MOBILE COMMUNICATION

MEDIUM ACCESS CONTROL

N.Junnubabu

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3. Medium Access Control

- Medium access control comprises all mechanisms that regulate user access to a medium using SDM, TDM, FDM, or CDM.
- MAC is thus similar to traffic regulations in the highway/multiplexing example.
- MAC 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.
- 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.

3.1. Motivation for a specialized MAC

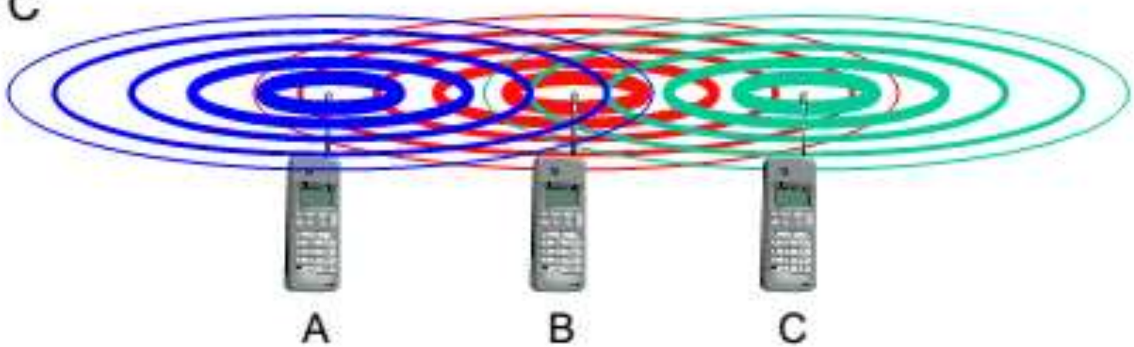
- Can we apply media access methods from fixed networks?
- Example CSMA/CD
  - Carrier Sense Multiple Access with Collision Detection.
  - send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3).
- Problems in wireless networks
  - signal strength 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”.

3.1. Motivation for a specialized MAC

3.1.1. 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

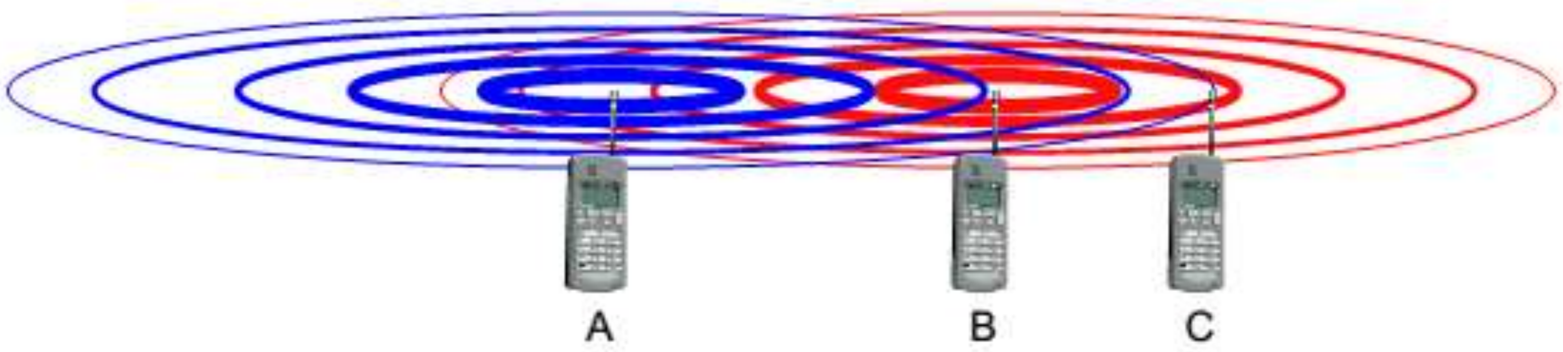
- B sends to A, C wants to send to another terminal (not A or B)
- C has to wait, CS signals a medium in use
- but A is outside the radio range of C, therefore waiting is not necessary
- C is “exposed” to B

3.1. Motivation for a specialized MAC

3.1.2. 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!

3.2. SDMA

- Space Division Multiple Access (SDMA) is used for allocating a **separated space** to users in wireless networks.
- A typical application involves assigning an optimal base station to a mobile phone user.
- The mobile phone may receive several base stations with different quality.
- A MAC algorithm could now decide which base station is best, taking into account which frequencies (FDM), time slots (TDM) or code (CDM) are still available (depending on the technology).
- Typically, SDMA is never used in isolation but always in combination with one or more other schemes.
- The basis for the SDMA algorithm is formed by **cells** and **sectorized** antennas which constitute the infrastructure implementing space division multiplexing (SDM).

3.3. FDMA

- Frequency division multiple access (FDMA) comprises all algorithms allocating frequencies to transmission channels according to the frequency division multiplexing (FDM) scheme.
- Allocation can either be **fixed** or **dynamic**.
- FDM is often used for simultaneous access to the medium by base station and mobile station in cellular networks.
- Here the two partners typically establish a **duplex channel**, i.e., a channel that allows for simultaneous transmission in both directions.
- The two directions, mobile station to base station and vice versa are now separated using different frequencies.
- This scheme is then called **frequency division duplex** (FDD).

3.3. FDMA

- Both partners have to know the frequencies in advance; they cannot just listen into the medium.
- The two frequencies are also known as **uplink**, i.e., from mobile station to base station or from ground control to satellite, and as **downlink**, i.e., from base station to mobile station or from satellite to ground control.

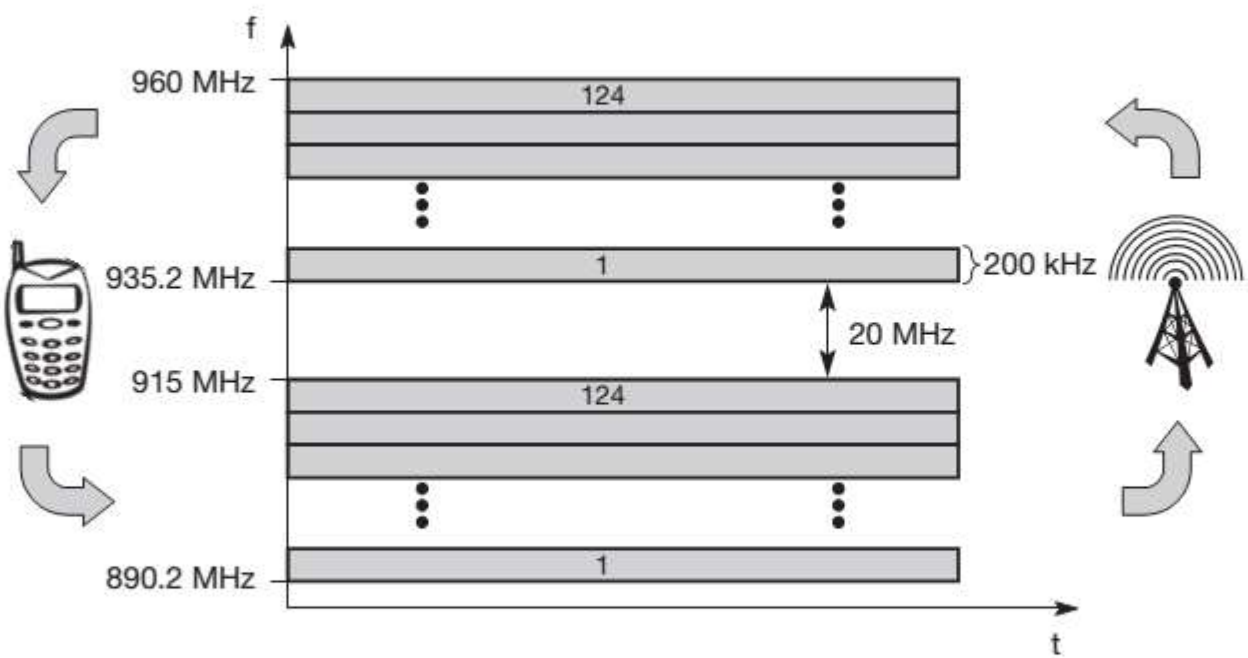


Figure 3.3
Frequency division multiplexing for multiple access and duplex

3.3. FDMA

- The basic frequency allocation scheme for GSM is fixed and regulated by national authorities.
- All uplinks use the band between **890.2 and 915 MHz**, all downlinks use **935.2 to 960 MHz**.
- According to FDMA, the base station, shown on the right side, 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 $\mathbf{f_u = 890\ MHz + n \cdot 0.2\ MHz}$, the downlink frequency is $\mathbf{f_d = f_u + 45\ MHz}$, i.e., $\mathbf{f_d = 935\ MHz + n \cdot 0.2\ MHz}$ for a certain channel n.
- The base station selects the channel.
- Each channel (uplink and downlink) has a bandwidth of **200 kHz**.

3.4. TDMA

- Compared to FDMA, time division multiple access (TDMA) offers a much more flexible scheme, which comprises all technologies that allocate certain time slots for communication, i.e., controlling TDM.
- Now tuning into a certain frequency is not necessary, i.e., the receiver can stay at the same frequency the whole time.
- Using only one frequency, and thus very simple receivers and transmitters, many different algorithms exist to control medium access.
- Listening to different frequencies at the same time is quite difficult, but listening to many channels separated in time at the same frequency is simple.
- Almost all MAC schemes for **wired networks** work according to this principle, e.g., Ethernet, Token Ring, ATM etc.

3.4. TDMA

- Synchronization between sender and receiver has to be achieved in the time domain.
- Again this can be done by using a fixed pattern similar to FDMA techniques, i.e., allocating a certain time slot for a channel, or by using a dynamic allocation scheme.
- **Dynamic allocation schemes** require an identification for each transmission (e.g., sender address) or the transmission has to be announced before hand.
- MAC addresses are quite often used as identification.
- This enables a receiver in a broadcast medium to recognize if it really is the intended receiver of a message.
- **Fixed schemes** do not need an identification, but are not as flexible considering varying bandwidth requirements.

3.4. TDMA

3.4.1. Fixed TDM

- The simplest algorithm for using TDM is allocating time slots for channels in a fixed pattern. This results in a fixed bandwidth.
- These patterns guarantee a fixed delay – one can transmit, e.g., every 10 ms as this is the case for standard DECT systems.
- MAC is quite simple, as the only crucial factor is accessing the reserved time slot at the right moment.
- If this synchronization is assured, each mobile station knows its turn and no interference will happen.
- The fixed pattern can be assigned by the base station, where competition between different mobile stations that want to access the medium is solved.

3.4. TDMA

- Figure 3.4 shows how these fixed TDM patterns are used to implement multiple access and a duplex channel between a base station and mobile station.
- Assigning different slots for uplink and downlink using the same frequency is called **time division duplex** (TDD).

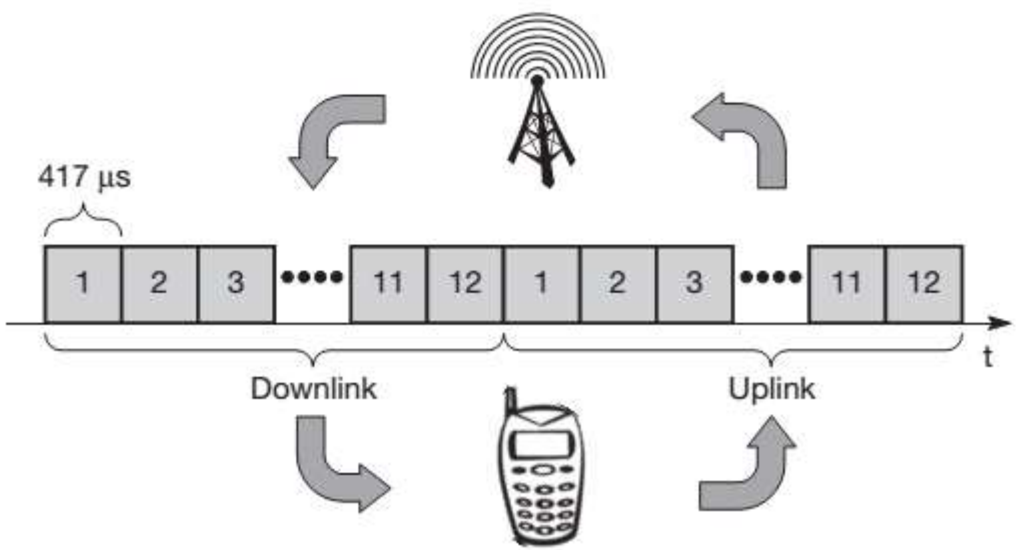


Figure 3.4
Time division multiplexing for multiple access and duplex

3.4. TDMA

- As shown in the figure, 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 example, which is the standard case for 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.

3.4. TDMA

- While the fixed access patterns, as shown for DECT, are perfectly apt for connections with a **constant data rate** (e.g., classical voice transmission with 32 or 64 kbit/s duplex), they are very inefficient for **bursty data** or **asymmetric connections**.
- In the case of web browsing, where no data transmission occurs while reading a page, whereas clicking on a hyperlink triggers a data transfer from the mobile station, often to the base station, often followed by huge amounts of data returned from the web server.

3.4. TDMA

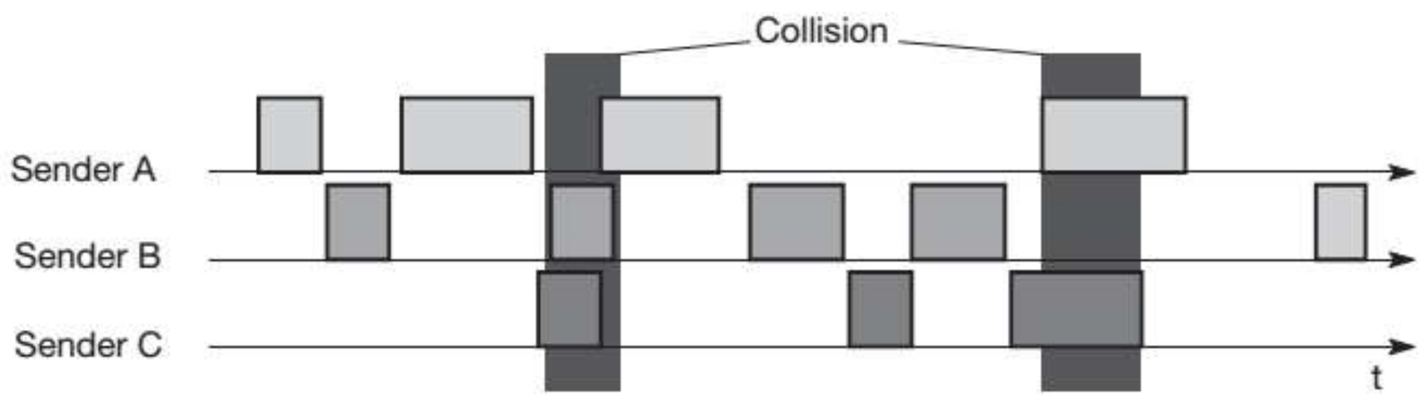
3.4.2. Classical Aloha

- A scheme which was invented at the University of Hawaii and was used in the ALOHANET for wireless connection of several stations.
- Aloha neither coordinates medium access nor does it resolve contention on the MAC layer.
- Instead, each station can access the medium at any time.
- This is a random access scheme, without a central arbiter controlling access and without coordination among the stations.
- If two or more stations access the medium at the same time, a collision occurs and the transmitted data is destroyed.
- Resolving this problem is left to higher layers (e.g., retransmission of data).

3.4. TDMA

- The simple Aloha works fine for a light load and does not require any complicated access mechanisms.
- On the classical assumption that data packet arrival follows a Poisson distribution, maximum throughput is achieved for an 18 per cent load.

Figure 3.5
Classical Aloha multiple access

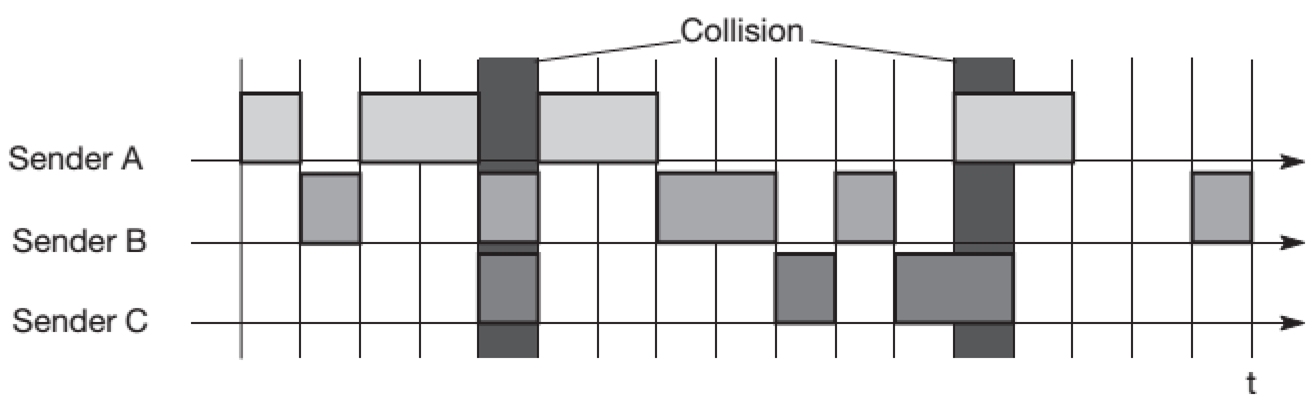


3.4. TDMA

3.4.3. Slotted Aloha

- The first refinement of the classical Aloha scheme is provided by the introduction of **time slots** (slotted Aloha).
- In this case, all senders have to be synchronized, transmission can only start at the beginning of a time slots.
- Still, access is not coordinated.
- Under the assumption stated above, the introduction of slots raises the throughput from 18 per cent to 36 per cent, i.e., slotting doubles the throughput.

Figure 3.6
Slotted Aloha
multiple access



3.4. TDMA

3.4.4. Carrier sense multiple access

- One improvement to the basic Aloha is sensing the carrier before accessing the medium.
- Sensing the carrier and accessing the medium only if the carrier is idle decreases the probability of a collision.
- But, as already mentioned in the introduction, hidden terminals cannot be detected.
- If a hidden terminal transmits at the same time as another sender, a collision might occur at the receiver.
- This basic scheme is still used in most wireless LANs.

3.4. TDMA

- Several versions of CSMA exist.
- In **non-persistent CSMA**, stations sense the carrier and start sending immediately if the medium is idle.
- If the medium is busy, the station pauses a random amount of time before sensing the medium again and repeating this pattern.
- In **p-persistent CSMA** systems nodes also sense the medium, but only transmit with a probability of p, with the station deferring to the next slot with the probability 1-p, i.e., access is slotted in addition.
- In **1-persistent CSMA** systems, all stations wishing to transmit access the medium at the same time, as soon as it becomes idle.
- This will cause many collisions if many stations wish to send and block each other.

3.4. TDMA

- To create some fairness for stations waiting for a longer time**, back-off algorithms** can be introduced, which are sensitive to waiting time as this is done for standard Ethernet.
- **CSMA with collision avoidance** (CSMA/CA) is one of the access schemes used in wireless LANs following the standard IEEE 802.11.
- Here sensing the carrier is combined with a back-off scheme in case of a busy medium to achieve some fairness among competing stations.
- Another, very elaborate scheme is **elimination yield – non-preemptive multiple access** (EY-NMPA) used in the HIPERLAN 1 specification.
- Here several phases of sensing the medium and accessing the medium for contention resolution are interleaved before one “winner” can finally access the medium for data transmission.

3.4. TDMA

3.4.5. Demand assigned multiple access

- A general improvement of Aloha access systems can also be achieved by reservation mechanisms and combinations with some (fixed) TDM patterns.
- These schemes typically have a reservation period followed by a transmission period.
- During the reservation period, stations can reserve future slots in the transmission period.
- While, depending on the scheme, collisions may occur during the reservation period, the transmission period can then be accessed without collision.
- Alternatively, the transmission period can be split into periods with and without collision.

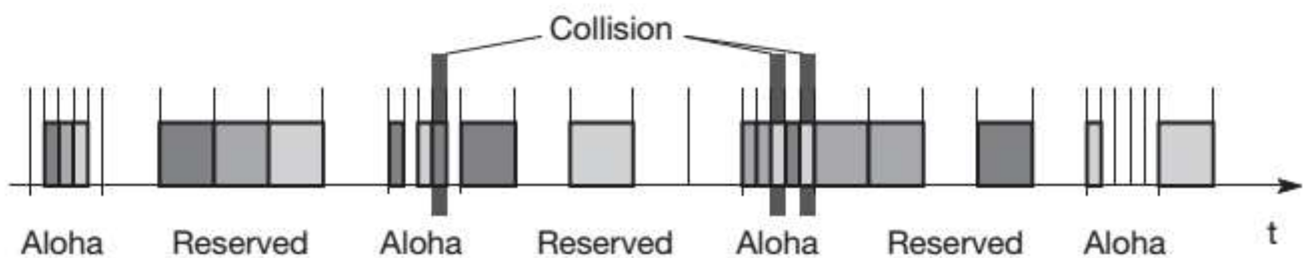
3.4. TDMA

- In general, these schemes cause a higher delay under a light load (first the reservation has to take place), but allow higher throughput due to less collisions.
- One basic scheme is **demand assigned multiple access** (DAMA) also called **reservation Aloha**, a scheme typical for **satellite systems**.
- DAMA has two modes.
- During a contention phase following the slotted Aloha scheme, all stations can try to reserve future slots.
- For example, different stations on earth try to reserve access time for satellite transmission.
- Collisions during the reservation phase do not destroy data transmission, but only the short requests for data transmission.

3.4. TDMA

- If successful, a time slot in the future is reserved, and no other station is allowed to transmit during this slot.
- Therefore, the satellite collects all successful requests (the others are destroyed) and sends back a reservation list indicating access rights for future slots.

Figure 3.7
Demand assignment multiple access with explicit reservation



- All ground stations have to obey this list.
- To maintain the fixed TDM pattern of reservation and transmission, the stations have to be synchronized from time to time.
- DAMA is an explicit reservation scheme. Each transmission slot has to be reserved explicitly.

3.4. TDMA

3.4.6 Packet Reservation Multiple Access (PRMA)

- In PRMA, slots can be reserved implicitly according to the following scheme.
- A certain number of slots forms a frame.
- The frame is repeated in time i.e., a fixed TDM pattern is applied.
- A base station, which could be a satellite, now broadcasts the status of each slot to all mobile stations.
- All stations receiving this vector will then know which slot is occupied and which slot is currently free.
- A successful transmission of data is indicated by the station’s name.
- All stations wishing to transmit can now compete for this free slot in Aloha fashion.
- The already occupied slots are not touched.

3.4. TDMA

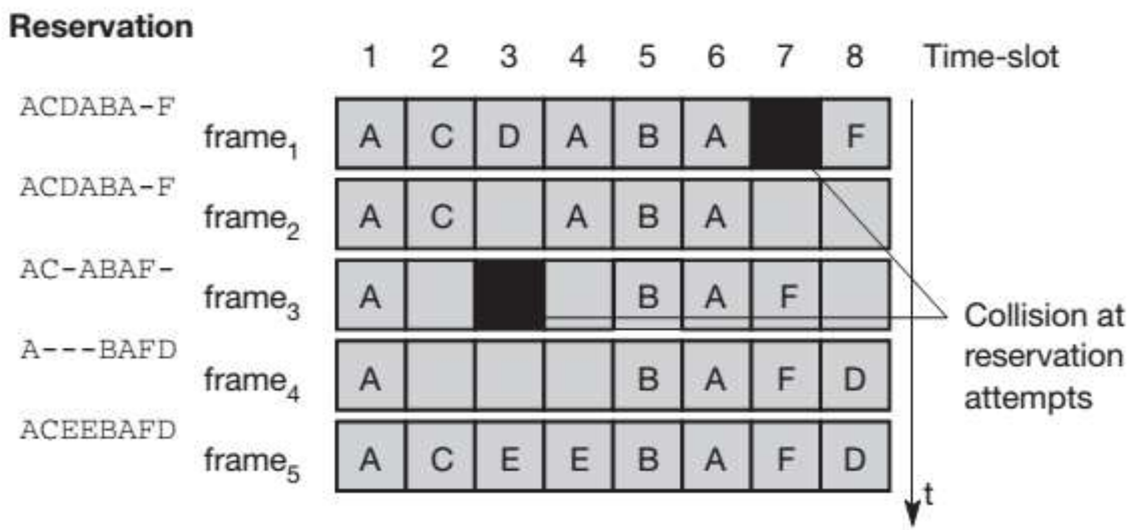


Figure 3.8
Demand assignment multiple access with implicit reservation

3.4. TDMA

3.4.7. Reservation TDMA

- An even more fixed pattern that still allows some random access is exhibited by reservation TDMA.
- In a fixed TDM scheme N mini-slots followed by N * k data-slots form a frame that is repeated.
- Each station is allotted its own mini-slot and can use it to reserve up to k data-slots.
- This guarantees each station a certain bandwidth and a fixed delay.
- Other stations can now send data in unused data-slots.

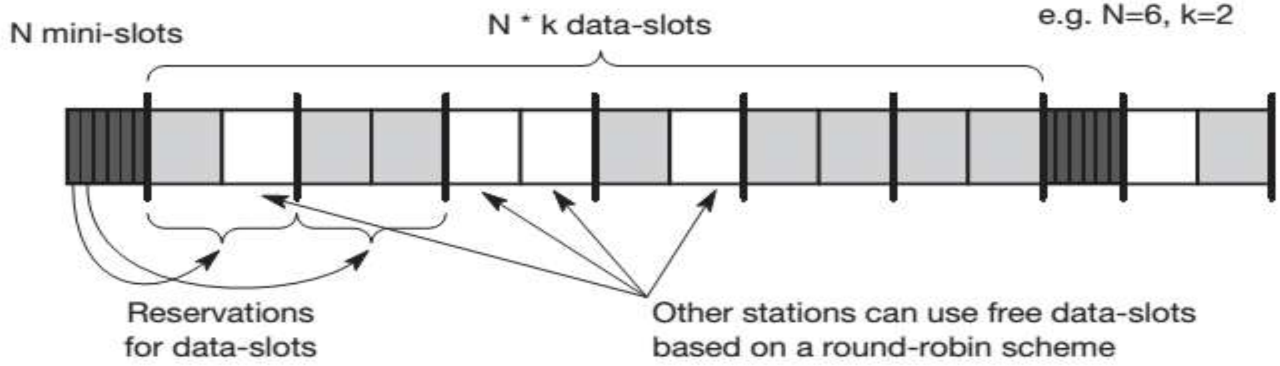


Figure 3.9
Reservation TDMA access scheme

3.4. TDMA

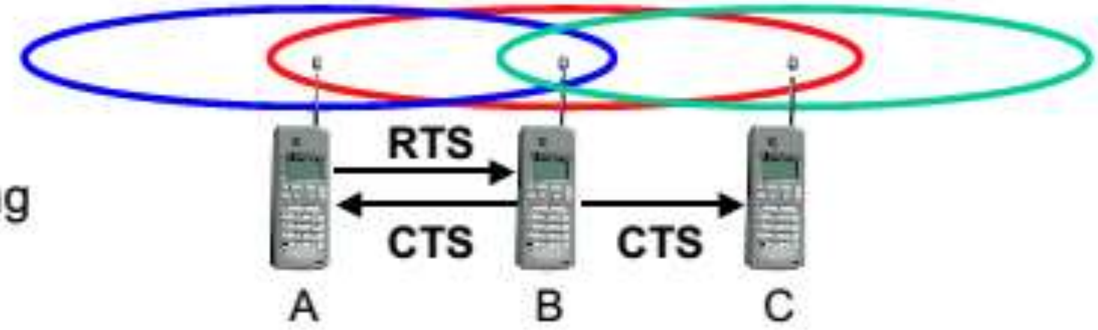
3.4.8. Multiple access with collision avoidance

- Multiple access with collision avoidance (MACA) presents a simple scheme that solves the **hidden terminal** problem, does not need a base station, and is still a random access Aloha scheme – but with dynamic reservation.
- MACA 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

3.4. TDMA

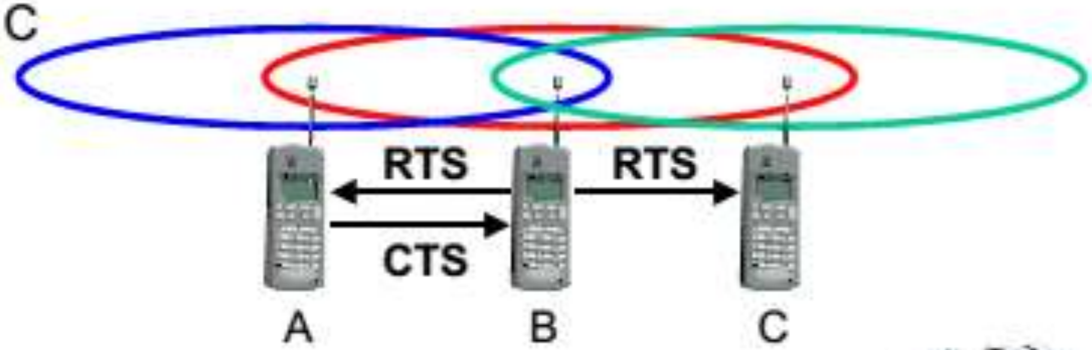
MACA avoids the problem of hidden terminals

- 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



3.4. TDMA

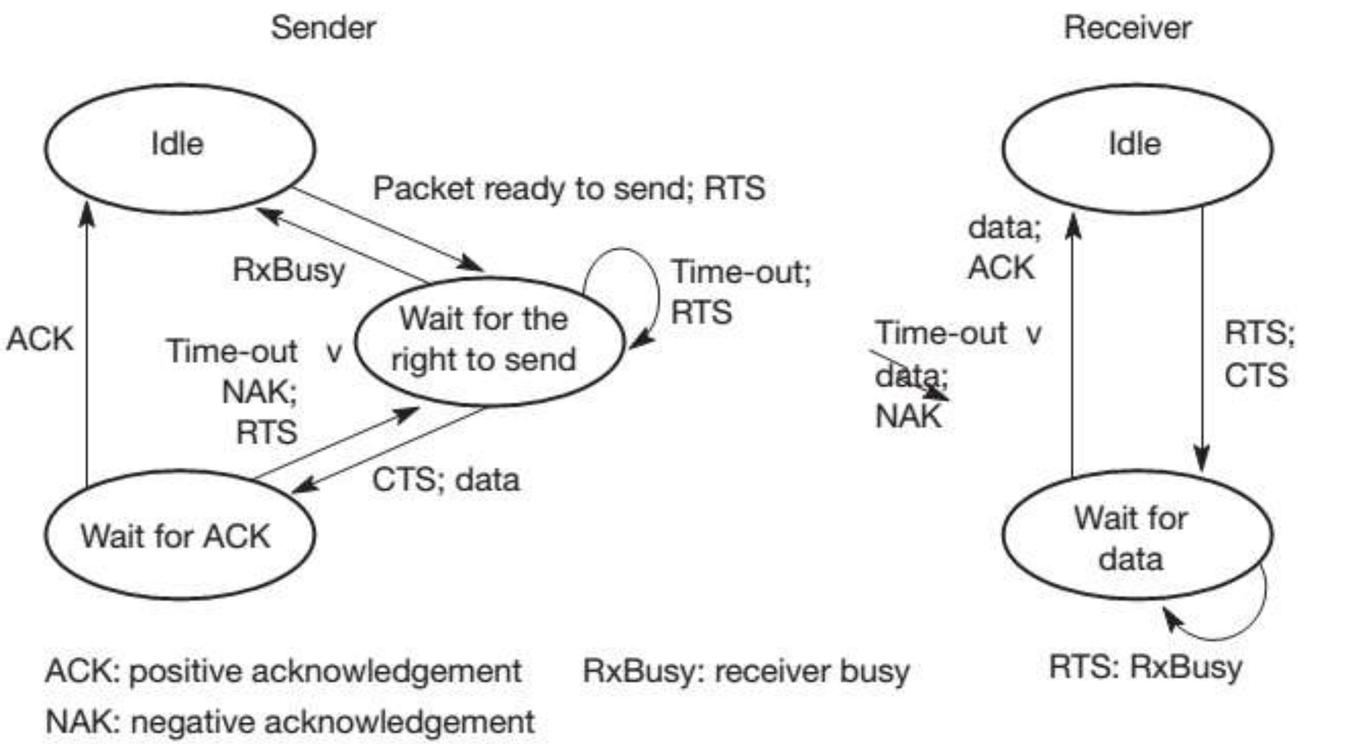


Figure 3.12
Protocol machines for multiple access with collision avoidance

3.4. TDMA

3.4.9 Polling

- Where one station is to be heard by all others, polling schemes can be applied.
- Polling is a strictly centralized scheme with one master station and several slave stations.
- The master can poll the slaves according to many schemes: round robin, randomly, according to reservations etc.
- The master could also establish a list of stations wishing to transmit during a contention phase.
- After this phase, the station polls each station on the list.
- Similar schemes are used, e.g., in the Bluetooth wireless LAN and as one possible access function in IEEE 802.11 systems

3.4. TDMA

3.4.10 Inhibit sense multiple access

- This scheme, which is used for the packet data transmission service Cellular Digital Packet Data (CDPD) in the AMPS mobile phone system, is also known as digital sense multiple access (DSMA).
- Here, the base station only signals a busy medium via a busy tone (called BUSY/IDLE indicator) on the downlink.
- After the busy tone stops, accessing the uplink is not coordinated any further.
- The base station acknowledges successful transmissions, a mobile station detects a collision only via the missing positive acknowledgement.
- In case of collisions, additional back-off and retransmission mechanisms are implemented.

3.5. CDMA

- Codes with certain characteristics can be applied to the transmission to enable the use of code division multiplexing (CDM).
- Code division multiple access (CDMA) systems use exactly these codes to separate different users in code space and to enable access to a shared medium without interference.
- A code for a certain user should have a good autocorrelation and should be orthogonal to other codes.
- Two vectors are called orthogonal if their inner product is 0, as is the case for the two vectors (2, 5, 0) and (0, 0, 17):

  $$(2, 5, 0)*(0, 0, 17) = 0 + 0 + 0 = 0.$$

- But also vectors like (3, –2, 4) and (–2, 3, 3) are orthogonal:

  $$(3, -2, 4)*(-2, 3, 3) = -6 - 6 + 12 = 0.$$

- The Barker code (+1, –1, +1, +1, –1, +1, +1, +1, –1, –1, –1), for example, has a good autocorrelation, i.e., the inner product with itself is large, the result is 11.

3.5. CDMA

- Two senders, A and B, want to send data.
  - CDMA assigns the following unique and orthogonal key sequences: key A_k = 010011 for sender A, key B_K = 110101 for sender B.
  - Sender A wants to send the bit $A_d = 1$, sender B sends $B_d = 0$.
  - To illustrate this example, let us assume that we code a binary 0 as –1, a binary 1 as +1.
  - We can then apply the standard addition and multiplication rules.
- Both senders spread their signal using their key as chipping sequence.
  - Sender A then sends the signal

$$A_s = A_d * A_k = +1*(-1, +1, -1, -1, +1, +1) = (-1,+1, -1, -1, +1, +1).$$

  - Sender B does the same with its data to spread the signal with the code:

$$B_s = B_d*B_k = -1*(+1, +1, -1, +1, -1, +1) = (-1, -1, +1, -1, +1, -1).$$

3.5. CDMA

- Both signals are then transmitted at the same time using the same frequency, so, the signals superimpose in space.
  - Discounting interference from other senders and environmental noise from this simple example, and assuming that the signals have the same strength at the receiver, the following signal C is received at a receiver: $C = A_s + B_s = (–2, 0, 0, –2, +2, 0)$.
- The receiver now wants to receive data from sender A and, therefore, tunes in to the code of A, i.e., applies A's code for de-spreading:

  $C * A_k = (–2, 0, 0, –2, +2, 0) * (–1, +1, –1, –1, +1, +1) = 2 + 0 + 0 + 2 + 2 + 0 = 6$. As the result is much larger than 0, the receiver detects a binary 1.
  - Tuning in to sender B, i.e., applying B's code gives

  $C * B_k = (–2, 0, 0, –2, +2, 0)*(+1, +1, –1, +1, –1, +1) = –2 + 0 + 0 – 2 – 2 + 0 = –6$. The result is negative, so a 0 has been detected.

3.5. CDMA

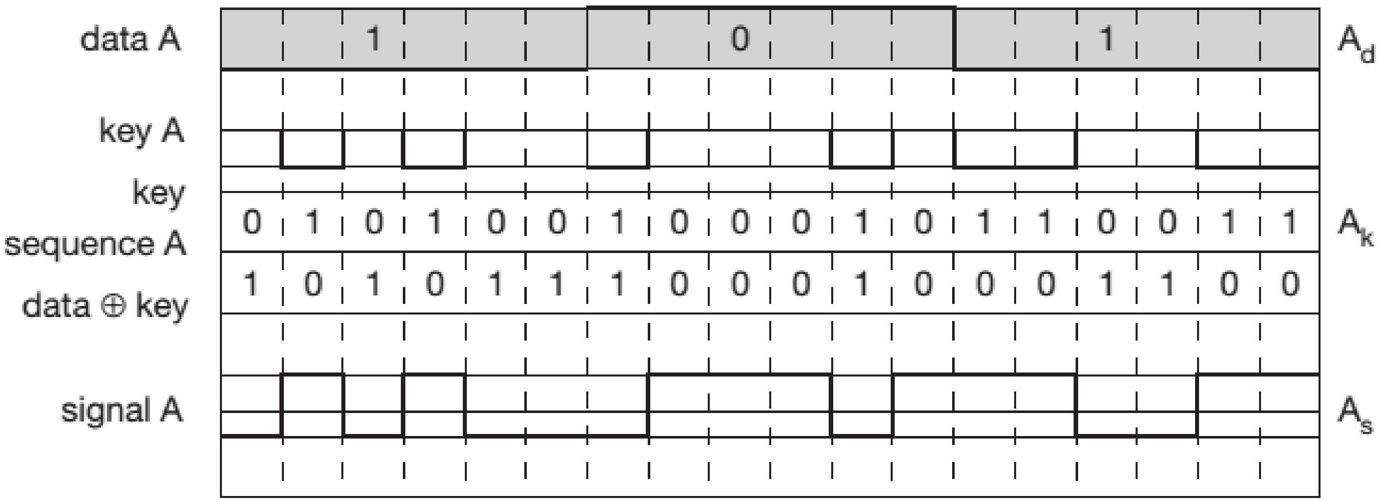


Figure 3.14
Coding and spreading of data from sender A

3.5. CDMA

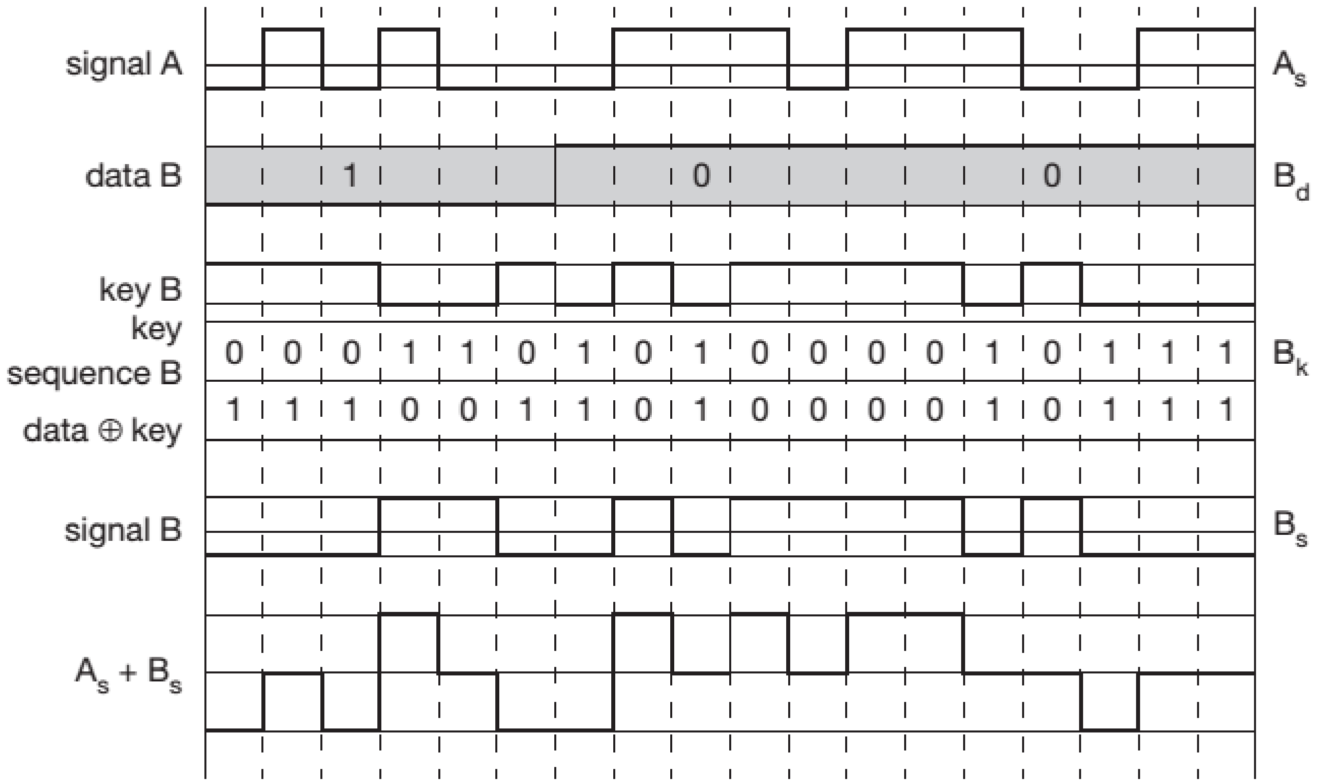


Figure 3.15
Coding and spreading of data from sender B

3.5. CDMA

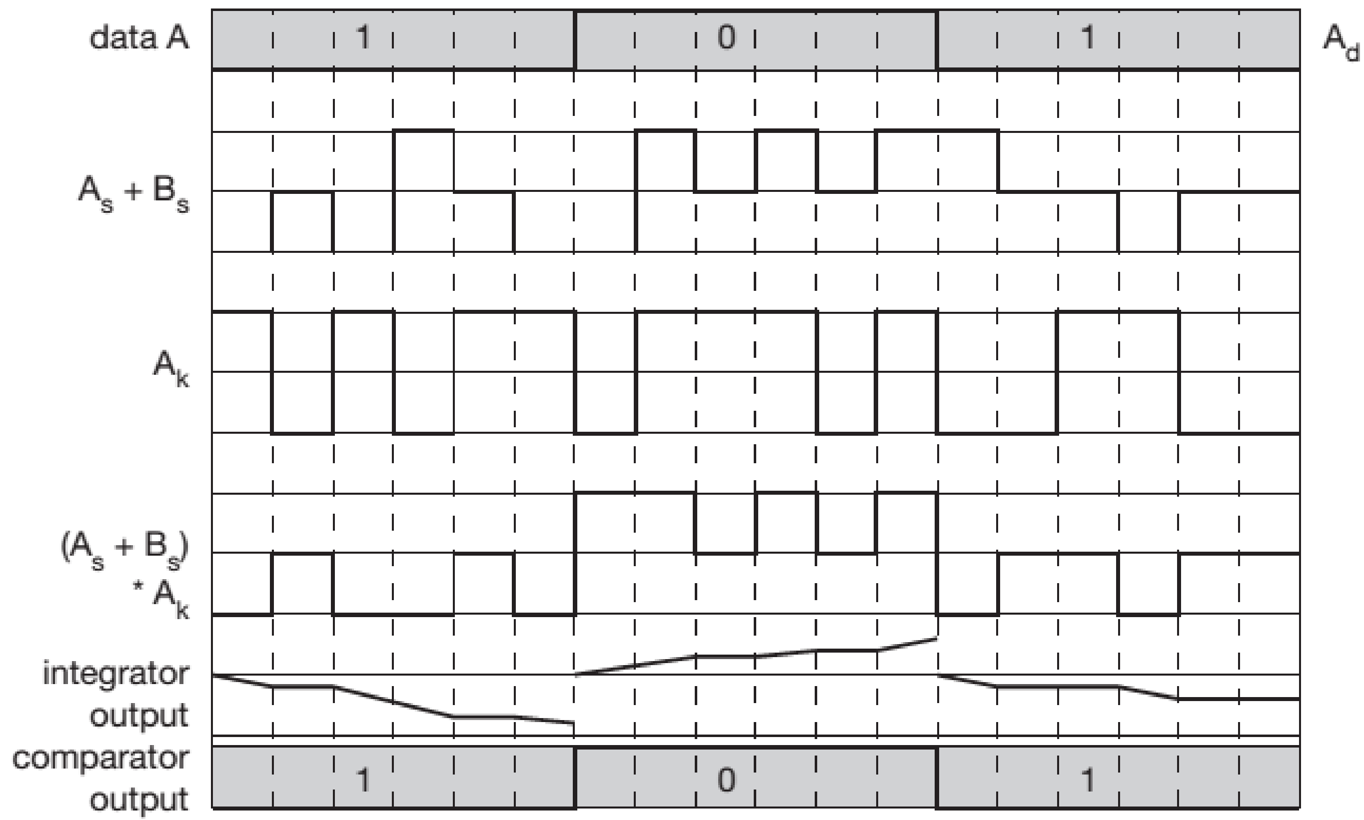
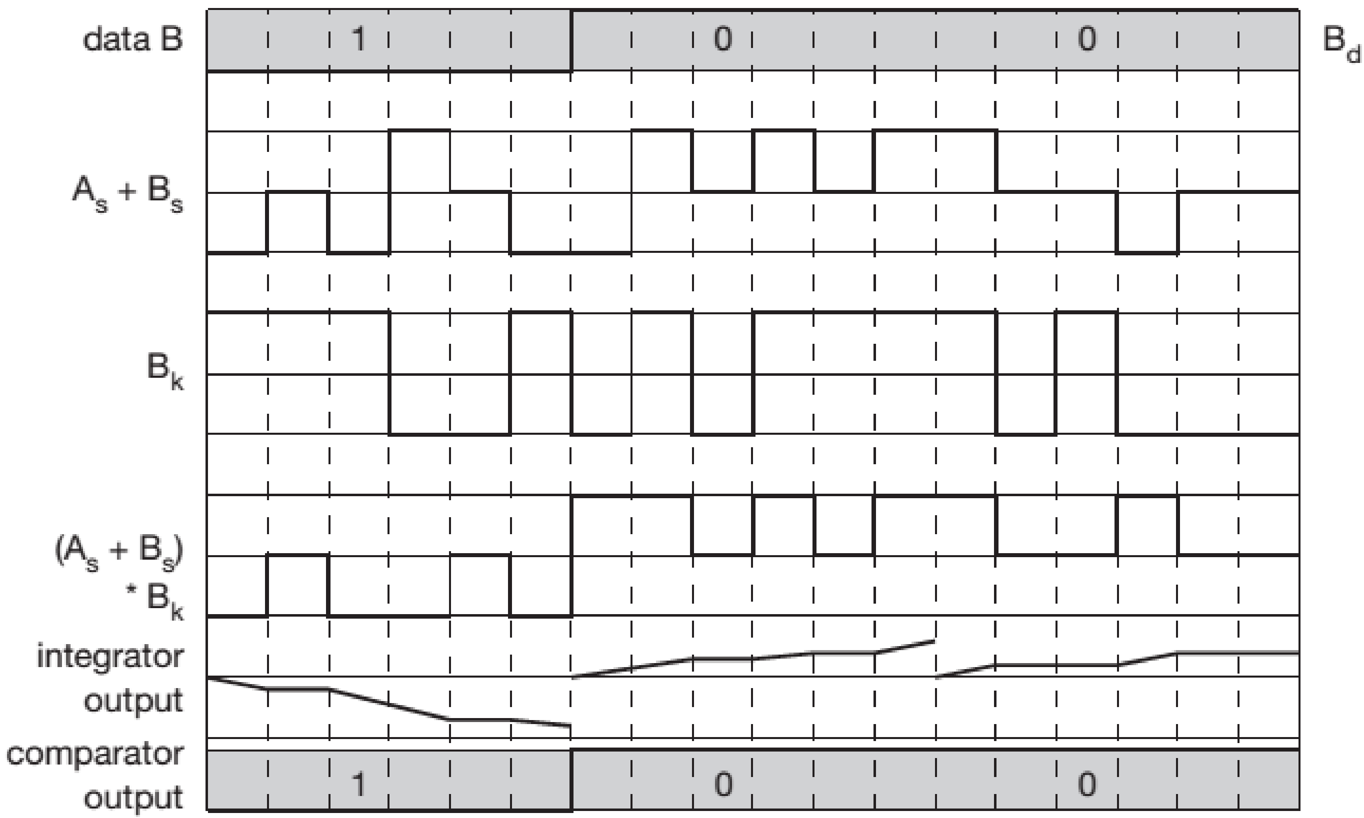


Figure 3.16
Reconstruction of A's data

3.5. CDMA

Figure 3.17
Reconstruction of B's data



3.5. CDMA

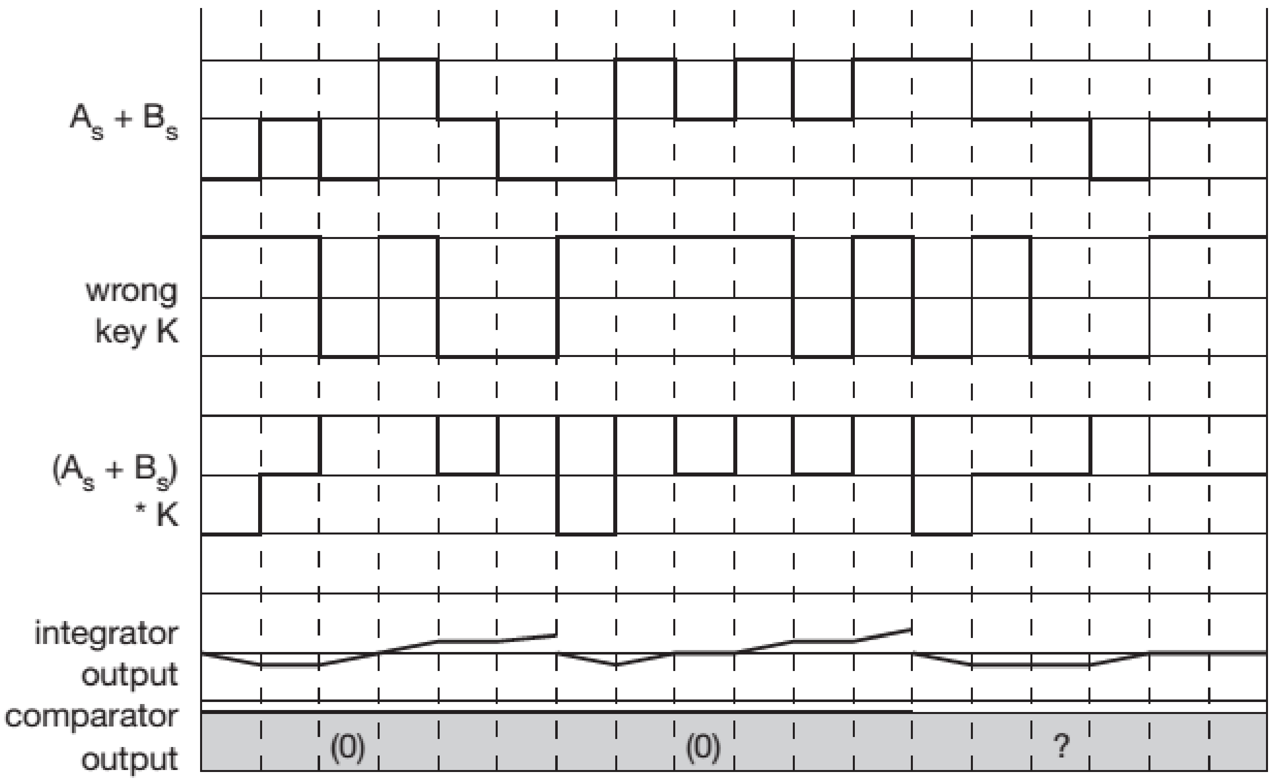


Figure 3.18
Receiving a signal with the wrong key

3.5. CDMA

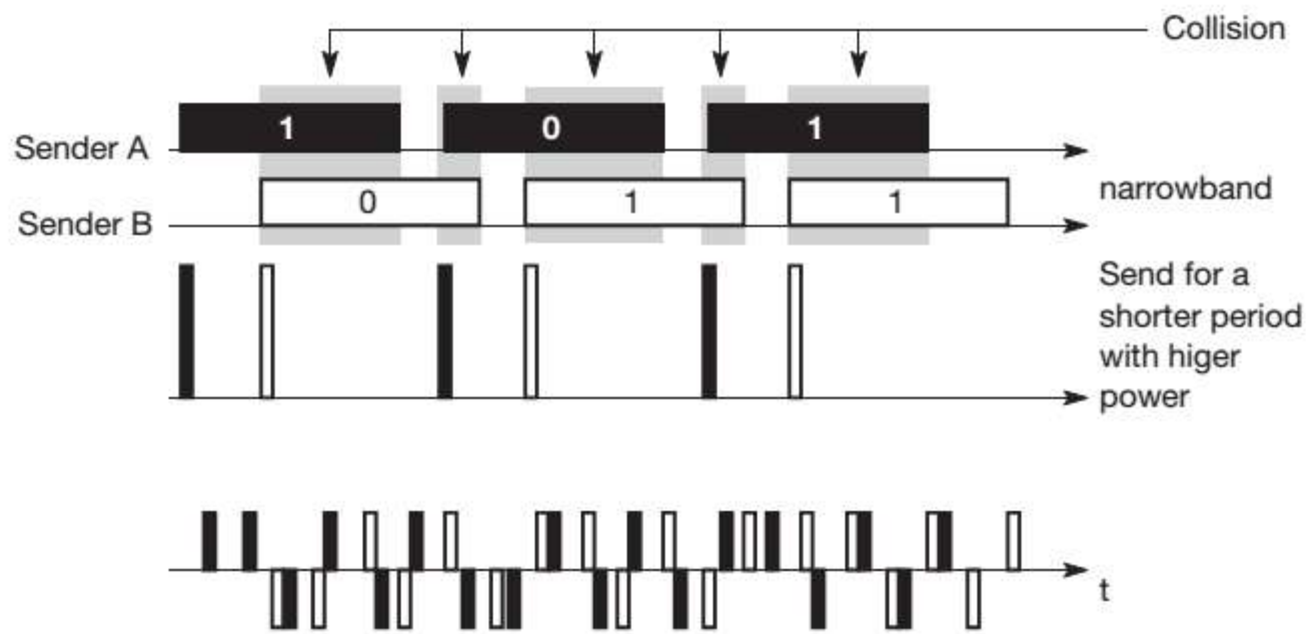
3.5.1 Spread Aloha multiple access

- CDMA senders and receivers are not really simple devices.
- Communicating with n devices requires programming of the receiver to be able to decode n different codes.
- For mobile phone systems, a lot of the complexity needed for CDMA is integrated in the base stations.
- What happens if we combine the spreading of CDMA and the medium access of Aloha or, in other words, what if we use CDMA with only a single code, i.e., without CD?
- The resulting scheme is called spread Aloha multiple access (SAMA) and is a combination of CDMA and TDMA

3.5. CDMA

- SAMA works as follows:

Figure 3.19
Spread Aloha multiple access



- Each sender uses the same spreading code. The standard case for Aloha access is shown in the upper part of the figure.

3.5. CDMA

- Sender A and sender B access the medium at the same time in their narrowband spectrum, so that all three bits shown cause a collision.
- The same data could also be sent with higher power for a shorter period as shown in the middle, but now spread spectrum is used to spread the shorter signals, i.e., to increase the bandwidth (spreading factor s = 6 in the example).
- Both signals are spread, but the chipping phase differs slightly.
- Separation of the two signals is still possible if one receiver is synchronized to sender A and another one to sender B.
- The signal of an unsynchronized sender appears as noise.

3.6. Comparison of S/T/F/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 km²	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