Wireless Networks: Medium Access Control

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Slides adapted from "Mobile Communications" by J. Schiller

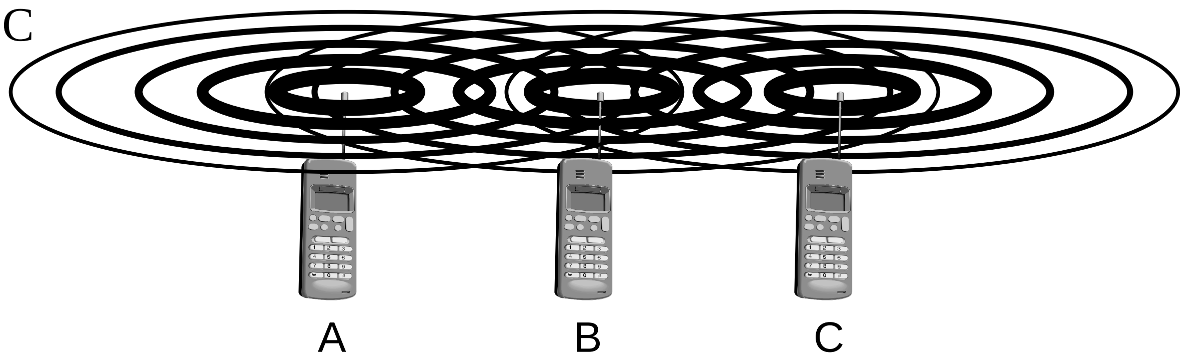
Motivation

- Can we apply media access methods from fixed networks?

- Example CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Problems in wireless networks
  - signal strength decreases proportional to the square of the distance
  - the sender would apply CS and CD, but the collisions happen at the receiver
  - it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
  - furthermore, CS might not work if, e.g., a terminal is “hidden”

Motivation - hidden and exposed terminals

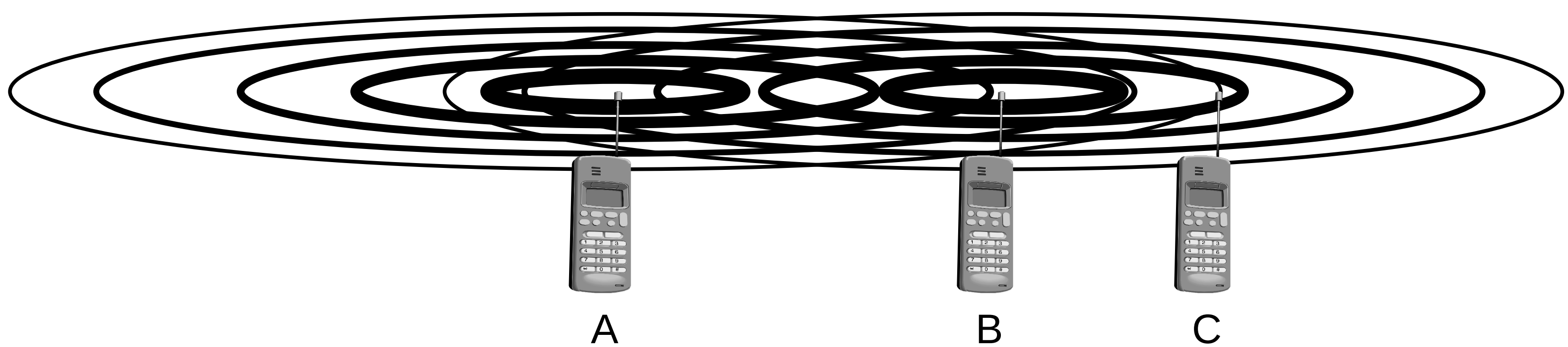
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a “free” medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is “hidden” for C



- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is “exposed” to B

Motivation - near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A's signal
  - C cannot receive A



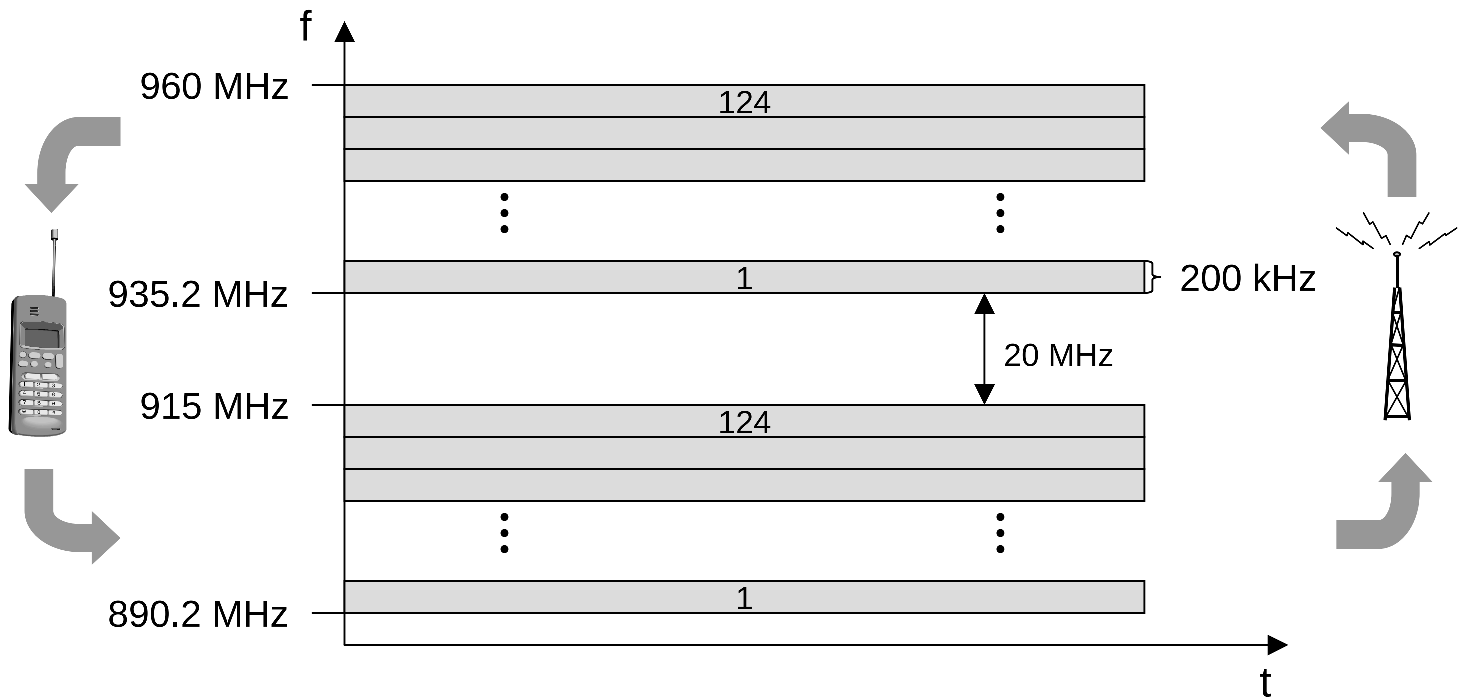
- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks - precise power control needed!

Access methods SDMA/FDMA/TDMA

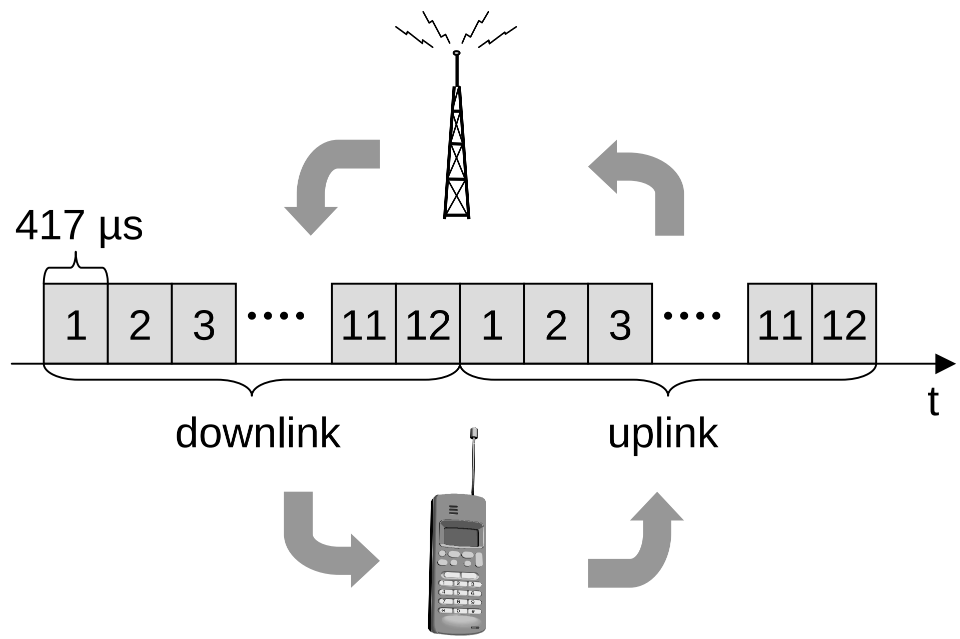
- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- 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

- The multiplexing schemes are now used to control medium access!

FDD/FDMA - general scheme, example GSM



TDD/TDMA - general scheme, example DECT



Frequency Division Multiple Access

- Concept:
  - assign different frequency bands to different users
  - no sharing of a frequency band between two users
  - user separation using band-pass filters
  - continuous flow
  - two-way: two frequency bands or Time Division Duplex (TDD)
- Advantages: simple receivers
  - longer symbol duration: no-need for equalization
    - low inter-symbol interference
    - e.g., 50kb/s QPSK =>40 μs >> 1-10μs delay spread
- Drawbacks:
  - frequency guard bands, costly tight RF band-filters,
  - long fading duration: need slow frequency hopping
  - may need spatial diversity (multiple antennas/beam forming) Rx/Tx

Frequency Selection

- Frequency management:
  - Fixed (cellular phones-base stations): reuse factor
  - On demand (cellular phones-mobile terminals)
  - Dynamic (cordless/WLAN): based on sensing interference levels
  - Problems: congestion management, dynamic load, …

- Antenna implications:
  - High antennas (e.g., 50m): higher coverage but higher interference between base stations (need for synchronization)
  - Low antennas: higher attenuation, lower coverage, better reuse

- Conclusion:
  - Pure FDMA is only interesting for simple cordless systems (CT-2)

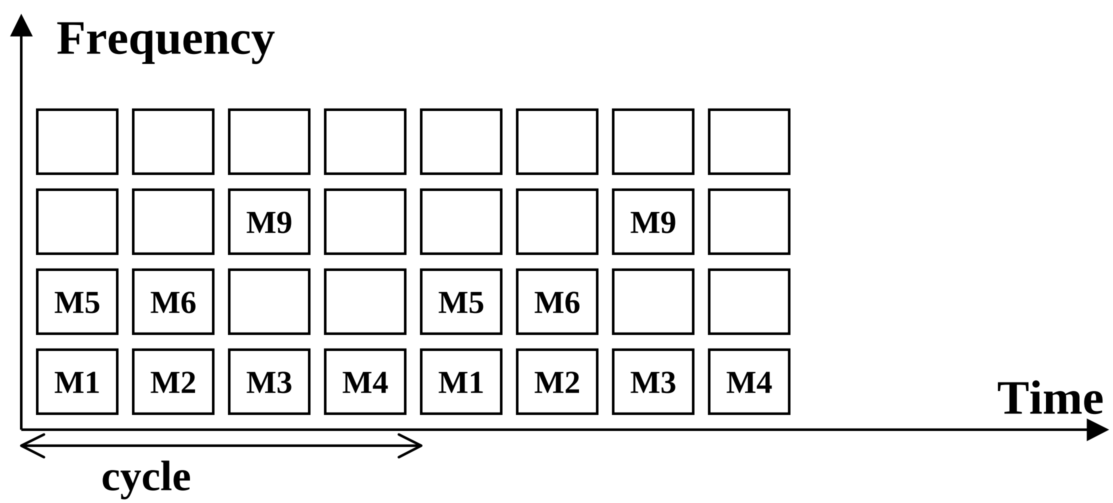
Time Division Multiple Access

- Concept:
  - use the same frequency over non-overlapping periods of time
- Advantages:
  - simple filters (window)
  - transmit and receive over the same frequency channel
- Drawbacks:
  - users must be synchronized with BS (master clock over a BCH)
  - guard times: common 30-50μs, may be less in recent systems
  - short symbol duration: need for equalization, training sequences...
    - high inter-symbol interference
    - e.g., 50Kbps, QPSK, 8 users:
      - 5 μs symbol duration
      - delay spread: 1μs (cordless), upto 20μs for cellular

FDMA/TDMA

- First channel allocation:
  - random access channel (RACH) to send short requests
  - ALOHA type protocol over the RACH

- One can use both FDMA and TDMA
  - examples: GSM system, D-AMPS



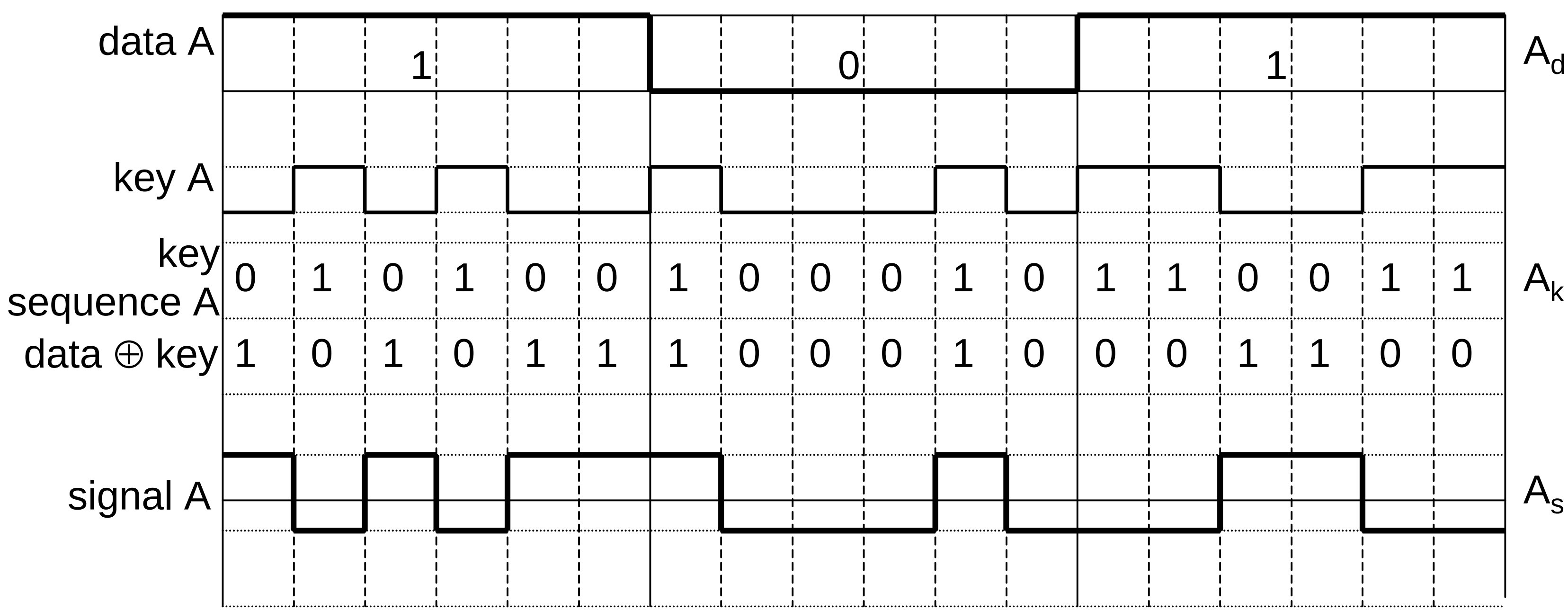
Access method CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
  - codes generate signals with "good-correlation" properties
  - signals from another user appear as "noise" (use spread spectrum technology)
  - signals are spread over a wideband using pseudo-noise sequences (e.g., each sender has a unique random number, the sender XORs the signal with this random number)
  - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function
- Disadvantages:
  - higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have the same strength at a receiver (near-far effect)
- Advantages:
  - all terminals can use the same frequency => no planning needed; macrodiversity
  - huge code space (e.g. 2^{32}) compared to frequency space
  - interferences (e.g. white noise) is not coded
  - forward error correction and encryption can be easily integrated

CDMA in theory

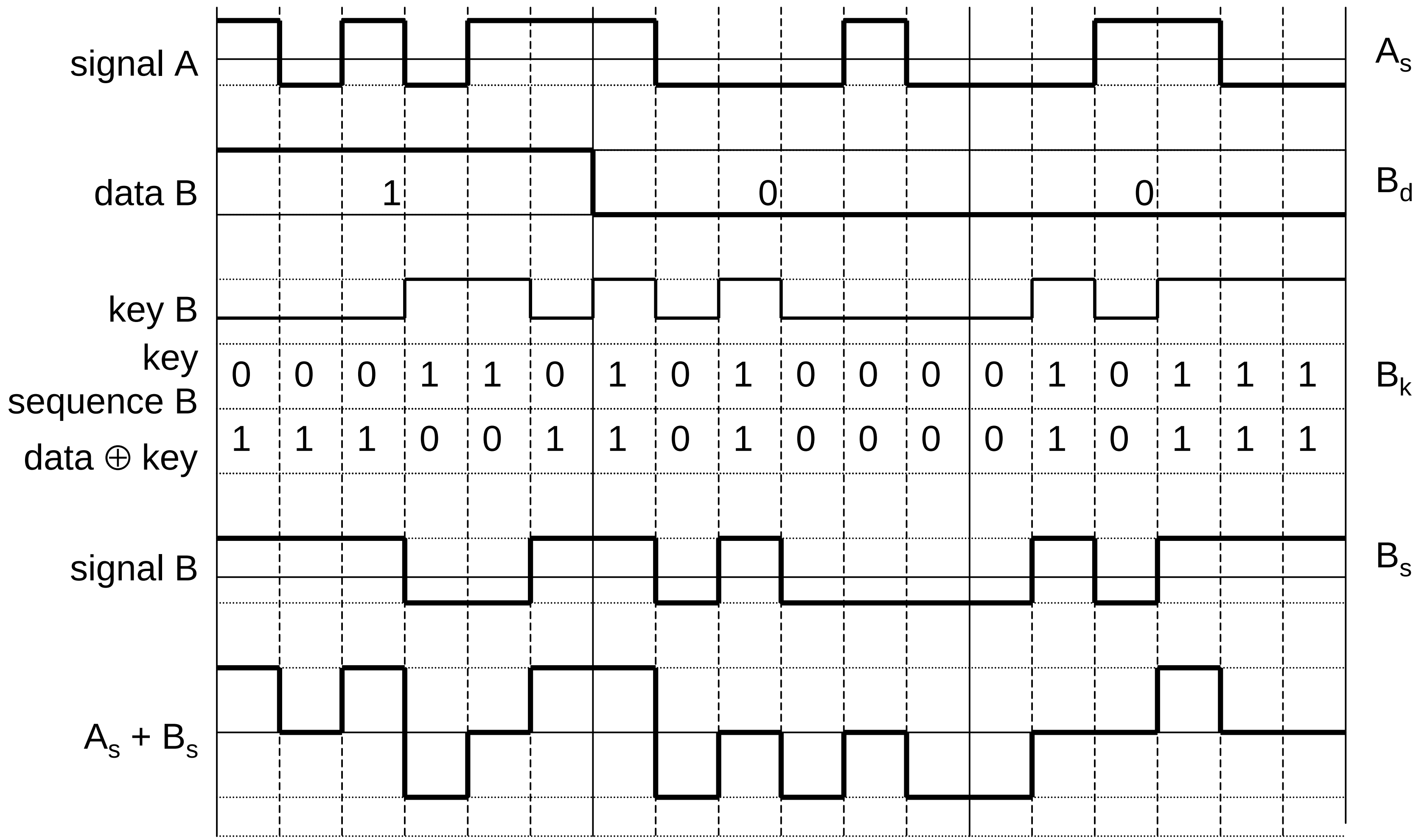
- Sender A
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0“= -1, „1“= +1)
  - sending signal $A_s = A_d * A_k = (-1, +1, -1, -1, +1, +1)$
- Sender B
  - sends $B_d = 0$, key $B_k = 110101$ (assign: „0“= -1, „1“= +1)
  - sending signal $B_s = B_d * B_k = (-1, -1, +1, -1, +1, -1)$
- Both signals superimpose in space
  - interference neglected (noise etc.)
  - $A_s + B_s = (-2, 0, 0, -2, +2, 0)$
- Receiver wants to receive signal from sender A
  - apply key A_k bitwise (inner product)
    - $A_e = (-2, 0, 0, -2, +2, 0) \bullet A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was „1“
  - receiving B
    - $B_e = (-2, 0, 0, -2, +2, 0) \bullet B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6$, i.e. „0“

CDMA on signal level I

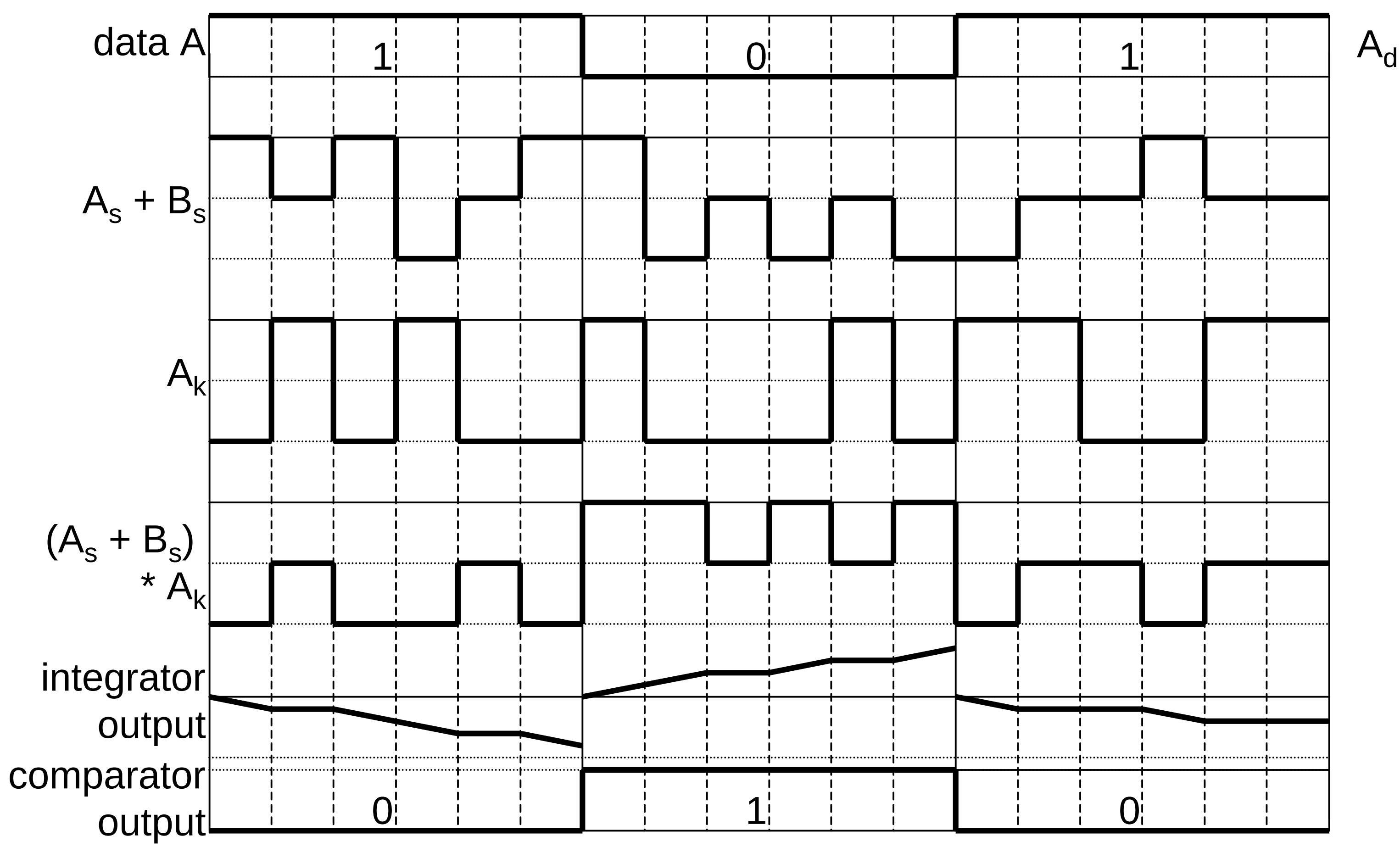


Real systems use much longer keys resulting in a larger distance between single code words in code space.

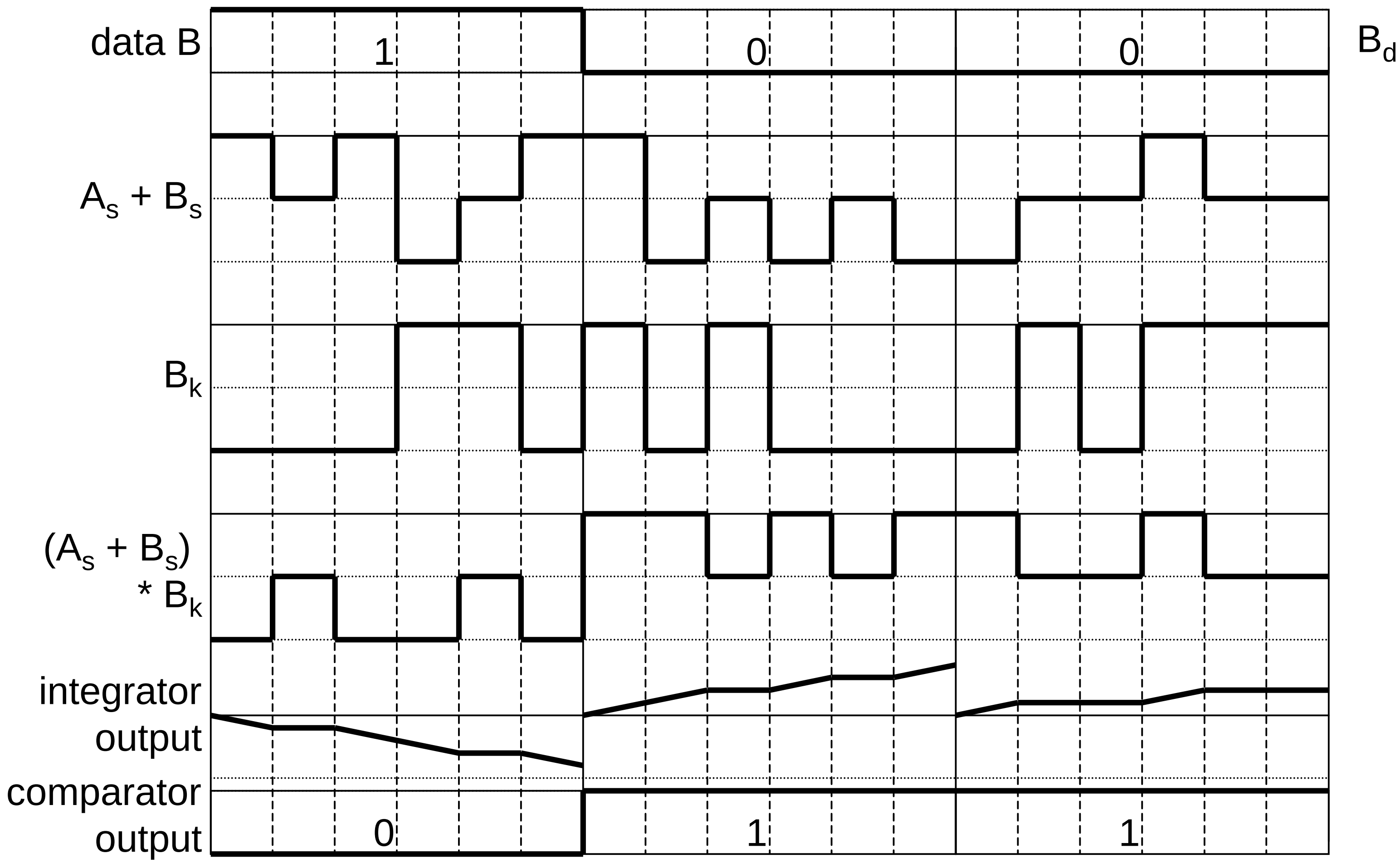
CDMA on signal level II



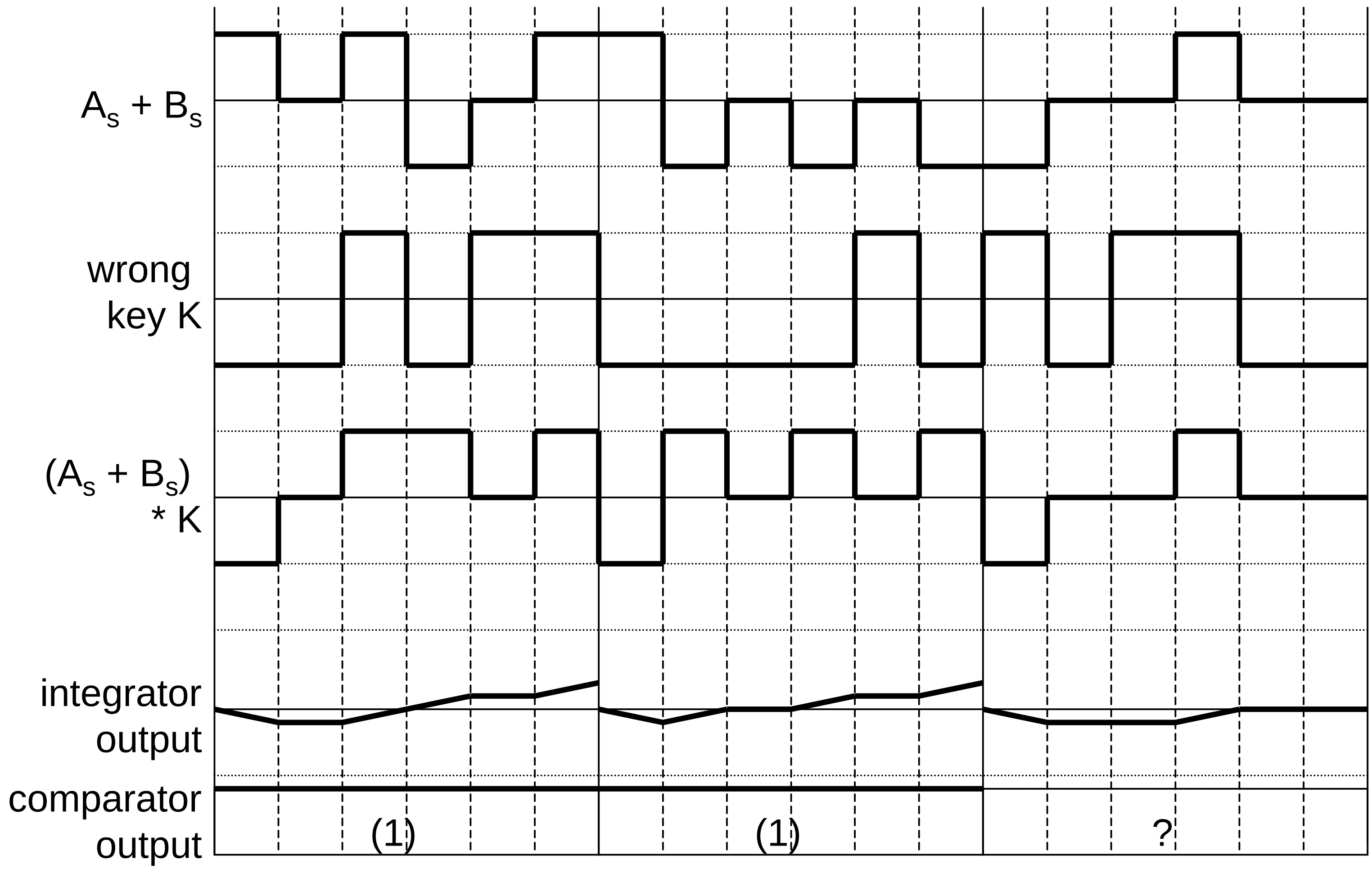
CDMA on signal level III



CDMA on signal level IV

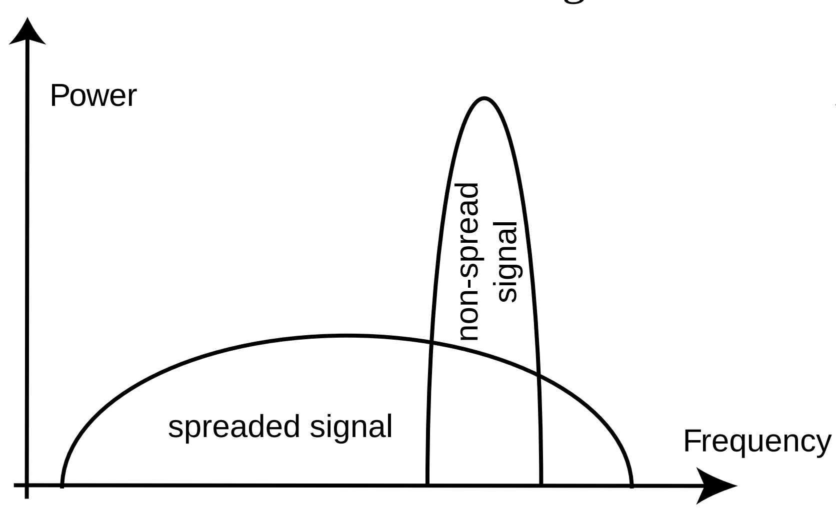


CDMA on signal level V

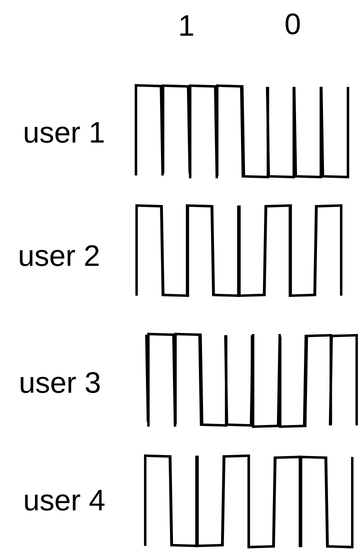


CDMA: Direct Sequence

- Each mobile is allocated a PN sequence:
- The elements of the PN-sequence are called chips
- To transmit one bit 1/0 send the PN-Seq/inv-PN-Seq
- Example Hadamard Matrix:
  - Each mobile uses one row
  - The rows are orthogonal

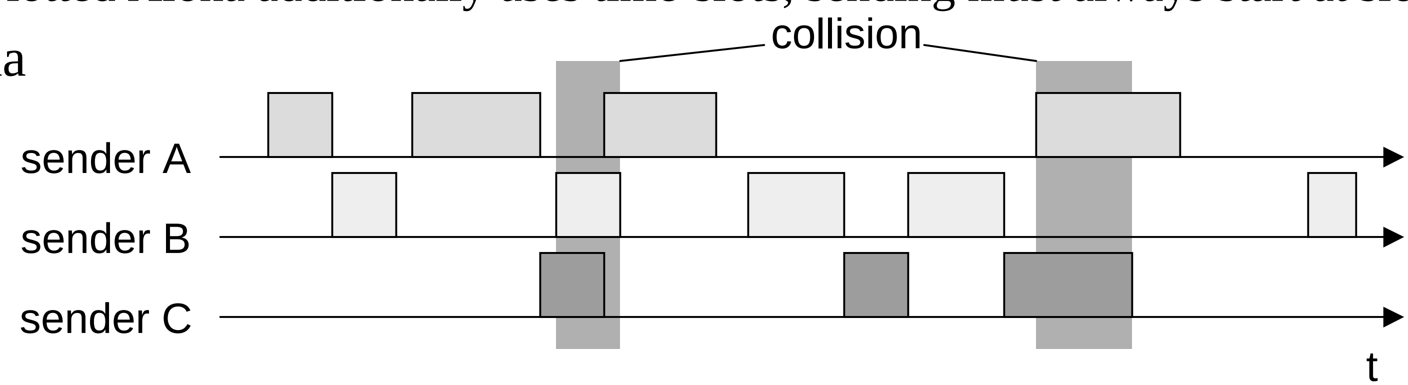


$$H_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

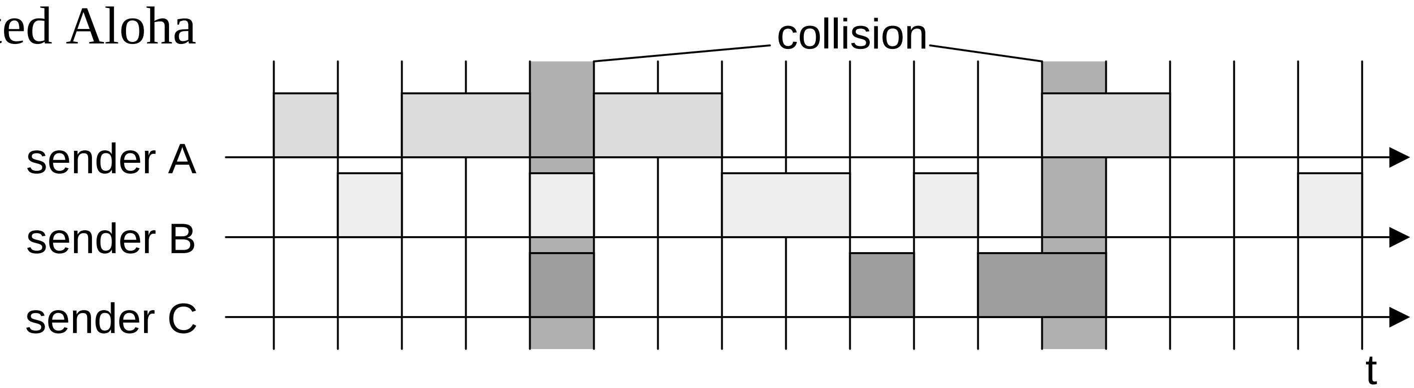


Aloha/slotted aloha

- Mechanism
  - random, distributed (no central arbiter), time-multiplex
  - Slotted Aloha additionally uses time-slots, sending must always start at slot boundaries
- Aloha



- Slotted Aloha



Carrier Sense Protocols

Use the fact that in some networks you can *sense* the medium to check whether it is currently free

- 1-persistent CSMA
- non-persistent CSMA
- p-persistent protocol
- CSMA with collision Detection (CSMA/CD): not applicable to wireless systems

- 1-persistent CSMA
  - when a station has a packet:
    - it waits until the medium is free to transmit the packet
    - if a collision occurs, the station waits a random amount of time
  - first transmission results in a collision if several stations are waiting for the channel

Carrier Sense Protocols (*Cont'd*)

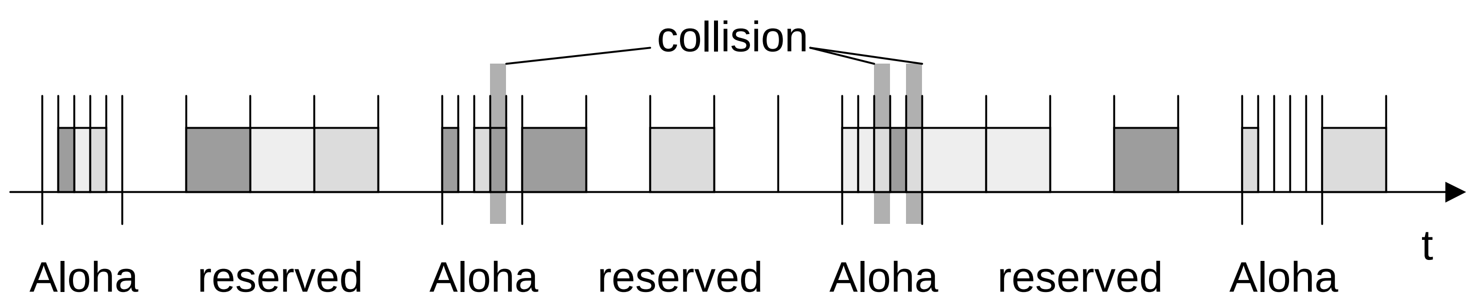
- non-persistent CSMA
  - when a station has a packet:
    - if the medium is free, transmit the packet
    - otherwise wait for a random period of time and repeat the algorithm
  - higher delays, but better performance than pure ALOHA
- p-persistent protocol
  - when a station has a packet wait until the medium is free:
    - transmit the packet with probability p
    - wait for next slot with probability $1-p$
  - better throughput than other schemes but higher delay
- CSMA with collision Detection (CSMA/CD)
  - stations abort their transmission when they detect a collision
  - e.g., Ethernet, IEEE802.3 but not applicable to wireless systems

DAMA - Demand Assigned Multiple Access

- Channel efficiency only 18% for Aloha, 36% for Slotted Aloha (assuming Poisson distribution for packet arrival and packet length)
- Reservation can increase efficiency to 80%
  - a sender *reserves* a future time-slot
  - sending within this reserved time-slot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite links
- Examples for reservation algorithms:
  - *Explicit Reservation according to Roberts (Reservation-ALOHA)*
  - *Implicit Reservation (PRMA)*
  - *Reservation-TDMA*

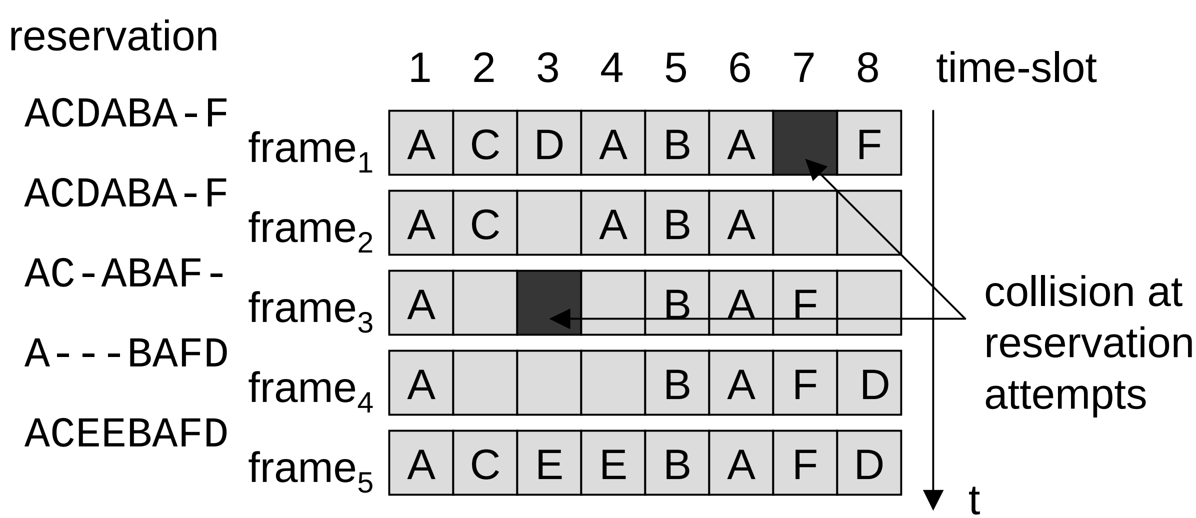
Access method DAMA: Explicit Reservation

- Explicit Reservation (Reservation Aloha):
  - two modes:
    - *ALOHA mode* for reservation:
      competition for small reservation slots, collisions possible
    - *reserved mode* for data transmission within successful reserved slots (no collisions possible)
  - it is important for all stations to keep the reservation list consistent at any point in time and, therefore, all stations have to synchronize from time to time



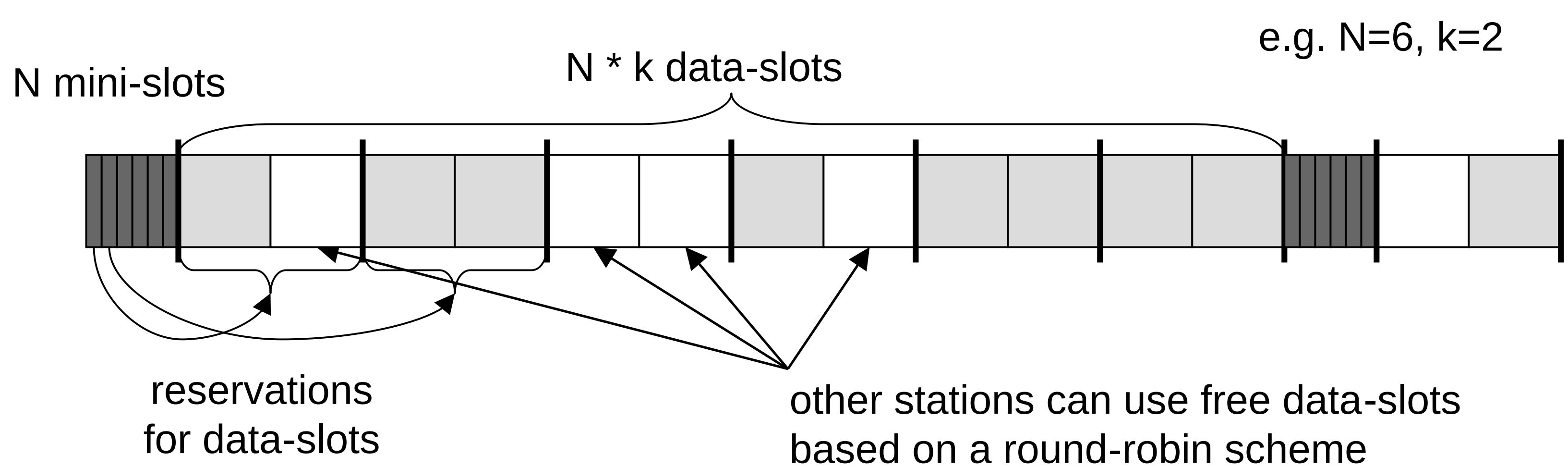
Access method DAMA: PRMA

- Implicit reservation (PRMA - Packet Reservation MA):
  - a certain number of slots form a frame, frames are repeated
  - stations compete for empty slots according to the slotted aloha principle
  - once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames as long as the station has data to send
  - competition for this slots starts again as soon as the slot was empty in the last frame



Access method DAMA: Reservation-TDMA

- Reservation Time Division Multiple Access
  - every frame consists of N mini-slots and x data-slots
  - every station has its own mini-slot and can reserve up to k data-slots using this mini-slot (i.e. $x = N * k$).
  - other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)



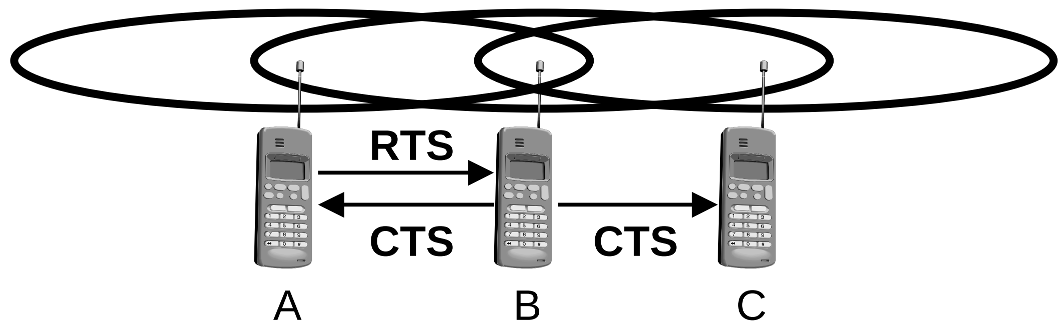
MACA - collision avoidance

- MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - RTS (request to send): a sender request the right to send from a receiver with a short RTS packet before it sends a data packet
  - CTS (clear to send): the receiver grants the right to send as soon as it is ready to receive
- Signaling packets contain
  - sender address
  - receiver address
  - packet size

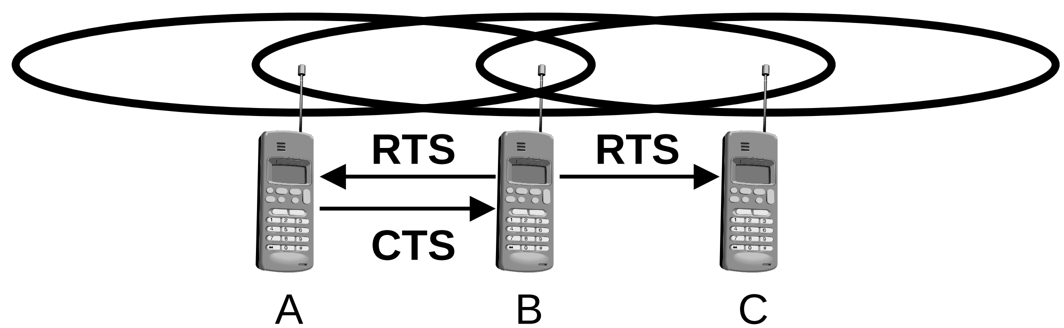
- Variants of this method can be found in IEEE802.11 as DFWMAC (Distributed Foundation Wireless MAC)

MACA examples

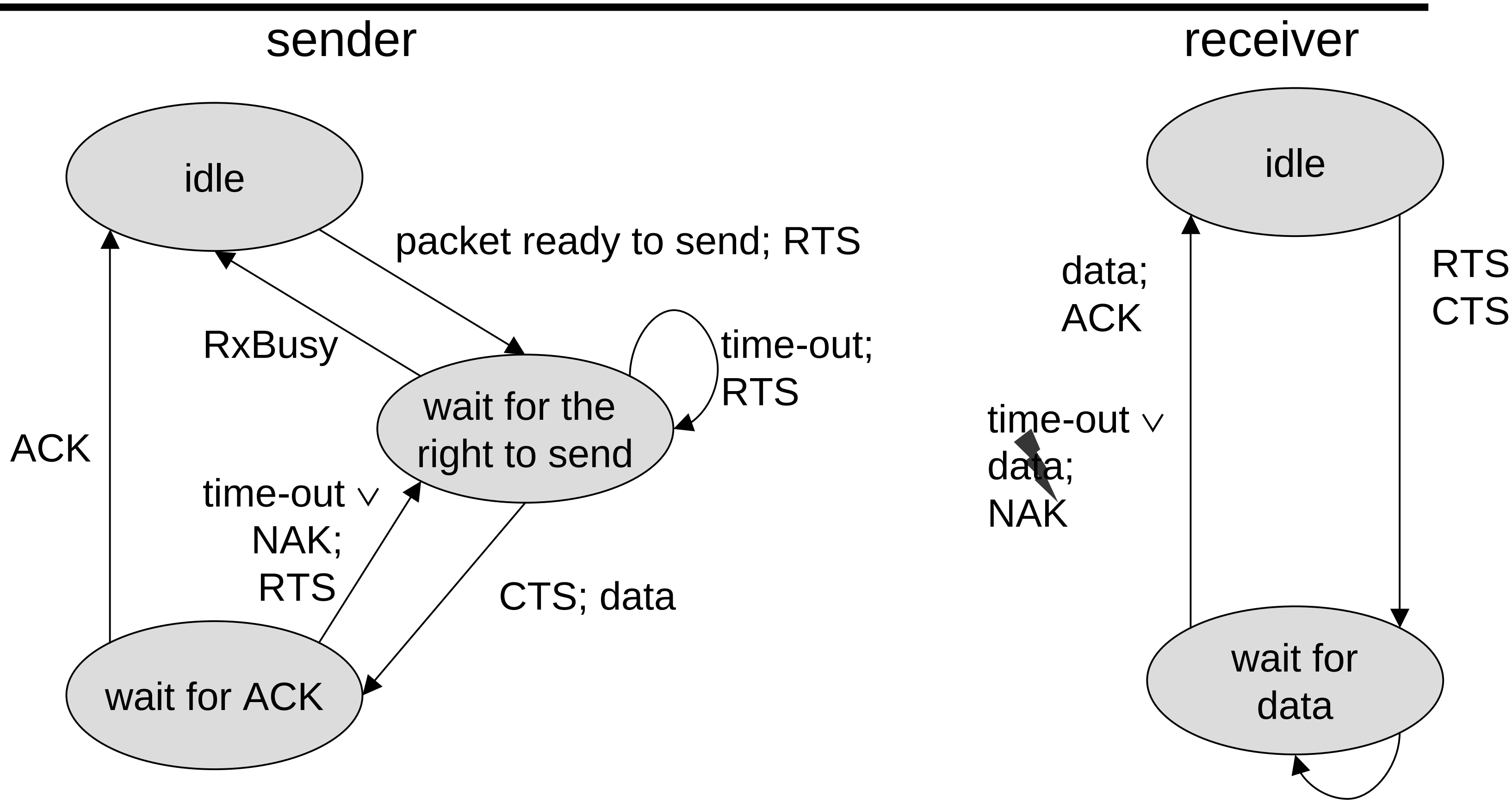
- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B



- MACA avoids the problem of exposed terminals
  - B wants to send to A, C to another terminal
  - now C does not have to wait for it cannot receive CTS from A



MACA variant: DFWMAC in IEEE802.11



ACK: positive acknowledgement
NAK: negative acknowledgement

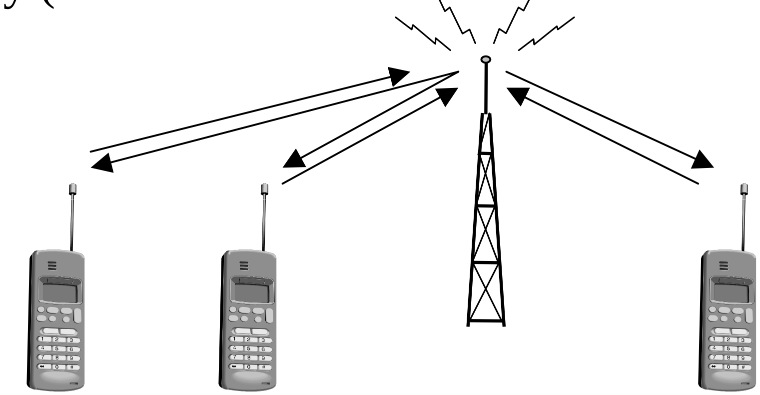
RxBusy: receiver busy

Polling mechanisms

- If one terminal can be heard by all others, this “central” terminal (a.k.a. base station) can poll all other terminals according to a certain scheme
  - now all schemes known from fixed networks can be used (typical mainframe - terminal scenario)
- Example: Randomly Addressed Polling
  - base station signals readiness to all mobile terminals
  - terminals ready to send can now transmit a random number without collision with the help of CDMA or FDMA (the random number can be seen as dynamic address) or with collisions (over the Random Access CHannel)
  - the base station now chooses one address for polling from the list of all random numbers (collision if two terminals choose the same address)
  - the base station acknowledges correct packets and continues polling the next terminal
  - this cycle starts again after polling all terminals of the list

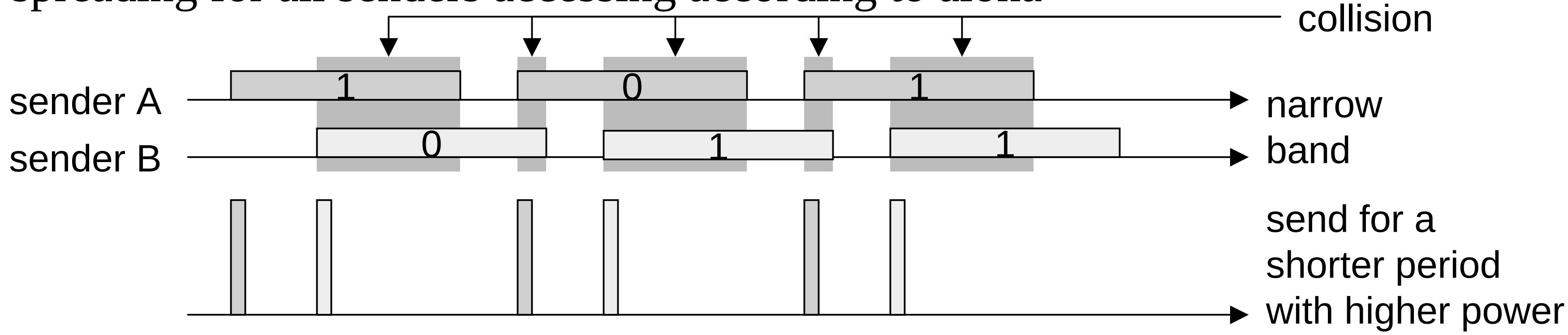
ISMA (Inhibit Sense Multiple Access)

- Current state of the medium is signaled via a “busy tone”
  - the base station signals on the downlink (base station to terminals) if the medium is free or not
  - terminals must not send if the medium is busy
  - terminals can access the medium as soon as the busy tone stops
  - the base station signals collisions and successful transmissions via the busy tone and acknowledgements, respectively (media access is not coordinated within this approach)
  - mechanism used, e.g., for CDPD (USA, integrated into AMPS)

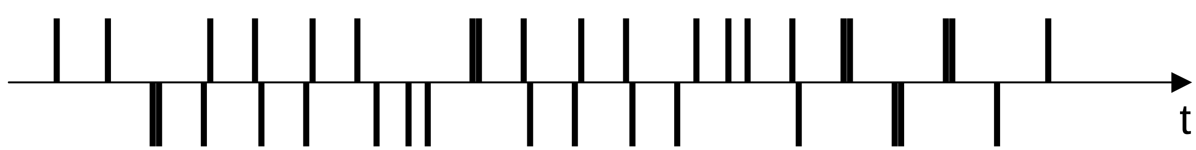


SAMA - Spread Aloha Multiple Access

- Aloha has only a very low efficiency, CDMA needs complex receivers to be able to receive different senders with individual codes at the same time
- Idea: use spread spectrum with only one single code (chipping sequence) for spreading for all senders accessing according to aloha



spread the signal e.g. using the chipping sequence 110101 („*CDMA without CD*")



Problem: find a chipping sequence with good characteristics

Comparison SDMA/TDMA/FDMA/CDMA

Approach	SDMA	TDMA	FDMA	CDMA
Idea	segment space into cells/sectors	segment sending time into disjoint time-slots, demand driven or fixed patterns	segment the frequency band into disjoint sub-bands	spread the spectrum using orthogonal codes
Terminals	only one terminal can be active in one cell/one sector	all terminals are active for short periods of time on the same frequency	every terminal has its own frequency, uninterrupted	all terminals can be active at the same place at the same moment, uninterrupted
Signal separation	cell structure, directed antennas	synchronization in the time domain	filtering in the frequency domain	code plus special receivers
Advantages	very simple, increases capacity per km^2	established, fully digital, flexible	simple, established, robust	flexible, less frequency planning needed, soft handover
Dis-advantages	inflexible, antennas typically fixed	guard space needed (multipath propagation), synchronization difficult	inflexible, frequencies are a scarce resource	complex receivers, needs more complicated power control for senders
Comment	only in combination with TDMA, FDMA or CDMA useful	standard in fixed networks, together with FDMA/SDMA used in many mobile networks	typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)	still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA

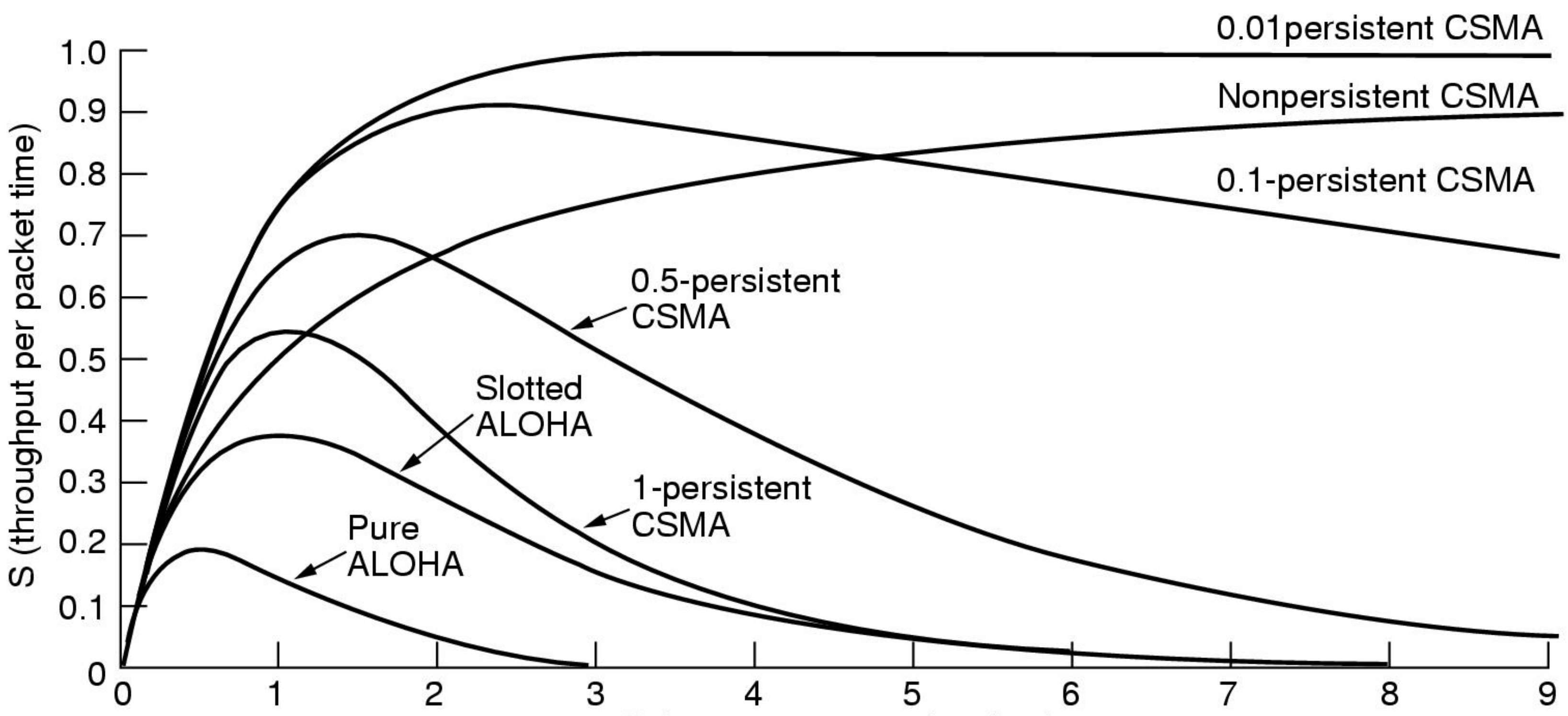
Throughputs of Some Random Access Protocols

Protocol	Throughput
Pure-ALOHA	$S = Ge^{-2G}$
Slotted-ALOHA	$S = Ge^{-G}$
Non slotted 1-persistent	$S = \frac{G[1+G+aG(1+G+aG/2)]e^{-G(1+2a)}}{G(1+2a)-(1-e^{-aG})+(1+aG)e^{-G(1+a)}}$
Slotted 1-persistent CSMA	$S = \frac{G[1+G-e^{-aG}]e^{-G(1+a)}}{(1+a)-(1-e^{-aG})+ae^{-G(1+a)}}$
Nonpersistent non slotted CSMA	$S = \frac{Ge^{-aG}}{(1+2a)+e^{-aG}}$
Nonpersistent slotted CSMA	$S = \frac{aGe^{-aG}}{1-e^{-aG}+a}$

G: load (includes both successful transmissions and retransmissions)

S: successful transmission

a: ratio of propagation delay to the packet transmission delay


S (throughput per packet time)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
0.01persistent CSMA
Nonpersistent CSMA
0.1-persistent CSMA
0.5-persistent CSMA
Slotted ALOHA
1-persistent CSMA
Pure ALOHA