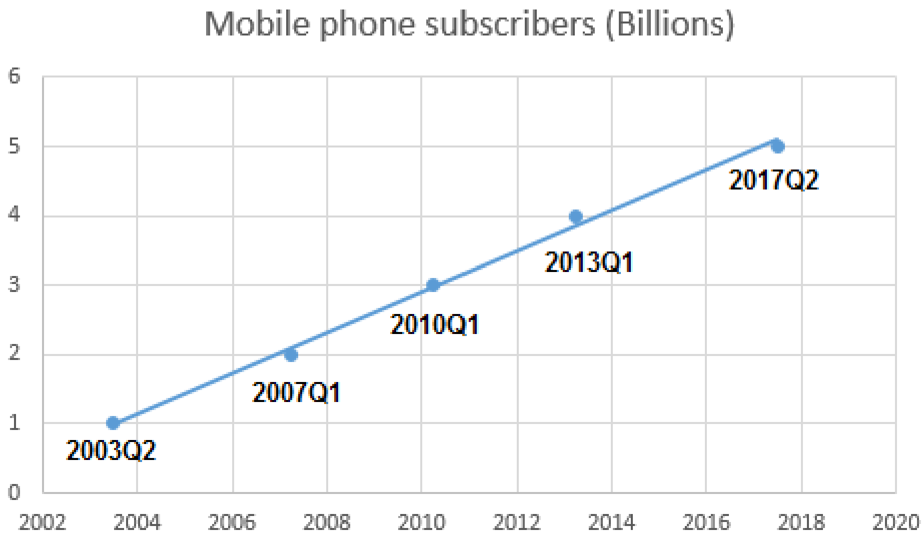
Introduction to 5G Communications

Importance of mobile communications

Mobile communications is consistently ranked
as one of mankind's breakthrough technologies

Annual worldwide mobile service provider revenue exceeds 1 trillion USD
and mobile services generate about 5% of global GDP

5 billion people (2/3 of the world) own at least 1 mobile phone (> 8B devices)
with over ½ of these smartphones
and over ½ of all Internet usage from smartphones



Generations of cellular technologies

	1G	2G	3G	4G	5G
standards	AMPS	IS-136, GSM Groupe Spécial Mobile	UMTS 3GPP R4 - R7	LTE R8-R9, R10-R14	3GPP 15, 16
era	1980s	1990s	2000s	2010s	2020s
services	analog voice	digital voice messages	WB voice packet data	voice, video Internet, apps	*everything*
devices					
data rate	0	100 kbps (GPRS)	10 Mbps (HSPA)	100+ Mbps (LTE/LTE-A)	10 Gbps (NR)
delay		500 ms	100 ms	10s ms	5 ms

This course

- Introduction to cellular communications
- Cellular system architecture
- Limitations of 4G, 5G design goals (ITU-R M.2083)
- 5G architecture (gNb, NR, RAN, NGCN), Co-existence options
- 4G Air Interface and basic improvements (framing, CA, channel coding)
- MIMO and massive MIMO, New spectral bands and millimeter waves, Innovative coverage strategies (OneWeb, Aquila)
- 5G Radio Access Network and functional splits
- Transport options (XGS-PON, 802.3by/cd/bs, FlexE, eCPRI, TSN, DetNet)
- Cloud RAN (cRAN) and virtual RAN (vRAN), HetNets, MOCN and MORAN
- Survey of SDN, NFV, and MEC
- Network slicing
- 5G core network (NGCN), standalone and non-standalone modes
- 5G security
- Use case – eMBB (enhanced Mobile BroadBand) and fixed wireless
- Use case – URLLC (Ultra Reliable Low Latency Communications)
- Use cases – mMTC, IoT, CI and smart city, V2X, AR/VR

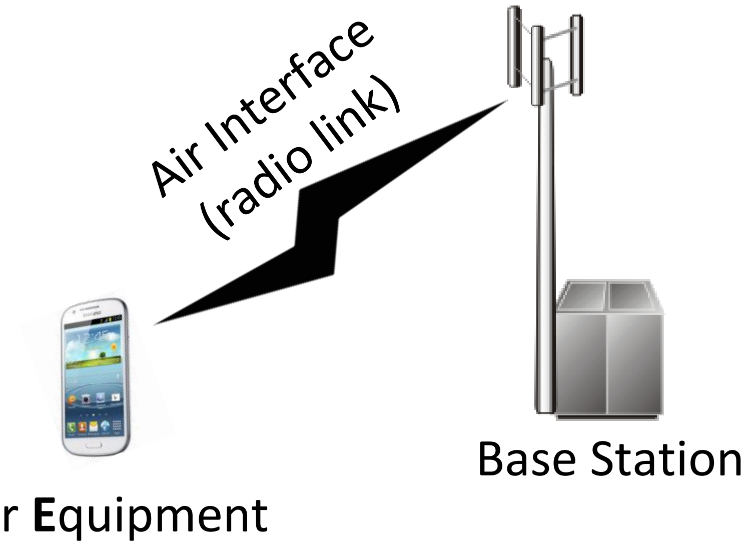
Cellular Communications

What is mobile communications?

When they hear *mobile* or *cellular* communications

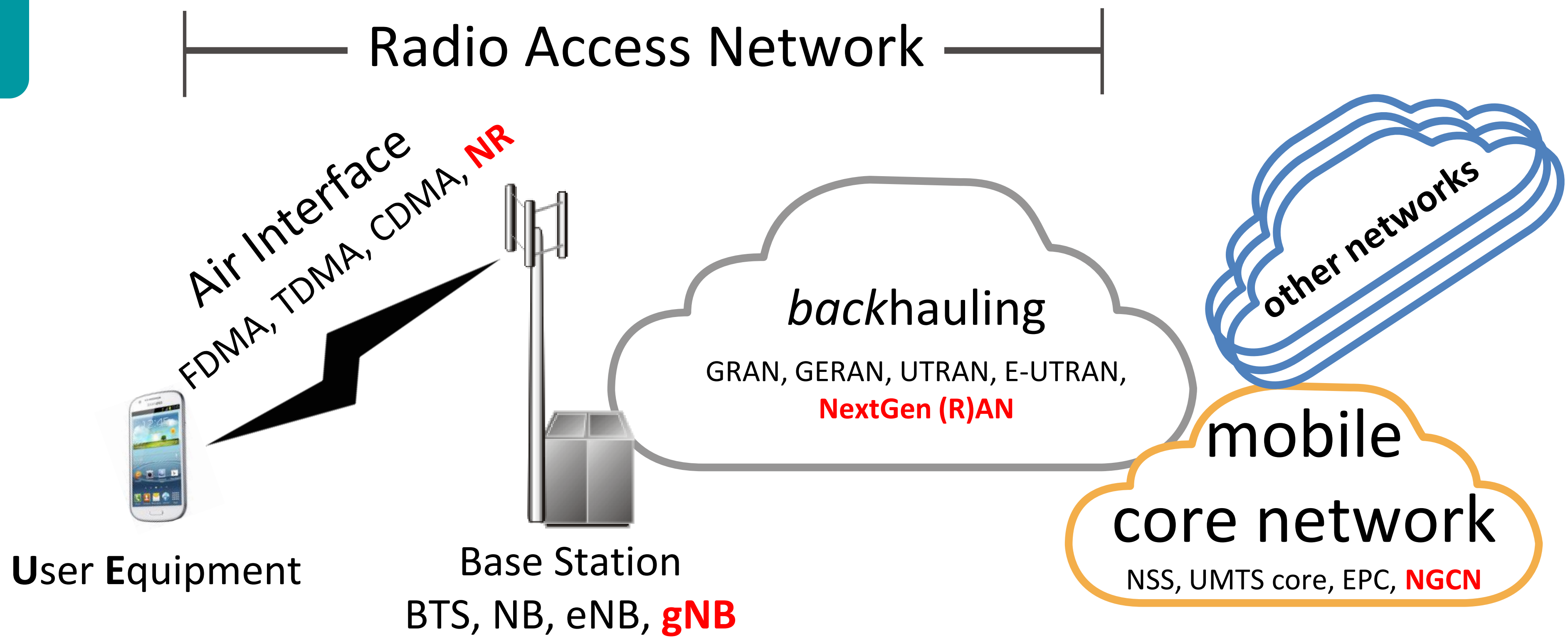
most people think only about the radio link (air interface) between

- a mobile phone (**U**ser **E**quipment)   and
- a cellular base station (BTS/nodeB)



But this is only a small part of the story

Basic cellular segments

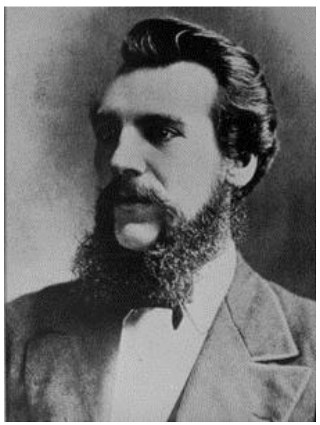


To fully understand this architecture

we need first to understand how it evolved

The telephone

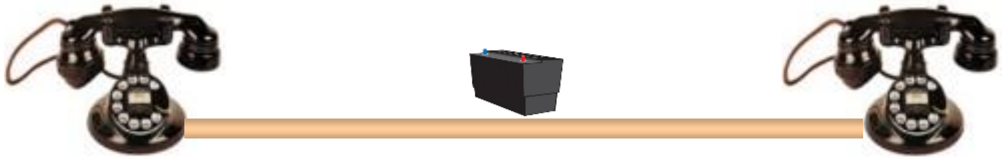
Everyone knows that the father of the **telephone** was
Alexander Graham Bell (patent 174,465)
(along with his assistant Thomas Watson)



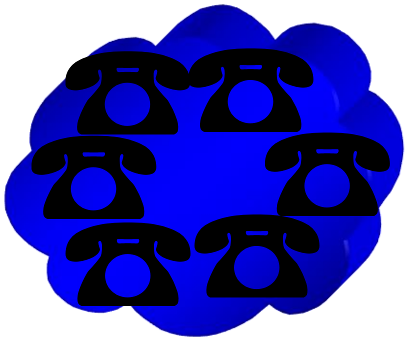
But they did not invent the **telephone network**

Point to point vs. network

Bell's business model was to sell phones to customers



which supports point-to-point communications
but breaks down (the N^2 problem) if we desire universal connectivity

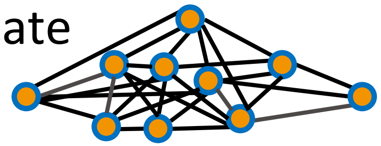


It also suffers from being a **product** model, rather than a **service** model
placing all operational responsibility on the end-user

Network importance

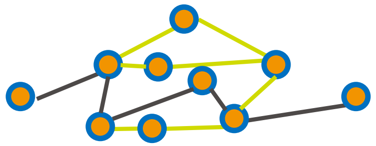
Early telegraph *connections* were individual *links*

However, it is impossible (or at least very inefficient)
to directly connect every 2 entities that need to communicate



Instead, one builds a **network**

Networks are arbitrary connected *graphs*



- edges are **links**
  - copper wires
  - optical fibers
  - free-space electromagnetic transmissions
- nodes may be
  - end-points (customers)
  - switches
  - middleboxes

Network value

While communicating with only one peer has value
the capability of communicating with **N** peers has *more* value

What do we mean quantitatively by the value **V** of a network ?
Each peer is willing to pay for the capability of contacting N peers
The value is the payment of all peers

Values superlinear in N cause networks to *merge*

- **Metcalfe's Law** (follows from the number of *peer-peer calls*)
  $\mathbf{V \sim N^2}$
- **Reed's Law** (follows from the number of *conference calls*)
  $\mathbf{V \sim 2^N}$
- **Odlyzko's Law** (follows from Zipfian distribution of *peers of interest*)
  $\mathbf{V \sim N \log N}$
- **Stein's LinkedIn Law** (follows from **F**riend **O**f **A** **F**riend connectivity)
  $\mathbf{V \sim N^{4/3}}$

Father of the telephone *network*

The father of the telephone **network** was **Theodore Vail**

- Cousin of Alfred Vail (Morse's co-worker)
- Ex-General Superintendent of US Railway Mail Service
- First general manager of Bell Telephone
- **Father of the PSTN**

Organized telephony as a **service** (like the *postal service*!) *

Why *else* is he important?

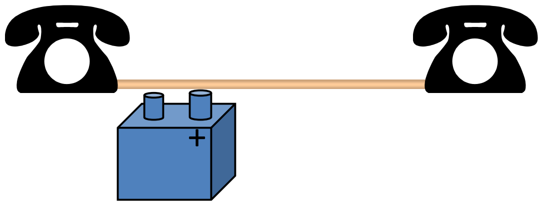
- Established principle of reinvestment in R&D
- Established Bell Telephones IPR division
- Executed merger with Western Union to form AT&T
- Solved major technological problems
  - use of copper wire
  - use of twisted pairs

* **Vailism** is the philosophy that public services should be run as closed centralized monopolies for the public good

Product vs. service

In the Bell-Watson model
the customer pays once, but is responsible for

- installation
  - wires
  - wiring
- operations
  - power
  - fault repair
  - performance (distortion and noise)
- infrastructure maintenance



while the Bell company is responsible only
for providing functioning telephones

In the Vail model the customer pays a monthly fee
and the **S**ervice **P**rovider assumes responsibility for everything
including fault repair and performance maintenance

The SP owns the telephones and maybe even the wires in the walls !

The PSTN

The **P**ublic **S**witched **T**elephone **N**etwork

- was the first large communications network
- was not planned, but rather grew by mergers and acquisitions
- is not a network, but rather an internetwork of regional networks

The PSTN was originally an analog network
but when digital communications

- was proven better (Shannon theory)
- became practical (invention of transistor)

the PSTN migrated to become a digital core with analog subscriber lines

Many innovations were invented for the PSTN, including:

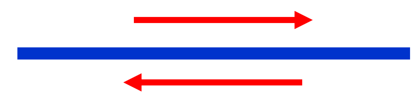
- multiplexing
- network planning, addressing
- OAM, control and management planes, billing

The PSTN is presently being phased out (being replaced by the Internet)
but many issues remain before it will be completely shut down

Multiplexing terminology

There are mechanisms to efficiently utilize *links* in a *network*

- Duplexing (half/full duplex)
  sending information in both directions on same link
  examples: FDD, TDD



- Multiplexing (**mux**)
  sending multiple flows of information on same link
  examples: FDM, TDM

- Inverse multiplexing
  sending a single flow of information on multiple links
  examples: LAG, link bonding, ECMP, VCAT

- **M**ultiple **A**ccess
  multiplexing uncoordinated users
  examples, FDMA, TDMA, CDMA

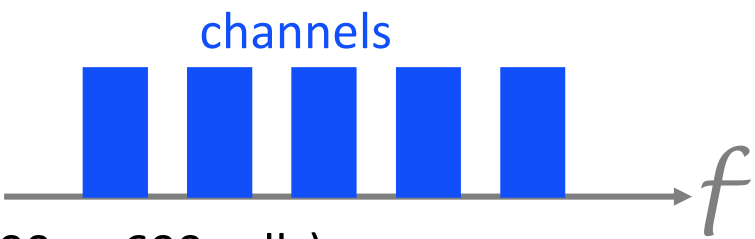
Multiplexing in the old PSTN

In 1900, 25% of telephony revenues went to copper mines

- standard was 18 gauge (about 1.2mm), long distance even heavier
- two wires per loop to combat cross-talk

A method was needed to place multiple calls on a single link (trunk)

from 1918: “Carrier system” (FDM)



- group: 12 calls on a single trunk
- supergroup: 5 groups (60 calls)
- master group: 5 or 10 supergroups (300 or 600 calls)
- supermaster groups, jumbo groups, etc.

from 1963: T-carrier system (TDM)

- T1 = 24 conversations per trunk (two groups on 2 trunk)
- PDH hierarchy
- SDH hierarchy

The old PSTN

The PSTN was originally an **analog** network

Analog voltages travel end-to-end over copper wires

Voice signals arrive at destination (attenuated, distorted, and noisy)

- Amplifiers can be used to combat attenuation
- Loading coils can be used to combat distortion

Routing was originally performed *manually* at *exchanges*
Routing became mechanical and then electrical

Digitization of the PSTN

The FDM hierarchy was based on 4 KHz voice channels
   not because that is really sufficient for speech
   rather since that was the output of microphones in the early 1900s

When migrating to digital, the channels were digitized at 8000 samples/sec.

With logarithmic quantization, 8 bits per sample is sufficient
   leading to a basic digital voice channel (DS0) of 64 kbps (*timeslot*)

The rate of 8000 frames per second defines all later PSTN digital signals
   network is **C**onstant **B**it **R**ate (bit rate consumed even when no information)
   and synchronous (accurate timing needed for bit recovery)

The first multiplexed level (DS1) is Time Division Multiplexing is **synchronous**
   all DSOs are sampled simultaneously

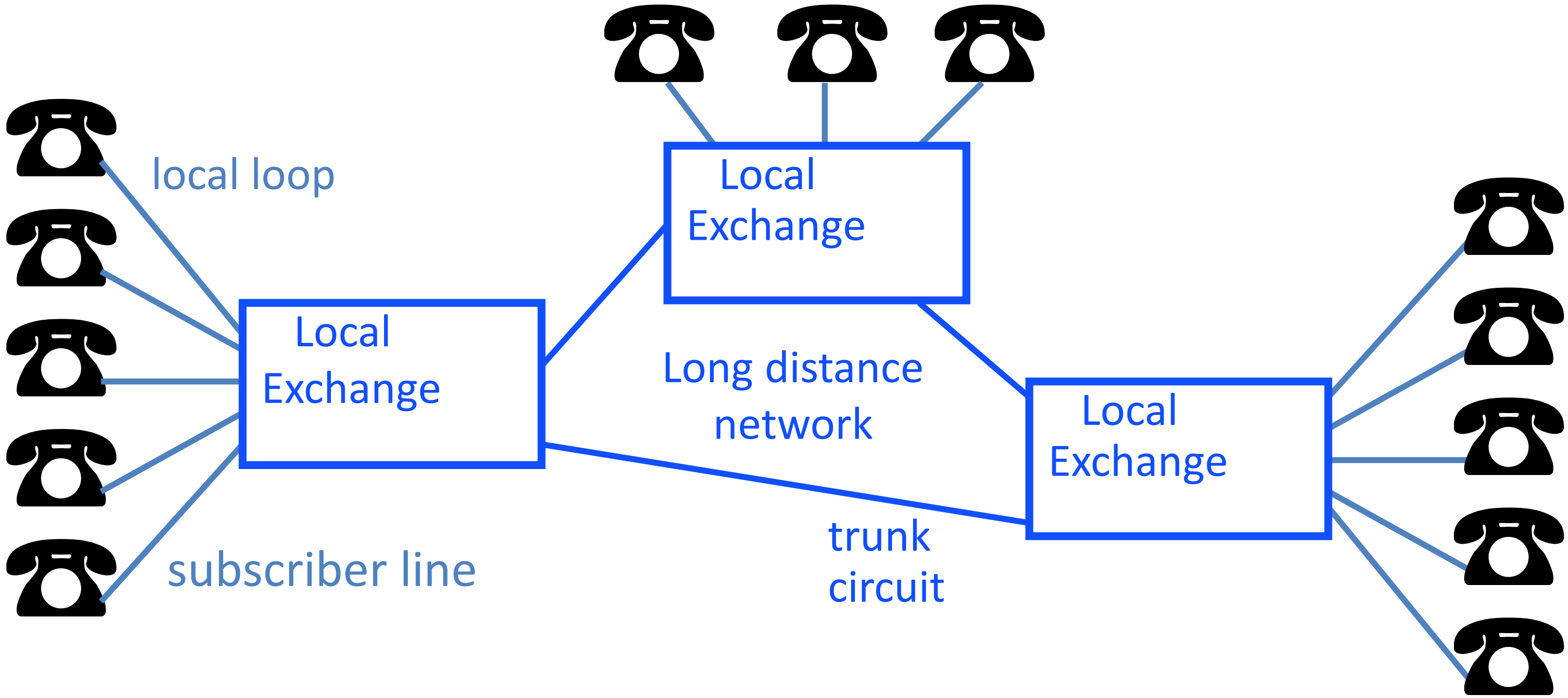
The following levels (DS2, DS3, DS4) are **plesiochronous** (PDH)
   multiplexed lower levels are only nominally of the same frequency

The higher levels are once again synchronous (SDH)
   multiplexed lower levels float in virtual containers

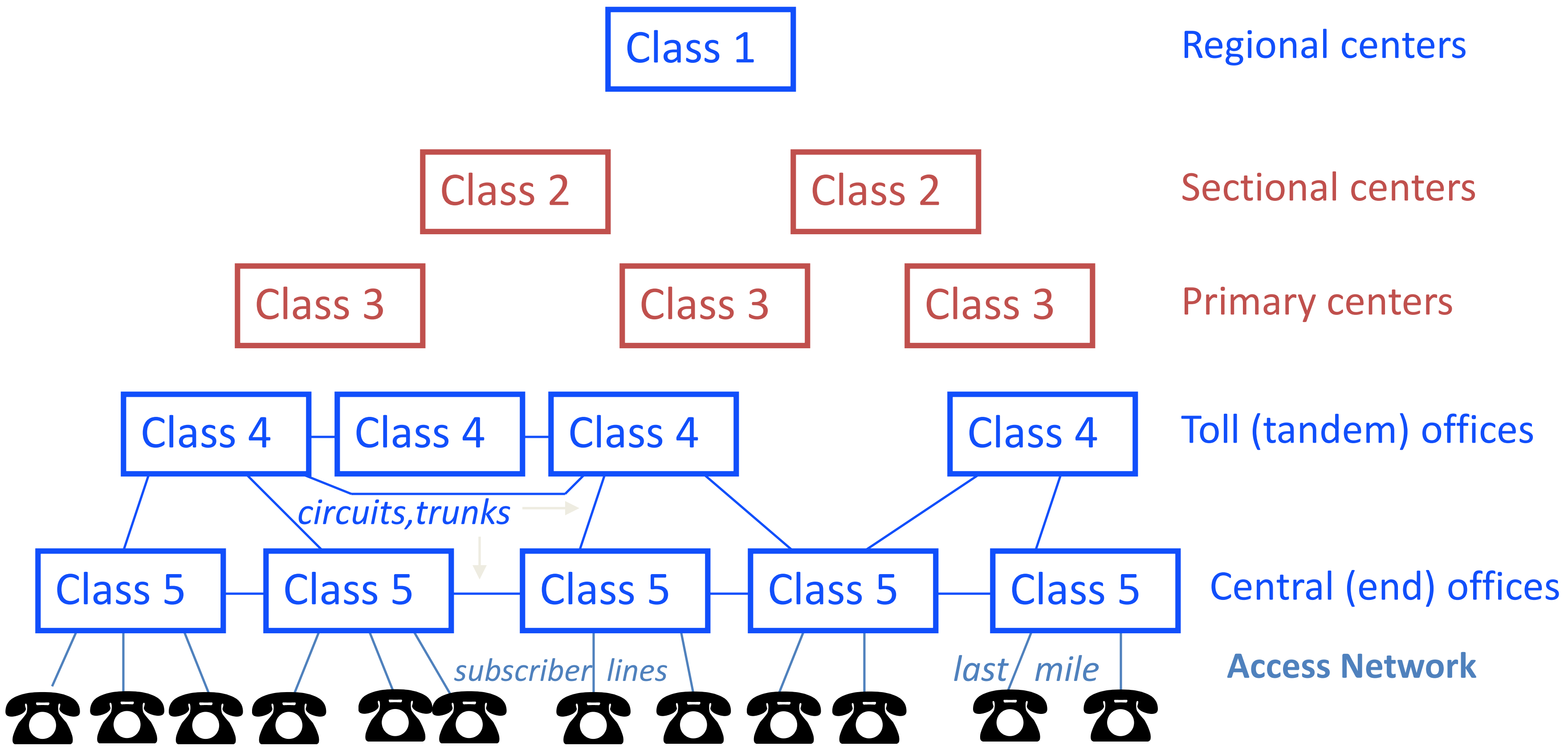
PSTN Topology

Many local telephone exchanges had sprung up

Bell Telephone acquired them
and interconnected them for long distance



Old US PSTN

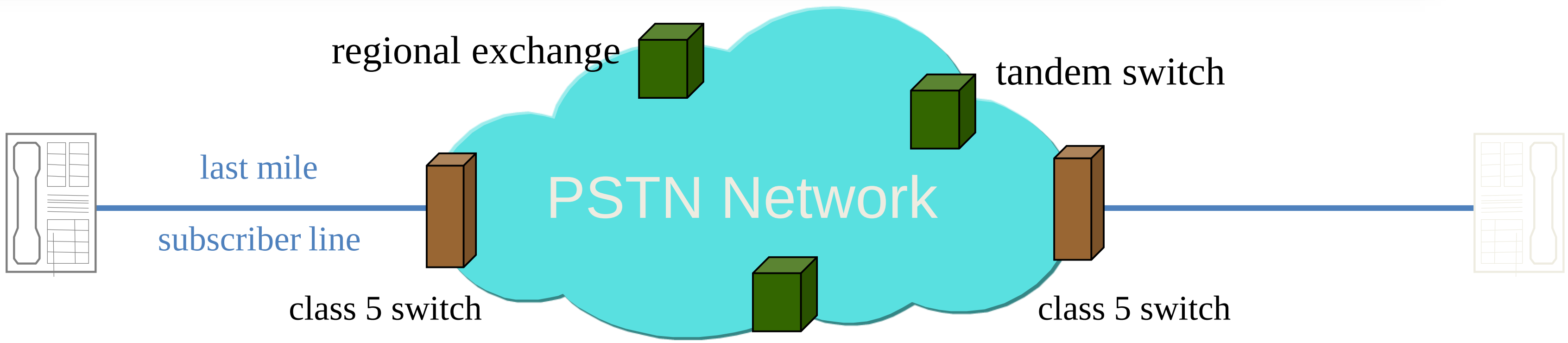


Class 5 switch is the sole interface to the subscriber lines

Class 5 switches are interconnected

but if no connection available Class 4 switches provide interconnection

The PSTN after 1960



Analog voltages and copper wire used only in “last mile”,
but core designed to mimic original situation

- Voice signal filtered to 4 KHz at input to digital network

Time Division Multiplexing of digital signals in the network

- Extensive use of fiber optic and wireless physical links
- T1/E1, PDH and SONET/SDH “synchronous” protocols

Universal dial-tone and automatic switching

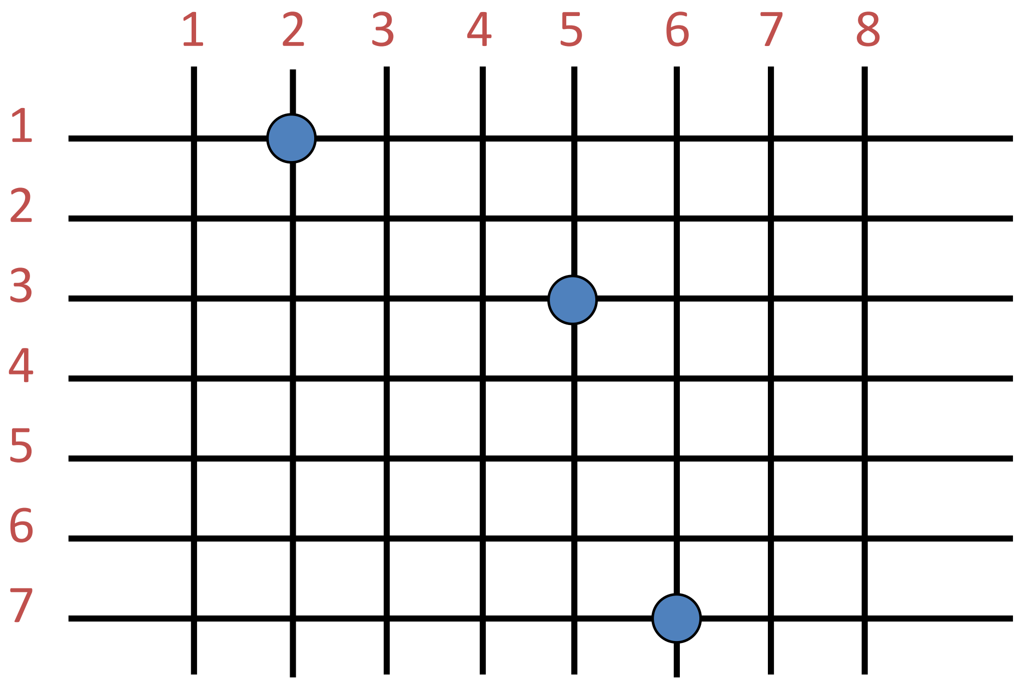
Signaling can be channel/trunk associated or via separate network (SS7)

Automatic routing

- Circuit switching (route is maintained for duration of call)
- Complex routing optimization algorithms (LP, Karmarkar, etc)

Analog switching

Analog Crossbar switch



Complexity increases rapidly with number of timeslots

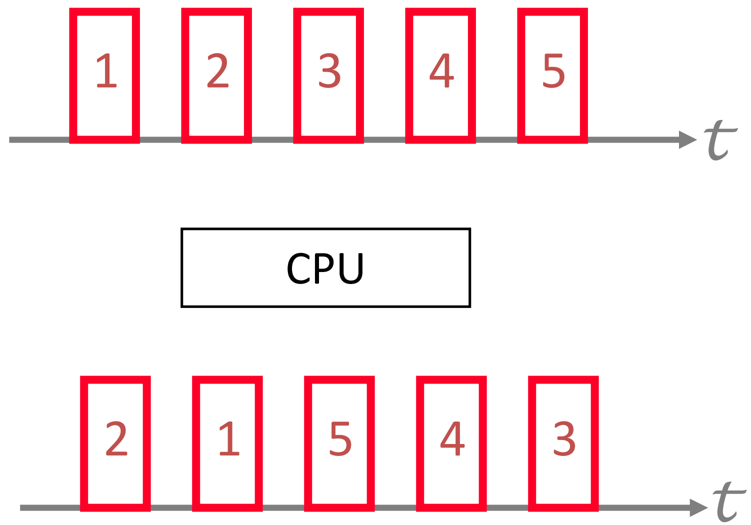
Switch introduces no transit delay

so end-to-end propagation time is time-of-flight (@ 200 meters / μsec)

TDM switching

Digital Crossconnect (DXC)

(depicted for a single TDM trunk)



The crossconnect switch

- extracts a byte
  - from timeslot N
  - in TDM trunk S
- places the byte
  - in timeslot M
  - in TDM trunk T

Complexity increases linearly with number of timeslots

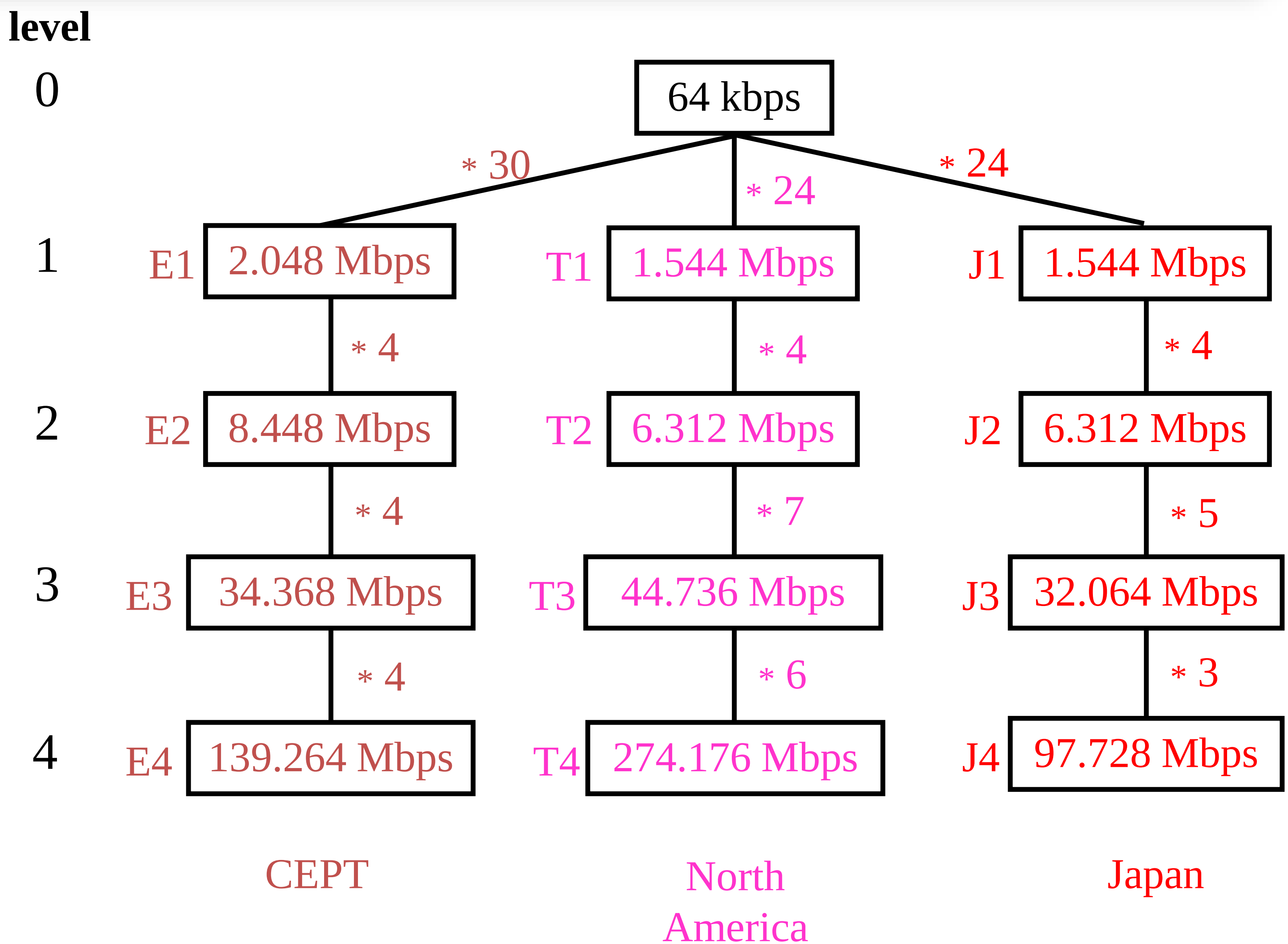
Switching time is theoretically 1 frame duration ($\frac{1}{8000}$sec = 125 μsec)

constant and independent of bit-rate

So that end-to-end propagation time is

- time-of-flight (@ 200 meters / μsec)
- number of switches * 125 μsec

PDH hierarchies



SONET/SDH hierarchies

SONET	SDH	rate	T1	T3	E1	E3	E4
OC-1		51.84M	28	1	21	1	
OC-3	STM-1	155.52M	84	3	63	3	1
OC-12	STM-4	622.080M	336	12	252	12	4
OC-48	STM-16	2488.32M	1344	48	1008	48	16
OC-192	STM-64	9953.28M	5376	192	4032	192	64

PDH couldn't scale to higher rates due to overhead increasing

SONET/SDH is still based on 8000 frames per second

higher data-rates are achieved by larger frames

The newer (non-PSTN) OTN has constant frame size

higher data-rates are achieved by more frames per second

Packet switching

The PSTN is based on circuit switching

once a call is set up it takes 64 kbps even when no one is talking

so that on average 50% of the resources is wasted

In order to improve efficiency, networks have migrated to packet switching

at least at *higher* layers

Modern telephony networks are **P**acket **S**witched **N**etworks

based on IP, MPLS, and Ethernet technologies

- The final *sunsetting* of the PSTN raises questions :
  - who will be responsible for *identity* and *phone numbers* ?
  - what are the correct *billing* models ?
  - who will provide *life-line* services ?
  - how will provide location-enabled emergency services ?

History of wireless

1865 Maxwell predicts existence of electromagnetic waves

1888 Hertz demonstrates that Maxwell's waves do exist

1892 Crookes describes a wireless telegraph

1894 Marconi demonstrates wireless telegraphy system (UK patent 12,039)
Marconi's telegraph credited with saving 700 people on the Titanic

1899 Guarini-Foresio builds 1st wireless repeater (granted Belgian patent)

1900 de Moura transmits wireless voice in Brazil (granted 3 US patents in 1904)

1919 Isidor Goldberg (Pilot Radio Corp) sells radio kits to the public
in 1937 offers the first TV receiver

1920 first regular public broadcast radio in Detroit Michigan

1922 first mention of wireless telephone in newspapers

1940s WWII military use of wireless voice
including handheld voice transceivers

1946 AT&T offers MTS Mobile Telephone Service

Wireless telephony is limited

MTS mobile service started on 17 June 1946 in St. Louis, Missouri
and was available in hundreds of US cities by 1948

This system was limited:

- manual call set-up
- **P**ush **T**o **T**alk (half duplex) operation
- transceiver weighed over 35 kg
- 5,000 customers placed about 30,000 calls per week
- expensive service - $15 ($150) per month, $0.40 ($4) per local call
- only 3 customers in any city could simultaneously use the service
  since only 3 RF channels were available
  (**I**mproved **MTS** increased to 12 channels = 1 group)

All such systems suffer from 3 problems:

1. very limited user density
   (IMTS limited to 40,000 customers in US, 2000 in NYC, 30 min wait for call)
2. limited coverage
3. no mobility (no handoff - today called *nomadic* communications)

Extending wireless telephony

MTS and IMTS just replaced
- a Class 5 switch with a base-station
- a last mile copper link with a wireless one

The obvious extension utilizes multiple base-stations (Class 5 switches!)
but such a system still suffers from major disadvantages:

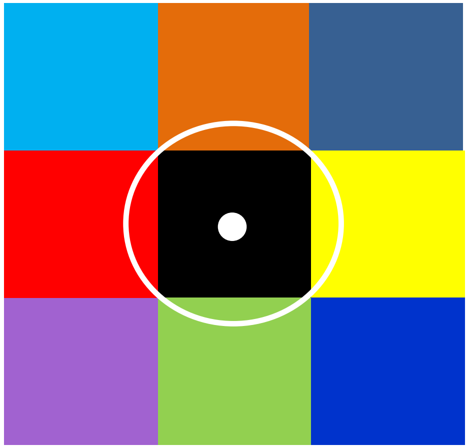
- coverage areas
  - interference between neighboring base-stations (frequency re-use)
  - reception of wireless phone by neighboring base-stations
  - reception of neighboring base-stations by wireless phone
  - lack of reception
- not knowing which base-station (if any) can reach a given wireless phone
- need to redial if wireless phone moves to different coverage area
- physical phone limitations (weight, battery life, ...)
- lack of confidentiality

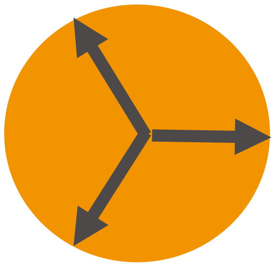
Mobility

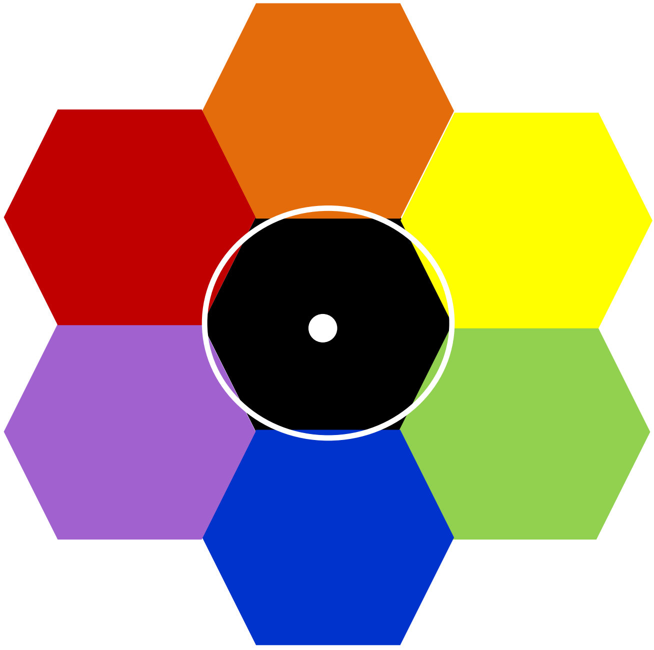
Many new ideas were required to create a true mobile telephony system :

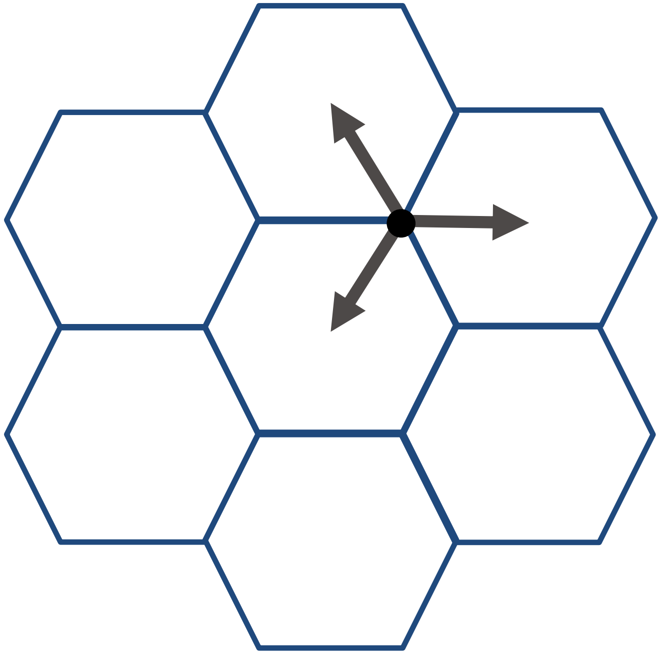
- as early as 1947 Bell Labs devised local (hexagonal) *cells* for car-phones
- Philip Porter proposed using 3 directional antennas at cell corners
- Porter also proposed dial-then-send to conserve air time
- Richard Frenkiel and Joel Engel (Bell) designed schemes for cellular frequency reuse that multiplied the reuse factor by 1,000
- Amos Joel (Bell) developed *handoff* (changing cell without dropping call) patent 3,663,762 filed 1970 (leading to court ruling that AT&T invented mobile)
- Motorola developed a hand-held mobile phone called DynaTAC patent 3,906,166 Martin Cooper et al, Mororola
  - 1.1 kilograms and measured 23 by 13 by 4.5 cm
  - talk time of just 30 minutes and took 10 hours to re-charge
- April 3, 1973, Martin Cooper (Motorola) walking in Manhattan placed the first handheld mobile call to Joel Engel

Cells, cells, cells

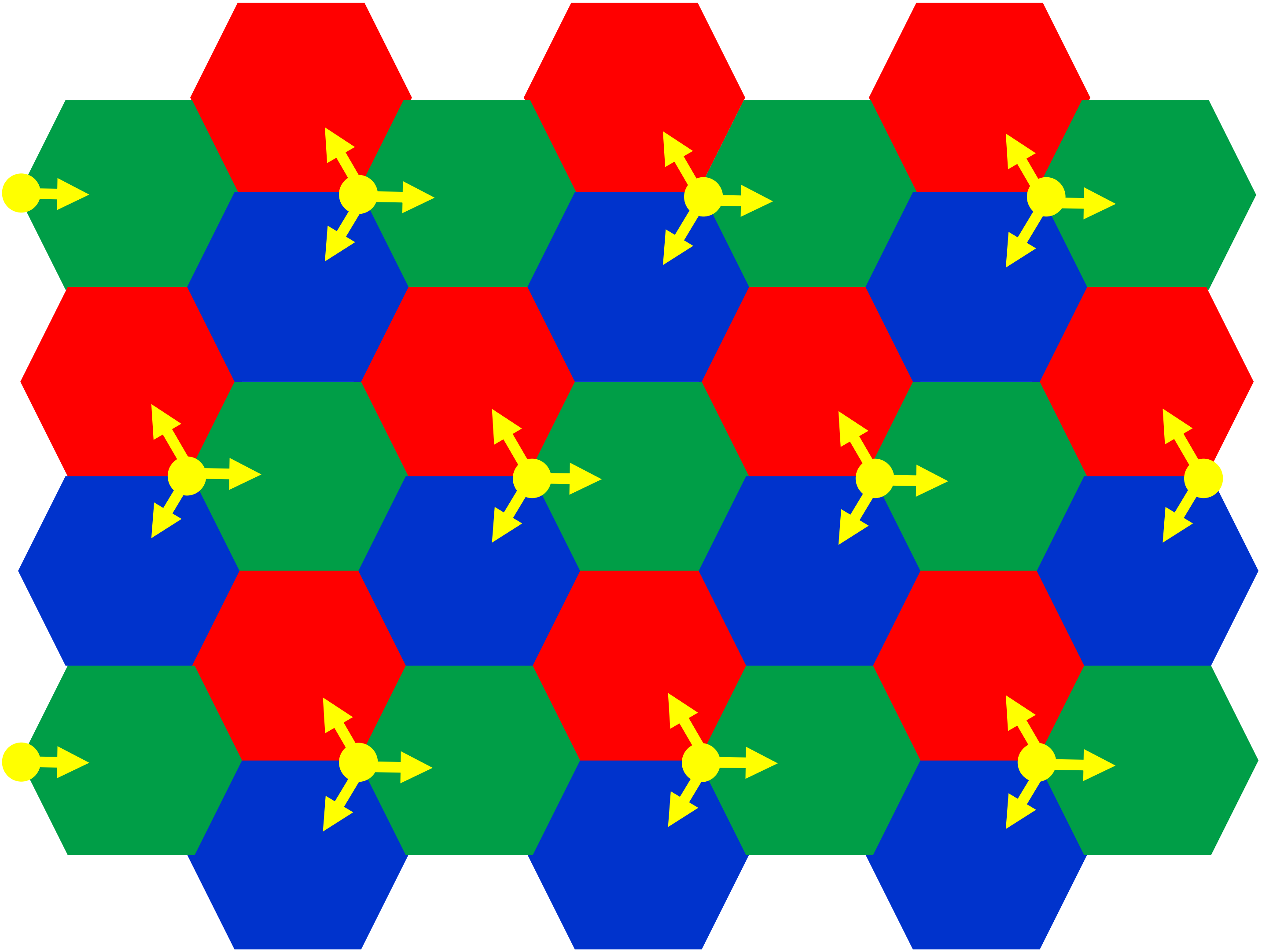








Porter's hexagonal scheme



Mobile telephony service

1971 AT&T request to FCC for cellular service

1982 FCC approved Advanced Mobile Phone Service (AMPS)

- 1986 Israel was the 2nd country to adopt
- 1st generation of mobile communications
- RF frequencies in the 850 MHz band
- FM modulation, duplexing using FDD, multiple access using FDMA
- each SP received a block of 333 (later 416) voice channel pairs
- 1st use of sophisticated logic for cell and channel allocation

1990 analog AMPS was replaced by Digital AMPS (D-AMPS)

- EIA/TIA Interim Standards IS-54 and IS-136 (2nd generation)
- same RF frequency bands as AMPS, but QPSK modulation
- bands divided into 30 kHz channels
- duplexing using FDD
- multiple access using FDMA and TDMA
  - originally each frequency channel muxed into 3 TDMA channels
  - later versions muxed into 6 channels

2G, 3G, 4G

The second generation of cellular (FDMA, GSM, CDMA) migrated to digital
to improve spectral efficiency, obtain privacy, and use error correction
also added **S**hort **M**essaging **S**ervice (as an after-thought)

2.5G (HSCSD, GPRS, EDGE) added data for Internet access (WAP)

3G (UMTS) united the world using W-CDMA air interface
to attain higher data rates (2 Mbps)

3.5G further increased data rates (14.4 Mbps)

4G once again shifted air interface to OFDMA
in order to attain data rates (100 Mbps) sufficient for streaming video
for the 1st time, 4G neglects voice (except for packet voice – VoLTE)

4.5G (LTE-A) increases the data-rate to 300 Mbps (and maybe more)

5G addresses all of the known drawbacks of 4G
if we get it right – there will be no need for future generations!

Work has begun on **B**eyond **5G**

I want 5G, and even 6G, technology in the United States as soon as possible.
- Donald Trump