UNIVERSITAS KOMPUTER INDONESIA

Chap 2 Mobile Communication

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Issue Vital to cellular

1. Frequency allocation/reuse
    1. Licensed
    2. Many providers
2. Multiple Access
    1. Many users
    2. Wide area of coverage
    3. Traffic management
3. Location management
    1. High mobility (in cars, trains)
    2. Multiple suppliers
    3. Handoff management, roaming
4. General principles
5. Handled differently by different generations

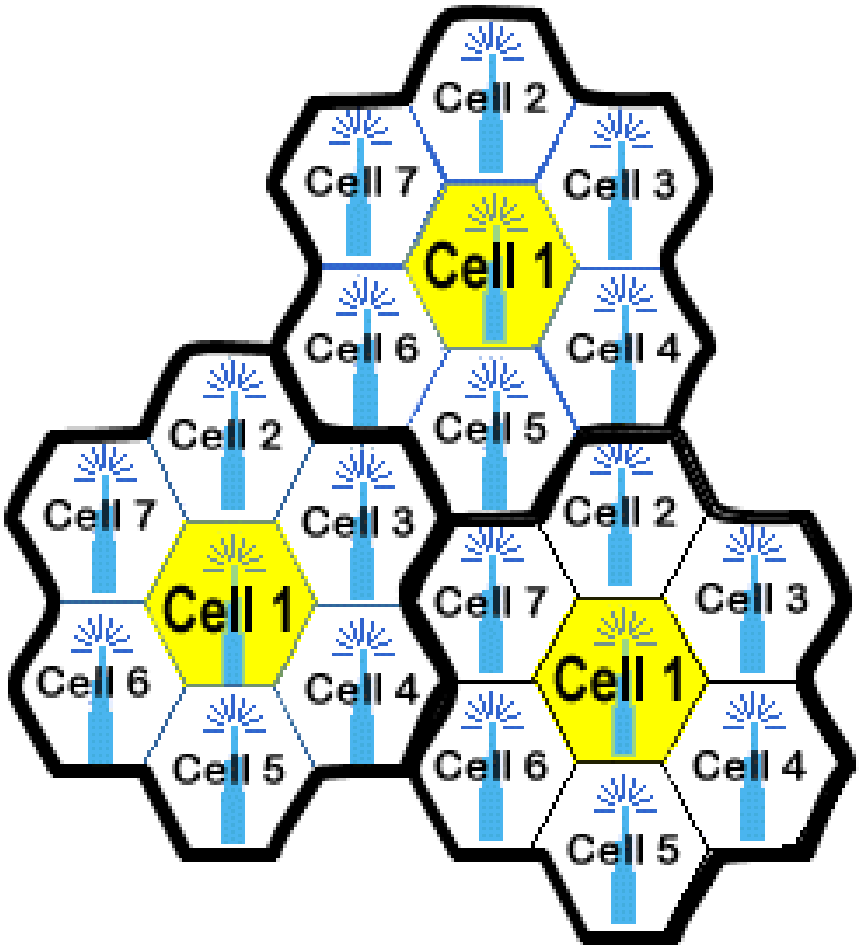
1. Frequency Reuse

The concept of frequency reuse is based on assigning to each cell a group of radio channels used within a small geographic area

- Cells are assigned a group of channels that is completely different from neighbouring cells
- The coverage area of cells is called the footprint and is limited by a boundary so that the same group of channels can be used in cells that are far enough apart

1. Frequency Reuse

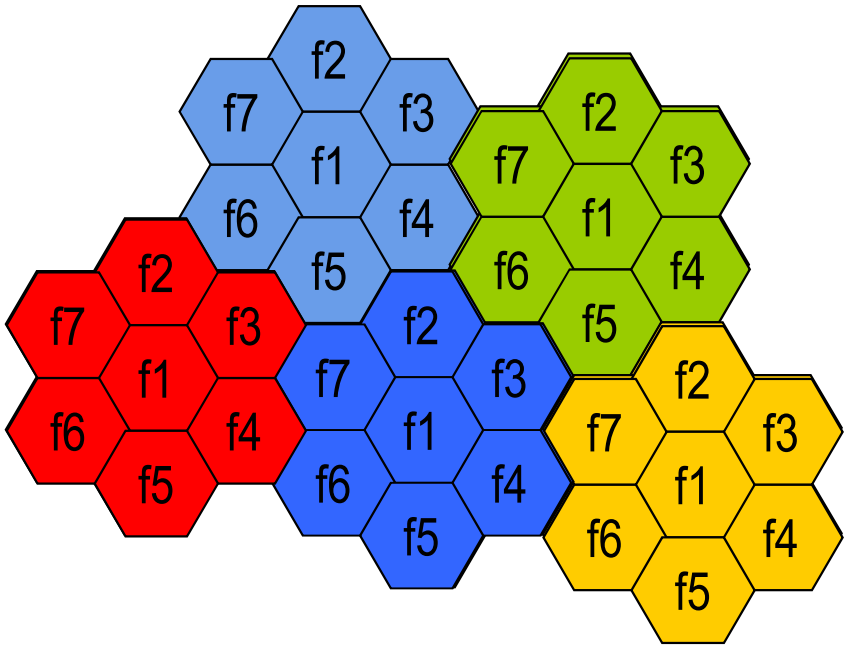
- Cells with the same number have the same set of frequencies



Frequency Reuse

1. Frequency Reuse

Frequency Reuse using 7 frequencies allocations

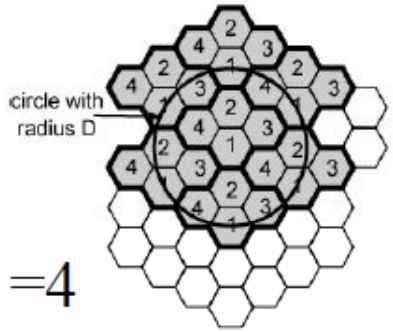


Each cell is generally 4 to 8 miles in diameter with a lower limit around 2 miles.

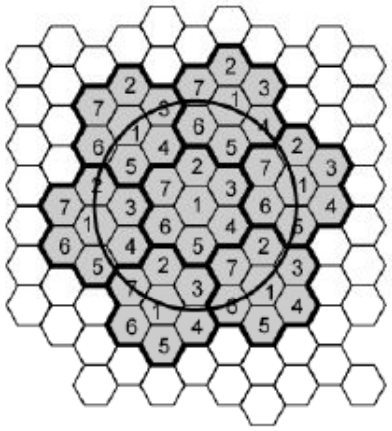
1. Frequency Reuse

Cellular Frequency Reuse

Cluster Size =4

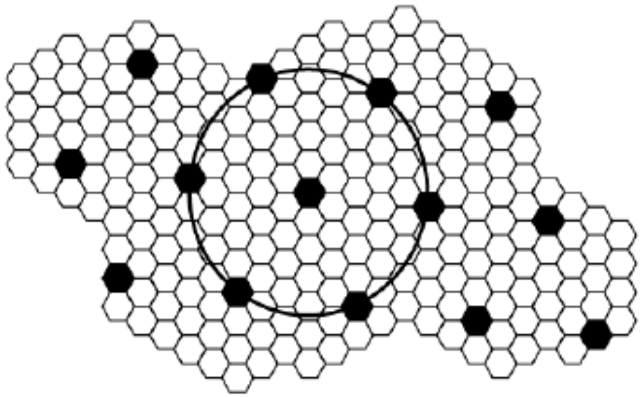


(a) Frequency reuse pattern for N = 4



(b) Frequency reuse pattern for N = 7

Cluster Size =7

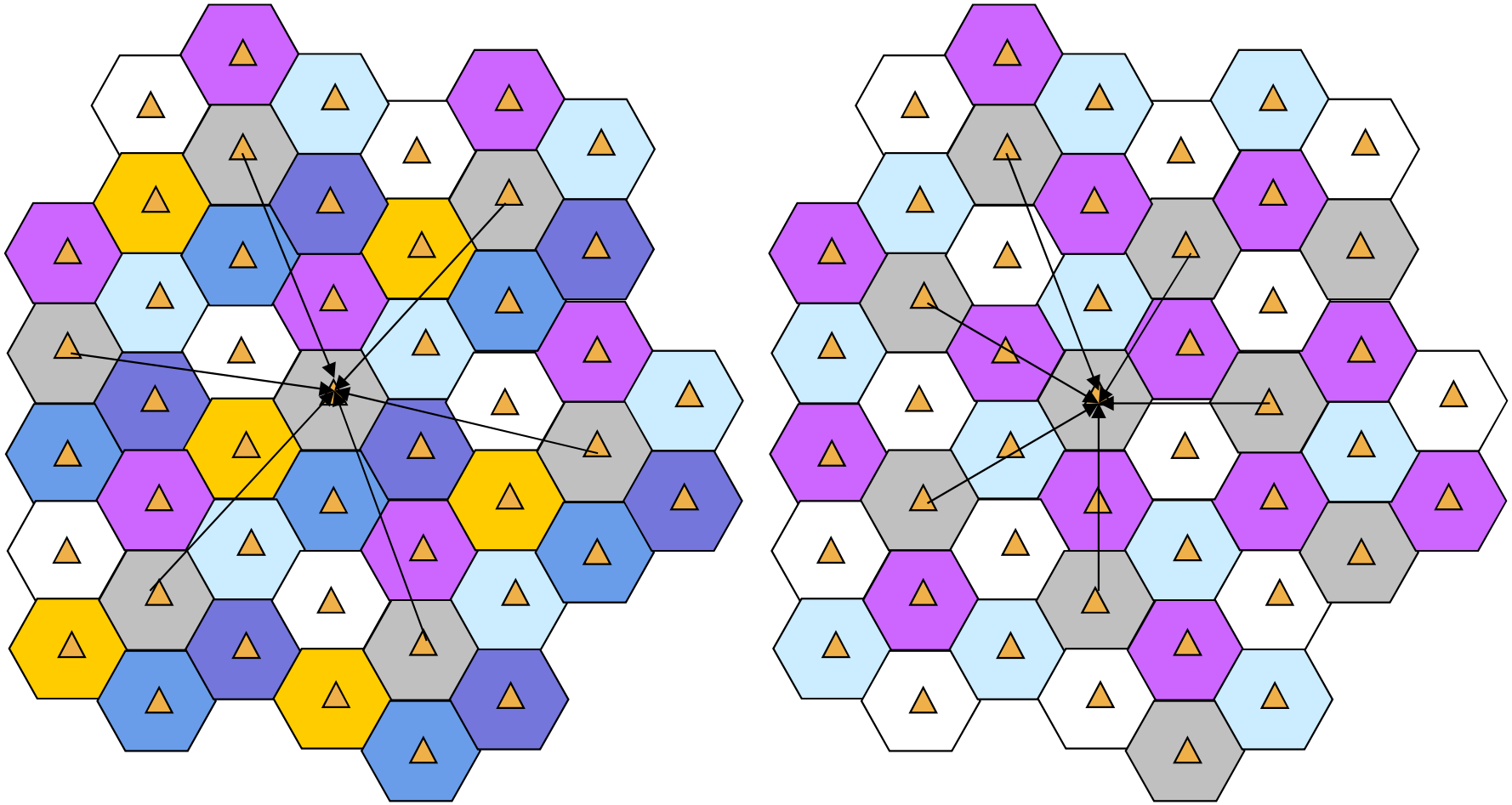


(c) Black cells indicate a frequency reuse for N = 19

Cluster Size =19

1. Frequency Reuse

Problem with Smaller Clustersize

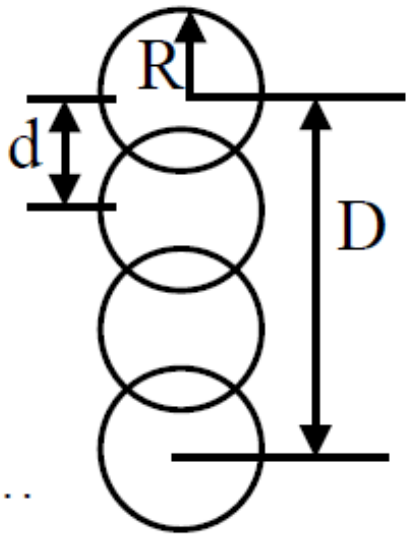


Interfering cells are closer by when clustersize is smaller.

1. Frequency Reuse

Characterizing Frequency Reuse

- D = minimum distance between centers of cells that use the same band of frequencies (called co-channels)
- R = radius of a cell
- d = distance between centers of adjacent cells ($d = R\sqrt{3}$)
- N = number of cells in repetitious pattern (**Cluster**)
  - Reuse factor
  - Each cell in pattern uses unique band of frequencies
- Hexagonal cell pattern, following values of N possible
  - $N = I^2 + J^2 + (I \times J)$, $I, J = 0, 1, 2, 3, \ldots$
- Possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, …
- $D/R = \sqrt{3N}$
- $D/d = \sqrt{N}$



Frequency Reuse Example

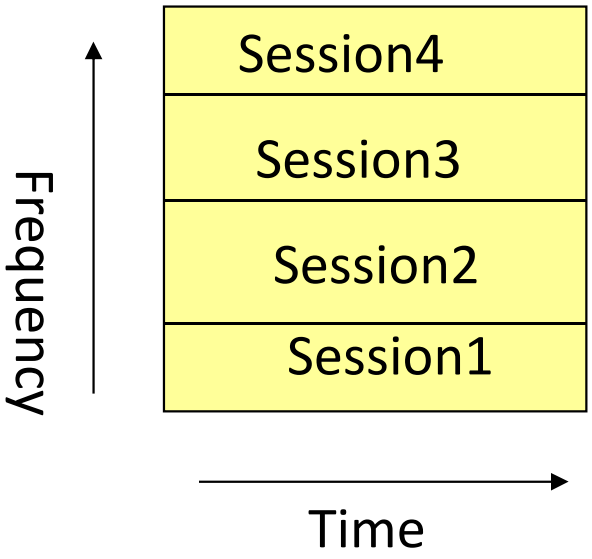
What would be the minimum distance between the centers of two cells with the same band of frequencies if cell radius is 1 km and the reuse factor is 12?

$$D/R = \sqrt{3N}$$

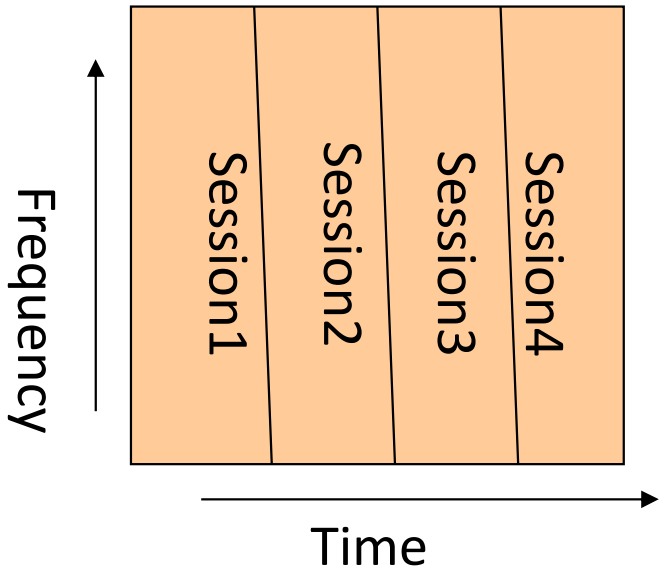
$$D = (3 \times 12)^{1/2} \times 1 \text{ km}$$

$$= 6 \text{ km}$$

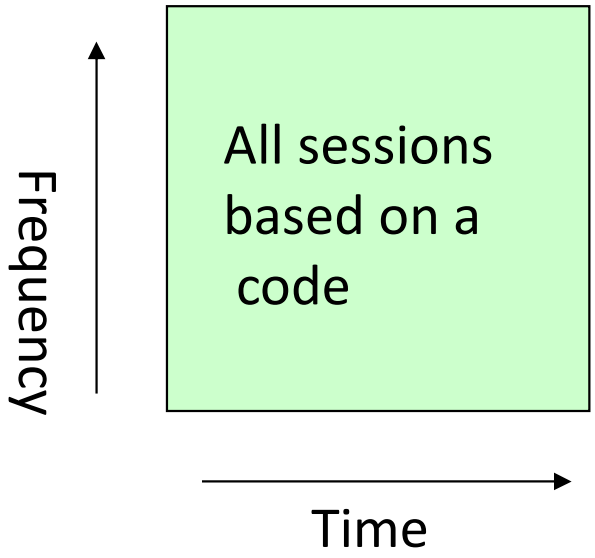
2. Multiple Access Techniques: How to allocate users



Frequency Division
Multiple Access (FDMA)
1G Cellular (AMPS)



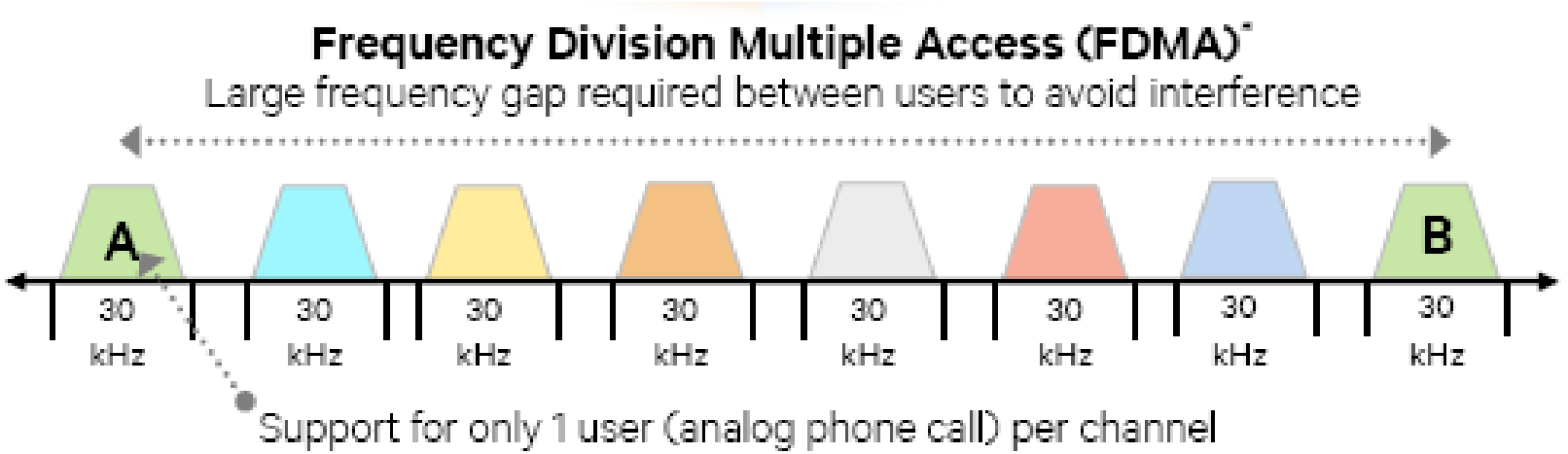
Time Division
Multiple Access (TDMA)
2G TDMA
3G TDMA



2G CDMA (IS-95)
3G CDMA

Code Division
Multiple Access (CDMA)

2. Multiple Access Techniques: How to allocate users



* Example shown based on AMPS 1G technology

Mobile 2G (Digital)

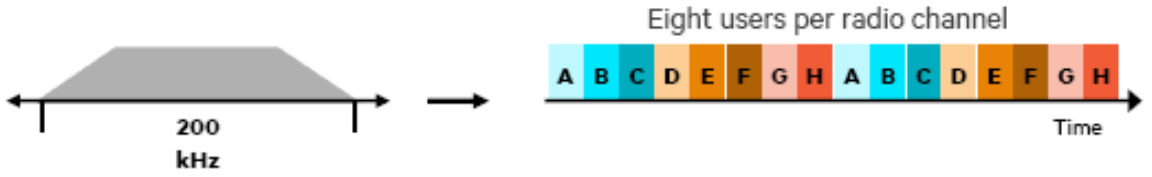
GSM

Standardized by ETSI in 1990 (phase 1)

Initiated in Europe

Still widely used today (>4B connections WW[1])

Simple data services with GPRS

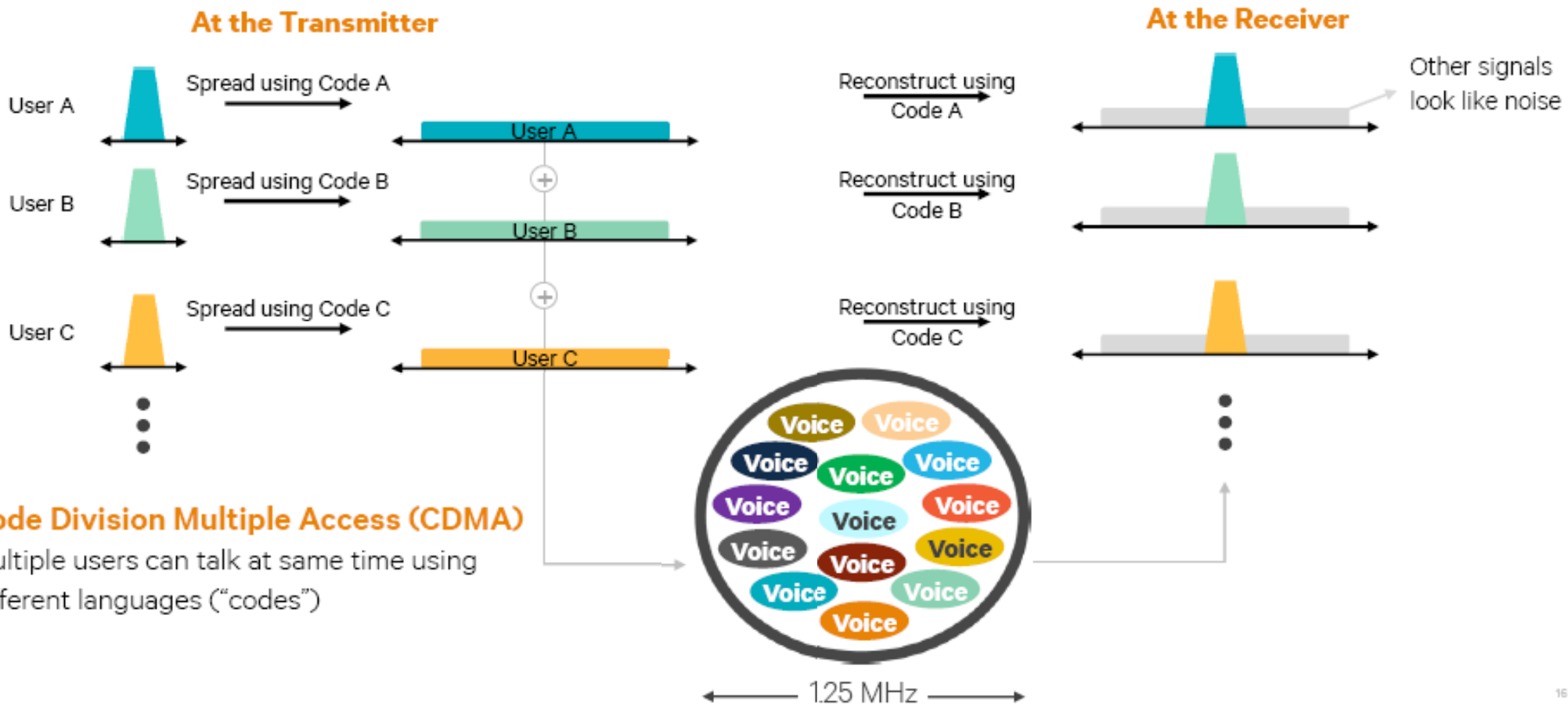


Also required potentially unreliable "hard" handoffs

Switch channels between adjacent cells – potential for dropped calls

2. Multiple Access Techniques: How to allocate users

CDMA enables users to share the same frequency and communicate at the same time



Code Division Multiple Access (CDMA)

Multiple users can talk at same time using different languages ("codes")

CDMA Signal Spreading

User #1 Data = 0 0

Spreading code: 0101

2 Bits

Code: 0101 0101

Data : 0000 0000

XOR

0101 0101

User #1 spread message:

0101 0101

CDMA Signal Spreading

User #2 Data = 1 0

Spreading code: 0011

2 Bits

Spread the signal:

Code: 0011 0011
Data : 1111 0000

XOR

1100 0011

User #2 spread message:
1100 0011

CDMA Signal Spreading

User #3 Data = 1 1

Spreading code: 0000

2 Bits

Spread the signal:

Code: 0000 0000
Data : 1111 1111

XOR

1111 1111

User #3 spread message:

1111 1111

CDMA Signal Spreading

Combining all 3 signals
Let's create waveform s

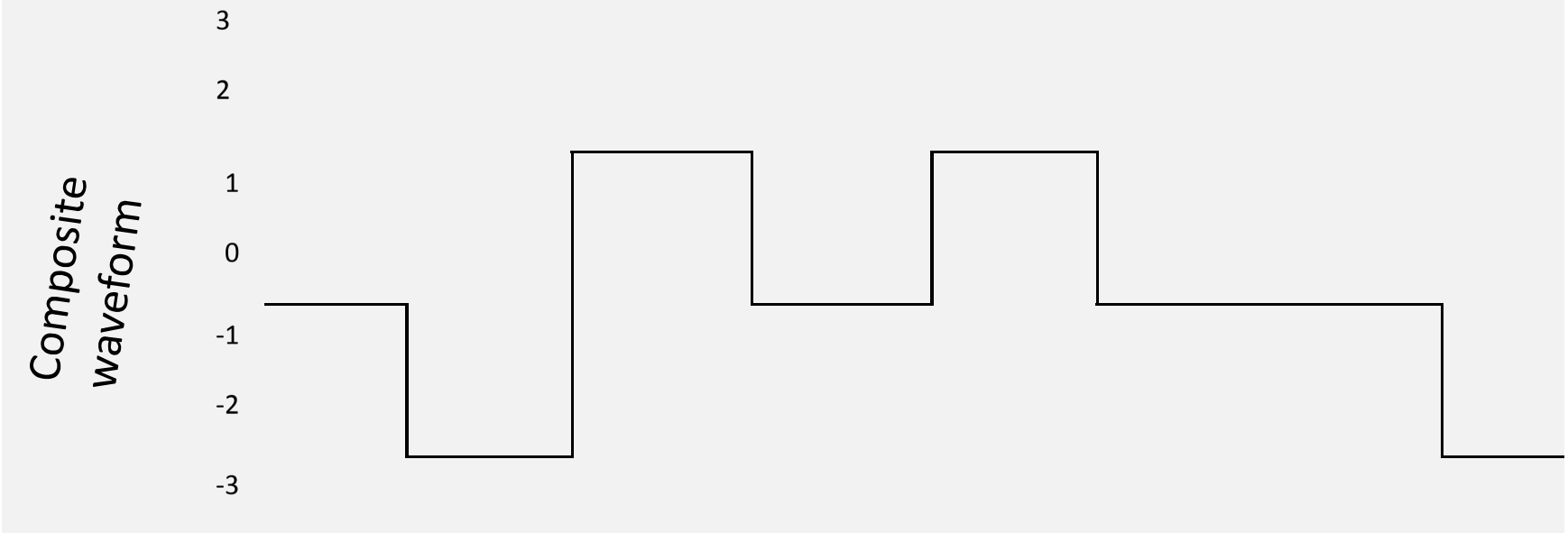
0 bit → +1 V
1 bit → - 1 V

Combining All 3 Signals

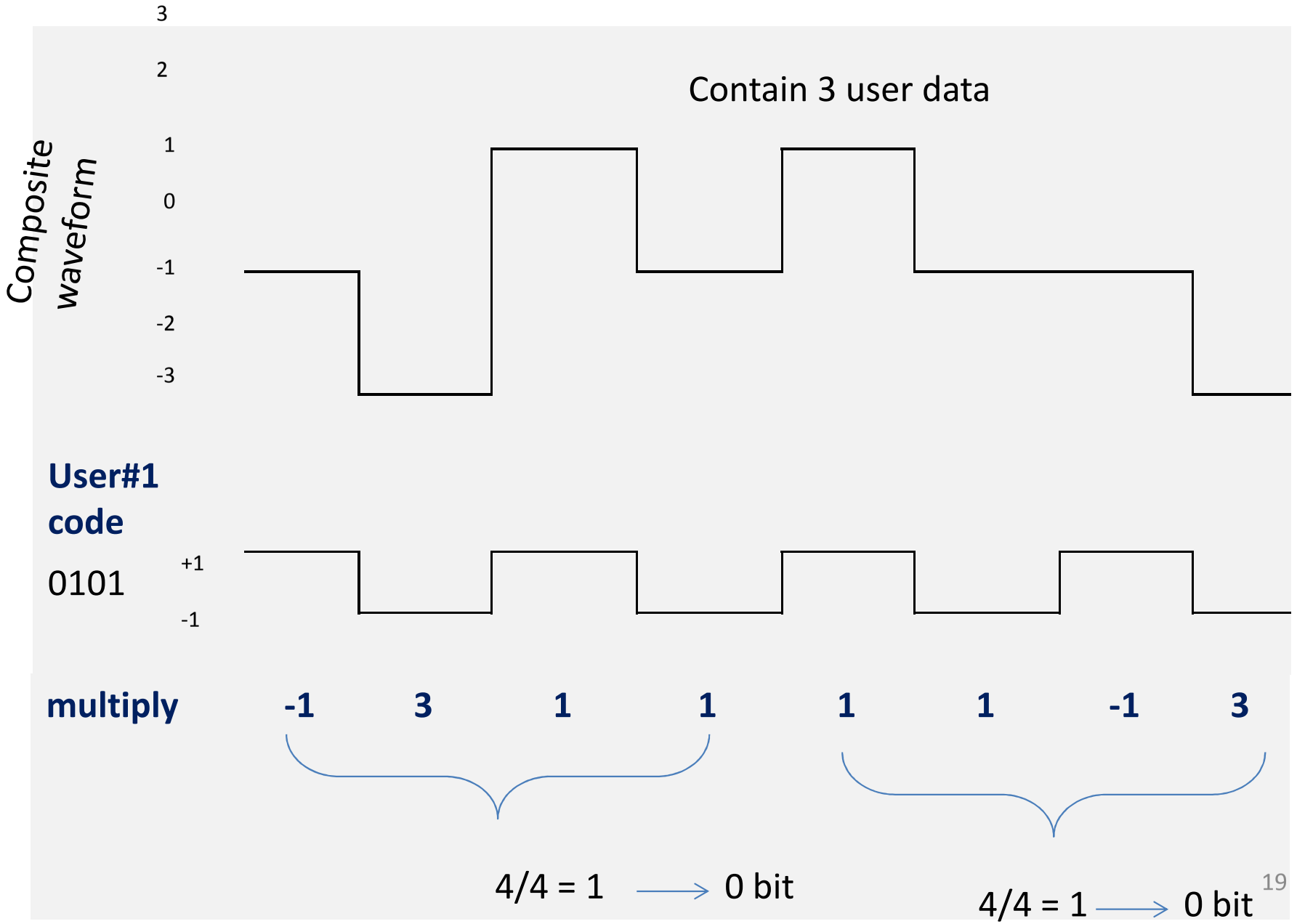
User #1	0	1	0	1	0	1	0	1
User #2	1	1	0	0	0	0	1	1
User #3	1	1	1	1	1	1	1	1

Combining All 3 Signals

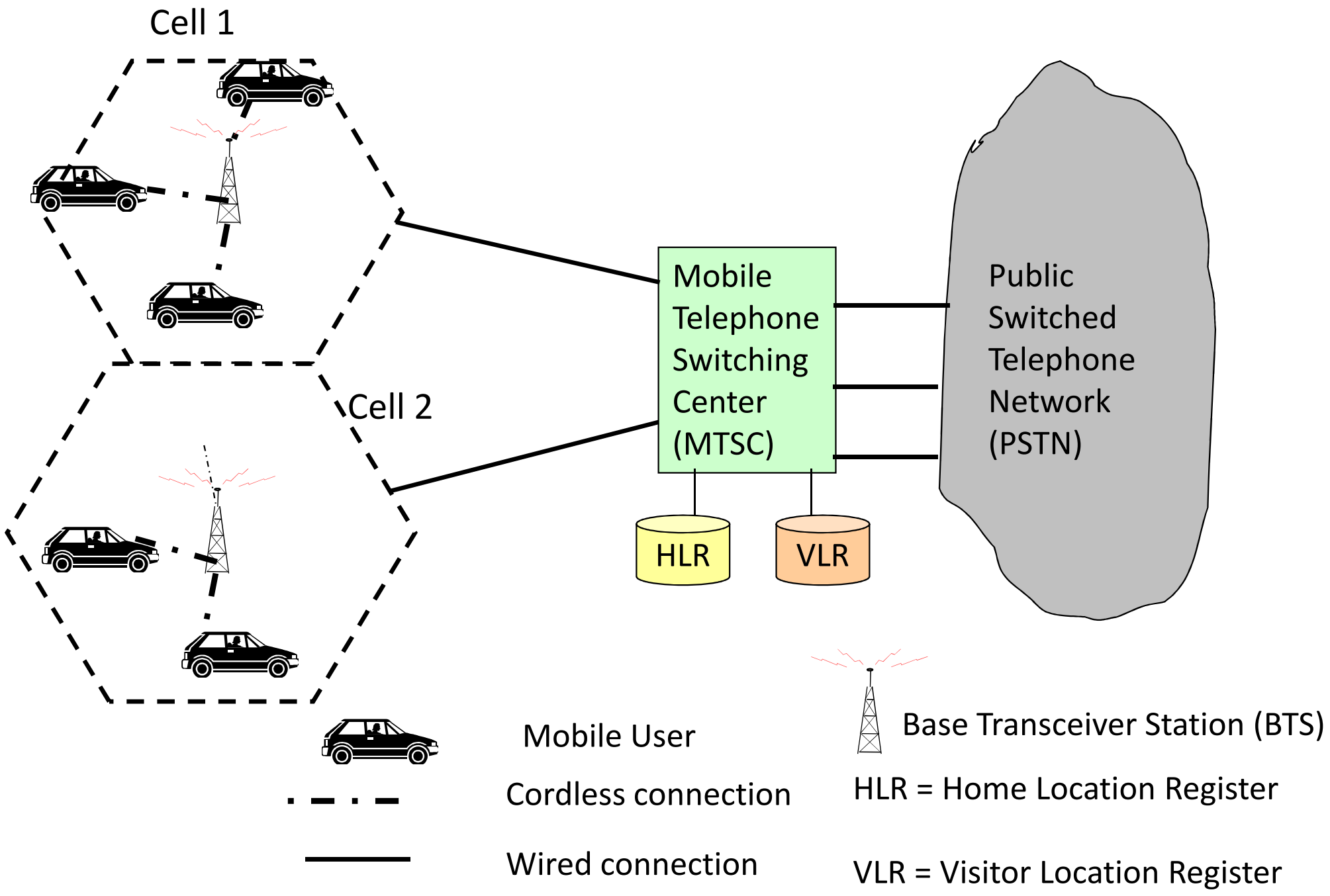
User #1	0	1	0	1	0	1	0	1
User #2	1	1	0	0	0	0	1	1
User #3	1	1	1	1	1	1	1	1
	-1	-3	1	-1	1	-1	-1	-3



Combining All 3 Signals



3. A Cellular Network and mobility problem

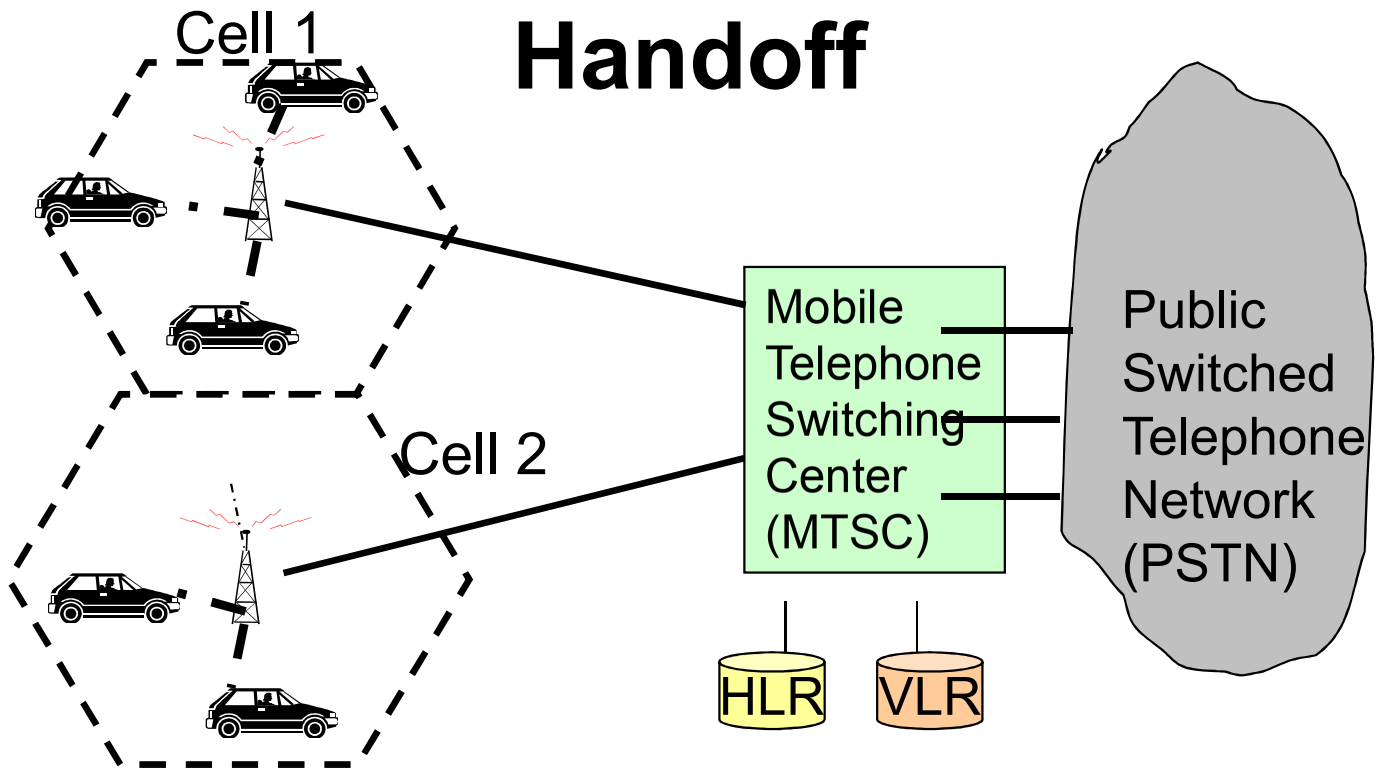


3. A Cellular Network and mobility problem

Overview of Location Services

- Cell-id based location.
  - assigned an id of the cell that you are in.
  - cell-id is stored in a database.
  - As you move from one cell to another, you are assigned a different cell-id and the location database is updated.
  - most commonly used in cellular networks. (HLR, VLR)
- Neighborhood polling: Connected mobile units only move to adjacent cells
- Angle of arrival (AOA). the angle at which radio waves from your device "attack" an antenna is used to calculate the location of the device.
- Time taken. In this case, the time taken between the device and the antenna is used to calculate the location of the device.
- Network assisted Global Positioning System (GPS). a GPS chip is installed inside a phone and thus the location of the user is tracked.

3. A Cellular Network and mobility problem



Handoffs (typically 30 mseconds):

1. At any time, mobile station (MS) is in one cell and under the control of a BS
2. When a MS leaves a cell, BS notices weak signal
3. BS asks surrounding BSs if they are getting a stronger signal
4. BS transfers ownership to one with strongest signal
5. MTSO assigns new channel to the MS and notifies MS of new boss

BREAK FOR 5 MINUTE

Powered by evolving mobile technologies for better experiences

Mobile 1G
AMPS, NMT, TACS

N/A

Analog Voice

Mobile 2G
D-AMPS, GSM/GPRS, cdmaOne

<0.5 Mbps[1]

Digital Voice + Simple Data

Mobile 3G
CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA

63+ Mbps[2]

Mobile Broadband

Mobile 4G LTE
LTE, LTE Advanced

300+ Mbps[3]

Faster and Better

Richer Content (Video)

More Connections

Evolving mobile technologies deliver great mobile experiences

Appreciating the magic of mobile requires understanding the evolution from 1G to 4G LTE

1. 1G established seamless mobile connectivity introducing mobile voice services
2. 2G digital wireless technologies increased voice capacity delivering mobile to the masses
3. 3G optimized mobile for data enabling mobile broadband services, and is evolving for faster and better connectivity
4. 4G LTE delivers more capacity for faster and better mobile broadband experiences, and is also expanding in to new frontiers

Mobile 1G established the foundation of mobile

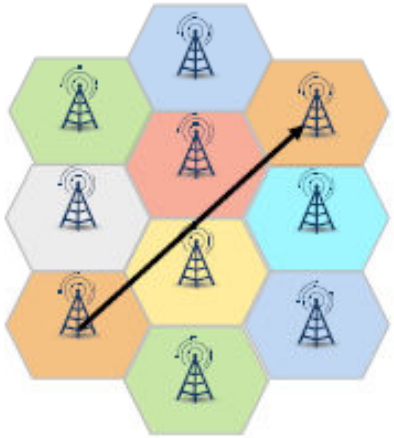
1 Licensed Spectrum

Cleared spectrum for exclusive use by mobile technologies

Operator-deployed **base stations** provide access for subscribers

2 Frequency Reuse

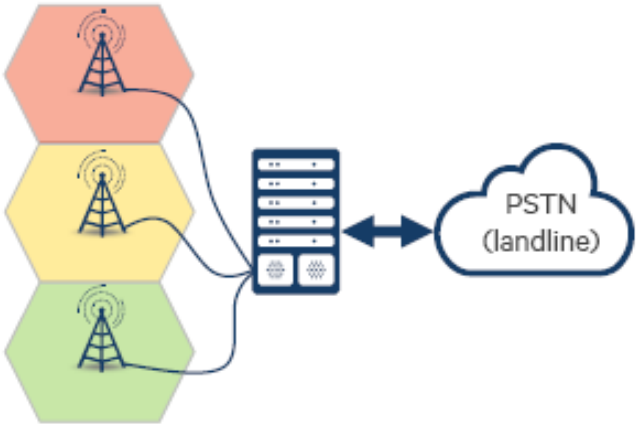
Reusing frequencies without interference through geographical separation



Neighboring **cells** operate on different frequencies to avoid interference

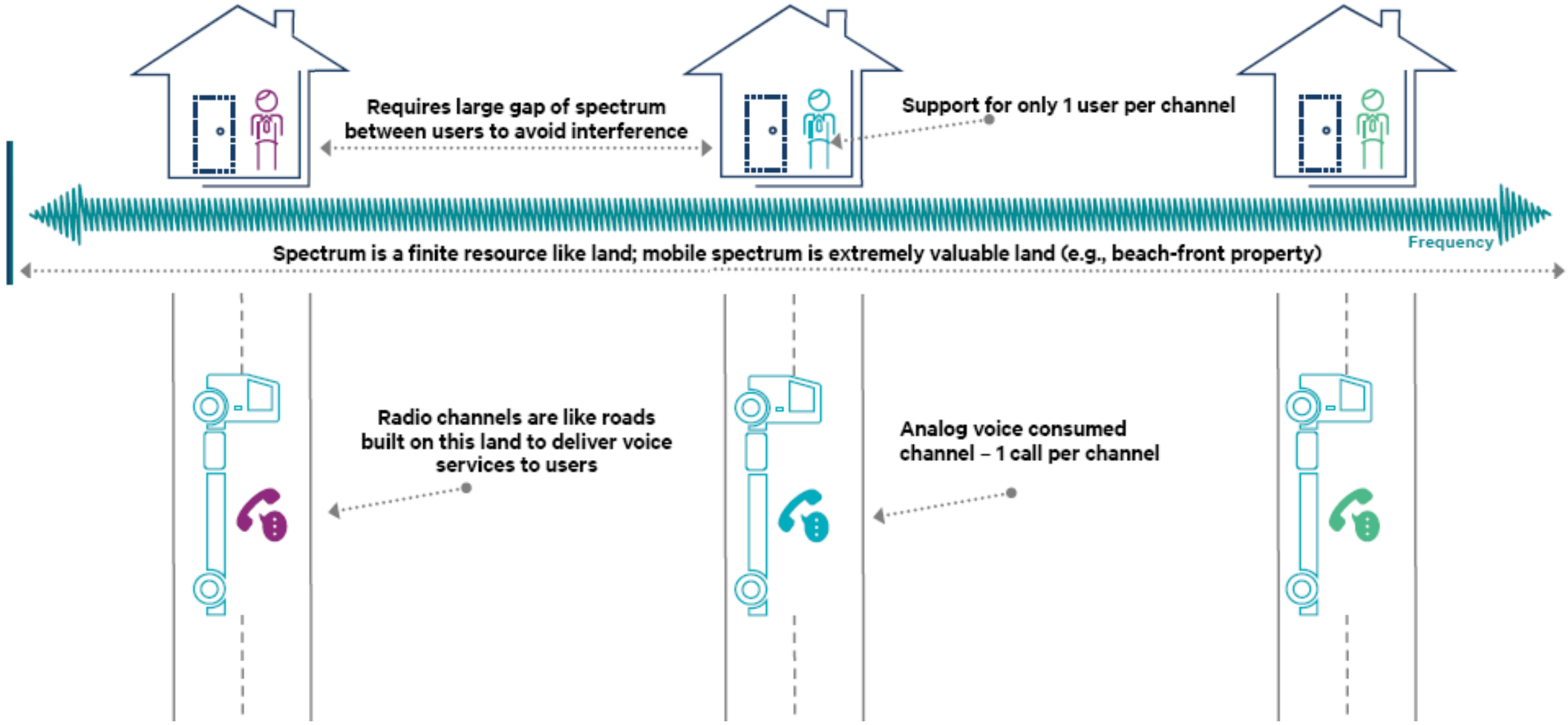
3 Mobile Network

Coordinated network for seamless access and seamless mobility



Integrated, transparent **backhaul network** provides seamless access

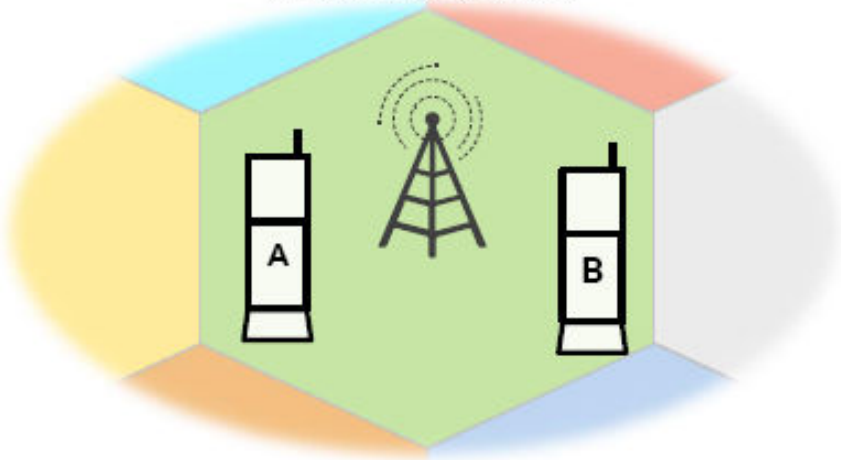
Mobile 1G was amazing, but limited



1G analog voice was amazing, but limited

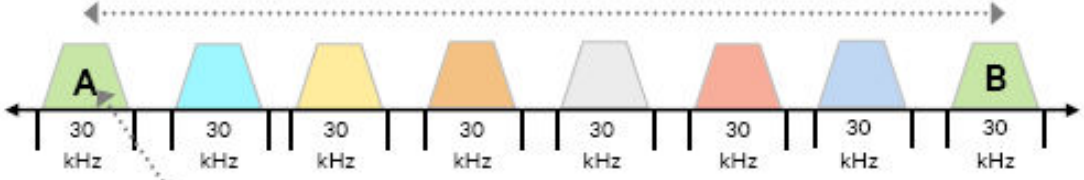
Limited Capacity

Analog transmissions are inefficient at using limited spectrum



Frequency Division Multiple Access (FDMA)*

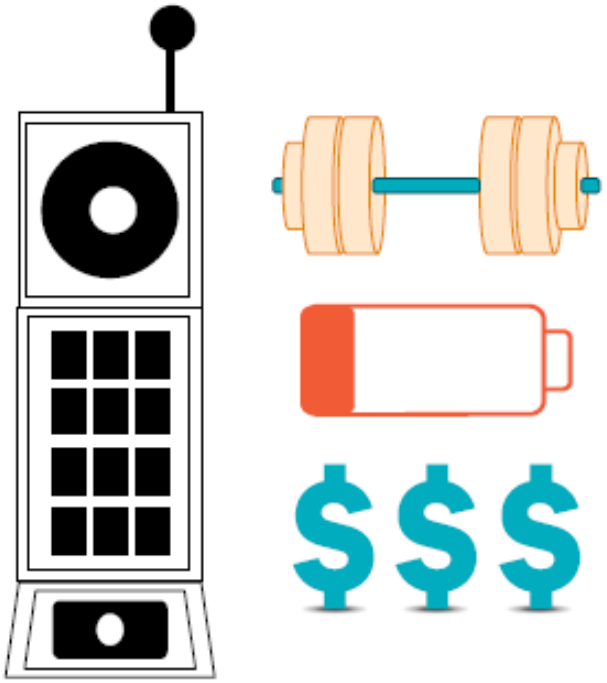
Large frequency gap required between users to avoid interference



Support for only 1 user (analog phone call) per channel

Limited Scalability

Analog devices are large/heavy, power inefficient, and high cost



* Example shown based on AMPS 1G technology

Mobile 2G digital technologies increased voice capacity

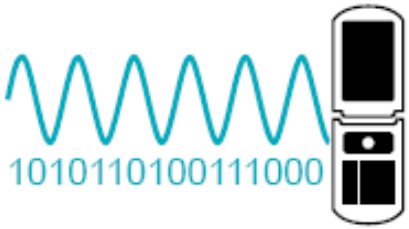
Delivering mobile voice services to the masses – more people, in more places

Mobile 1G
AMPS, NMT, TACS

Foundation of Mobile
Seamless Mobility

Mobile 2G
D-AMPS, GSM/GPRS,
cdmaOne

Mobile for the Masses
More Voice Capacity



1980s 1990s

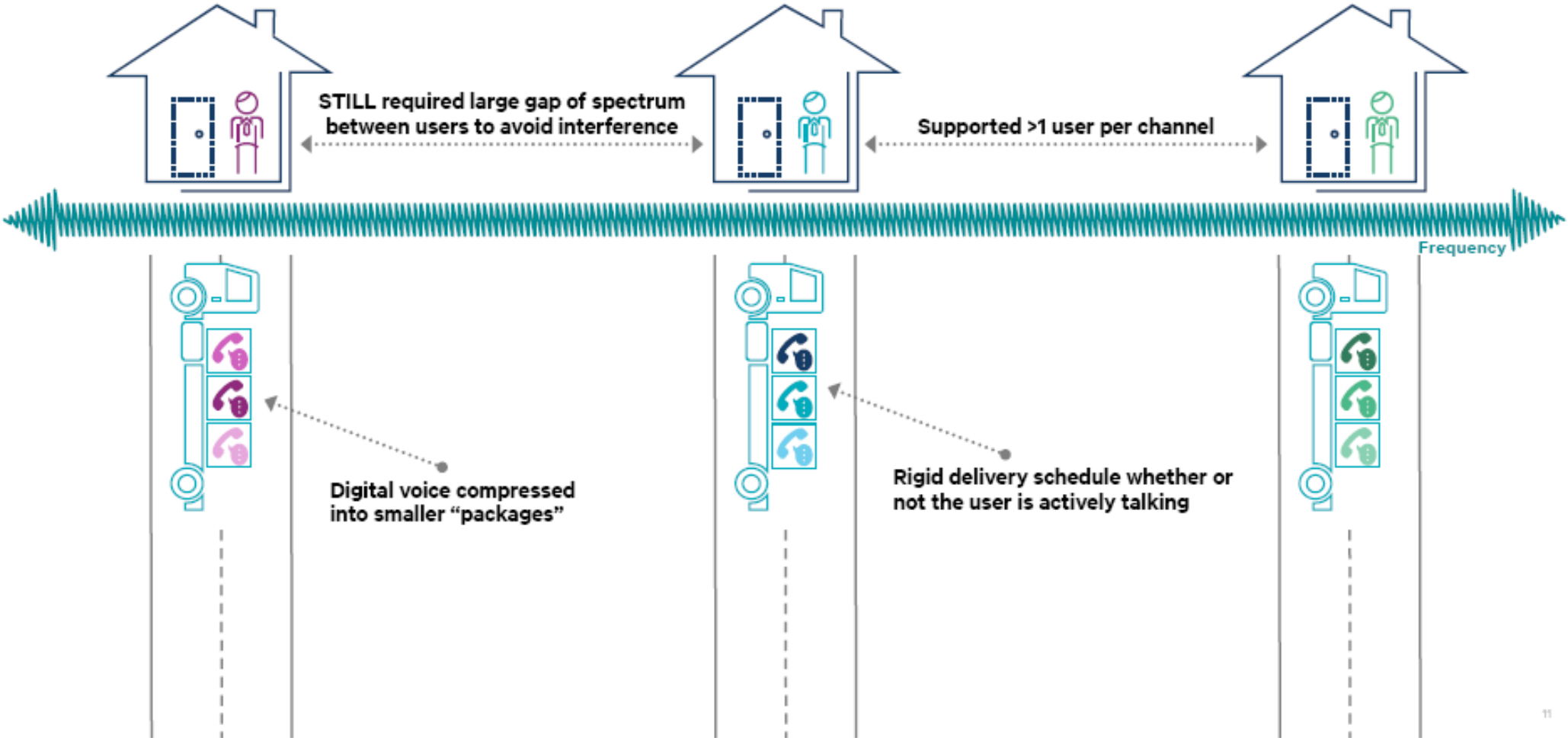
Advantages of Digital Communications for Wireless

- Voice, data and fax can be integrated into a single system
- Better compression can lead to better channel utilization
- Error correction codes can be used for better quality
- Sophisticated encryption can be used

Integrating Data Over Cellular

- Direct access to digital channel
- Voice and data using one handset
- PCS 1900 (GSM-1900)
  - 9.6 kbps circuit switched data
  - 14.4 kbps under definition
  - Packet mode specified
  - Short message service
- IS-95-based CDMA
  - 13 kbps circuit switched data
  - Packet mode specified
  - Short message service

Early Mobile 2G technologies enabled more users per channel

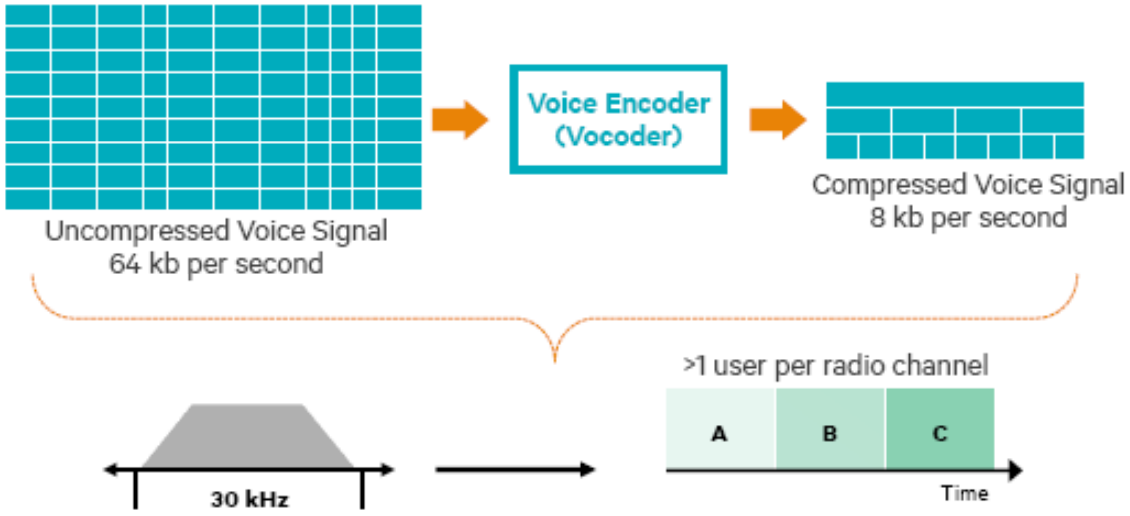


Mobile 2G digital wireless technologies enabled more users

Initial 2G technologies (D-AMPS, GSM) based on TDMA

More Voice Capacity

Digital transmissions enable compressed voice and multiplexing multiple users per channel

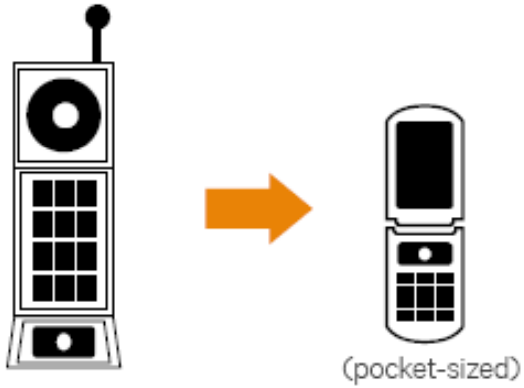


Time Division Multiple Access (TDMA)

Allows multiple users per radio channel with each user talking one at a time

Scalable Technology

Digital components cost/weight far less plus deliver more secure signal



Different Mobile 2G TDMA techniques were standardized

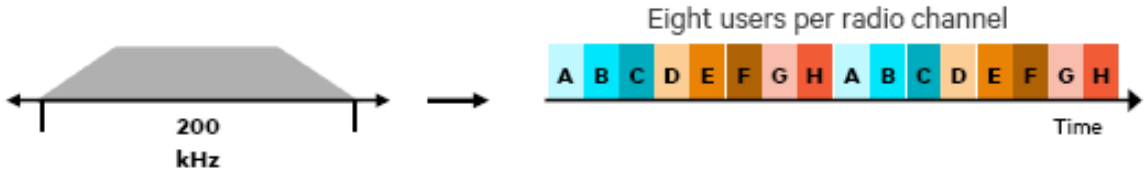
Mobile 1G (Analog)
AMPS, NMT, TACS

Mobile 2G (Digital)
D-AMPS

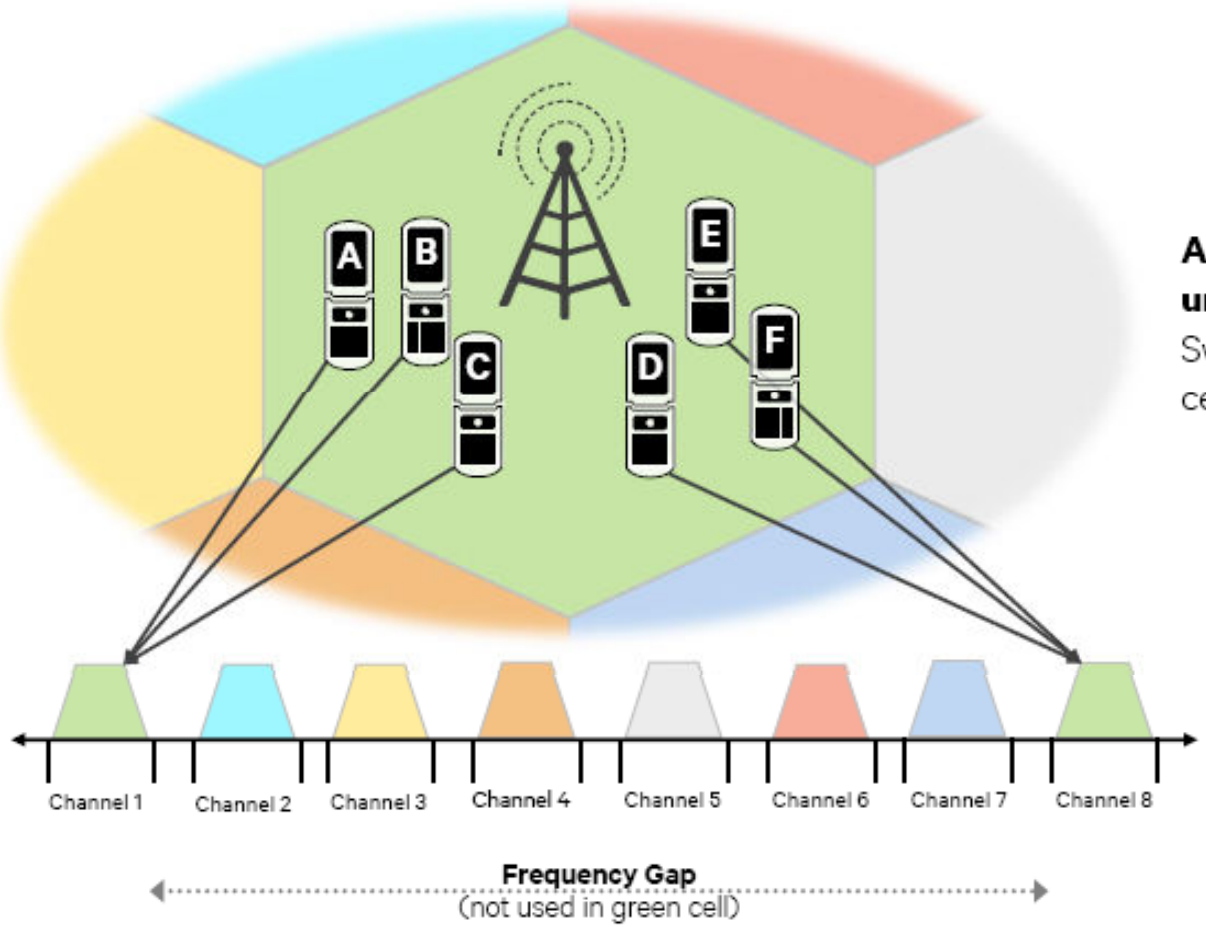
Standardized as IS-54 by TIA in 1992
Mainly in North America
No longer utilized

Mobile 2G (Digital)
GSM

Standardized by ETSI in 1990 (phase 1)
Initiated in Europe
Still widely used today (>4B connections WW[1])
Simple data services with GPRS



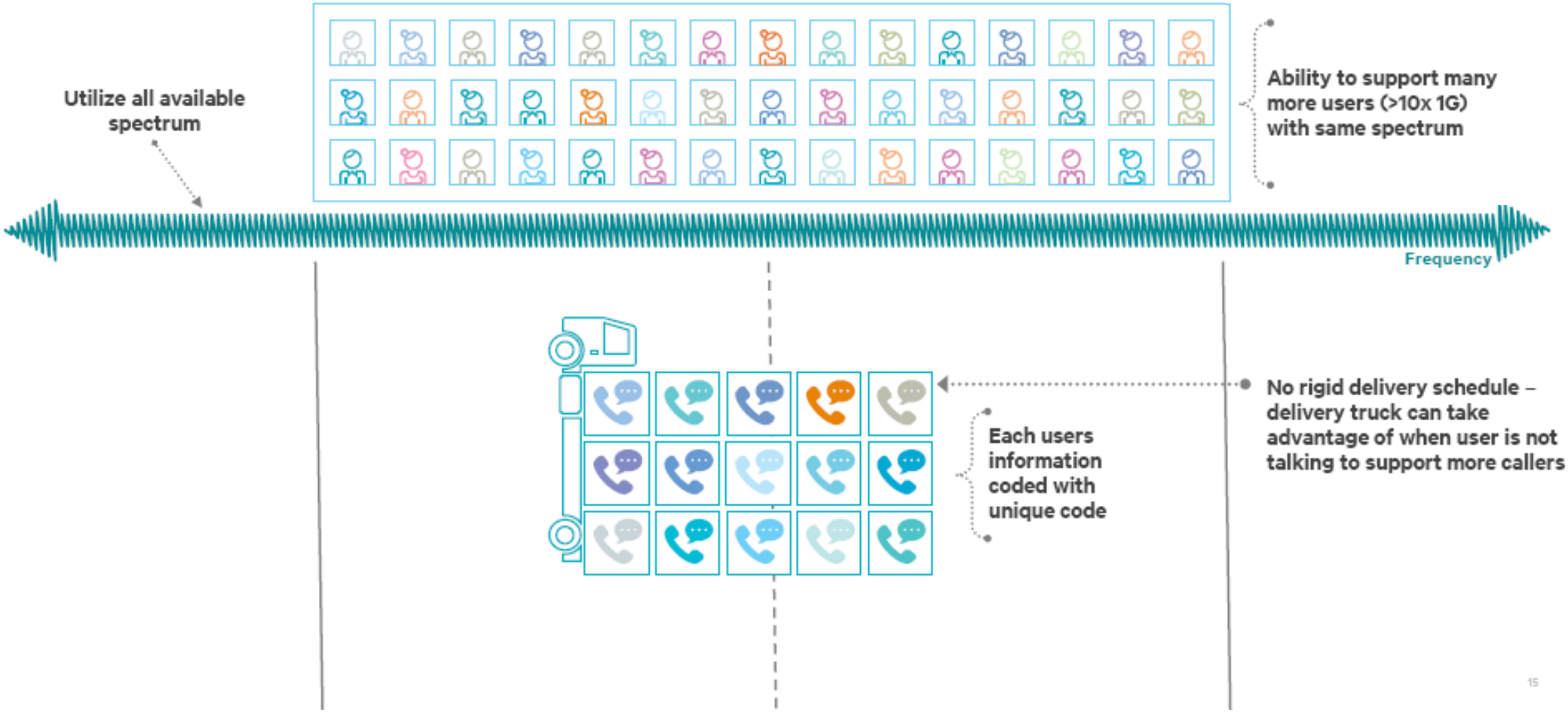
TDMA still required large frequency gaps to reduce interference



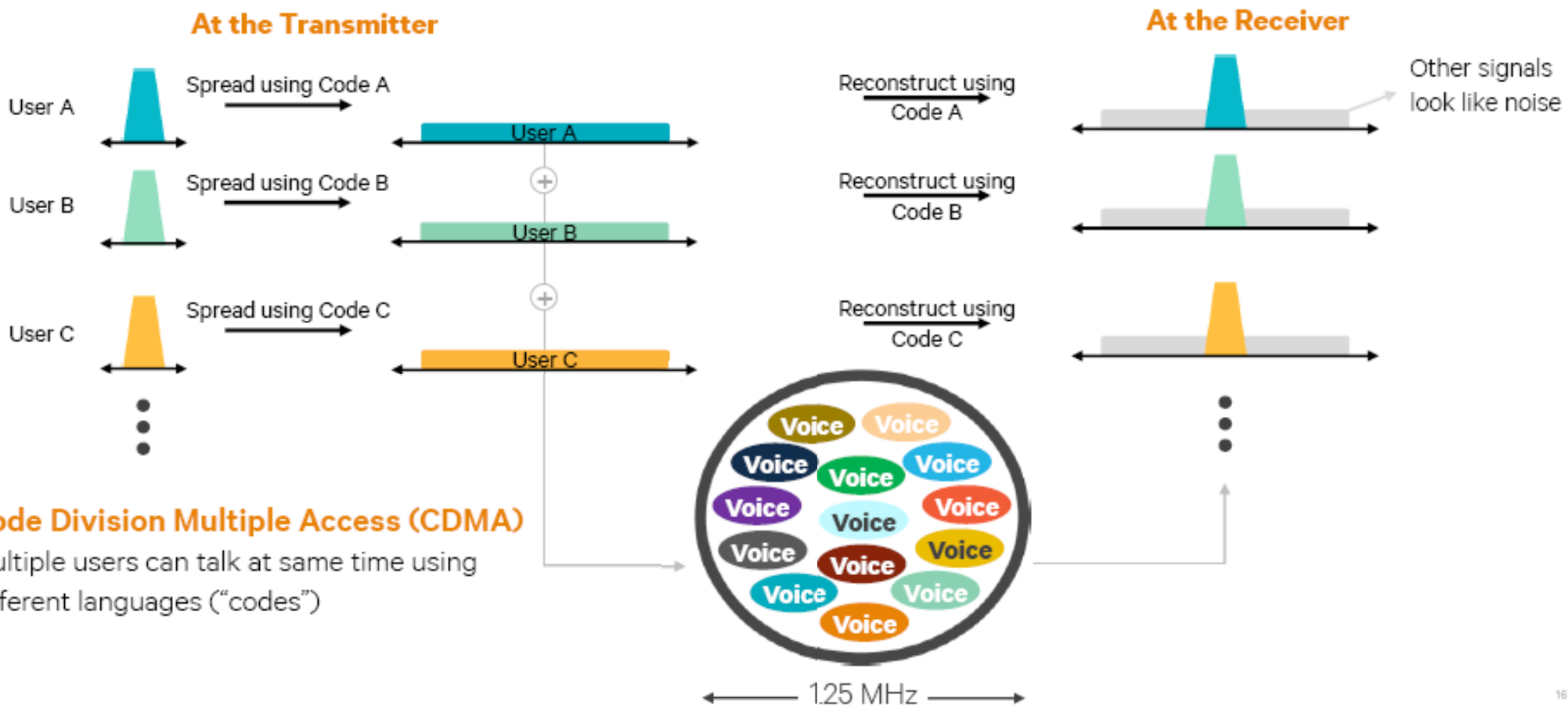
Also required potentially unreliable "hard" handoffs

Switch channels between adjacent cells – potential for dropped calls

CDMA utilizes all the available spectrum to support more users



CDMA enables users to share the same frequency and communicate at the same time



Code Division Multiple Access (CDMA)

Multiple users can talk at same time using different languages ("codes")

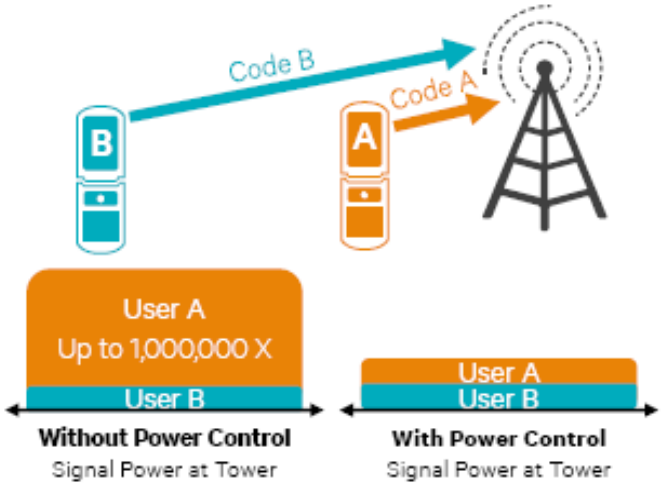
Complex challenge to commercialize CDMA

1 Near-Far Power Challenge

Users close to the tower overpower the uplink signal minimizing capacity on the shared channel

Solution:

Continuous control of transmit power based on signal strength



2 Cell-Edge Challenge

Interference caused by users in close proximity, on the same frequency, and communicating with different towers

Solution:

Users simultaneously communicate with multiple towers at cell edge

+ Soft (vs. Hard) Handoffs

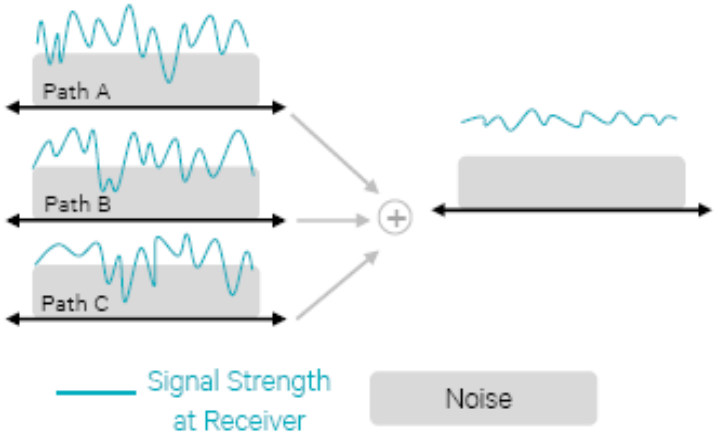
Additional benefit of simultaneous connections – more reliable handoffs

3 Multipath Fading Challenge

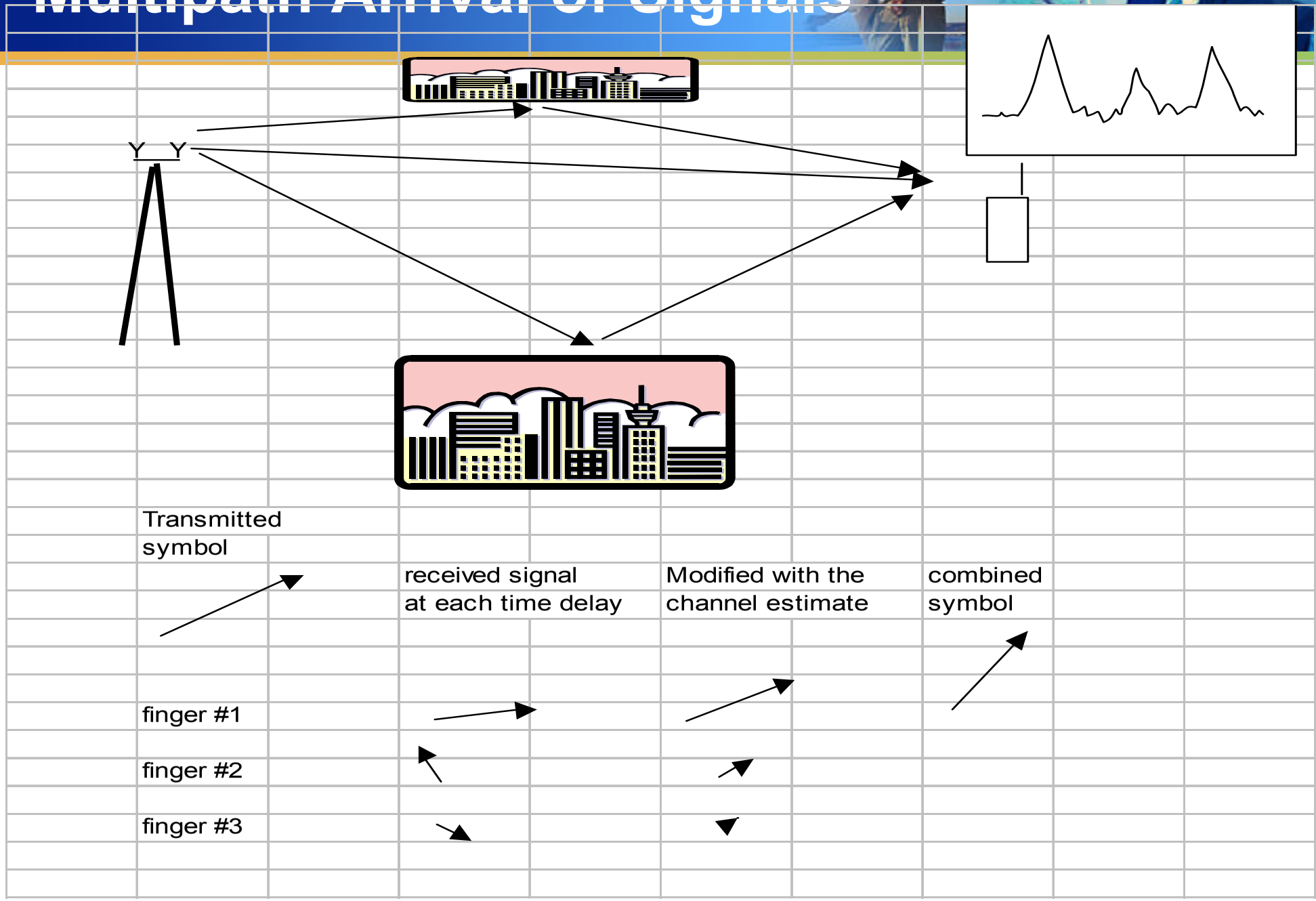
Interference caused by the reception of the same signal over multiple paths resulting in poor signal-to-noise ratio

Solution:

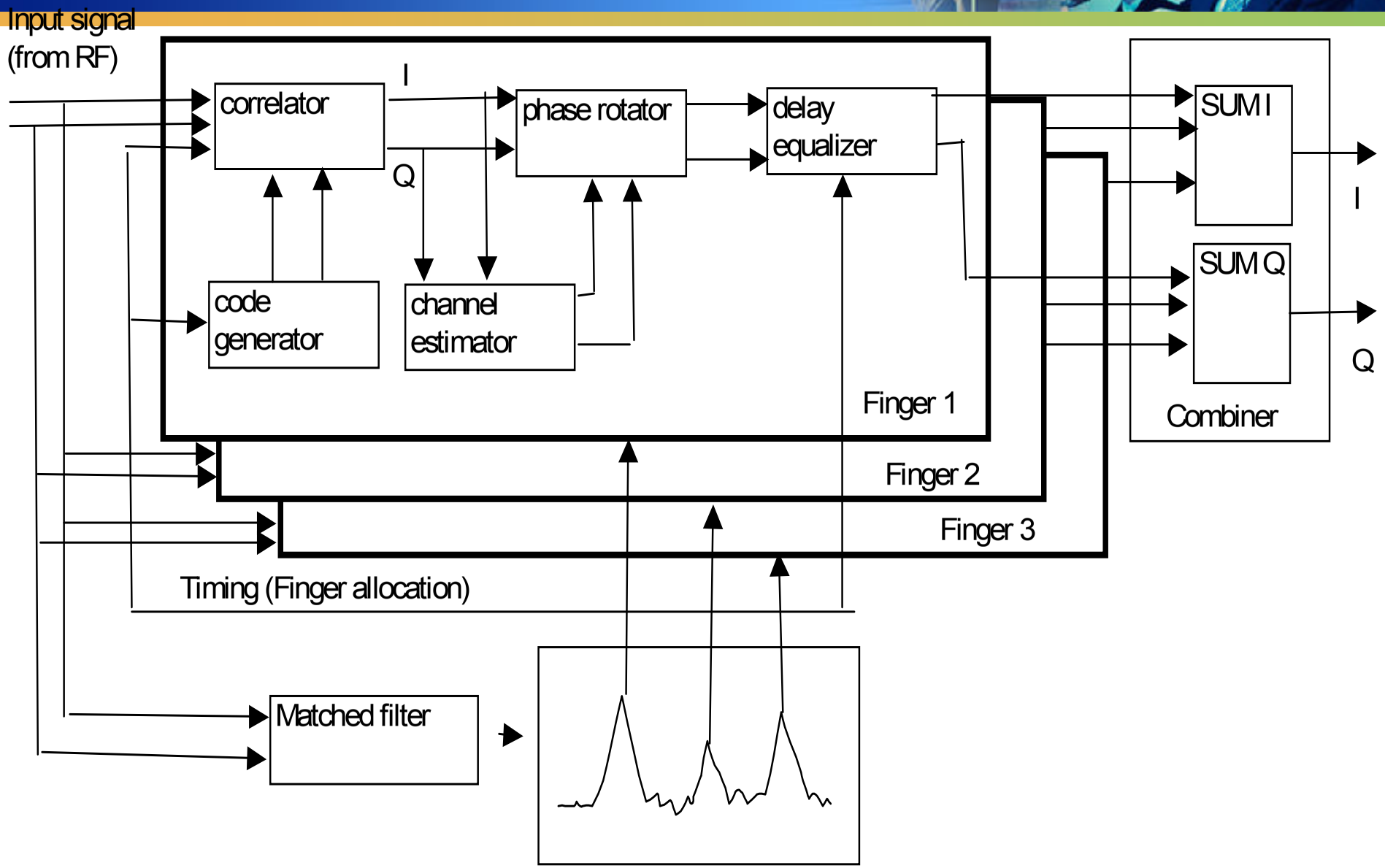
Advanced ("rake") receivers combine energy of multiple signal paths



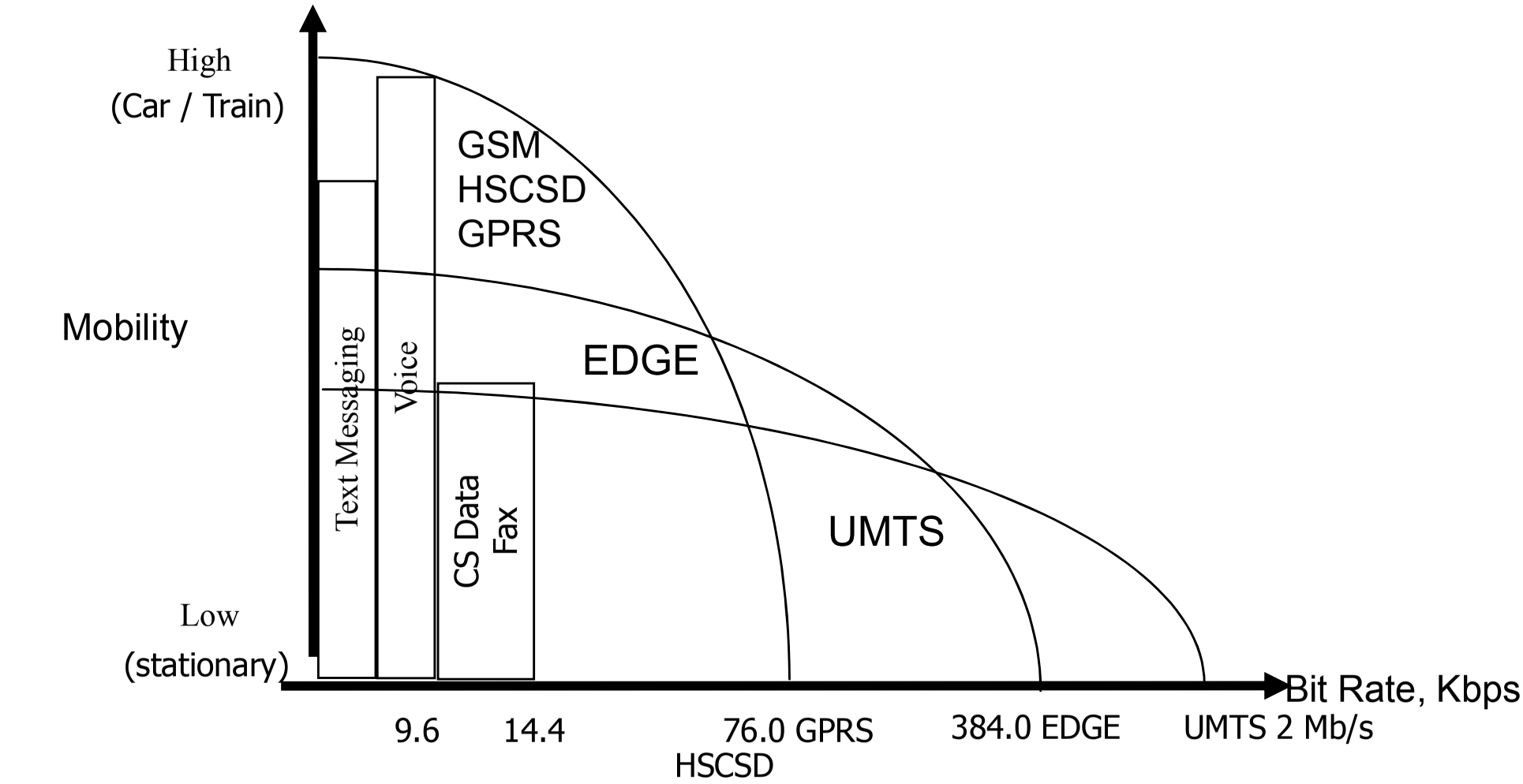
Multipath Arrival of Signals



CDMA Rake Receiver



GSM/UMTS Bit rate, Mobility and Services

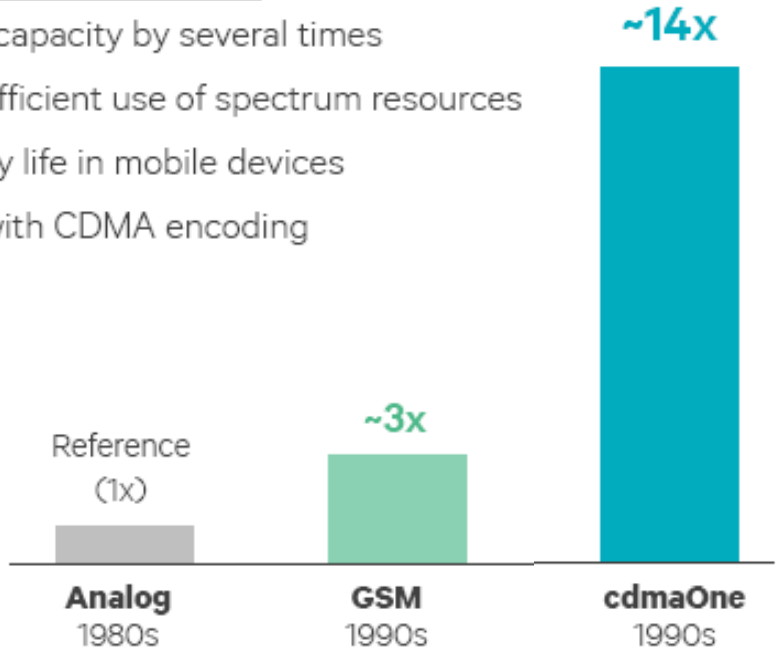


CDMA delivered unprecedented voice capacity and much more

Qualcomm efforts lead to new CDMA standard (IS-95) referred to as cdmaOne

CDMA Benefits

- Increased voice capacity by several times
- Provided more efficient use of spectrum resources
- Increased battery life in mobile devices
- Better security with CDMA encoding



Potential Voice Capacity Improvements[1]

CDMA Timeline[2]

February 1990
First CDMA field trial completed by Qualcomm and NYNEX

March 1992
Standards committee formed in Telecommunications Industry Association

May 1995
IS-95 revision A (cdmaOne) released

December 1995
First commercial deployment

December 1999
cdmaOne subscribers pass 50 million worldwide (>80 operators in >30 countries)

CDMA is the foundation for Mobile 3G technologies

Differences Between First and Second Generation Systems

- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital
- Encryption – all second generation systems provide encryption to prevent eavesdropping
- Error detection and correction – second-generation digital traffic allows for detection and correction, giving clear voice reception
- Channel access – second-generation systems allow channels to be dynamically shared by a number of users

Enhanced Devices

New devices are being introduced

Voice

3G Clam
Voice

3G Candybar
Voice

Voice/Data

3G Candybar
Voice, Data

3G Clam
Voice, Data

iMode
Voice, Data

Voice/Data/Image/ Video

3G Candybar
Voice, Data, Video

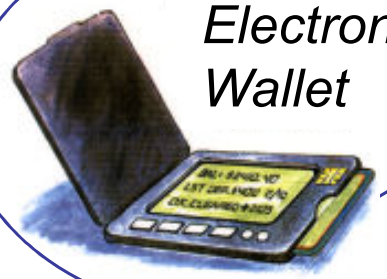
2-Way Communicator
Data/voice

Card Phone

PDA/PHS
Data, Voice

Mini Computer
Data

Electronic Wallet



Embedded

Data/Voice

Data

GSM (Global System for Mobile Communications)

- Completely designed from scratch (no backward compatibility)
- Uses 124 channels per cell, each channel can support 8 users through TDM (992 users max)
- Some channels used for control signals, etc
- Several flavors based on frequency:
  - GSM (900 MHz)
  - GSM 1800 (called DCS 1800)
  - GSM 1900 (called DCS 1900) - used in North America
- GSM 1900 phone only works in North America.
- In Europe, you can **transfer your SIM** (Subscriber Identity Module) card to a phone of the correct frequency. This is called SIM-roaming.

GSM Radio Link (Cont)

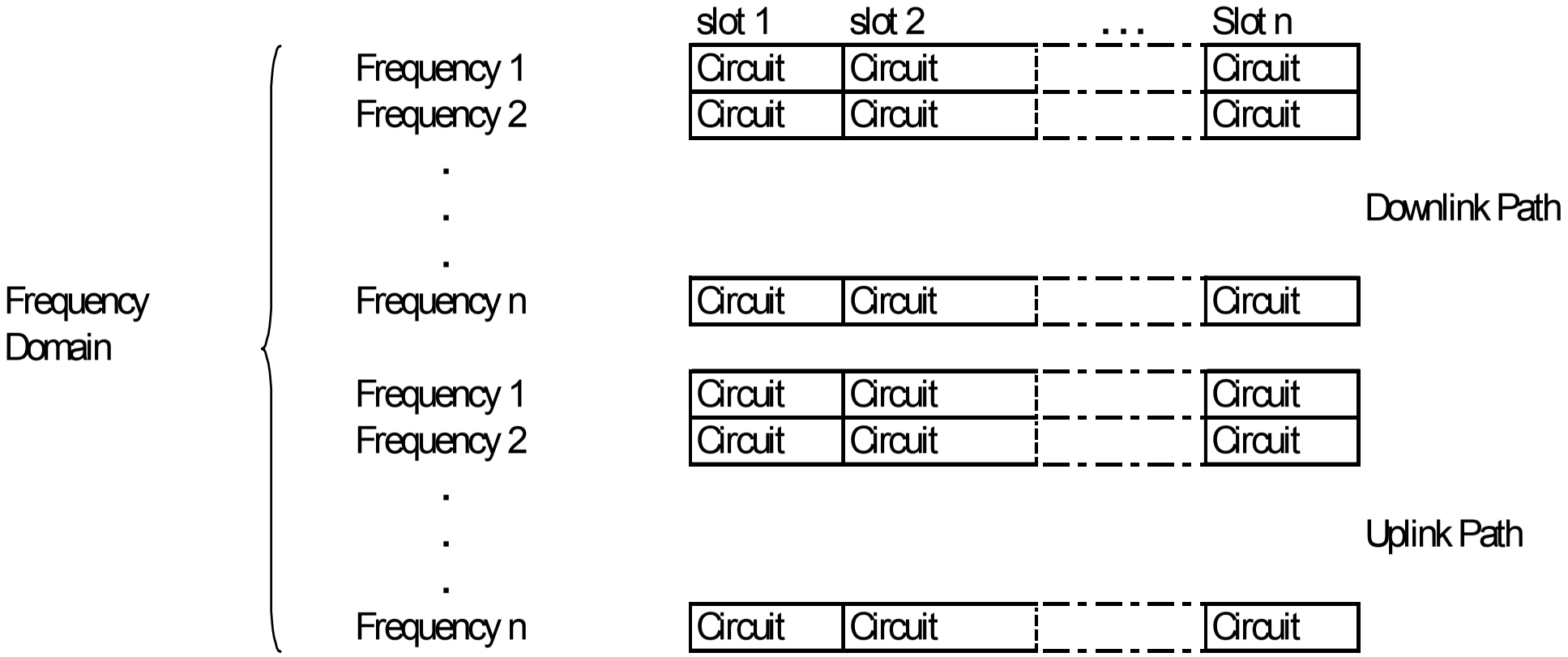
- 890-915 MHz uplink, 935-960 MHz downlink
- 25 MHz ⇒ 124 × 200kHz Channels
- Each channel is TDMA with burst (slot) period of 15/26 ms.
- Eight burst periods = TDMA frame of 120/26 ms.
- One channel = one burst period per TDMA frame.
- 26 TDMA frames ⇒ one Multiframe
  24 are used for traffic, 1 for control, and 1 is unused.
  Slow Associated Control Channel (SACCH)
  If SACCH does not have sufficient capacity, Fast Associated Control Channel (FACCH) is used by stealing ½ of some bursts.
- Stealing bits identify whether the 1/2-slot carries data or control
- 200 kHz = 270.8 kbps/8 slots ⇒ 34 kbps/slot
  15/26 ms/slot ⇒ 270.8*15/26 = 156.25 bits/slot
  ⇒ 9.6 kbps/user after encryption and FEC overhead
- Full rate vocoders ⇒ Voice is sampled at 64 kbps compressed to 16 kbps.

Representative Wireless Standards

- GSM/TDMA
  - Time Division Multiplexing based access
- CDMA
  - Code Division Multiplexing based access
- OFDM
  - Orthogonal Frequency Division Multiplexing

Many toys to play with

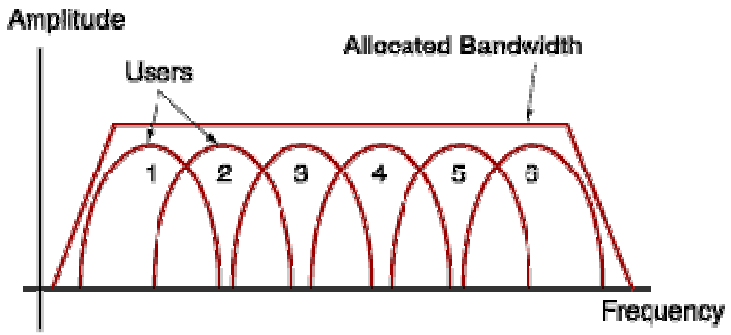
TDMA/FDMA



Give the same air to all

Orthogonal Frequency Division Multiplexing (OFDM)

- Successor to Frequency Hopping and Direct Sequence CDMA
- Capability to cancel multipath distortion in a spectrally efficient manner without requiring multiple local oscillators (802.11a and 802.16)
- Based on use of IFFT and FFT
- Frequency orthogonality as compared to code orthogonality in CDMA using Walsh Code



GSM Specs

- Subscriber Identify Module (SIM) contains a micro-controller and storage. Contains authentication, encryption, and accounting info.
  Owners need 4-digit PIN.
- SIM cards can contain additional info such as emergency medical info.
- Mobile Assisted Handoff: Mobile sends identities of six candidate base stations for handoff. MSC selects.
- Short Message Service (SMS)
  - Up to 160 characters
  - Sent over control channel
  - Unicast or broadcast

Cellular System Capacity Example

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.

A. Using FDMA/FDD:
   1. How much bandwidth is available per cell using FDD?
   2. How many users per cell can be supported using FDMA?
   3. What is the cell area?
   4. What is the cell radius assuming circular cells?

B. If the available spectrum is divided in to 35 channels and TDMA is employed within each channel:
   1. What is the bandwidth and data rate per channel?
   2. How many time slots are needed in a TDMA frame to support the required number of users?
   3. If the TDMA frame is 10ms, how long is each user slot in the frame?

Cellular System Capacity (Cont)

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.
- A. Using FDMA/FDD:
  1. How much bandwidth is available per cell using FDD?
     49 MHz/7 = 7 MHz/cell
     FDD $\Rightarrow$ 3.5 MHz/uplink or downlink
  2. How many users per cell can be supported using FDMA?
     10 kbps/user = 10 kHz $\Rightarrow$ 350 users per cell
  3. What is the cell area?
     100 users/sq km $\Rightarrow$ 3.5 Sq km/cell
  4. What is the cell radius assuming circular cells?
     $\pi r^2 = 3.5 \Rightarrow r = 1.056$ km

Cellular System Capacity (Cont)

B. If the available spectrum is divided in to 35 channels and TDMA is employed within each channel:

1. What is the bandwidth and data rate per channel?

   3.5 MHz/35 = 100 kHz/Channel = 100 kbps

2. How many time slots are needed in a TDMA frame to support the required number of users?

   10 kbps/user $\Rightarrow$ 10 users/channel

3. If the TDMA frame is 10ms, how long is each user slot in the frame?

   10 ms/10 = 1ms

4. How many bits are transmitted in each time slot?

   1 ms x 100 kbps = 100 b/slot

CDMA established the foundation for 3G technologies

Mobile 3G evolved into two competing standards both based on CDMA

3G 3rd Generation Partnership Project 2 "3GPP2"

IS-95 (cdmaOne)
Initial CDMA standard from Qualcomm
May 1995

CDMA2000
Uses 1.25 MHz carrier; easy migration from cdmaONE
July 2000 (Revision A)

EV-DO (Evolution-Data Optimized)
Optimized data channel for CDMA2000 providing mobile broadband services
October 2000 (Release 0)

WCDMA (UMTS)
Uses 5 MHz carrier; leverages GSM core network
June 2001 (Release 99)

HSPA (High Speed Packet Access)
Optimized data channel for WCDMA providing mobile broadband services
June 2004 (Release 5)

3GPP A GLOBAL INITIATIVE

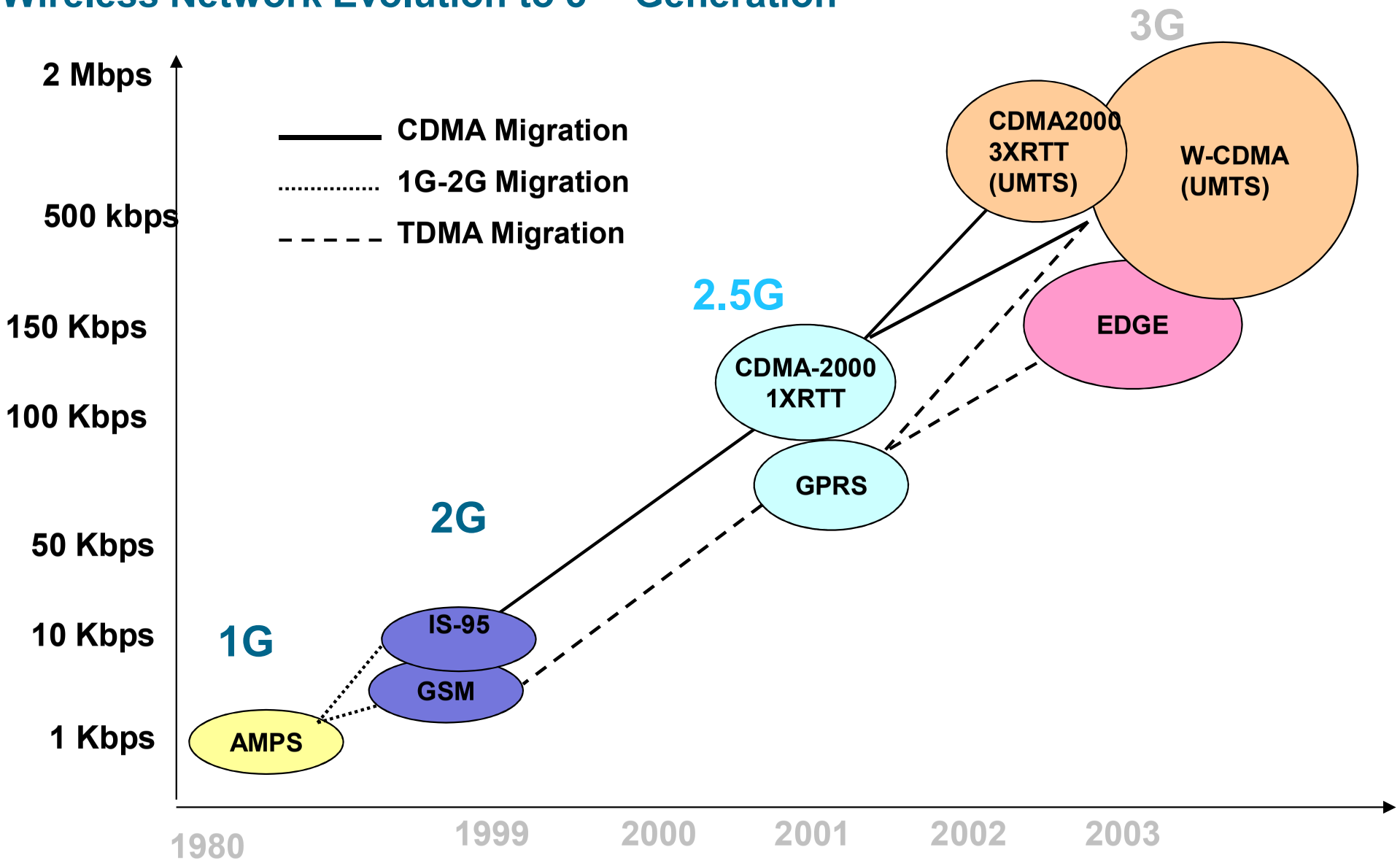
Evolution

Influenced

19

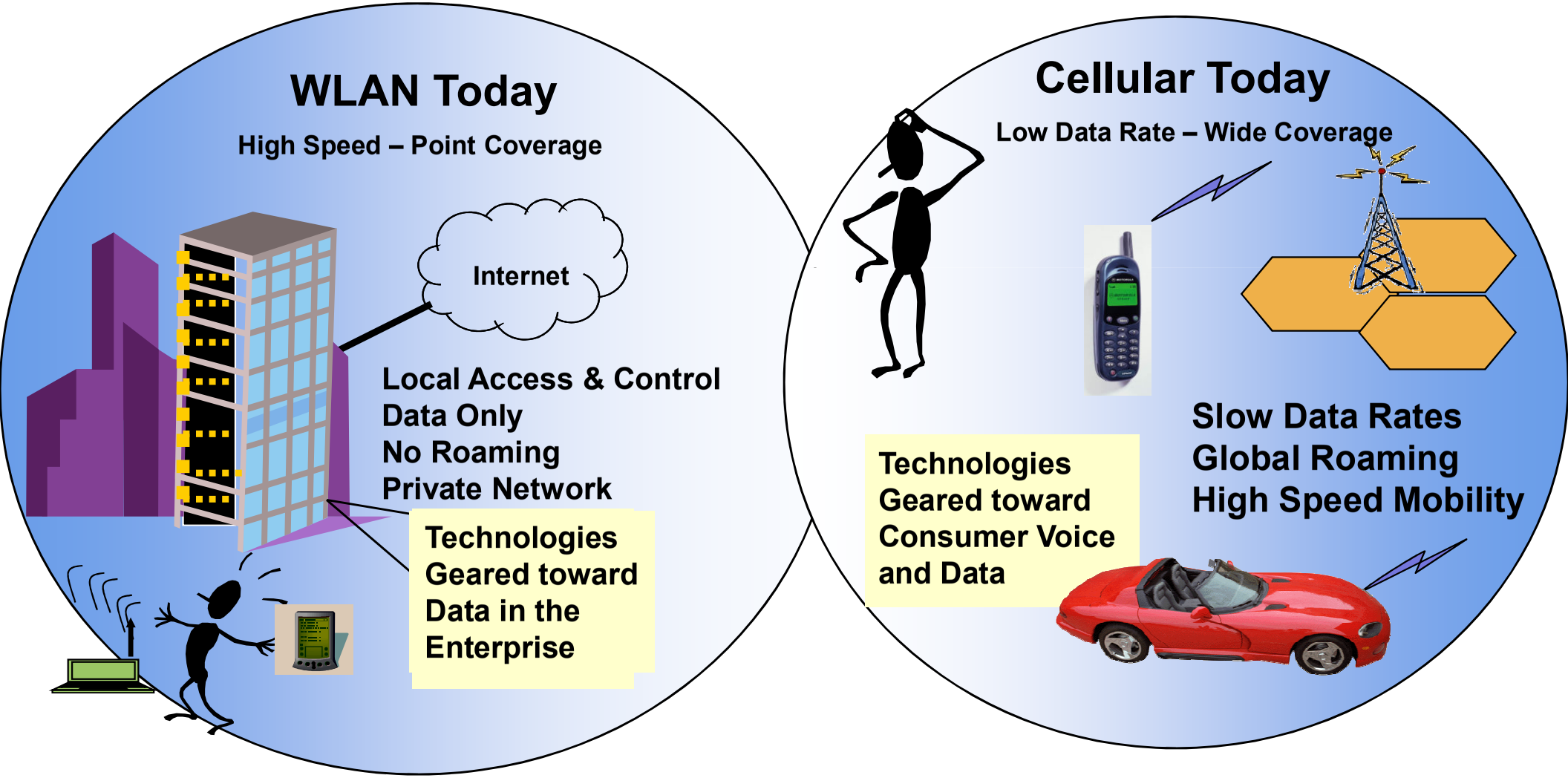
Note: ITU IMT-2000 compliant 3G standards included EDGE, TD-SCDMA, and WiMAX; CDMA2000 and WCDMA were the most commercially successful

Wireless Network Evolution to 3rd Generation



WLAN & Cellular Convergence
Is there opportunity here?

- IEEE 802.11 vs 3G Cellular



Integrate Cellular with WLAN

iMGW Platform

Common Features/Capabilities
- Authentication
- Billing
- Preferences/Call Control
- Access Capable (802.11, BT, Cellular)

Enterprise or Hot Spot

Nomadic

Internet

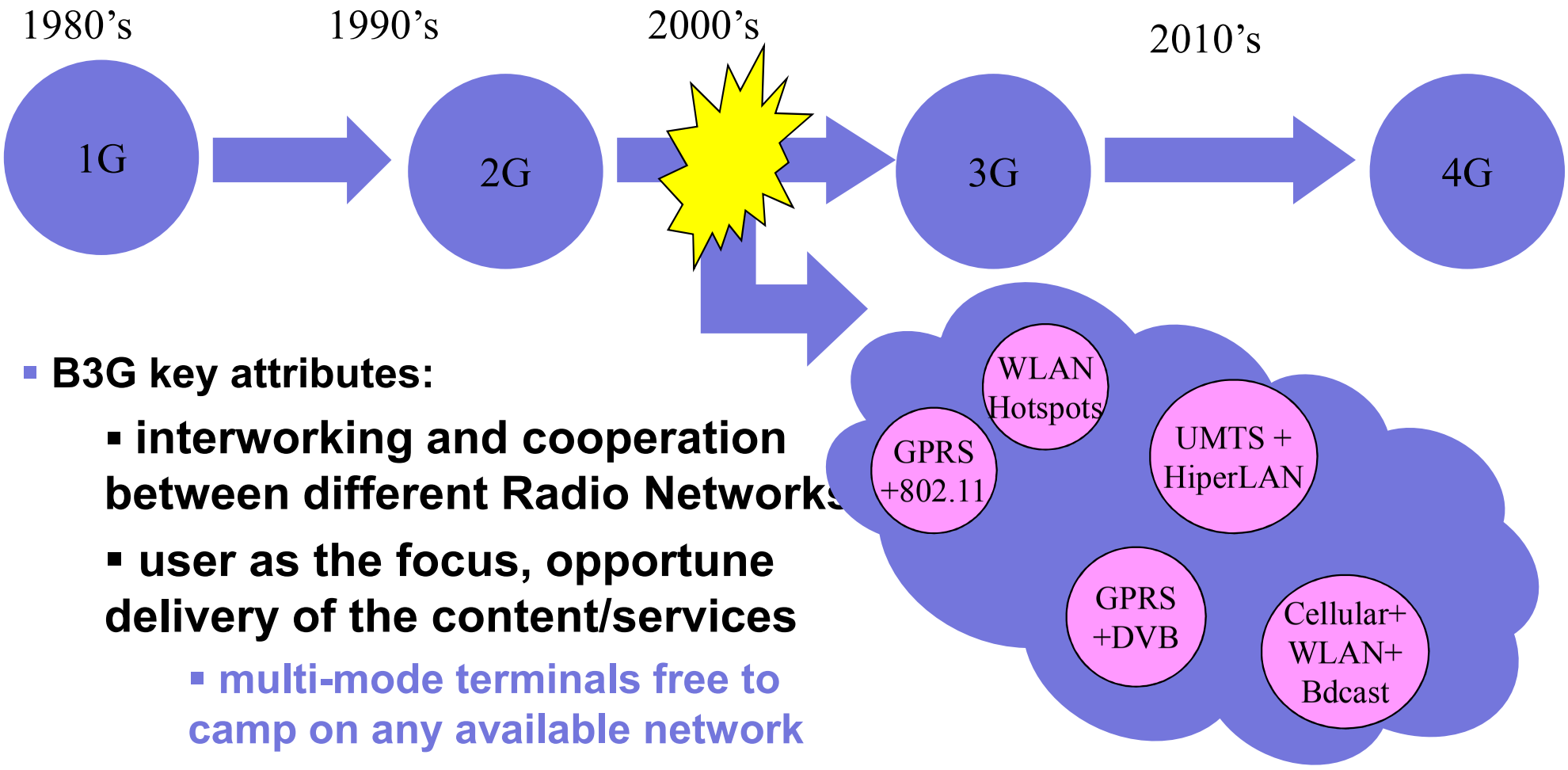
802.11
Or Any
WLAN
Technology

Benefits:
Local Access, Common Control
Data & Voice
Point to Point Roaming
VPN over Public Network
Increasing Data Rates in More Places
Seamless Roaming and Billing
High Speed Mobility …

Home

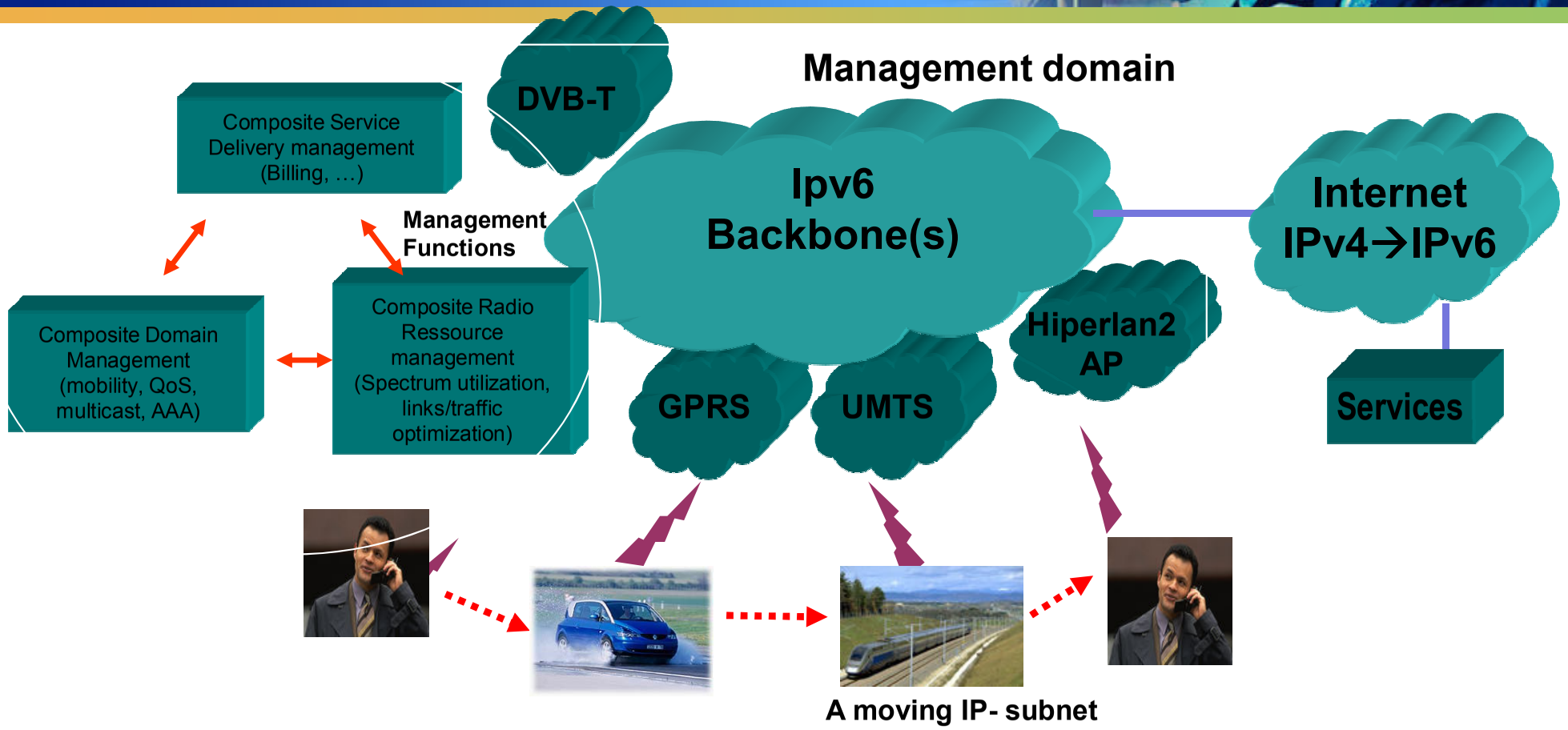
Technology Tailored for a Seamless Solution

Beyond 3G (B3G)



- **B3G key attributes:**
  - **interworking and cooperation between different Radio Networks**
  - **user as the focus, opportune delivery of the content/services**
    - **multi-mode terminals free to camp on any available network**
  - **fully IP based**
  - **disruptive technology**
    - **potentially complementary to 3G**
    - **potentially competitive to 3G**

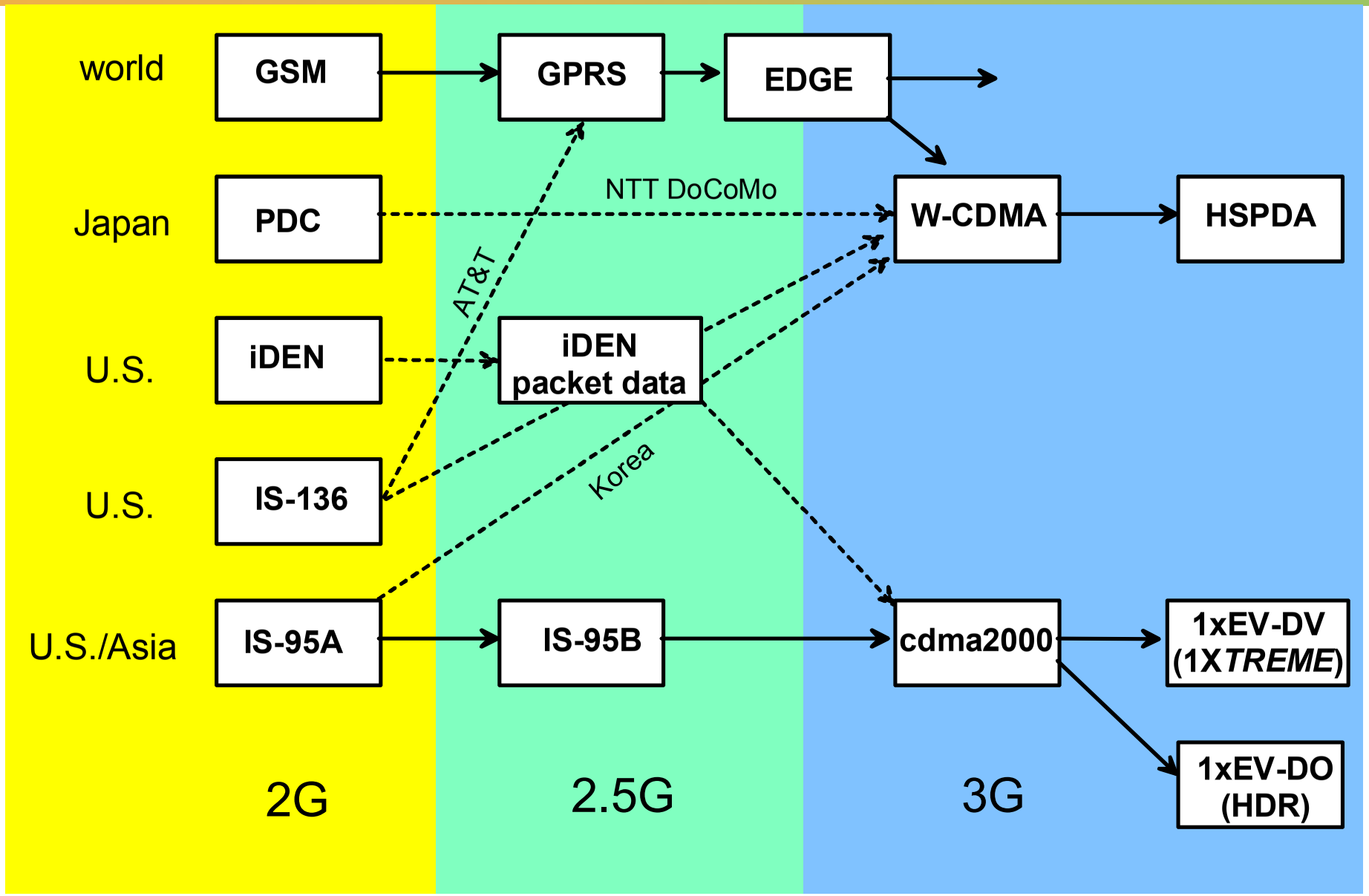
B3G Vision



Main Attributes:

- Core network IPv6 based
  - Better support of mobility, security and “unlimited” address space
- Wireless access points become IP gateways
  - Different radio access technologies deployed within a domain
  - Optimization of the radio resources

Technology Evolution



Short Message Service SMS

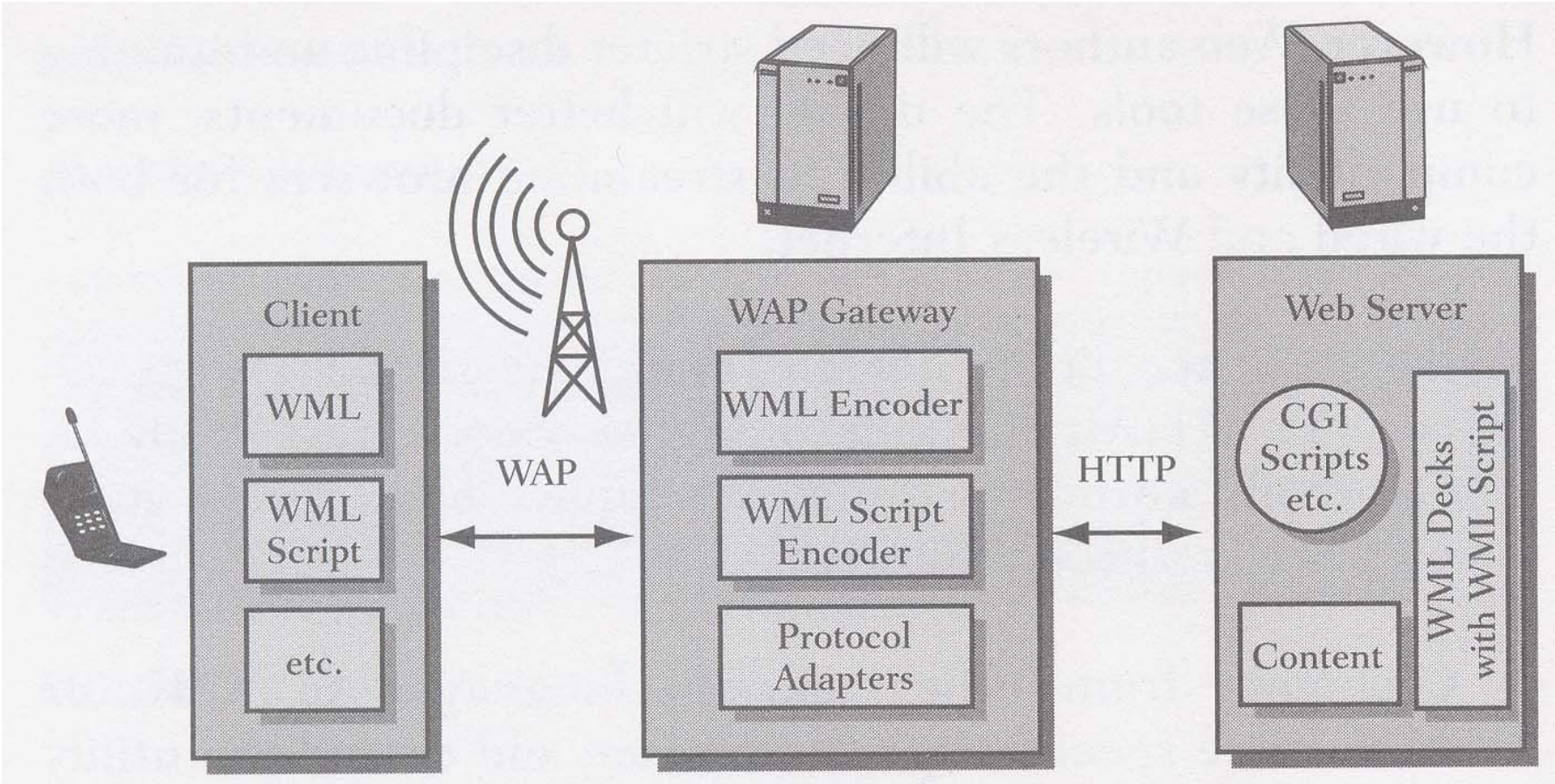
- A messaging service supported by cell phones that allows short text messages to be sent between mobile devices.
- All GSM phones support SMS, but not all CDMA or TDMA cell phones support yet.
- SMS teaches consumers to use wireless devices for non-voice services.
- SMS loses value as latency increases
  - How to reduce the latency? Ans: SMSC

General Packet Radio Service (GPRS)

- GPRS is a the first available 2.5G packet-switched standard.
- It is the first packet data service on wireless digital networks.
- GPRS will be the backbone of GSM and TDMA networks for wireless data packet communications.
- It can transfer data at 115 kbps.

Wireless Application Protocol (WAP)

- WAP is an application protocol for cell phones.



The Promise of 3G

Data Transmission Speed - k bps

2,000
384
144
128
64
32
9.6
0

1G
2G
3G

Video Streaming
Still Imaging
Audio Streaming
Text Messaging
Voice

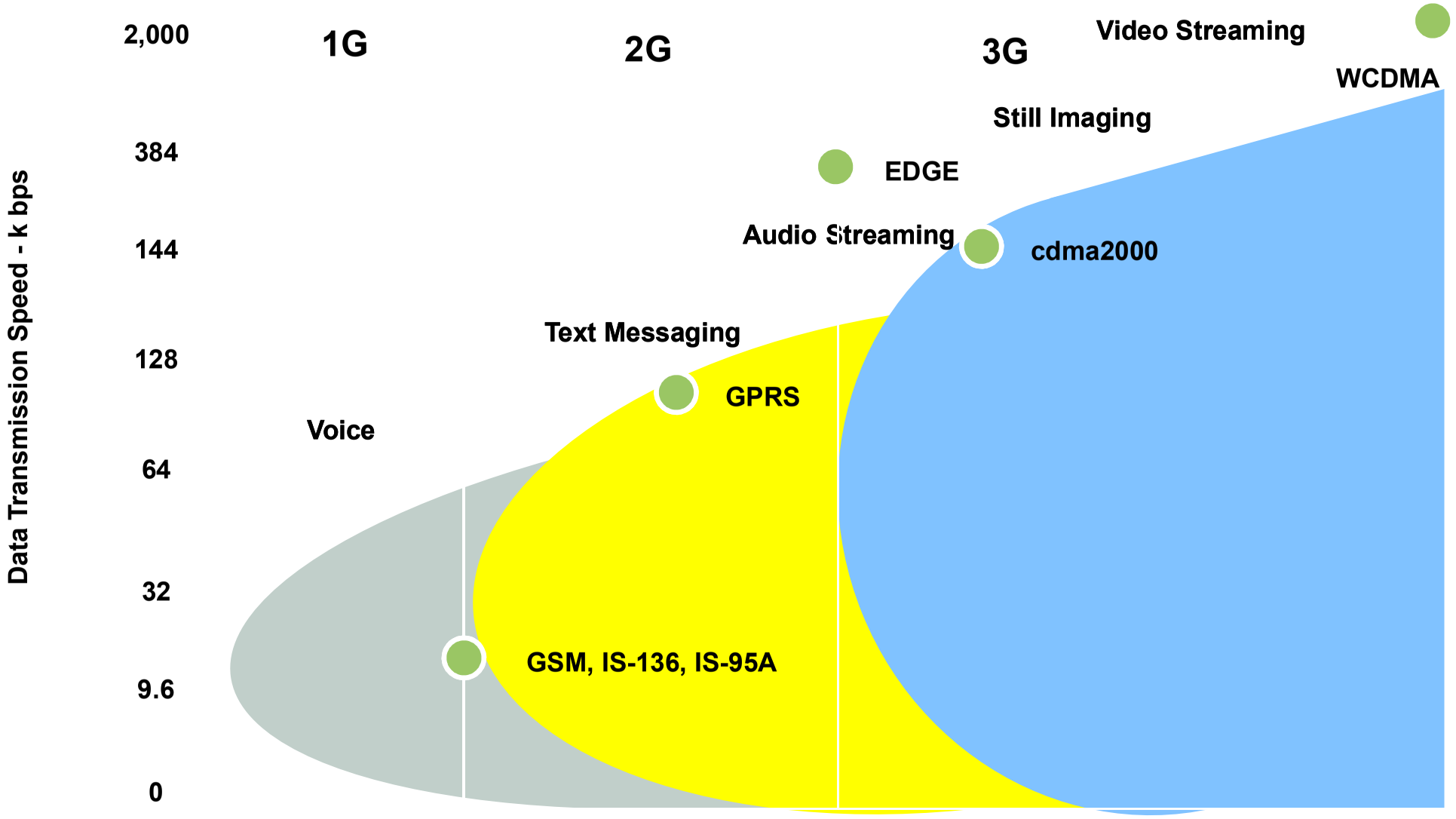
Remote Medical Service (image)
Video Conference (High quality)
Video on Demand: Sports, News Weather
Video Conference (Lower quality)
Mobile TV
Image
Viideo Surveillance, Video Mail, Travel
JPEG Still Photos
Electronic Newspaper
Voice Mail
Electronic Publishing
E-Commerce
Karaoke
Mobile Radio
Fax
E-Mail
Telephone (Voice)
Data
Weather, Traffic, News, Sports, Stock updates
Audio
Voice-driven Web Pages
Streaming Audio







Technology Data Rates

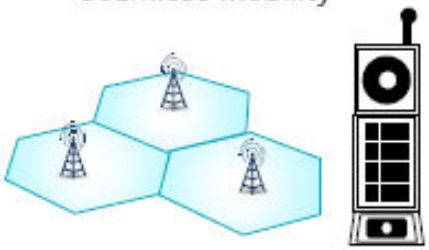


Mobile 3G evolved mobile for data

Introducing high-speed internet access for the first time

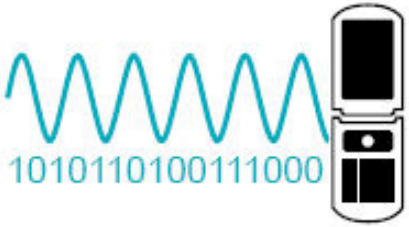
Mobile 1G
AMPS, NMT, TACS

Foundation of Mobile
Seamless Mobility



Mobile 2G
D-AMPS, GSM/GPRS, cdmaOne

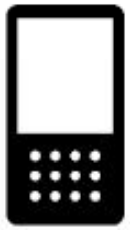
Mobile for the Masses
More Voice Capacity



Mobile 3G
CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA

Mobile Broadband
Data Optimized

3GPP
A GLOBAL INITIATIVE
3G 3rd Generation Partnership Project 2 "3GPP2"



1980s 1990s 2000s

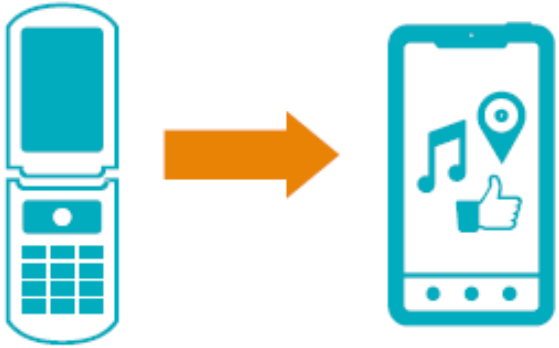
Mobile voice was amazing, but consumers wanted more

A new, insatiable demand for internet access and data services emerges

Broadband Internet

Consumers introduced to broadband internet access in the home/office

The Smartphone



Amazing innovations in device technology resulted in the era of the smartphone

Mobile Everywhere

2 → 39 → 92

1990 2000 2010

Average mobile subscriptions per 100 people[1]

Thanks to 2G technologies, more and more people had a mobile subscription

EV-DO optimized 3G for data enabling mobile broadband

Data Enabled
Simple Data Services

Mobile 2G
<0.5 Mbps[1]

Capable of efficiently supporting small data files

Data Optimized
Mobile Broadband

CDMA2000/EV-DO
14.7 Mbps[2]

CDMA2000
Voice Services

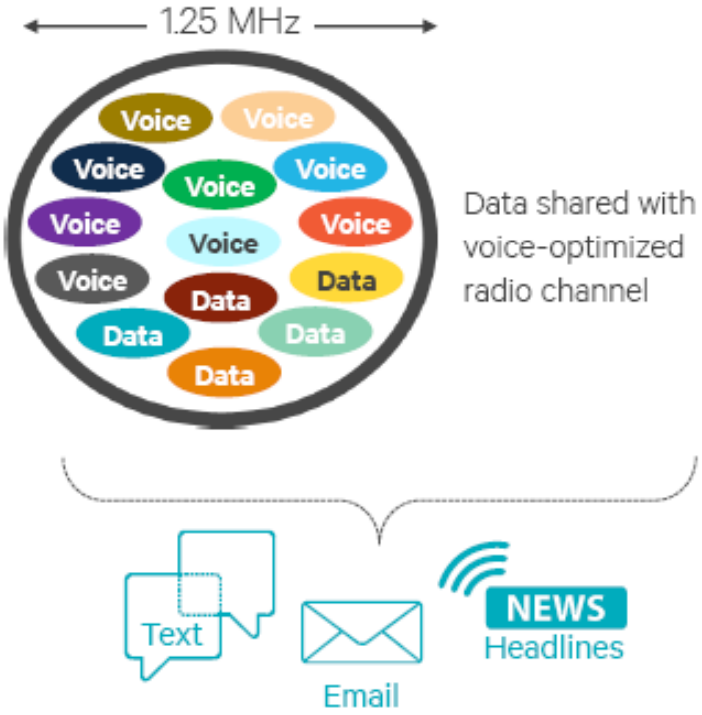
EV-DO
Data optimized channel with support for larger package sizes

[1] Based on peak data rate – GSM/GPRS
[2] Based on peak data rate for downlink EV-DO Rev. B

Qualcomm pioneered EV-DO introducing mobile broadband

Mobile 2G

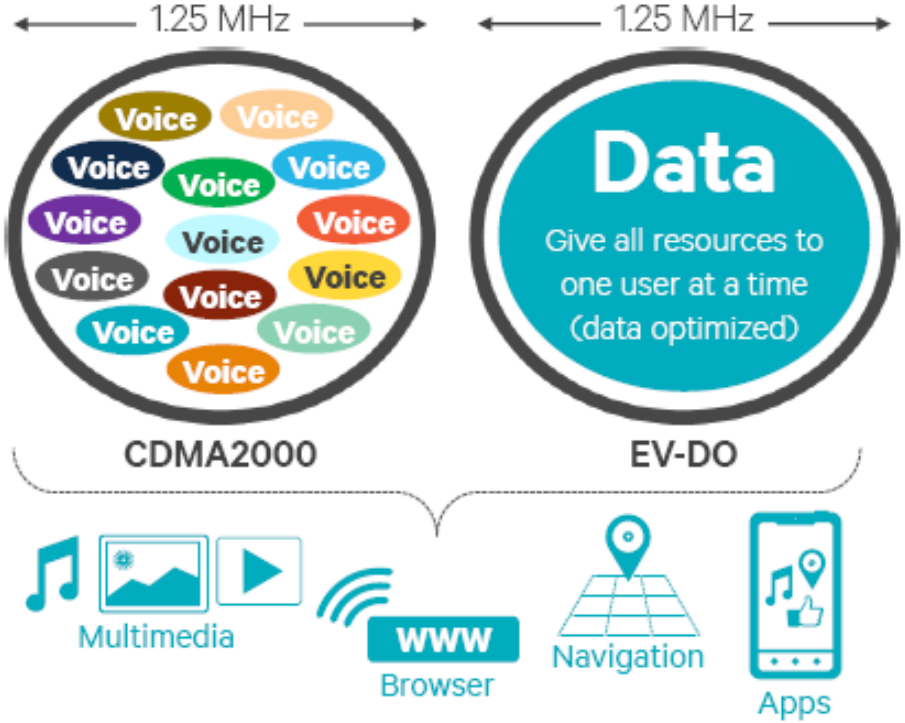
Data Enabled



Simple Data Services

CDMA2000/EV-DO

Data Optimized



Mobile Broadband Services

EV-DO inventions are the foundation to mobile broadband

1 Data Optimized Channel

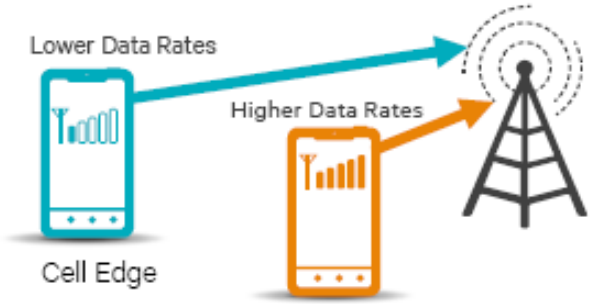
Splits channel into time intervals enabling a single user to get all the resources at once

Enables richer content

2 Adaptive Modulation

Uses higher order modulation to get more bps per Hz for users with good signal quality

Increases peak data rates



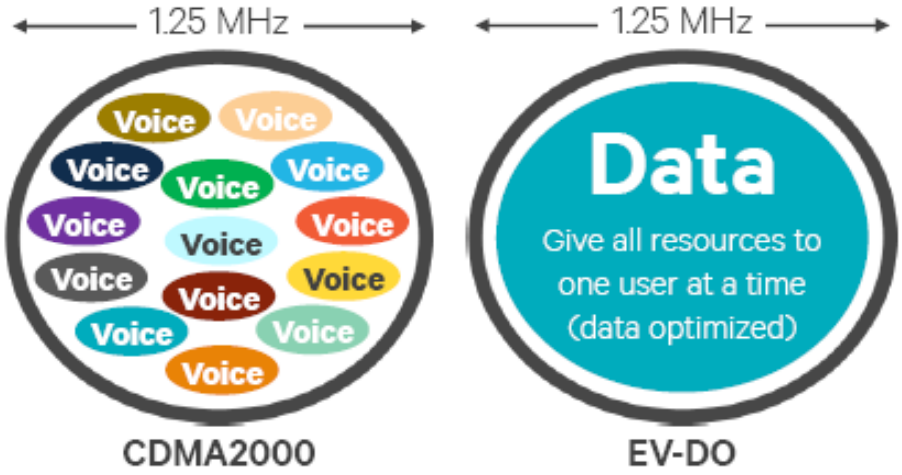
3 Opportunistic Scheduling

Optimizes channel by scheduling users at the time instances when users have good radio signal conditions (with fairness)

Increases overall capacity

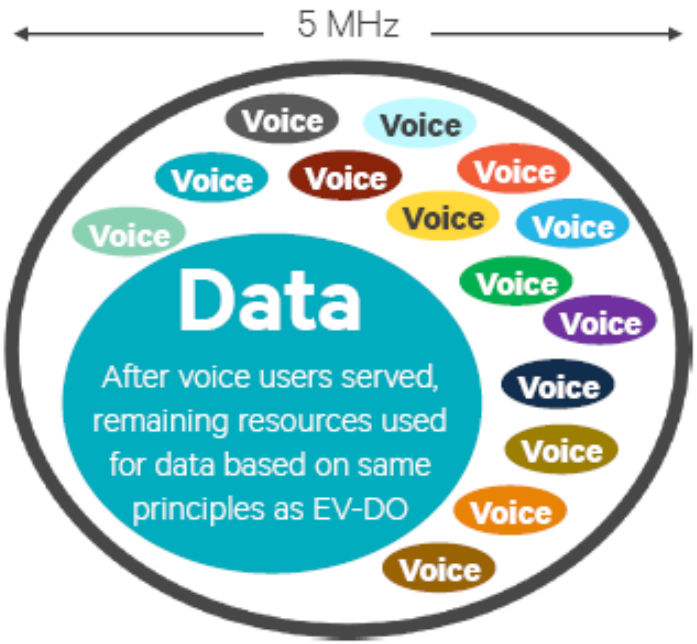
CDMA2000/EV-DO blazed the trail for WCDMA/HSPA

CDMA2000/EV-DO



3G 3rd Generation Partnership Project 2 "3GPP2"

WCDMA/HSPA



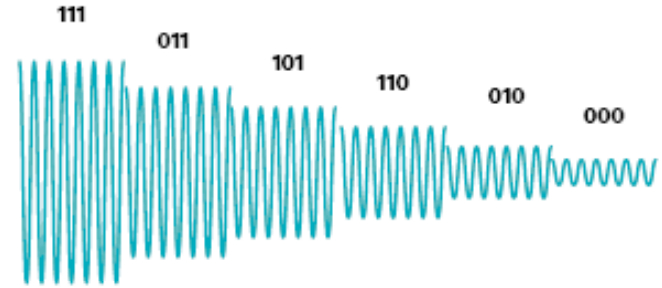
3GPP A GLOBAL INITIATIVE

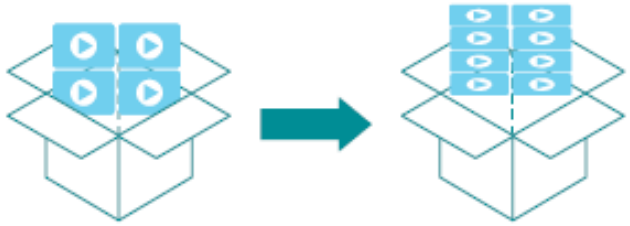
Mobile 3G evolved to HSPA+ and EV-DO Rev. B

Delivering higher data rates, more capacity, and enhanced mobile broadband experiences

Higher Order Modulation (HOM)

Introduces 64-QAM enabling 50% more bits per second per Hz (bps/Hz)

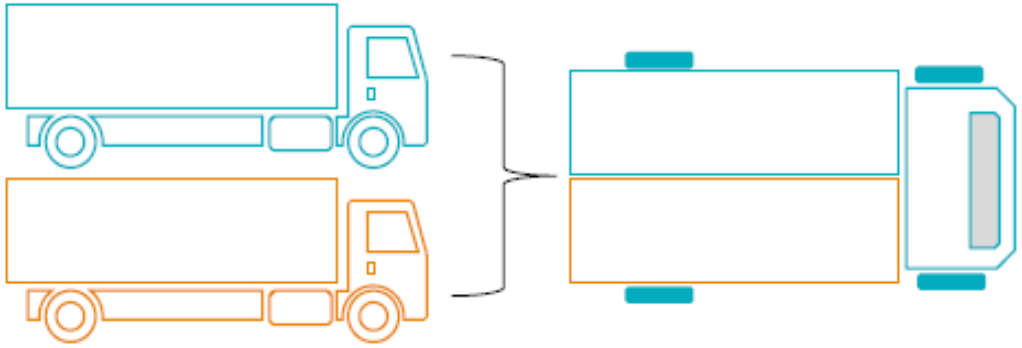




Enabling packing 50% more data into packages

Carrier Aggregation

Aggregating spectrum enabling increased user and peak data rates

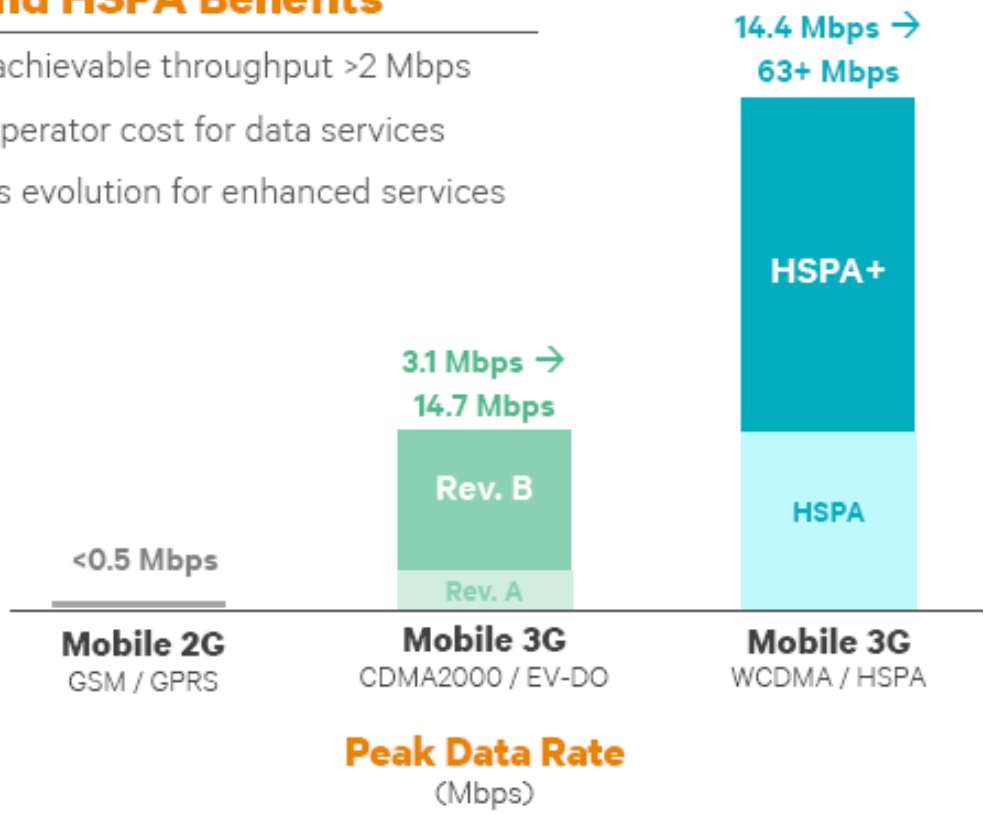


Aggregate channels for higher data rates

3G technologies optimized mobile for data

EV-DO and HSPA Benefits

- Delivered achievable throughput >2 Mbps
- Reduced operator cost for data services
- Continuous evolution for enhanced services



Mobile Broadband Timeline[1]

1999
Qualcomm introduces EV-DO

January 2002
First EV-DO commercial launch

Q4 2004
3GPP release 6 with HSPA is published based on WCDMA technology

Q1 2007
EV-DO passes 50 million connections

Q108
HSPA passes 50 million connections

June 2008
First HSPA+ (21 Mbps) commercial launch

September 2010
First DC-HSPA+ (42 Mbps) commercial launch

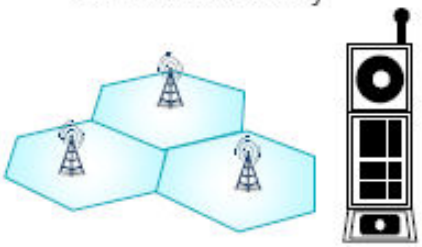
3G technologies continue to evolve
Surpassed 2B connections in 2013[2]

Mobile 4G LTE is evolving to provide more data capacity

Delivering faster and better mobile broadband experiences

Mobile 1G
AMPS, NMT, TACS

Foundation of Mobile
Seamless Mobility



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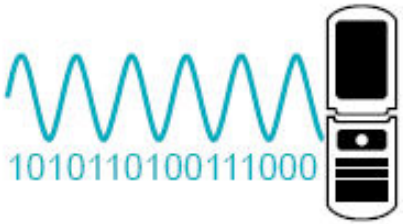
More Voice Capacity



Mobile 3G
CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA

Mobile Broadband
Data Optimized

Mobile 4G LTE
LTE, LTE Advanced

Faster and Better Mobile Broadband
More Data Capacity

1980s 1990s 2000s 2010s

Mobile 4G LTE complements 3G to boost data capacity

Multimode 3G/LTE is the foundation for successful 4G LTE

4G LTE

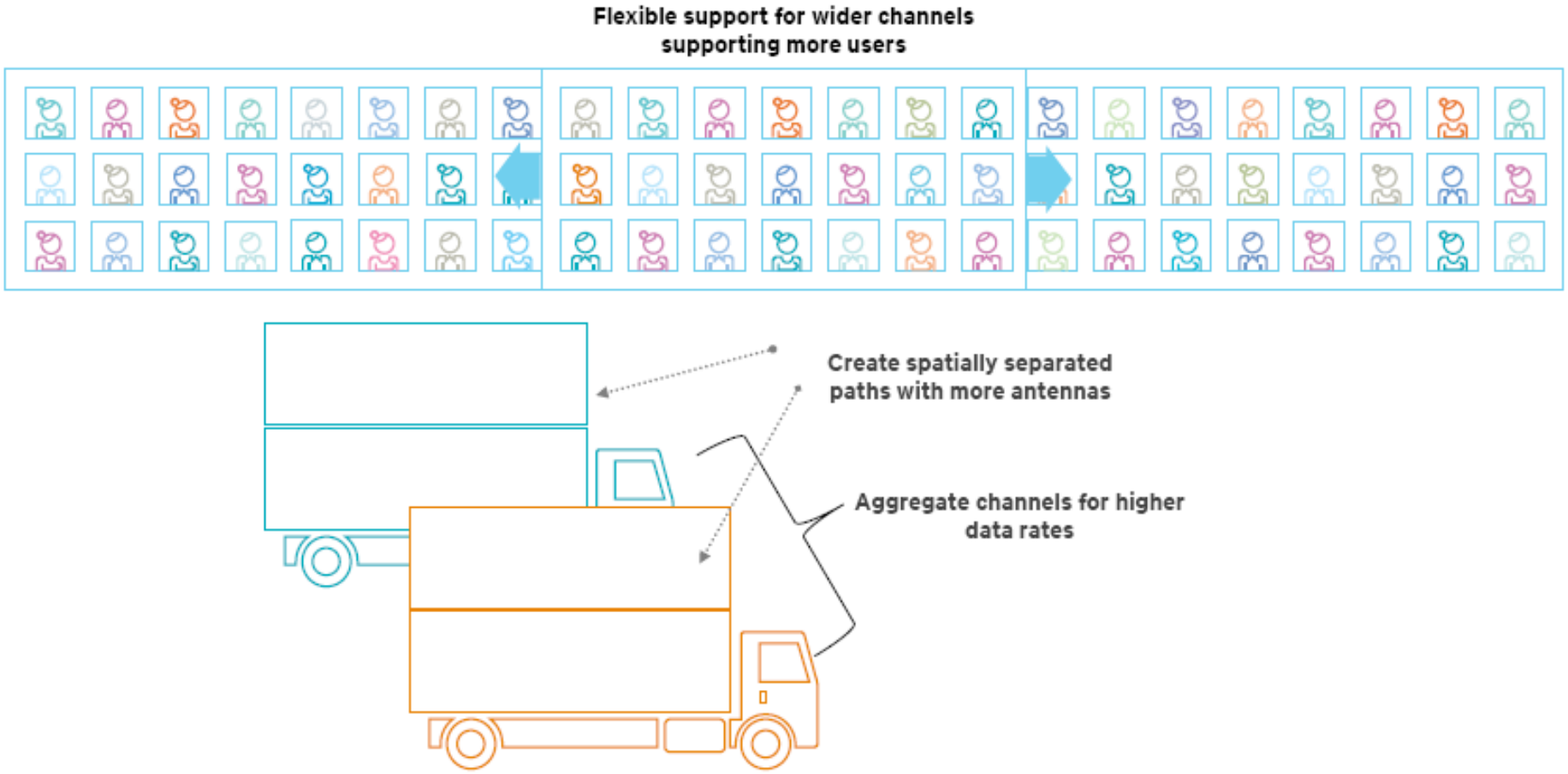
Providing more data capacity for richer content and more connections

3G

Enabling a consistent broadband experience outside 4G LTE coverage

Delivering ubiquitous voice services and global roaming

Mobile 4G LTE delivers more data capacity



Mobile 4G LTE delivers more data capacity

Download, browse, stream, and game faster than ever with faster and better connectivity

Connect Faster

Wider Channels
Flexible support for channels up to 20 MHz enabled with OFDMA

More Antennas
Advanced MIMO techniques to create spatially separated paths; 2x2 MIMO mainstream

Carrier Aggregation
Aggregate up to 100 MHz for higher data rates – 2 carrier (2C) commercial; 3C announced[1]

Connect Real-time

Simplified Core Network
All IP network with flattened architecture resulting in less equipment per transmission

Low Latencies
Optimized response times for both user and control plane improves user experience

Mobile 4G LTE is the first global standard for mobile broadband

Global LTE network launches

279 Launches

101 Countries

Large device ecosystem

1,563 Devices

>100 Vendors

LTE FDD & LTE TDD

Two modes, common standard, same ecosystem

Frequency Division Duplex (FDD)
Paired spectrum enables better coverage

Time Division Duplex (TDD)
Unpaired spectrum enables asymmetrical DL/UL for more DL capacity

Mobile 3G and 4G technologies continue to evolve to deliver faster and better mobile broadband experiences

Mobile 3G and 4G LTE continue to evolve

Delivering a faster and better mobile broadband experiences

4G LTE has evolved to LTE Advanced

Providing more data capacity and expanding into new frontiers

3G networks have continued to evolve and improve—so much so some call it 4G

Providing a consistent broadband experience outside LTE coverage

Mobile 3G/4G technologies are evolving for more data capacity

Shannon's Law

$$C \approx W \cdot n \cdot \log_2(1 + SNR)$$

Capacity — Spectrum — Antennas — Signal Quality

LTE Advanced

More Spectrum

Making the best use of all spectrum types with more licensed spectrum as the top priority, e.g., ASA, ~3.5 GHz, unlicensed spectrum

More Antennas

Advanced multiple antenna techniques to create spatially separated data paths, e.g., 4 way receive diversity, 4x4 MIMO

Interference Mitigation

Advanced receivers and antenna techniques, e.g., LTE FeICIC/IC, HSPA+ advanced device receiver