Mobile Networking

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Contents

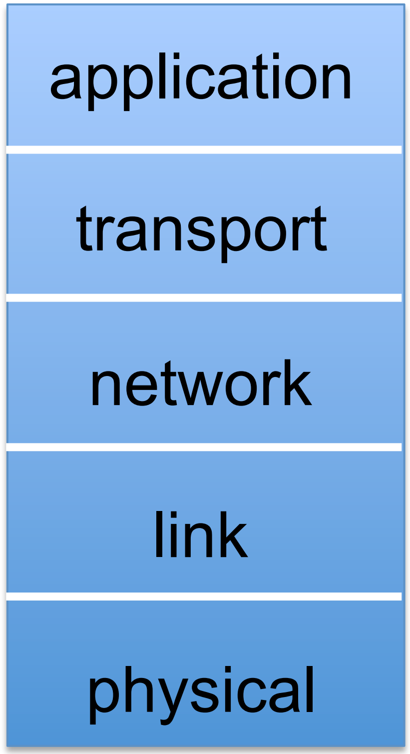
- Introduction to Medium Access Control
- Wireless MAC: Main Challenges
  - Hidden, Exposed, Near and Far Terminals
- MAC Protocol Taxonomy
  - SDMA, FDMA, CDMA, TDMA
- Frequency Division Multiple Access
  - Fixed and FHSS
- Code Division Multiple Access
  - CDMA vs DSSS

From Physical layer to MAC layer!

MEDIUM ACCESS CONTROL

Internet Protocol Stack

- *Application:* supporting network applications
  - FTP, SMTP, HTTP
- *Transport:* process-process data transfer
  - TCP, UDP
- *Network:* routing of datagrams from source to destination
  - IP, routing protocols
- *Link:* data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP
- *Physical:* bits "on the wire or wireless"



Link Layer: Context

- Datagram transferred by different link protocols over different links:
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- Each link protocol provides different services
  - e.g., may or may not provide rdt over link

Transportation analogy:

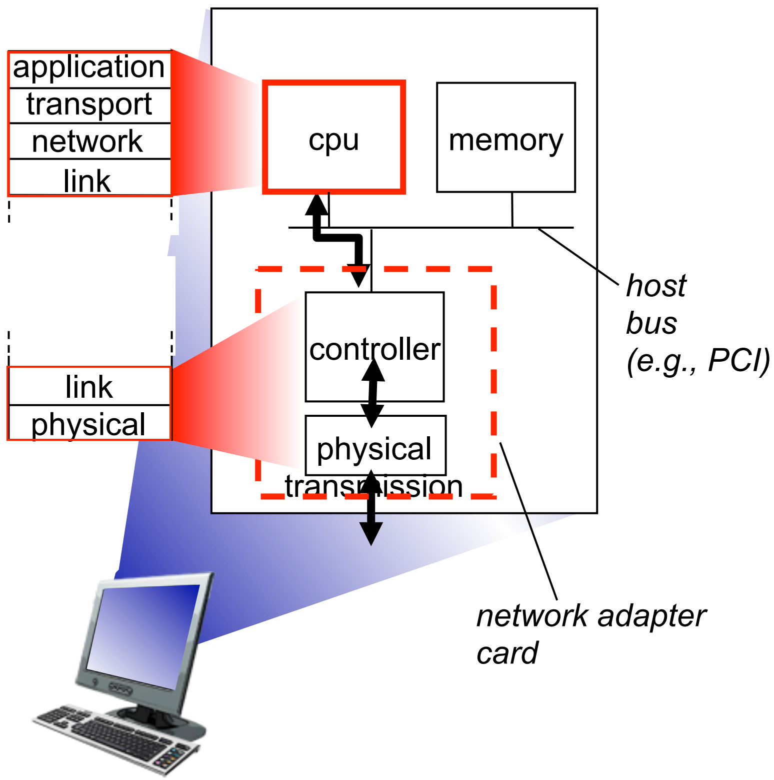
- trip from Princeton to Lausanne
  - limo: Princeton to JFK
  - plane: JFK to Geneva
  - train: Geneva to Lausanne
- tourist = datagram
- transport segment = communication link
- transportation mode = link layer protocol
- travel agent = routing algorithm

Link Layer Services

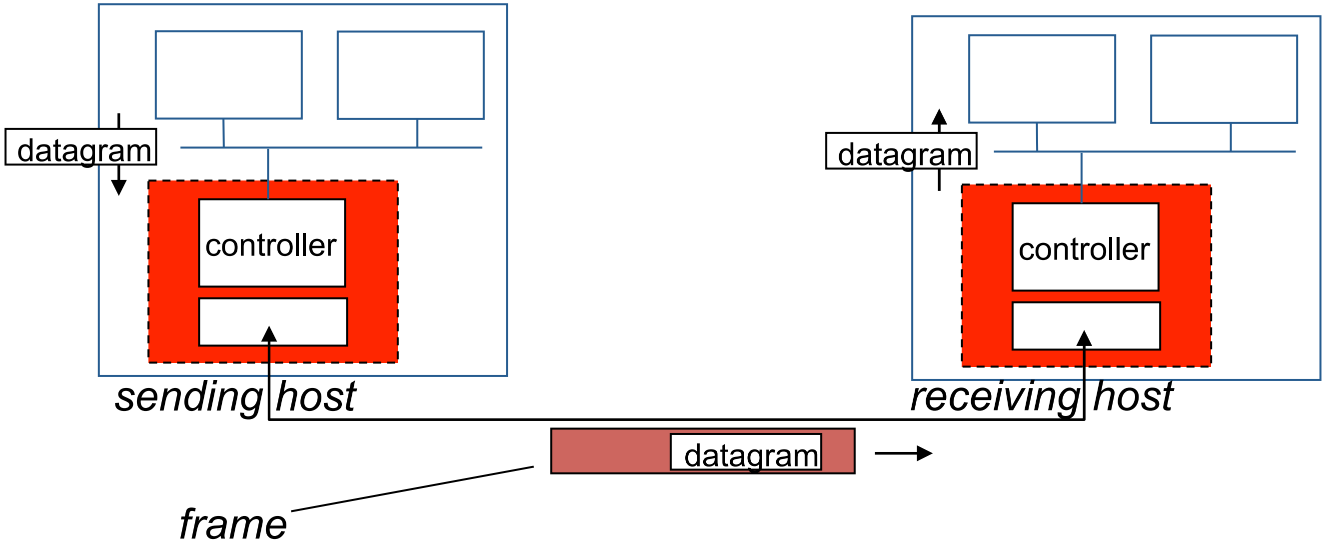
- *Flow control:*
  - pacing between adjacent sending and receiving nodes
- *Error detection:*
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame
- *Error correction:*
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission
- *Half-duplex and Full-duplex*
  - with half duplex, nodes at both ends of link can transmit, but not at same time

Where is the link layer implemented?

- In each and every host
- link layer implemented in "adaptor" (aka *network interface card* NIC) or on a chip
  - Ethernet card, 802.11 card; Ethernet chipset
  - implements link, physical layer
- Attaches into host's system buses
- Combination of hardware, software, firmware



Adaptors Communicating



- **sending side:**
  - encapsulates datagram in frame
  - adds error checking bits, rdt, flow control, etc.
- **receiving side**
  - looks for errors, rdt, flow control, etc
  - extracts datagram, passes to upper layer at receiving side

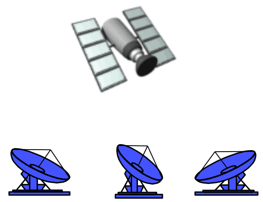
Multiple Access Links, Protocols

Two types of "links":

- point-to-point
  - PPP for dial-up access
  - point-to-point link between Ethernet switch, host
- *broadcast (shared wire or medium)*
  - Old-fashioned Ethernet
  - Upstream HFC
  - 802.11 wireless LAN

shared wire (e.g., cabled Ethernet)

shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

Multiple Access Protocols

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
  - *collision* if node receives two or more signals at the same time

Multiple Access Protocol

- Distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- Communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

An Ideal Multiple Access Protocol

Given: broadcast channel of rate R bps

Desiderata:

1. When one node wants to transmit, it can send at rate R.
2. When M nodes want to transmit, each can send at average rate R/M
3. Fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. Simple

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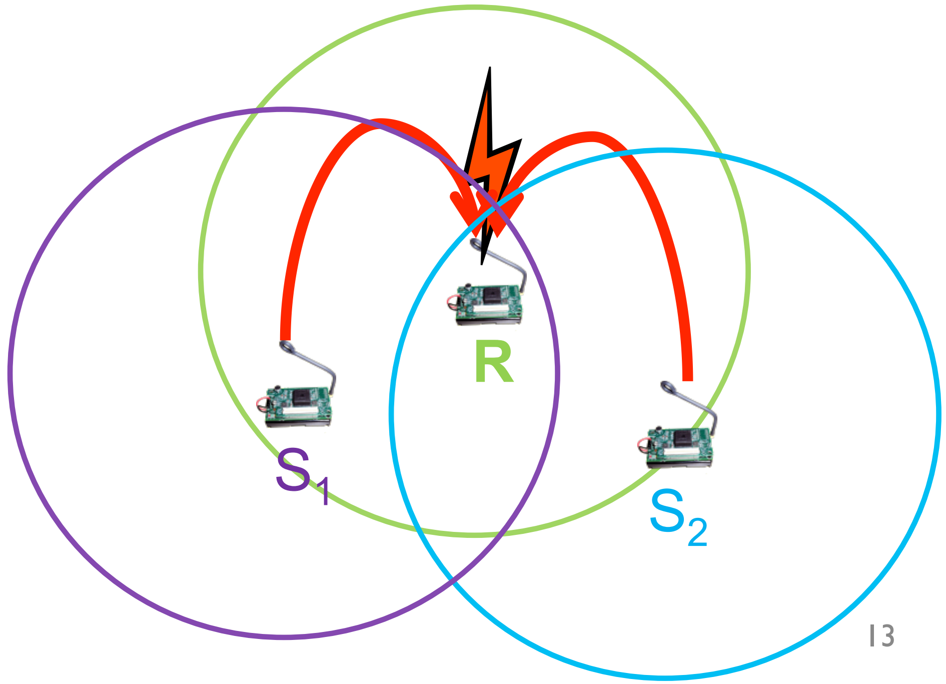
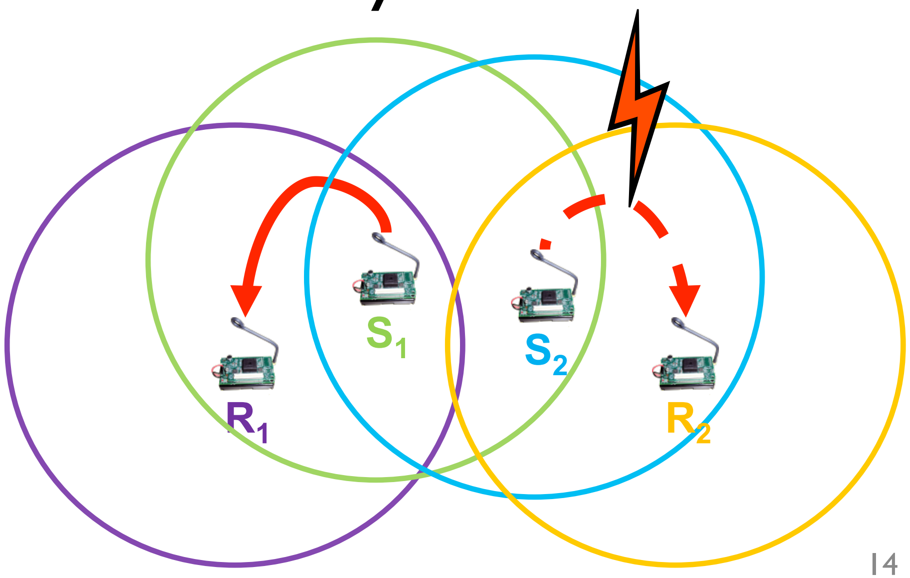
Hidden Terminals

- **Hidden terminals**
  - S_1 sends to R, S_2 cannot receive S_1
  - S_2 wants to send to R, S_2 senses a "free" medium (CS fails)
  - Collision at R, S_1 cannot receive the collision (CD fails)
  - S_1 is "hidden" for S_2



Exposed terminals

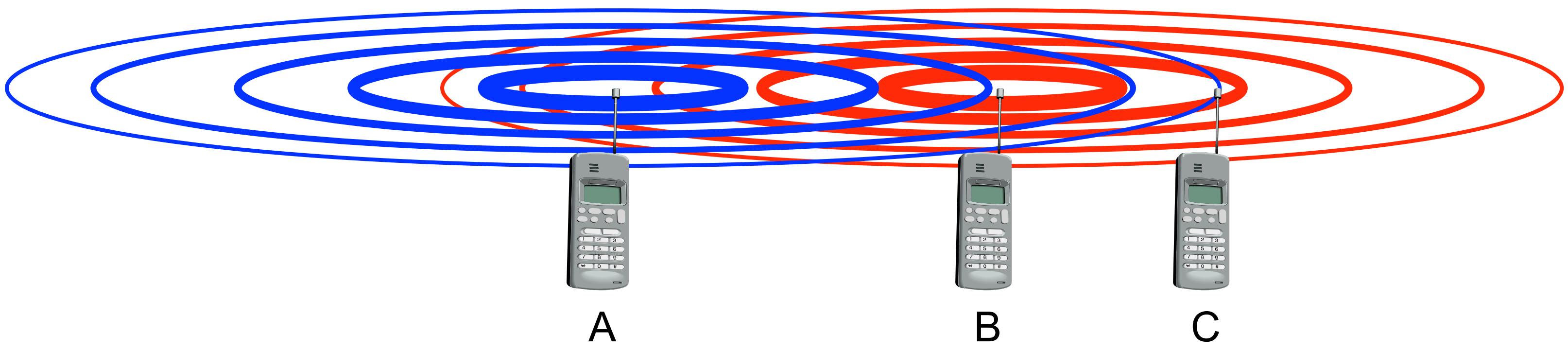
- **Exposed terminals**
  - S_1 sends to R_1, S_2 wants to send to another terminal (not S_1 or R_1)
  - S_2 has to wait, CS signals a medium in use
  - But R_1 is outside the radio range of R_2, therefore waiting is not necessary
  - S_2 is "exposed" to S_1



Near and Far terminals

- Terminals A and B send, C receives
  - Signal strength decreases (at least) proportionally to the square of the distance
  - The signal of terminal B therefore drowns out A's signal

  ➔ C cannot receive A



- Also severe problem for CDMA-networks - precise power control needed!

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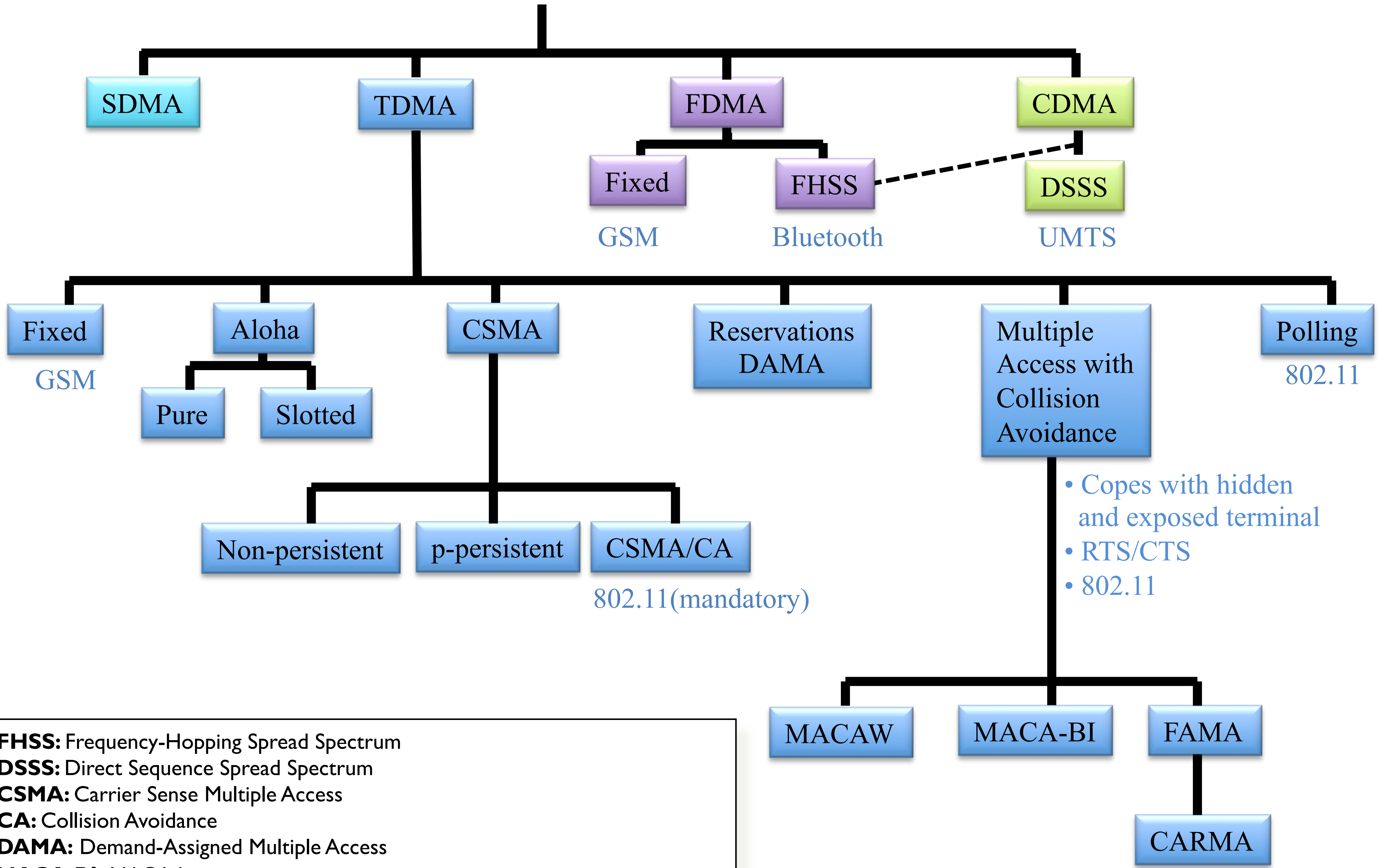
MAC Protocols: Taxonomy

three broad classes:

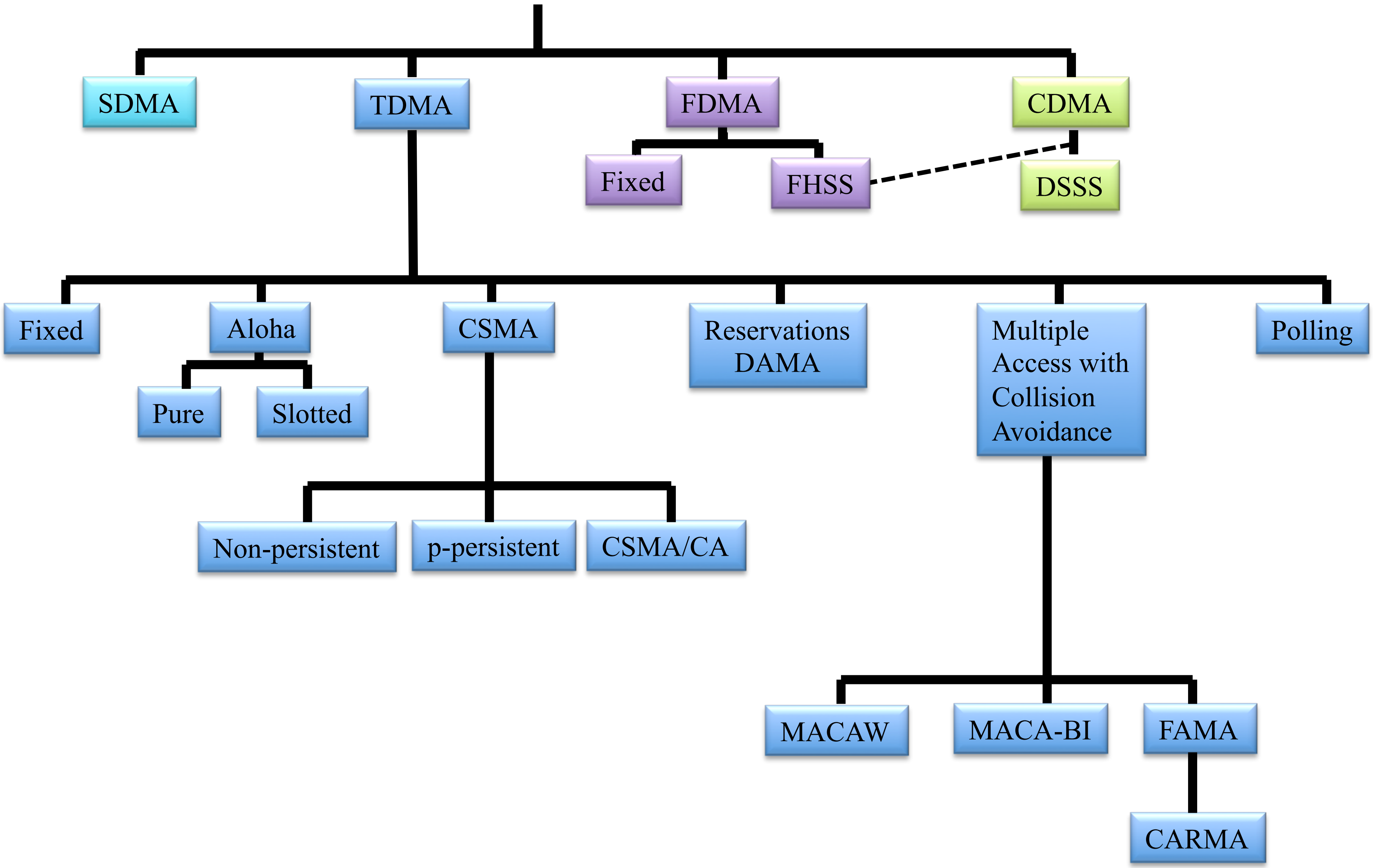
- *channel partitioning*
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use
- *random access*
  - channel not divided, allow collisions
  - "recover" from collisions
- *"taking turns"*
  - nodes take turns, but nodes with more to send can take longer turns

Medium Access Control Mechanisms for Wireless



FHSS: Frequency-Hopping Spread Spectrum
DSSS: Direct Sequence Spread Spectrum
CSMA: Carrier Sense Multiple Access
CA: Collision Avoidance
DAMA: Demand-Assigned Multiple Access
MACA-BI: MACA by invitation
FAMA: Floor Acquisition Multiple Access
CARMA: Collision Avoidance and Resolution Multiple Access

Medium Access Control Mechanisms for Wireless



Access Methods SDMA/TDMA/FDMA/CDMA

- **SDMA (Space Division Multiple Access)**
  - segment space into sectors, use directed antennas
  - cell structure
- **TDMA (Time Division Multiple Access)**
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time
- **FDMA (Frequency Division Multiple Access)**
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- **CDMA (Code Division Multiple Access)**
  - assign an appropriate code to each transmission channel (DSSS, Direct Sequence Spread Spectrum)
  - frequency hopping over separate channels (FHSS, Frequency Hopping Spread Spectrum)

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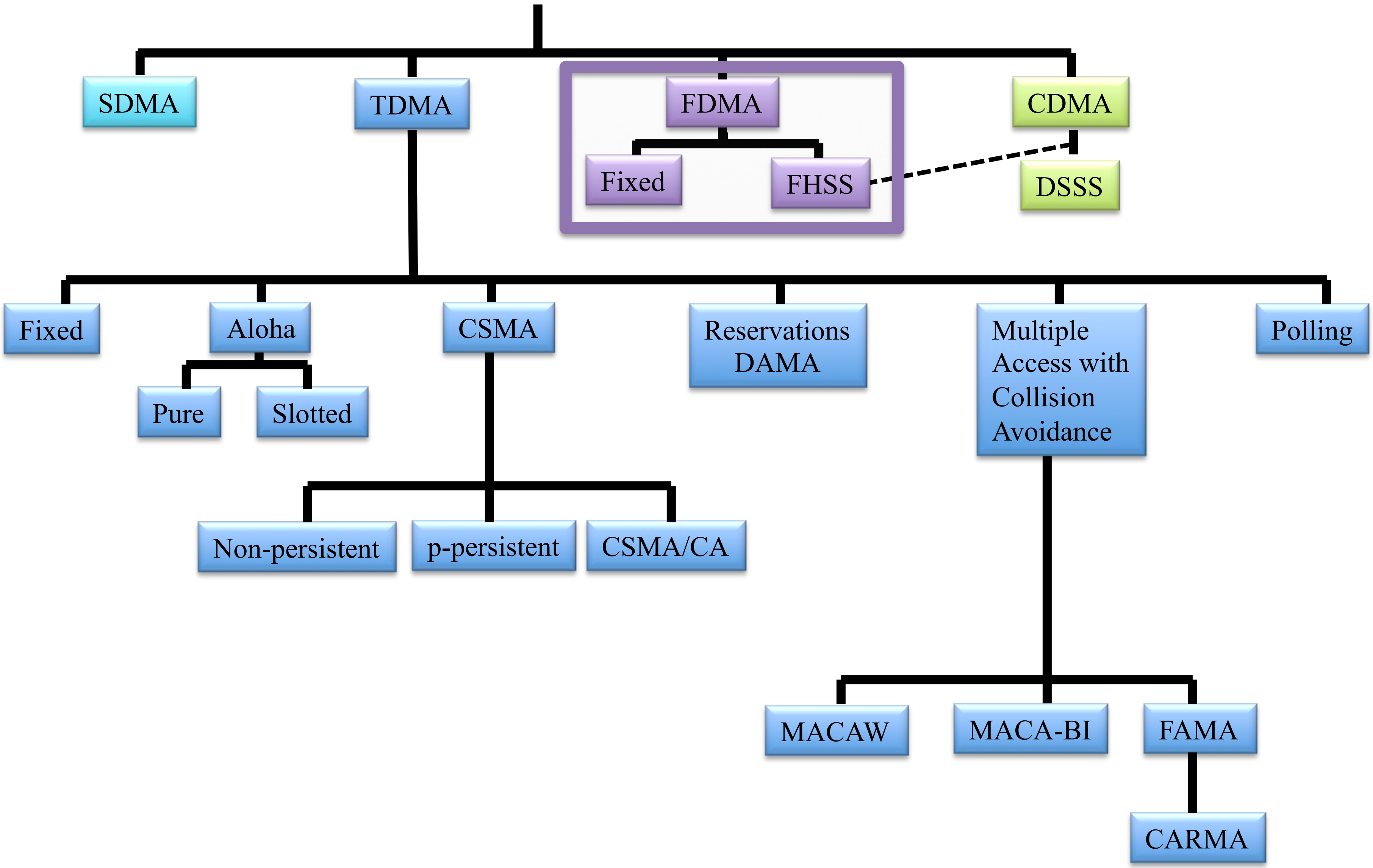
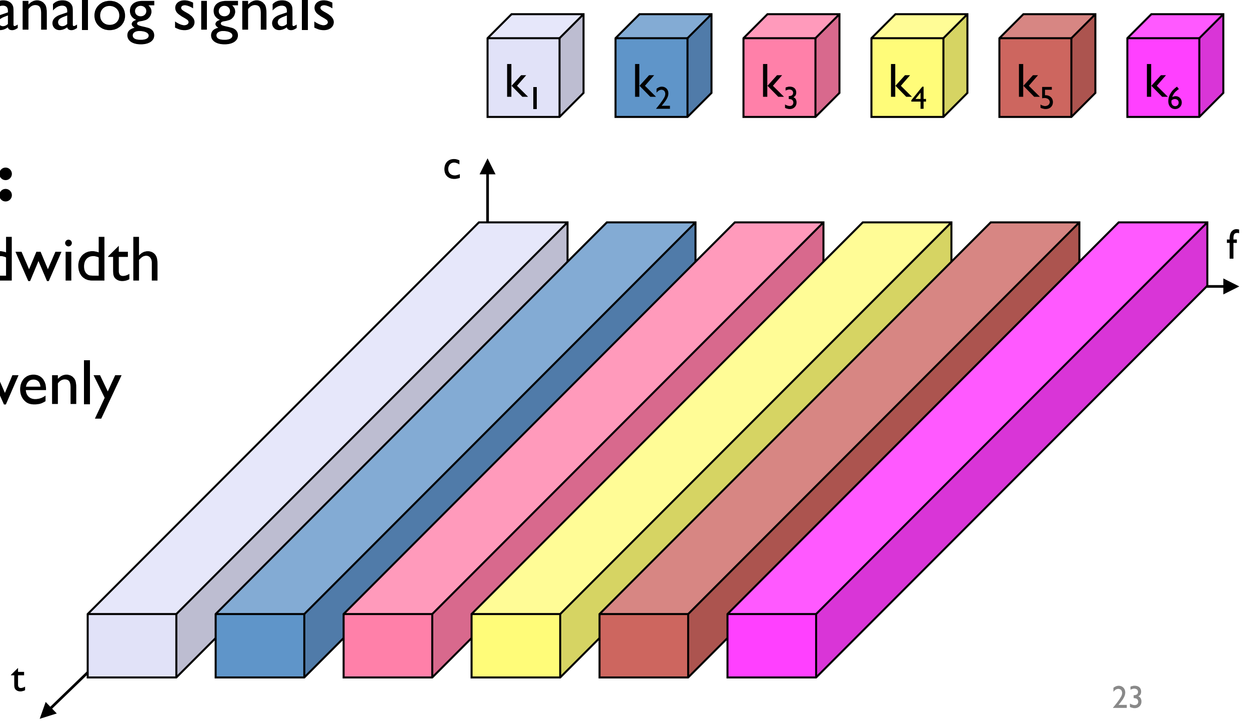
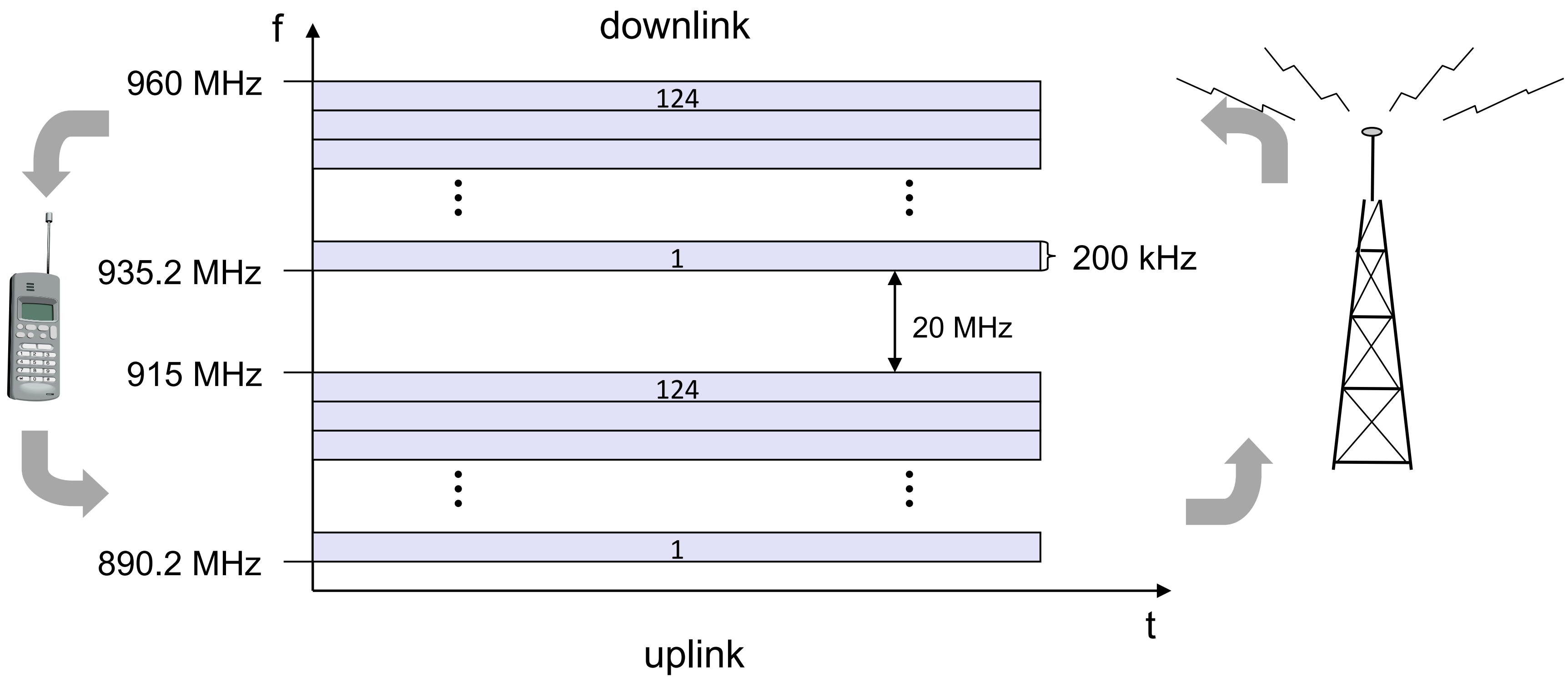


Frequency Multiplex

- Separation of the whole spectrum into smaller frequency bands.
- A channel gets a certain band of the spectrum for the whole time.
- **Advantages:**
  - works also for analog signals
- **Disadvantages:**
  - wastage of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces



FDMA/FDD – Example: GSM

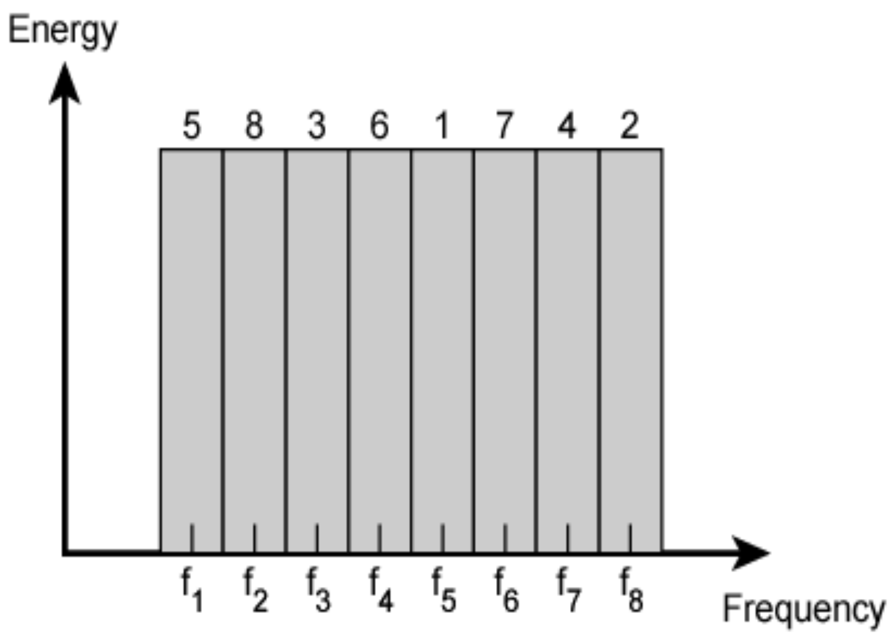


FDD: Frequency Division Duplex

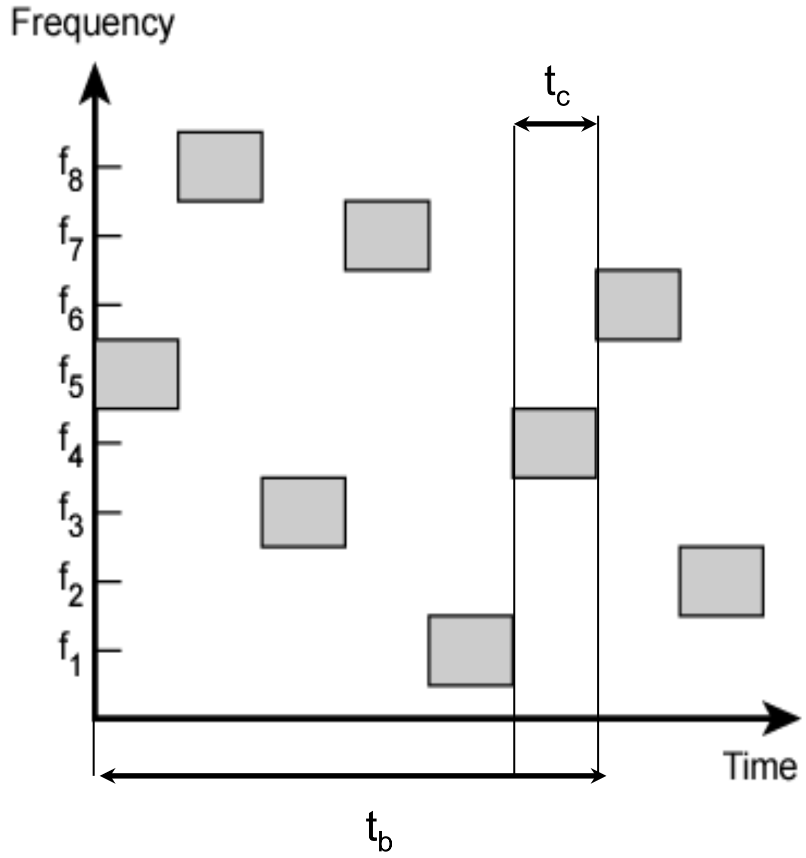
Frequency Hopping Spread Spectrum (FHSS)

- Signal broadcast over seemingly random series of frequencies
- Receiver hops between frequencies in sync with transmitter
- Eavesdroppers hear unintelligible blips
- Jamming on one frequency affects only a few bits
- Rate of hopping versus Symbol rate
  - ***Fast Frequency Hopping:*** One bit transmitted in multiple hops.
  - ***Slow Frequency Hopping:*** Multiple bits are transmitted in a hopping period
- Example: Bluetooth (79 channels, 1600 hops/s)

Frequency Hopping Spread Spectrum (FHSS)



(a) Channel assignment



(b) Channel use

t_b : duration of one bit

t_c : duration of one chip

Fast Frequency Hopping: $t_b > t_c$

Chip: name of the sample period in spread-spectrum jargon

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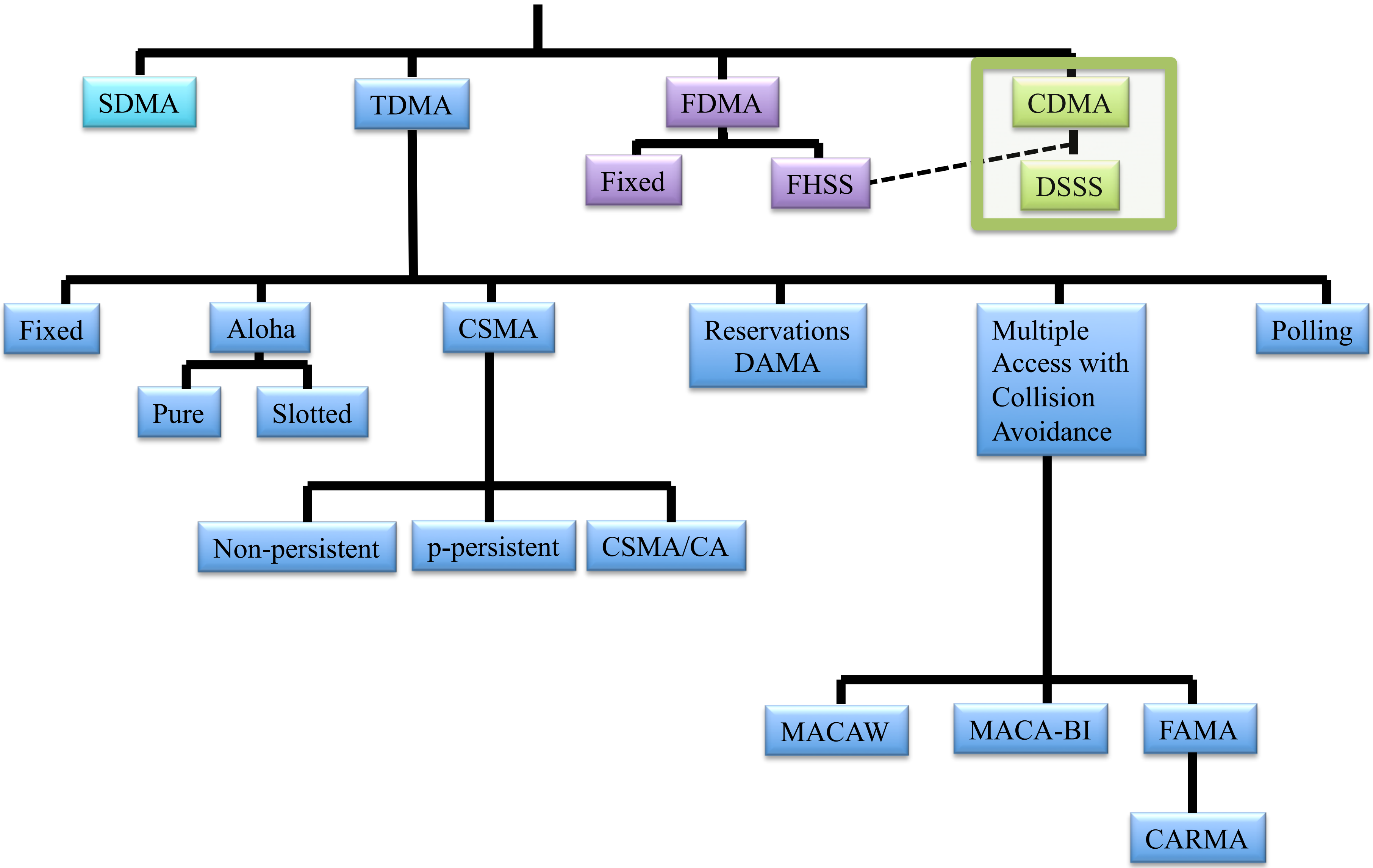
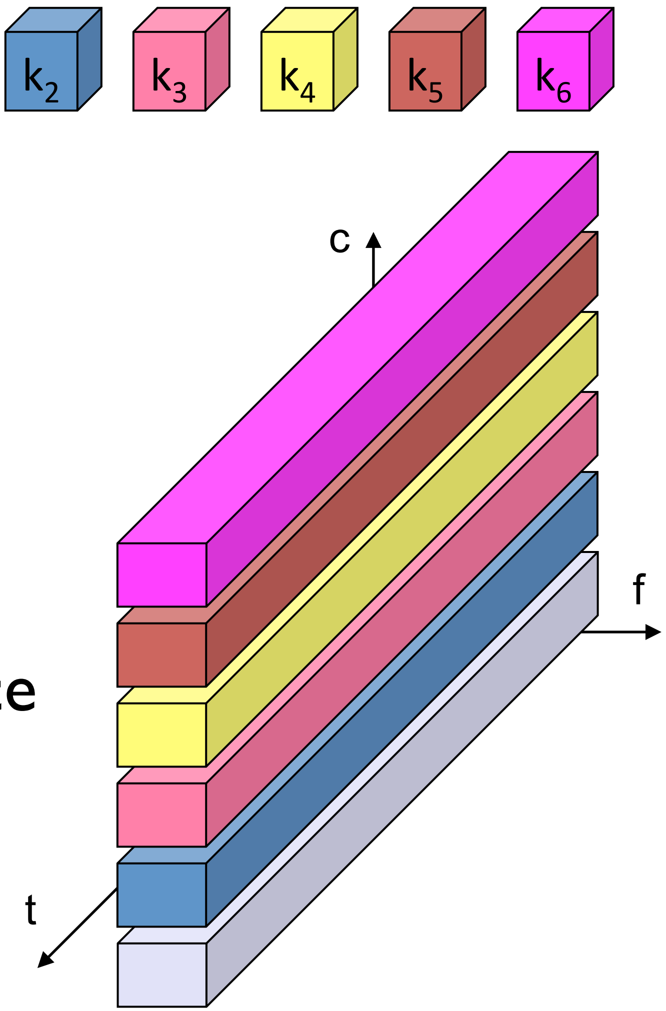


Code Multiplex

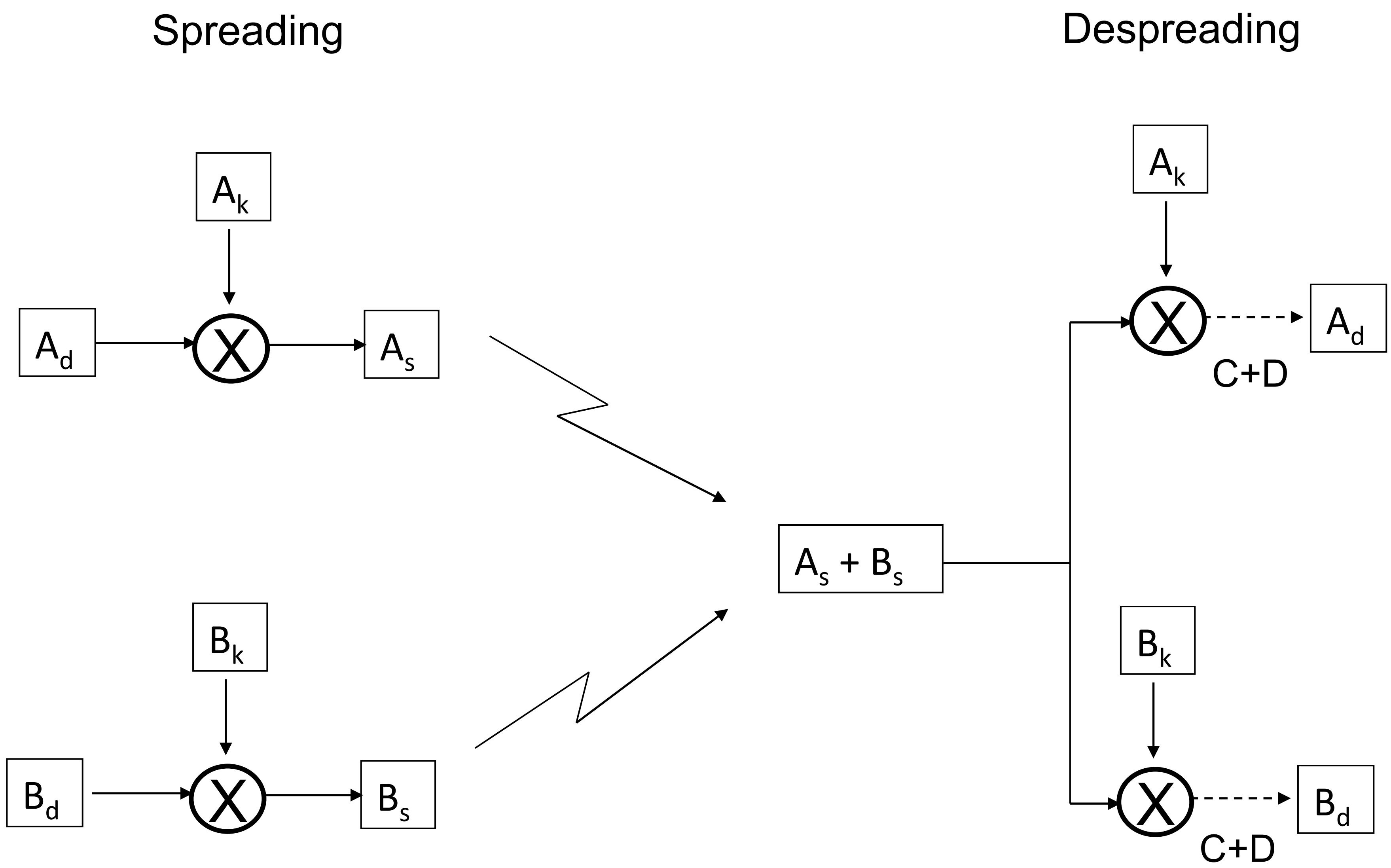
- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - good protection against interference and eavesdropping
- Disadvantage:
  - more complex signal regeneration
- Implemented using spread spectrum technology



Code Division Multiple Access (CDMA)

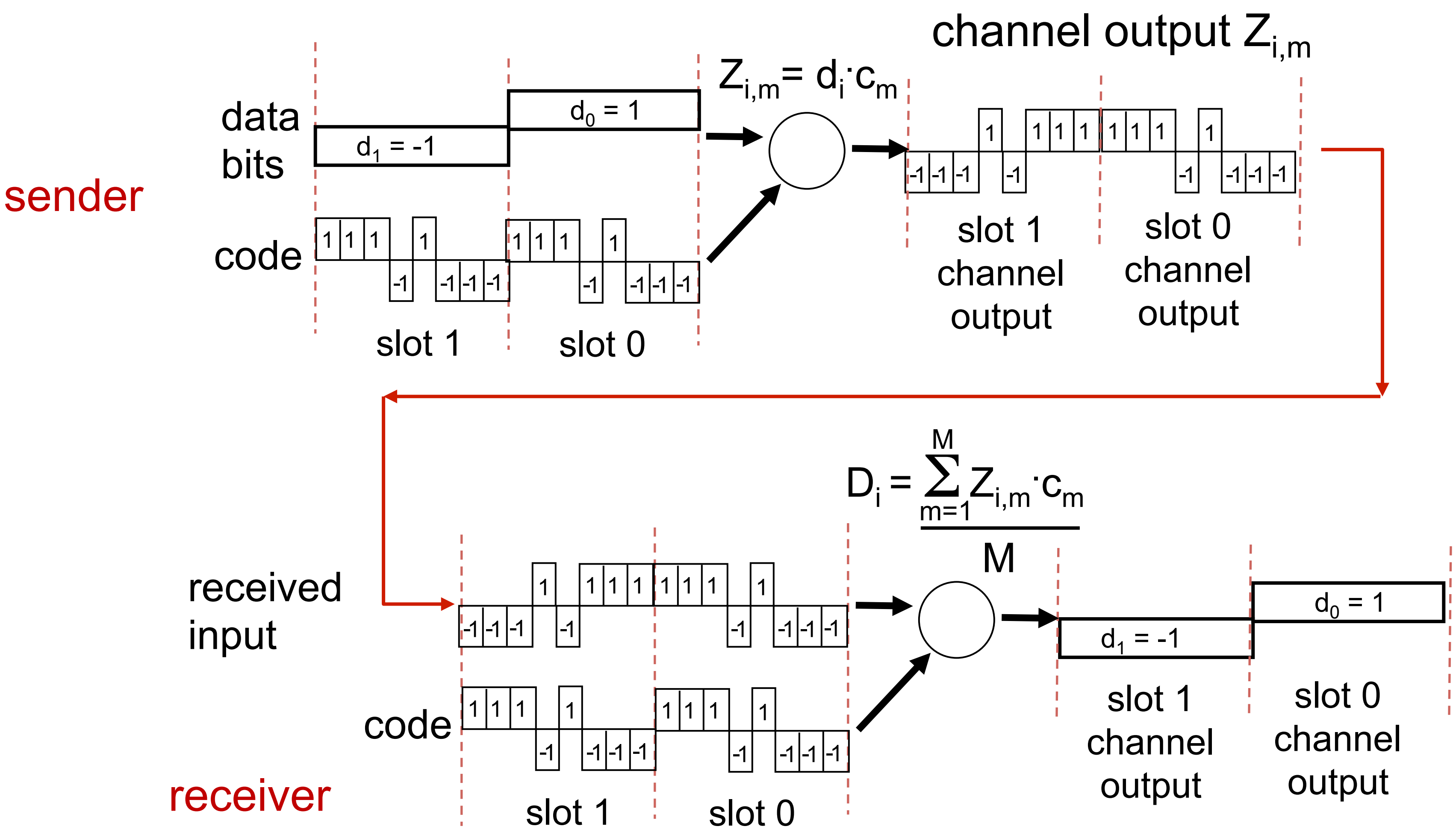
- **Principles**
  - all terminals send on the same frequency and can use the whole bandwidth of the transmission channel
  - each sender has a unique code
  - The sender XORs the signal with this code
  - the receiver can "tune" into this signal if it knows the code of the sender
  - tuning is done via a correlation function
- **Disadvantages:**
  - higher complexity of the receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have approximately the same strength at the receiver
- **Advantages:**
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g., 2^{32}) compared to frequency space
  - more robust to eavesdropping and jamming (military applications…)
  - forward error correction and encryption can be easily integrated

CDMA: Principle (Very Simplified)

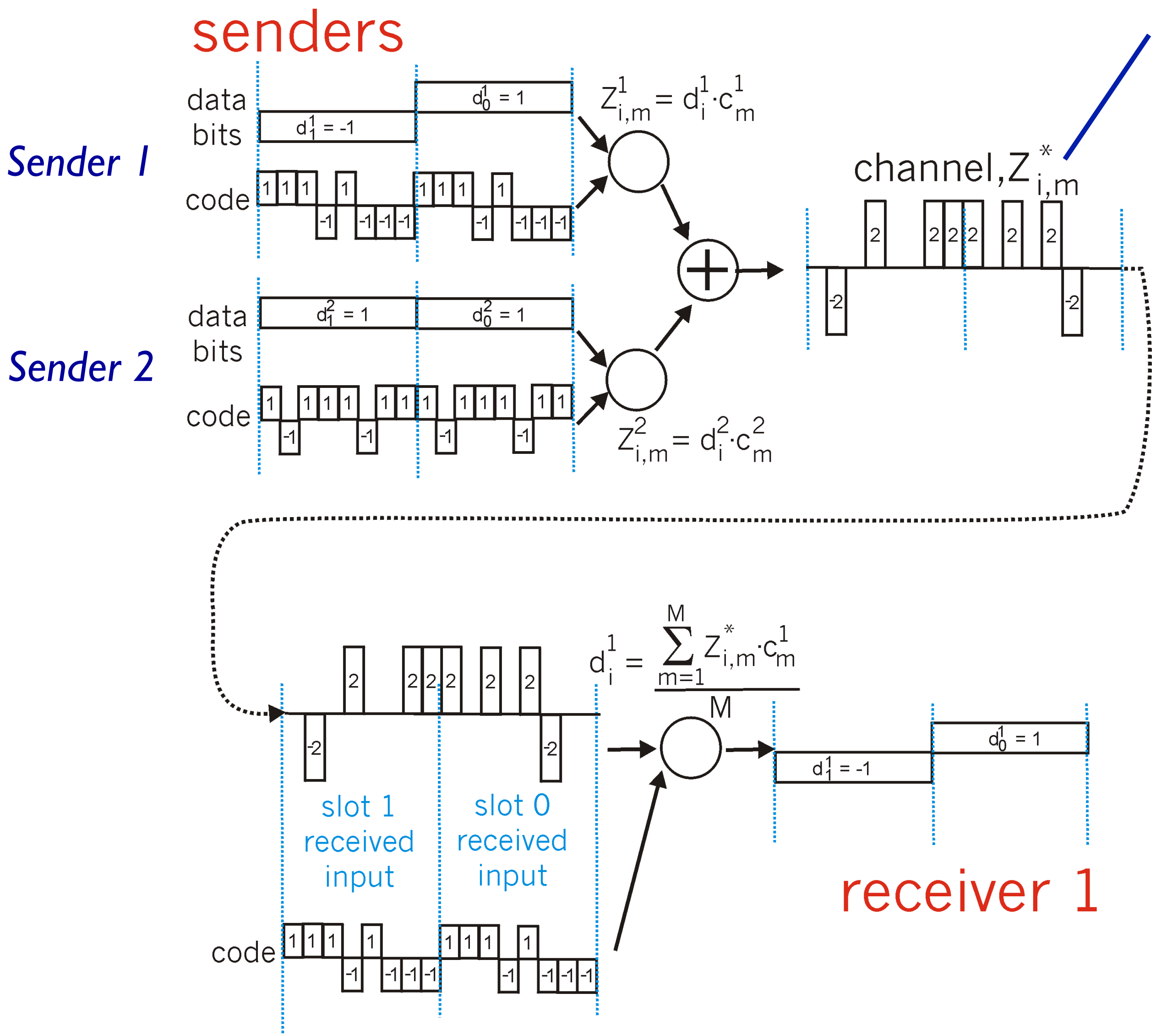


C+D: Correlation and Decision

CDMA Encode/Decode



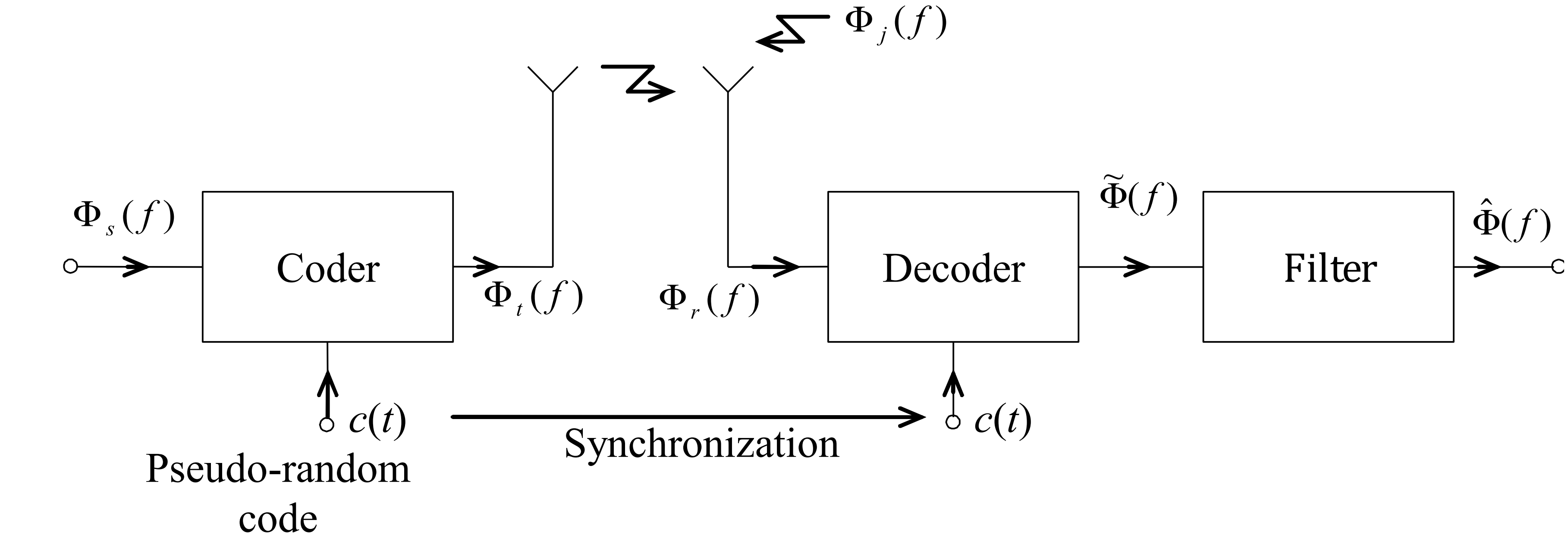
CDMA: Two-sender Interference

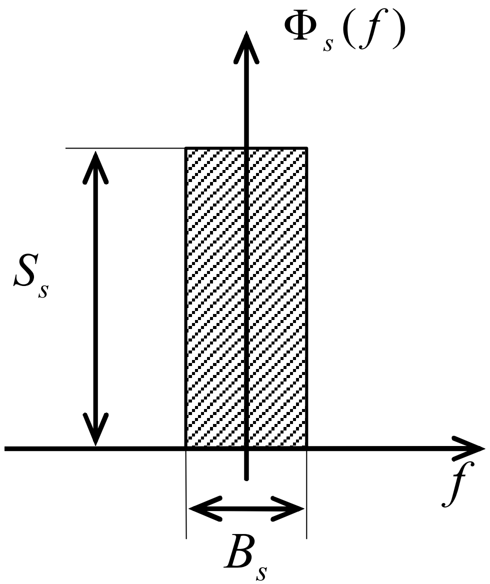


channel sums together transmissions by sender 1 and 2

using same code as sender 1, receiver recovers sender 1's original data from summed channel data!

Spread Spectrum Principle





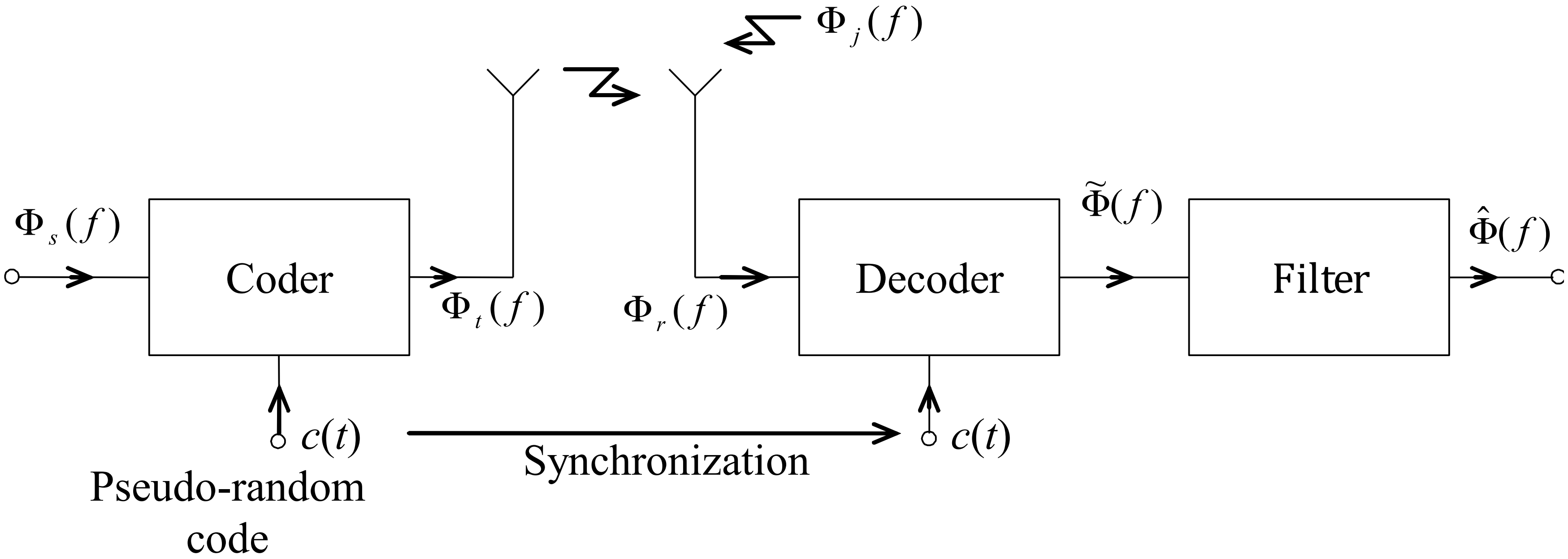
$\Phi_s(f)$ power density spectrum of the original signal

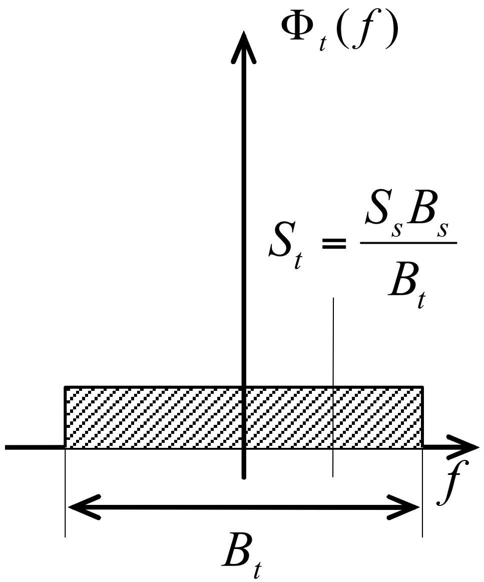
$\Phi_j(f)$ power density spectrum of the jamming signal

S_s power density of the original signal

B_s bandwidth of the original signal

Spread Spectrum Principle





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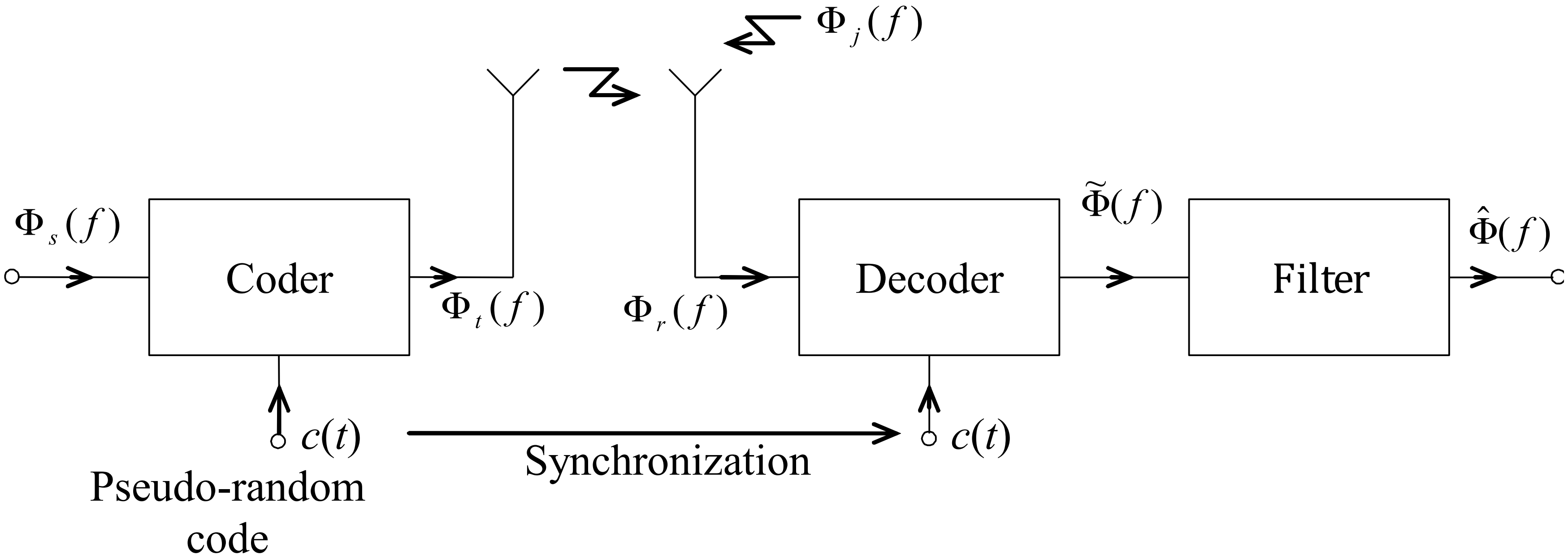

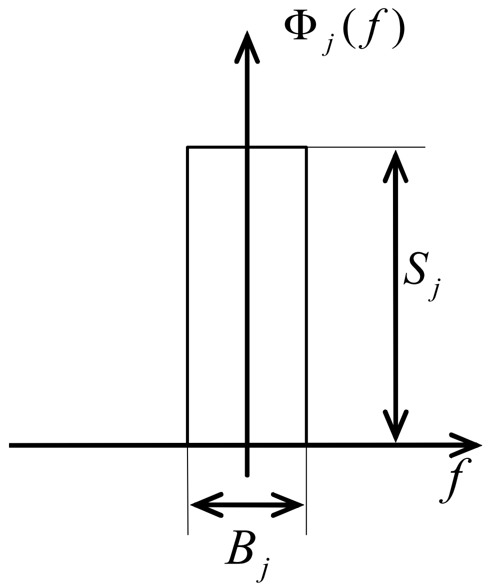

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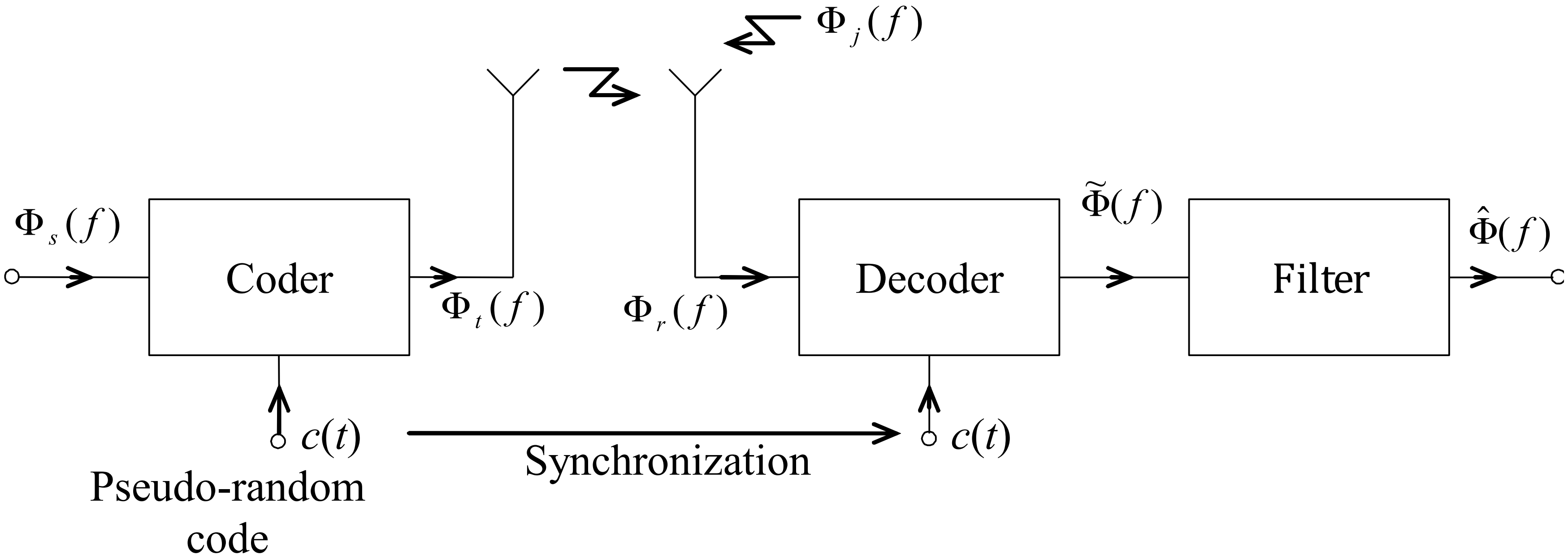

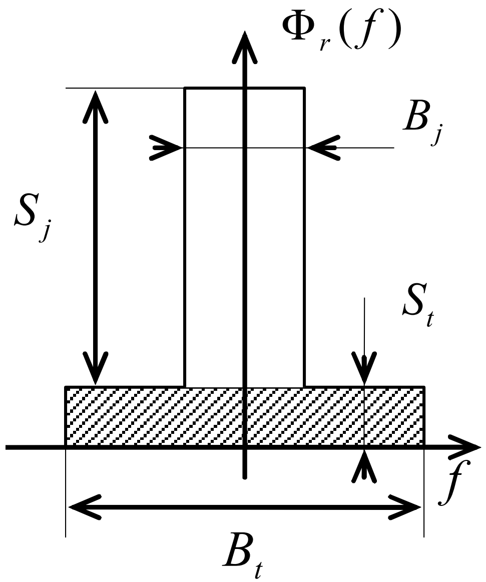

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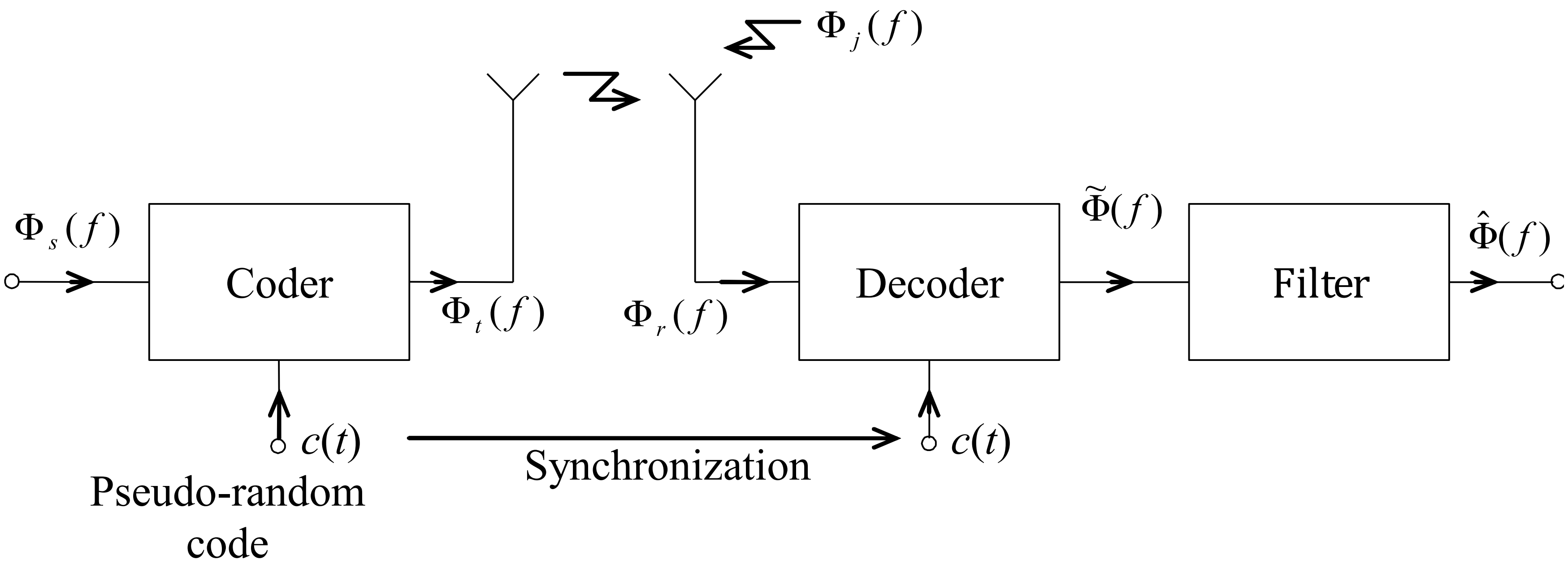
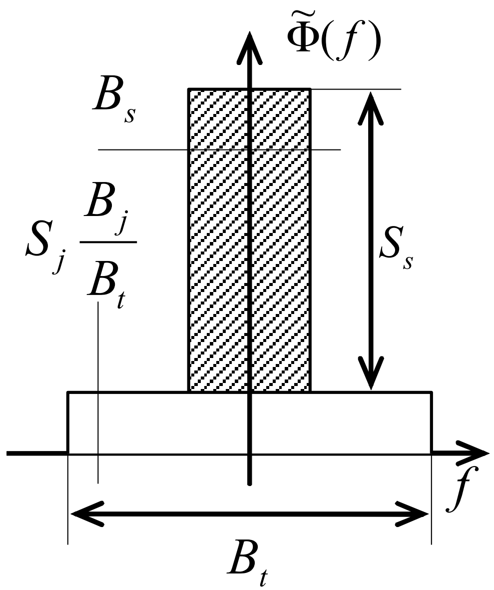
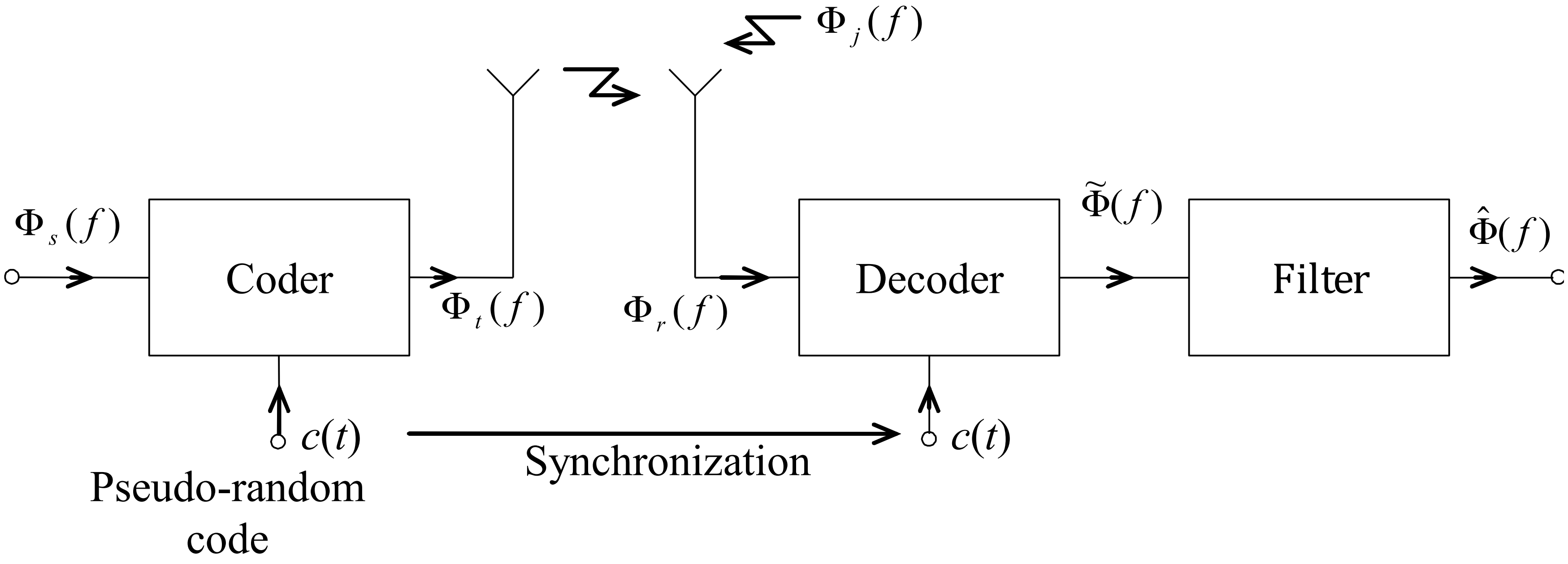


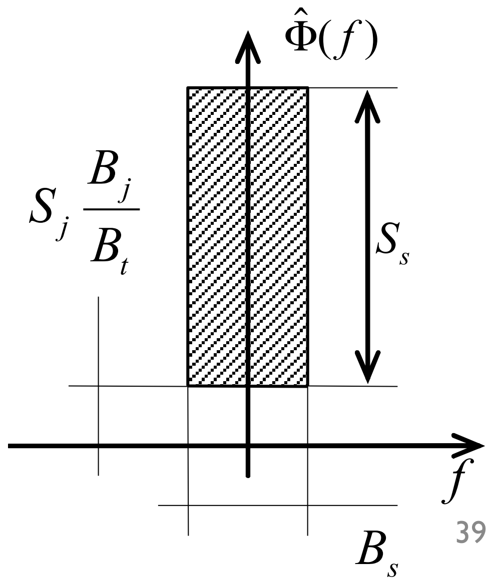
$$\frac{P_{signal}}{P_{jamming}} = \frac{S_s B_s}{S_j \frac{B_j}{B_t} B_s} = \underbrace{\frac{S_s B_s}{S_j B_j}}_{\left(\frac{P_{signal}}{P_{jamming}}\right)_{original}} \cdot \underbrace{\frac{B_t}{B_s}}_{\text{Processing gain}}$$



Processing gain: Increase in received signal power thanks to spreading

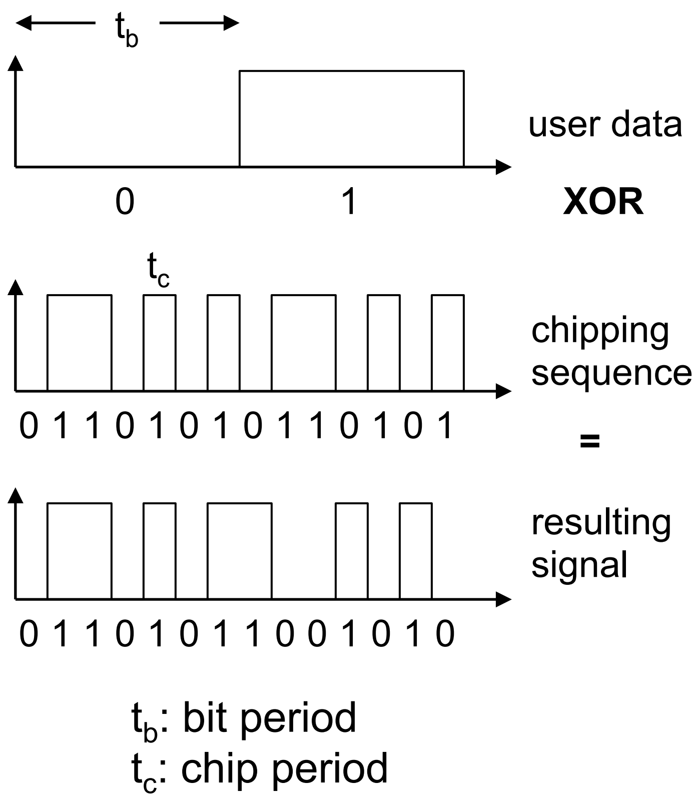
Spread Spectrum Principle





Direct Sequence Spread Spectrum (DSSS)

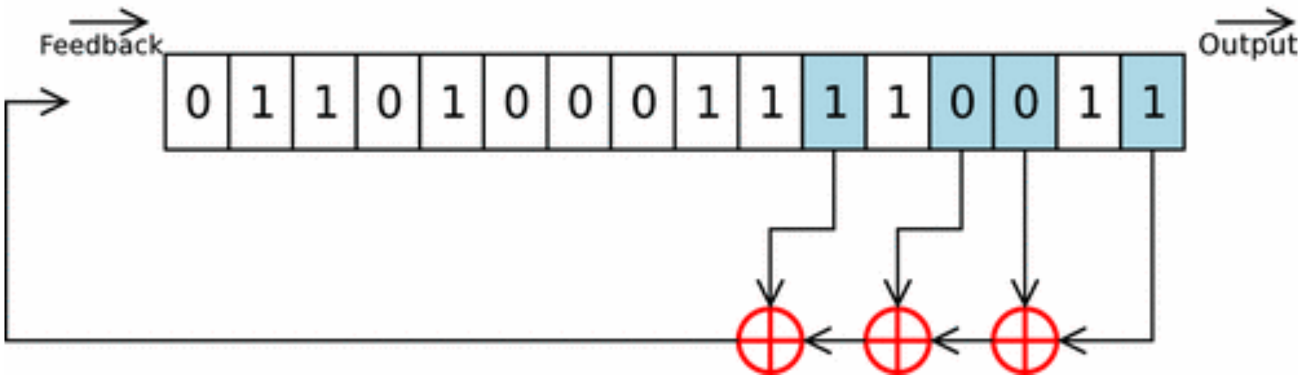
- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - neighboring base stations can use the same frequency range
    - neighboring base stations can detect and recover the signal
    - ➔ enables *soft handover*
- Disadvantages
  - precise power control necessary
  - complexity of the receiver



Categories of Spreading (chipping) Sequences

- **Spreading Sequence Categories**
  1. Pseudo-random Noise (PN) sequences
  2. Orthogonal codes
- **FHSS systems**
  - PN sequences most common
- **DSSS beside multiple access**
  - PN sequences most common
- **DSSS CDMA systems**
  - PN sequences
  - Orthogonal codes

Generating a Pseudo-random Noise chip sequence with a linear feedback shift-register (LFSR)



number of registers: n

period: $N = 2^n - 1$

Properties of PN sequences:

- **Property 1:** In a PN sequence we have: $\Pr\{0\} = \dfrac{1}{2\cdot\left(1-\dfrac{1}{N}\right)}$ $\Pr\{1\} = \dfrac{1}{2\cdot\left(1+\dfrac{1}{N}\right)}$

  $$\Pr\{0\} \approx \Pr\{1\} \approx \frac{1}{2} \quad \textit{for} \;\; n \geq 10 \Rightarrow \frac{1}{N} \leq 10^{-3}$$

- **Property 2:** For a window of length *n* slide along output for *N* (=2^n-1) shifts, each *n*-tuple appears once, except for the all zeros sequence
- **Property 3:** The periodic autocorrelation of a PN sequence is:

$$R(\tau) = \begin{cases} 1 & \tau = 0, N, \; 2N, \; \ldots \\ -\dfrac{1}{N} & \text{otherwise} \end{cases}$$

Orthogonal Codes

- **Orthogonal codes**
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- **Types**
  - Walsh codes
  - Variable-Length Orthogonal codes

Walsh Codes

- Set of Walsh codes of length *n* consists of the n rows of an *n* x *n* Hadamard matrix:

$$H_1 = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \quad H_k = \begin{pmatrix} H_{k-1} & H_{k-1} \\ H_{k-1} & \overline{H_{k-1}} \end{pmatrix}$$

- Sylvester's construction:

$$H_1 = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \quad H_2 = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix} \quad \cdots$$

- Every row is orthogonal to every other row and to the logical not of every other row
- Requires tight synchronization
  - Cross correlation between different shifts of Walsh sequences is not zero

Typical Multiple Spreading Approach

- Spread data rate by an orthogonal code (channelization code)
  - Provides mutual orthogonality among all users in the same cell
- Further spread result by a PN sequence (scrambling code)
  - Provides mutual randomness (low cross correlation) between users in different cells