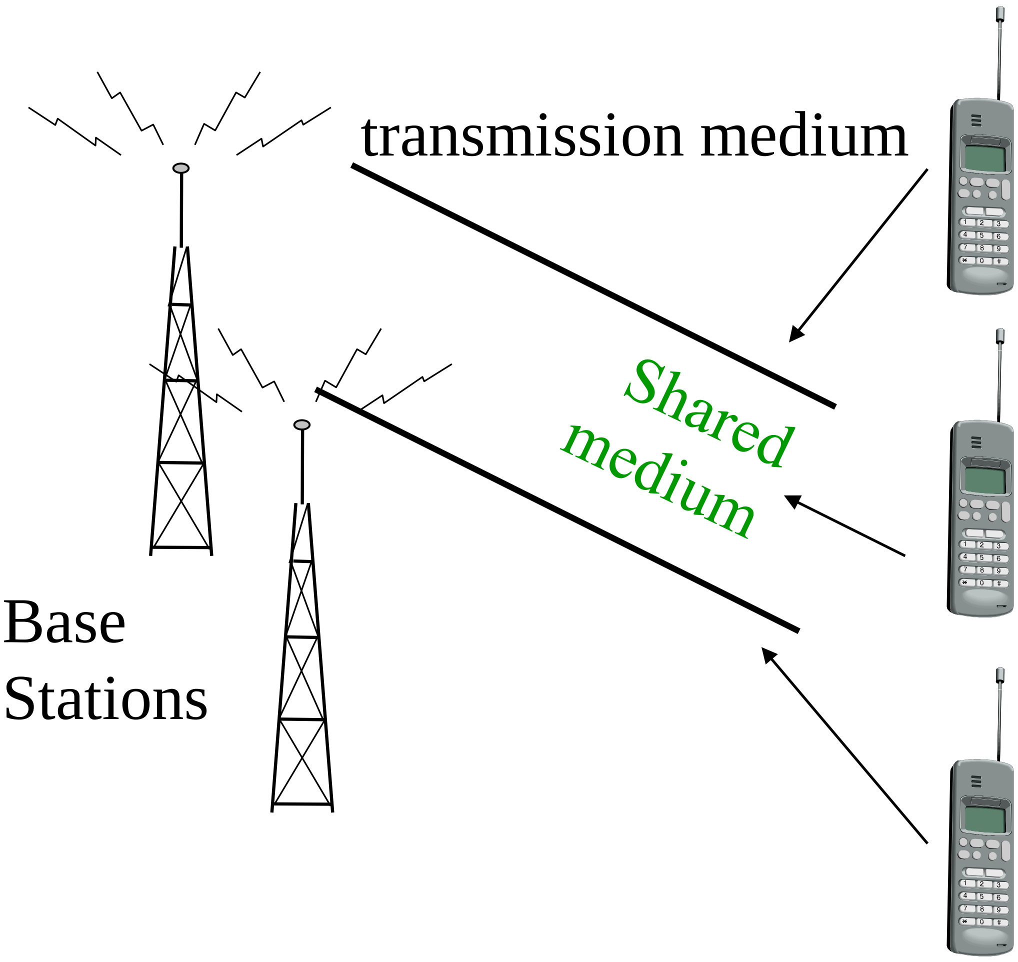
Fundamentals of Wireless Communication

Outline

- Characteristic of wireless communication
- Basic Modulation Techniques
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Shift Keying (PSK)
- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)

Shared Medium in Wireless Networks



- Wireless users access the network via the shared medium
- Access capacity and interference are major issues

Problems with Shared Medium

How do you speak to your friend?

- Wireless Communication: If he is next to you, speak to him directly
- Wired Communication: If he is far away from you, use a (wired) telephone
- Why do not talk directly through the air for long distance?
  - Too far and unclear to hear (signal attenuation)
  - Loud talking creates noises to others (interference)

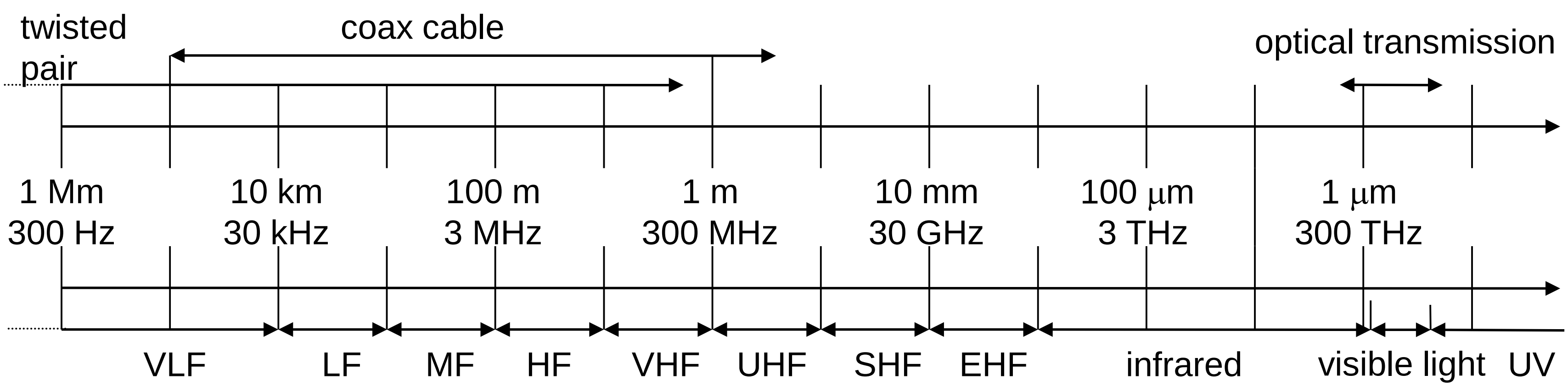
Problems of interference and signal attenuation

- Problem of interference (noise)
- Problem of signal strength attenuation (signals propagated in all directions)
- Noise + Weak signal => High Error Rates
  - Low data-rate
  - Frequent disconnections, …

Frequencies for Radio Transmission

- Low frequency (LF): used by submarines for communication, since they can penetrate water better and follow the earth's surface
- Medium frequency (MF) and high frequency (HF): for radio station broadcast as Amplitude Modulation (AM) and Frequency Modulation (FM)
- VHF-/UHF-ranges: hundreds MHz
  - For mobile radio and TV station broadcast
- SHF and higher: for microwave links and satellite communication
- Wireless LANs use frequencies in UHF to SHF range
  - Some systems planned up to EHF (5G)
  - Limitations due to absorption by water and oxygen molecules, weather dependent fading, signal loss in heavy rainfalls, etc.
- Infrared: for direct transmission (line-of-sight), i.e., between mobile phones, PDA, etc.

Frequencies for Radio Transmission



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

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

- **Wavelength and Frequency**: $\lambda = c/f$, where $c \cong 3x10^8$m/s (speed of light)

General Frequency Ranges

- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Microwave frequency range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- Infrared frequency range
  - ~ 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point applications within confined areas (objects may block signals)

Frequencies and Regulations

Values in MHz

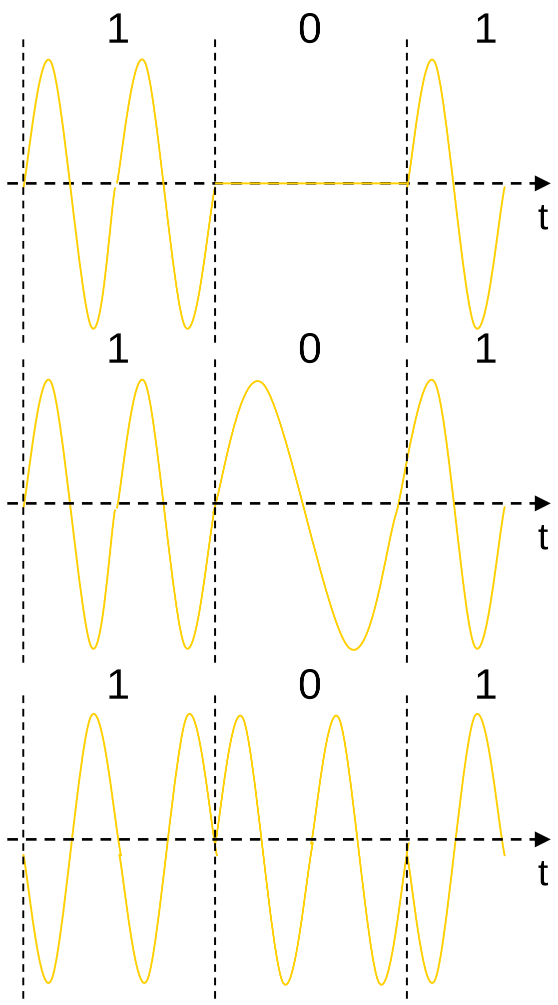
	Europe	USA	Some Asia Countries
Cellular Phones	**GSM** 450-457, 479-486/460-467,489-496, 890-915/935-960, 1710-1785/1805-1880 **UMTS** (FDD) 1920-1980, 2110-2190 **UMTS** (TDD) 1900-1920, 2020-2025	**AMPS**, **TDMA**, **CDMA** 824-849, 869-894 **TDMA**, **CDMA**, **GSM** 1850-1910, 1930-1990	**PDC** 810-826, 940-956, 1429-1465, 1477-1513
Cordless Phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 254-380
Wireless LANs	**IEEE 802.11** 2400-2483 **HIPERLAN 2** 5150-5350, 5470-5725	902-928 **IEEE 802.11** 2400-2483 5150-5350, 5725-5825	**IEEE 802.11** 2471-2497 5150-5250
Others	**RF-Control** 27, 128, 418, 433, 868	**RF-Control** 315, 915	**RF-Control** 426, 868

How to represent data in EM waves?

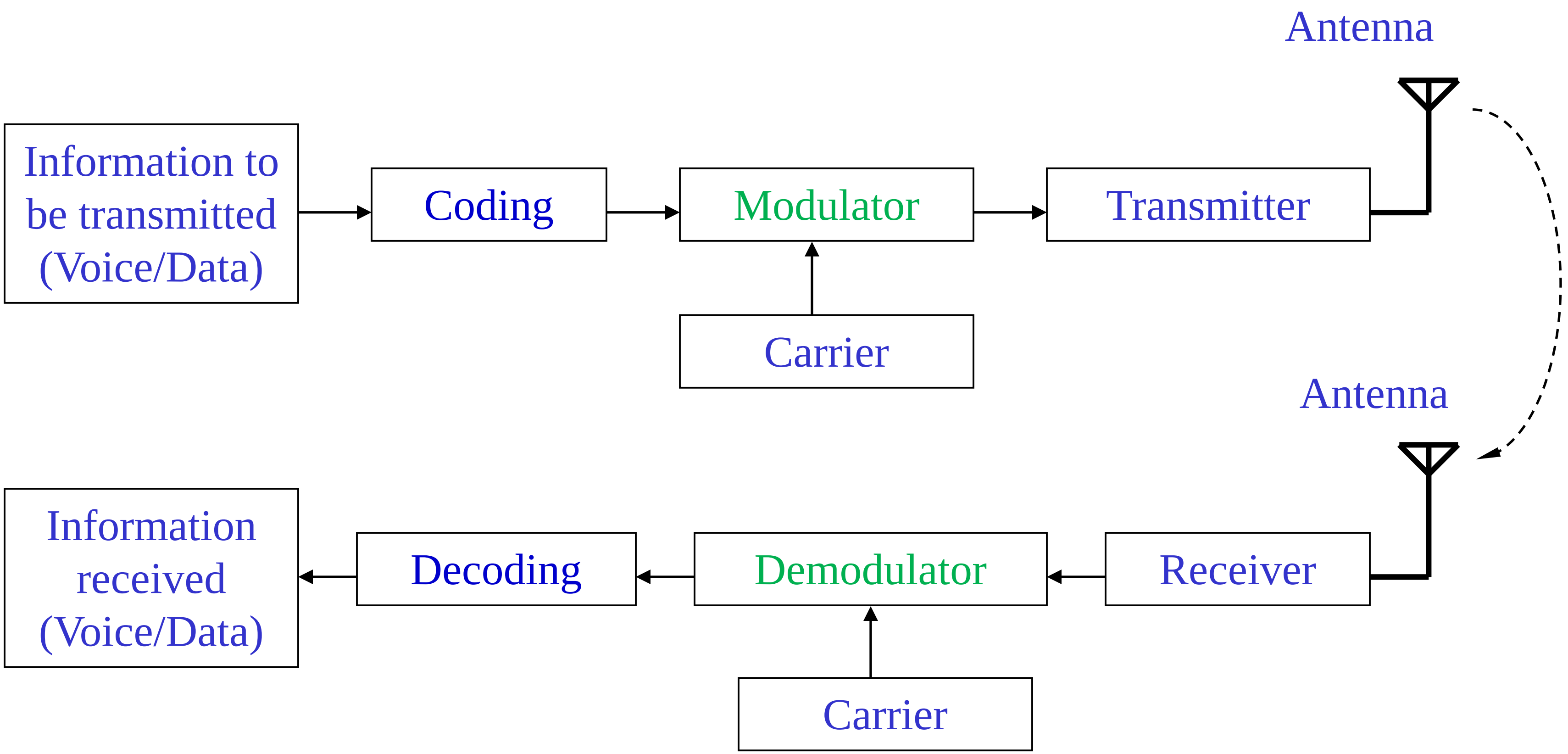
- Assign a certain frequency band (for a channel) as a base frequency (called carrier) for sending signals
- A carrier (base frequency) is a periodic sine/cosine wave
- Modulation is to convert digits to analog signals
  - Input: a sequence of bit stream (0/1)
  - Output: modulate the base signal (periodic wave) based on the input values (0/1 stream)

Digital Modulation

- Amplitude Shift Keying (ASK)
  - very simple
  - low bandwidth requirements
  - very sensitive to interferences
- Frequency Shift Keying (FSK)
  - binary FSK:
    - Assign one frequency f1 to binary 1
    - Assign another frequency f2 to binary 0
  - needs more bandwidth
- Phase Shift Keying (PSK)
  - shifting 180° (for example) each time the value changes
  - more complex but robust against interference



Modulation and Demodulation

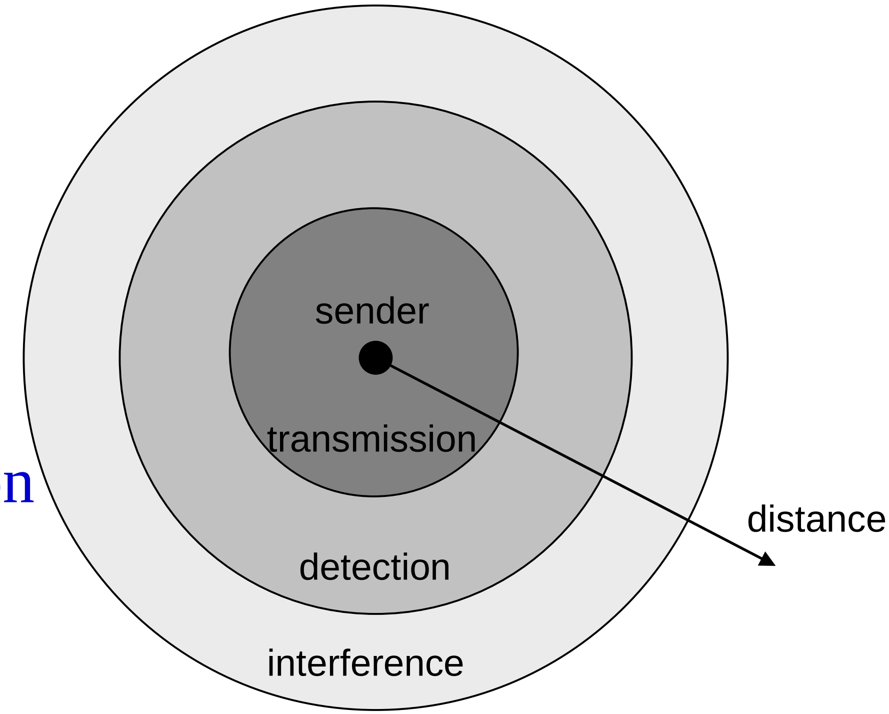


Signal Propagation

- Signals (EM waves) propagates in free space like light (straight line)
  - No wire to guide the propagation direction (so in all directions)
  - The receiver may require to be in the line-of-sight (LOS) of the sender. But radio waves normally can penetrate objects and the loss in power depends on the frequency.
- Path loss
  - Receiving power inversely proportional to the distance from the sender, i.e., $1/d^2$ in vacuum. Why?
  - Much severe in real environments due to other factors resulted from the environment. What are the other factors?
- How about the situation in wired communication?
  - In perfect medium (i.e., copper wire), the path loss is almost zero (decreasing in a much lower rate)

Signal Propagation Ranges

- Transmission range
  - Communication possible
  - Low error rate
- Detection range
  - Possible for detecting signal
  - Not possible for communication
- Interference range
  - Signals may not be detected
  - Signal adds to the background noises

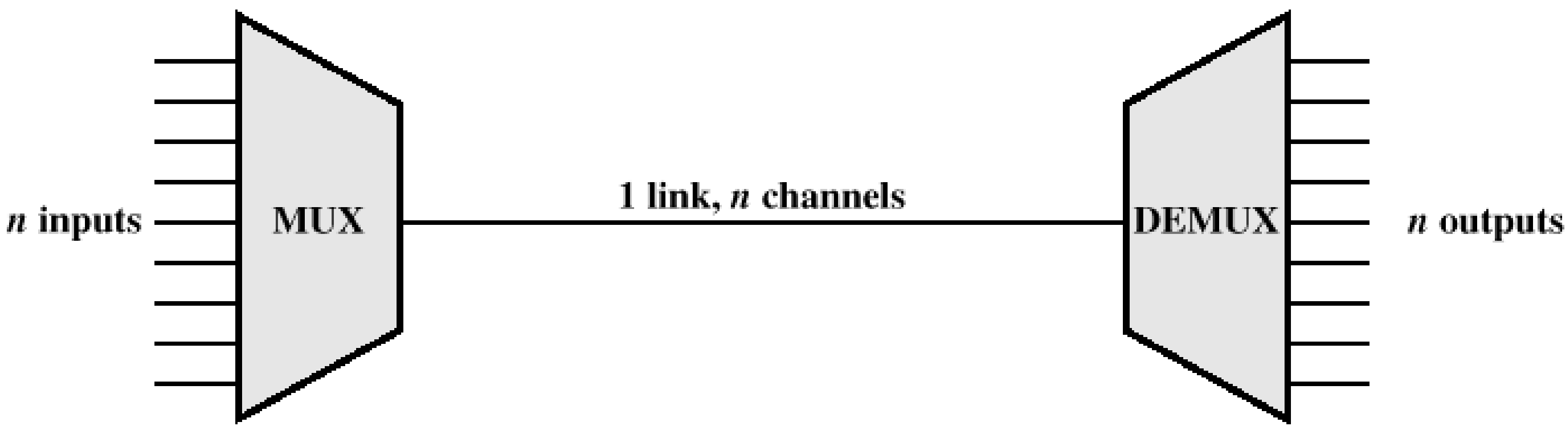


Multiplexing

- How to share the medium with others, when multiple transmitters sending signals at the same time through the shared medium?
- Goal: Minimize the degree of interferences and maximize the bandwidth usage for all users

Multiplexing

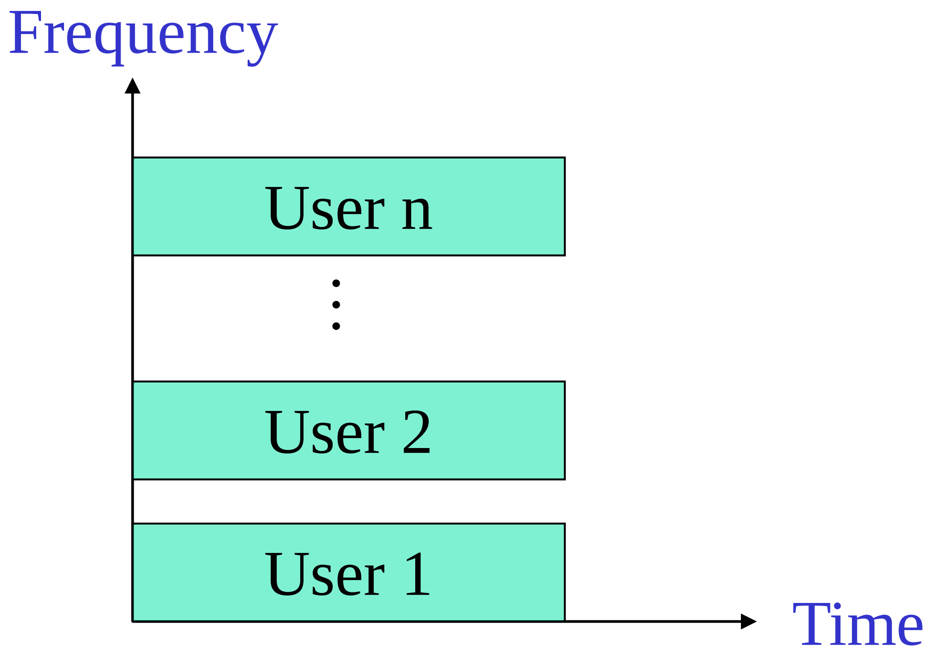
- Capacity of the medium usually exceeds capacity required for transmitting signals of a single user
- Multiplexing - carrying signals of multiple users on a single medium (similar to 1 line for n channels in wired case)
  - More efficient use of transmission medium



Multiplexing Techniques

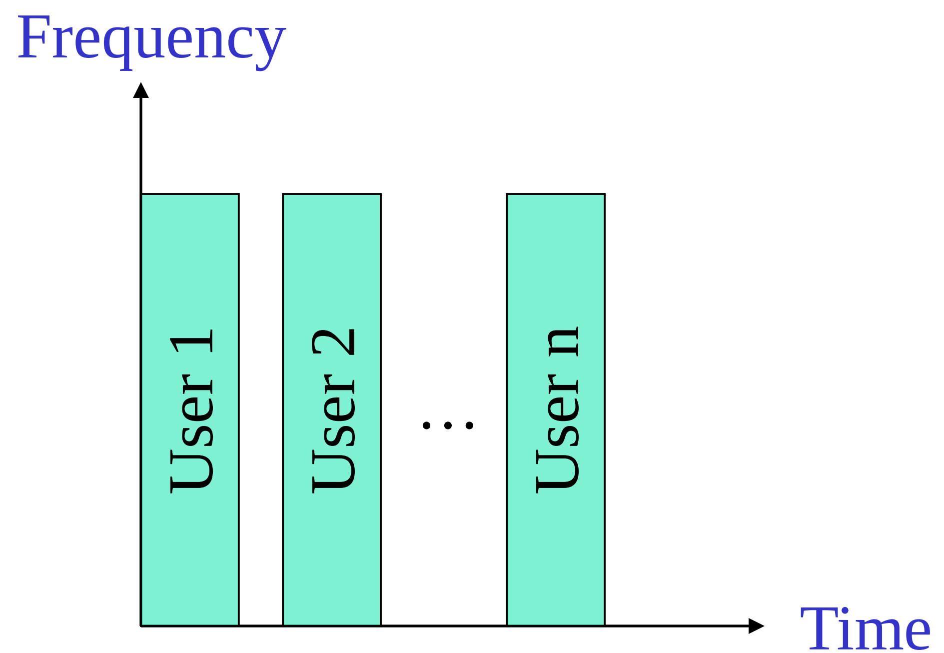
- Frequency-division multiplexing (FDM)
  - The bandwidth of the medium exceeds the required bandwidth of a single user
- Time-division multiplexing (TDM)
  - The achievable bit rate of the medium exceeds the required data rate of a single user
- Code-division multiplexing (CDM)
  - Each sender uses a unique random number (code) and XORs the signal with this random number

Frequency Division Multiple Access (FDMA)



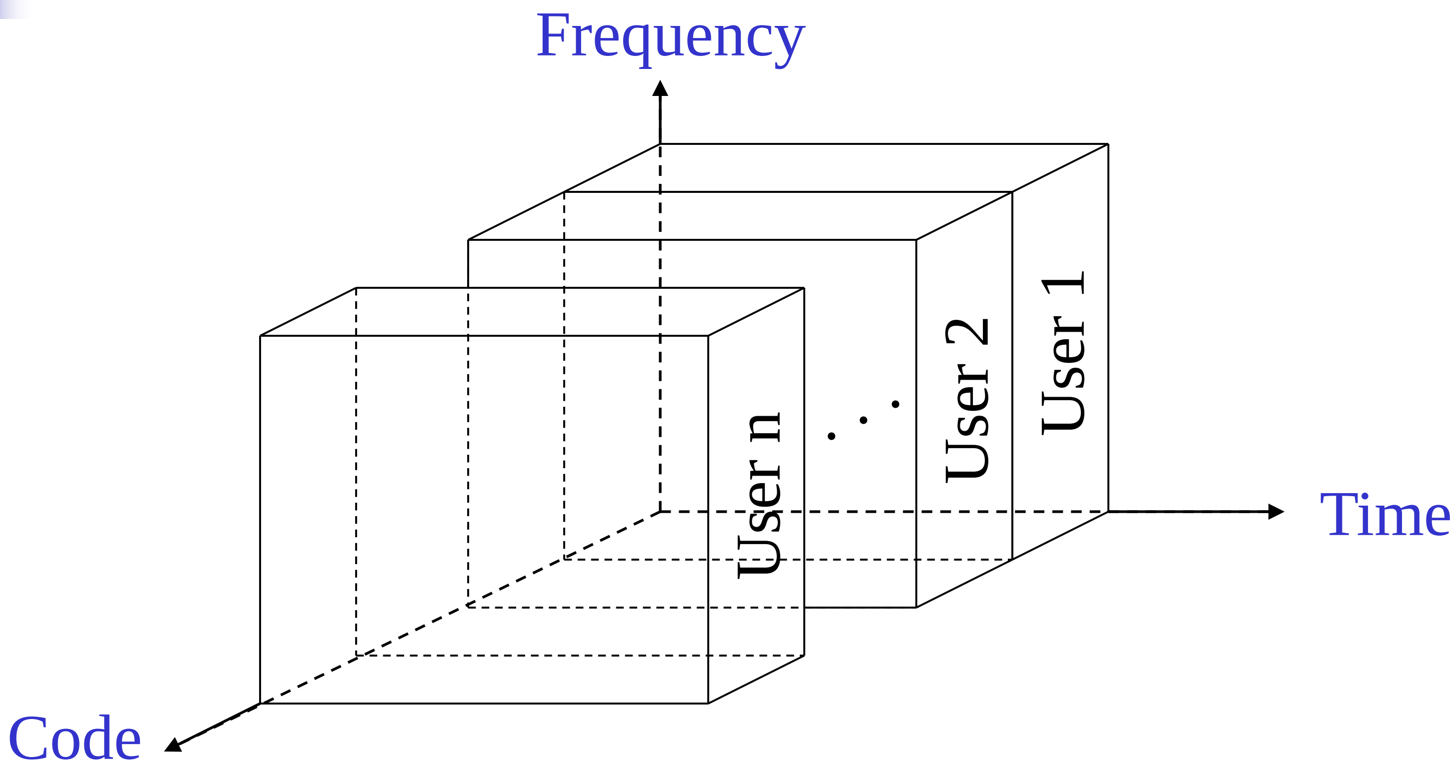
- One channel (frequency-band) per user for all time
- 1st generation systems use FDMA

Time Division Multiple Access (TDMA)



- One time-slot in a period per user to use the entire frequency-spectrum
- Most of 2nd generation systems use TDMA

Code Division Multiple Access (CDMA)

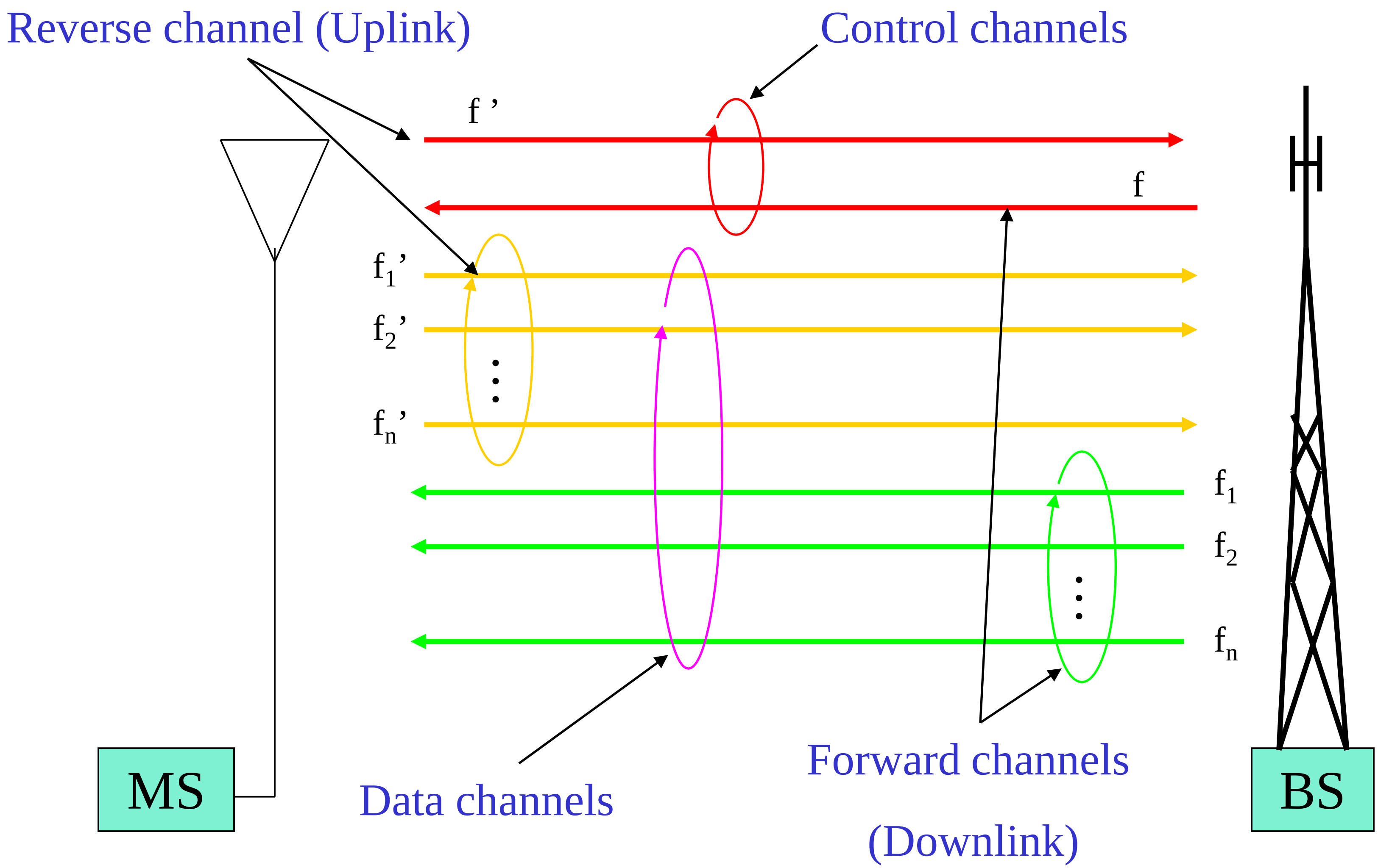


- Users share bandwidth by using code sequences that are orthogonal to each other
- Most of 3G (and some 2G) systems use CDMA systems
  - 3G in China: TD-SCDMA (Time Division-Synchronous Code Division Multiple Access)

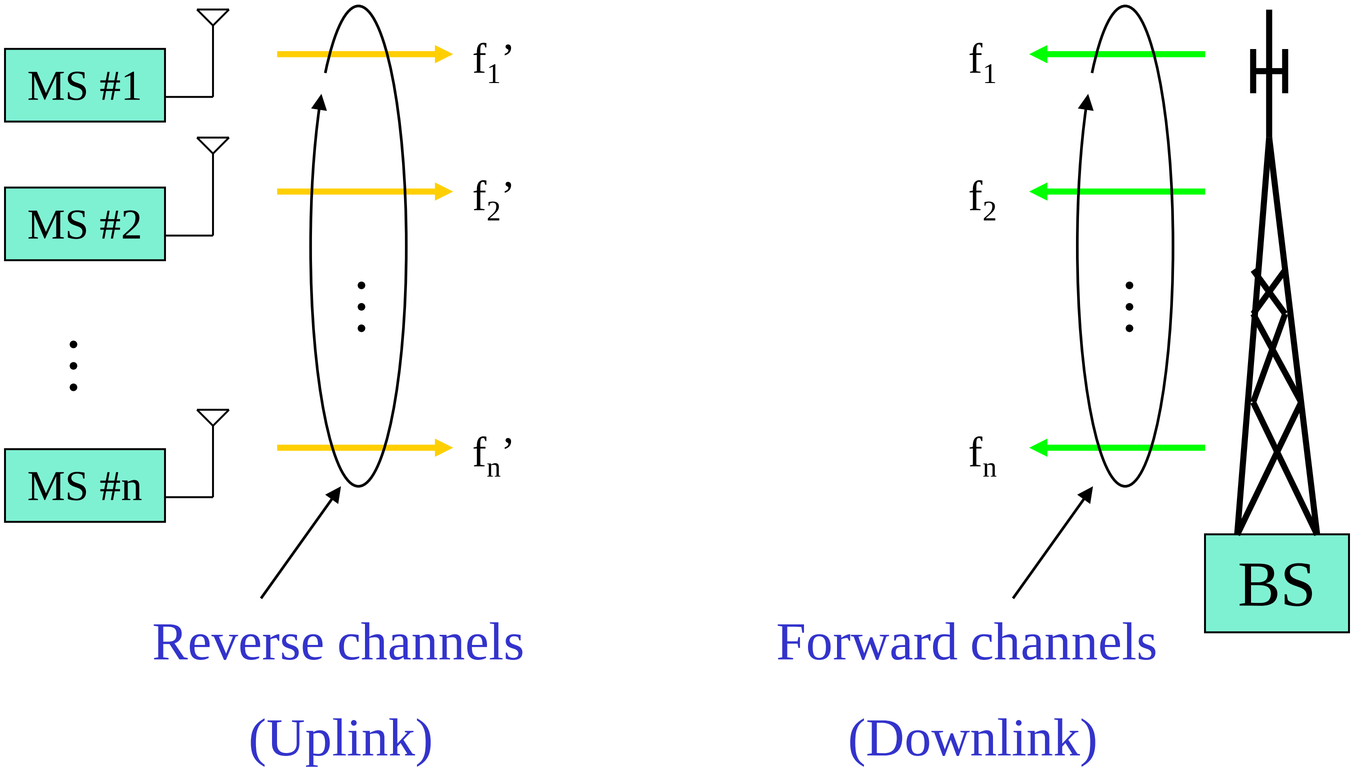
Types of Channels

- Control channel
  - Forward (Downlink) control channel
  - Reverse (Uplink) control channel
- Traffic channel
  - Forward traffic (Downlink) channel
  - Reverse traffic (Uplink) channel

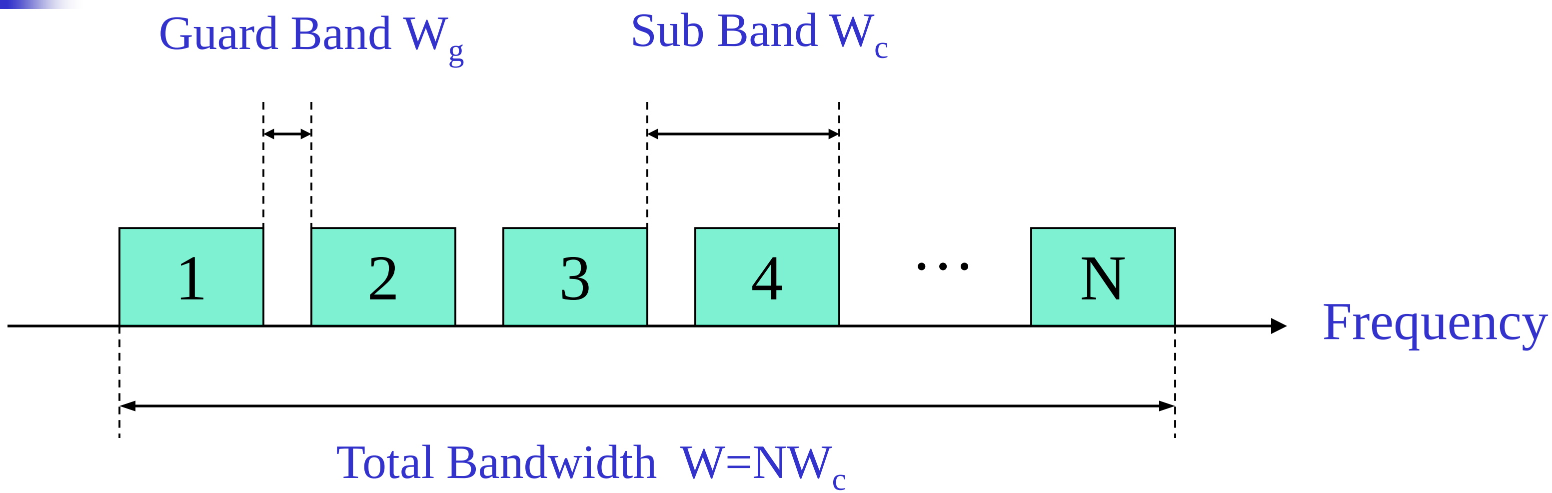
Types of Channels (Cont'd)

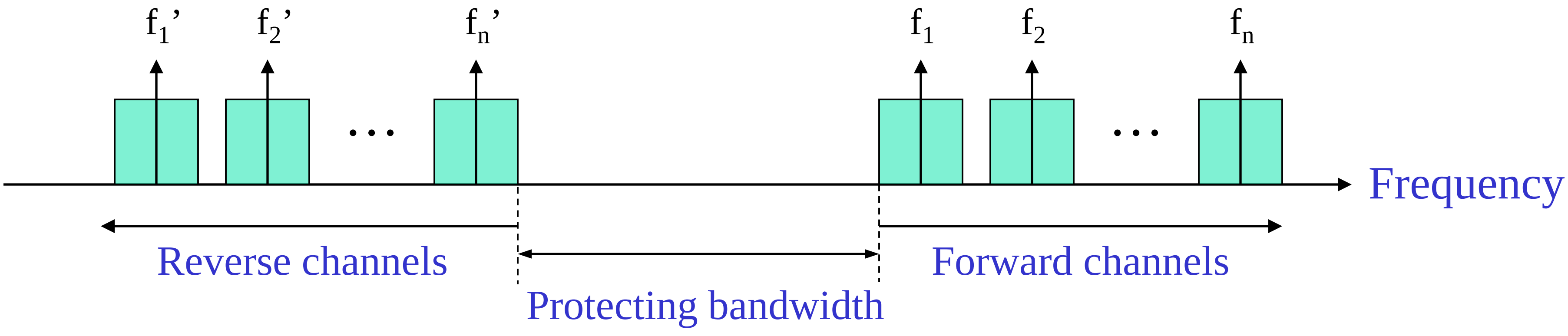


FDMA

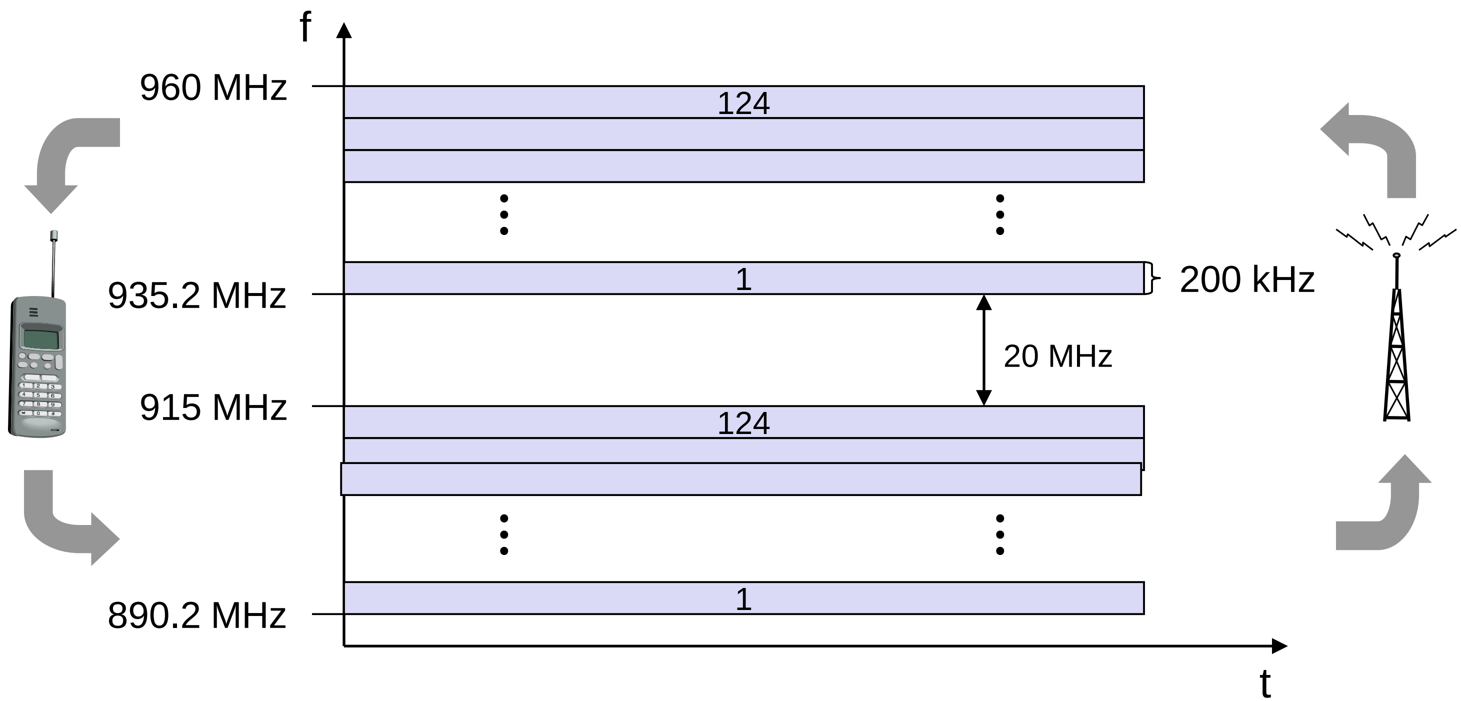

MS #1
MS #2
MS #n
f1’
f2’
fn’
f1
f2
fn
BS
Reverse channels
(Uplink)
Forward channels
(Downlink)

FDMA: Frequency Spectrum





FDD/FDMA -Example of GSM



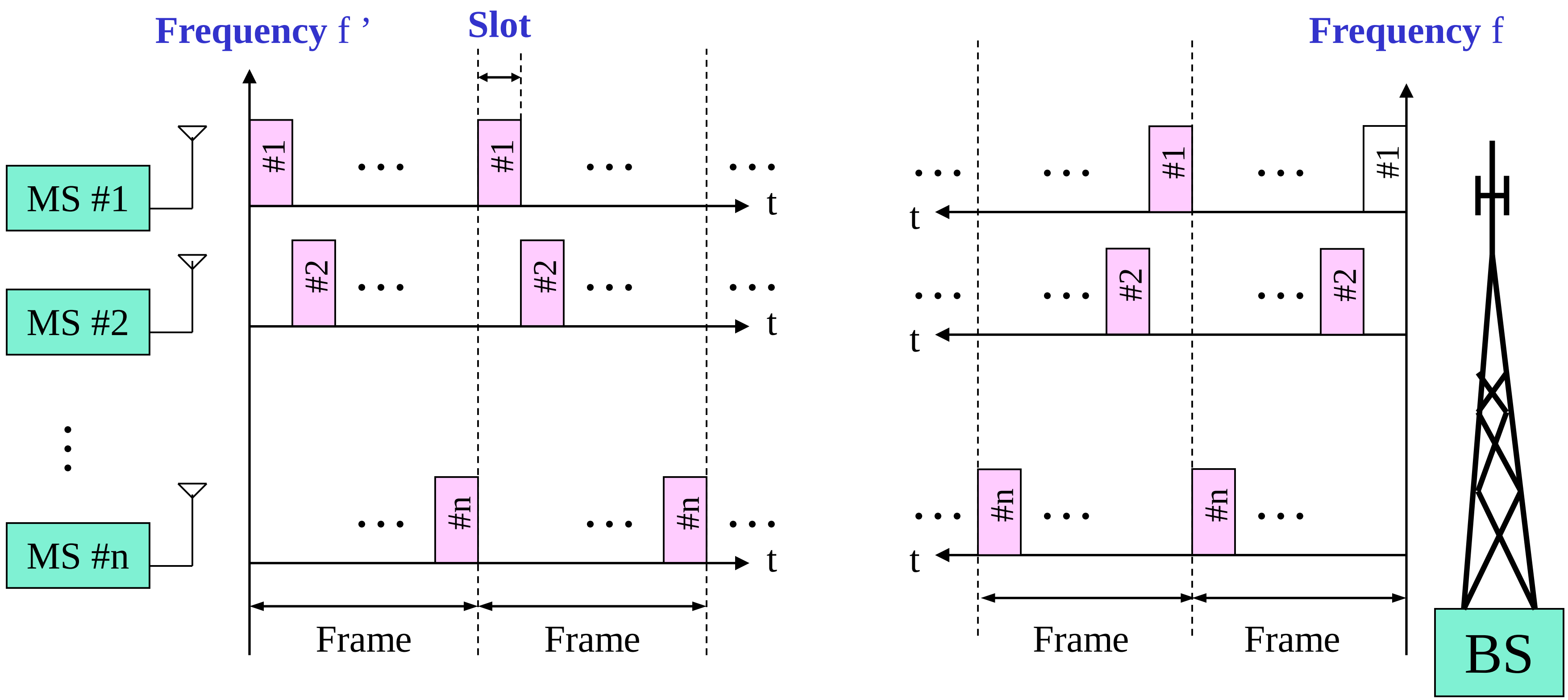
GSM: 900MHz (890MHz ~ 960MHz)

Uplink: 890.2MHz to 915MHz

Downlink: 935.2MHz to 960MHz

Each channel has 0.2MHz, 124 channels for each direction

TDMA



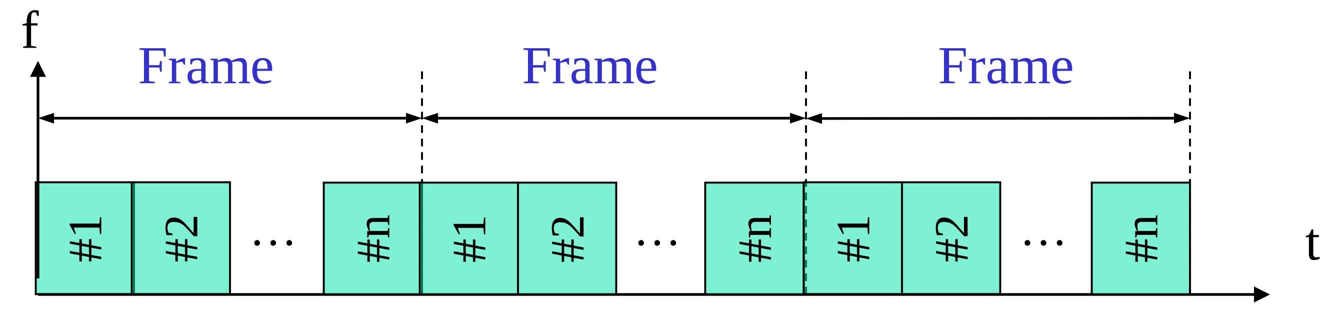
Reverse channels

(Uplink)

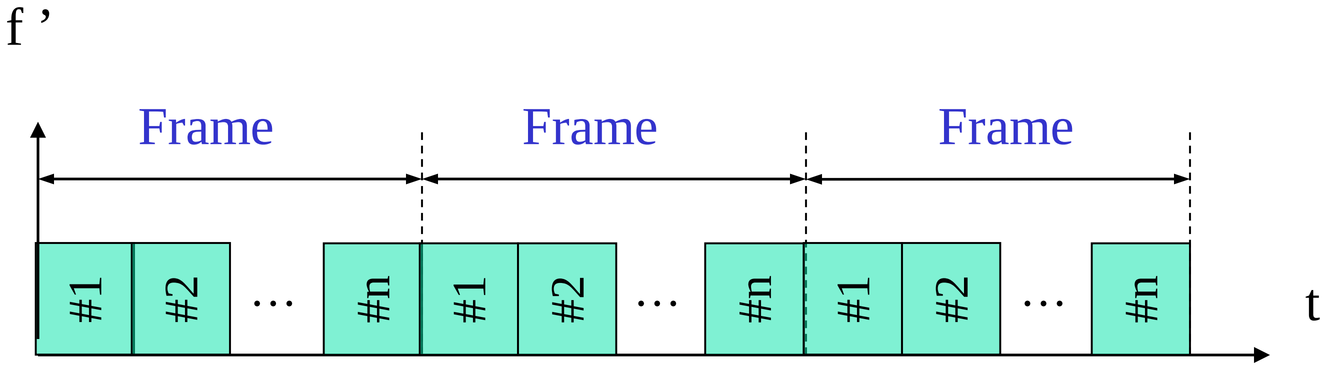
Forward channels

(Downlink)

TDMA: Channel Structure

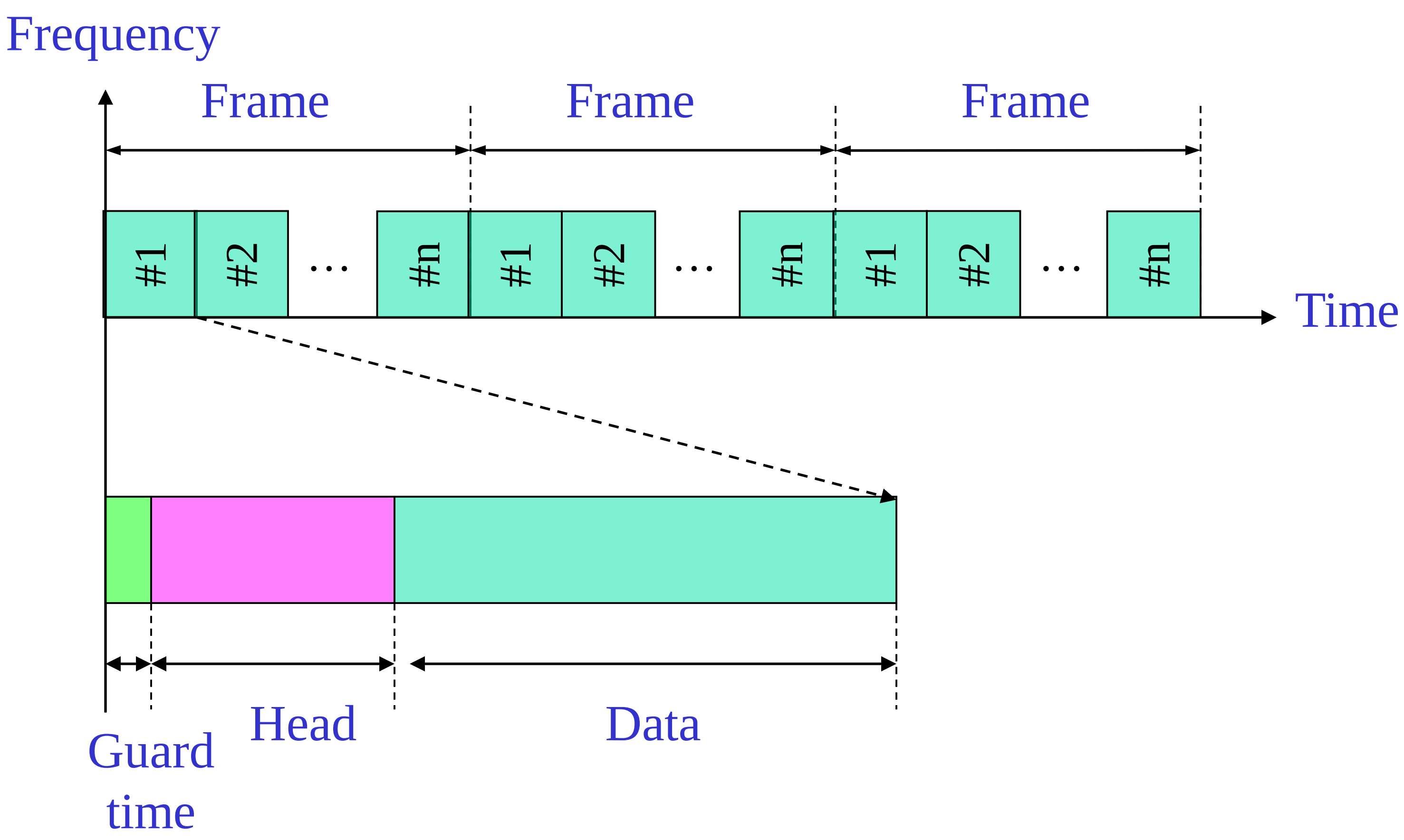


(a). Forward channel

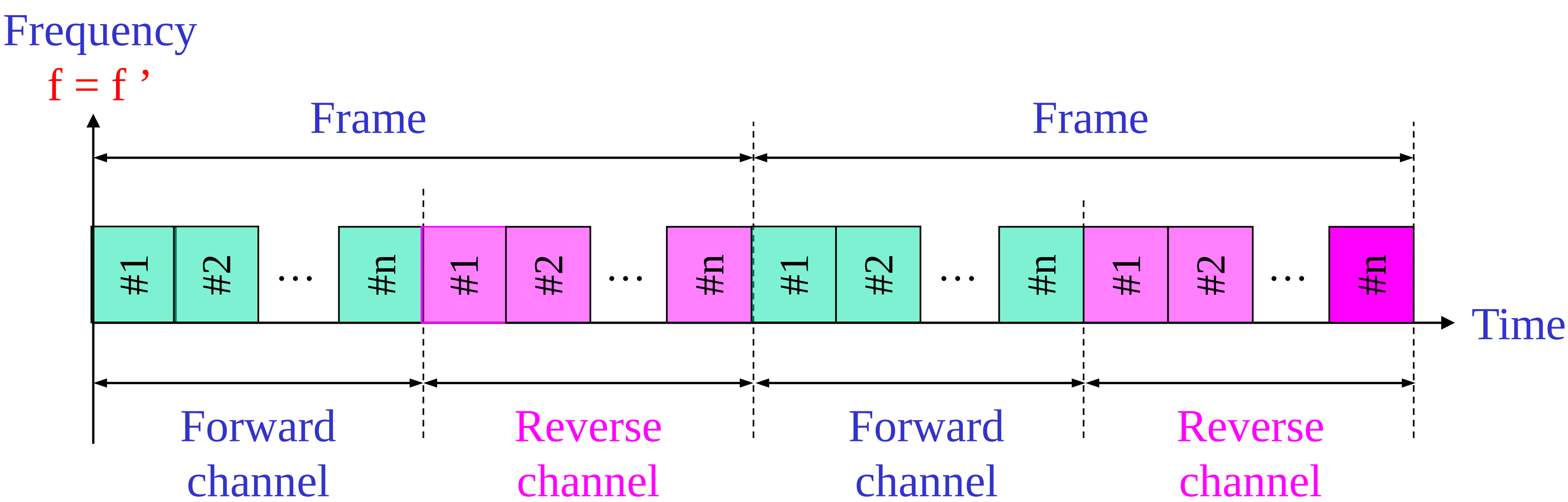


(b). Reverse channel

TDMA: Frame Structure

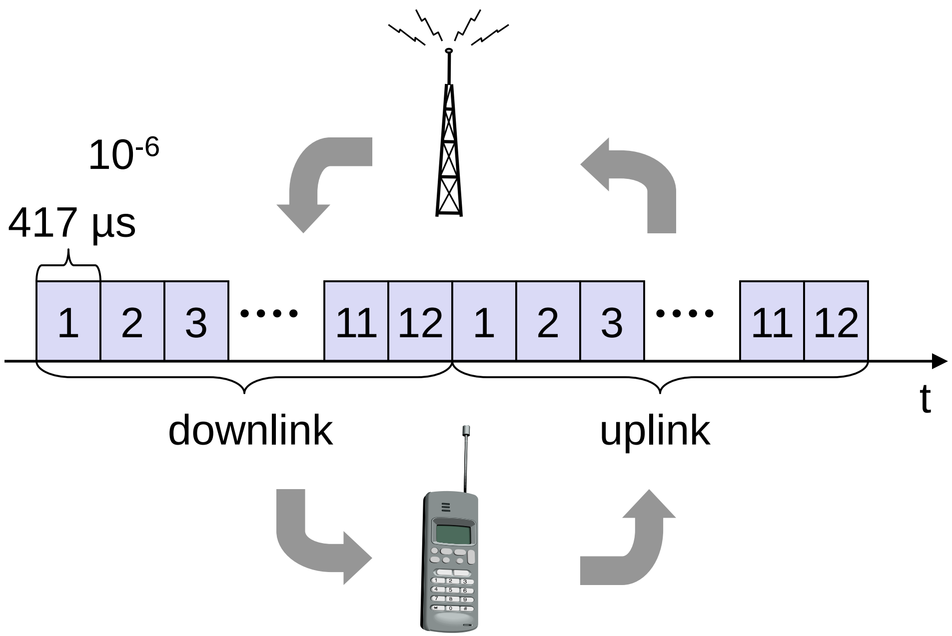


TDMA: Channels in Simplex Mode



Channels in Simplex Mode

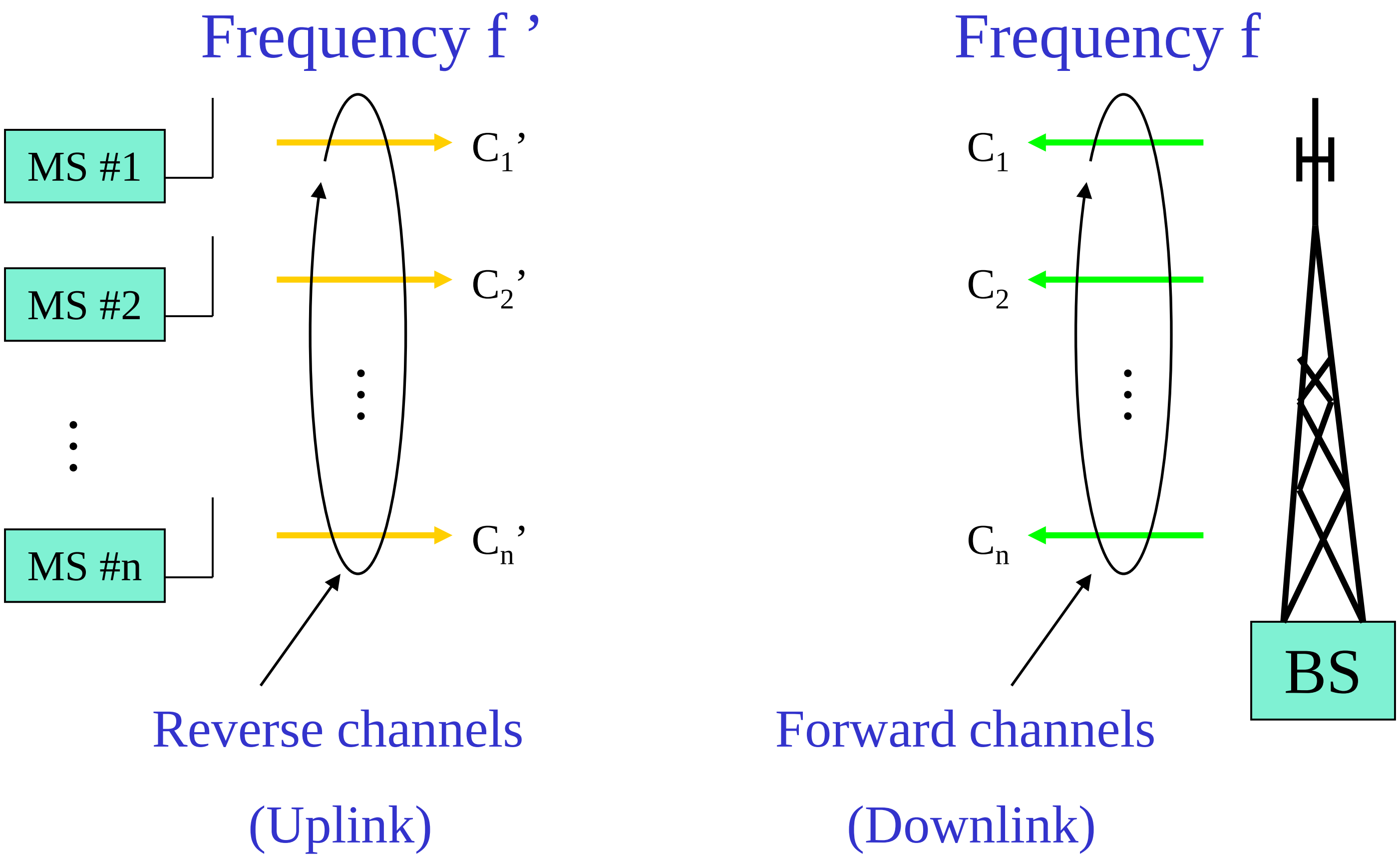
TDD/TDMA - General Scheme



417 x 12 = 5004

Fixed period of 5ms

Code Division Multiple Access (CDMA)



Note: codes in CDMA need to be orthogonal or having low correlation

CDMA Principles

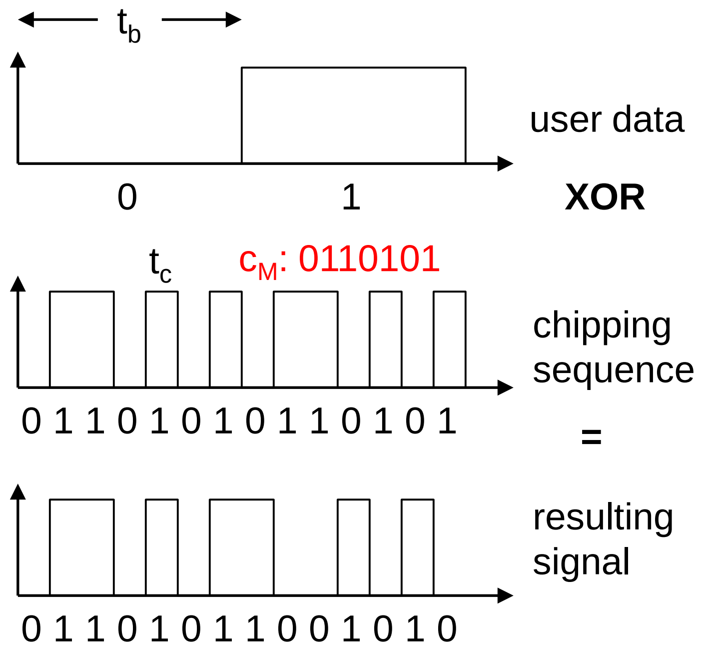
- All terminals send on the same frequency and at the same time
  - can use the whole bandwidth of the transmission channel
- Each sender uses a unique random number (code)
  - sender XORs the signal with this code
  - the codes separate the signals from different senders
- The receiver “tunes” into the signal stream coded by the targeted sender’s code
  - tuning is done via a correlation function
  - receiver uses the code to identify the signals targeted to it and decodes the signals
  - multiple receivers can receive their own data simultaneously as they use different codes

CDMA Encoding

- Each user is assigned a unique signature bit-sequence (CDMA code), denoted by $C_M = (c_1, c_2, \ldots, c_m)$. Each bit in C_M is called a chip
- Each data bit, d_i, is encoded by XOR it with code C_M:

  $Z_{i,M} = d_i \text{ XOR } C_M = (z_{i1}, z_{i2}, \ldots, z_{im})$

  $Z_{i,M}$ is the resulting bit-sequence of original bit d_i
- One data bit is now sent as a sequence of m bits, leading to higher bandwidth consumption



t_b: bit period t_c: chip period

$t_c = t_b/m$

The receiver can recover the original data bits by XOR the received bit sequence with the code

Example: Encoding of CDMA

Data bit representation

$0: +1;\ 1: -1$ // '+1' represents '0', '−1' for '1'

$d_i = -1$ // suppose original data bit $d_i = 1$

Signature sequence (suppose)

$C_M = (c_1, c_2, \ldots, c_8) = (+1, +1, +1, -1, +1, -1, -1, -1)$

$Z_{i,M} = d_i\, C_M = (-1) \times (+1), (-1) \times (+1), \ldots, (-1) \times (-1)$

Encoder Output

$(Z_{i,1}, Z_{i,2}, \ldots, Z_{i,8}) = (-1, -1, -1, +1, -1, +1, +1, +1)$

transmitting sequence in binary = (1, 1, 1, 0, 1, 0, 0, 0)

Decoding of CDMA Signals

- When no interference, d_i can be recovered at receiver by:

$$d_i = \frac{1}{m}\sum_{j=1}^{m} z_{i,j} c_j$$

decode $Z_{i,M}$ by C_M to recover d_i in the example!

- With N interfering users, the signal at the receiver becomes:

$$z^*_{i,j} = \sum_{n=1}^{N} z^n_{i,j}$$

each received bit $z^*_{i,j}$ is overlapping of signals from N users

- How can a CDMA receiver recover the original data bit?
  - Recovery of noisy signals requires orthogonal codes

Orthogonal Codes in CDMA

- In order for the receiver to be able to extract out a particular sender's signal, the CDMA codes must be of low correlation
- Correlation of two codes, ($c_{i,1}$,…, $c_{i,m}$) and ($c_{j,1}$,…, $c_{j,m}$), are defined by:

$$\text{correlation}(C_i, C_j) = \frac{1}{m}\sum_{k=1}^{m} c_{i,k}c_{j,k}$$

e.g., C_1 = {1, 1, 1, -1, 1, -1, -1, -1}, C_2 = {1, -1, 1, 1, 1, -1, 1, 1}

correlation(C_1, C_2) = 0

- Correlation value of two codes is in range (–1, 1)
  - When correlation is 0, the two codes are orthogonal
  - When it is 1 or –1, two codes match each other exactly
  - The lower correlation value, the better CDMA codes

Code Division Multiple Access

- Advantages:
  - All terminals can use the same frequency, no planning needed
  - Huge code space (e.g. 2^{32}) compared to frequency space
    - But orthogonal codes are not too many
  - Interferences is not coded

- Disadvantages:
  - Higher complexity of coding/decoding
  - Receiver has to listen to the medium all the time and start receiving if there is any signal for it

Comparisons of FDMA, TDMA, and CDMA

Operation	FDMA	TDMA	CDMA
Allocated Bandwidth	12.5 MHz	12.5 MHz	12.5 MHz
Frequency reuse	7*	7*	1
Required channel BW	0.3 MHz	0.3 MHz	1.25 MHz
No. of RF channels	12.5/0.3=416	12.5/0.3=416	12.5/1.25=10
Channels/cell	416/7* =59	416/7* =59	12.5/1.25=10
Control channels/cell	2	2	2
Usable channels/cell	57	57	8
Calls per RF channel	1	4**	40***
Voice channels/cell	57x1=57	57x4=228	8x40=320
Capacity vs FDMA	1	4	5.6

* Frequency reused every 7 cells

** Depends on the number of slots

*** Depends on the number of codes

Summary

- Wireless signal and interference
- Digital Modulation
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
- Multiplexing Techniques
  - Frequency-division multiplexing (FDMA)
  - Time-division multiplexing (TDMA)
  - Code-division multiplexing (CDMA)
    - Correction of two CDMA codes

Exercise & Discussion

- What limits the number of simultaneous users in a TDMA, FDMA, and CDMA system?
- How does an admission of a new user into the system affect the other existing users in TDMA, FDMA, and CDMA?