Mobile Networks Introduction

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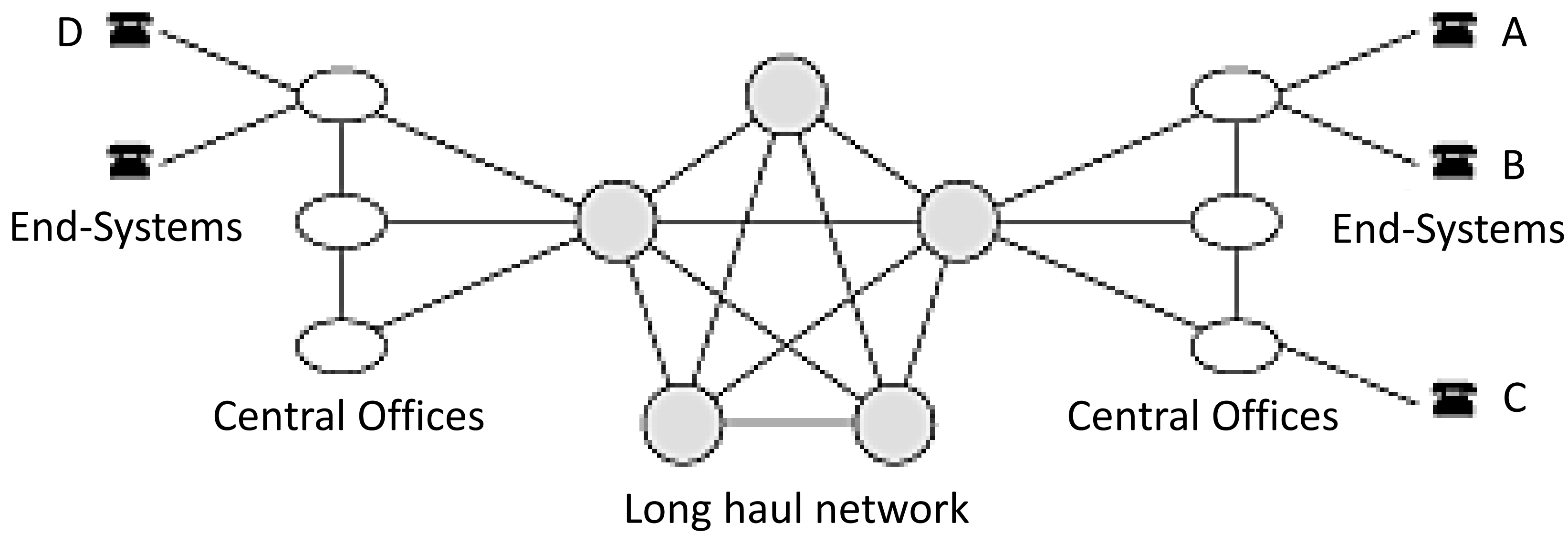
Trends in communications

- 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 80’s
  - The coming of age of the data world, in the early 90’s
  - The pervasiveness of mobility, in the mid 90’s.
  - IP (Internet) is a must-have, in the 00’s
  - Data everywhere, in 10’s
  - Digital world, starting in the early 10’s

The communication network

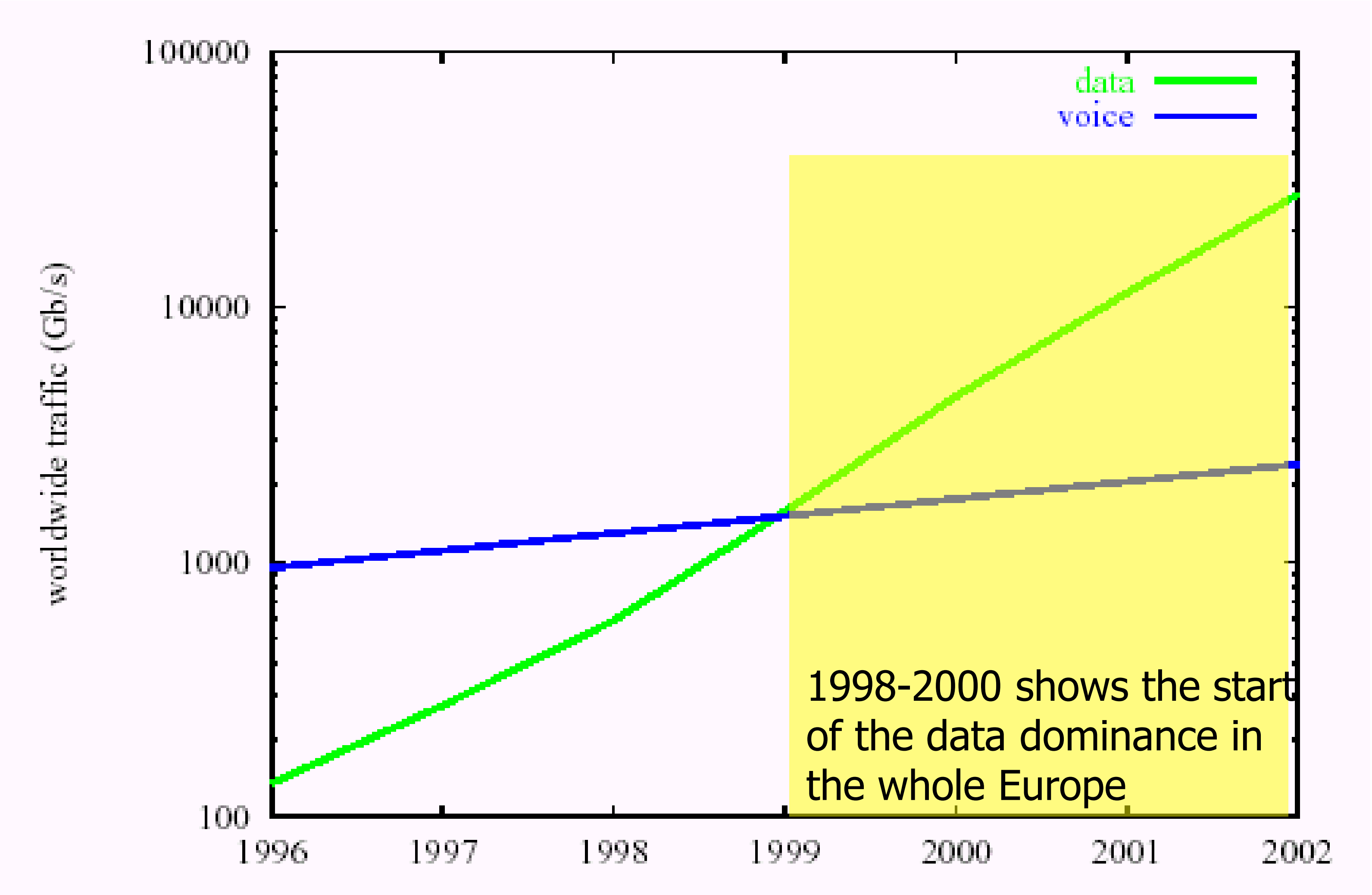
Before mobile Communications, there where Fixed Communications

Telephone System



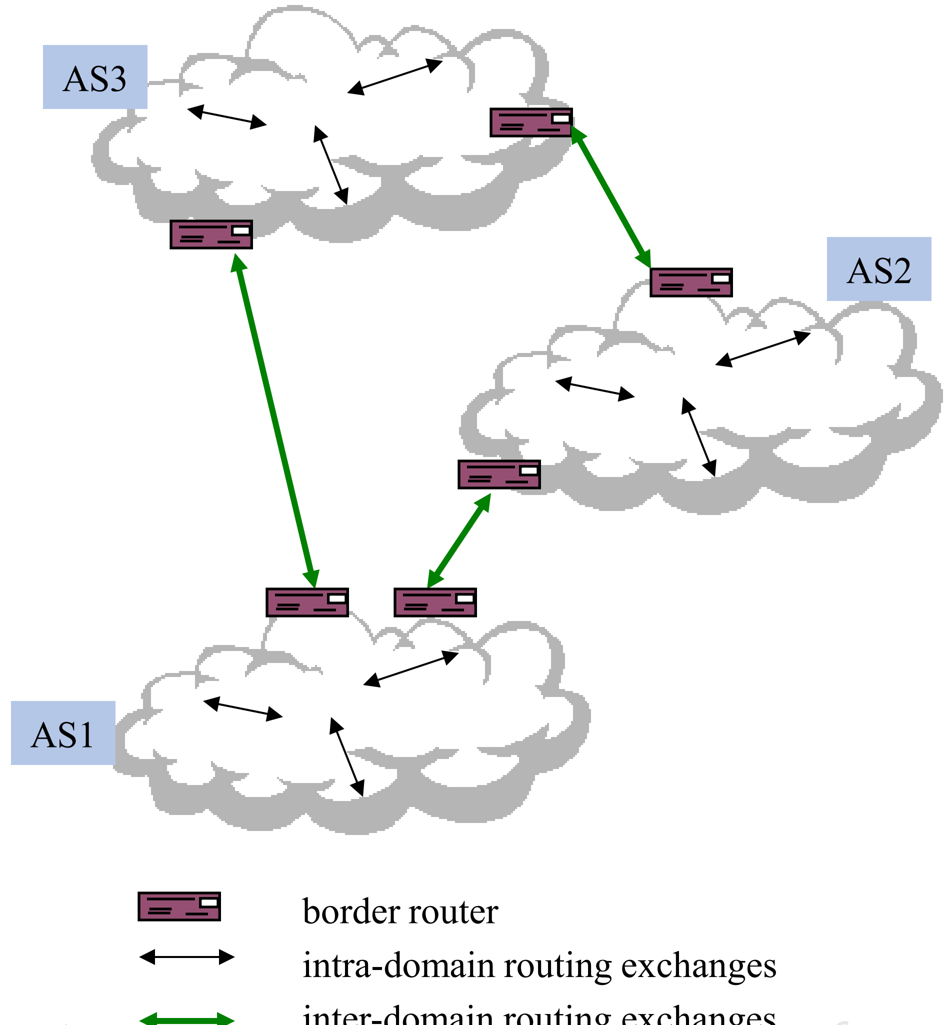
- Uses switched circuits (virtuals...)
- Access via low bandwidth circuits
- "out-of-band" call establishment using signaling system based in packets (SS7)
- Channels between switching exchanges carry multiple calls
  - Multiplexing (analogue or digital)

Evolution: Voice vs Data



Internet structure

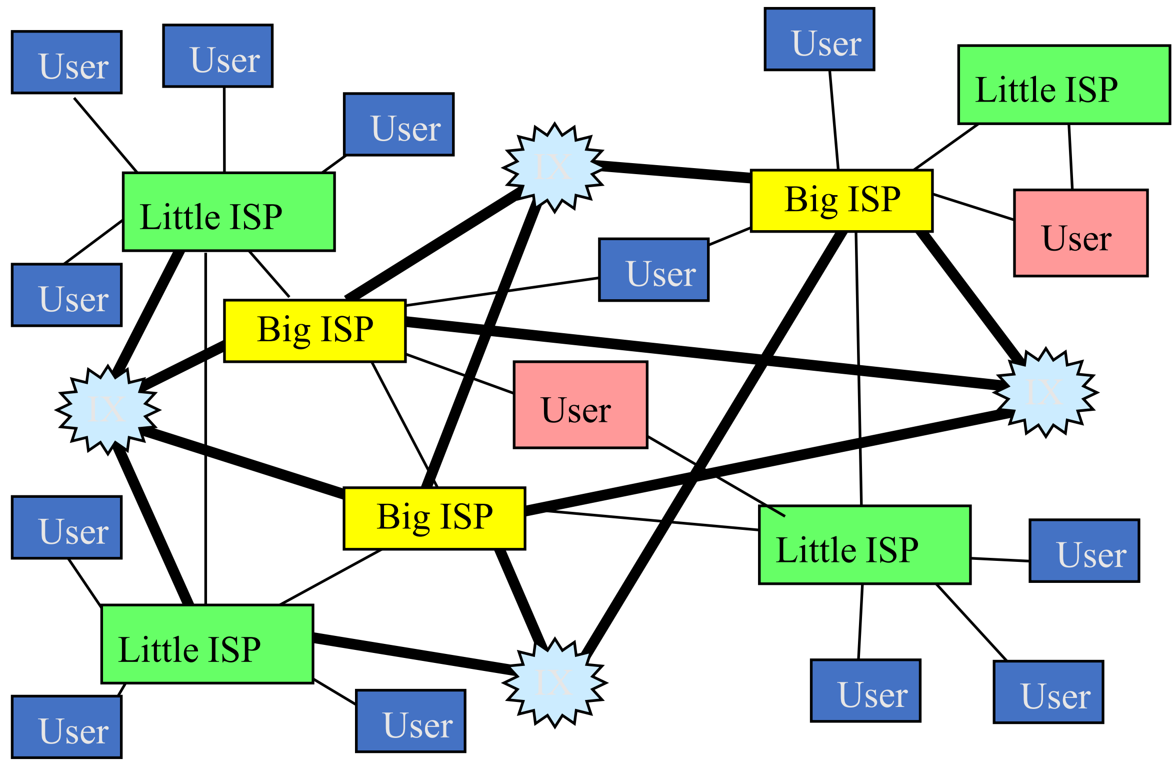
- Administrative borders define
  - Autonomous Systems (AS)
    - **Intra-domain routing**
    - Individual internal policies
    - May use different metrics between domains
    - protocols: RIPv2, OSPFv2
  - AS interconnections
    - **Inter-domain routing**
    - Connectivity information
    - protocols: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



Internet: currently

- Self-organized set of interconnected autonomous components
  - More than 60.000 autonomous domains (with more than 100K numbers allocated)
    - Single guarantee is running TCP-IP
    - Works by packet switching
    - More than 340 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-directional 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

Real structure



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

“Data vs voice”: packet switching vs circuit switching

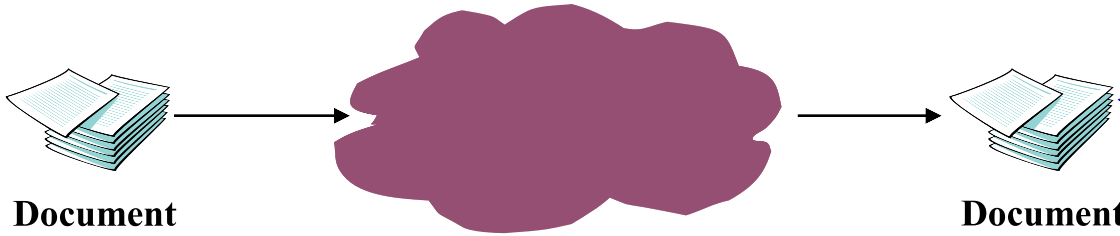
Packet switching solves everything?

- Great for burst information
  - Resource sharing
  - No call 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

Transport service (operator/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.

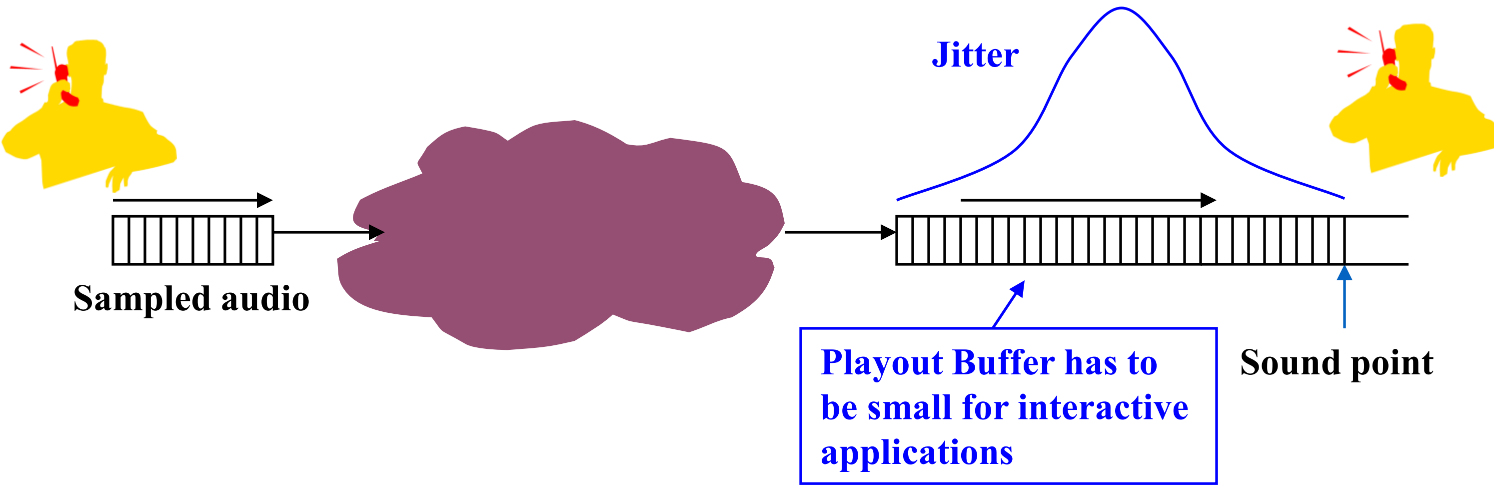
Elastic operations (Performance): All traffic has not the same requirements



The document is only useful when it is completely received. This means that what is important is the average delay, and not the instant delay

- 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…

Inelastic applications



- Interactive applications
  - Sensitive to packet delay (telephony, gaming)
  - Maximum delay may be limited
- Non-interactive applications
  - Adapt to larger ranges of delays (streaming audio, video)

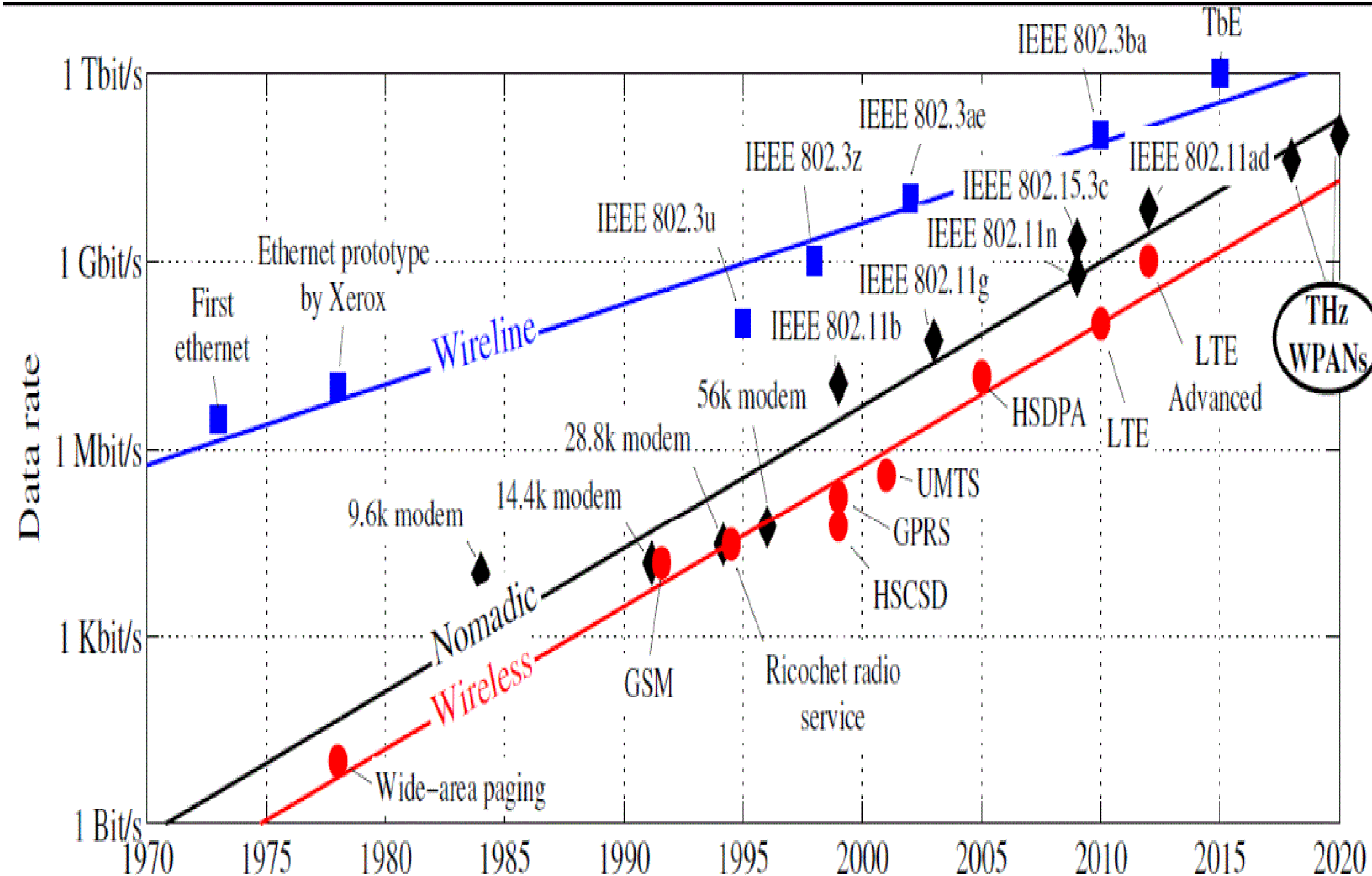
Application requirements

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 video:10K-5Mbps	yes, 100’s ms
Streamed audio/video	supports	See above	yes, few secs
Interactive gaming	supports	Some Kbps	yes, 100’s ms
Finance applications	lossless	elastic	Yes and no

The Mobile Network

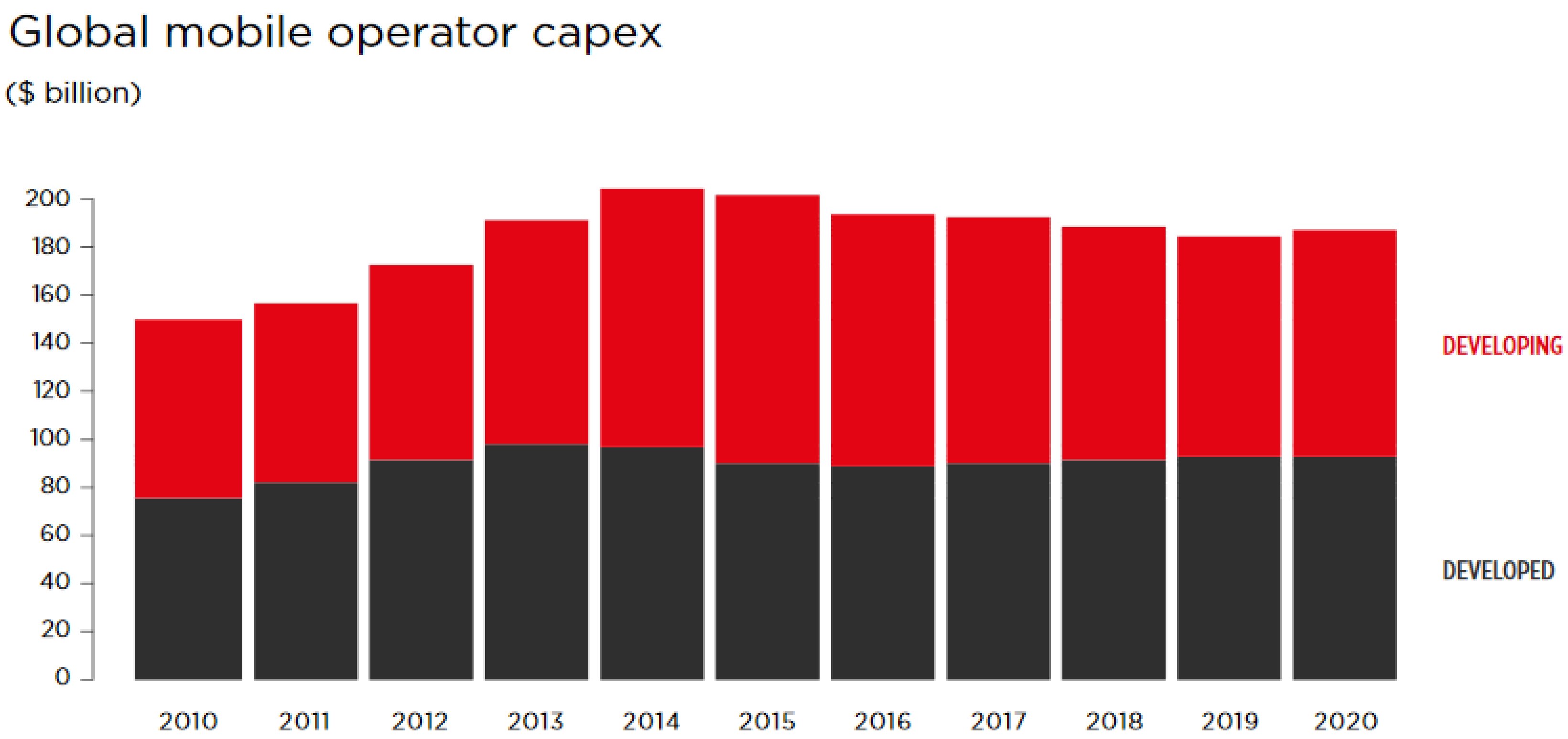
Economical and societal motivations

Edholm’s Law

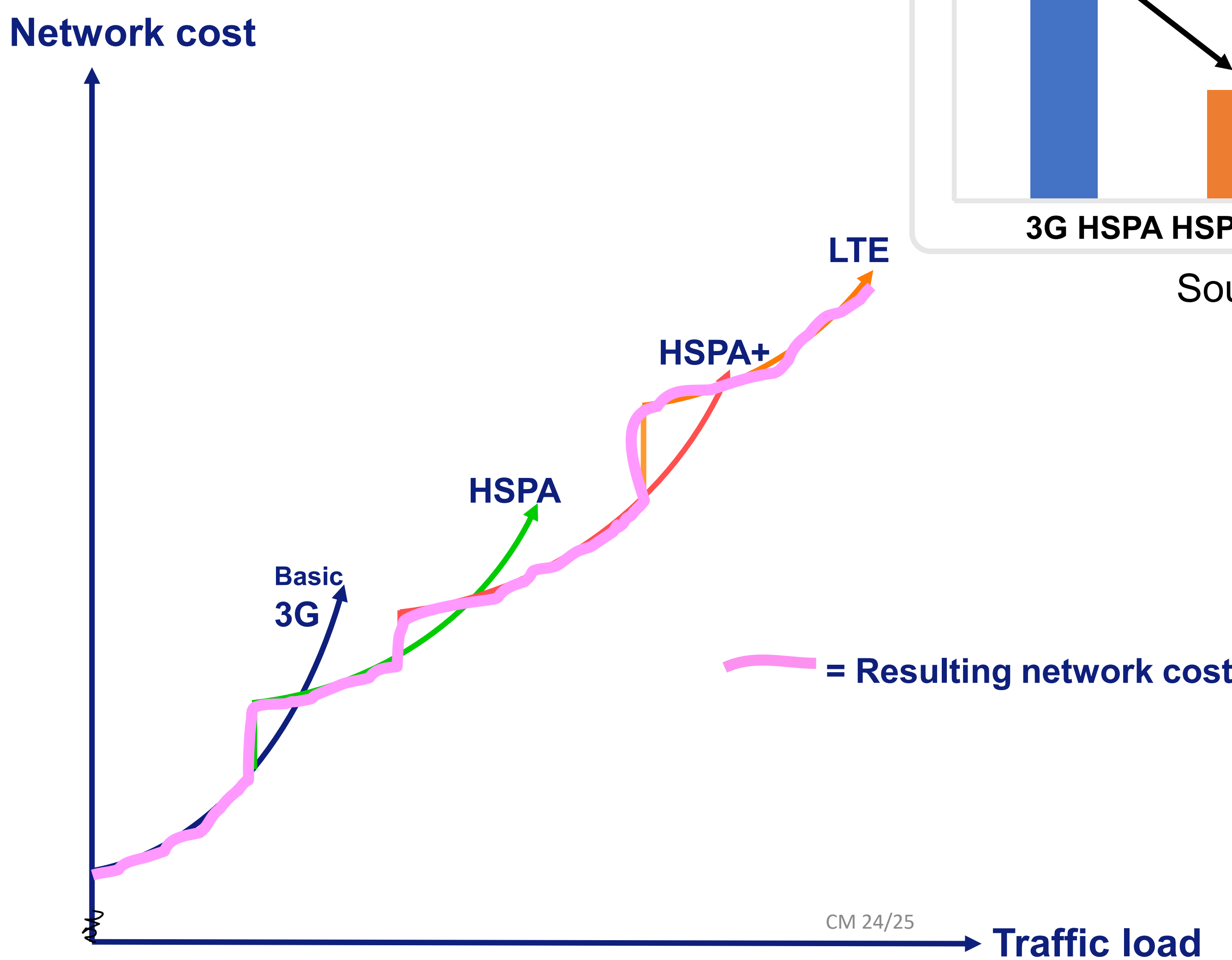


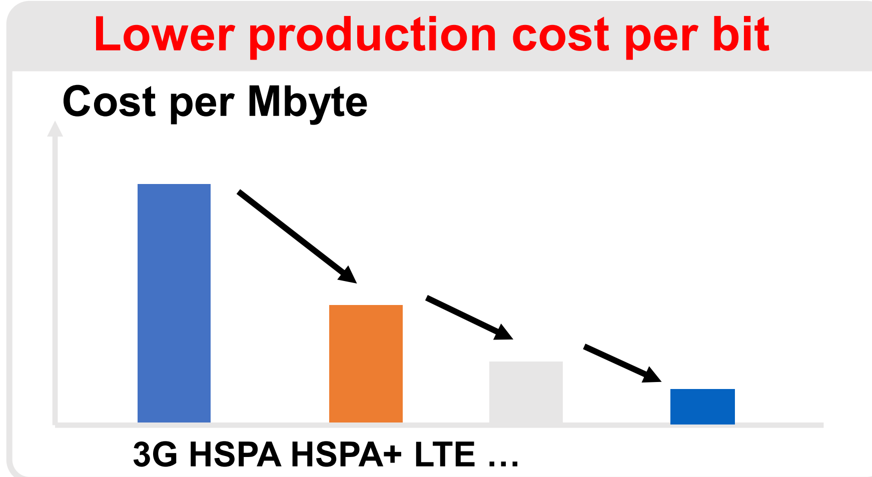
Data rate
1 Tbit/s
1 Gbit/s
1 Mbit/s
1 Kbit/s
1 Bit/s
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Wireline
Nomadic
Wireless
First ethernet
Ethernet prototype by Xerox
IEEE 802.3u
IEEE 802.3z
IEEE 802.3ae
IEEE 802.3ba
TbE
IEEE 802.15.3c
IEEE 802.11ad
IEEE 802.11n
IEEE 802.11g
IEEE 802.11b
56k modem
28.8k modem
14.4k modem
9.6k modem
THz WPANs
LTE Advanced
LTE
HSDPA
UMTS
GPRS
HSCSD
GSM
Ricochet radio service
Wide–area paging

Cost of investment in telecom



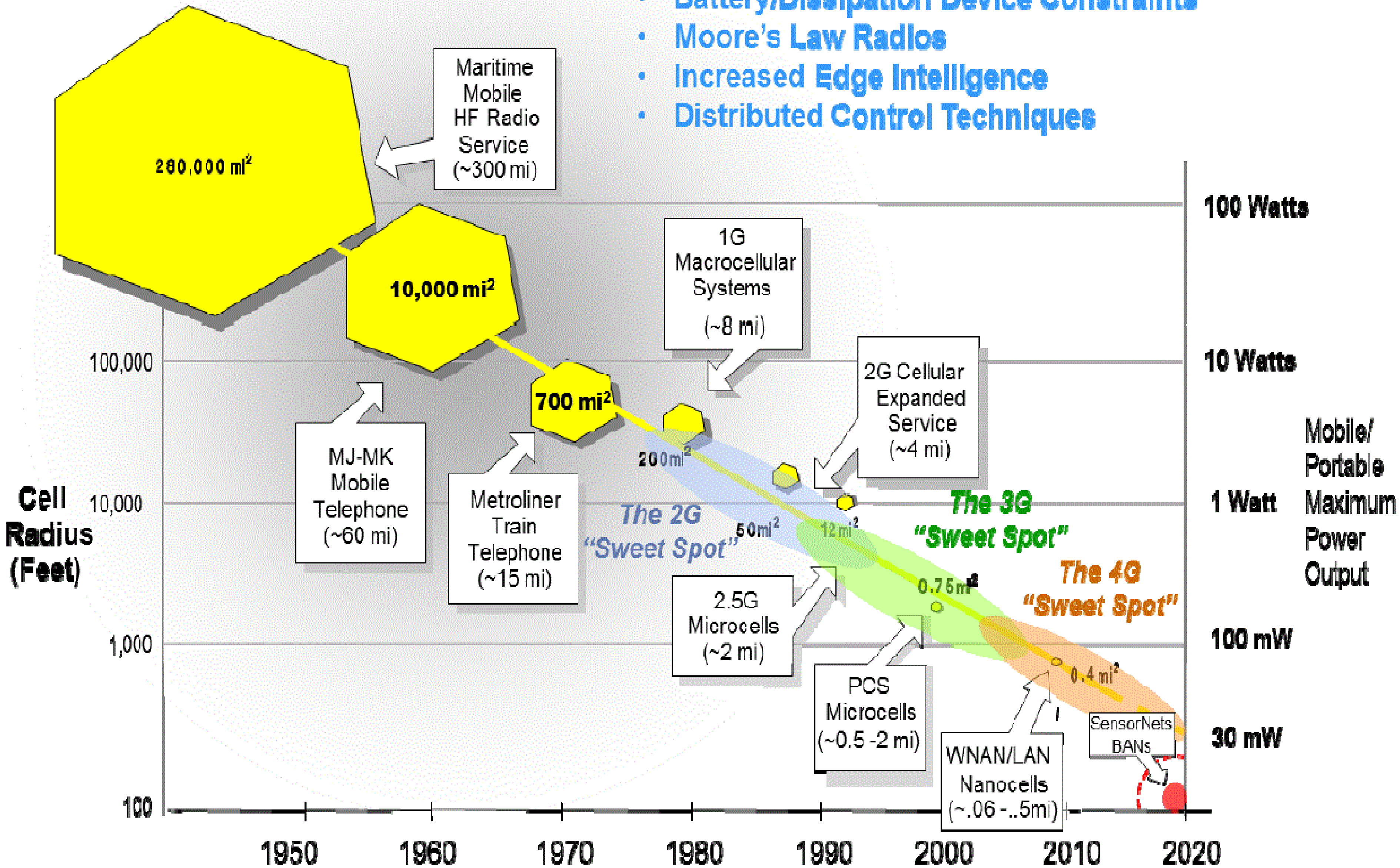
Motivations for technologies



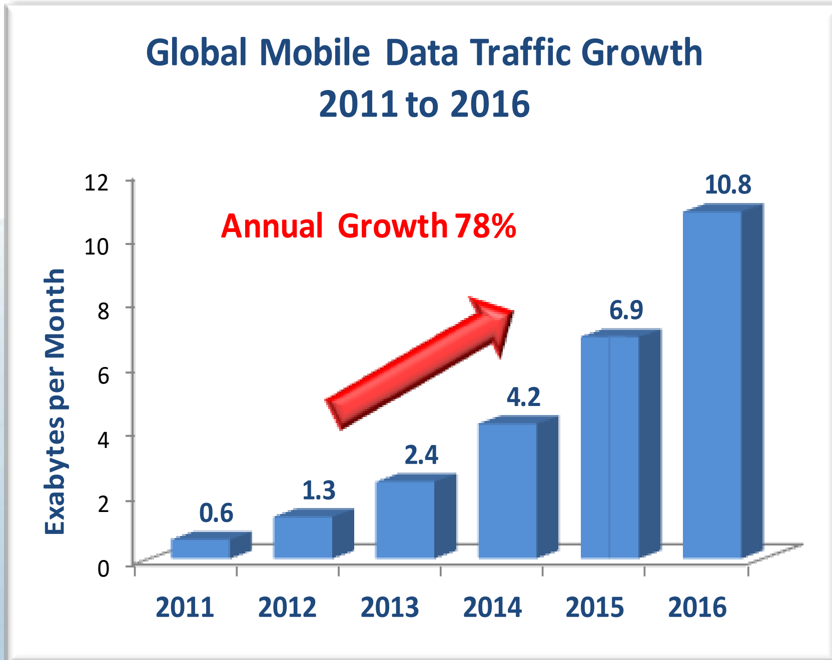


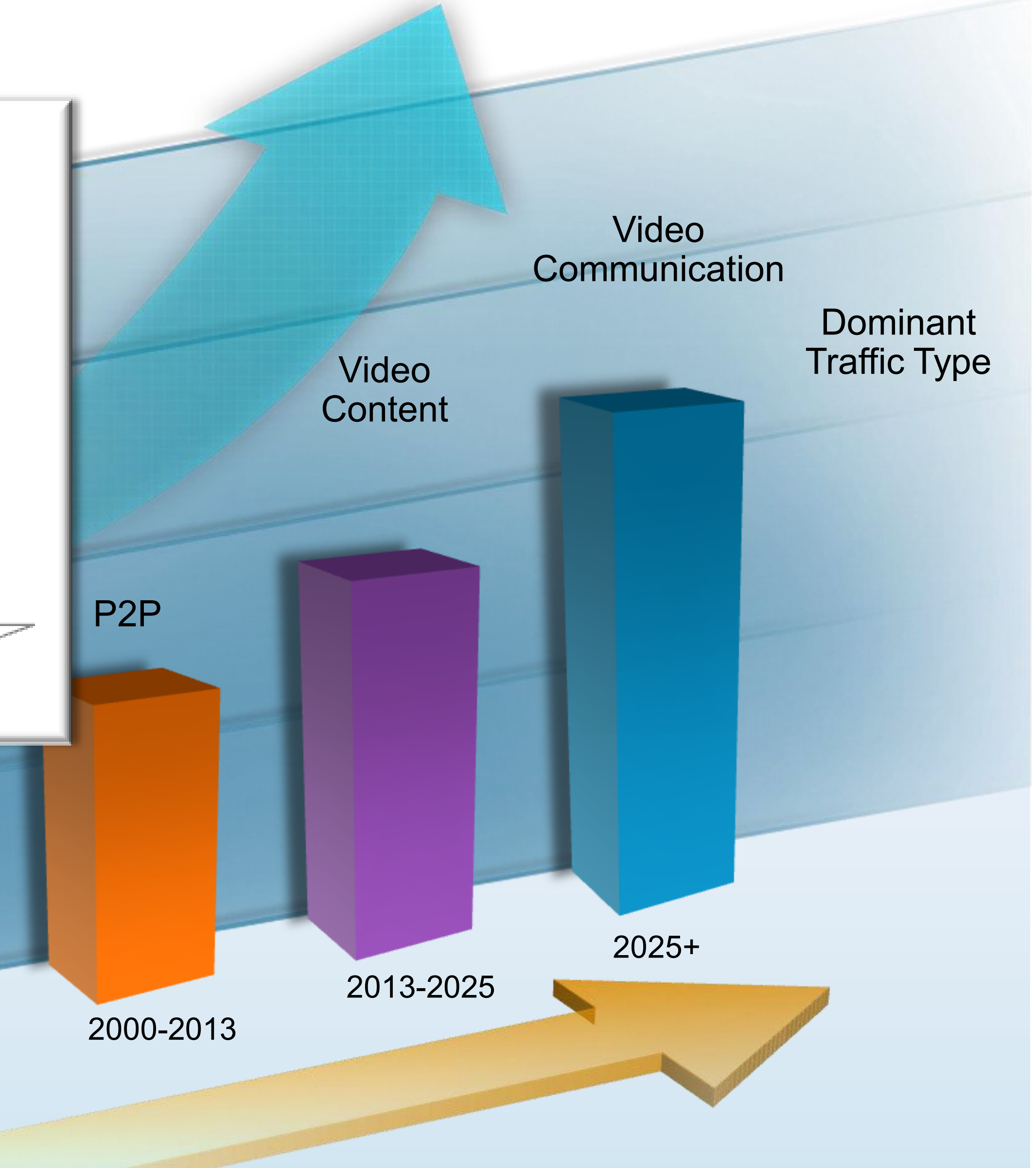
Source: NSN

- Increased Bandwidth Demand/User
- Battery/Dissipation Device Constraints
- Moore's Law Radios
- Increased Edge Intelligence
- Distributed Control Techniques



Dramatic Traffic Growth Fueled by Video





Source: Cisco Global IP Traffic Forecast, 2007

The things that surrond us

Source: EC

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

Context

Security

Identity

Authentication

Services

Mobility

Quality of Experience

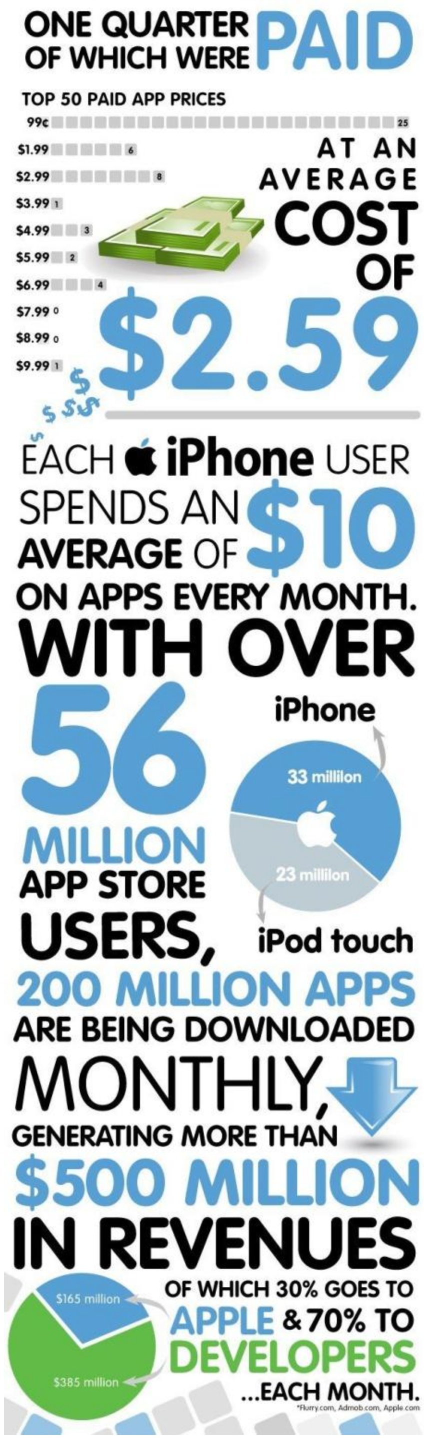
Charging

Accounting

… and many others …

The market turned to SERVICES (+/- 2016)

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

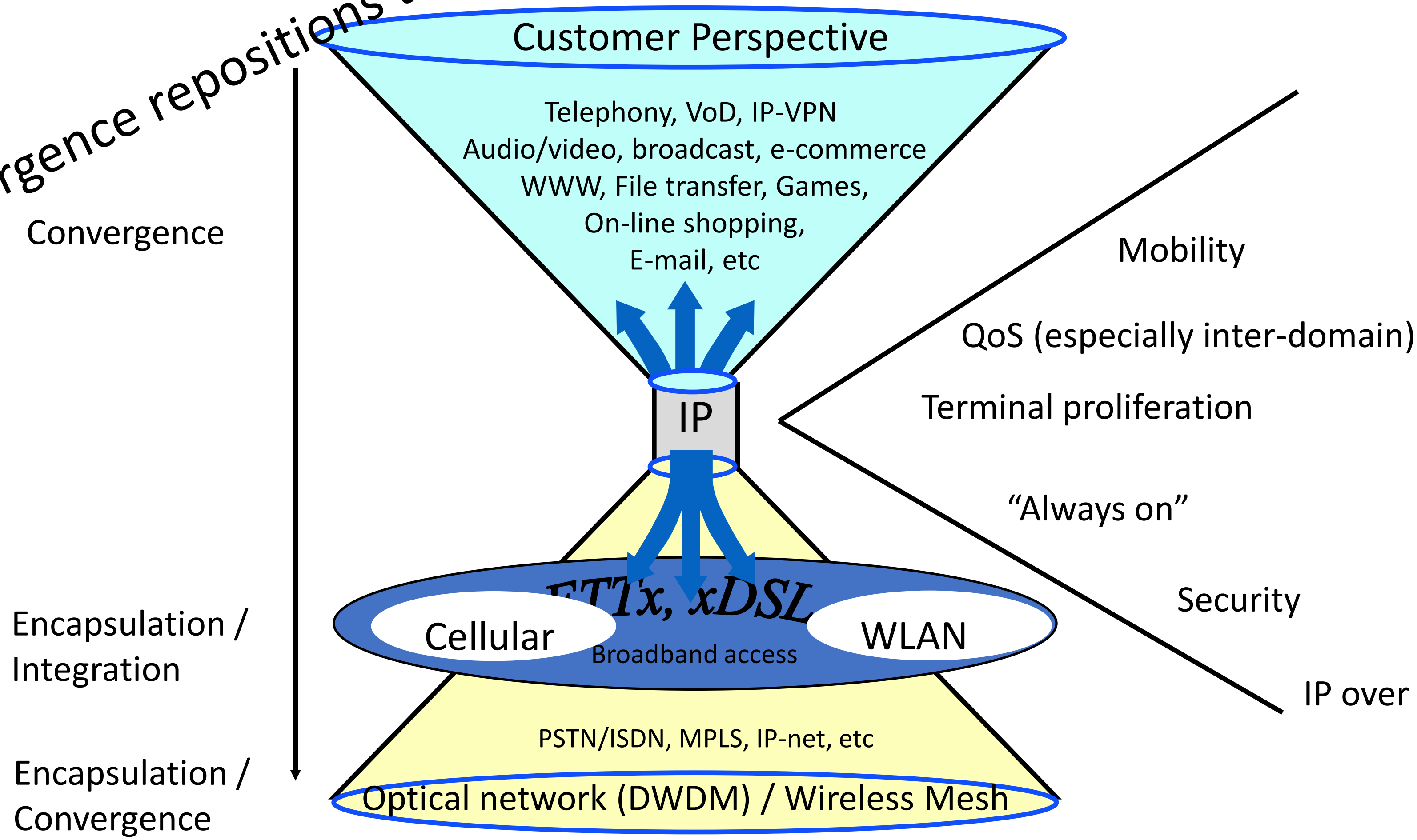


Source: GigaOM

User behaviour and trends

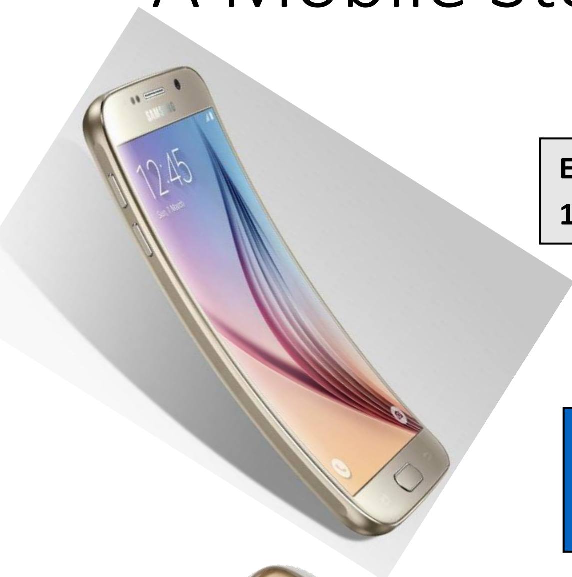
- Increased Internet—based services
  - **Phone market is now saturated**
  - **“Everything” came to “data communications”**
- Increased broadband requirements
  - **P2P being replaced by service-based**
  - **Internet access 2x every 2 years – fiber access now blooming**
  - **70% broadband penetration**
- 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**

IP convergence repositions the whole ecossystem!



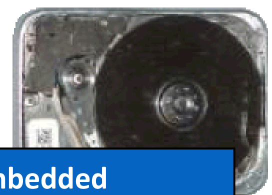
Source: Siemens

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

The wireless framework (Summary)

- 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 Location-based Services (LBS)
  - Now proximity is a dynamic variable for the user

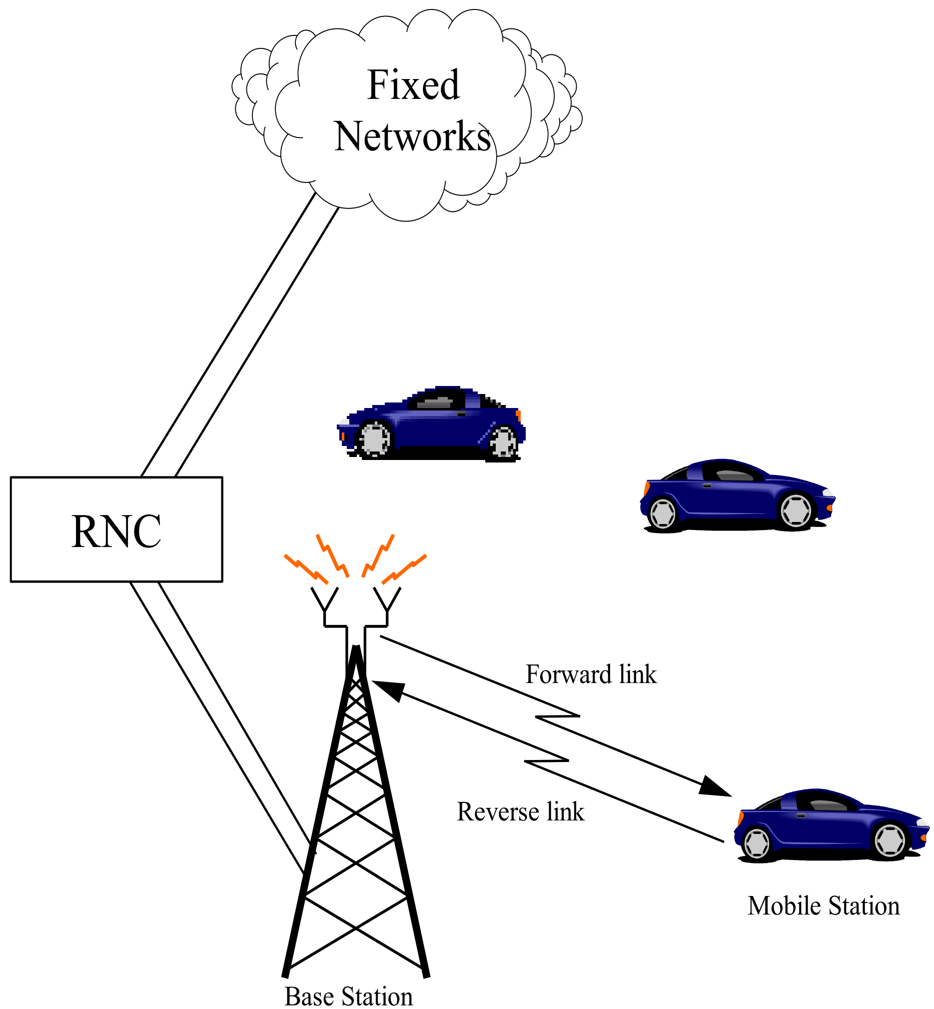
The Mobile Network

Generic technical aspects and challenges

Wireless Systems

CM 24/25

- 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



RNC - Radio Network Controller

Mobile hassles

1. Wireless connections limitations
   - Multiple independent access 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

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**

Scaling:
You mean *Everywhere?!?!*

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

Remember!

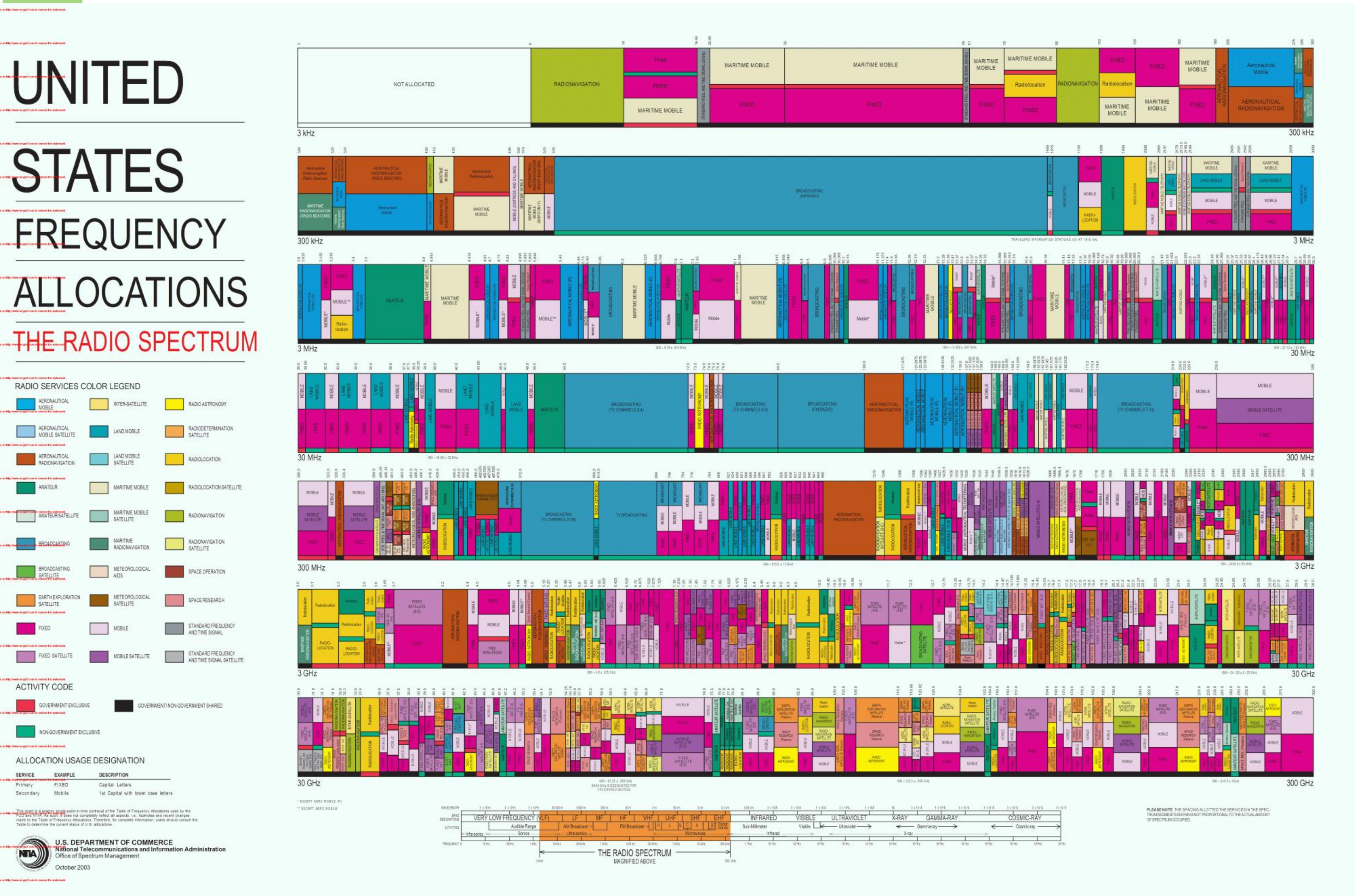
- Addressing
  - Total number of IPv4 addresses is ~4 200 millions
- Routing
  - Routing tables are already quite large
- Security
  - Securing everything? With certificates?
- Multimedia bandwidths
  - In wireless?!?
- Sensors and actuators
  - Electric grid on the net?!?!

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

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, …


UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
AERONAUTICAL MOBILE
AERONAUTICAL MOBILE SATELLITE
AERONAUTICAL RADIONAVIGATION
AMATEUR
AMATEUR SATELLITE
BROADCASTING
BROADCASTING SATELLITE
EARTH EXPLORATION SATELLITE
FIXED
FIXED SATELLITE
INTER-SATELLITE
LAND MOBILE
LAND MOBILE SATELLITE
MARITIME MOBILE
MARITIME MOBILE SATELLITE
MARITIME RADIONAVIGATION
METEOROLOGICAL AIDS
METEOROLOGICAL SATELLITE
MOBILE
MOBILE SATELLITE
RADIO ASTRONOMY
RADIODETERMINATION SATELLITE
RADIOLOCATION
RADIOLOCATION SATELLITE
RADIONAVIGATION
RADIONAVIGATION SATELLITE
SPACE OPERATION
SPACE RESEARCH
STANDARD FREQUENCY AND TIME SIGNAL
STANDARD FREQUENCY AND TIME SIGNAL SATELLITE
ACTIVITY CODE
GOVERNMENT EXCLUSIVE
GOVERNMENT/ NON-GOVERNMENT SHARED
NON-GOVERNMENT EXCLUSIVE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM
MAGNIFIED ABOVE

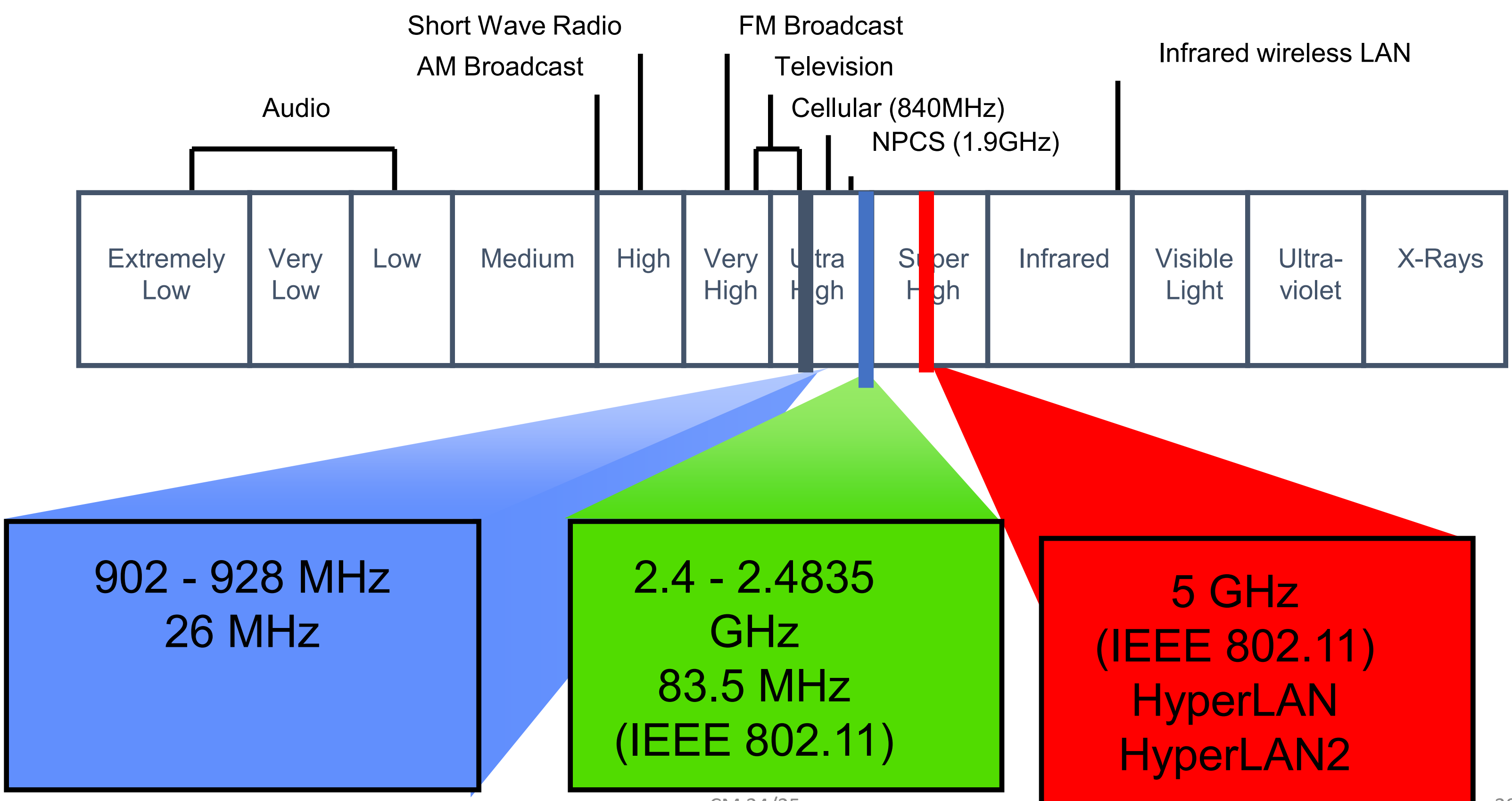
Source: FCC

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, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

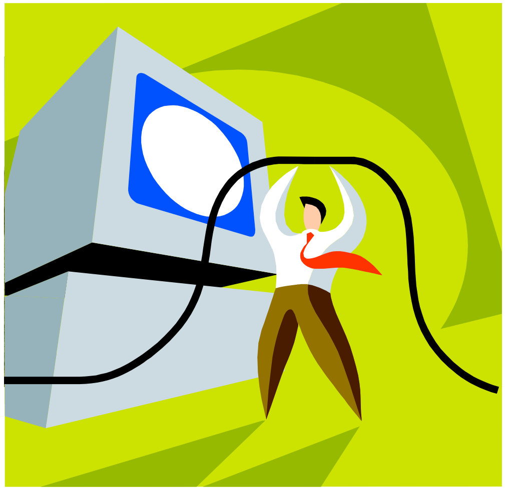
Frequency Bands

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



Physical Layer

Problems we face



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, ..

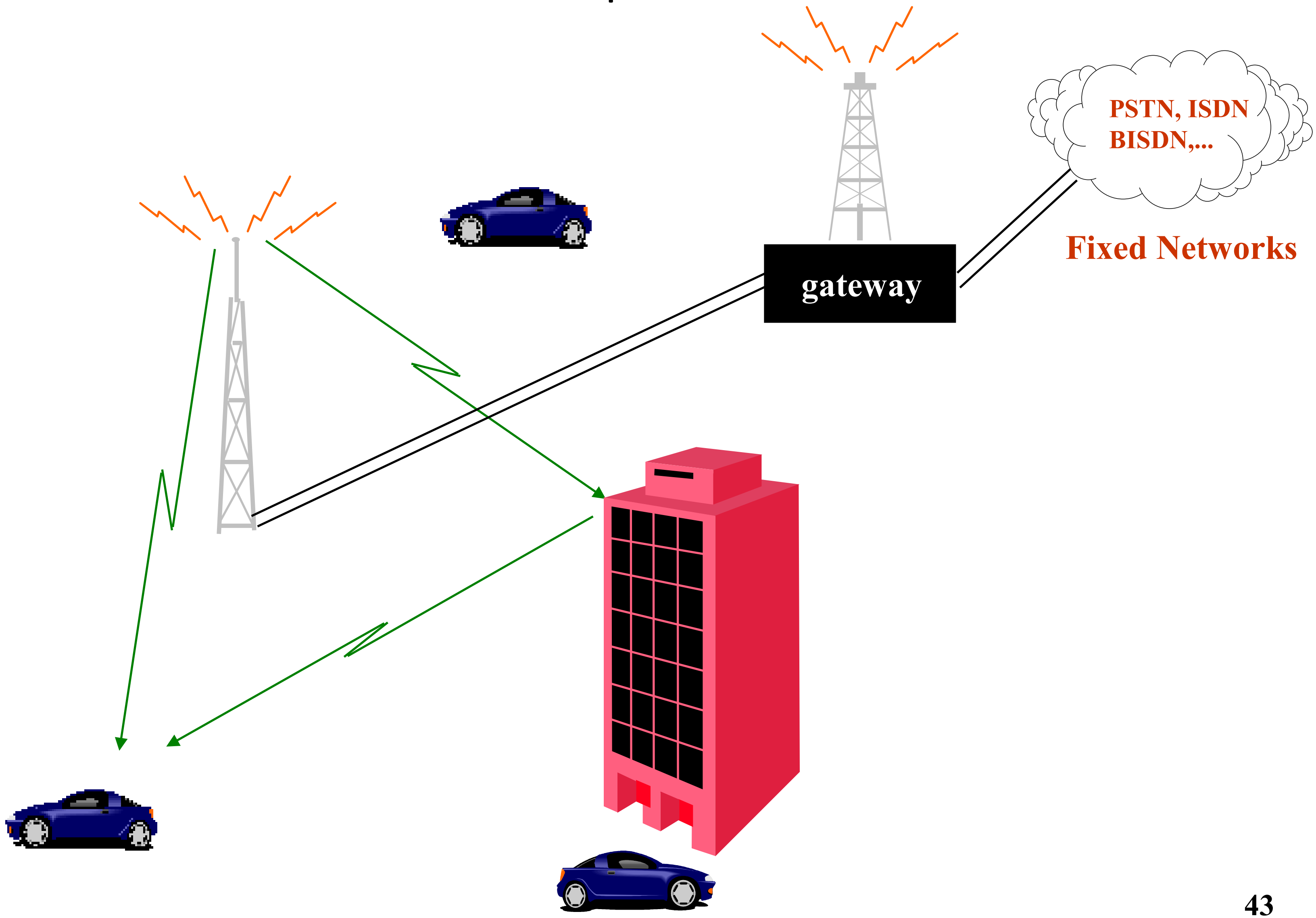
What is Hard about Wireless?

There are no wires!

Causes problems in many areas:

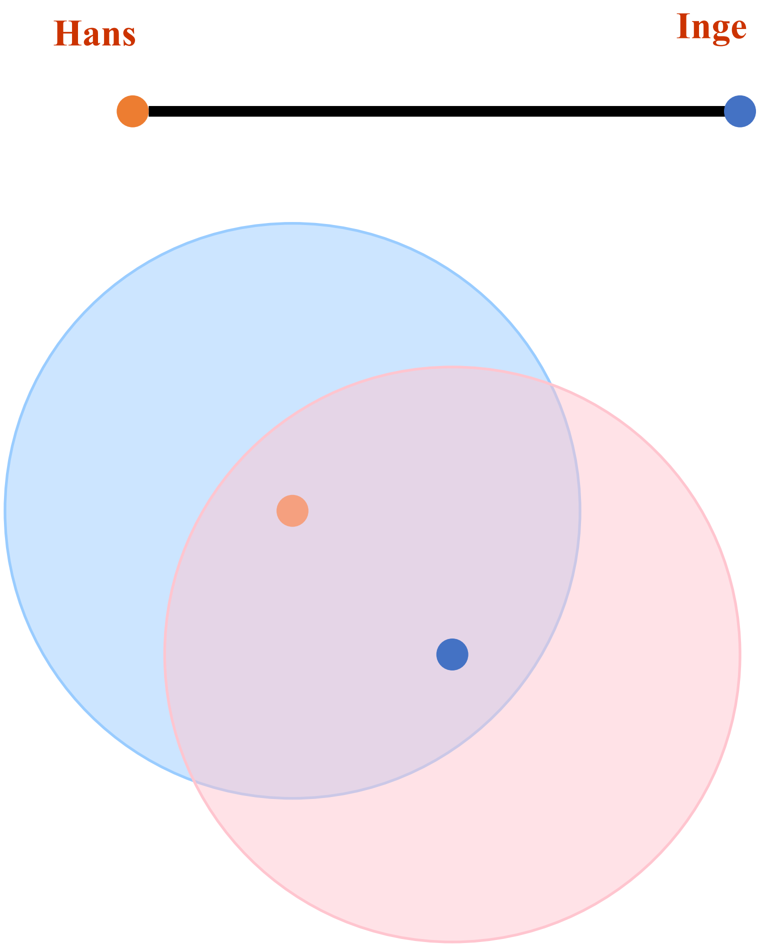
- Quality of transmission
- Interference and noise
- Capacity of the network
- Effects of mobility

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

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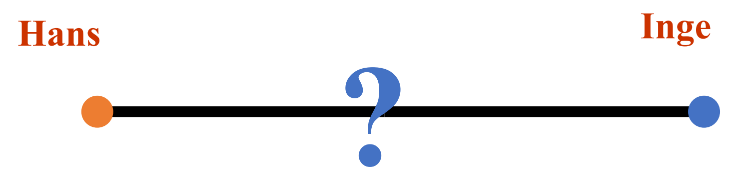
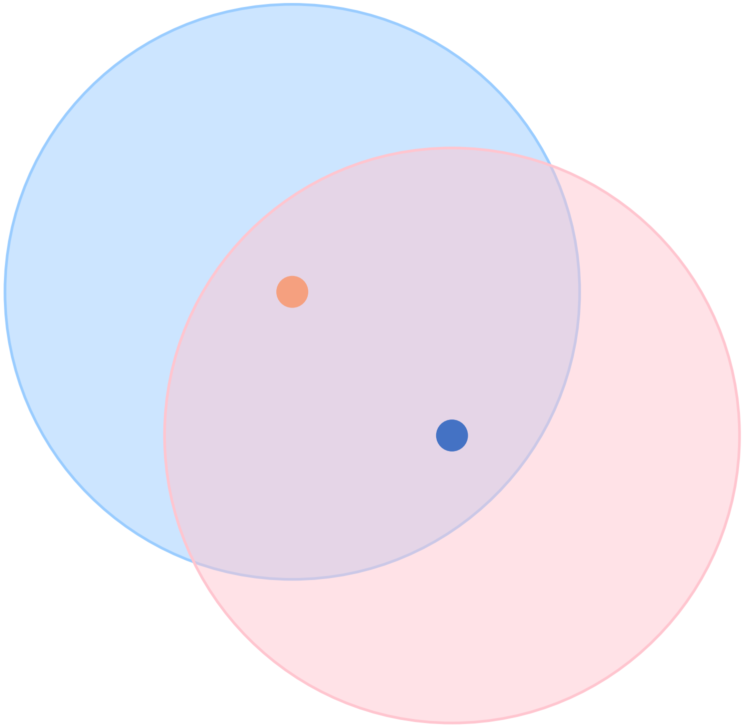
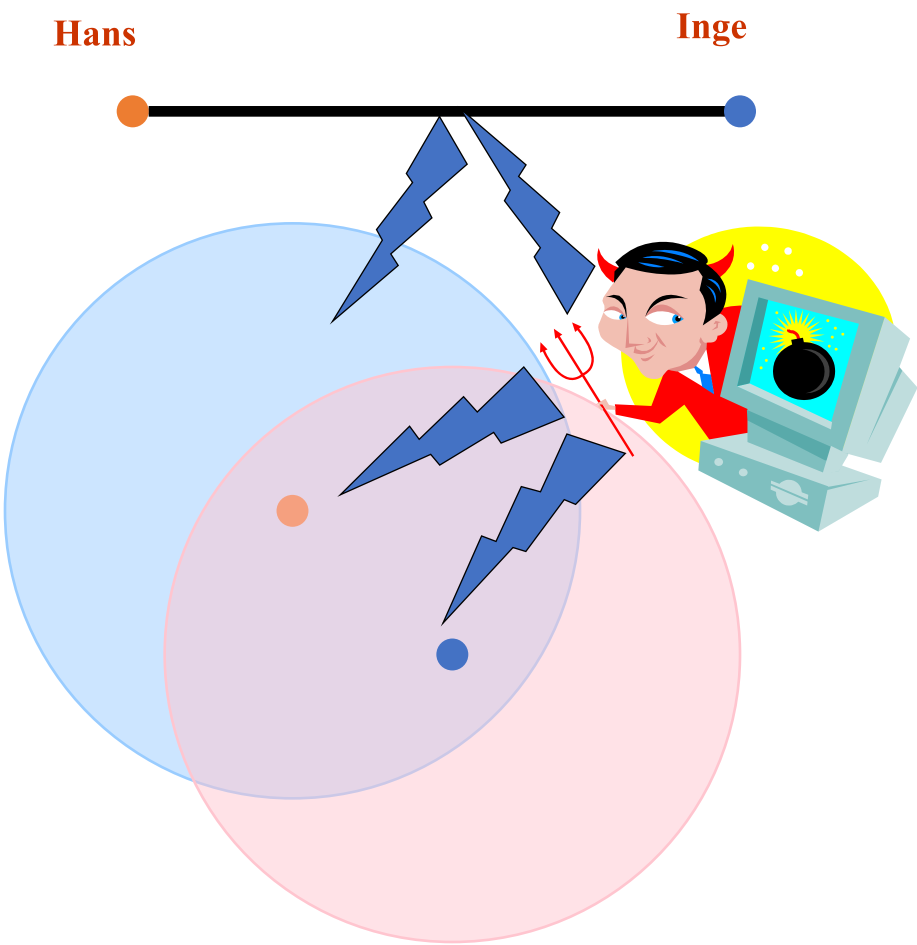




Wireless is very Sensitive to Noise …

- 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

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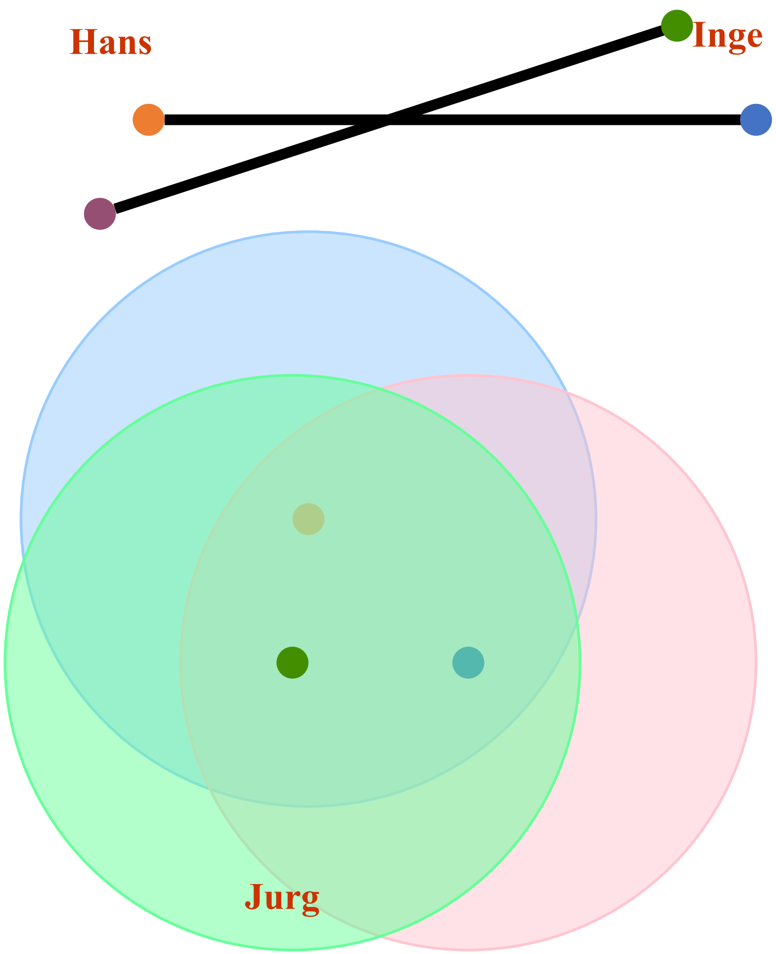
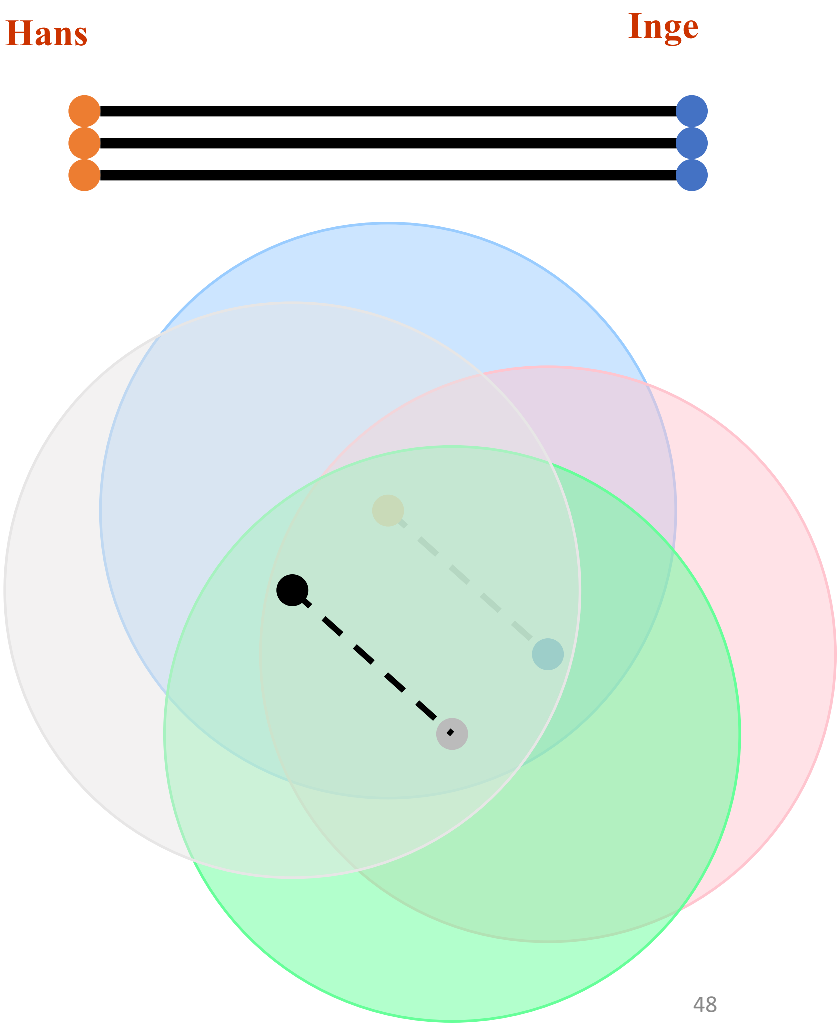


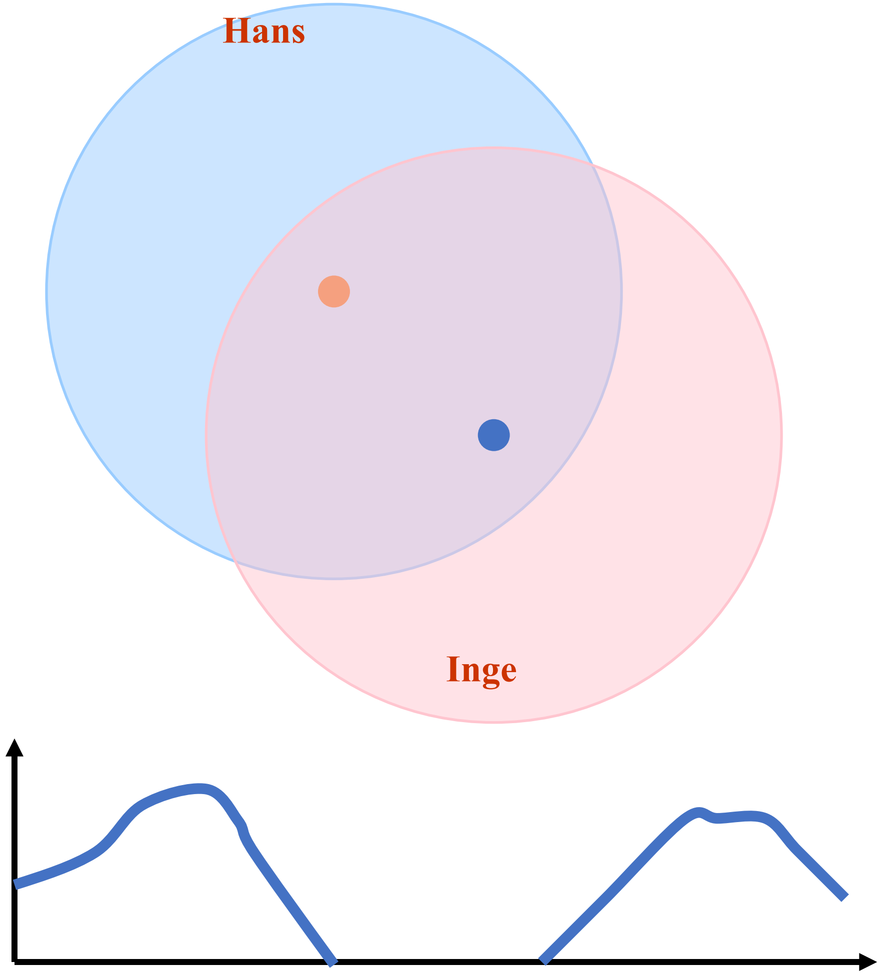
How Do We Increase Network Capacity?

- 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.



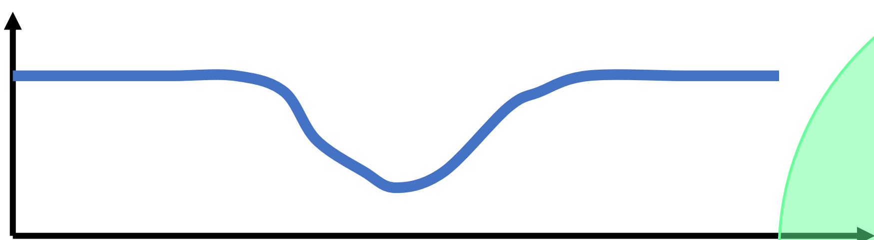
Mobility Affects the Link Throughput

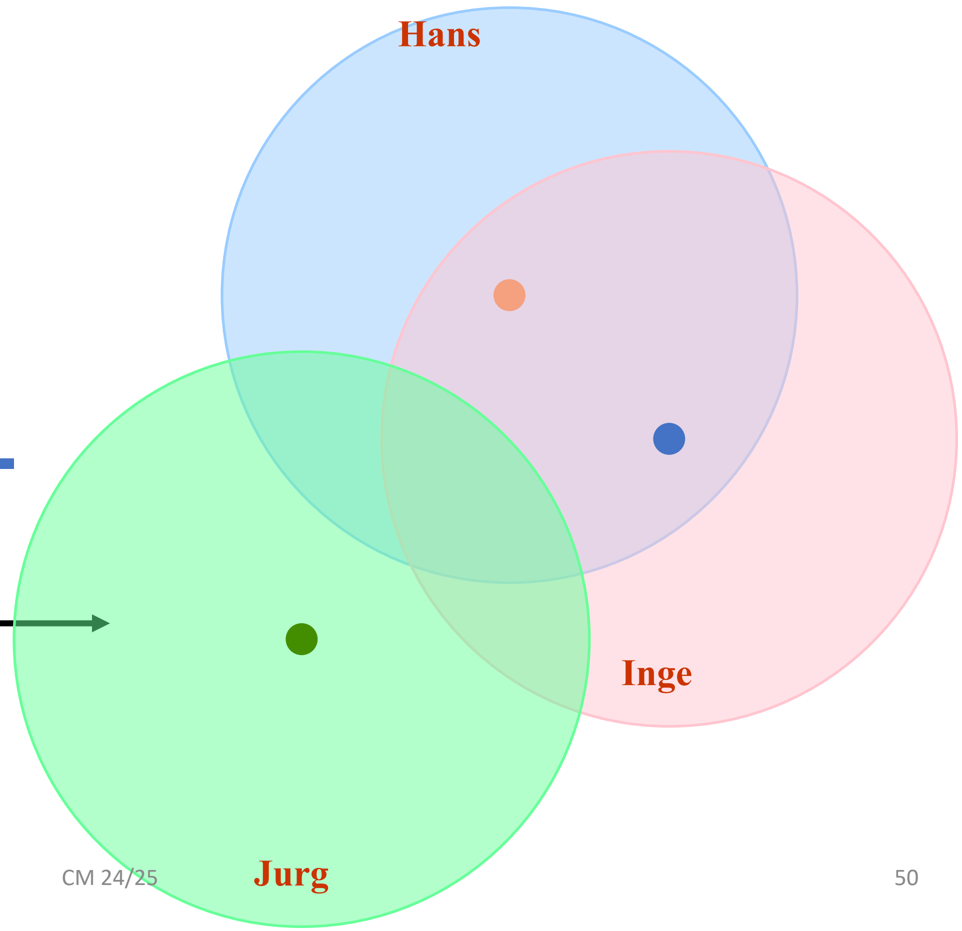
- Quality of the transmission depends on distance and other factors.
- Affects the throughput mobile users achieve.
- Worst case is periods with no connectivity!



Mobility is an Issue even for Stationary Users

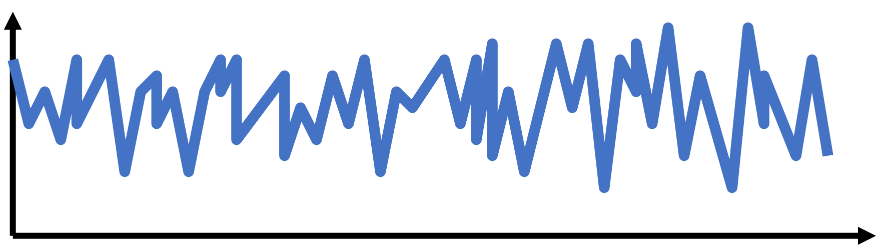
- Mobile people and devices affect the transmission channel of stationary nodes.

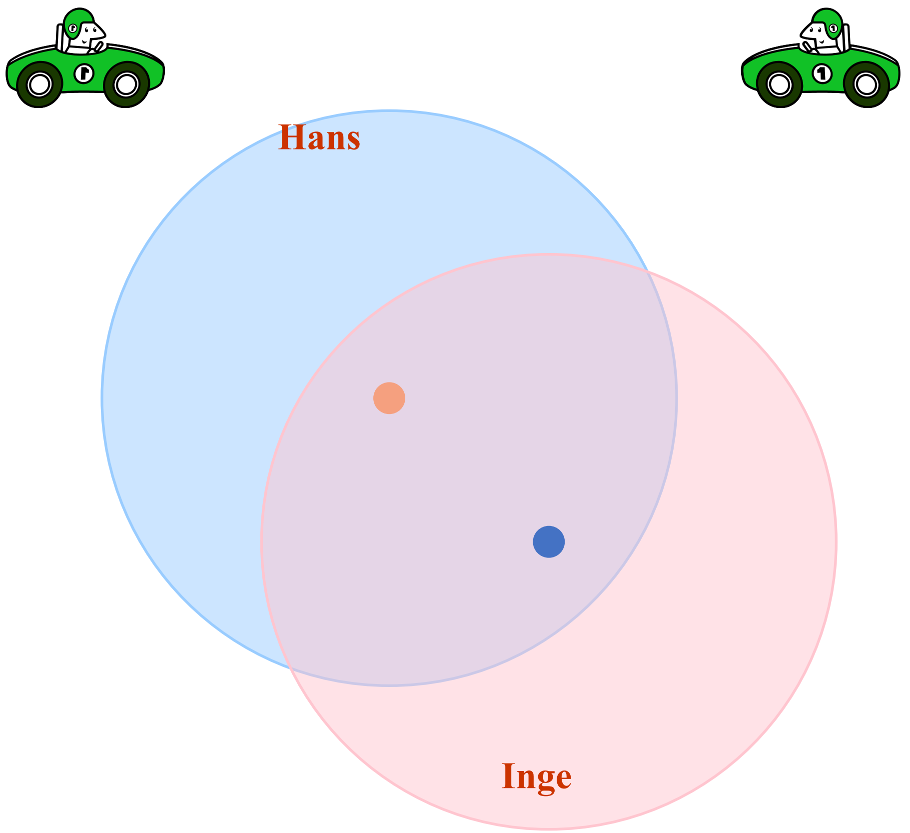




And It Gets Worse ...

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

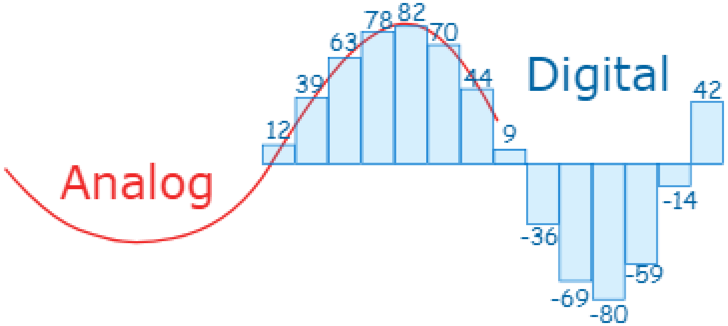




The Mobile Network

Basic principles of wireless signal properties

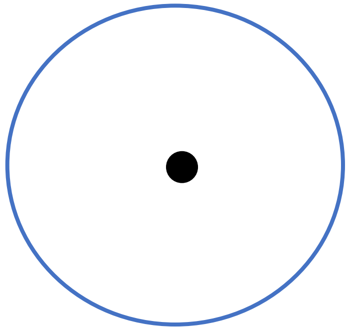
Time-Domain View

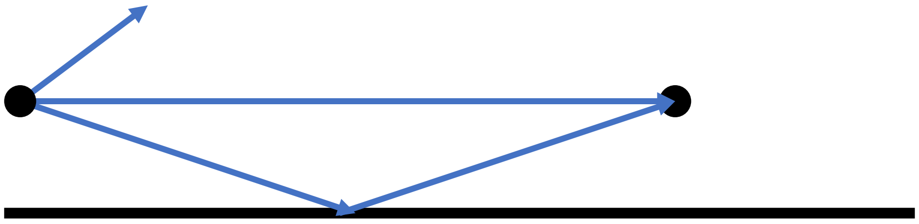


- Can be used to represent both an analog and a digital signal.
- Analog signal - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
  - E.g. voice signal traveling over traditional phone line
- Digital signal - signal intensity maintains a constant level 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

Two Graphical Views of an Electromagnetic Signal

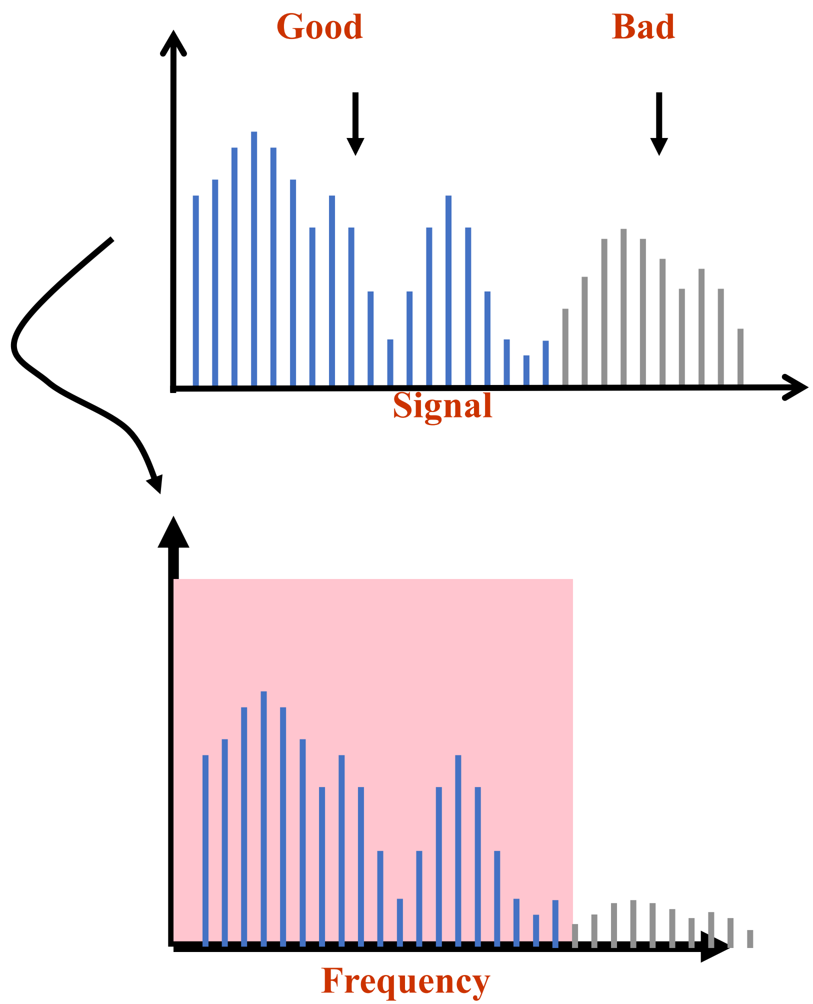
- Both are real in some way
- Think of it as energy that radiates from an antenna and is picked up by another antenna.
  - Helps explain properties such as attenuation
- Can also view it as a "ray" that propagates between two points.
  - Helps explain properties such as reflection and multipath





Transmission Channel Considerations

- 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



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 (signal theory)- 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

More on spectral efficiency, and the relationship between data rate and bandwidth: https://www.techplayon.com/spectral-efficiency-5g-nr-and-4g-lte/

Propagation Modes

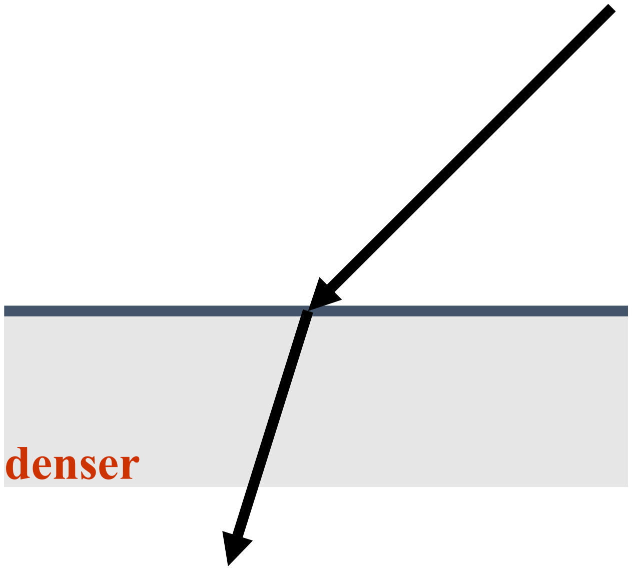
- Line-of-sight (LOS) propagation.
  - Most common form of propagation
  - Happens above ~ 30 MHz
  - Subject to many forms of degradation (next set of slides)
- Ground-wave propagation.
  - More or less follows the contour of the earth
  - For frequencies up to about 2 MHz, e.g. AM radio
- Sky wave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

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.
- Mobility: moving receiver causes another form of self interference.
  - Big change in signal strength

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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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
- 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

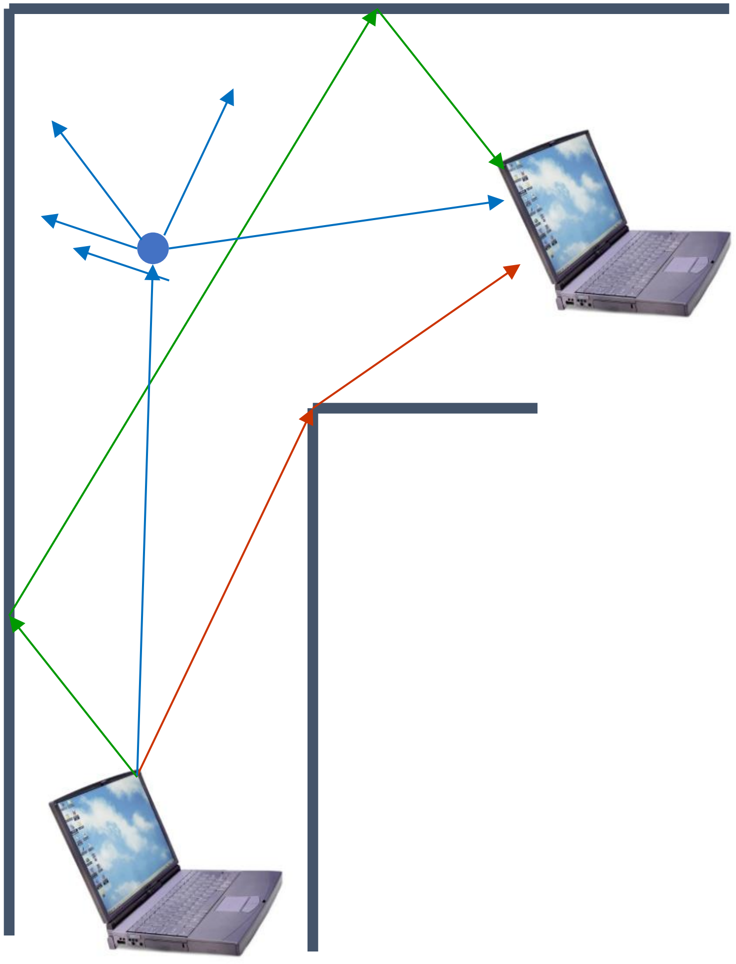
Fairly Predictable
➢Can be planned for or avoided

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

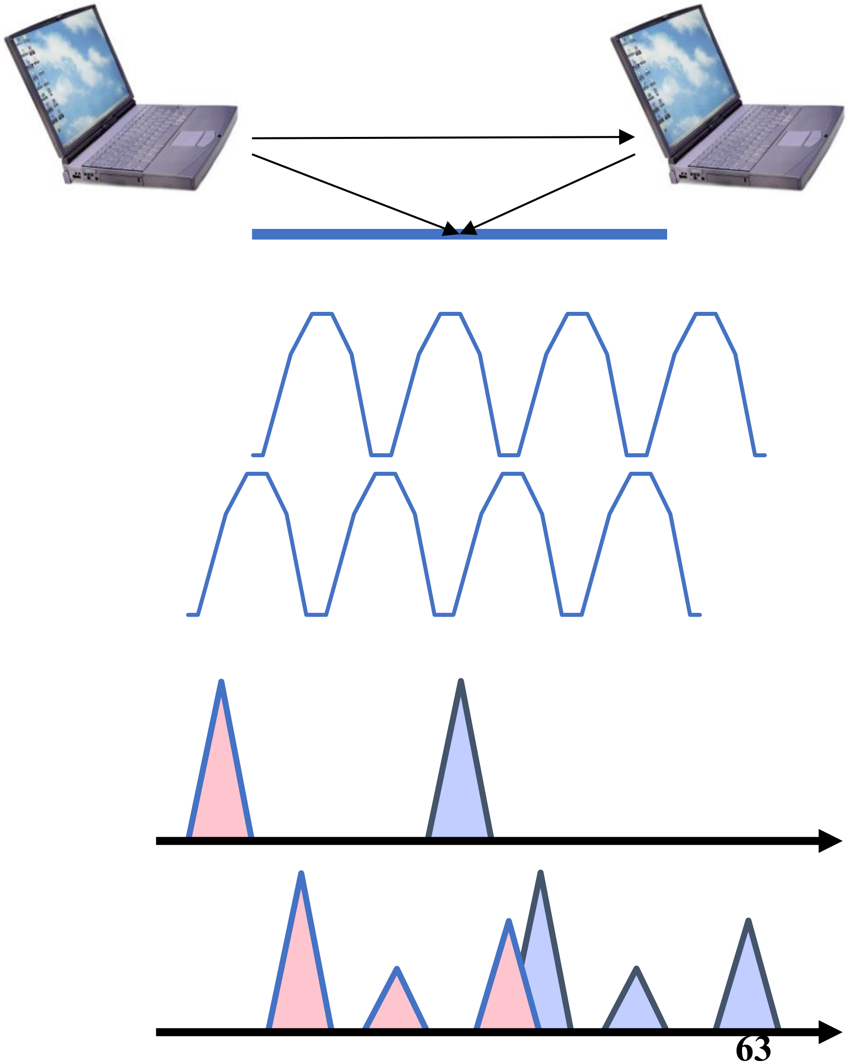
Propagation Mechanisms

- 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.



Multipath Effects

- Receiver receives multiple copies of the signal, each following a different path.
- Copies can either strengthen or weaken each other.
- Small changes in location can result in big changes in signal strength.
- Difference in path length can cause intersymbol interference (ISI).



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

Multiple Users Can Share the Spectrum

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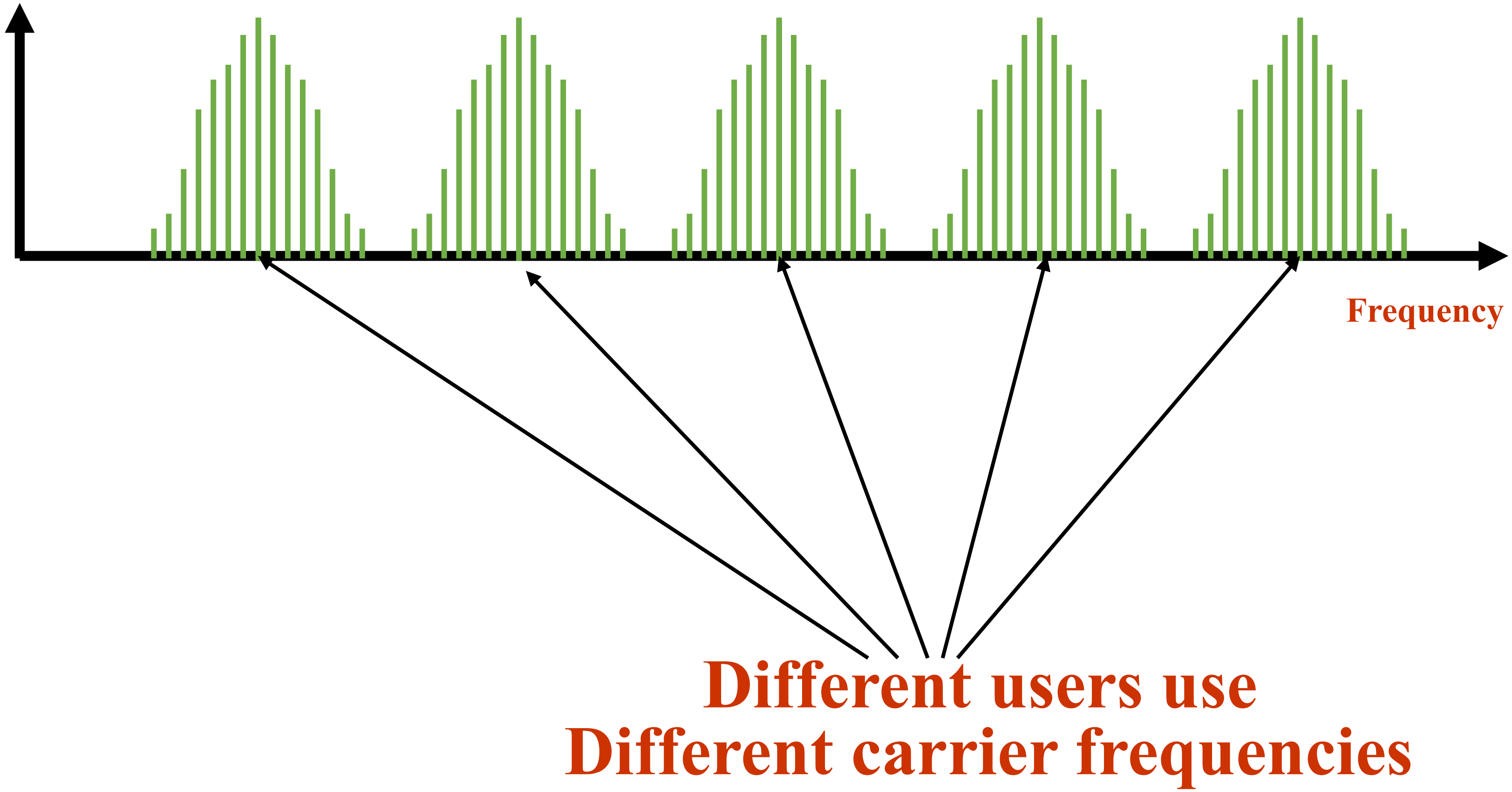
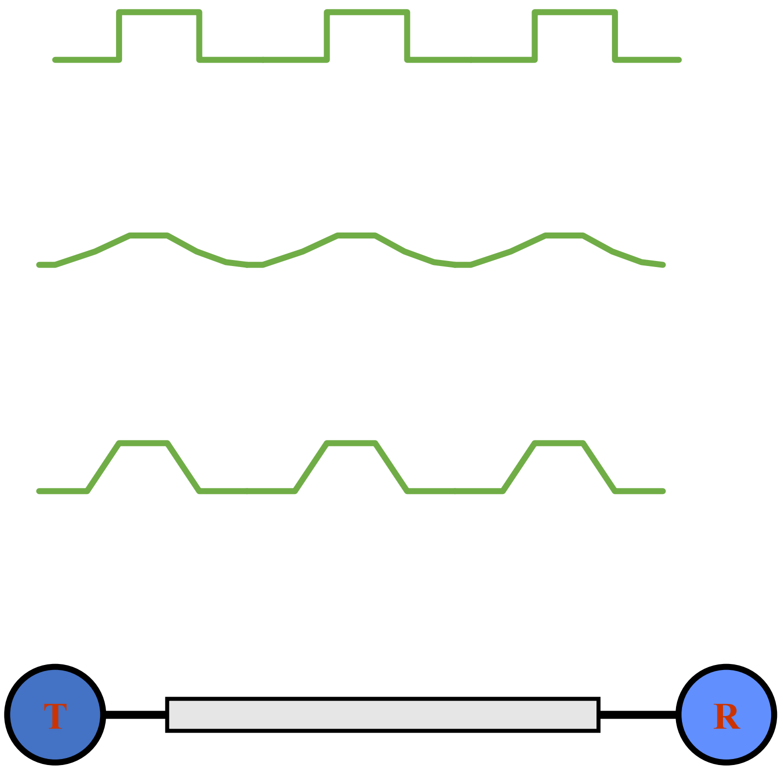


So Why Don’t we Always Send a High Bandwidth Signal?

- 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



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)

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

How is a signal considered good or bad?

(how do we measure signals)

RSSI – Received Signal Strength Indicator

- Measures how well a client device can hear (receive) a signal from a router/basestation/etc.
- Useful to determine if the signal is good enough to have a wireless connection
- Alternative for measuring signal strength: dBm (decibel-miliwatts)
  - Unit of power expresswed in a logarithmic scale representative to 1 mW

- RSSI
  - Relative index
  - Measures the quality of the received signal
  - Each manufacturer can have different scales
  - Cisco [0; 100] 100 → RSSI_MAX

- dBm
  - Absolute number
  - Measures the signal strength
  - The closer to 0 dBm, the better

dBm

$$dB = 10\log\frac{P}{P(ref)}$$

- P(ref) reference value→ 1mW
- P → value in mW that you want to convert

UNDERSTANDING

Signal Strength(dBm)	**Depiction in profile**
> -60 dBm	Excellent
-60 to -89 dBm	Good
-90 to -99 dBm	Fair
<=-100 dBm	Weak

RSRP – Reference Signal Received Power

- Average power level of the reference signals transmitted by a cell tower, as received by a user device
- Measured in dBm
- The power level value is used to determine the quality of a connection to a mobile network cell
  - This is used to help decide to which cell a user connects to (i.e., cell selection)

RSRP

RSRP	Signal strength	Description
>= -80 dBm	Excellent	Strong signal with maximum data speeds
-80 dBm to -90 dBm	Good	Strong signal with good data speeds
-90 dBm to -100 dBm	Fair to poor	Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to -100, performance will drop drastically
<= -100 dBm	No signal	Disnonnection

RSRQ – Reference Signal Received Quality

- Evaluates how efficiently the reference signals are being used by the mobile device
  - Interference from other cells or devices
  - Network load
  - Environmental factors
- RSRQ = (N * RSRP) / RSSI
  - N → Number of resource blocks used for the measurement
- RSRQ → [-19.5 dB; -3 dB]
- RSRP → How strong a signal is
- RSRQ → How efficient the connection is considering (i.e.,) noise

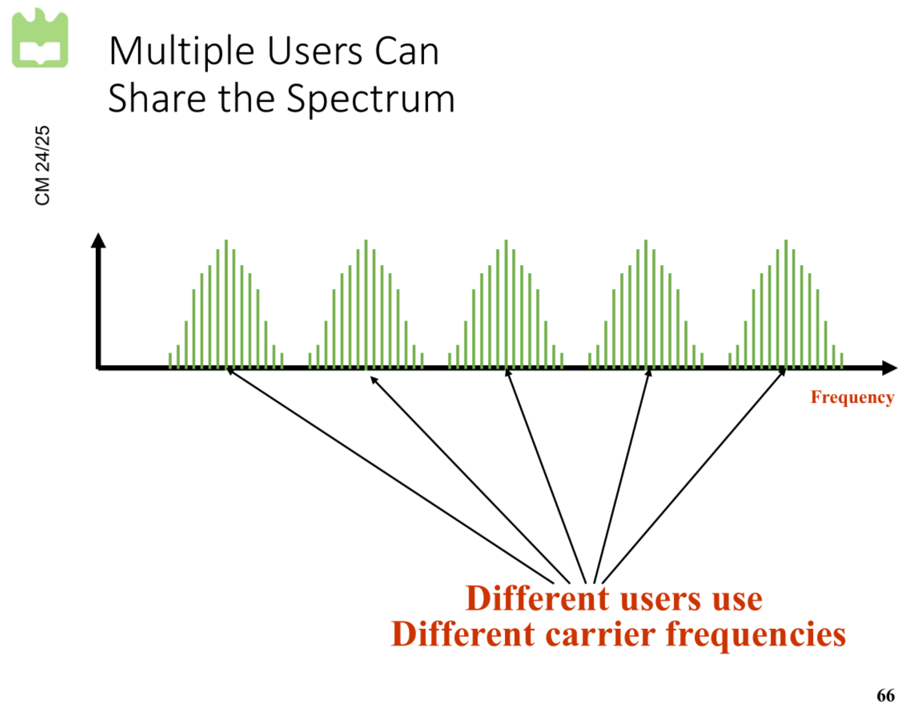
SINR – Signal-to-Interference-plus-Noise Ratio

- Indicates how well the mobile device can separate the desired signal from unwanted interference and noise
  - How effective is the network connection to deliver data
- SINR = Signal Power / (Interference Power + Noise Power)

RF Conditions	RSRP (dBm)	RSRQ (dB)	SINR (dB)
Excellent	>=-80	>=-10	>=20
Good	-80 to -90	-10 to -15	13 to 20
Mid Cell	-90 to -100	-15 to -20	0 to 13
Cell Edge	<=-100	<-20	<=0

Channels

- Remember this slide:



Channels

- Specific frequency ranges and bands to transmit and receive data over the air
- Each channel uses a different frequency
  - Allowing multiple devices to communicate simultaneously without interfering with each other

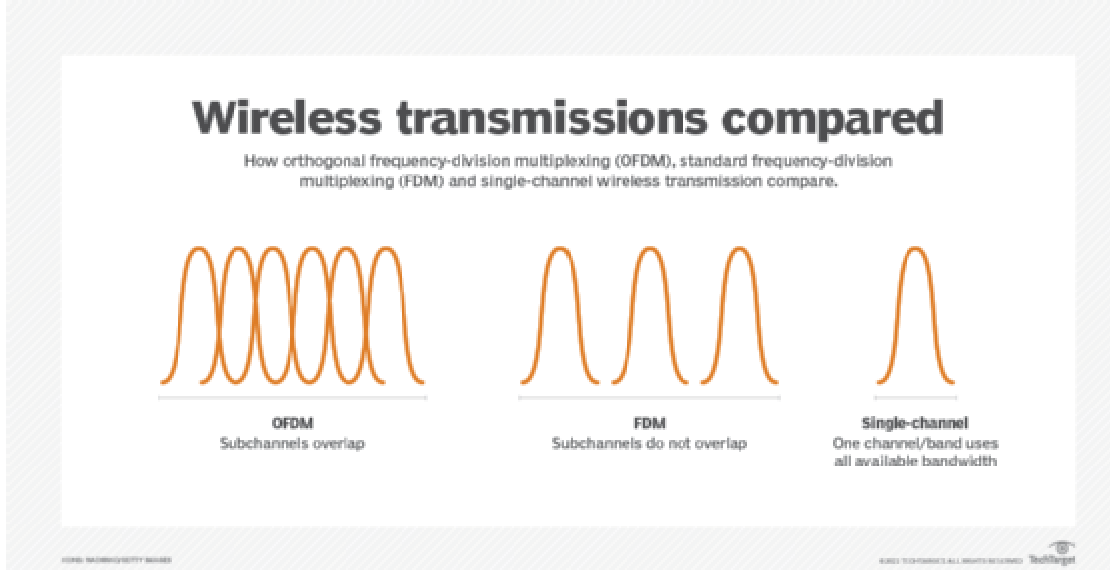
- Allocation
  - Fixed
    - Pre-assigned
    - Simple
    - Less efficient
  - Dynamic
    - Allocated in real-time due to demand
    - More efficient use of spectrum

Channels

- Width
  - Narrow [25 ; 200] KHz
    - Good coverage
    - Limited data rates
  - Broad [5 MHz; GHz…]
    - Lower coverage
    - Higher data rates

- Note:
  - Higher frequencies usually have wider bandwidth (width of the frequency range), allowing MORE DATA to be transmitted
    - i.e., wider channels
    - E.g., 2.4GHz Wi-Fi vs 5GHz Wi-Fi

Channels



- Note 2
  - Higher frequencies can use finer divisions of the channel (sub-carriers)
  - How is this used? MODULATION SCHEMES
- Example: Orthogonal Frequency Division Multiplexing (OFDM)
  - Splits a channel into multiple subcarriers
  - Each subcarrier is modulated with a high-order modulation scheme
- What is this “high-order modulation scheme”?
  - How data is encoded in the carrier signal
  - Higher-order allows for more bits of data to be transmitted per symbol
    - This is possible because higher frequencies are being used (better signal clarity)

Channels

- There are different channels
  - Control
  - Traffic
  - Broadcast
  - …