Mobile Communications

Semester B, Mandatory modules, ECTS Units: 3

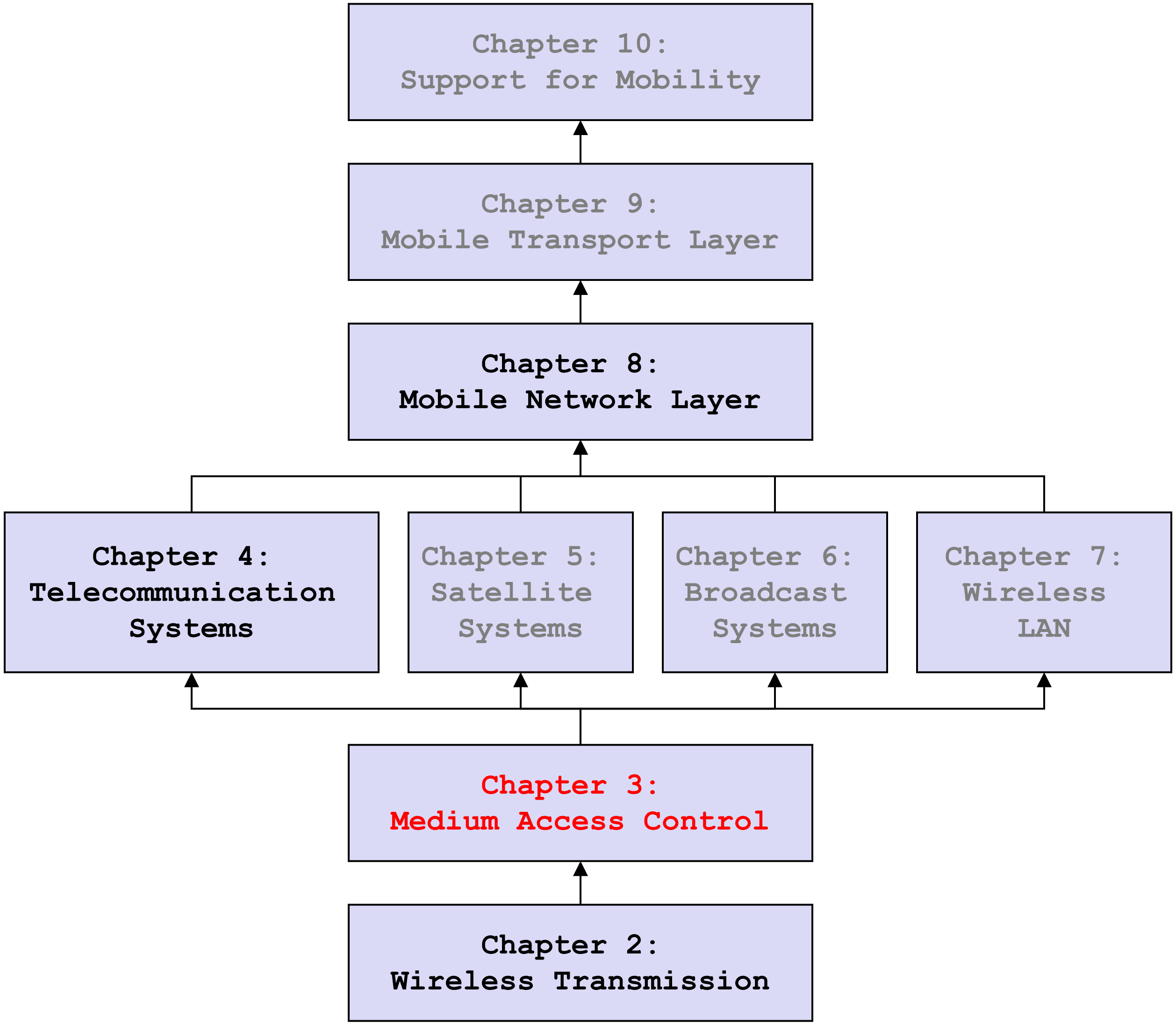
George Pavlides

http://georgepavlides.info

Book: Jochen H. Schiller, “Mobile Communications” Second Edition, Addison-Wesley, Pearson Education Limited, ISBN 0321123816

Presentation based on the course presentation by
Prof. Dr.-Ing. Jochen H. Schiller, Freie Universität Berlin - Computer Systems & Telematics

course outline



Medium Access Control

Motivation

SDMA, FDMA, TDMA

Aloha, reservation schemes

Collision avoidance, MACA

Polling

CDMA, SAMA

Comparison

MAC in the OSI model

- OSI - Open Systems Interconnection model
  - ISO/IEC 7498-1

7- Application: provides services & protocols to applications
- Protocols: FTP, DNS, Telnet, HTTP, SNMP, NFS

6- Presentation: provides coding and conversion functions to the application layer such as compression, decompression, encryption and decryption
- Protocols: Binary, ASCII, GIF, Encryption

5- Session: controls sessions - sets up, manages and tears down sessions between presentation layer entities
- Protocols: SMB, RPC, SQL, NetBIOS, SAP

4- Transport: provides flow control to prevent loss of data - supports reliable (connection-oriented, TCP) and unreliable (connectionless-oriented, UDP) data transport
- Protocols: TCP, UDP, SPX, SSL, TLS, SCTP

3- Network: end to end delivery logical addressing fragmentation for MTU Routing
- Protocols: IP, ICMP, IPsec, IGMP, IPX, AppleTalk

2- Data Link: provides media access(MAC) error detection and assembles frames from bits
- **Hubs, Switches or Bridges**
- **Protocols: ARP, PPP, PPTP, L2TP, Ethernet, Frame Relay**

1- Physical: media interface - sends and receive bits, provides specification voltage, wire speed and cable pin-outs
- Protocols: RS-232,DSL,POTS, BLUETOOTH, SONET/SDH, T1, E1

purpose for this chapter

- Introduction to several Medium Access Control (MAC) algorithms specifically adapted to the wireless domain
- Medium access control (MAC)
  - comprises all mechanisms that **regulate user access to a medium**
  - similar to **traffic regulations** in the highway
    - The fact that several vehicles use the same street crossing requires rules to avoid collisions; one mechanism to enforce these rules is traffic lights
  - **belongs to layer 2,** the data link control layer (DLC)
    - Layer 2 is subdivided into the **logical link control (LLC),** layer 2b, **and the MAC,** layer 2a (Halsall, 1996)
    - The task of DLC is to establish a reliable point to point or point to multi-point connection between different devices over a wired or wireless medium

layer 2: data link layer

- The data link layer provides the functional and procedural means
  - to **transfer data between network entities** and
  - to **detect and possibly correct errors** that may occur in the physical layer
- **Originally intended for point-to-point and point-to-multipoint media**, characteristic of wide area media in the telephone system
- LAN architecture, which included broadcast-capable multi-access media, was developed independently of the ISO work in IEEE Project 802
  - IEEE work assumed sub-layering and management functions not required for WAN use
- In modern practice
  - **only error detection**, not flow control using sliding window, is present in data link protocols such as Point-to-Point Protocol (PPP)
  - **on local area networks**, the **IEEE 802.2 LLC layer is not used** for most protocols on the Ethernet
  - on other local area networks, its **flow control and acknowledgment mechanisms are rarely used**
  - Sliding window flow control and acknowledgment is used at the transport layer by protocols such as TCP, but is still used in niches where X.25 offers performance advantages

MAC

- In the seven-layer OSI model, MAC is a sub-layer of the data link layer(layer 2)
- The MAC sub-layer
  - **provides addressing** and **channel access control mechanisms** that make it possible for several terminals or network nodes to communicate within a multiple access network that incorporates a shared medium, e.g. Ethernet
  - **acts as an interface between the logical link control (LLC) sub-layer and the network's physical layer**
  - **emulates a full-duplex logical communication channel** in a multi-point network
    - This channel may provide unicast, multicast or broadcast communication service
- The hardware that implements the MAC is referred to as a **medium access controller**

MAC

- According to 802.3-2002 section 4.1.4, the functions required of a MAC are
  - receive/transmit normal frames
  - half-duplex retransmission and backoff functions
  - append/check FCS (frame check sequence)
  - interframe gap enforcement
  - discard malformed frames
  - append(tx)/remove(rx) preamble, SFD (start frame delimiter), and padding
  - half-duplex compatibility: append(tx)/remove(rx) MAC address

MAC

- Addressing
  - The LAN addresses used in IEEE 802 networks and FDDI networks are called **MAC addresses**
    - **FDDI: Fiber distributed data interface**, provides a 100 Mbit/s optical standard for data transmission in local area network that can extend in range up to 200 kilometers
  - a MAC address is a **unique serial number**
    - once a MAC address has been assigned to a particular network interface (**typically at time of manufacture**), that device should be uniquely identifiable amongst all other network devices in the world
  - **guarantees** that each device in a network will have a different MAC address (analogous to a street address)
  - **makes it possible** for data packets to be delivered to a destination within a sub-network

MAC

- Channel access control mechanisms
  - also known as a **multiple access protocol**
  - makes it possible for **several stations connected to the same physical medium** to share it
    - Examples of shared physical media are bus networks, ring networks, hub networks, wireless networks and half-duplex point-to-point links
  - the multiple access protocol
    - **may detect or avoid data packet collisions** if a packet mode contention based channel access method is used
    - or **reserve resources to establish a logical channel** if a circuit switched or channelization based channel access method is used

purpose for this chapter

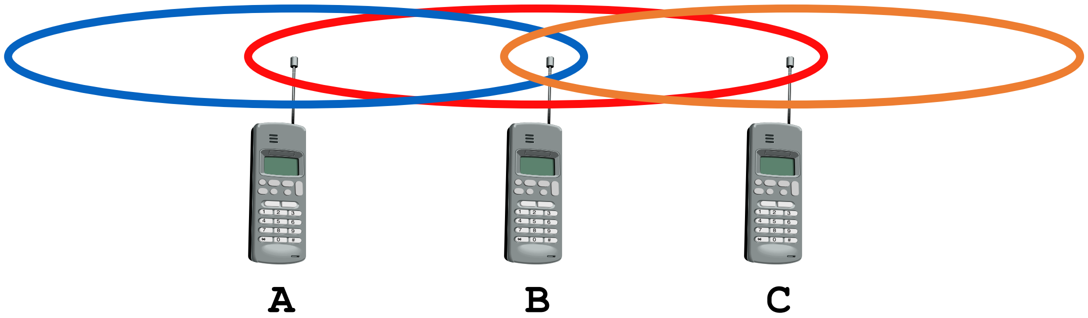
- This chapter aims to **explain why special MACs are needed in the wireless domain** and why standard MAC schemes known from wired networks often fail
- While SDM and FDM are typically used in a rather fixed manner
  - i.e. a certain space or frequency (or frequency hopping pattern) is assigned for a longer period of time
  - **the main focus of this chapter is on TDM mechanisms**
    - TDM can be used in a very flexible way, as tuning in to a certain frequency does not present a problem, but time can be allocated on demand and in a distributed fashion
- Well-known algorithms are **Aloha** (in several versions), **different reservation schemes**, or **simple polling**

motivation

- Can we apply media access methods from fixed networks?
- Example **CSMA/CD**
  - Carrier Sense Multiple Access with Collision Detection
  - send as soon as the medium is free, listen into the medium if a collision occurs
  - legacy 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

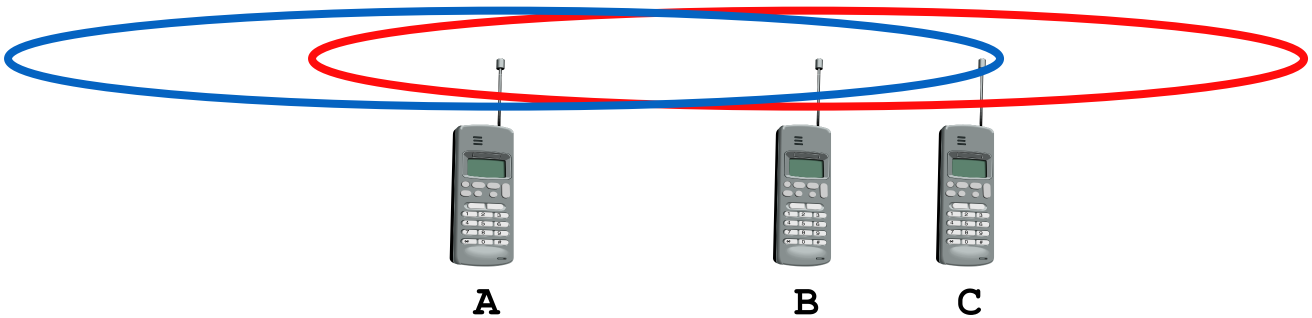
- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a “free” medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is “hidden” for C



- 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!

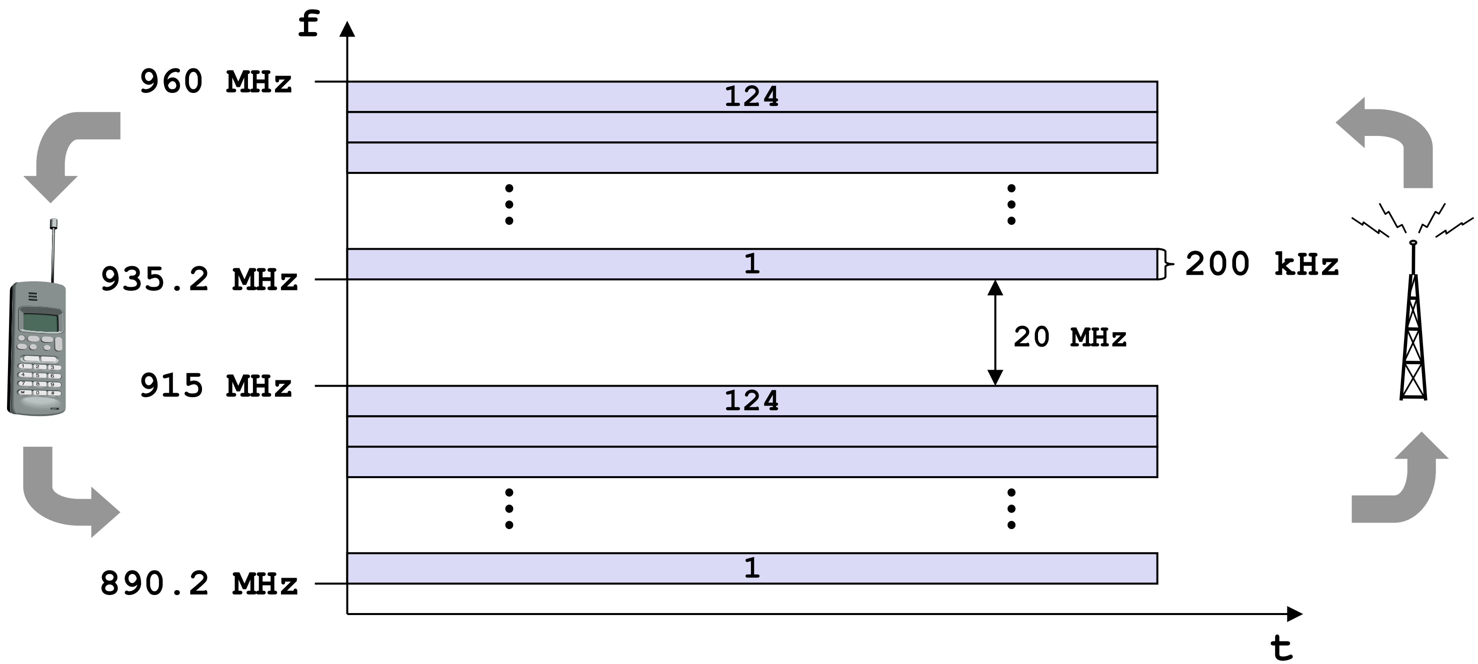
access methods SDMA/FDMA/TDMA

- **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 presented in previous chapter are now used to control medium access!

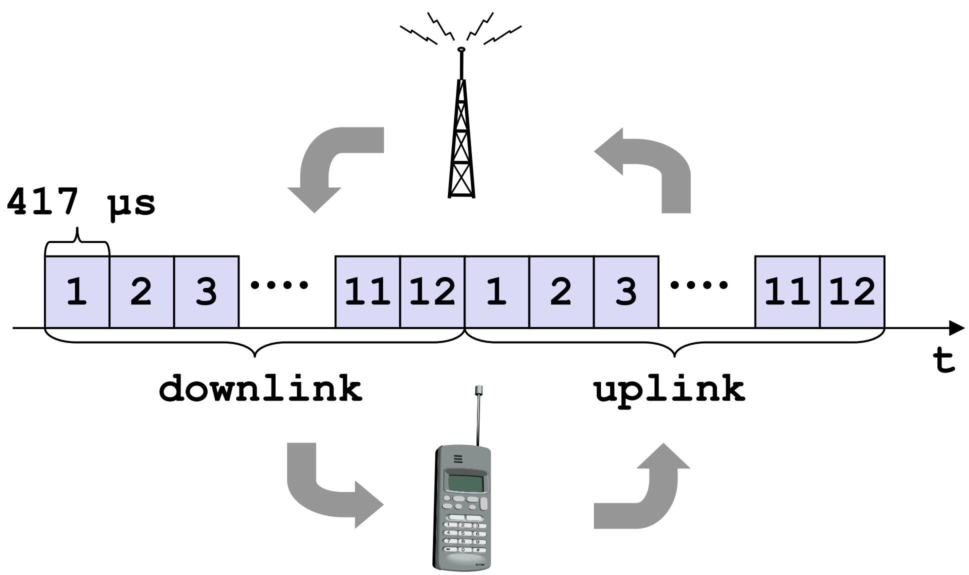
FDD/FDMA - general scheme, example GSM

- According to FDMA, the base station allocates a certain frequency for up- and downlink to establish a duplex channel with a mobile phone
- Up- and downlink have a fixed relation
  - If the uplink frequency is $f_u = 890\text{ MHz} + n \cdot 0.2\text{ MHz}$, the downlink frequency is $f_d = f_u + 45\text{ MHz}$, i.e., $f_d = 935\text{ MHz} + n \cdot 0.2\text{ MHz}$ for a certain channel n.



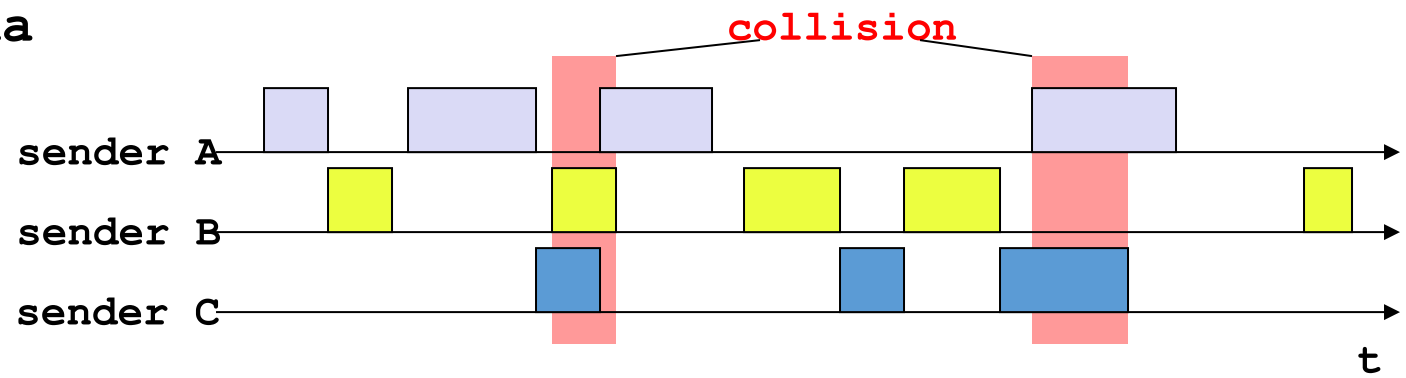
TDD/TDMA - general scheme, example DECT

- The base station uses one out of 12 slots for the downlink, whereas the mobile station uses one out of 12 different slots for the uplink
  - Uplink and downlink are separated in time. Up to 12 different mobile stations can use the same frequency without interference using this scheme
  - Each connection is allotted its own up- and downlink pair
  - In the DECT cordless phone system, the pattern is repeated every 10 ms, i.e., each slot has a duration of 417 µs. This repetition guarantees access to the medium every 10 ms, independent of any other connections

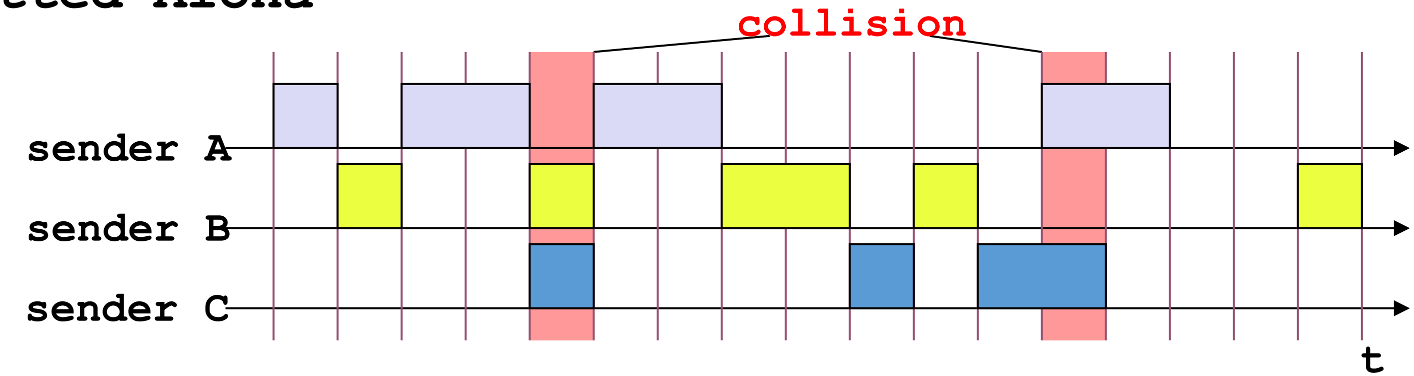


aloha/slotted aloha

- What if TDM is applied without controlling access?
  - 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**

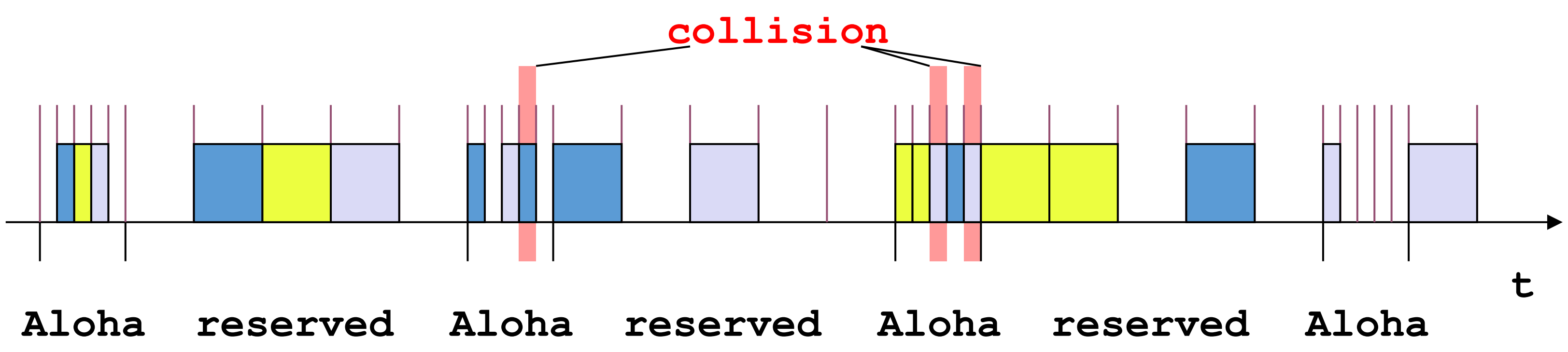


demand assigned multiple access (DAMA)

- 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

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



DAMA - PRMA

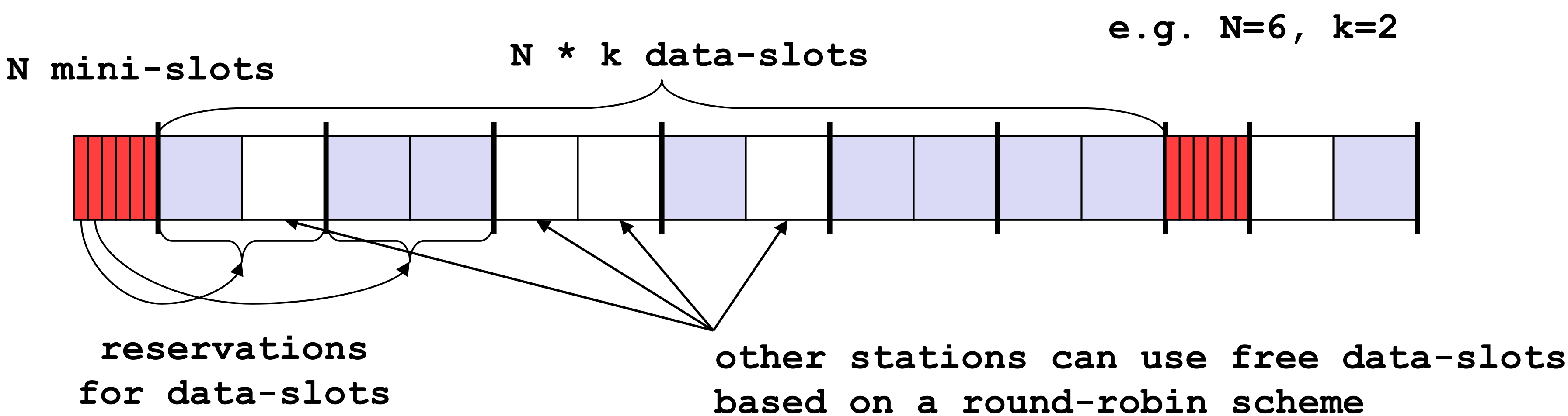
- **Implicit reservation** (PRMA - Packet Reservation Multiple Access)
  - a certain number of slots (8 in the example) form a frame, and frames are repeated in time
  - stations compete for empty slots according to the slotted aloha principle
  - once a station reserves a slot successfully, this slot 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

reservation		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**time-slot**
ACDABA-F	**frame$_1$**	**A**	**C**	**D**	**A**	**B**	**A**		**F**	
ACDABA-F	**frame$_2$**	**A**	**C**		**A**	**B**	**A**			
AC-ABAF-	**frame$_3$**	**A**				**B**	**A**	**F**		
A---BAFD	**frame$_4$**	**A**				**B**	**A**	**F**	**D**	
ACEEBAFD	**frame$_5$**	**A**	**C**	**E**	**E**	**B**	**A**	**F**	**D**	**t**

collision at reservation attempts

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)
  - guarantees certain bandwidth and fixed delay

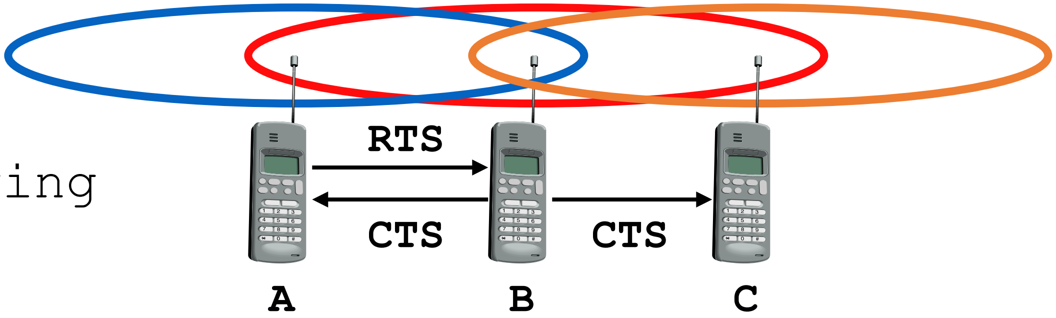


MACA - collision avoidance

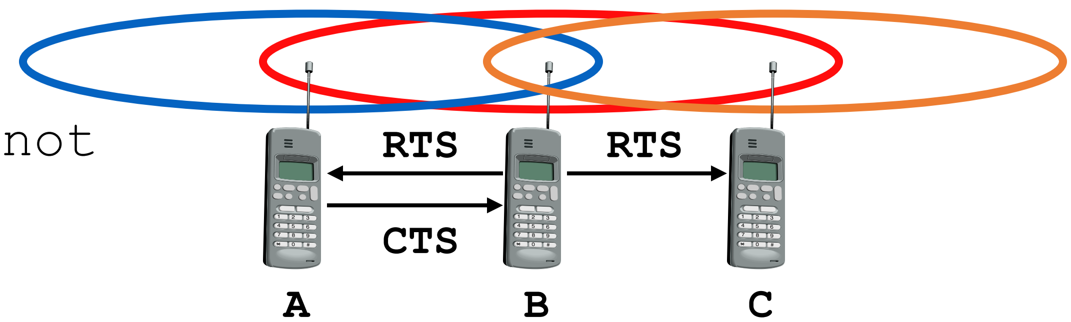
- **MACA - Multiple Access with Collision Avoidance** uses short signaling packets for collision avoidance
  - **RTS** (request to send): a sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - **CTS** (clear to send): the receiver grants the right 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 IEEE 802.11 as DFWMAC (Distributed Foundation Wireless MAC)

MACA examples

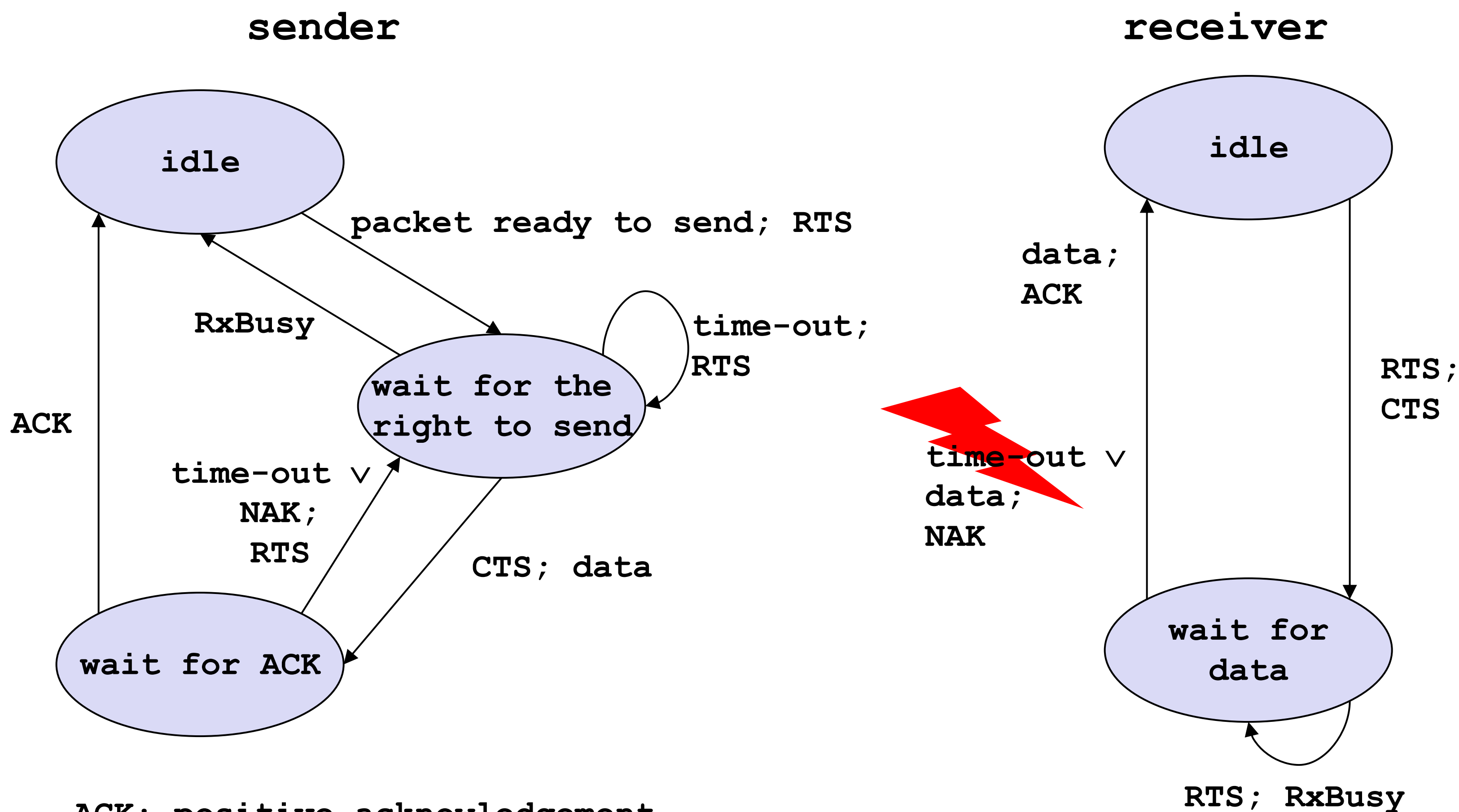
- **MACA avoids the problem of hidden terminals**
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B



- **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

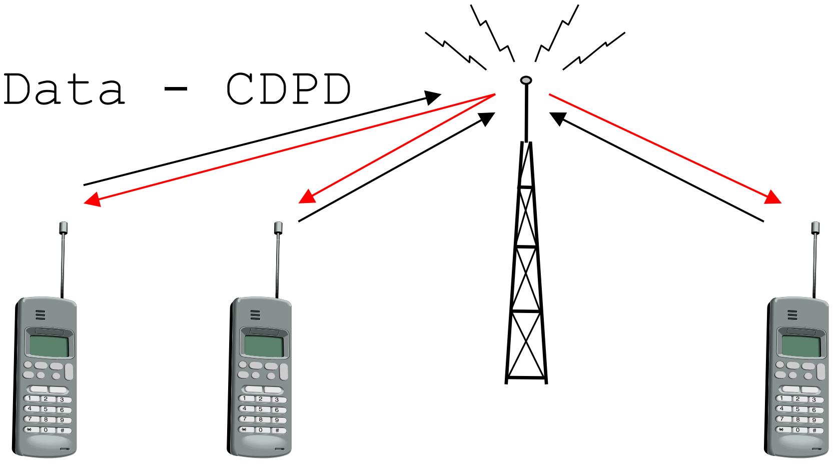
simplified state machines for a sender and receiver

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)
  - 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

inhibit sense multiple access (ISMA)

- 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 Cellular Digital Packet Data - CDPD (USA, integrated into AMPS)



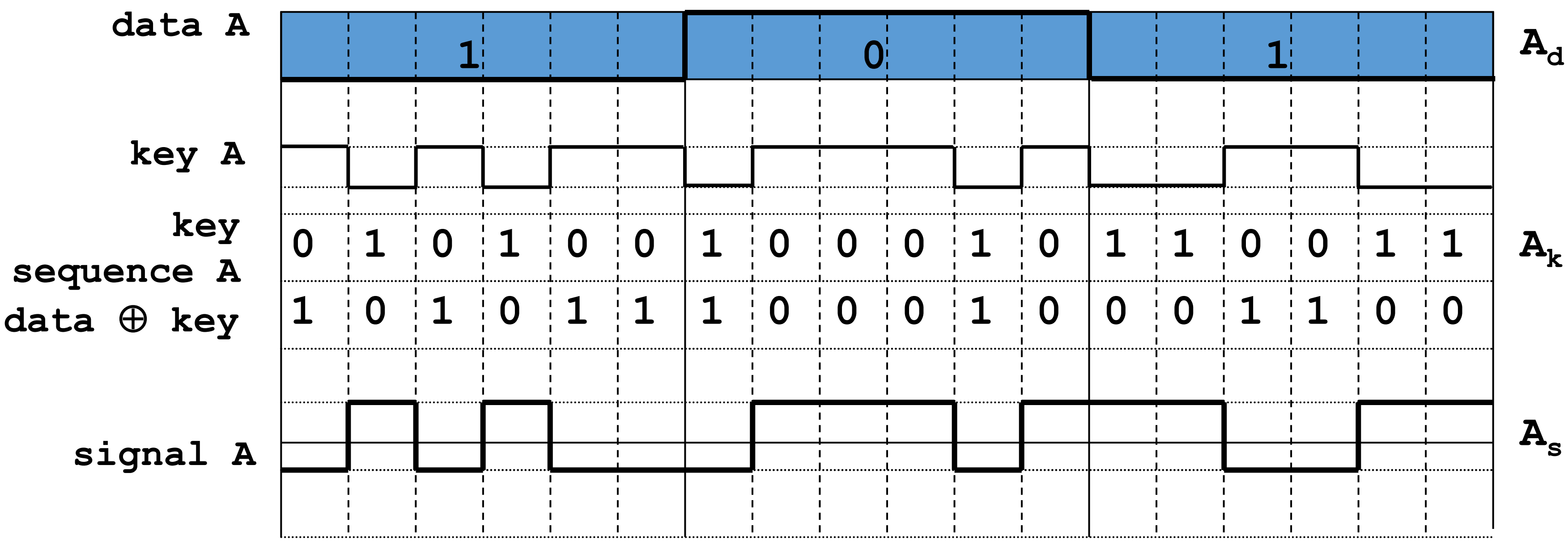
access method CDMA

- 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
  - **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
- Advantages:
  - all terminals can use the **same frequency**, no planning needed
  - **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

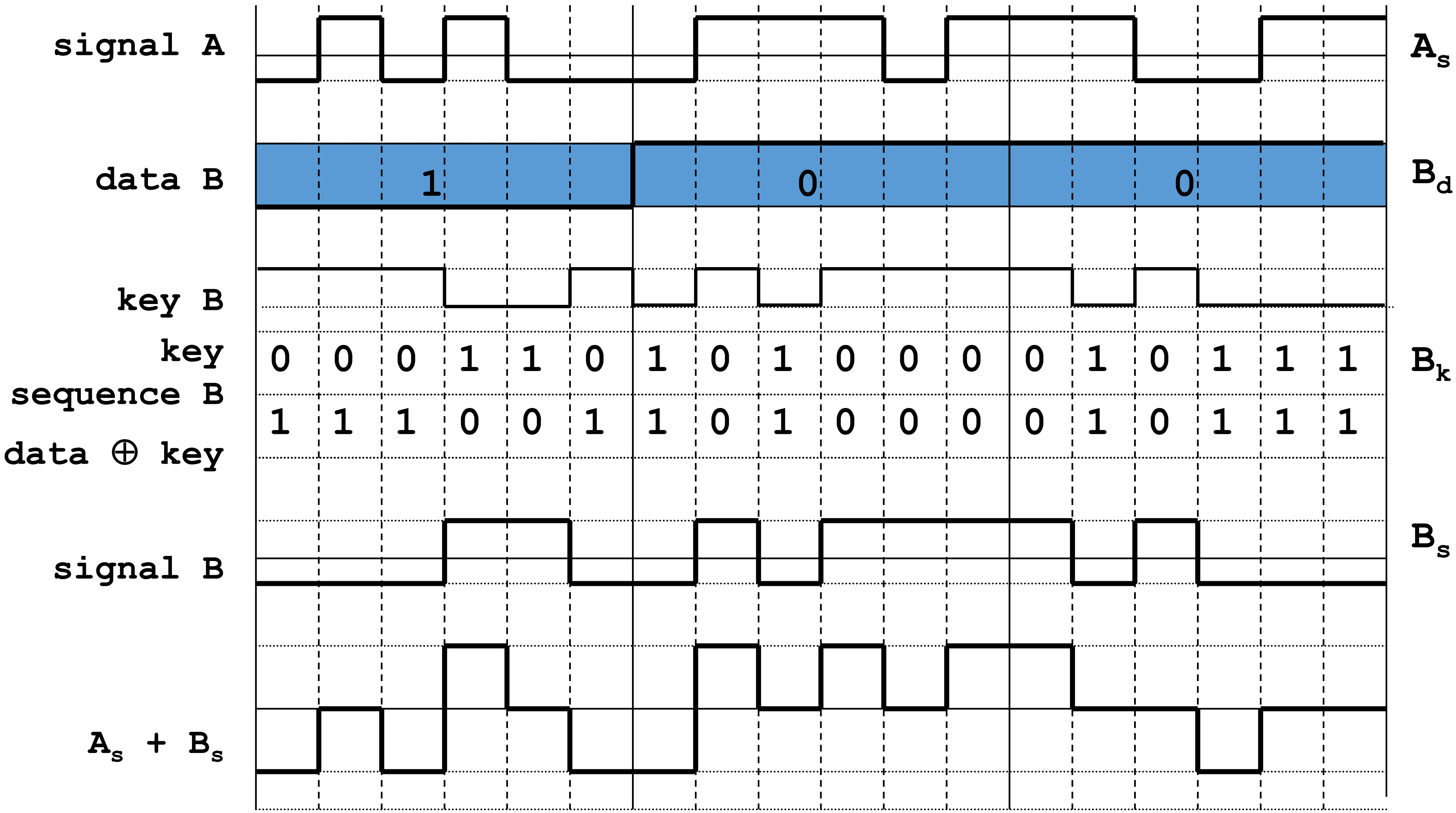
- Sender A
  - sends A_d = 1, key A_k = 010011 (assign: "0"= -1, "1"= +1)
  - sending signal $A_s = A_d * A_k$ = (-1, +1, -1, -1, +1, +1)
- Sender B
  - sends B_d = 0, key B_k = 110101 (assign: "0"= -1, "1"= +1)
  - sending signal $B_s = B_d * B_k$ = (-1, -1, +1, -1, +1, -1)
- Both signals superimpose 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) • 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) • B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6, i.e. "0"

CDMA on signal level – sender A

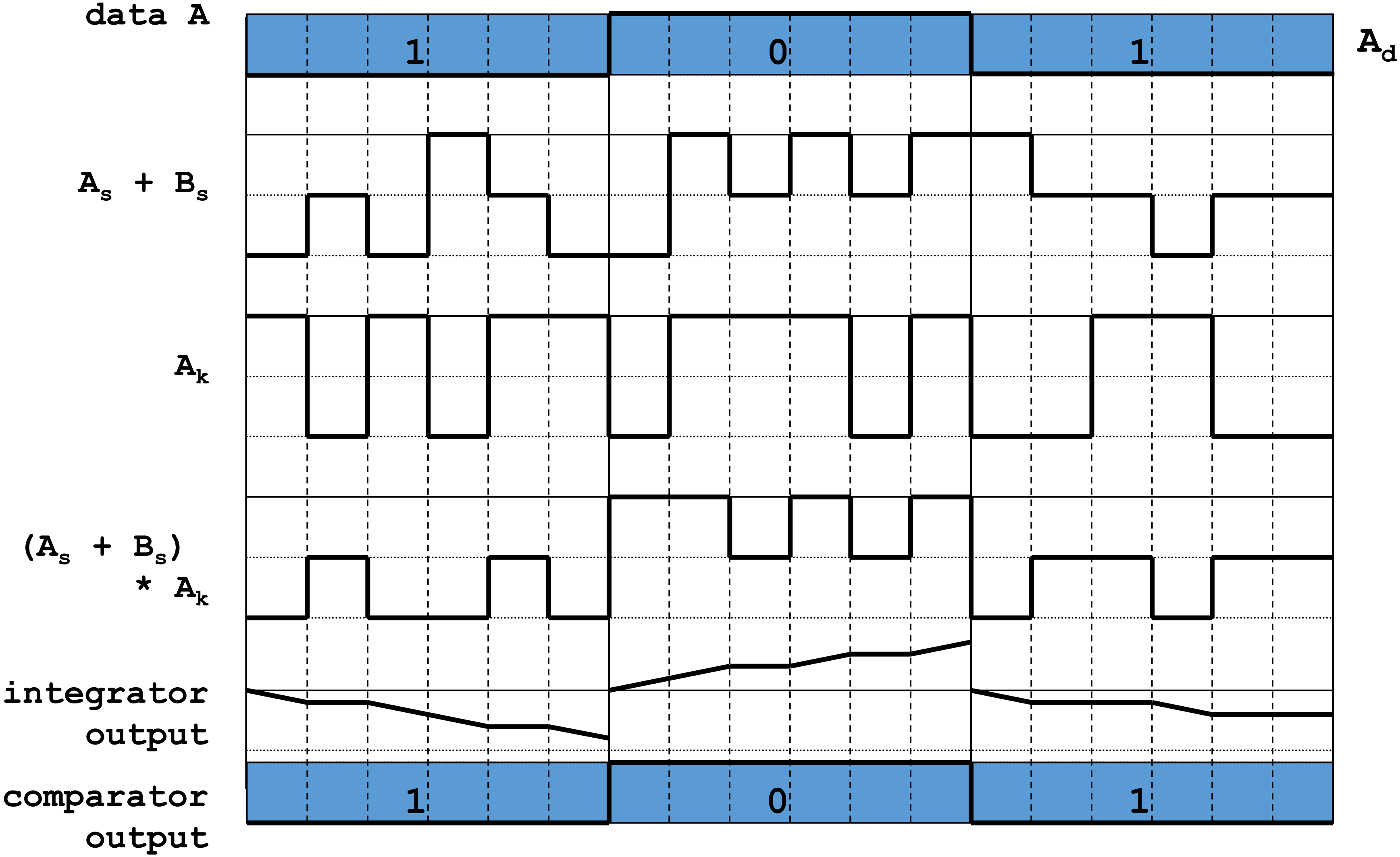


Real systems use much longer keys resulting in a larger distance between single code words in code space.

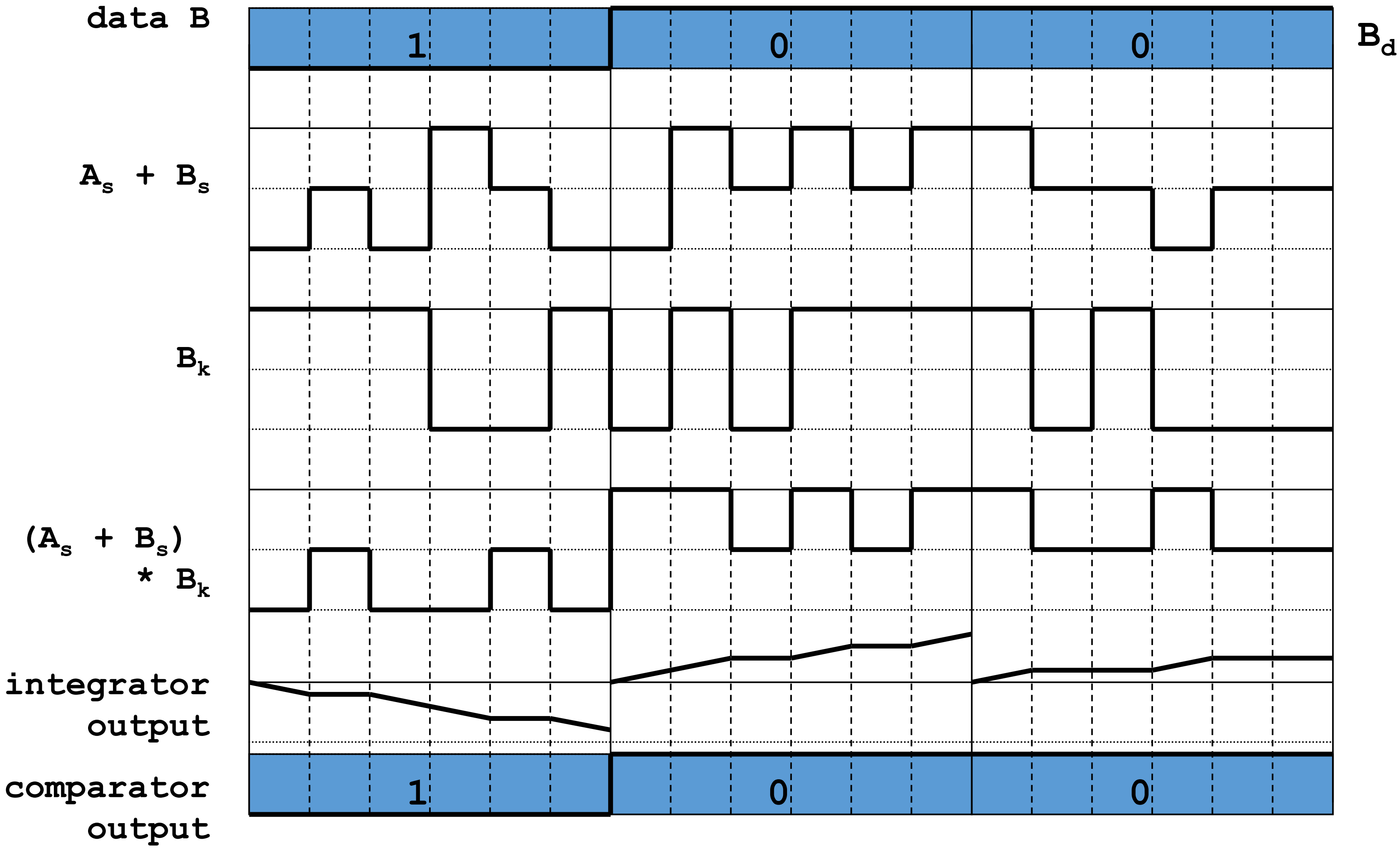
CDMA on signal level – sender A+B



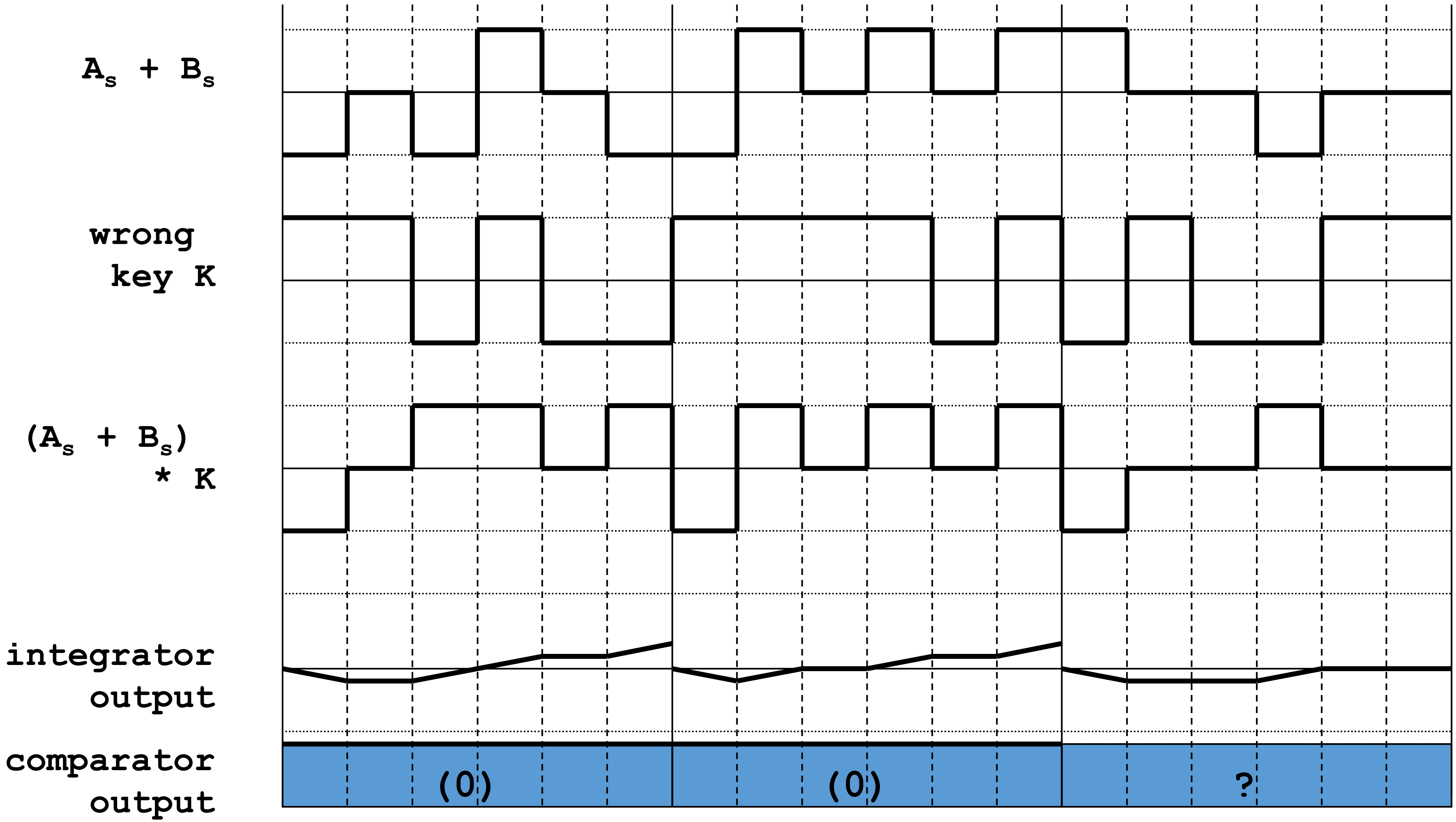
CDMA on signal level – receiver for A



CDMA on signal level – receiver for B

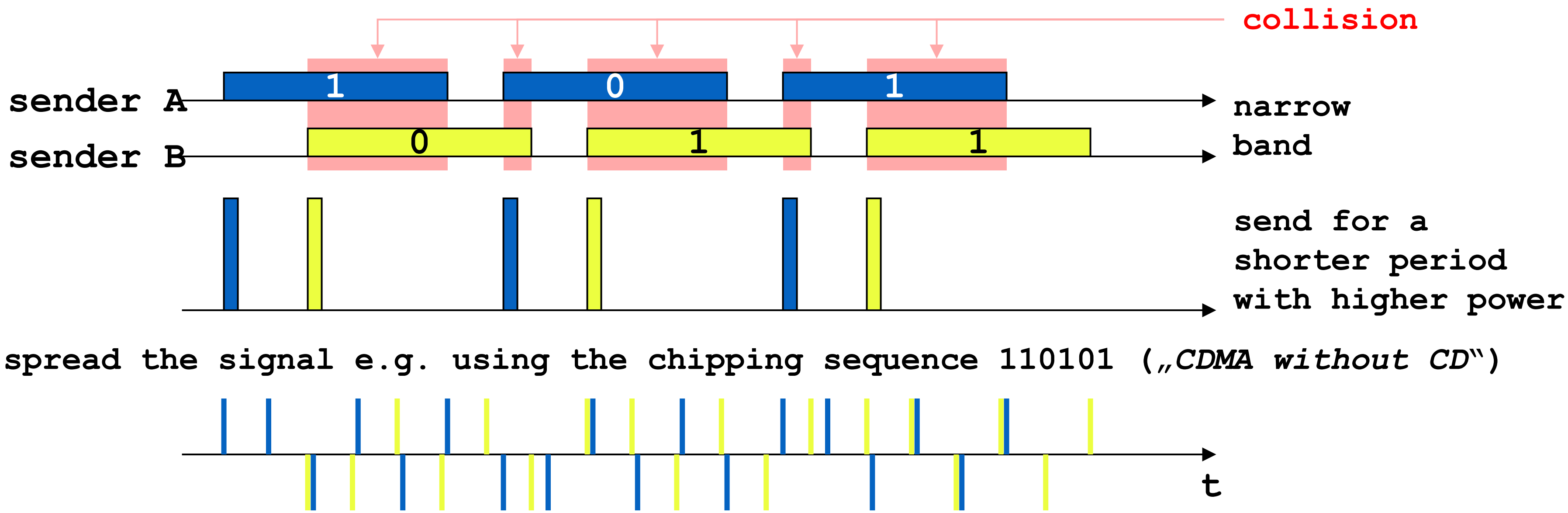


CDMA on signal level – receiver with wrong key



spread aloha multiple access (SAMA)

- 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



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