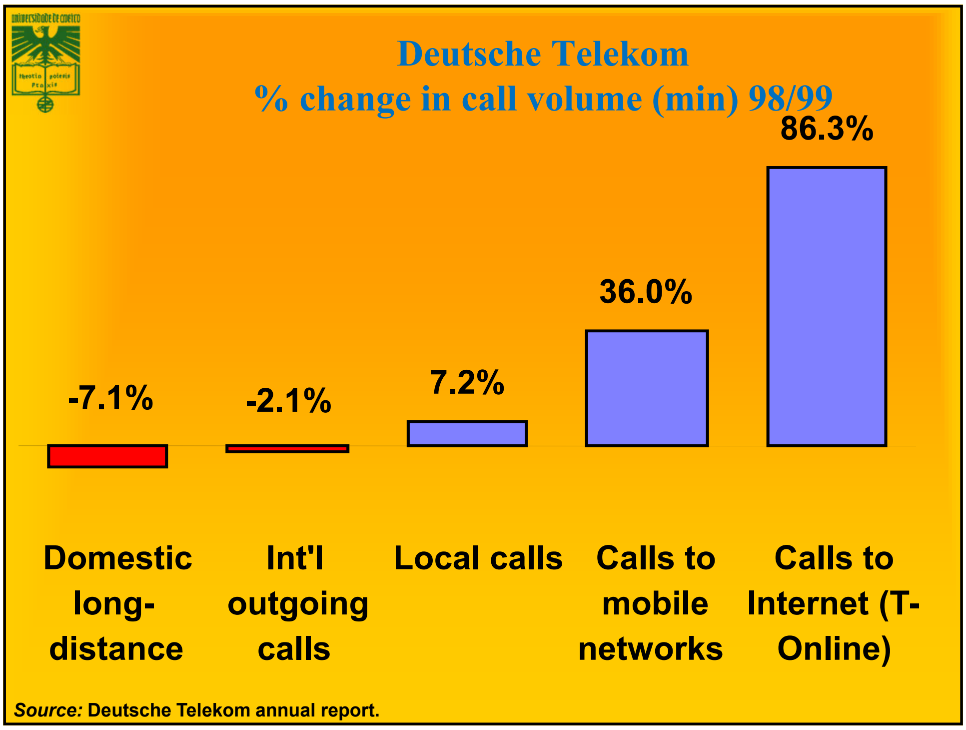
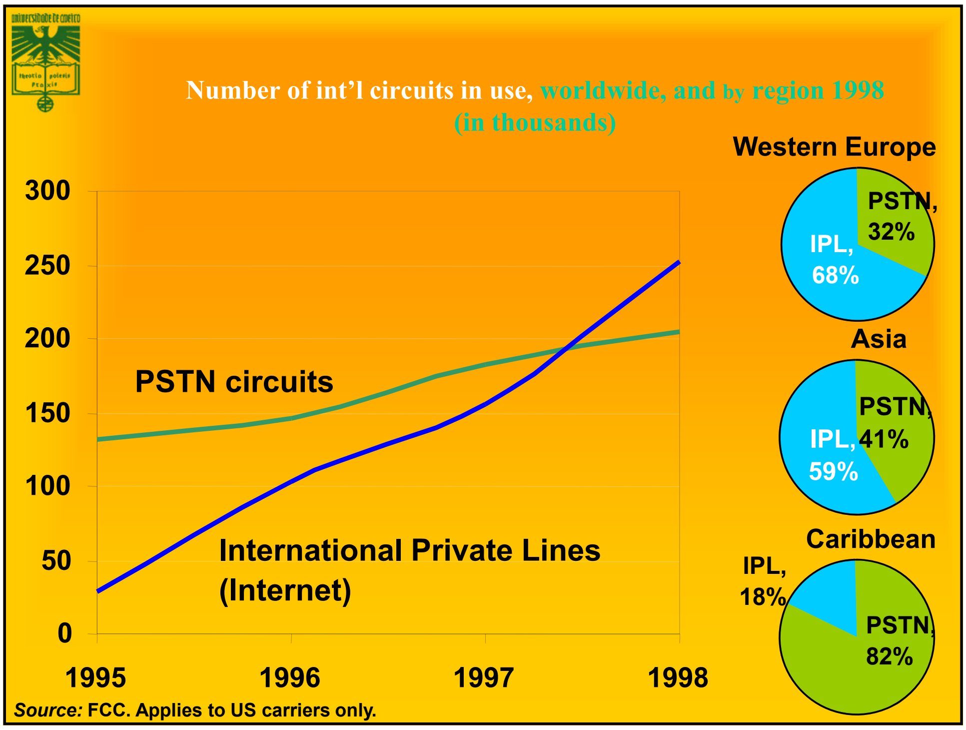

Deutsche Telekom
% change in call volume (min) 98/99
86.3%
36.0%
7.2%
-7.1%
-2.1%
Domestic long-distance
Int'l outgoing calls
Local calls
Calls to mobile networks
Calls to Internet (T-Online)
Source: Deutsche Telekom annual report.

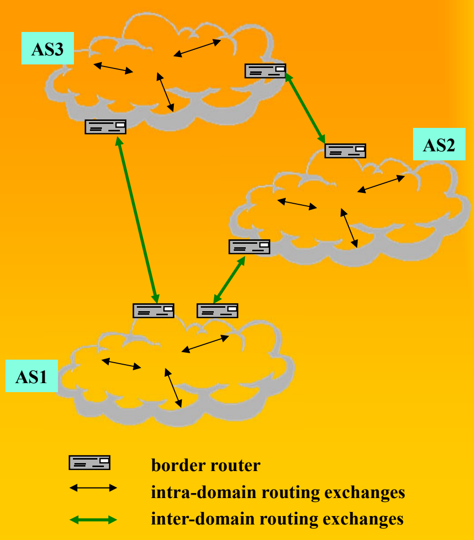

Number of int'l circuits in use, worldwide, and by region 1998
(in thousands)
Western Europe
PSTN, 32%
IPL, 68%
Asia
PSTN, 41%
IPL, 59%
Caribbean
IPL, 18%
PSTN, 82%
300
250
200
150
100
50
0
1995
1996
1997
1998
PSTN circuits
International Private Lines
(Internet)
Source: FCC. Applies to US carriers only.

The communication network

The Internet

Internet structure

- **Administrative borders define**
  - Autonomous Systems (AS)
    - **Intra-domain routing**
    - Individual internal policies
    - May use different metrics between domains
    - protocols: RIPv2, OSPFv2
  - Ass interconnections
    - **Inter-domain routing**
    - Connectivity information
    - protocols: BGP



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Internet: currently

- **Self-organized set of interconnected autonomous components**
  - **More than 60.000 autonomous domains (with omre than 84K numbers allocated)**
    - Single guarantee is running TCP-IP
    - Works by packet switching
    - More than 330 millions of registered domains (URL)!
- **Commercial traffic larger than non-commercial**
  - **Exponential growth in all numbers (number of users, traffic)**
- **Different machines (networks) can offer different services**
  - **Each user can select what it uses**
- **Only bi-direccional media that support communications**
  - **One to one (unicast, e.g. email); one to many (multi-cast, e.g., electronic news)**
- **NB: Internet networks are operated AUTONOMOUSLY**
  - **After connecting to the Internet, the network becomes PART of the Internet**

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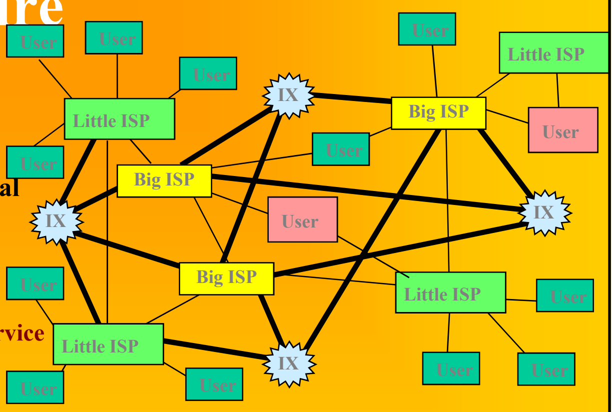
Real structure



- **Apparently hierarchical**
  - **Backbone ISP provides service a ISPs increasingly smaller**
  - **Smaller ISPs eventually providing service end users.**
- **But hierarchy is not respected**
  - **Private connection agreements**
  - **Mechanisms for improvement of the network**
  - **All companies provie service to (some) users**
  - **Service providers connect to multiple connection provider**
  - **Users connect to multiple ISPs**

"Data vs voice": packet swithcing vs circuit switching

Packet switching solves everything?

- Great for burst information
  - Resource sharing
  - No cal setup time
- When excessive congestion: delays and losses
  - Needs reliable data transfer protocols
- Providing circuit switching services?
  - For multimedia applications we need bandwidth and delay
    - Problem not yet completely solved

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Transport service (operador/ISP) vs applications

- Packet loss
  - Some apps (audio/video real time) handle losses
  - Other applications (file transfer, telnet) require 100% of success in transmission
- Bandwidth
  - Some applications (multimedia) need a minimum bandwidth to be effective
  - Other applications ("elastic applications", ex. email, file transfer) use the bandwidth available
- Timing
  - Some applications (Internet voice, multiuser games) require low delays to be effective
  - Other applications (without real time requirements) do not have strict delays end-to-end.

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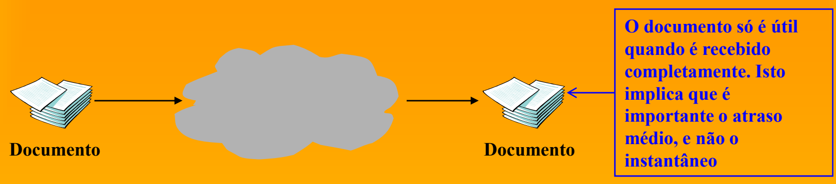
Elastic operations



- **Elastic applications**
  - **Interactive data transfer (e.g. HTTP, FTP)**
    - Sensitive to the medium delay, not to rare occurrences
  - **Bulk data transfer (e.g. mail, news)**
    - Not sensitive to delay
    - Best effort works…

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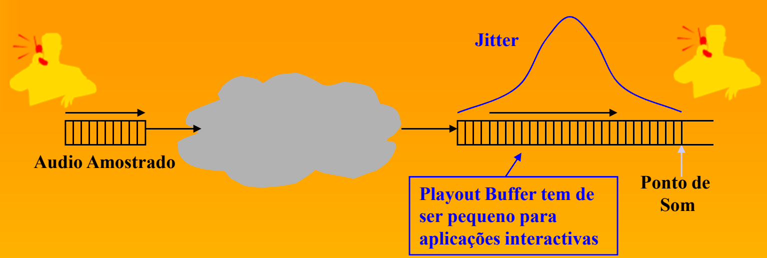
Inelastic applications



- **Interactiv applications**
  - **Sensistive to packet delay (telephony)**
  - **Maximum delay may be limited**
- **Non-interactive applications**
  - **Adapt to larger ranges of delays (streaming audio, video)**

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Application requirements

Applications	Losses	BW	Timing
File transfer	lossless	elastic	no
e-mail	lossless	elastic	no
Web documents	lossless	elastic	no
Real time audio/video	supports	audio: 5K-1Mbps	yes, 100's mseg
Streamed audio/video	supports	video:10K-	yes, poucos
Interactive gaming	supports	5Mbps	segs
Finance applications	lossless	See above	yes, 100's mseg
		Some Kbps	Yes and no
		elastic	

The communication network

The Mobile network

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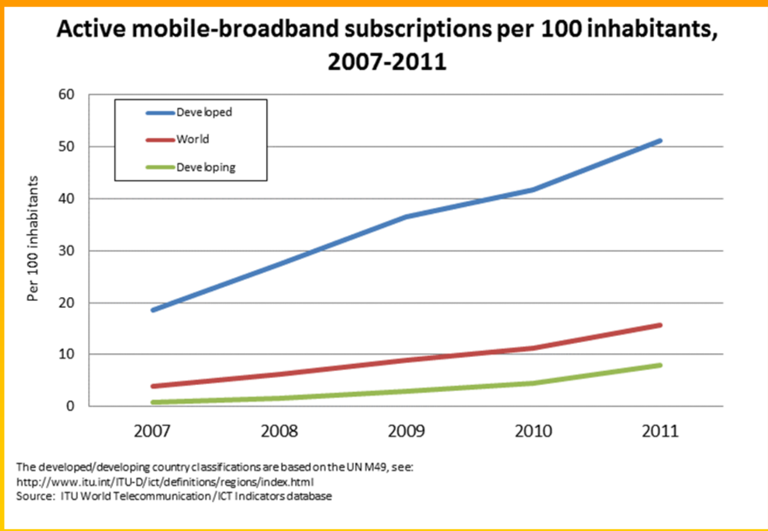
Data vs voice traffic

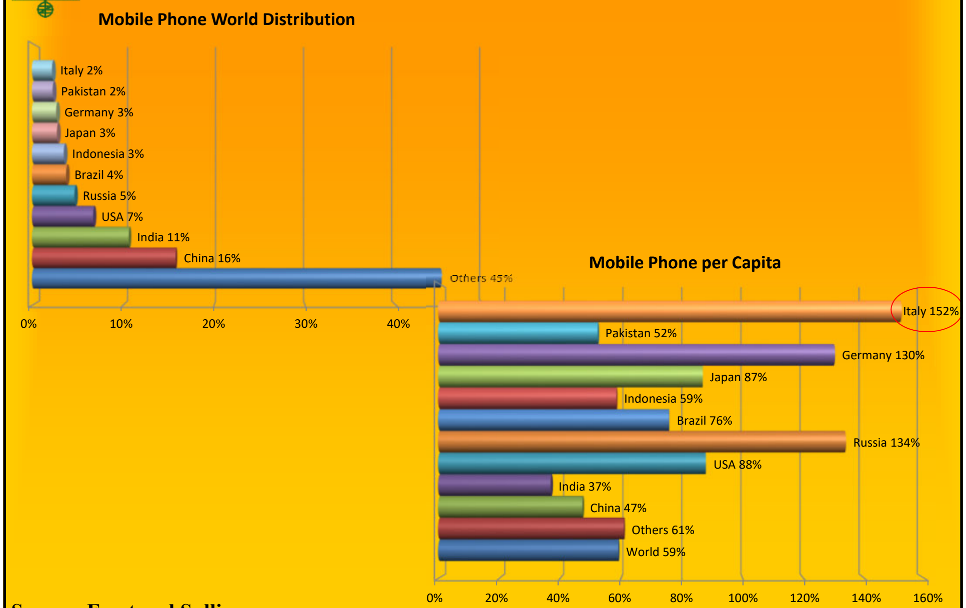


Dec/2004 → Sep/2014

- Global Mobile Users 1.52/6.91 billion (Analogue Users 34/0?m)
- Global GSM users 1.25/4.4 billion
- Global CDMA Users 202/701m Global TDMA users 120/0?m
- US Mobile users 140/ 335.6m
- Total European users 342.43/780m
- Total African users 53/629.7m
- Total 3G users 130m/ 1880m
- #1 Mobile Country China (300/1273m) (GSM 282/582m)
- #1 Network In Europe T-Mobil (28m)
- #1 In Infrastructure Ericsson
- Global monthly SMS 36/400 per user
- SMS Sent Global 135 billion/10000billion
- SMS sent in UK 3/2004 2.1 billion

Source: 3G world Stats

Mobile Market



Source: Frost and Sullivan

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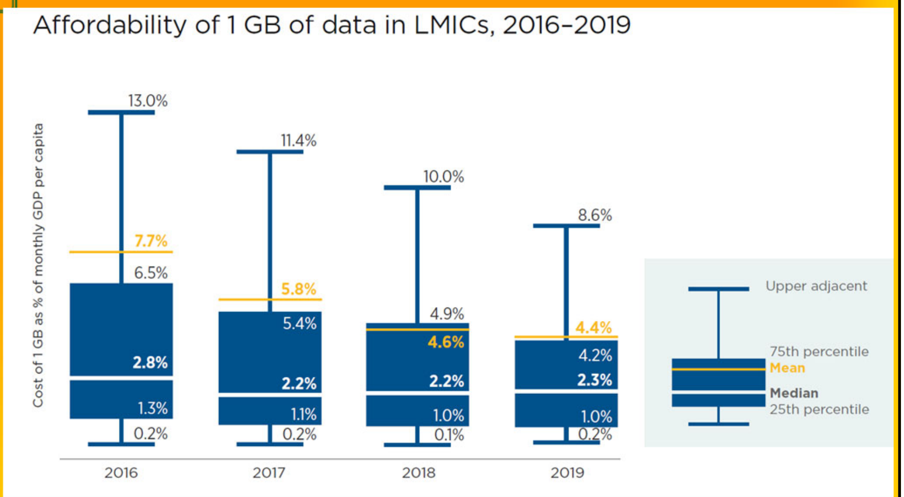

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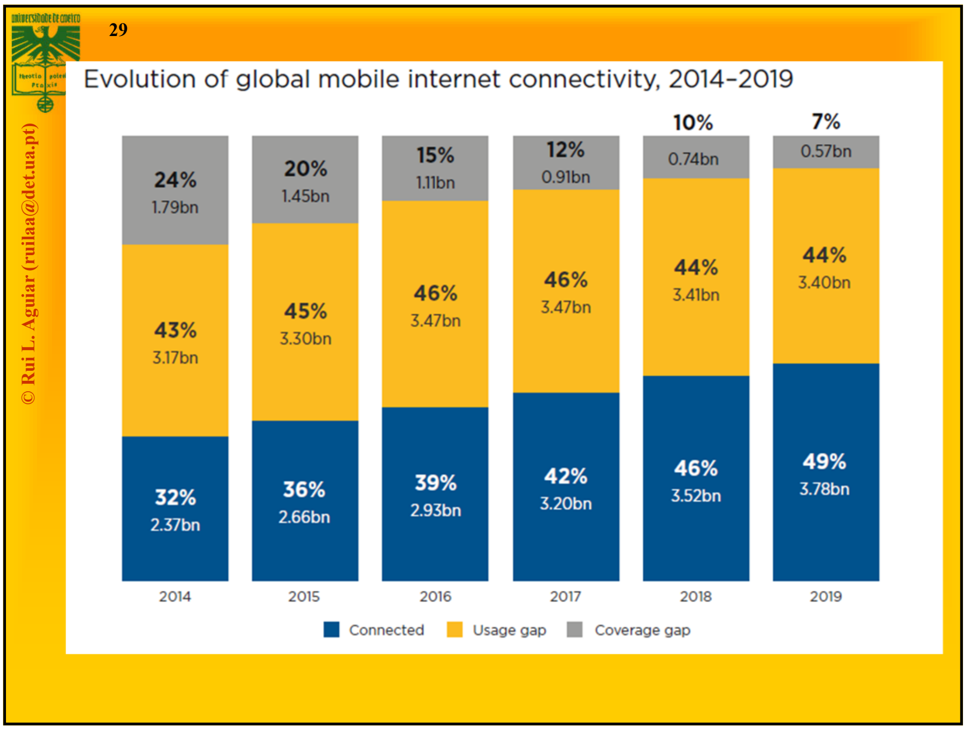
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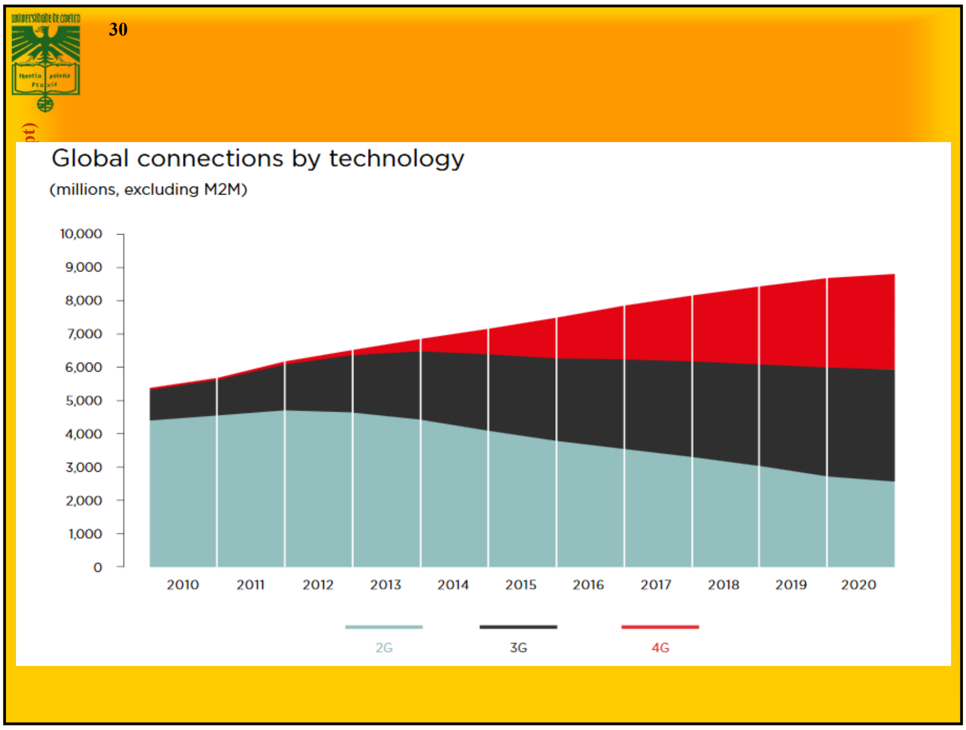
Evolution of global mobile internet connectivity, 2014–2019
24%
1.79bn
43%
3.17bn
32%
2.37bn
20%
1.45bn
45%
3.30bn
36%
2.66bn
15%
1.11bn
46%
3.47bn
39%
2.93bn
12%
0.91bn
46%
3.47bn
42%
3.20bn
10%
0.74bn
44%
3.41bn
46%
3.52bn
7%
0.57bn
44%
3.40bn
49%
3.78bn
2014
2015
2016
2017
2018
2019
Connected
Usage gap
Coverage gap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Global connections by technology
(millions, excluding M2M)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2G
3G
4G

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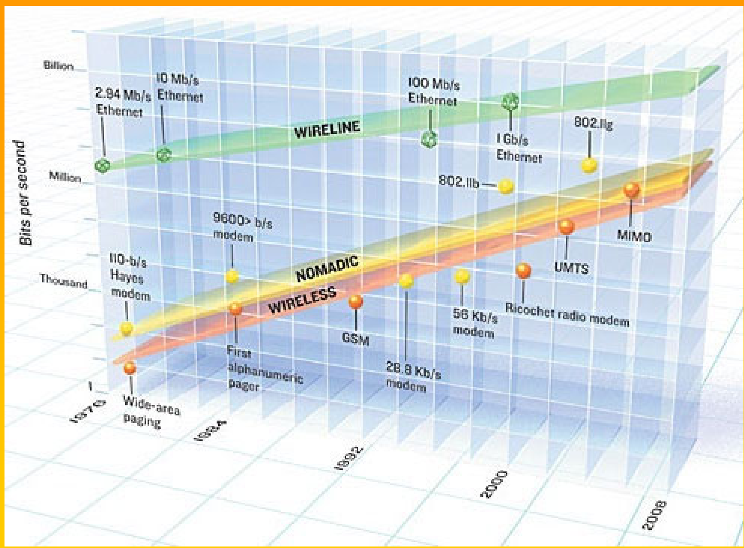
Edholm's Law



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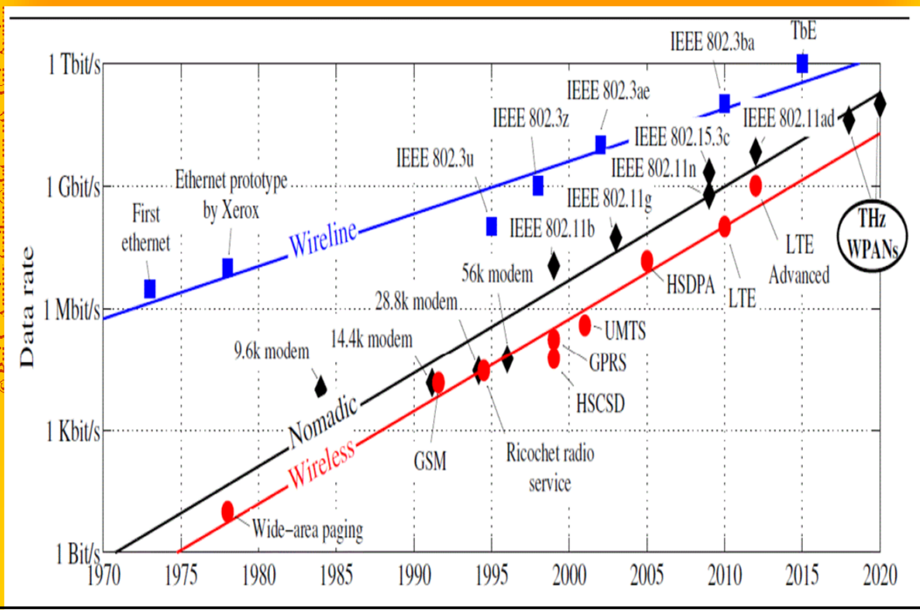
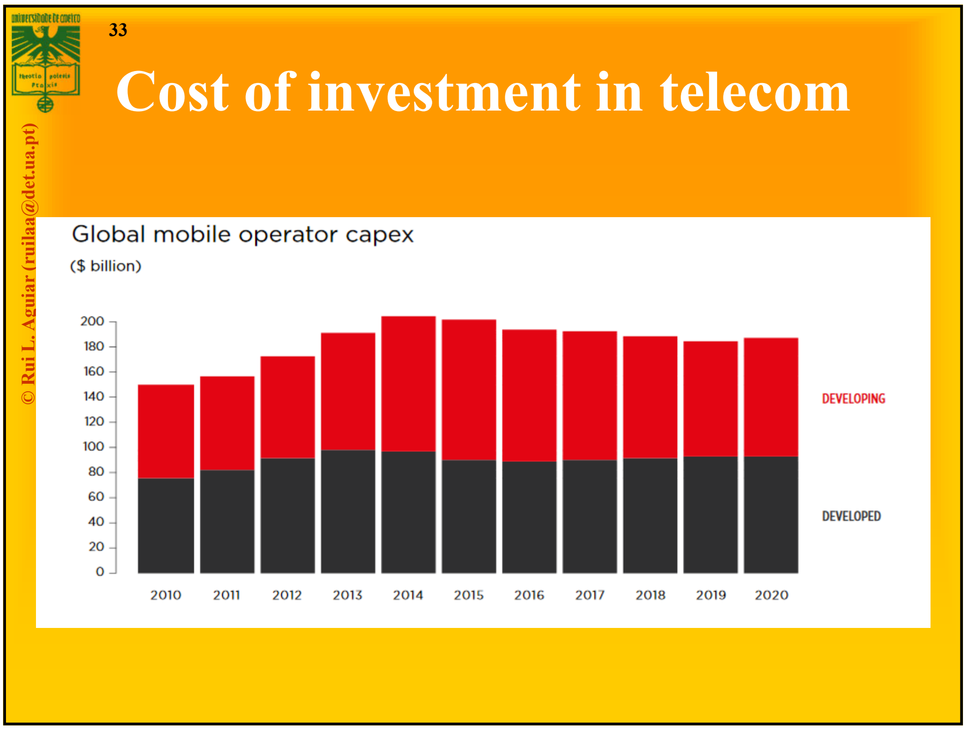
Edholm's Law

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Cost of investment in telecom
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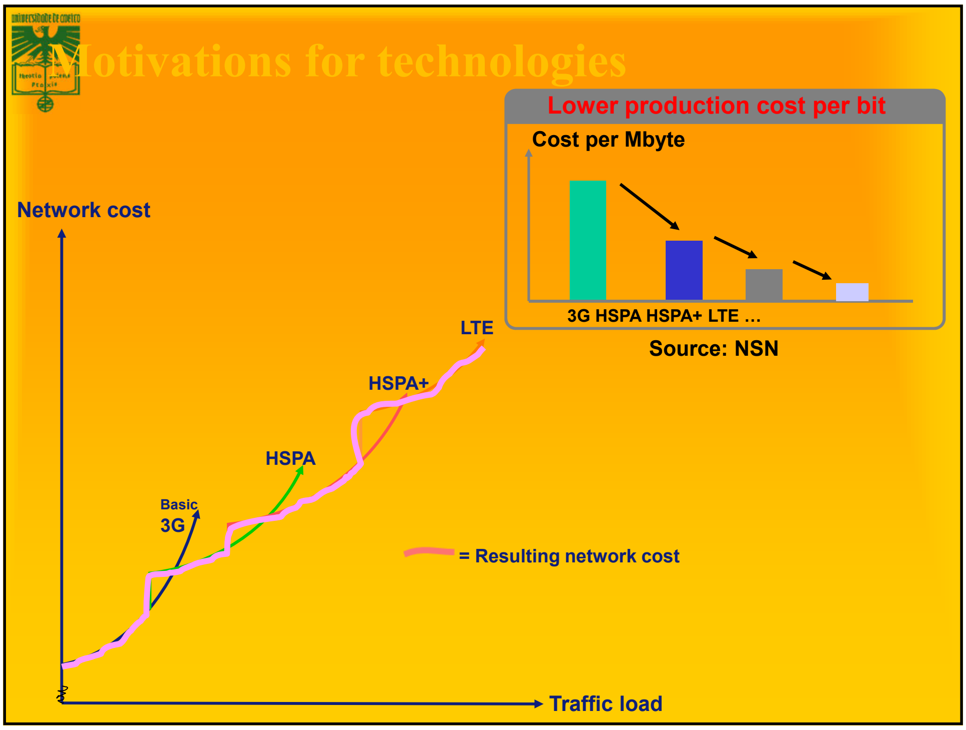
Global mobile operator capex
($ billion)
200
180
160
140
120
100
80
60
40
20
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
DEVELOPING
DEVELOPED


Motivations for technologies
Lower production cost per bit
Cost per Mbyte
3G HSPA HSPA+ LTE …
Source: NSN
Network cost
Basic 3G
HSPA
HSPA+
LTE
= Resulting network cost
Traffic load

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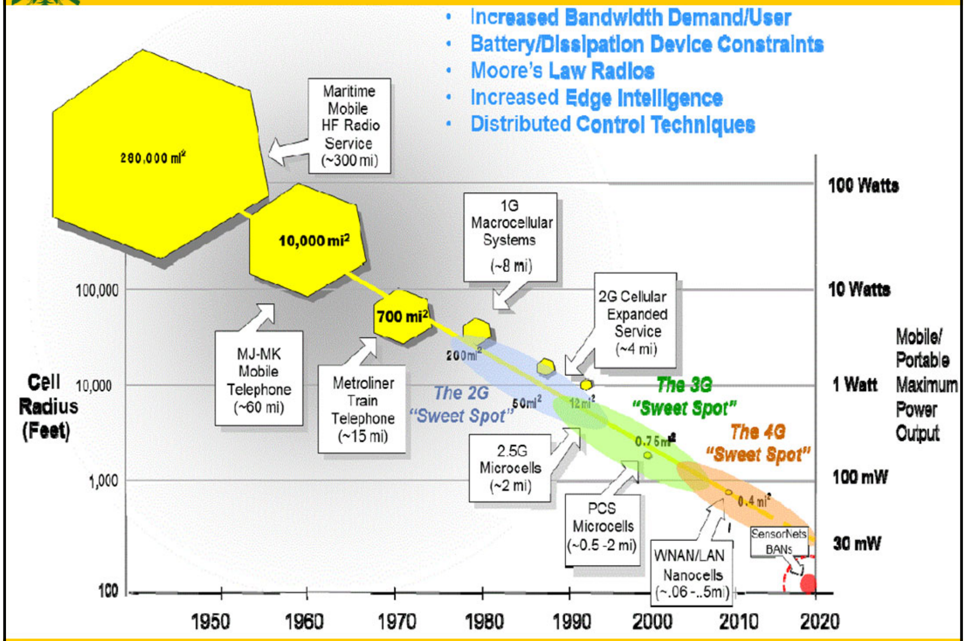

Increased Bandwidth Demand/User
Battery/Dissipation Device Constraints
Moore's Law Radios
Increased Edge Intelligence
Distributed Control Techniques
260,000 mi²
Maritime Mobile HF Radio Service (~300 mi)
10,000 mi²
1G Macrocellular Systems (~8 mi)
700 mi²
200 mi²
50 mi²
12 mi²
0.75 mi²
0.4 mi²
2G Cellular Expanded Service (~4 mi)
MJ-MK Mobile Telephone (~60 mi)
Metroliner Train Telephone (~15 mi)
The 2G "Sweet Spot"
The 3G "Sweet Spot"
The 4G "Sweet Spot"
2.5G Microcells (~2 mi)
PCS Microcells (~0.5 -2 mi)
WNAN/LAN Nanocells (~.06 -.5mi)
SensorNets BANs
Cell Radius (Feet)
100,000
10,000
1,000
100
1950
1960
1970
1980
1990
2000
2010
2020
100 Watts
10 Watts
1 Watt
100 mW
30 mW
Mobile/ Portable Maximum Power Output

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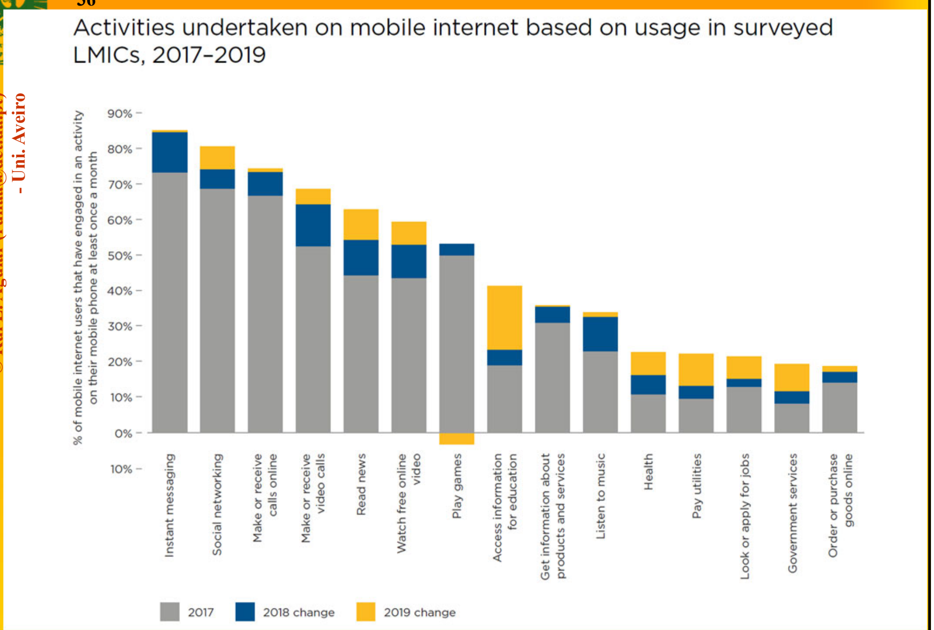
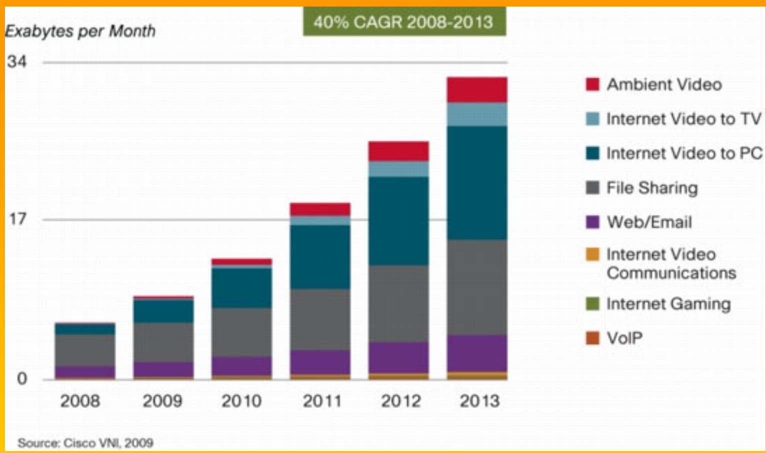


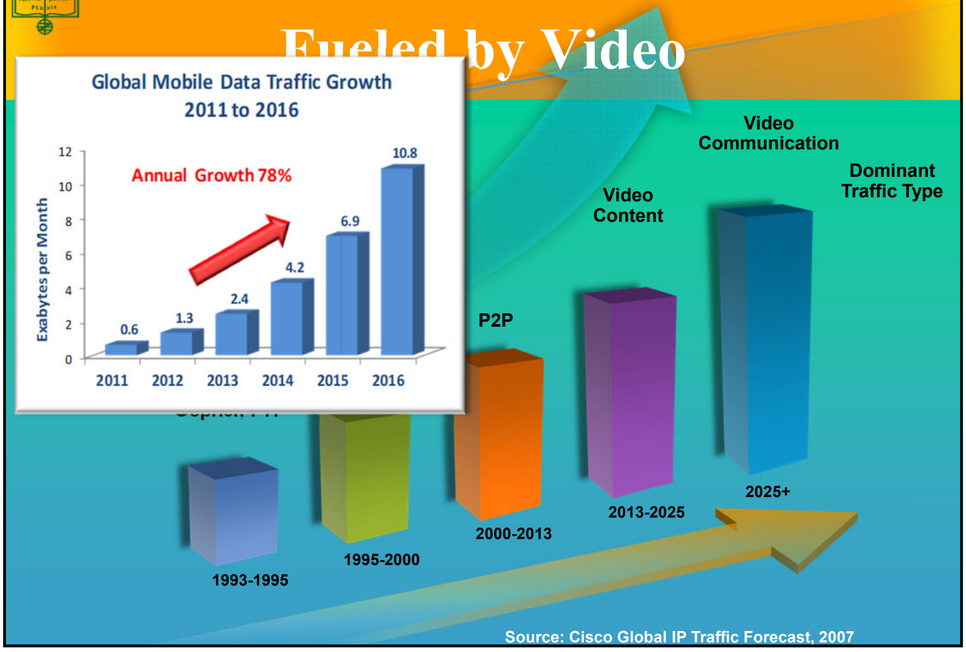
Activities undertaken on mobile internet based on usage in surveyed LMICs, 2017–2019
% of mobile internet users that have engaged in an activity on their mobile phone at least once a month
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
10%
Instant messaging
Social networking
Make or receive calls online
Make or receive video calls
Read news
Watch free online video
Play games
Access information for education
Get information about products and services
Listen to music
Health
Pay utilities
Look or apply for jobs
Government services
Order or purchase goods online
2017
2018 change
2019 change

Consumer Traffic, VNI



- http://newsroom.cisco.com/dlls/2009/prod_060909.html
- **1 Exabyte is appr. 250 mill. DVD's**

Dramatic Traffic Growth Fueled by Video



The things that surrond us

ICSNC 2009, Rui L Aguiar

Source: EC

Network is now more than bits and bytes – it adapt to users

Context

Security

Identity

Authentication

Services

Mobility

Quality of Experience

Charging

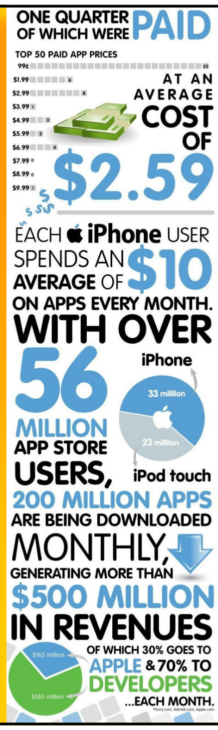
Accounting

… and many others …

Service market (2016)

Mobile Services are now a major contention between operators and manufacturers (AppleStore, OviStore, Android Market, Palm App Catalog)

Source: GigaOM



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Service market

Mobile Services are now a major contention between operators and manufacturers (AppleStore, OviStore, Android Market, Palm App Catalog)

Source: GigaOM

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The (mobile) Internet economy (2016)

Rank	Company	Region	Current Market Value ($B)	Q1:16 Cash ($B)	2015 Revenue ($B)
1	Apple	USA	$547	$233	$235
2	Google / Alphabet	USA	510	79	75
3	Amazon	USA	341	16	107
4	Facebook	USA	340	21	18
5	Tencent	China	206	14	16
6	Alibaba	China	205	18	15
7	Priceline	USA	63	11	9
8	Uber	USA	63	--	--
9	Baidu	China	62	11	10
10	Ant Financial	China	60	--	--
11	Salesforce.com	USA	57	4	7
12	Xiaomi	China	46	--	--
13	Paypal	USA	46	6	9
14	Netflix	USA	44	2	7
15	Yahoo!	USA	36	10	5
16	JD.com	China	34	5	28
17	eBay	USA	28	11	9
18	Airbnb	USA	26	--	--
19	Yahoo! Japan	Japan	26	5	5
20	Didi Kuaidi	China	25	--	--
Total			$2,752	$447*	$554*

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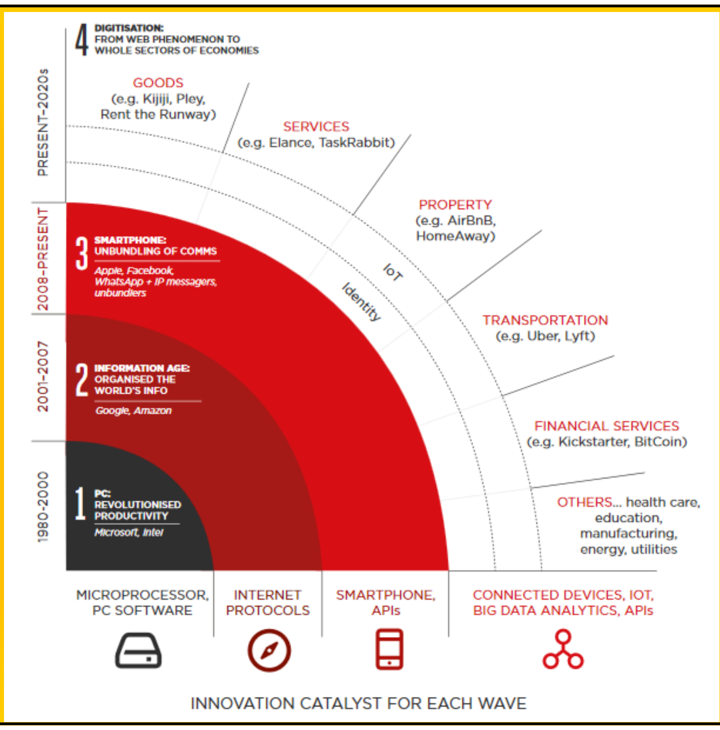
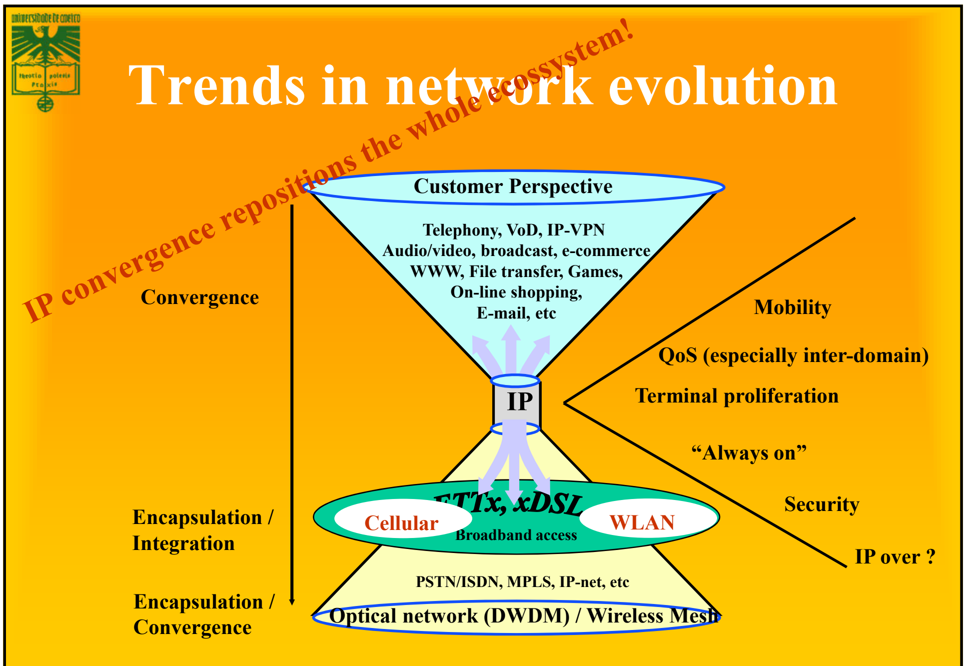


User behaviour and trends

- Increased Internet—based services
  - Phone market is now saturated
  - “Everything” came to “data communications”
- Increased broadband requirements
  - P2P being replaced by service-based
  - Internet access 2x every 2 years – fiber access now blooming
  - 70% broadband penetration
- Increased mobility and roaming
  - Always on and session continuity
  - Increased end-user content
    - Both WLAN and 4G
  - Increased context information
    - Increased personalization
    - Increased machine/vehicle/object communications

Trends in network evolution



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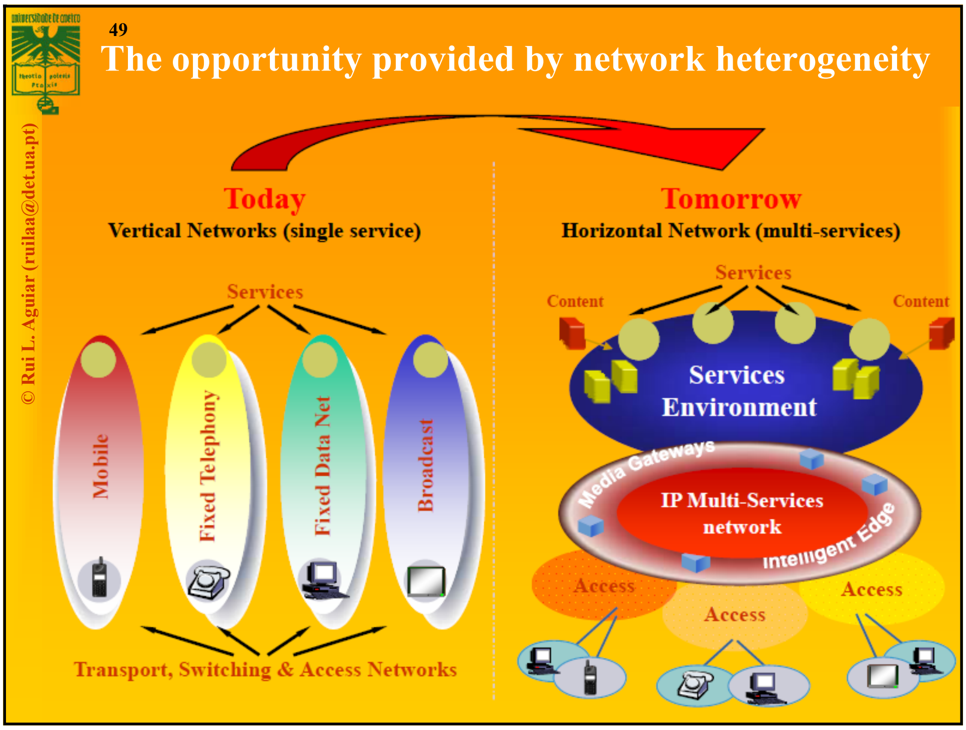
Source: Siemens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The opportunity provided by network heterogeneity
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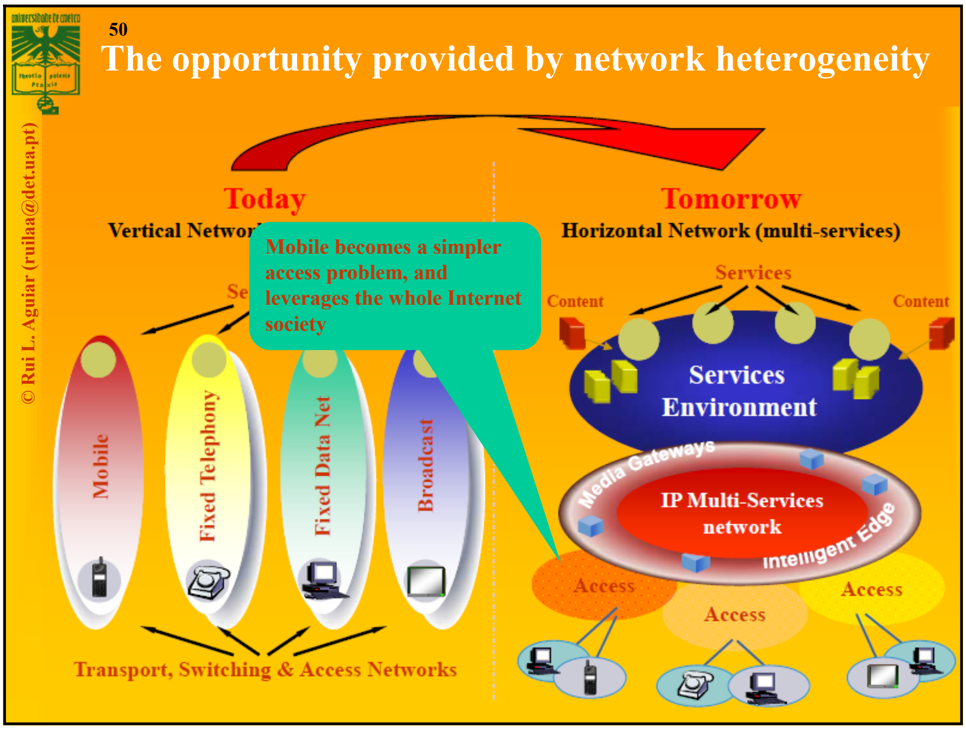
Today
Vertical Networks (single service)
Services
Mobile
Fixed Telephony
Fixed Data Net
Broadcast
Transport, Switching & Access Networks
Tomorrow
Horizontal Network (multi-services)
Services
Content
Content
Services Environment
Media Gateways
IP Multi-Services network
Intelligent Edge
Access
Access
Access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The opportunity provided by network heterogeneity
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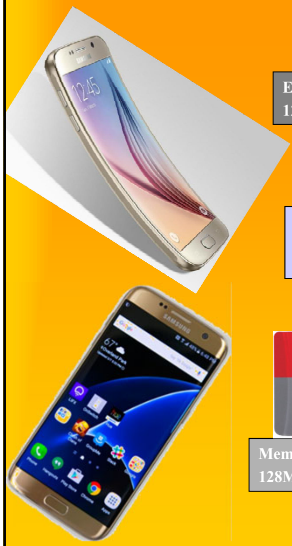
Today
Vertical Networ
Mobile becomes a simpler access problem, and leverages the whole Internet society
Mobile
Fixed Telephony
Fixed Data Net
Broadcast
Transport, Switching & Access Networks
Tomorrow
Horizontal Network (multi-services)
Services
Content
Content
Services Environment
Media Gateways
IP Multi-Services network
Intelligent Edge
Access
Access
Access

A Mobile Storage Revolution



…..

Embedded Flash
128MB >>> 64GB

- Small size to minimise handset cost
- Used for storing system data: applications, messages, contacts, ring-tones

Embedded (SD/H)DD
2GB >>> 256GB

- Large storage for user content
- But high impact on terminal cost

Memory Card
128MB >>> 1TB

- Large and removable storage for easy transfer of user content
- Interoperable with other consumer electronic devices
- Provides a distribution channel for selling content

… and a Multiplicity of Local Connectivity…

Today

- Bluetooth
- WiFi
- Memory cards
- USB
- Near Field Communications
  - device pairing & local network configuration
  - service discovery/initiation

Tomorrow

All of the above with the addition of:

- WLAN+ (802.11g++)
  - home and office connectivity
  - wireless extension of DSL in the home
- UWB
  - wireless USB
- TV/DVB

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The wireless framework

- Mobile systems is THE major business
- Operators are becoming increasingly focused on mobile customers
  - Most of market will be wireless anyway on the access
- Services are now a dominant aspect in this arena
  - Large economic fights ongoing
- Mobility brought a novel importance to LBS
  - Now proximity is a dynamic variable for the user

What's going on here?

But what is all the tech fuss about?

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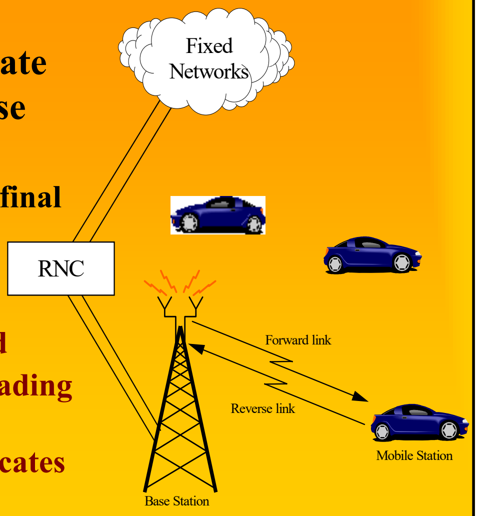
Wireless Systems

- Mobiles users communicate through fixed points (Base Stations/Access Points)
- Rely on radio transmission - final link between terminals and network
  - Finite resource, spectrum available is strictly limited
  - Multipath propagation, fading & interference
  - Terminal mobility complicates the system



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Mobile hassles

1. Wireless connections limitations
   - Multiple independent networks and technologies
   - (frequent) connection dropouts
   - (More) limited bandwidth
   - Lacking of mobility awareness by system/applications
2. Spectrum limitations
   - Bandwidth cannot be improved just by adding parallel connections
   - Spectrum is highly regulated
3. Mobile device limitations
   - Battery lifetime
   - Limited capabilities
4. Scaling considerations
   - Mobile devices counted by the 1.000 millions
   - Cost(s) needs to be low
   - Energy is becoming a problem

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Device Issues

- **By their own nature:**

SMALL!
LOW POWER!

- **Potentially Low Power devices**
  - **Limited computing performance**
  - **Low quality displays**
- **Potential Loss of Data**
  - **Easily lost**
  - **Must be conceived as being "network-integrated"**
- **Potentially small and limited User Interface**
  - **Limited real estate for keyboards**
  - **Icon intensive/handwriting/speech**
- **Potentially Small Local Storage**
  - **Flash memory rather than disk drive**

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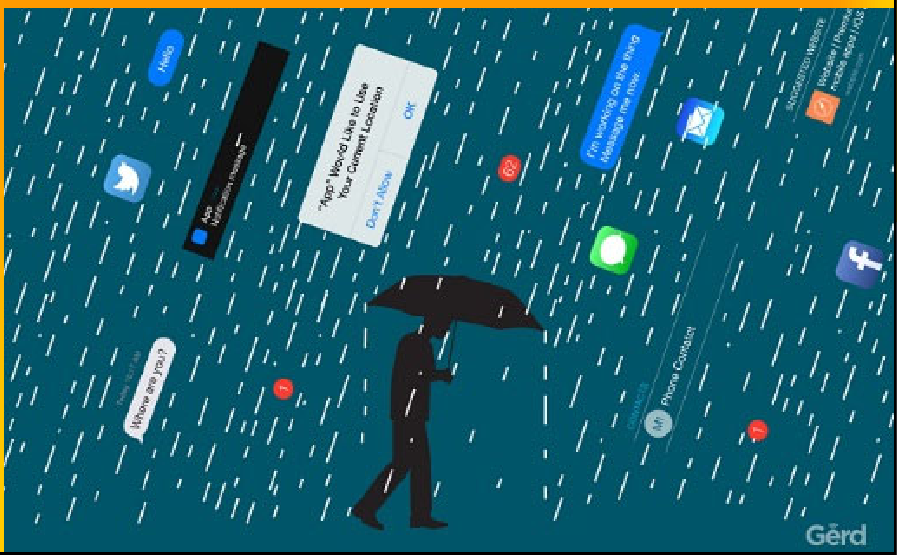
Scaling: You mean *Everywhere?!?!*



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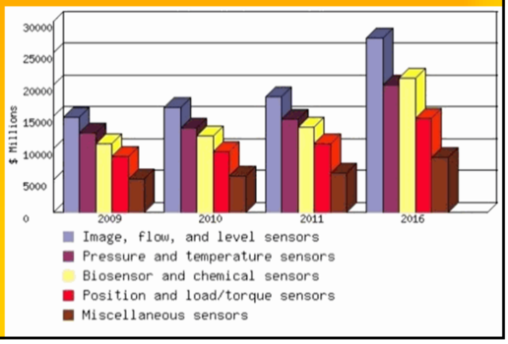
Scaling: You mean *Everywhere?!?!*

– 6.000 million users
– x10 sensors
– x2 general purpose computers
– x5 special purpose devices

☺☺☺

☹



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Remember!

- Addressing
  – Total number of IPv4 addresses is ~4 200 millions
- Routing
  – Routing tables are already quite large
- Security
  – Securing everything? With certificates?
- Multimedia bandwidths
  – In wireless?!?
- Sensors and actuators
  – Electric grid on the net?!?!

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Why is mobile hard?

- Mobile communications are hard to handle, specially because spectrum is a scarce good
  - One critical economic issue from the governments point of view
- Also the whole nature of mobile systems is problematic – including the device specific issues
  - Although it is improving, power is still a problem
- As mobile systems became dominant (even into broadband!), scaling is a problem
  - We never dreamed with such a large success

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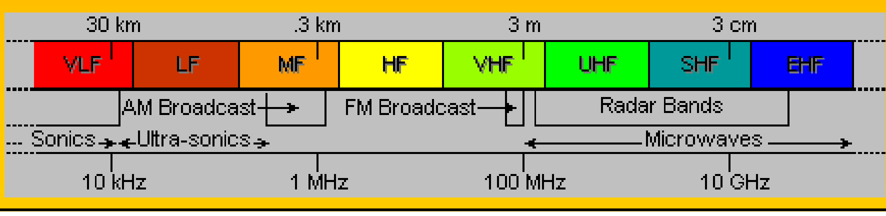
It gets worse than this: RF Spectrum

- RF Spectrum = Radio Frequency allocation
  - Electromagnetic signal that propagates through “ether” at the speed of light ☺
  - Ranges 3 KHz .. 300 GHz
    - Omnidirectional applications
    - Directional applications (above 5/10 GHz)
  - Or 100 km .. 0.1 cm (wavelength)



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Spectrum (only) looks like a lot!

- **300 GHz is huge amount of spectrum!**
  - Spectrum can also be reused in space
- **Not quite that much:**
  - Most of it is hard or expensive to use!
  - Noise and interference limits efficiency
  - Most of the spectrum is allocated by Regulators
  - ISM bands unlicensed – but subject to multiple constraints
- **Governments control who can use the spectrum and how it can be used.**
  - (ITU-T WRC. Anacom, Oftel, FCC…)
  - Need a license for most of the spectrum
  - Limits on power, placement of transmitters, coding, ..
  - Need rules to optimize benefit: guarantee emergency services, simplify communication, return on capital investment, …

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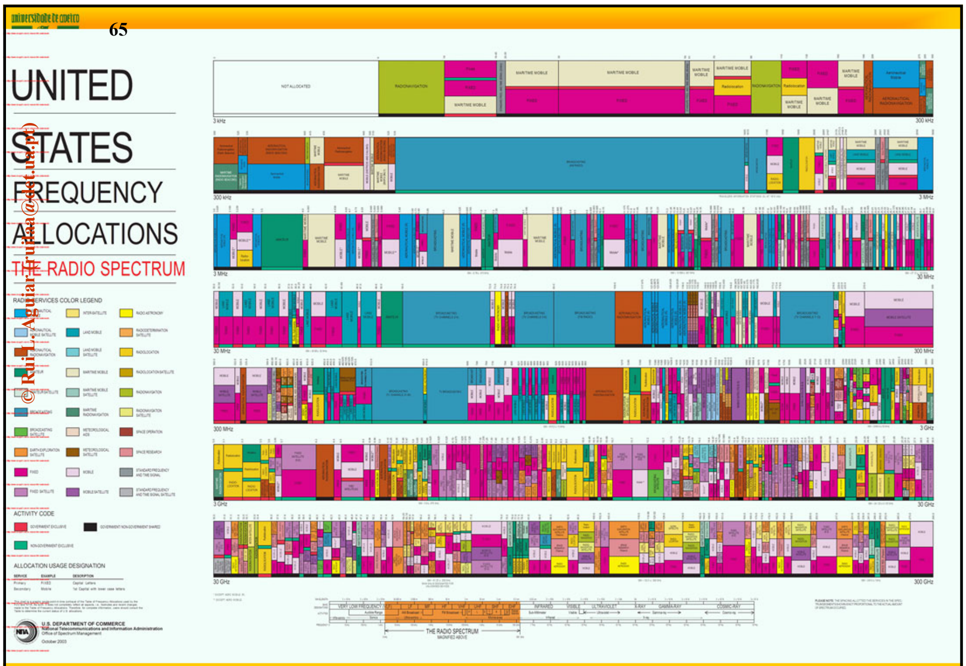

Source: FCC

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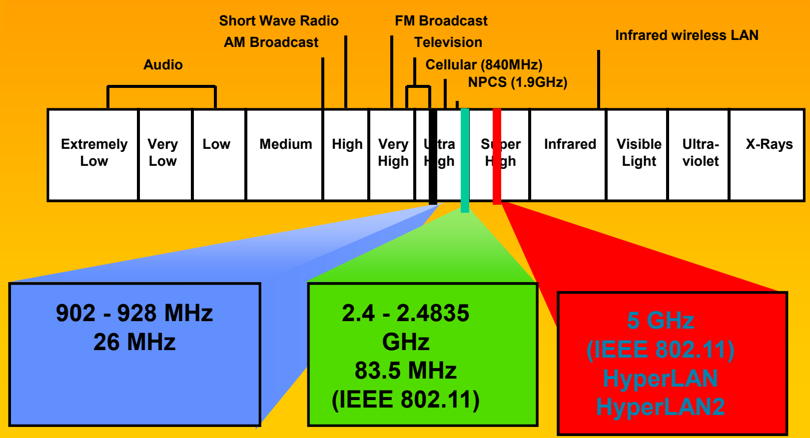
General Frequency Ranges

- Microwave frequency range
  - 1 GHz to 40 GHz and higher
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Infrared frequency range
  - Roughly, $3x10^{11}$ to $2x10^{14}$ Hz
  - Useful in local point-to-point multipoint applications within confined areas

Frequency Bands

- Industrial, Scientific, and Medical (ISM) bands
- Unlicensed, 22 MHz channel bandwidth



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Portugal

http://www.anacom.pt/streaming/qnafuk.pdf?contentId=29658&field=ATTACHED_FILE

http://www.anacom.pt/streaming/qnaf0506_integral_uk.pdf?contentId=354390&field=ATTACHED_FILE

Physical Layer

Problems we face

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Classifications of Transmission Media

- Copper: twisted pair versus coax cable
  - Variety of modulation techniques are used
- Fiber: modulate an optical signal
  - Lots of capacity available!
  - Typically uses simple modulation schemes
- Wireless: no solid medium to guided signal
  - Wide variety of distances: frequencies, distances, …
  - Often uses very aggressive modulation techniques (later)

Why Use Wireless?

There are no wires!

Has several significant advantages:

- No need to install and maintain wires
  - Reduces cost – important in offices, hotels, …
  - Simplifies deployment – important in homes, hotspots, …
- Supports mobile users
  - Move around office, campus, city, … - users get hooked
  - Remote control devices (TV, garage door, ..)
  - Cordless phones, cell phones, ..
  - WiFi, GPRS, WiMax, …

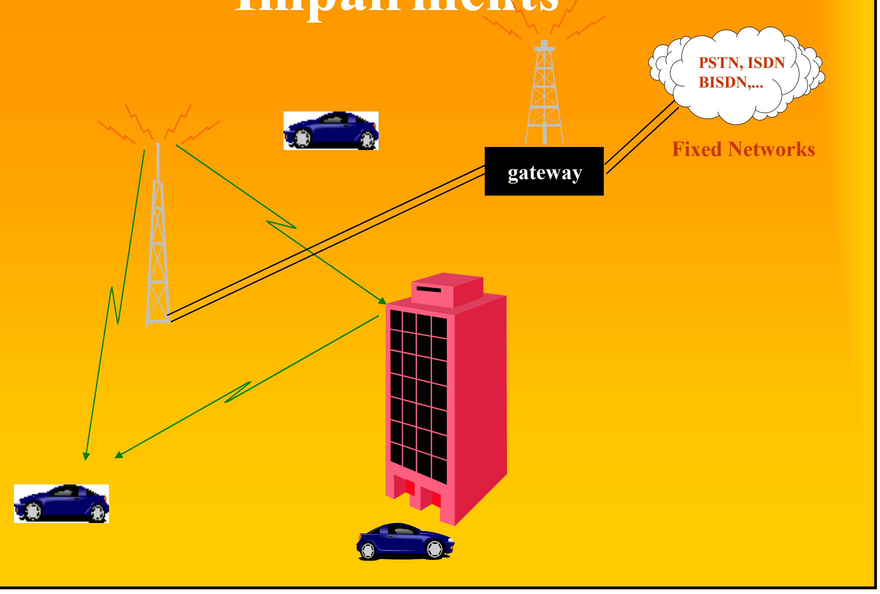
What is Hard about Wireless?

There are no wires!

Causes problems in many areas:

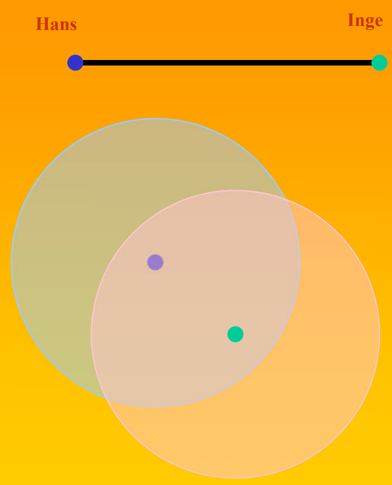
- **Quality of transmission**
- **Interference and noise**
- **Capacity of the network**
- **Effects of mobility**

Radio Transmission Impairments



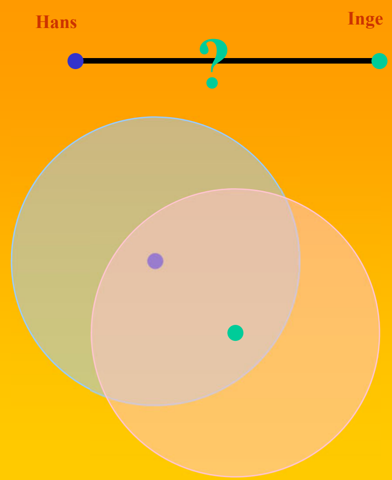
Communication based on Broadcasting

- **Wired communication is usually point-to-point.**
  - **Broadcast is hard to scale**
- **Wireless communication is inherently broadcast.**
  - **Well, usually**
- **Of course: it does allow nodes to move**



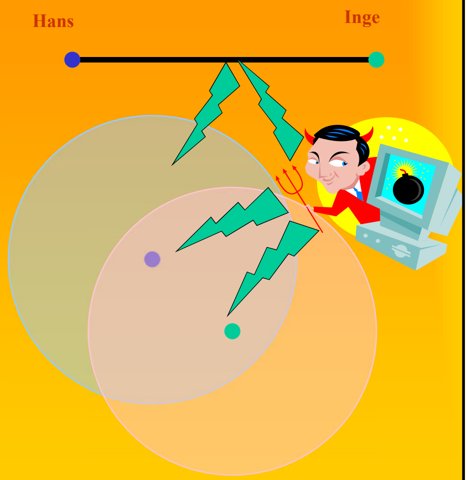
Mobility

- **Wired communication is usually point-to-point.**
  - **Broadcast is hard to scale**
- **Wireless communication is inherently broadcast.**
  - **Well, usually**
- **Of course: it does allow nodes to move**



Wireless is very Sensitive to Noise …

- Noise is naturally present in the environment from many sources.
- Interference can be from other users or from malicious sources.
- Impacts the throughput users can achieve.



… and Interference

- Noise is naturally present in the environment from many sources.
- Interference can be from other users or from malicious sources.
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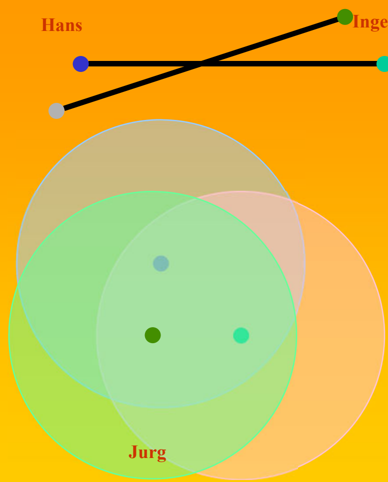
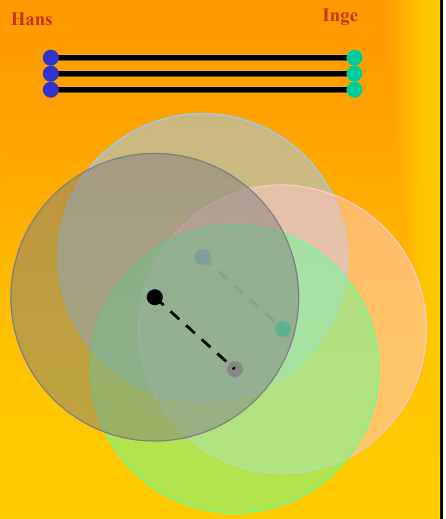


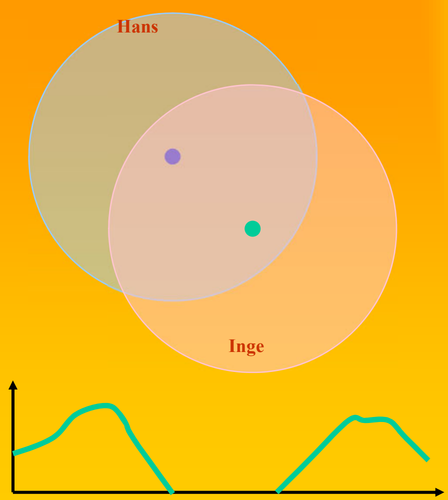
How Do We Increase Network Capacity?

- Easy to do in wired networks: simply add wires.
  - Fiber is especially attractive
- Adding wireless "links" increases interference.
  - Frequency reuse can help … subject to spatial limitations
  - Or use different spaces … subject to frequency limitations
- The capacity of the wireless network is fundamentally limited.



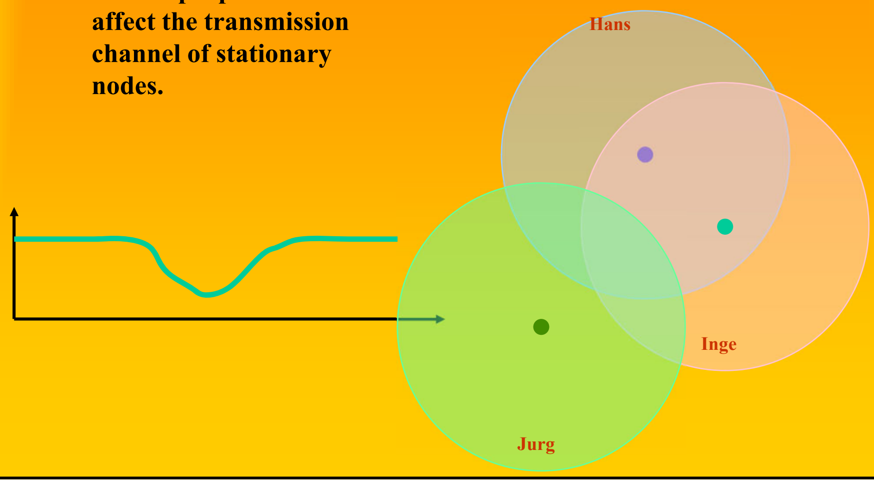
Mobility Affects the Link Throughput

- Quality of the transmission depends on distance and other factors.
  - Covered later in the course
- Affects the throughput mobile users achieve.
- Worst case is periods with no connectivity!



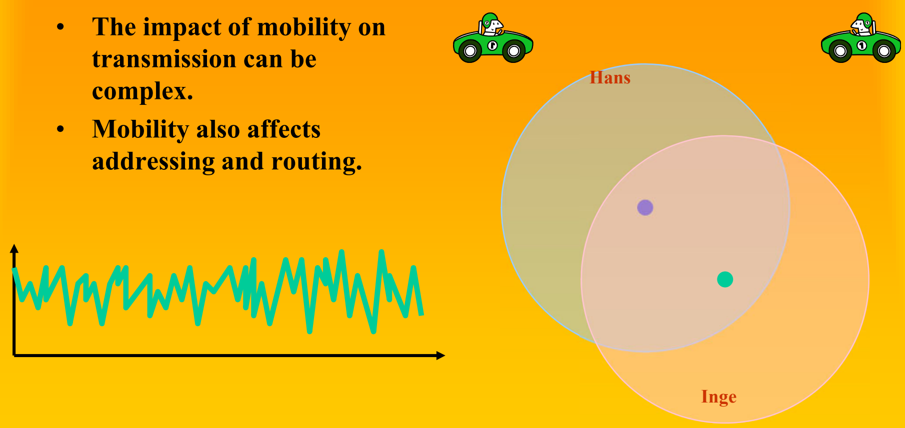
Mobility is an Issue even for Stationary Users

- **Mobile people and devices affect the transmission channel of stationary nodes.**



And It Gets Worse …

- **The impact of mobility on transmission can be complex.**
- **Mobility also affects addressing and routing.**



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Time-Domain View

- **Can be used to represent both an analog and a digital signal.**
- **Analog signal - signal intensity varies in a smooth fashion over time**
  - **No breaks or discontinuities in the signal**
  - **E.g. voice signal traveling over traditional phone line**
- **Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level.**
  - **E.g. stream of 1 and 0 values represented as "low" and "high" signal**

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Periodic versus Aperiodic Signals

- **Periodic signal - analog or digital signal pattern that repeats over time**
  - $s(t+T) = s(t)$
    - where T is the period of the signal
  - **Allows us to take a frequency view**
- **Aperiodic signal - analog or digital signal pattern that doesn't repeat over time**
- **Can "make" an aperiodic signal periodic by taking a slice T and repeating it**
  - **Often what we do implicitly**

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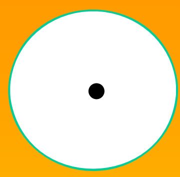
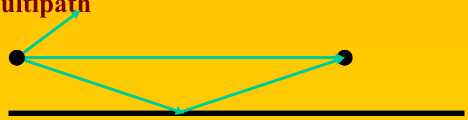
Two Graphical Views of an Electromagnetic Signal

- Both are real in some way
- Think of it as energy that radiates from an antenna and is picked up by another antenna.
  - Helps explain properties such as attenuation
- Can also view it as a “ray” that propagates between two points.
  - Helps explain properties such as reflection and multipath





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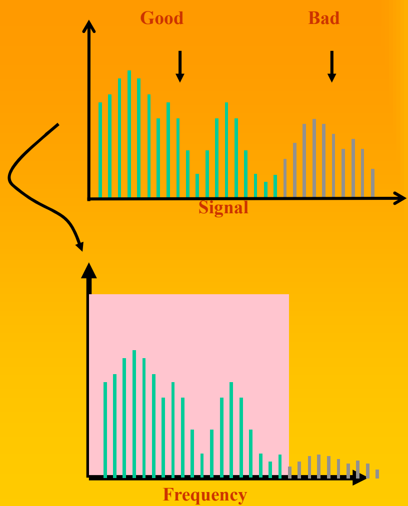
Transmission Channel Considerations

- Example: green frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the channel
  - Different types of fiber and copper have different properties
- As technology improves, these parameters change, even for the same wire
  - Electronics rule
- For wireless networks, limits are often imposed by policy
  - Can only use certain part of the spectrum
  - Regulatory/business considerations



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Channel Capacity

- **Data rate - rate at which data can be communicated (bps)**
  - **Channel Capacity – the maximum rate at which data can be transmitted over a given channel, under given conditions**
- **Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)**
- **Noise - average level of noise over the communications path**
- **Error rate - rate at which errors occur**
  - **Error = transmit 1 and receive 0; transmit 0 and receive 1**

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The Nyquist Limit

- **A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity 2B**
  - **E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second**
  - **Assumes binary amplitude encoding**
- ***For M levels:*** $C = 2B \log_2 M$
  - **M discrete signal levels**
- **More aggressive encoding can increase the actual channel bandwidth**
  - **Example: modems**
- **Factors such as noise can reduce the capacity**

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Shannon Capacity Formula

- **Equation:** $$C = B\log_2(1+\mathrm{SNR})$$
- **Represents theoretical maximum that can be achieved**
- **In practice, only much lower rates achieved**
  - **Formula assumes white noise (thermal noise)**
  - **Impulse noise is not accounted for**
  - **Attenuation distortion or delay distortion not accounted for**
- **We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel.**

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What is an Antenna?

- **Conductor that carries an electrical signal and radiates an RF signal.**
  - **The RF signal "is a copy of" the electrical signal in the conductor**
- **Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.**
  - **This signal can be interpreted (i.e. decoded)**
- **Efficiency of the antenna depends on its size, relative to the wavelength of the signal.**
  - **E.g. half a wavelength**

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Types of Antennas

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- Abstract view: antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic.
  - Not common – shape of the conductor tends to create a specific radiation pattern
  - Note that isotropic antennas are not very efficient!!
    - Unless you have a very large number of receivers
- Common shape is a straight conductor.
  - Creates a "disk" pattern
- Shaped antennas can be used to direct the energy in a certain direction.
  - Well-known case: a parabolic antenna
  - Pringles boxes are cheaper

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Directional Antenna Properties

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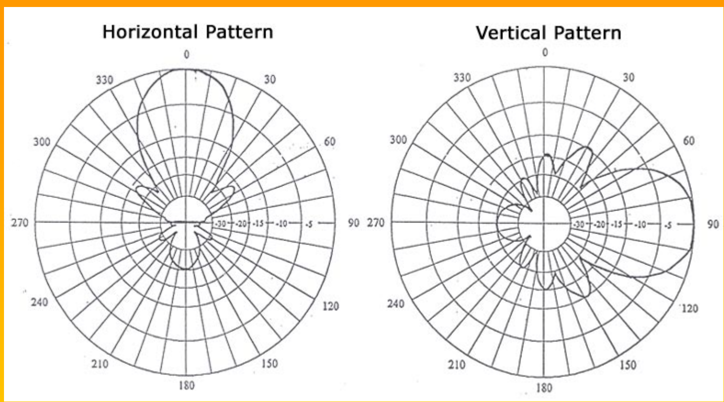

- dBi: antenna gain in dB relative to an isotropic antenna with the same power.
  - Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)

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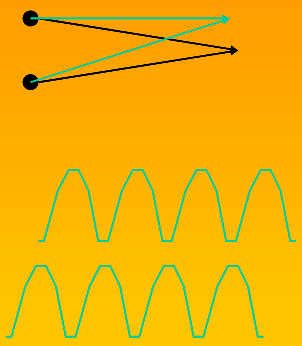
Multi-element Antennas

- **Multi-element antennas have multiple, independently controlled conductors.**
  - Signal is the sum of the individual signals transmitted (or received) by each element
- **Can electronically direct the RF signal by sending different versions of the signal to each element.**
  - For example, change the phase in two-element array.
- **Covers a lot of different types of antennas.**
  - Number of elements, relative position of the elements, control over the signals, …



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Propagation Modes

- **Line-of-sight (LOS) propagation.**
  - Most common form of propagation
  - Happens above ~ 30 MHz
  - Subject to many forms of degradation (next set of slides)
- **Ground-wave propagation.**
  - More or less follows the contour of the earth
  - For frequencies up to about 2 MHz, e.g. AM radio
- **Sky wave propagation.**
  - Signal “bounces” off the ionosphere back to earth – can go multiple hops
  - Used for amateur radio and international broadcasts

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Propagation Degrades RF Signals

- Attenuation in free space: signal gets weaker as it travels over longer distances
  - Radio signal spreads out – free space loss
  - Refraction and absorption in the atmosphere
  - Frequency dependent!
- Obstacles can weaken signal through absorption or reflection.
  - Part of the signal is redirected
- Multi-path effects: multiple copies of the signal interfere with each other.
  - Similar to an unplanned directional antenna
- Mobility: moving receiver causes another form of self interference.
  - Node moves ½ wavelength -> big change in signal strength

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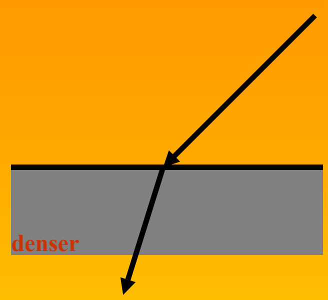
Refraction

- Speed of EM signals depends on the density of the material
  - Vacuum: 3×10^8 m/sec
  - Denser: slower
- Density is captured by refractive index
- Explains "bending" of signals in some environments
  - E.g. sky wave propagation
  - But also local, small scale differences in the air



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Free Space Loss

$$Loss = P_t / P_r = (4\pi\ d)^2 / (G_r\ G_t\ \lambda^2)$$
$$= (4\pi\ f\ d)^2 / (G_r\ G_t\ c^2)$$

- Loss increases quickly with distance (d^2).
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss depends on frequency: higher loss with higher frequency.
  - Can cause distortion of signal for wide-band signals

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Noise Sources

- Thermal noise: caused by agitation of the electrons
  - Function of temperature
  - Affects electronic devices and transmission media
- Intermodulation noise: result of mixing signals
  - Appears at $f_1 + f_2$ and $f_1 - f_2$
    - (when is this useful?)
- Cross talk: picking up other signals
  - E.g. from other source-destination pairs)
- Impulse noise: irregular pulses of high amplitude and short duration
  - Harder to deal with

Fairly Predictable
➢Can be planned for or avoided

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Other LOS Factors

- **Absorption of energy in the atmosphere.**
  - **Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)**
  - **Obviously objects also absorb energy**

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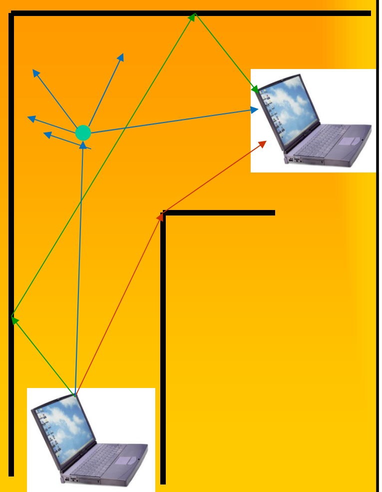
Propagation Mechanisms

- **Besides line of sight, signal can reach receiver in three other “indirect” ways.**
- **Reflection: signal is reflected from a large object.**
- **Diffraction: signal is scattered by the edge of a large object – “bends”.**
- **Scattering: signal is scattered by an object that is small relative to the wavelength.**



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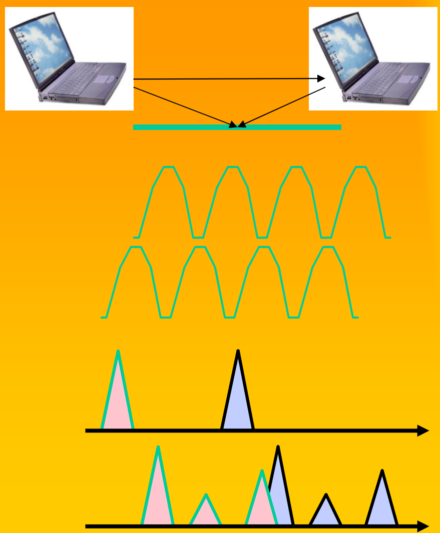
Multipath Effects

- Receiver receives multiple copies of the signal, each following a different path.
- Copies can either strengthen or weaken each other.
  - Depends on whether they are in our out of phase
- Small changes in location can result in big changes in signal strength.
  - Short wavelengths, e.g. 2.4 GHz -> 12 cm
- Difference in path length can cause intersymbol interference (ISI).



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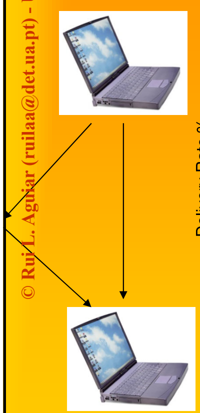
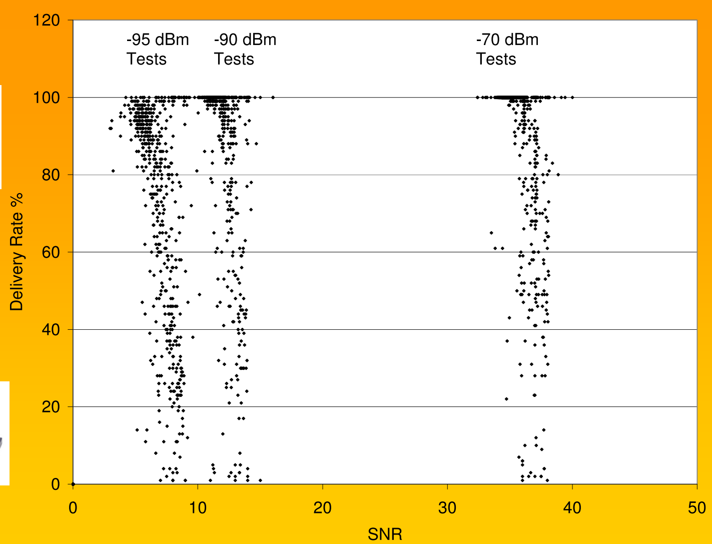
Multipath: "Random" Delivery Rates





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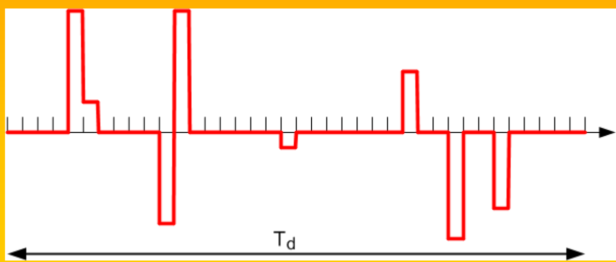
Multipath Channel Model

- Block constant: T_c coherence time
- Delay spread T_d
- L independent paths



T_c in the order of msec
T_d around 100 nsec, much smaller than T_c

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Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - Rain, moving objects, moving sender/receiver, …
- Fast versus slow fading.
  - Fast: changes in distance of about half a wavelength – result in big fluctuations in the instantaneous power
  - Slow: changes in larger distances affects the paths – result in a change in the average power levels around which the fast fading takes place
- Selective versus non-selective (flat) fading.
  - Does the fading affect all frequency components equally
  - Region of interest is the spectrum used by the channel

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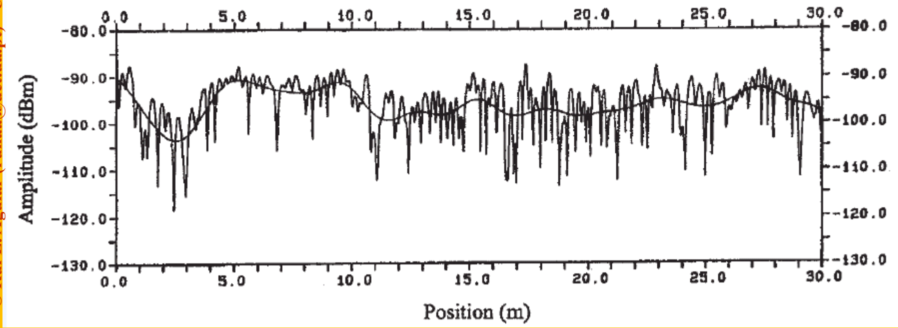
Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

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Fading Channel Models

- Statistical distribution that captures the properties of classes of fading channels.
- Raleigh distribution: multiple indirect paths but no dominating, direct LOS path.
  - E.g. urban environment with large cells, in buildings
- Ricean distribution: LOS path plus indirect paths.
  - Open space or small cells

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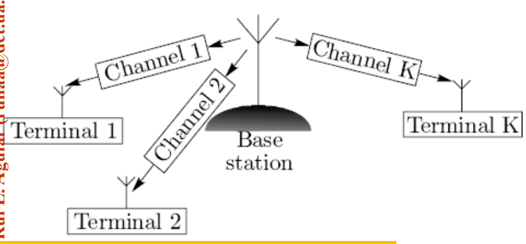
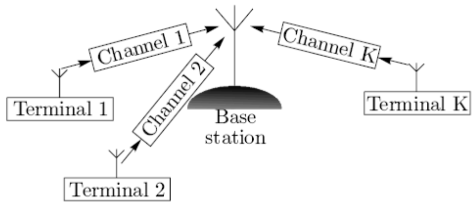
Uplink and downlink models

$$r_n(t) = (s * g_n)(t).$$



$$r(t) = \sum_{n=1}^{K} (s_n * g_n)(t)$$



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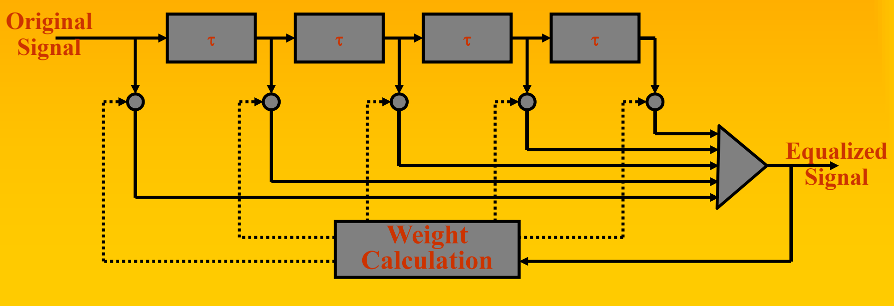
Dynamic Equalization

- Goal is to deal with intersymbol interference
- Idea is to combine multiple delayed copies of the signal



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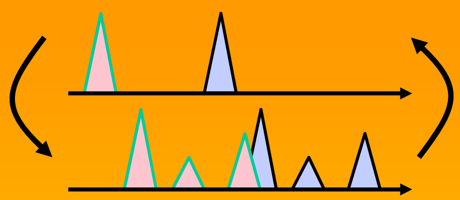
Equalization Discussion



- Use multiple delayed copies of the received signal to try to reconstruct the original signal
- Weights are set dynamically
  - Typically based on some known "training" sequence
- Effectively uses the multiple copies of the signal to reinforce each other
  - But only works for paths that differ in length by less than the depth of the pipeline

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Diversity Techniques

- Distribute signal over multiple "channels"
  - Channels experience independent fading
  - Reduces the error, i.e. only part of the signal is affected
- **Time diversity**: spread data out over time
  - Useful for bursty errors, e.g. slow fading
  - A specific form of channel coding
- **Space diversity**: use multiple nearby antennas and combine signals
  - Can be directional
- **Frequency diversity**: spread signal over multiple frequencies
  - For example, spread spectrum
  - Discussed later

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Introducing Redundancy

- **Protects digital data by introducing redundancy in the transmitted data.**
  - **Error detection codes: can identify certain types of errors**
  - **Error correction codes: can fix certain types of errors**
- **Block codes provide Forward Error Correction (FEC) for blocks of data.**
  - **(n, k) code: n bits are transmitted for k information bits**
  - **Simplest example: parity codes**
  - **Many different codes exist: Hamming, cyclic, Reed-Solomon, …**
- **Convolutional codes provide protection for a continuous stream of bits.**
  - **Coding gain is n/k**
  - **Turbo codes: convolutional code with channel estimation**

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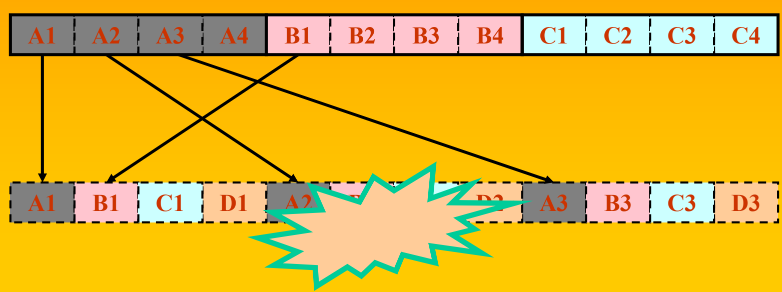
Time Diversity

- **Spread blocks out over time.**
- **Can use FEC or other error recovery techniques to deal with burst errors.**



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Space Diversity

- Use multiple antennas that pick up the signal in slightly different locations
- If there is no direct path (Raleigh), chances are that the signals are mostly uncorrelated
- If one antenna experiences deep fading, chances are that the other antenna has a strong signal
  - Antennas should be separated by ½ wavelength or more
- Applies to both transmit and receive side
  - Channels are symmetric
- Can use more than two antennas!

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Space Diversity Techniques

- On the receiving side:
  - Selection diversity: pick antenna with best SNR
  - Feedback/scanning: only switch if signals becomes weak
  - Maximal ratio combining: combine signals with a weight that is based on their SNR
- Transmitter can also use diversity, but needs help from receiver
  - Needs feedback on which antenna works best
- Diversity is very common in today's 802.11 devices
  - Uses simple techniques, e.g. selection diversity

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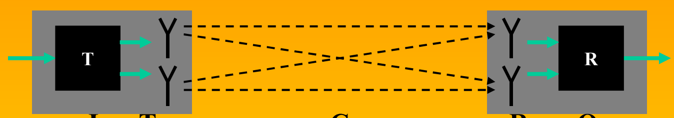
MIMO: Multiple In Multiple Out

- Use multiple antennas both transmitter and receiver in coordinated fashion
  - Maximize throughput or minimize interference
  - Can be viewed as generalization of earlier techniques

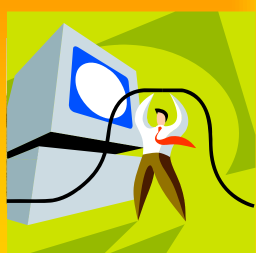


I x T x C x R = O

- Optimize T and R to achieve desired effect
  - But: each arrow in the channel represents multiple paths!
- Very effective if there is no direct line of sight

Mobile Networks

Modulation concepts



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Analog versus Digital Transmission

- **Analog: transmit analog signals without regard to content**
  - **Attenuation limits length of transmission link**
  - **Cascaded amplifiers boost signal's energy for longer distances but cause distortion**
    - Analog data can tolerate (some) distortion
    - But introduces errors in digital data
- **Digital: can recognize the content of signal**
  - **Attenuation endangers integrity of data**
  - **Repeaters can recover the signal and retransmit**
    - Also true of analog signal that carries digital data: repeater can recover signal and generate new clean analog signal

Signal Modulation

- **Sender changes the nature of the signal in a way that the receiver can recognize**
- **Amplitude modulation (AM): change the strength of the carrier based on information**
  - **High values -> stronger signal**
- **Frequency (FM) and phase modulation (PM): change the frequency or phase of the signal**
  - **Frequency or Phase shift keying**
- **Digital versions are sometimes called "shift keying"**
  - **Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying**
  - **Discussed later in more detail**

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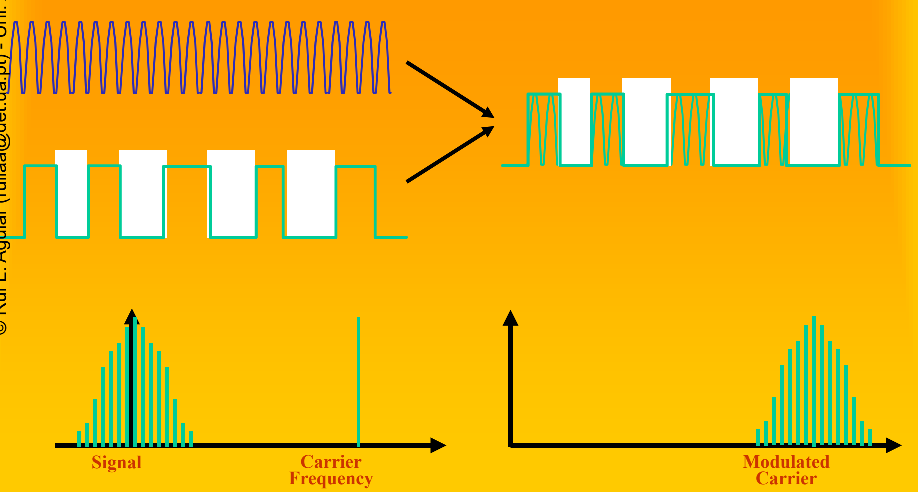
Baseband versus Carrier Modulation

- **Baseband modulation: send the "bare" signal**
  - Use the lower part of the spectrum
- **Baseband modulation has limited use**
  - Everybody competes – only makes sense for point-to-point links, but unattractive for wireless
  - Use of higher frequencies requires transmission of a single high bandwidth signal
  - Some media only transmit higher frequencies, e.g. optical
- **Carrier modulation: use the (information) signal to modulate a higher frequency (carrier) signal**
  - Can be viewed as the product of the two signals
  - Corresponds to a shift in the frequency domain
- **Also applies to frequency and phase modulation**
  - E.g. change frequency of the carrier instead of its amplitude

Amplitude Carrier Modulation



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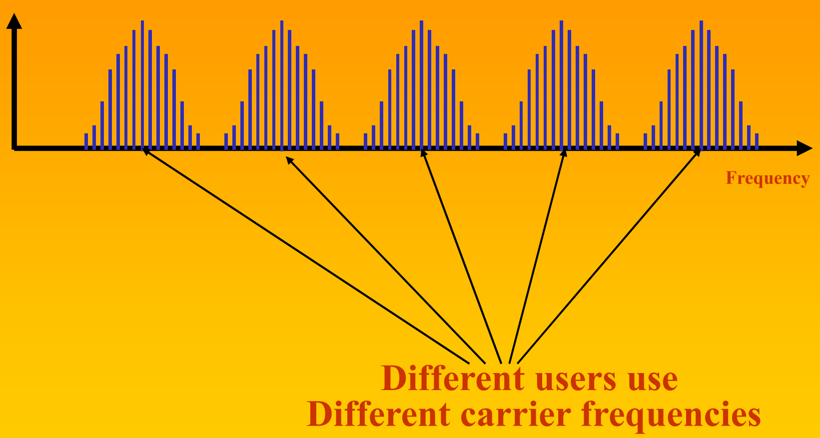
Multiple Users Can Share the Spectrum



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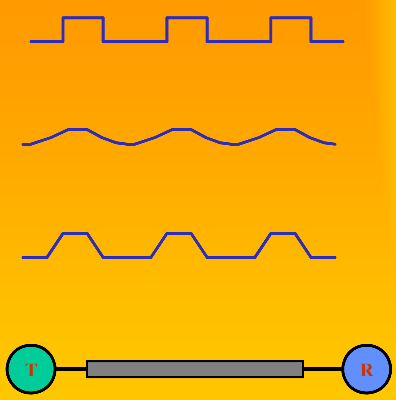
So Why Don't we Always Send a High Bandwidth Signal?

- Channels have a limit on the type of signals it can carry
  - Good transmission of signals only in certain frequency range
  - Signals outside of that range get distorted, e.g. attenuated
- Distortion can make it hard for receiver to extract the information
  - It is beneficial to match the signal to the channel
  - Limits the throughput of the channel



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Factors Used to Compare Modulation/Encoding Schemes

- Signal spectrum
  - With lack of high-frequency components, less bandwidth required
  - With no dc component, ac coupling possible
  - Transfer function of a channel is worse near band edges
- Clocking
  - Ease of determining beginning and end of each bit position
- Signal interference and noise immunity
  - Performance in the presence of noise
- Cost and complexity
  - The higher the signal rate to achieve a given data rate, the greater the cost

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Basic Modulation/Encoding Techniques

- Encode digital data in an analog signal
  - Modulation is often used as the terminology for analogue.
- Amplitude-shift keying (ASK)
  - Amplitude difference of carrier frequency
- Frequency-shift keying (FSK)
  - Frequency difference near carrier frequency
- Phase-shift keying (PSK)
  - Phase of carrier signal shifted

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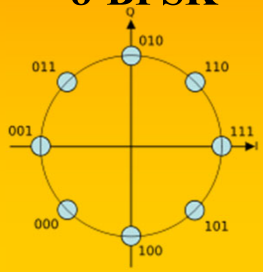
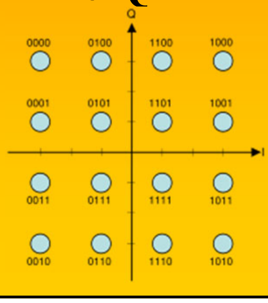
Constellation diagrams

- Used to represent current complex modulation formats, representing the possible modulation options as numbers in a complex plane. Ex.

8-BPSK



16-QAM



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Spread Spectrum

- Spread transmission over a wider bandwidth
  - Don't put all your eggs in one basket!
- Good for military: jamming and interception becomes harder
- Also useful to minimize impact of a "bad" frequency in regular environments
- What can be gained from this apparent waste of spectrum?
  - Immunity from various kinds of noise and multipath distortion
    - Including jamming
  - Can be used for hiding/encrypting signals
    - Only receiver who knows SS code can retrieve signal
  - Several users can independently share the same higher bandwidth with very little interference (later)
    - Code division multiple access (CDMA)

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Spread Spectrum Concept

- **Input fed into channel encoder**
  - **Produces narrow bandwidth analog signal around central frequency**
- **Signal modulated using sequence of digits**
  - **Spreading code/sequence**
  - **Typically generated by pseudonoise/pseudorandom number generator**
    - Not actually random
    - If algorithm good, results pass reasonable tests of randomness
    - Need to know algorithm and seed to predict sequence
- **Increases bandwidth significantly**
  - **Spreads spectrum**
- **Receiver uses same sequence to demodulate signal**
- **Demodulated signal fed into channel decoder**

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Basic Operation: Slow and Fast

- **Typically 2^k carriers frequencies forming 2^k channels**
- **Channel spacing corresponds with bandwidth of input**
- **Each channel used for fixed interval**
  - **300 ms in IEEE 802.11**
  - **Some number of bits transmitted using some encoding scheme**
    - Frequency shifted every T_c seconds
    - Duration of signal element is T_s seconds
  - **Sequence dictated by spreading code**
- **Slow FHSS has $T_c \geq T_s$**
- **Fast FHSS has $T_c < T_s$**
- **Generally fast FHSS gives improved performance in noise (or jamming)**

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Frequency Hopping Spread Spectrum (FHSS)

- Signal broadcast over seemingly random series of frequencies
- Receiver hops between frequencies in sync with transmitter
  - Each frequency has the bandwidth of the original signal
  - Dwell time is the time spent using one frequency
- Spreading code determines the hopping sequence
  - Must be shared by sender and receiver (e.g. standardized)
- Eavesdroppers hear unintelligible blips
- Jamming on one frequency affects only a few bits
  - Typically large number of frequencies used
    - Improved resistance to jamming

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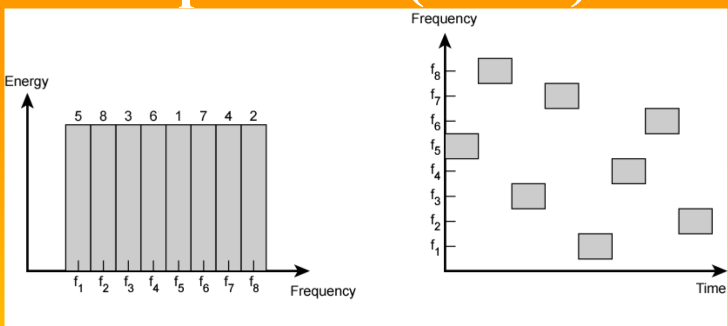
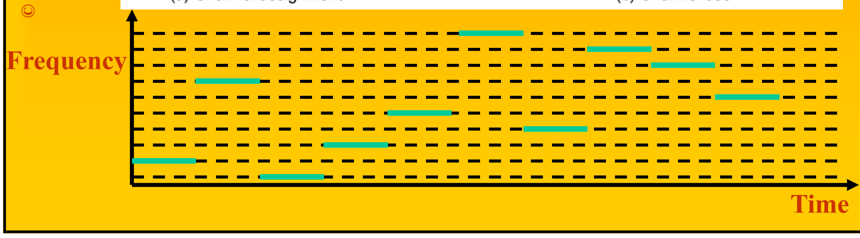
Frequency Hopping Spread Spectrum (FHSS)



(a) Channel assignment

(b) Channel use



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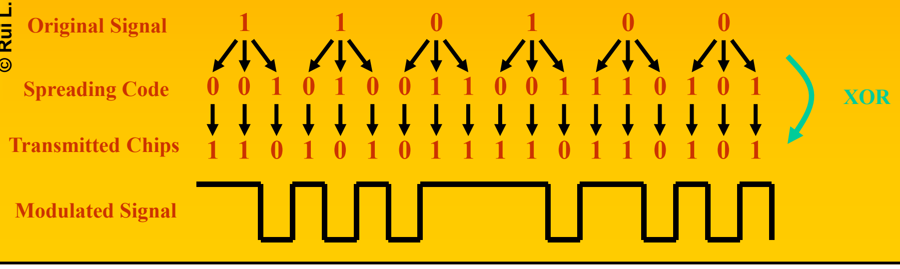
Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits (chips) in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of bits used
    - 10 bit spreading code spreads signal across 10 times bandwidth of 1 bit code
  - E.g. exclusive-OR of the bits with the spreading code
    - Data rate equal to original spreading code
- The resulting bit stream is used to modulate the signal



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Properties

- Since each bit it sent as multiple chips, you need more bps bandwidth to send the signal.
  - Number of chips per bit is called the spreading ratio
- Given the Nyquist and Shannon results, you need more spectral bandwidth to do this.
  - Spreading the signal over the spectrum
- Advantage is that is transmission is more resilient.
  - DSSS signal will look like noise in a narrow band
  - Can lose some chips in a word and recover easily
  - Performance similar to FHSS
- Multiple users can share bandwidth (easily).
  - Follows directly from Shannon (capacity is there)
  - Use a different chipping sequence

DSSS properties