Mobile Radio Communications

Session 6: Spread spectrum & multiple access

Spread spectrum

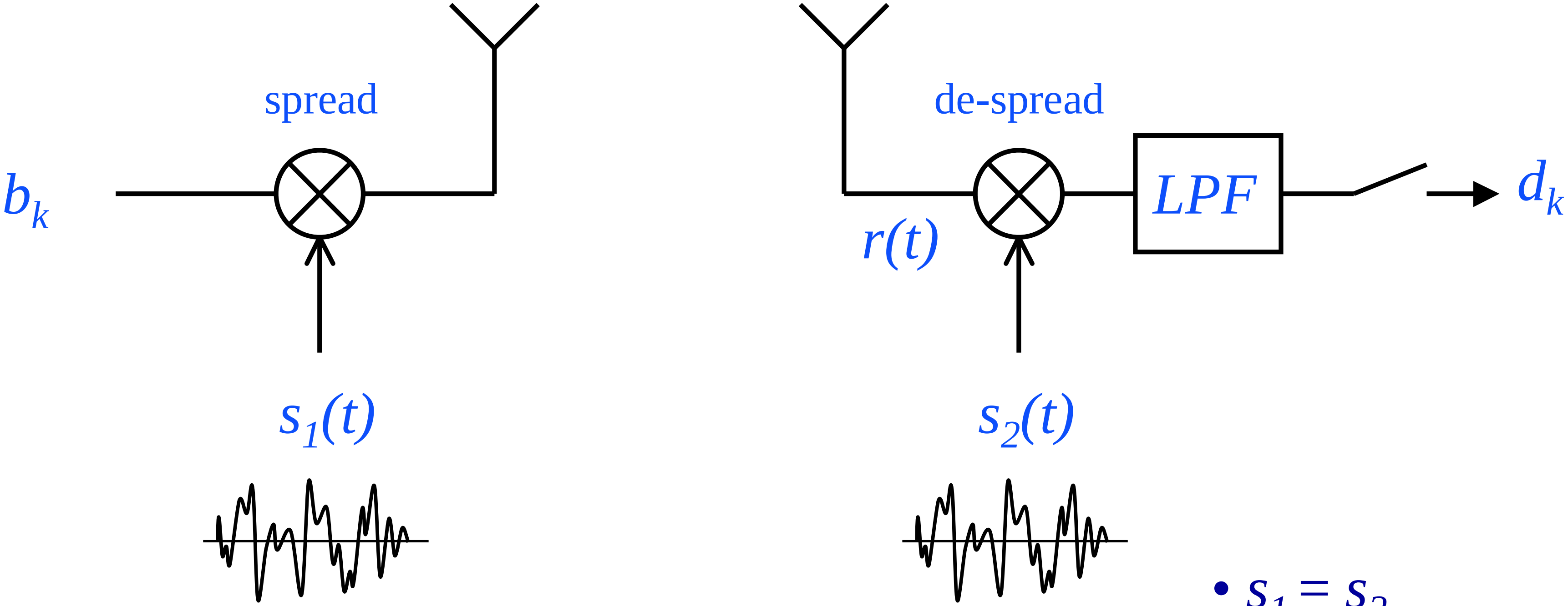
- Transmission bandwidth >> signal bandwidth

$$W >> B_s$$

- Coding
- Wideband FM

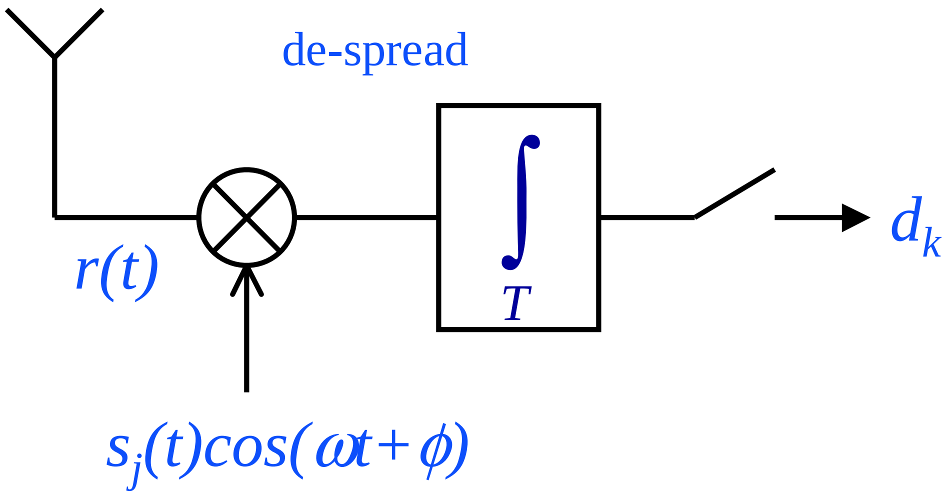
- Direct-sequence spreading
- Frequency-hop spreading
- Time-hop spreading

Direct-sequence spread spectrum (DSSS)



- $s_1 = s_2$
- $W >> B_s$
- $s(t)$ signature

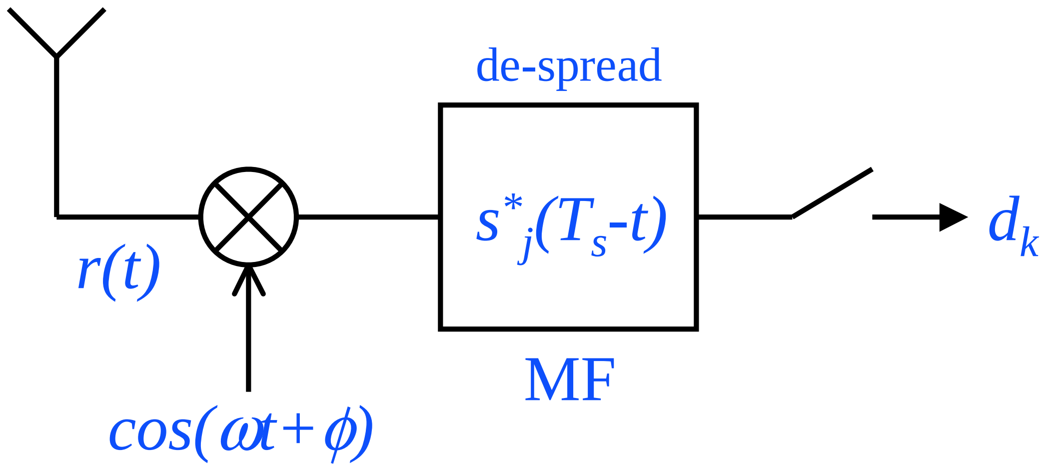
De-spreading (multiplier)



$$r(t) = \sqrt{\frac{2E_b}{T_s}}\, b_k s_i(t)\cos(\omega t + \theta)$$

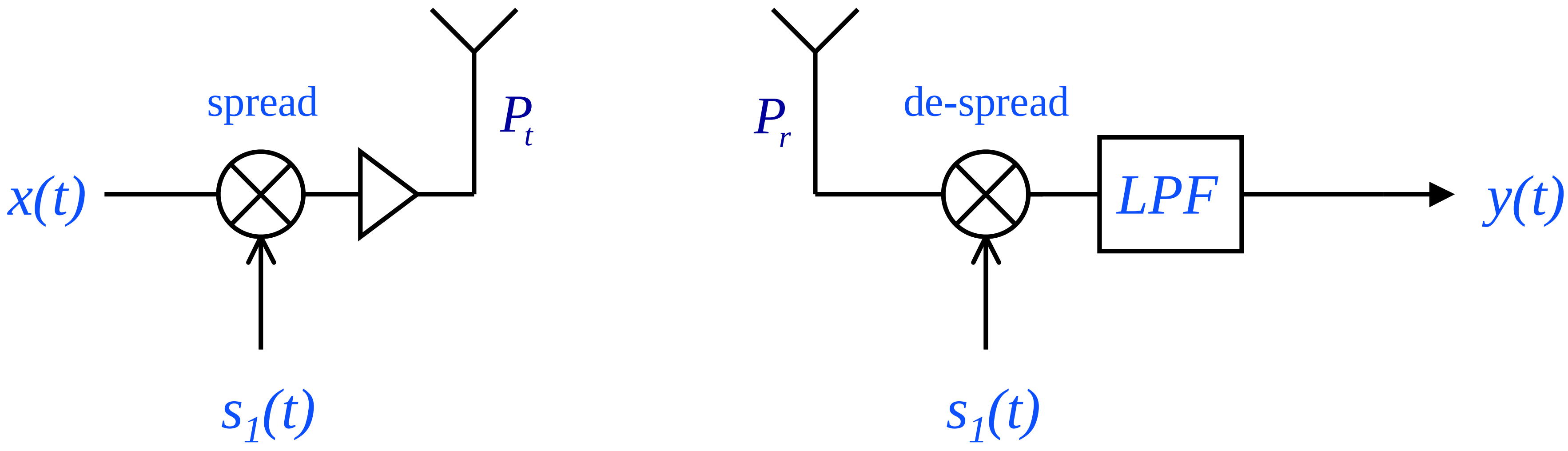
$$d_k\Big|_{t=T_s} = \int_{T_s} r(t)dt = \int_{T_s} b_k s_i(t)\cdot s_j(t)dt = \begin{cases} b_k\sqrt{\dfrac{E_b T_s}{2}} & i = j \\ 0 & i \neq j \end{cases}$$

De-spreading (matched filter)



$$d_k\big|_{t=T_s} = b_k\left[s_i(t) * s^*_j(T_s - t)\right]_{t=T_s} = \begin{cases} b_k\sqrt{\dfrac{E_b T_s}{2}} & i = j \\ 0 & i \neq j \end{cases}$$

Noise performance



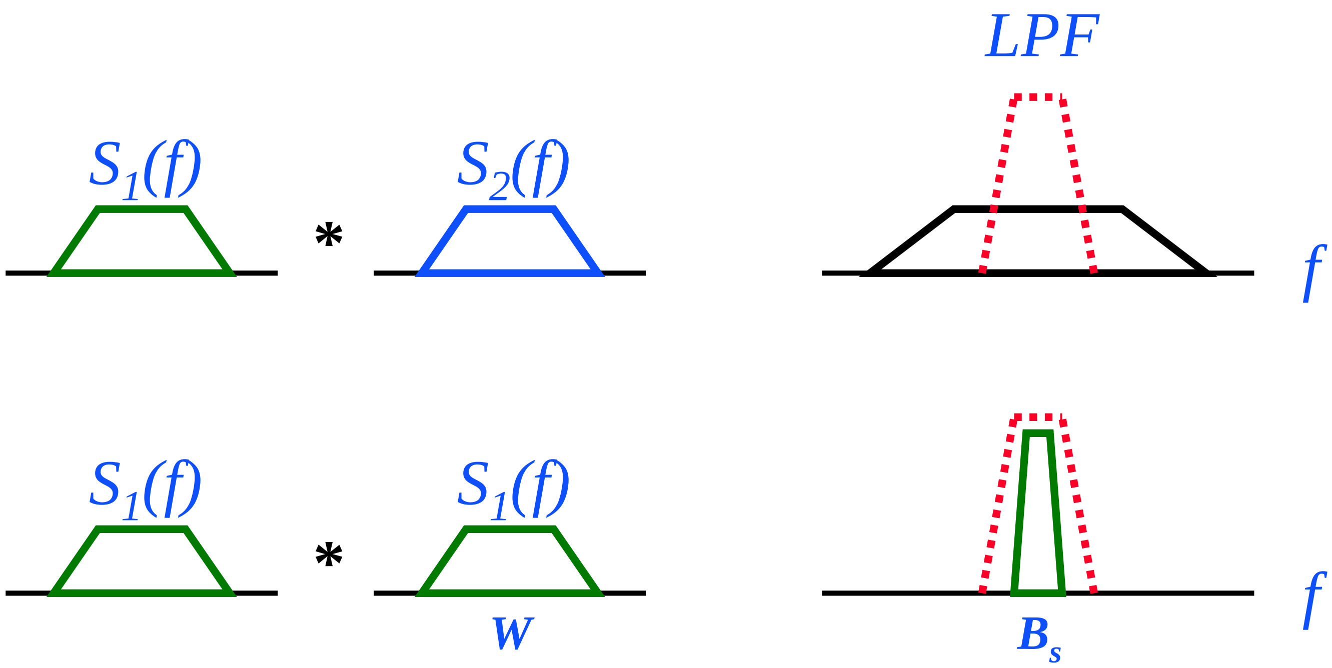
Signal: $P_r = E_b / T_b$ $\qquad$ $P_r = E_b / T_b$

Noise: $P_n = N_0 \cdot W$ $\qquad$ $P_n = N_0 \cdot B_s$

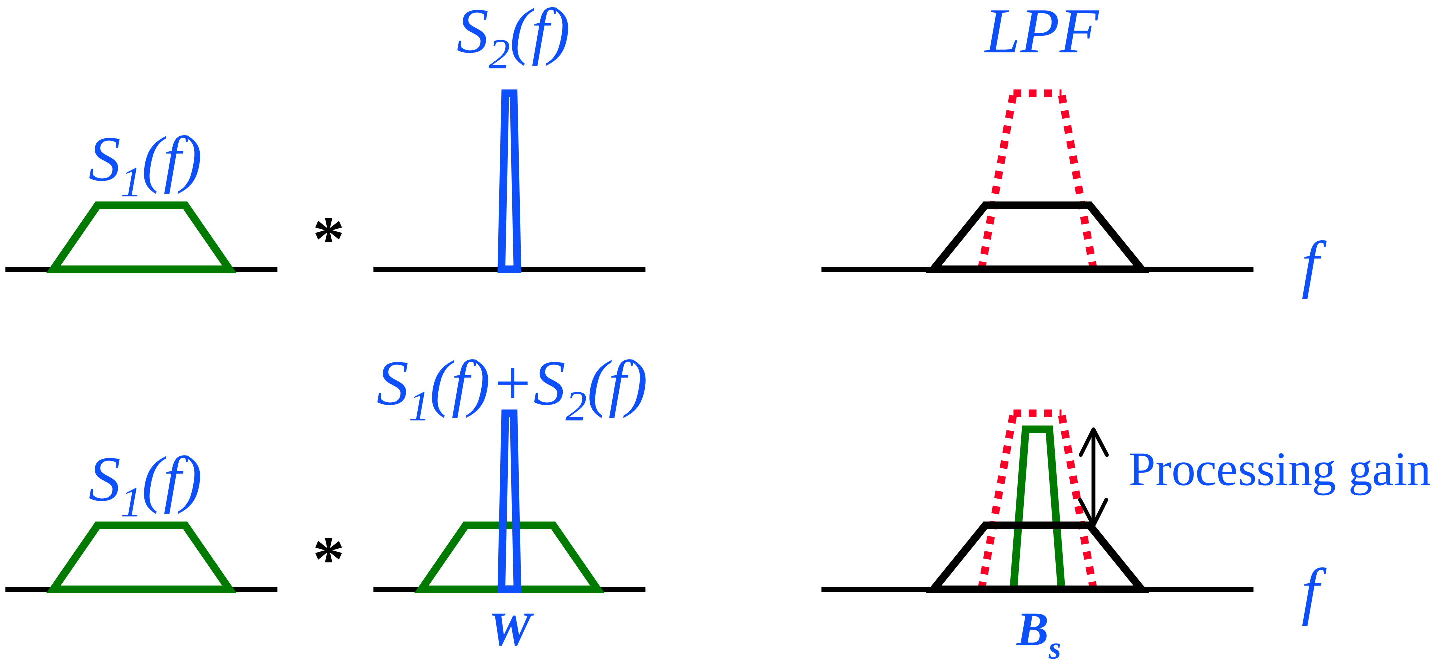
SNR: $\gamma_1 = \frac{E_b}{N_0} \cdot \frac{B_s}{W}$ $\qquad$ $\gamma_0 = \frac{E_b}{N_0}$

Interference performance

$$s_1(t)\cdot s_2(t) \quad \leftrightarrow \quad S_1(f) * S_2(f)$$



Interference performance



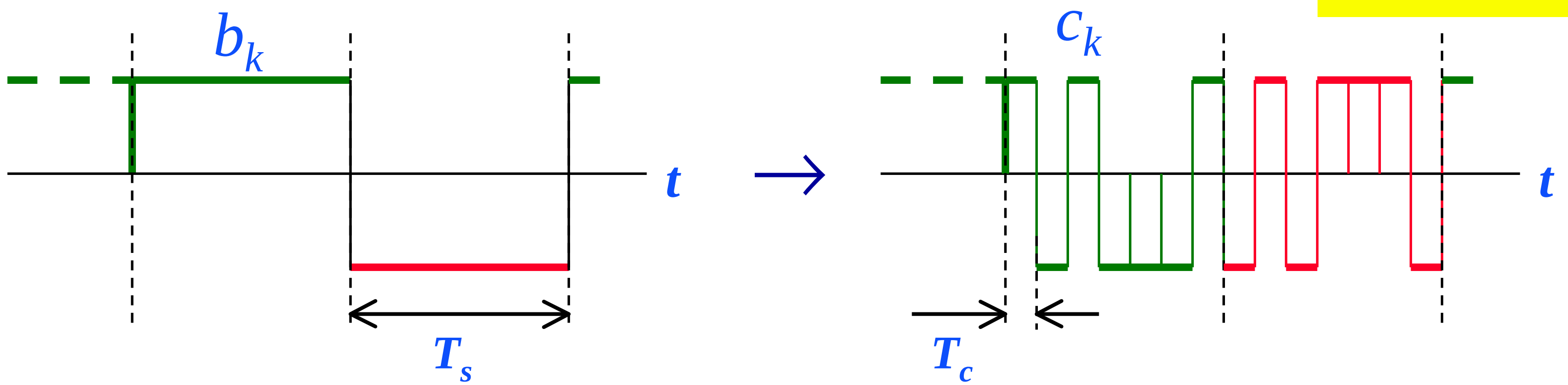
$$\textbf{Processing gain} = \frac{W}{B_s} \qquad (\neq \textbf{coding gain})$$

Spreading signature

- “noise”-like characteristics
  - flat output spectrum
  - autocorrelation function like Dirac impulse
- (pseudo) noise (PN) sequences
- random series of <u>chips</u>

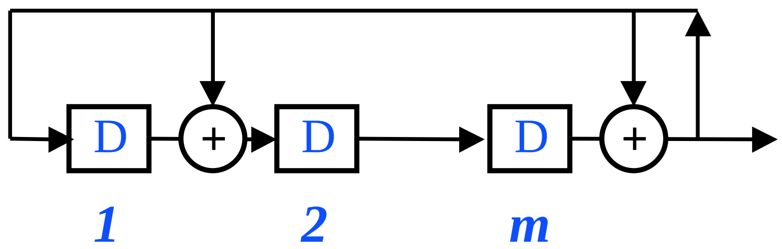
$$PG = \frac{W}{B_s} = \frac{T_s}{T_c}$$

$$b_k \rightarrow \{c_0, c_1, c_2, \ldots, c_{n-1}\}$$



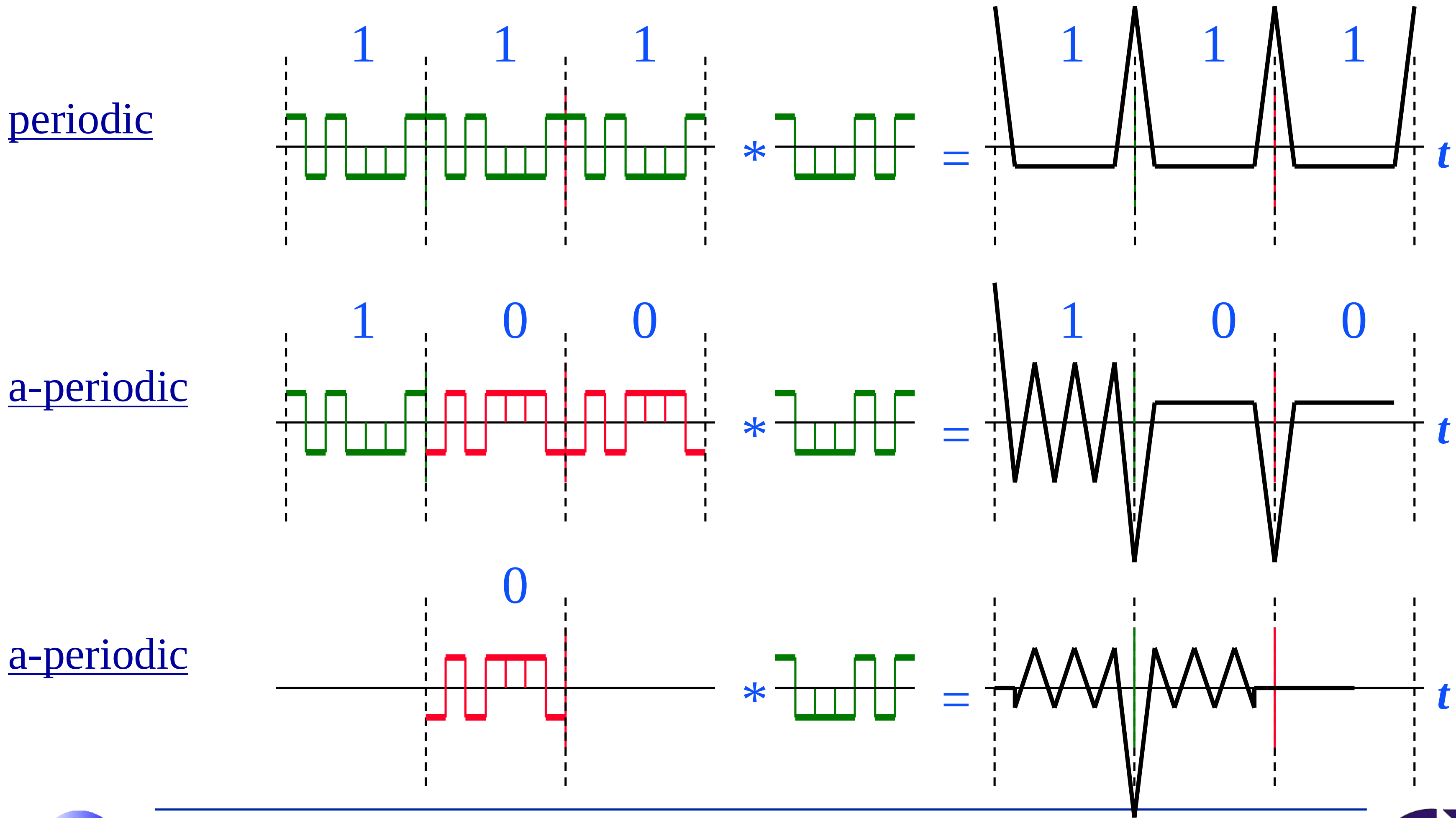
PN sequences

- **Maximum length (ML) chip sequences**
  - **good periodic auto-correlation**
- **Gold sequences**
  - **good cross-correlation**
- **Barker sequences**
  - **good a-periodic auto-correlation**

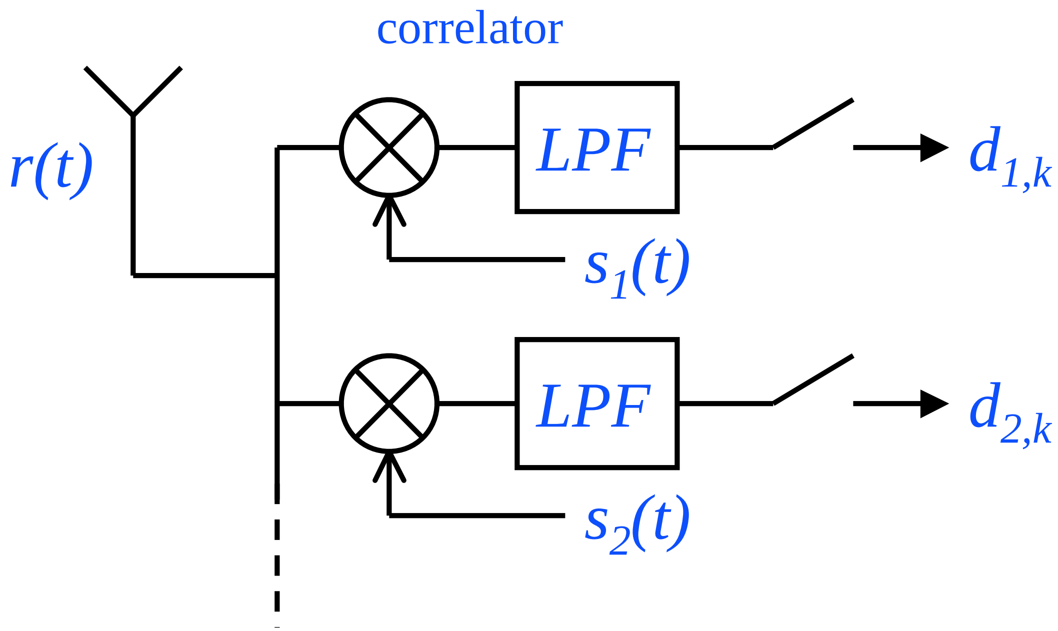


MFSR: $2^m - 1$ states

PN sequence auto-correlation



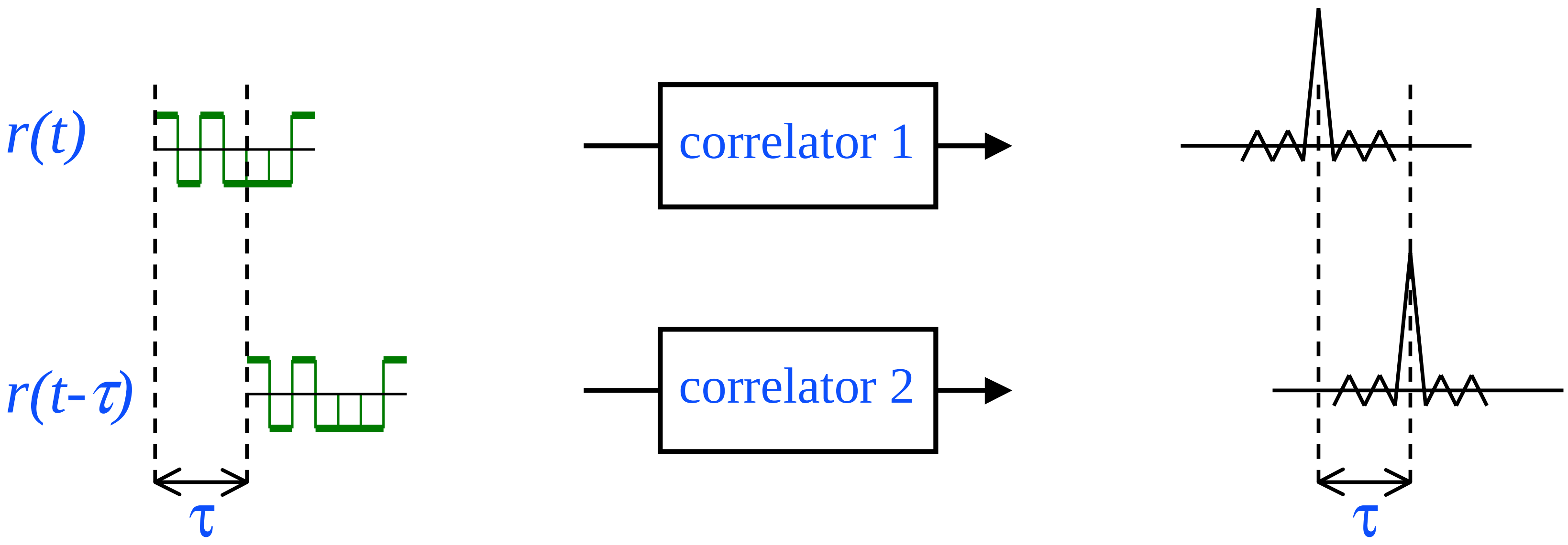
Multi-code concept



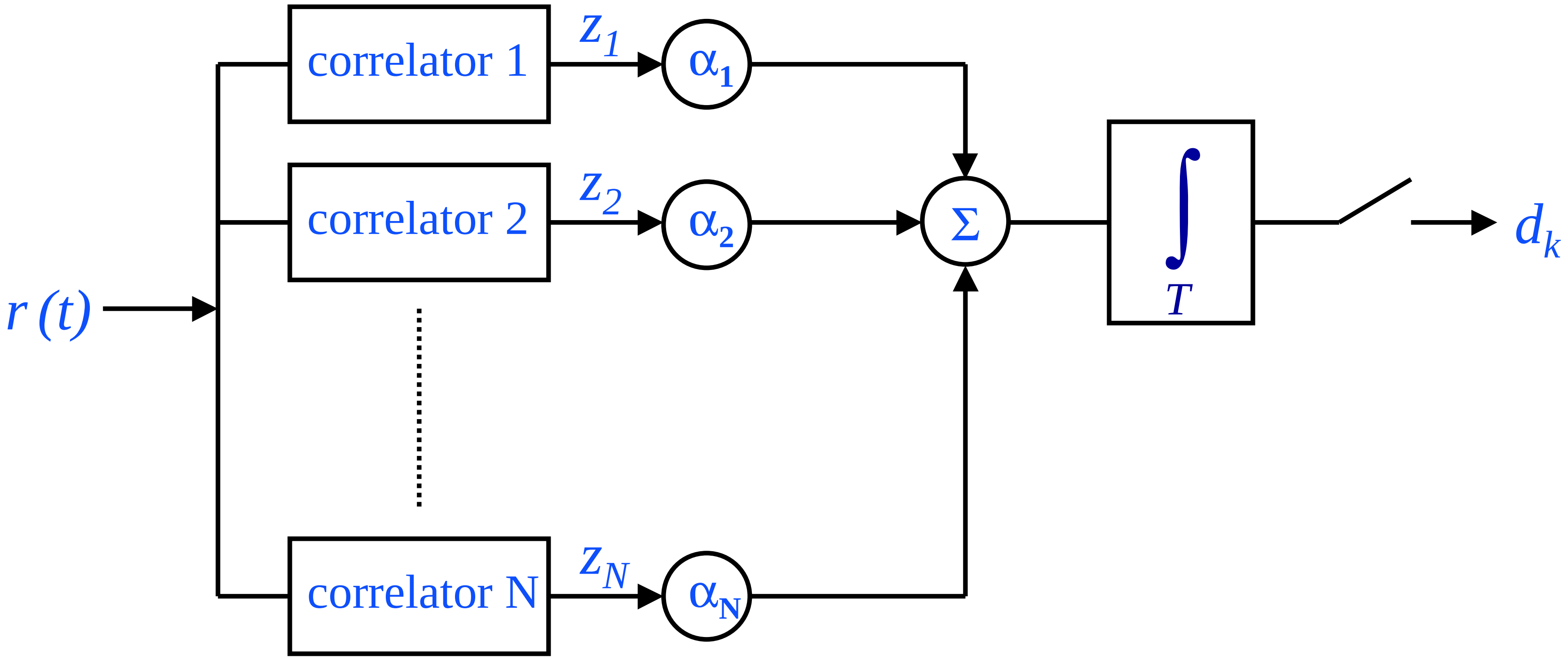
- **orthogonality:** $\int s_i(t) \cdot s_j(t) dt = 0 \quad i \neq j$
- **near-far problem: processing gain**
- **power control**

Frequency-selective fading

- multipath conditions
- delayed versions
- autocorrelation properties
- $B_s > B_{coh} \Rightarrow T_s < T_{rms}$

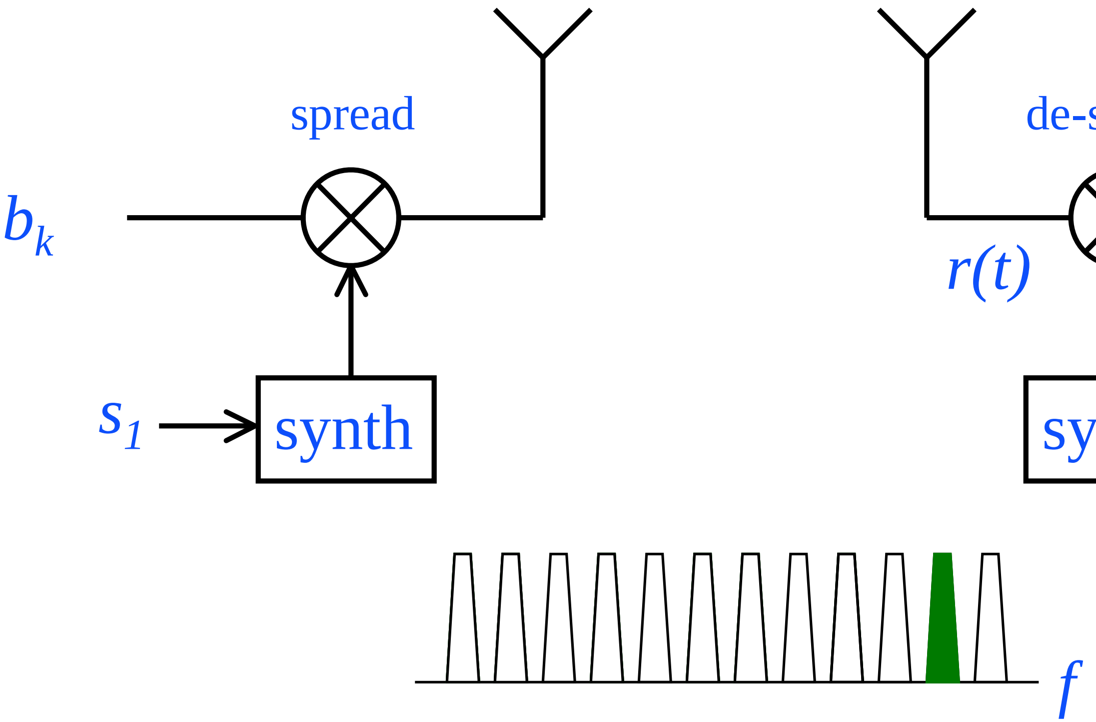


RAKE receiver



Optimize SNR: $a_i = \dfrac{z_i}{N_i}$ $\Rightarrow$ **maximal ratio combining**

Frequency-hop spread spectrum (FHSS)

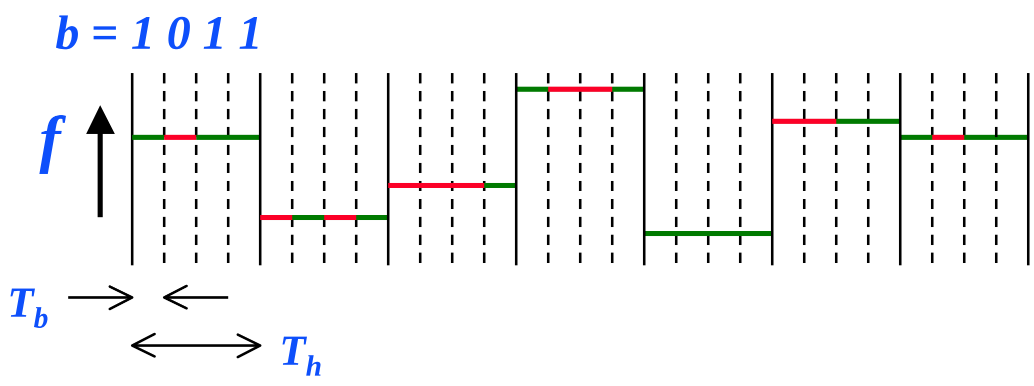


- $s_1 = s_2$ is a pseudo-random <u>hop</u> sequences

Slow/fast hopping

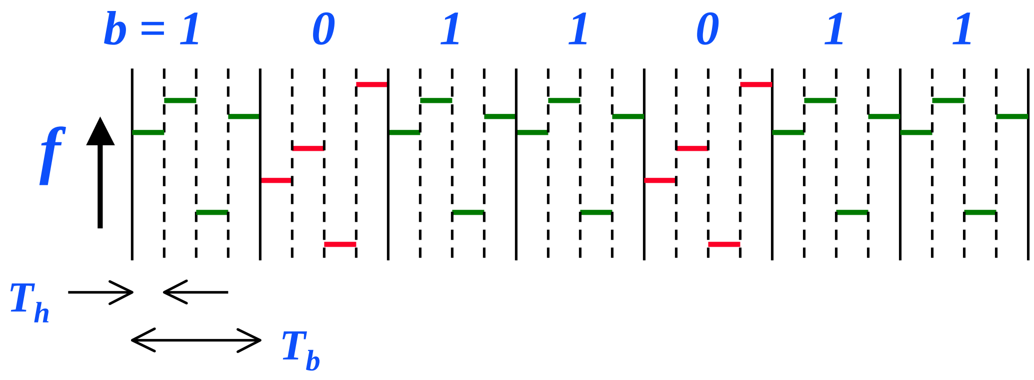
slow: $\{b_0, b_1, b_2, \ldots\} \rightarrow f_0$

$T_h > T_b$



fast: $b_0 \rightarrow \{f_0, f_1, f_2, \ldots\}$

$T_h < T_b$



Interference performance

- Narrow band instantaneously, wide band on average
- Filters reject interference not in instantaneous hop channel
- Better near-far resistance
- Resistant against narrowband jammers

$$\text{Processing gain} = \#\text{ of hop channels} = \frac{W}{B_s}$$

Interference performance

- **Collision probability:**

  K users
  M hop channels
  hop alignment

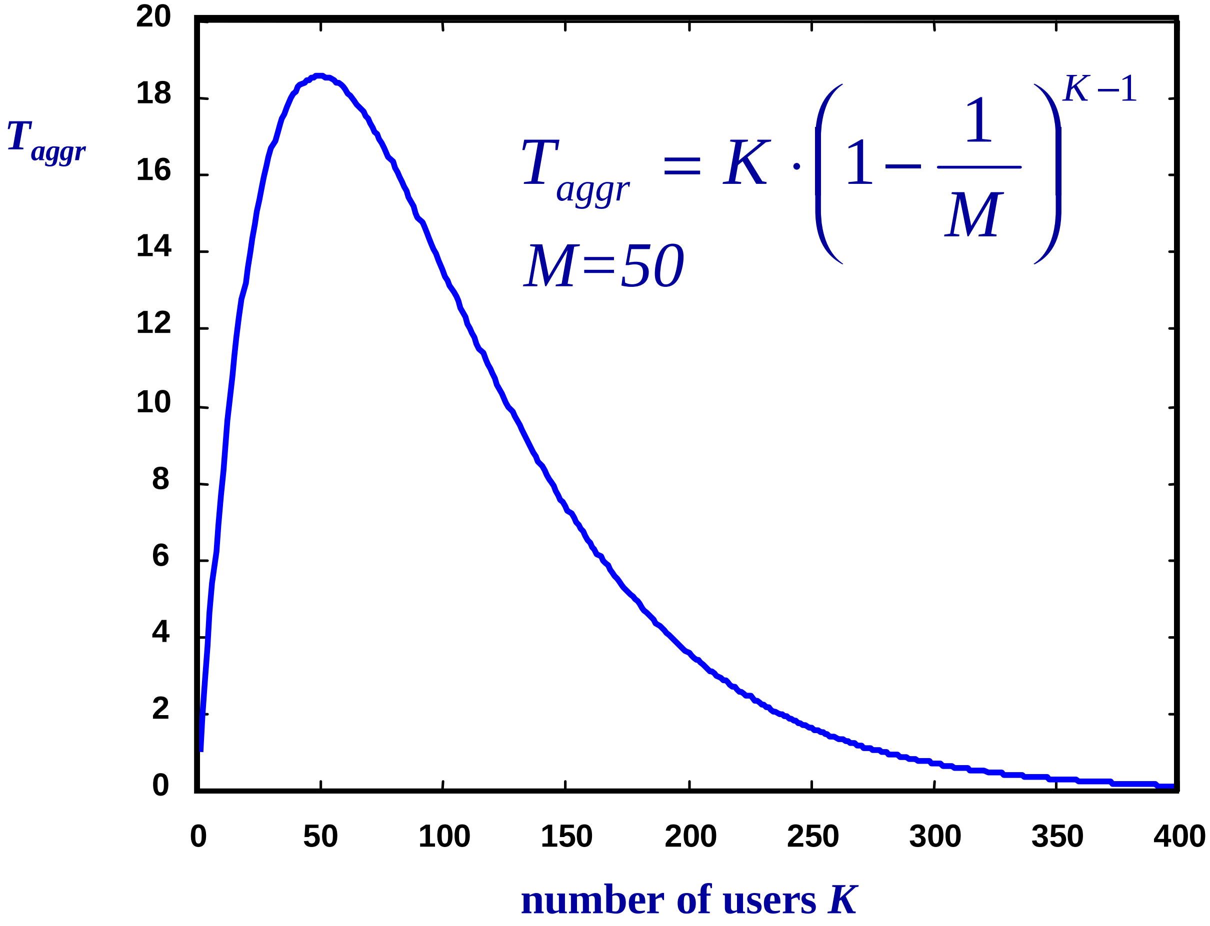
$$P_{hit} = 1 - \left(1 - \frac{1}{M}\right)^{K-1} \approx \frac{K-1}{M}$$

- **Average BER:**

  $BER_{hit}=0.5$
  $BER_{no\_hit}=0$

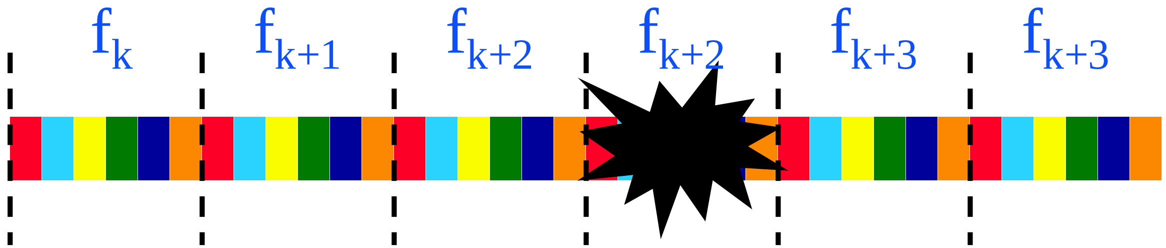
$$P_e \approx \tfrac{1}{2}\left(\frac{K-1}{M}\right)$$

Throughput performance



Coding & interleaving

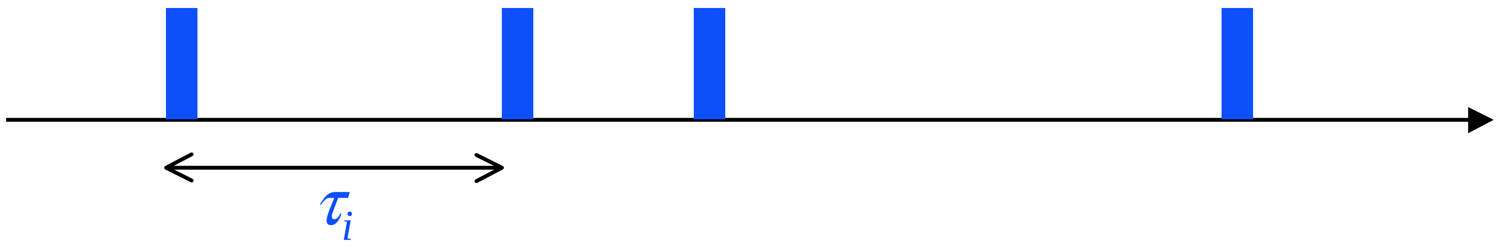
- Interleaving over hops



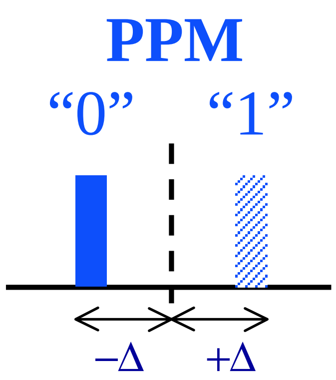
- De-interleaved

- Interference
- Frequency-selective fading
- Retransmit diversity

Time hopping



- **Pseudo-random interval τ_i (time sequence)**
- **Pulse width T_p**
- **Processing gain: duty cycle T_p/τ_{ave}**
- **Resistant against <u>intermittent</u> jammer**
- **PPM: pulse position modulation**



Time hopping

Comparison with FH:

FH	TH
instantaneous narrowband narrowband filter narrowband jammer	instantaneous wideband short scan window low duty cycle jammer

Synchronization

Spreading sequence

- chip sequence
- hop sequence
- time sequence

Phase in sequence

- sequence synchronization
- symbol synchronization

Synchronization

Before de-spreading:

$$\frac{E_c}{N_0} = \frac{T_c}{T_s}\frac{E_b}{N_0} = \frac{B_s}{W}\frac{E_b}{N_0}$$

$$\left.\begin{array}{l} \dfrac{E_b}{N_0} = 5dB \\ \dfrac{B_s}{W} = -18\,dB \end{array}\right\} \frac{E_c}{N_0} = -13\,dB$$

Search, synchronize, track

Wideband fundamentals

Spread spectrum

Does not improve SNR
Does provide frequency (or time) and interference diversity
Requires strict synchronization
Allows multi-user sharing same band

FEC coding

Does improve SNR
Single user

Wideband FM

Does improve SNR
Single user

Multiple Access Techniques

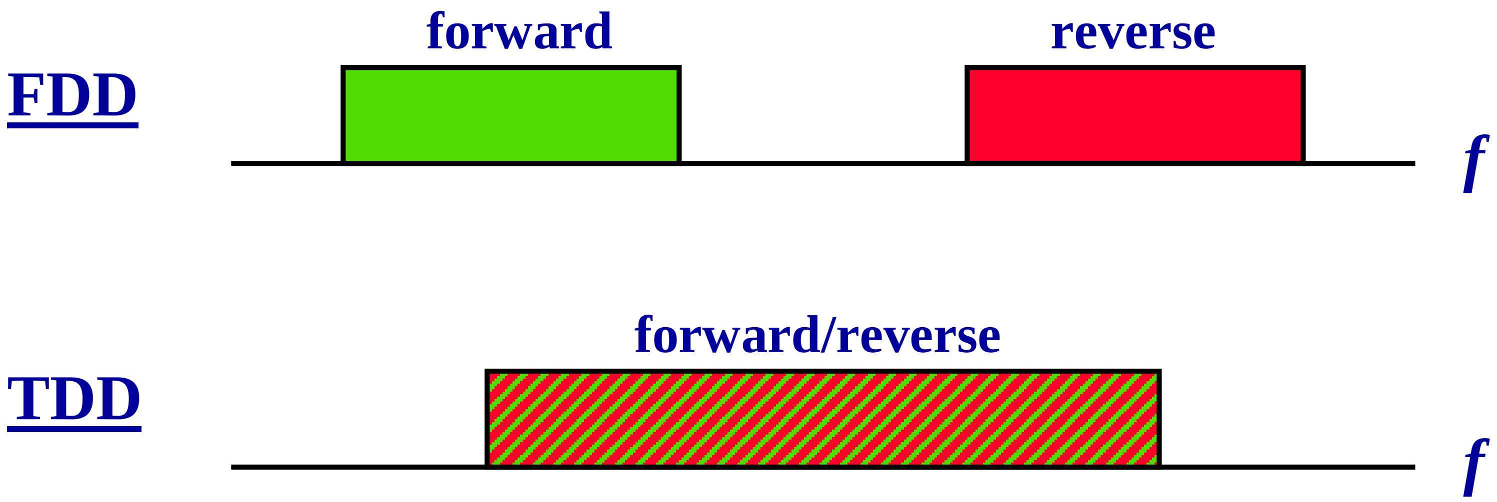
- Channel definition
  - Separation of forward and reverse transmission
  - Separation of control and traffic flows
  - Separation of users (orthogonality)
- Not to be confused with MAC (Medium Access Control)

Duplexing

- Simplex: one-directional
- Half-duplex: two-directional / push-to-talk
- Full-duplex: two-directional / unconditionally

- Only for full-duplex, division is required
  – Frequency Division Duplex (FDD)
  – Time Division Duplex (TDD)

Duplexing



Offset-FDD: uplink/downlink at different frequencies but also separated in time

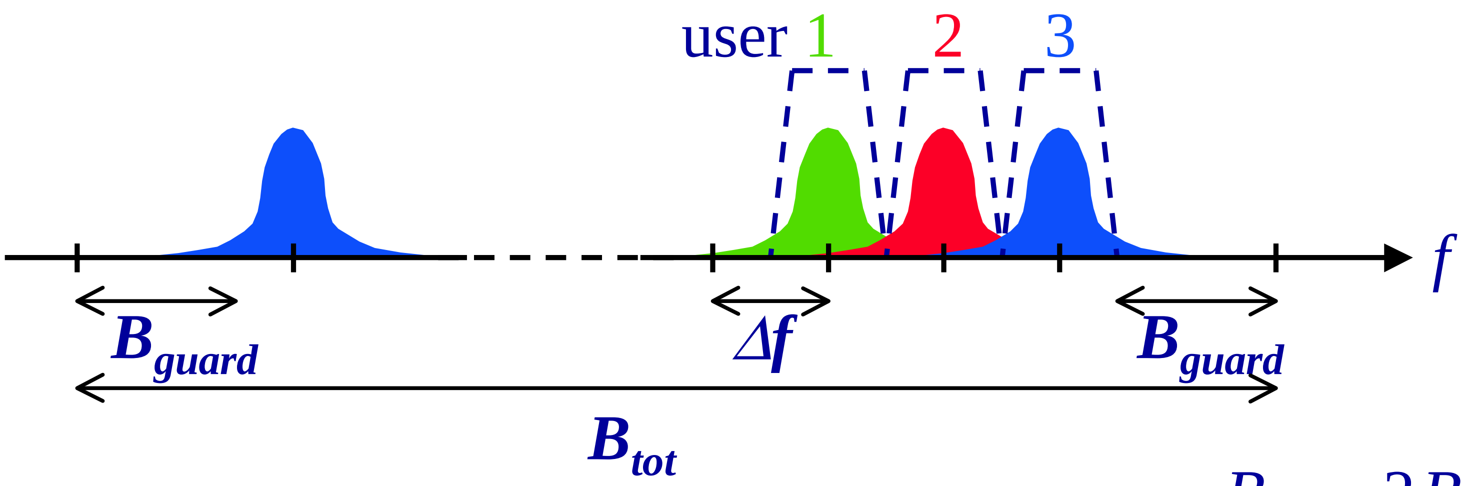
Multi-user systems

- **Separation of channels in**
  - **frequency** **FDMA**
  - **time** **TDMA**
  - **code** **CDMA**
  - **space** **SDMA**

Frequency Division Multiple Access

- **Division of frequency space in (narrow) frequency bands**
- **Only FDMA allows CW modulation**
  ⇒ used for first generation, analog systems
- **Narrowband modulation robust in dispersive channels**
- **FDMA/FDD uses duplexer**
- **Other MA techniques always used in combination with FDMA (also called <u>Multi Carrier</u> or MC)**

FDMA

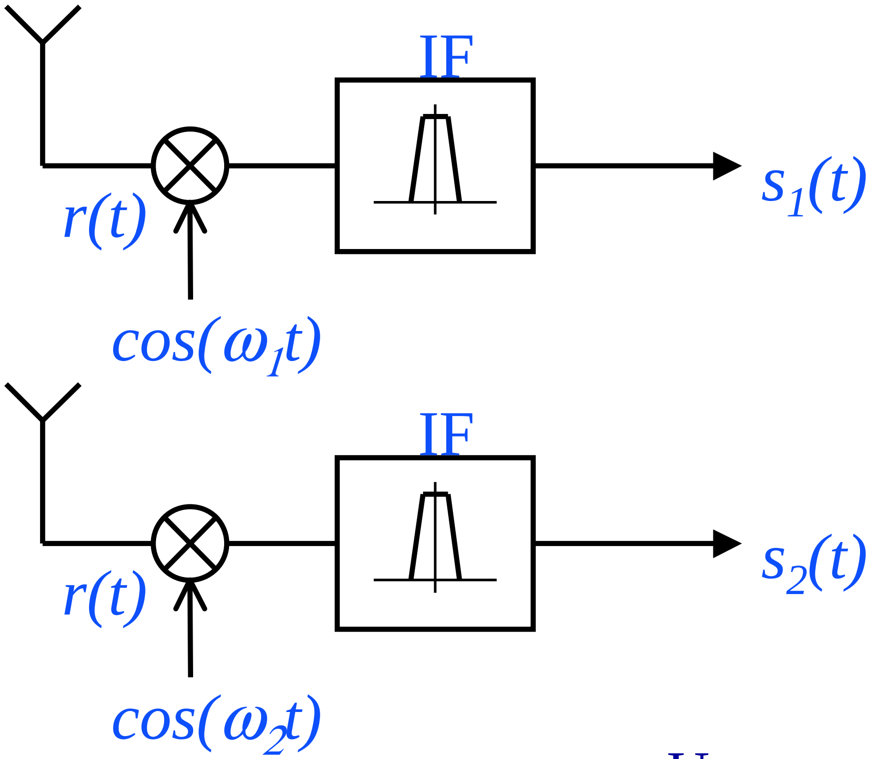


$$N_c = \frac{B_{tot} - 2B_{guard}}{\Delta f}$$

Drawbacks:

– No flexible service allocation (dynamic bandwidth)
– No sharing of channels (circuit-switched)
– High-Q filters & duplexers

FDMA receivers

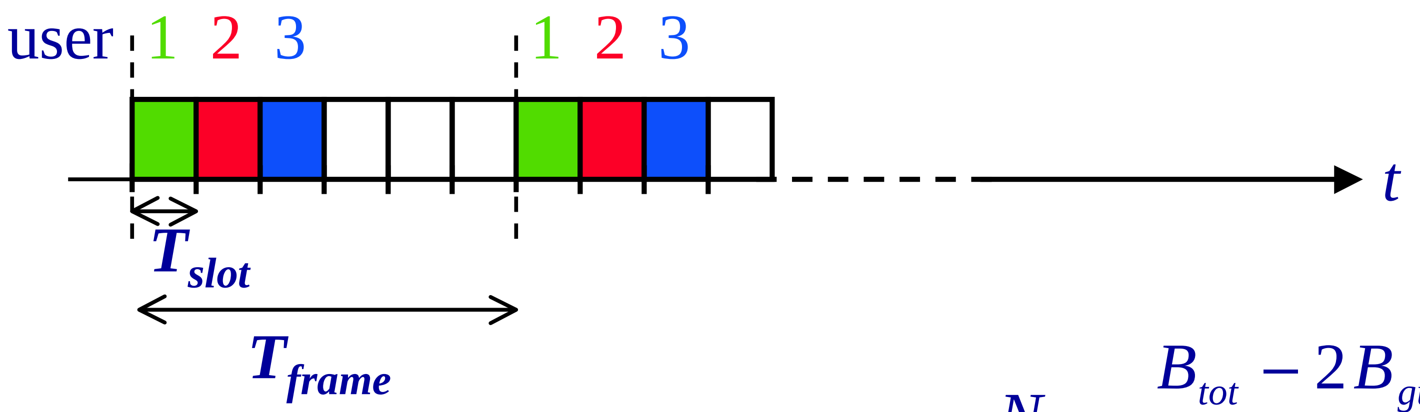


- User separation by LO + narrowband filter
- Crystals define orthogonality
- Spectral leakage: guard band, accurate crystals

Time Division Multiple Access

- Division of time space in (short) time slots
- Digital modulation required
  $\Rightarrow$ used for second generation, digital systems
- Used in combination with FDMA (MC)
- TDMA/offset-FDD or TDMA/TDD
- User separation by time windows (guard time)

TDMA



$$N_c = \frac{B_{tot} - 2B_{guard}}{\Delta f} \cdot \frac{T_{frame}}{T_{slot}}$$

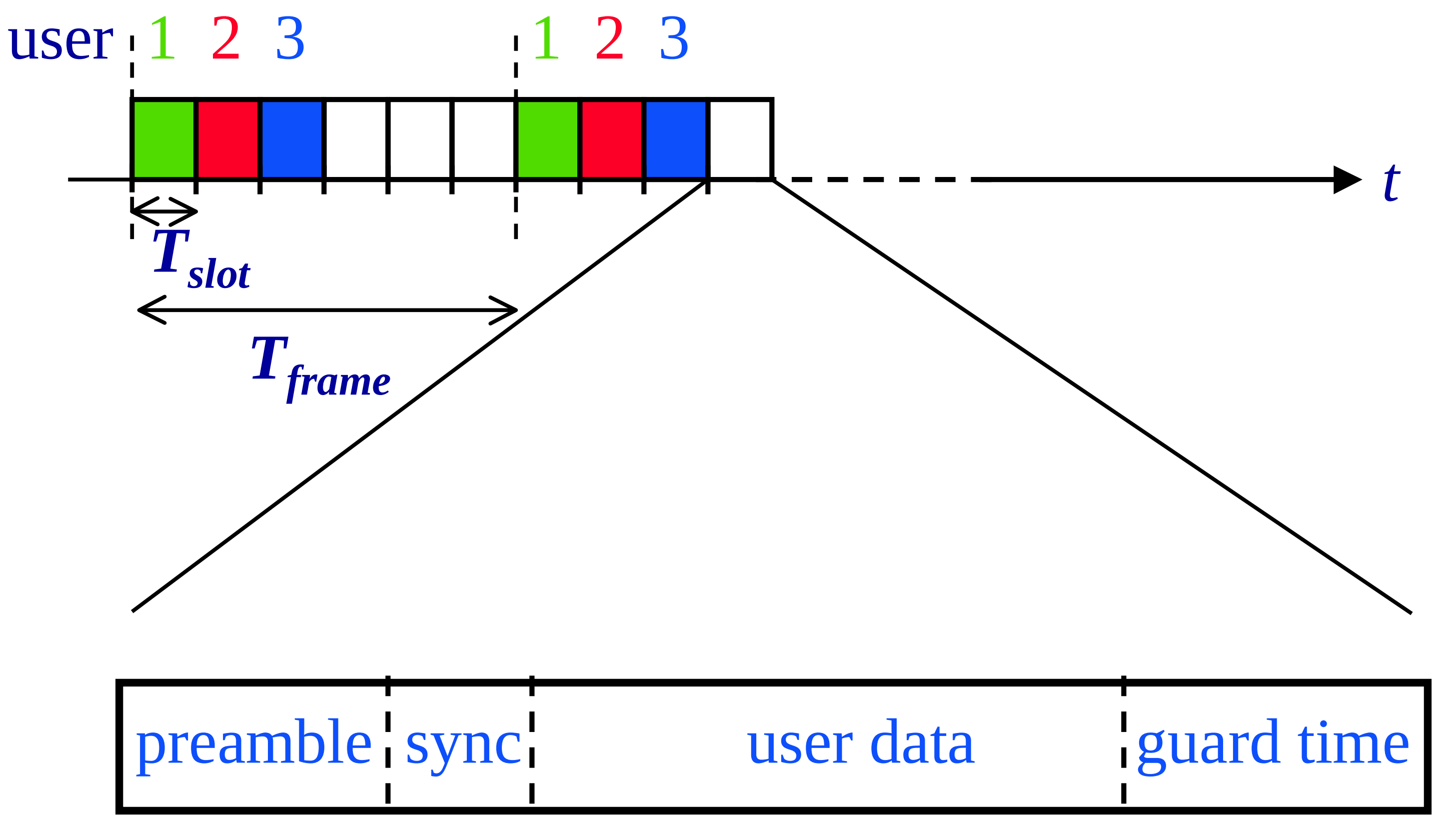
Drawbacks:

- Adaptive equalizer required
- Synchronization overhead (including guard times)

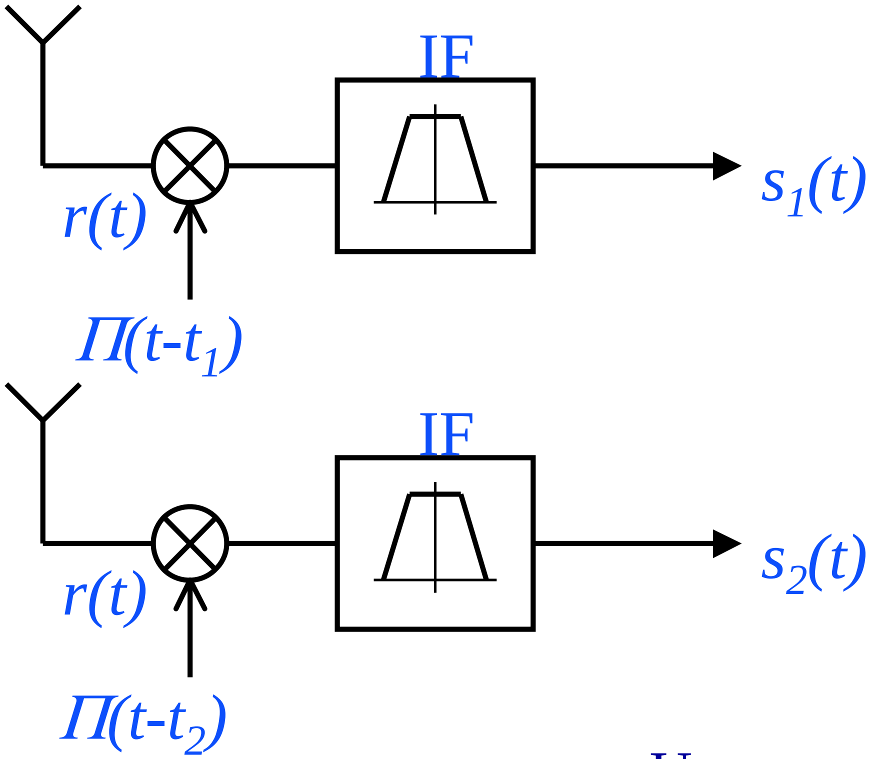
Advantages:

- Dynamic slot allocation
- Discontinuous transmission

TDMA burst


user
1 2 3
1 2 3
t
T_{slot}
T_{frame}
preamble
sync
user data
guard time

TDMA receivers



- User separation by time window
- Time synchronization determines orthogonality
- Time leakage: guard times, time advance

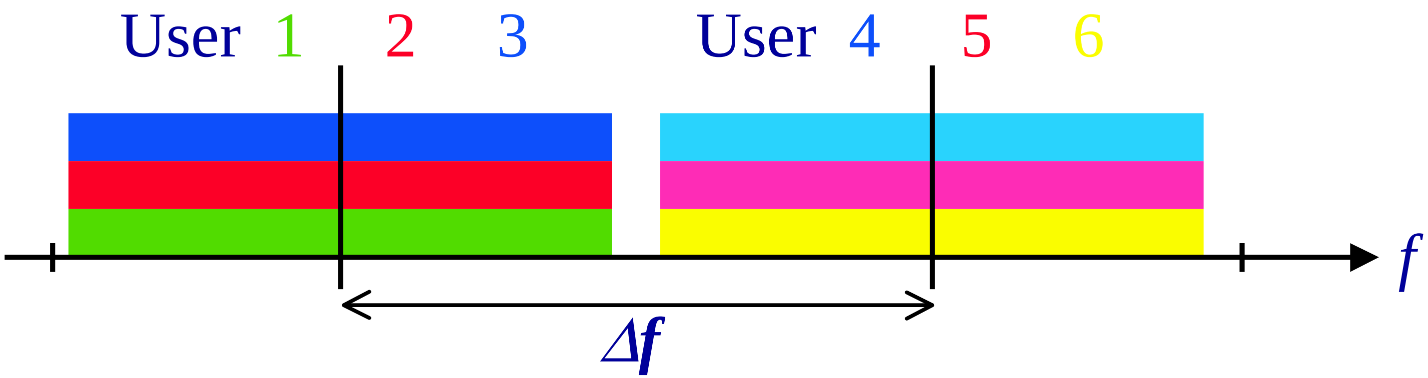
Code Division Multiple Access

- **Division of signal space in codes**

- **DS-CDMA**
  - spreading chip sequence (signature)
  - fading resistant (RAKE)
  - soft capacity (interference diversity)
  - macro diversity

- **FH-CDMA**
  - spreading hop sequence
  - near-far resistant (filters)

DS-CDMA



$$N_c = \frac{B_{tot} - 2B_{guard}}{\Delta f} \cdot N_{codes}$$

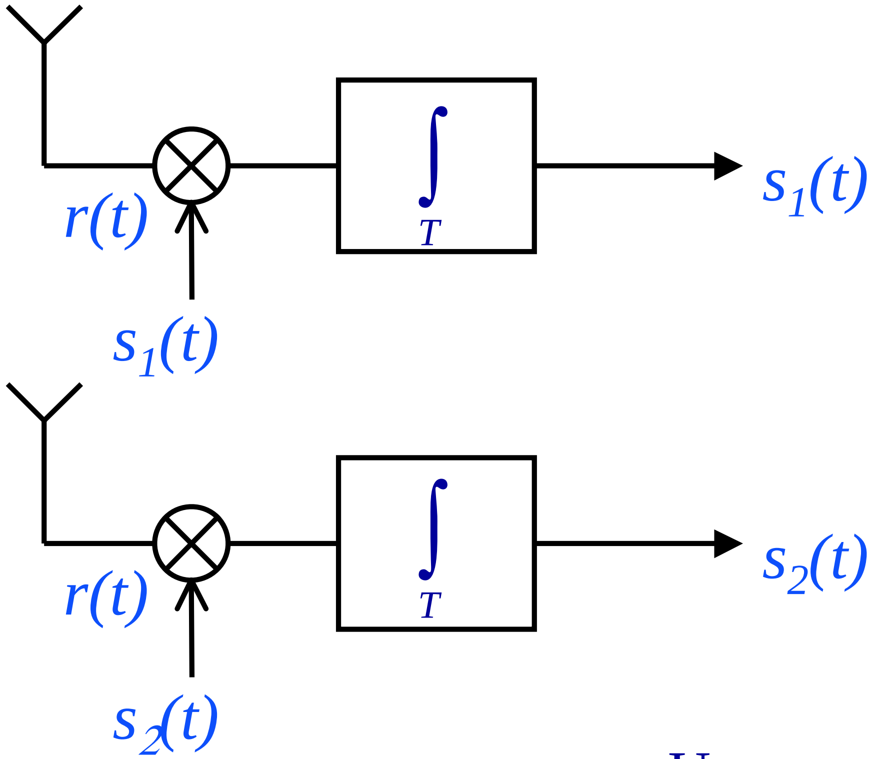
Drawbacks:

- Power control required
- Synchronization overhead

Advantages:

- Dynamic code allocation
- Interference/frequency diversity

DS-CDMA receivers



- User separation by spreading code
- Synchronization orthogonality
- Cross-correlation leakage

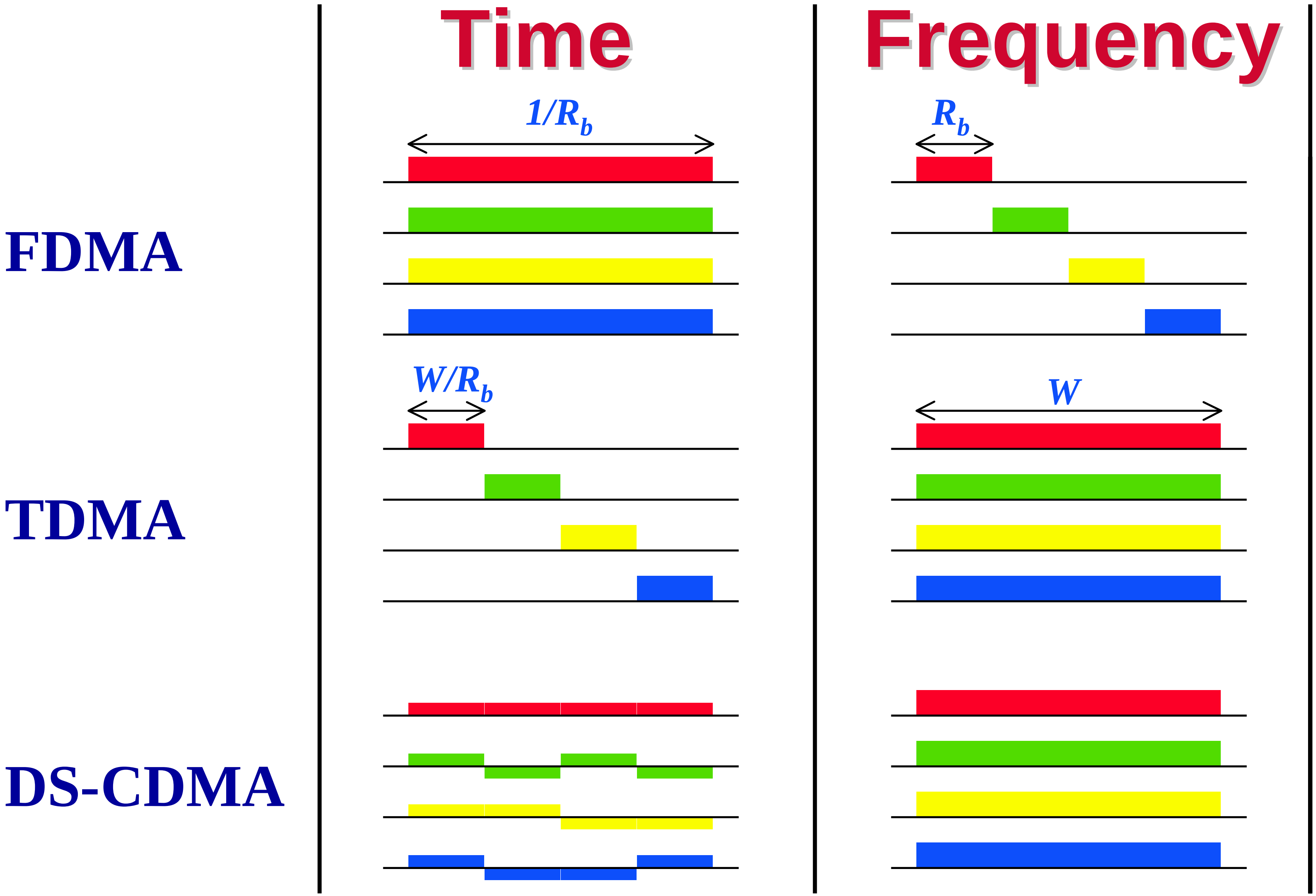
Capacity

- **User data rate R_b, spectrum band W**

- **FDMA**
  channel BW R_b
  $$N_{c,FDMA} = \frac{W}{R_b}$$

- **TDMA**
  # of slots is bit time/symbol time
  $$N_{c,TDMA} = \frac{W}{R_b}$$

- **DS-CDMA**
  # of orthogonal codes is processing gain
  $$N_{c,CDMA} = \frac{W}{R_b}$$


Time
Frequency
1/R_b
R_b
FDMA
W/R_b
W
TDMA
DS-CDMA

Second-order effects

- **Interference diversity (soft capacity)**
  - DS-CDMA
  - FH-TDMA

- **Orthogonality**
  - extra guard bands in FDMA
  - synchronization overhead in TDMA and CDMA

- **Fading**
  - extra link margin FDMA and TDMA
  - RAKE in DS-CDMA
  - Equalizer in TDMA

- **Dynamic bandwidth allocation**
  - multi slots for TDMA
  - multi codes for DS-CDMA

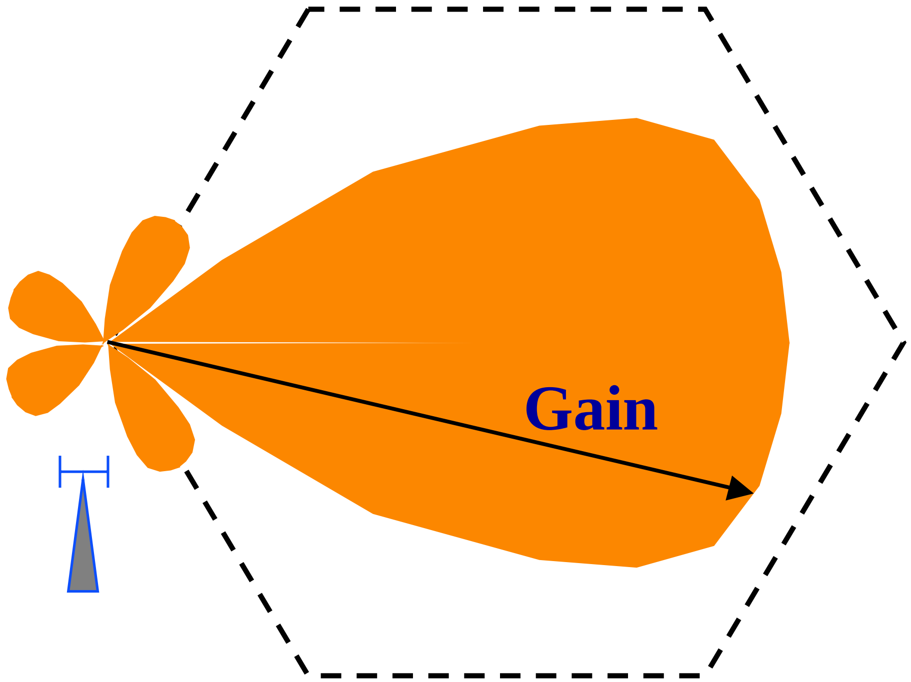
Hybrid systems

- **Combination with FDMA (Multi Carrier)**
  - in almost all cases since $B_{tot} >> W$
- **Combination with hopping**
  - DS/FH CDMA
  - FH TDMA (TDFH)
- **TCDMA**
  - TDMA with CDMA
  - avoiding near-far problem
  - Equalizer in TDMA

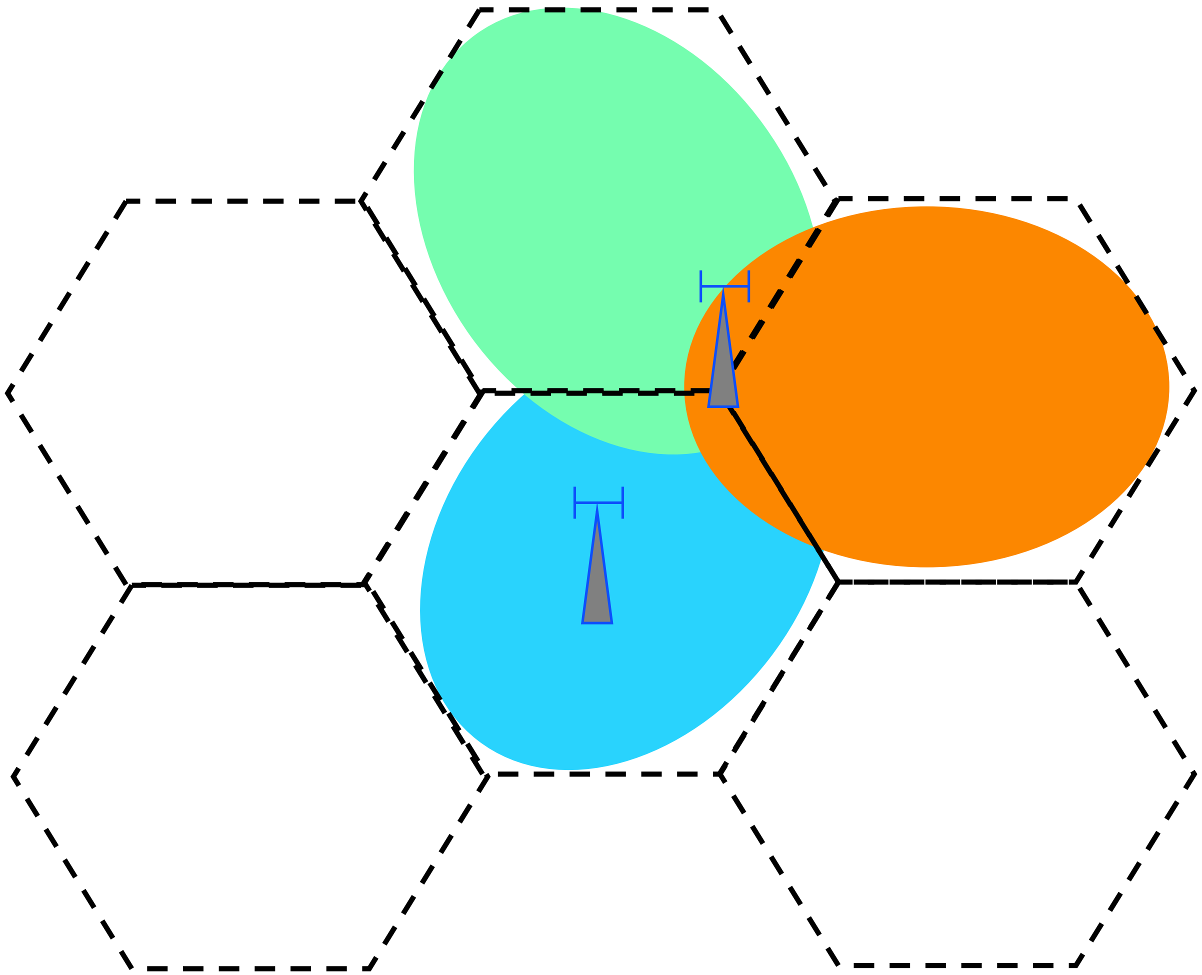
Space Division Multiple Access

- **Division of space in sectors**
- **Directional antennas**
  - fixed beam antennas
  - adaptive (smart) antennas
- **Capacity**
  - determined by antenna diagram
  - depends on beam width of main lobe
  - depends on side lobes
- **Combination with any other MA technique**

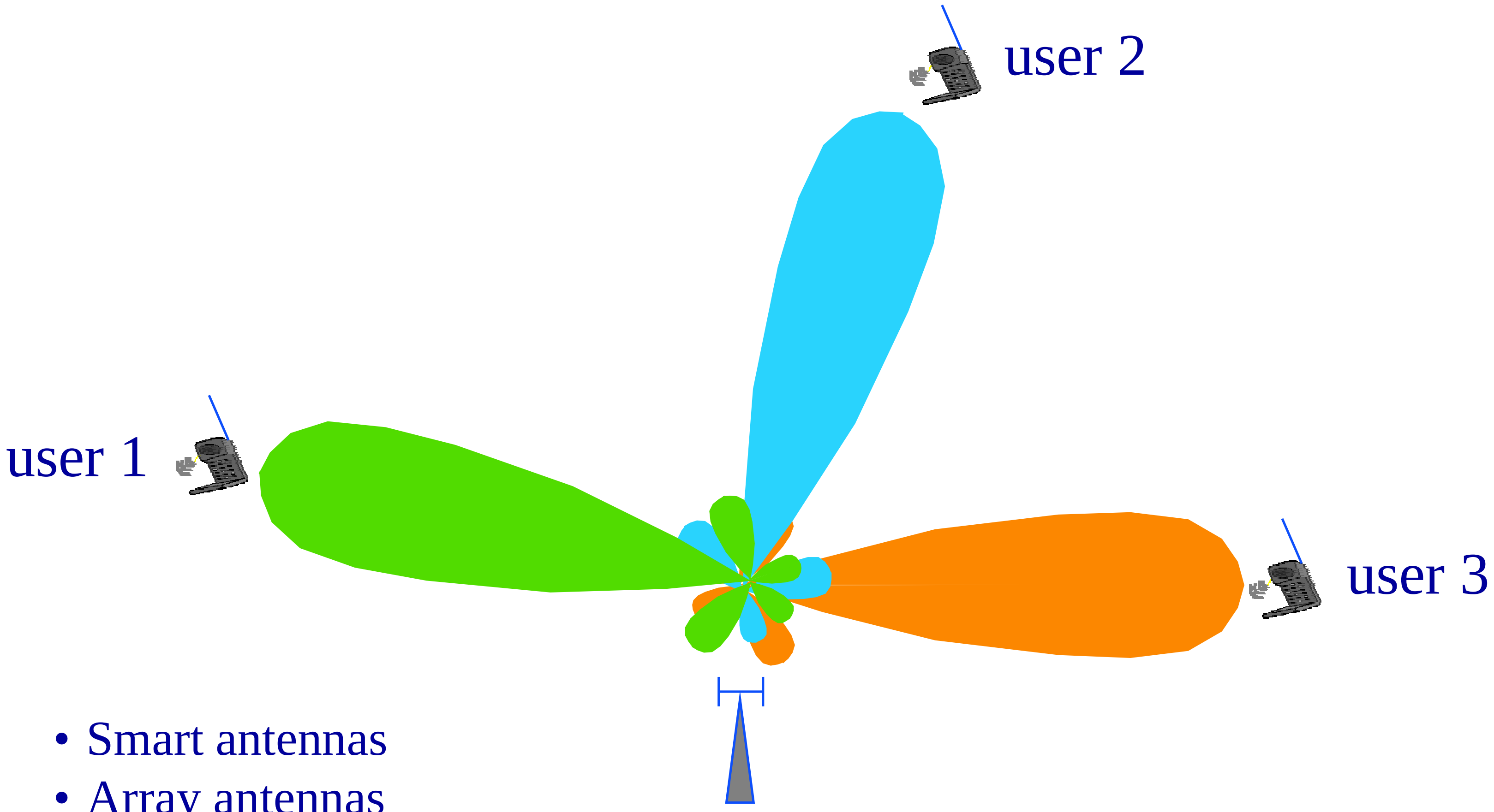
SDMA: directional antennas



SDMA: 120° Sectorization



SDMA

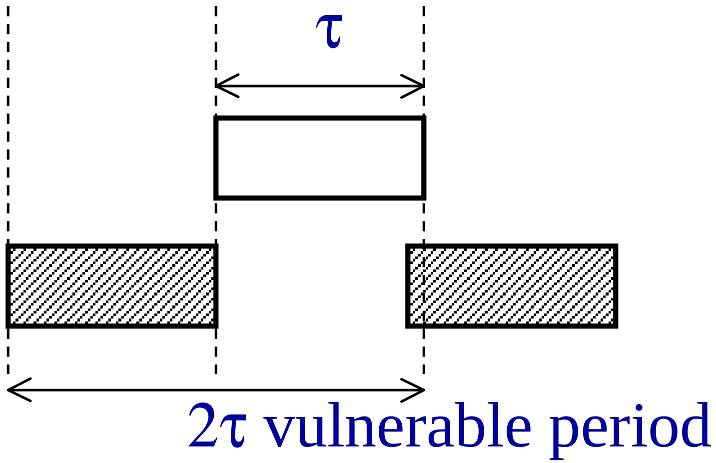


- Smart antennas
- Array antennas
- Pencil beams
- Tracking

Packet radio

- **Single channel (medium)**
- **Multiple users access same medium**
  - medium access control (MAC)
  - uncoordinated
    - random access
    - contention based
    - collisions
  - coordinated
    - scheduled access
    - contention free (reserved)
  - hybrid (combination of contention and contention-free)
  - push-to-talk

Throughput



- Constant packet length τ seconds
- Fixed data rate
- Random packet generation λ packets/s
- Poisson arrival distribution

$$R = \lambda \cdot \tau$$

$$T_{ch} = \lambda \cdot \tau \cdot \Pr(no\ collision)$$

$$\Pr(n\ arrivals\ \ within\ \ \tau) = \frac{R^n e^{-R}}{n!}$$

$$\Pr(0\ arrivals\ \ within\ \ \tau) = e^{-R}$$

ALOHA

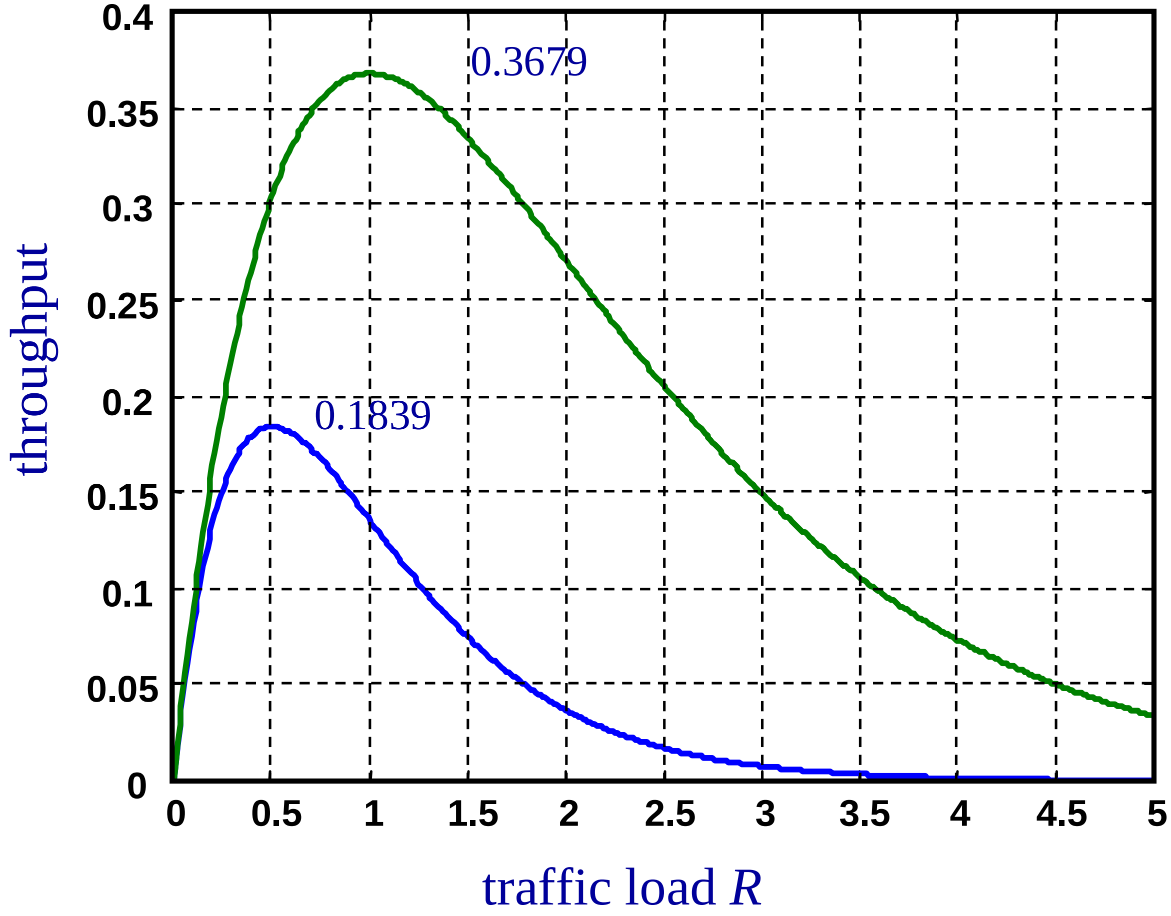
Pure ALOHA:

- Random access at any time
- Vulnerable period 2τ
- Collision probability $\Pr(0\ arrivals\ \ within\ \ 2\tau) = e^{-2R}$
- Throughput $T_{ch} = R \cdot e^{-2R}$

Slotted ALOHA:

- Random access at slot boundary only
- Vulnerable period τ
- Collision probability $\Pr(0\ arrivals\ \ within\ \ \tau) = e^{-R}$
- Throughput $T_{ch} = R \cdot e^{-R}$

Througput ALOHA



CSMA protocols

Carrier sense:

- Listen to channel
- Retry after random delay

CSMA/CD:

- Collision Detect
- Listen-while-talk
- Not for radio

CSMA/CA:

- Collision Avoidance
- Listen-before-talk

FOR NEXT TIME

- Read:
  Chapter 9: §9.1-9.5, 9.7, 9.8, 9.10
  Articles: HIPERLAN type 2
  IEEE 802.11 WLAN

- Solve problems:
  Chapter 5: 5.18, 5.20
  Chapter 8: 8.1, 8.2, 8.3, 8.7, 8.8, 8.12, 8.13