Lecture 18: Wireless Networks

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Wireless Communications

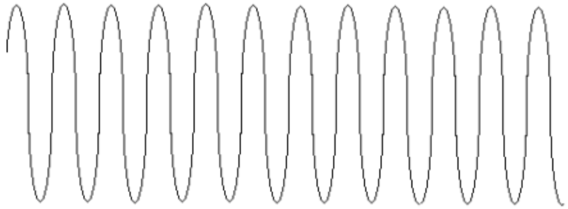
- A Brief History
  - In 1857, **James Maxwell** showed mathematically that electromagnetic waves could propagate through free space.
  - In 1888, **Heinrich Hertz** demonstrated the existence of electromagnetic waves.
    - "I do not think that the wireless waves I have discovered will have any practical application" ----- Hertz
  - In 1909, **Guglielmo Marconi** and **Karl Braun** were awarded the Nobel Prize for Physics for their contribution to wireless telegraphy.
  - 1982 Start of GSM in Europe (1G analog)

Radio Wave

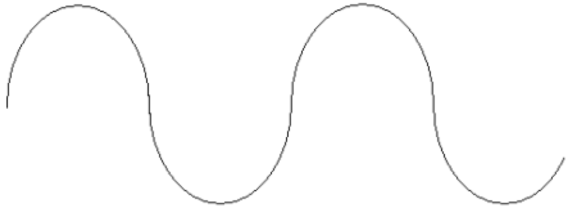
- A type of electromagnetic radiation with wave lengths
- Radio waves have frequencies from 300 GHz to as low as 3 kHz
- Human hearing range
  - 20Hz ~ 20kHz
- Can we hear radio wave?
  - No

Radio Wave: Some properties

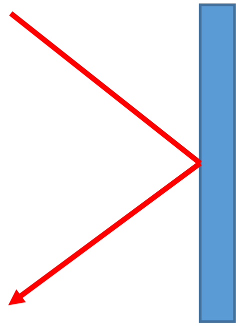
- Radio speed = wave length * frequency = 3*10^8
- Converted to/from electric power by using antenna
    - Antenna length is usually a multiple of a quarter-wavelength, λ/4
- Higher frequency
    - Shorter wave length
    - Shorter antenna
    - Deteriorate more significantly over long distances



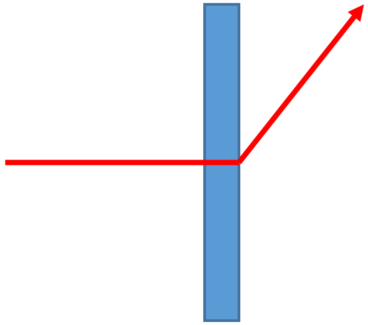
- Lower frequency
    - Longer wave length
    - Longer antenna



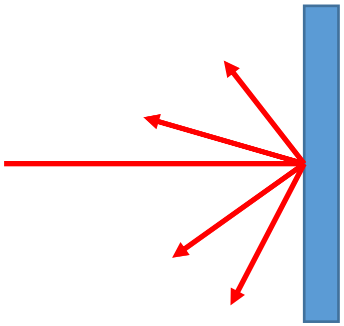
Radio Wave: Behaviours



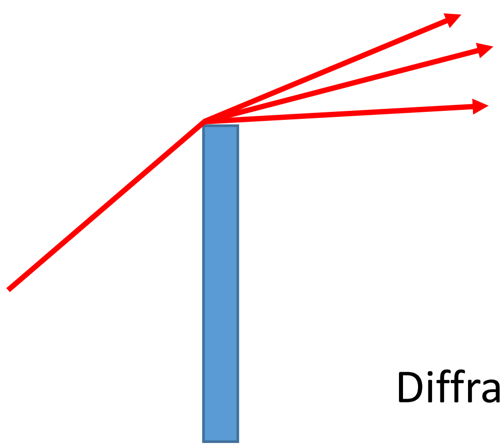
Reflection



Refraction

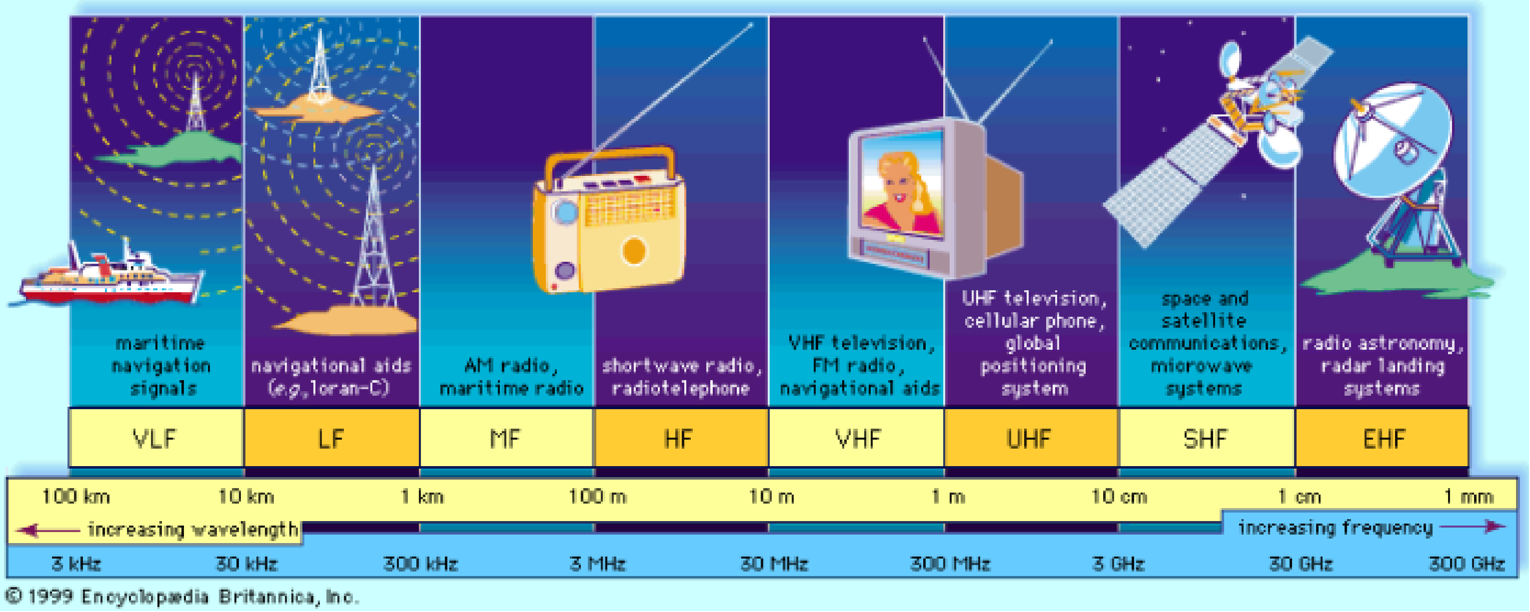


Scattering



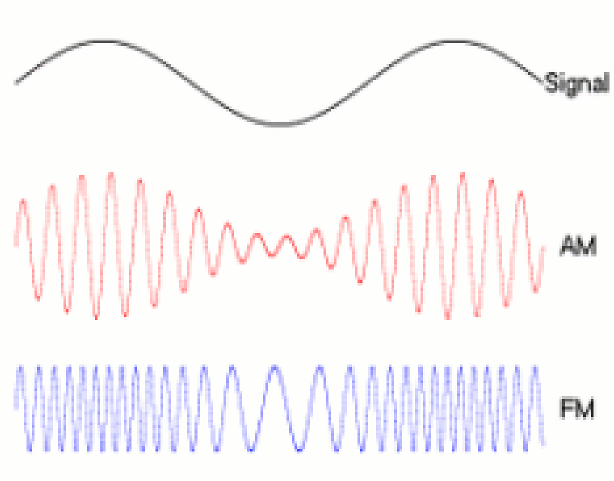
Diffraction

Use of Radio Wave Frequency



Radio Wave Modulation

- Transmit information via radio wave
  - Convert the information into electronic signal
  - Add the electronic signal into radio signal
- This process is called modulation - varying one or more properties of a radio wave



This is analogue signal.
The other kind is called digital signal.

Amplitude Modulation

Frequency Modulation

https://www.diffen.com/difference/AM_vs_FM

Wireless NW: Classification

- According to different network sizes
  - WWAN – Wireless Wide Area Networks
    - 2G/3G/4G/5G cellular networks
  - WLAN – Wireless Local Area Networks
    - WiFi (wireless fidelity), LiFi (Light fidelity)
  - WPAN – Wireless Personal Area Networks
    - Bluetooth
  - …

Covered in the next lecture in detail

Wireless in 5-layer Model

- 5-Layer Network (not OSI 7 layer)
  - Application
  - Transport
  - Network
  - Data link
  - Physical layer: Wireless/Wired

- Wireless network is in the context of the physical layer.

Terms of Wireless Networking

- Different medium access schemes
- Circuit-level solutions
  - Frequency division multiple access (FDMA)
  - Time division multiple access (TDMA)
  - Space division multiple access (SDMA)
  - Code division multiple access (CDMA)

Physical Layer

- Package level solutions
  - Carrier Sense Multiple Access (CSMA)

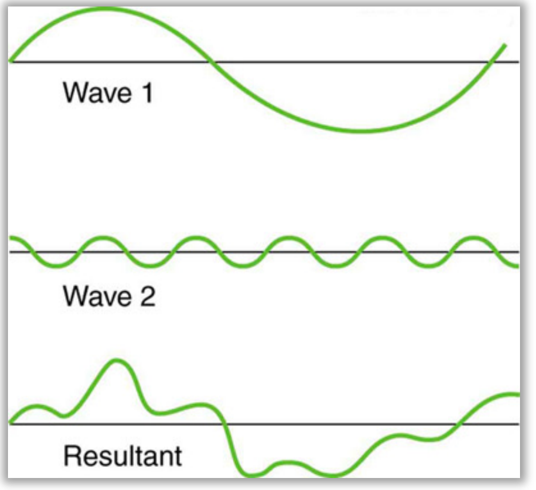
Data Link Layer

Physical Layer (Wireless)

Circuit-level solutions: FDMA, TDMA, SDMA, CDMA

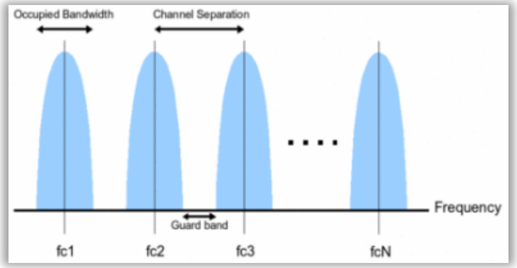
Wireless Medium: Interference

- Two transmitter may interfere with each other at the receiver
  - Constructive interference
  - Destructive interference
  - Receiver will “hear” the sum of the two signals (which usually means garbage)



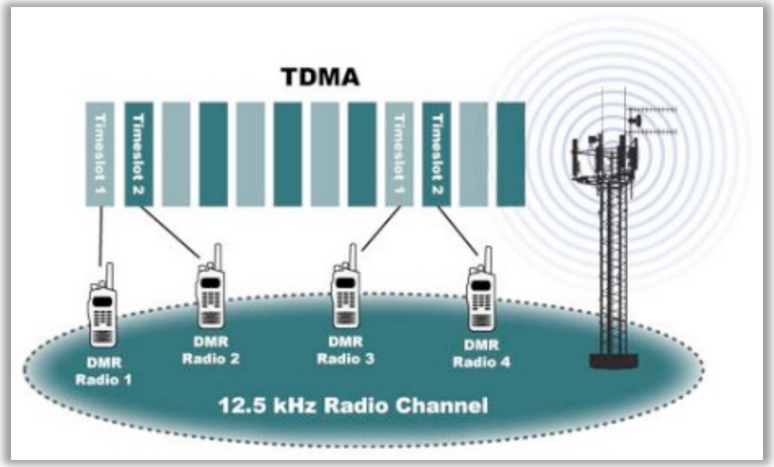
FDMA

- Each network user has its own frequency band, separated by guard bands
  - Guard bands lead to a waste of capacity.
  - Receivers tune to the right frequency.
  - Number of frequencies is limited.
  - The maximum flow rate per channel is fixed and small
- Supports both analogue data and digital data transmission.



TDMA

- All network users transmit data on same frequency, but at different times.
  - Needs time synchronisation
  - Users can be given different amounts of bandwidth
- Supports digital data only.



SDMA

- Two pairs of users can use the same frequency without interfering each other when they are located far away
  - A strong signal will mask a small area
  - Directional (smart) antenna are used commonly used in SDMA to control the radio broadcast space

CDMA

- Use the same frequency and transmit at the same time, but with different coding methods
- Mathematical background
  - The **Dot Product** (or Inner Product) of two vectors $a = [a_1, a_2, \dots, a_n]$ and $b = [b_1, b_2, \dots, b_n]$ is defined as:

$$a \cdot b = \sum_{i=1}^{n} a_i b_i = a_1 b_1 + a_2 b_2 + \cdots + a_n b_n$$

  - Two vectors must have the same dimension
  - Two vectors are orthogonal if their dot product is zero

CDMA

- More on mathematical background:
  - The Kronecker product: If A is an m × n matrix and B is a p × q matrix, then the Kronecker product:

$$A \otimes B = \begin{bmatrix} a_{11}B & \cdots & a_{1n}B \\ \vdots & \ddots & \vdots \\ a_{m1}B & \cdots & a_{mn}B \end{bmatrix}$$

  - E.g. A = (1, -1, 1, 1), B= (1, -1), A $\otimes$ B = ((1, -1), (-1, 1), (1, -1), (1, -1)) = (1, –1, –1, 1, 1, –1, 1, –1)

Example 2: Let $A=\begin{pmatrix}0 & -2\\ 3 & -1\end{pmatrix}$ and $B=\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix}$. Then,

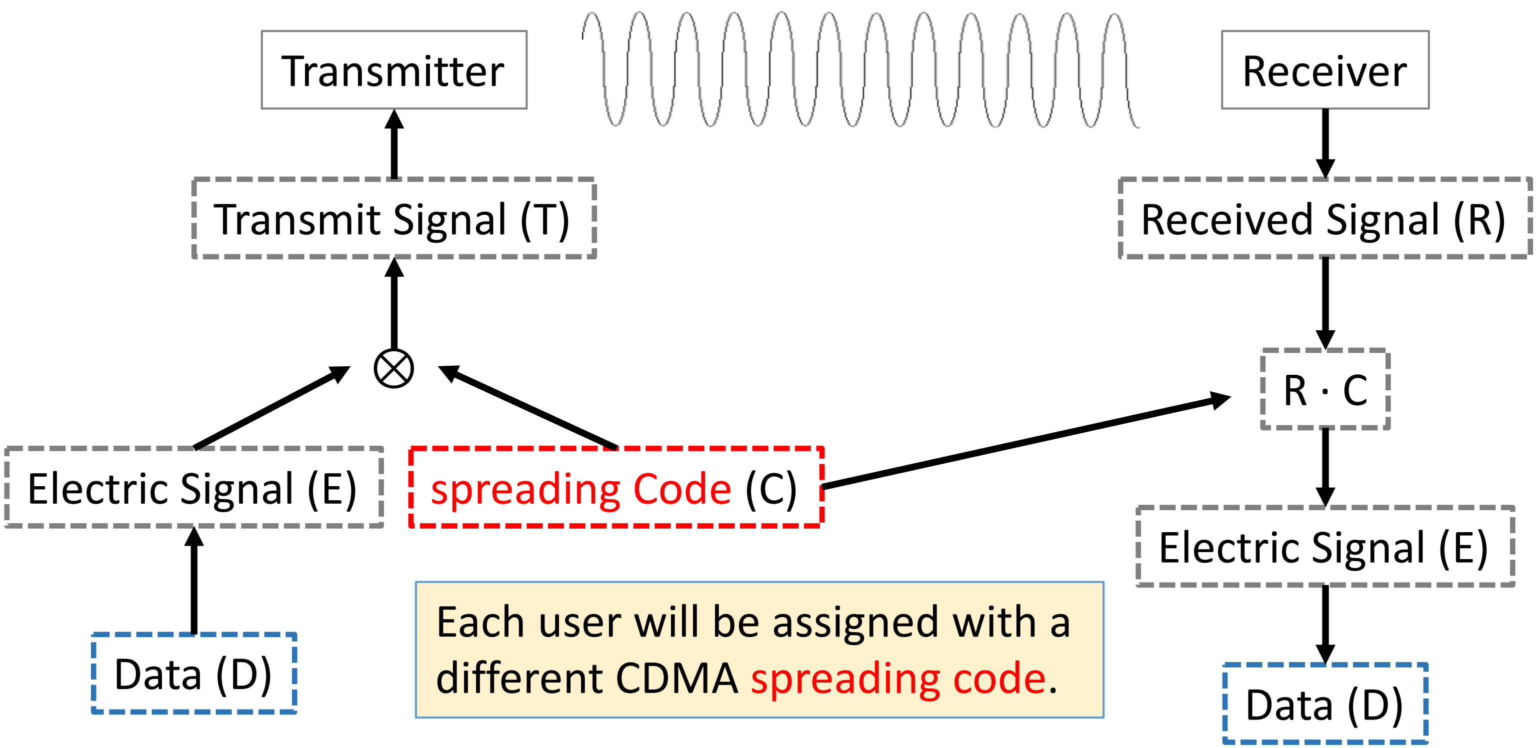
$$A\otimes B=\begin{pmatrix}0 & -2\\ 3 & -1\end{pmatrix}\otimes\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix}=\begin{pmatrix}0\cdot\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix} & -2\cdot\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix}\\ 3\cdot\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix} & -1\cdot\begin{pmatrix}2 & 1 & 5 & 0\\ -4 & -2 & 6 & 3\\ -3 & 2 & -1 & 4\end{pmatrix}\end{pmatrix}$$

$$=\begin{pmatrix}\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{pmatrix} & \begin{pmatrix}-4 & -2 & -10 & 0\\ 8 & 4 & -12 & -6\\ 6 & -4 & 2 & -8\end{pmatrix}\\ \begin{pmatrix}6 & 3 & 15 & 0\\ -12 & -6 & 18 & 9\\ -9 & 6 & -3 & 12\end{pmatrix} & \begin{pmatrix}-2 & -1 & -5 & 0\\ 4 & 2 & -6 & -3\\ 3 & -2 & 1 & -4\end{pmatrix}\end{pmatrix}=\begin{pmatrix}0 & 0 & 0 & 0 & -4 & -2 & -10 & 0\\ 0 & 0 & 0 & 0 & 8 & 4 & -12 & -6\\ 0 & 0 & 0 & 0 & 6 & -4 & 2 & -8\\ 6 & 3 & 15 & 0 & -2 & -1 & -5 & 0\\ -12 & -6 & 18 & 9 & 4 & 2 & -6 & -3\\ -9 & 6 & -3 & 12 & 3 & -2 & 1 & -4\end{pmatrix}.$$

https://digitalcommons.unf.edu/cgi/viewcontent.cgi?article=1025&context=etd

CDMA

- CDMA Coding makes use of the dot product and Kronecker product



CDMA: Example

- Given two senders that wants to communicate with the same base station.

- The base station will first generate two **orthogonal** spreading codes for these two senders.
  - Vectors are orthogonal if the inner product of the vectors is zero.
  - [1, 1] and [1, -1]

- After receiving the spreading codes, the communication may start.

CDMA: Example

- Assume that
  - A want to send bits {1, 0, 1, 1}, spreading code [1, 1].
  - B want to send bits {0, 0, 1, 1}, spreading code [1, -1].
- Firstly, convert them to signal:
  - {1, 0, 1, 1} -> {1, -1, 1, 1}
  - {0, 0, 1, 1} -> {-1, -1, 1, 1}

CDMA: Example

- Then encode every bit with the spreading code
  - signal A $\otimes$ code A = {[1, 1], [-1, -1], [1, 1], [1, 1]}
  - signal B $\otimes$ code B = {[-1, 1] , [-1, 1] , [1, -1] , [1, -1]}

- If these two signals are transmitted at the same time, overlapping happens

{[1, 1], [-1, -1], [1, 1], [1, 1]} + {[-1, 1] , [-1, 1] , [1, -1] , [1, -1]}

= (0, 2, -2, 0, 2, 0, 2, 0)

CDMA: Example

- Given the signal string {0, 2, -2, 0, 2, 0, 2, 0}
- To get the original signal of A:

Spreading code

$$[[0, 2], \quad [-2, 0], \quad [2, 0], \quad [2, 0]] \cdot [1, 1]$$
$$= [[0, -2]\cdot[1, 1], [-2, 0]\cdot[1, 1], [2, 0]\cdot[1, 1], [2, 0]\cdot[1, 1]]$$
$$= \{2, -2, 2, 2\}$$

- Any signal value above 1 will be recognized as 1, so the result would be (1, -1, 1, 1)

- Can you do the same to get the signal of B?
  - Spreading code of B is [1, -1]

CDMA: Example

Decoding*	Decoded A = string · code A = (0, -2, -2, 0, 2, 0, 2, 0) · (1, -1) = ((0 + 2), (-2 + 0), (2 + 0), (2 + 0)) = (2, -2, 2, 2)	Decoded B = string · code B = (0, -2, -2, 0, 2, 0, 2, 0) · (1, 1) = ((0 - 2), (-2 + 0), (2 + 0), (2 + 0)) = (-2, -2, 2, 2)

- All recovered!
- This means the original data of the two senders can be recovered from one single signal string

- Remember: data can be recovered as long as the spreading codes are **orthogonal**

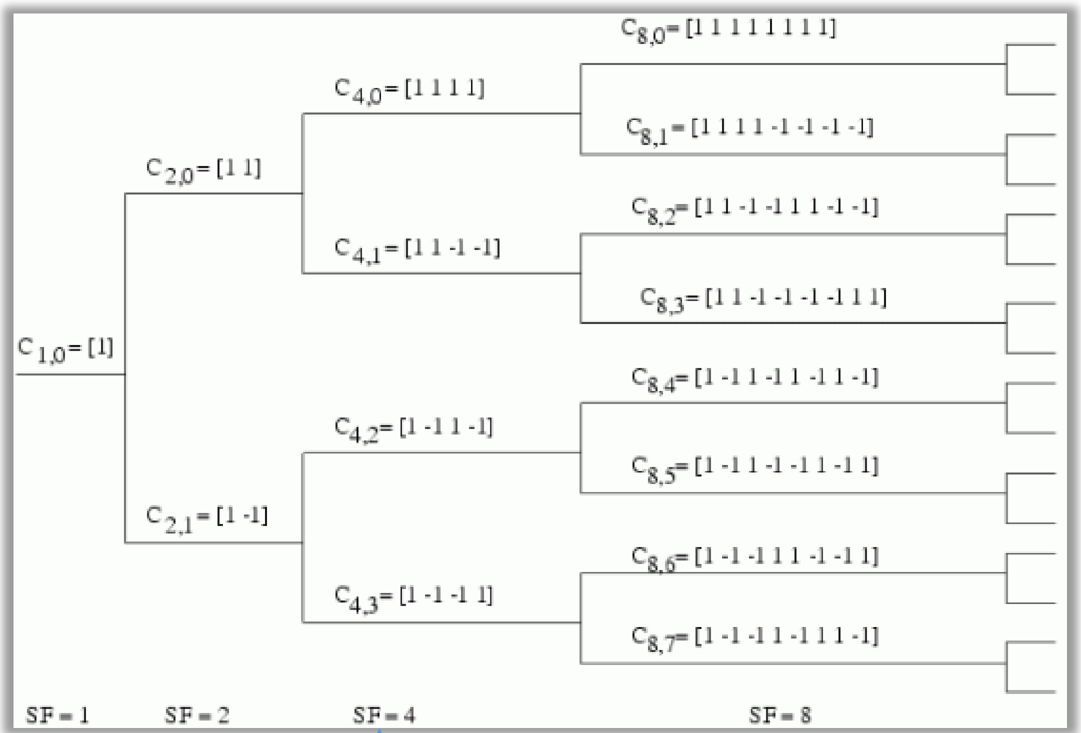
CDMA

- Spreading codes
  - Spreading means increasing the signal bandwidth
  - Spreading codes are orthogonal, based on the orthogonal variable spreading factor (OVSF) technique
  - Limited orthogonal codes must be re-used in every cell (base station)
  - Additional long (scrambling) codes needed for inter-cell interference

Hedy Lamarr, Austrian-American actress, pioneer in filming, inventor of spreading technology

CDMA

- Orthogonal variable spreading factor (OVSF) tree

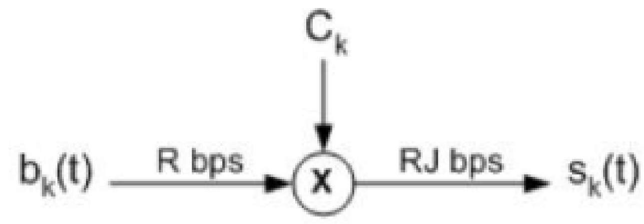


Supports 2 4 8 …users

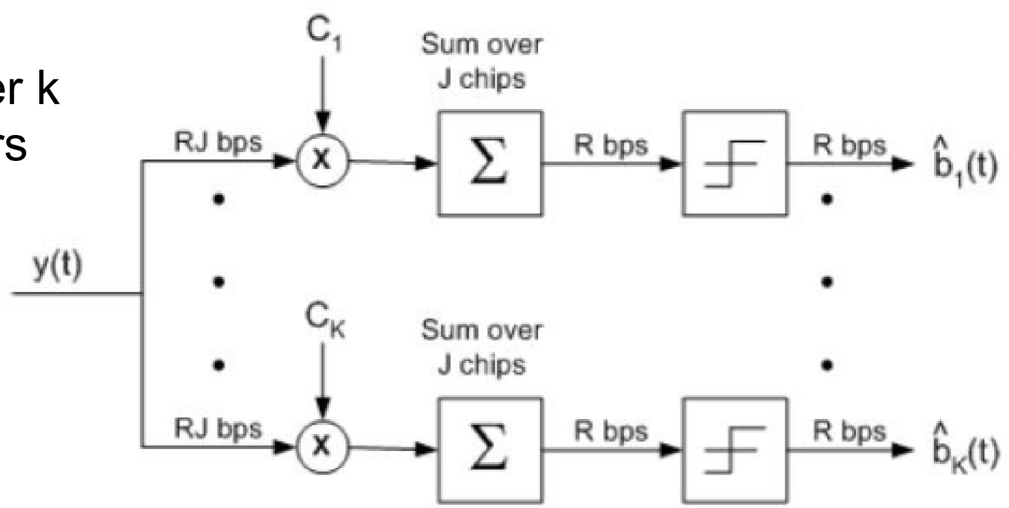
CDMA

- Transmitter & Receiver

bk(t): bits for user k
Ck: spreading code
J: "spreading factor"
sk(t): transmitted signal for user k
y(t): received signal for all users



The Basic CDMA Transmitter (User k)



The Basic CDMA Receiver (K Users)

Extended Reading

- https://www.tutorialspoint.com/cdma/index.htm

Data Link Layer (Wireless)

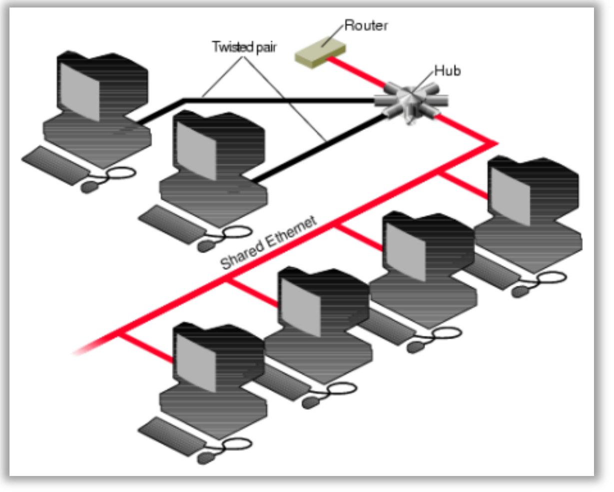
Package level solutions: CSMA

Carrier Sense Multiple Access

- Principle
  - Listen to medium and wait until it is free (no one else is talking)
  - If the medium is not free, wait for a random back off time then start talking
- Two categories
  - CSMA with collision detection (CSMA/CD)
  - CSMA with collision avoidance (CSMA/CA)

CSMA/CD

- Procedure
  - Listen to medium and wait until it is free
  - Then start talking, but listen to see if someone else starts talking too
  - If a collision occurs, stop and then start talking after a random back off time



- This scheme is used for hub-based Ethernet

Collision Detection

- Advantages
  - More efficient than basic CSMA
- Disadvantages
  - Requires ability to detect collisions
  - What if in wireless channels? – Hidden nodes
  - Transmit signal is usually much stronger than received signal, hence, it is difficult to “listen” while transmitting

CSMA/CA

- Procedure
  - Listen to medium and wait until it is free
  - When the medium is free, send a "request to send" (RTS)
  - Wait for a "clear to send" (CTS) from the receiver
  - Transmit actual data packet after receiving the CTS
  - Receive an acknowledgement (ACK) from the receiver

- This scheme is used for WLAN

Collision Avoidance

- Advantages
  - Small control frames lessen the cost of collisions (when data is large)
  - RTS + CTS provide “virtual” carrier sense which protects against hidden terminal collisions (where A can’t hear B)

- Potential Problem?
  - Mobility of the hidden node
  - Exposed node - some (but not all) stations can hear transmissions from stations not in the local area
- Possible solutions
  - Busy Tone Multiple Access (BTMA)
  - Token passing