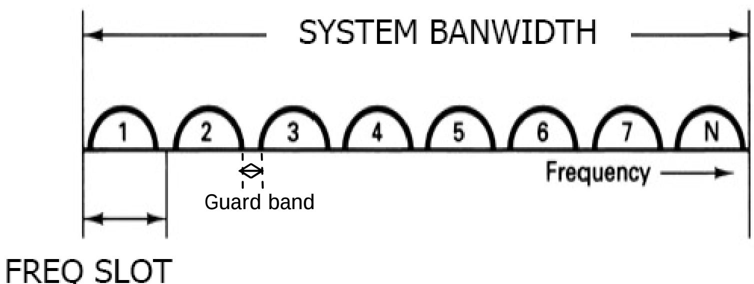
MULTIPLE-ACCESS TECHNIQUES

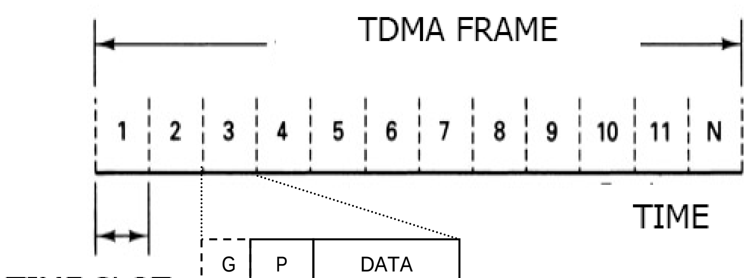
CHANNELIZATION AND MULTI-ACCESS TECHNIQUES

- **Multiple access system**: A large number of geographically separated users share a common communication medium to transmit information to a receiver. There must be a coordinated effort to share the resource – otherwise all users would be interfering with each other.



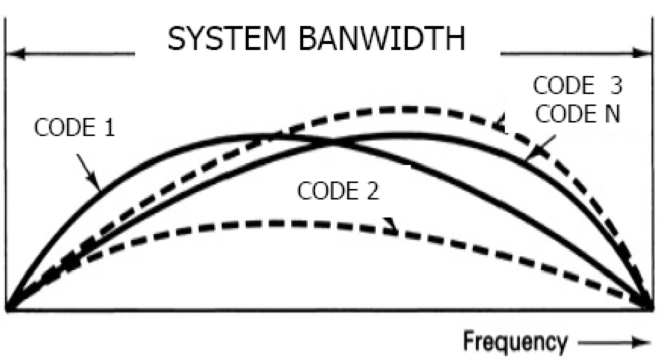
FDMA

Frequency Division Multiple Access (FDMA): Divide the bandwidth of the communication medium into N **non-overlapping frequency slots** and assign a slot to each user upon request.



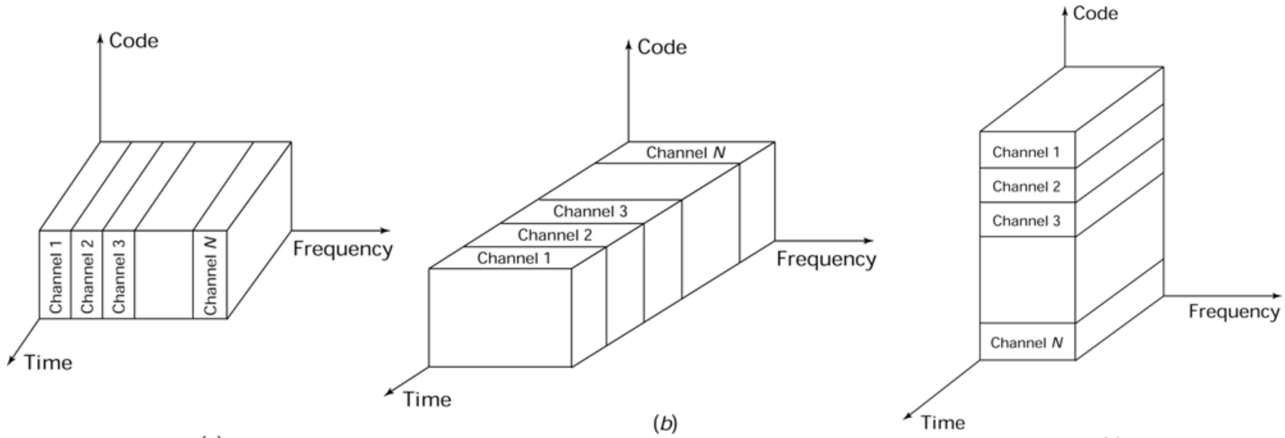
TDMA

Time Division Multiple Access (TDMA): Use the entire bandwidth of the communication medium and establish a time frame T_f. Divide this time frame into N **non-overlapping time slots**, each of duration T_f/N. Assign a time-slot to each user upon request.



CDMA

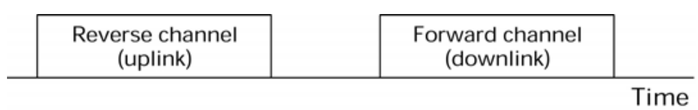
Code Division Multiple Access (CDMA): (also called SSMA) Allow users to share the entire bandwidth simultaneously by use of spread-spectrum codes. Signals from various users are separated at the receiver by cross-correlation of the received signal with each of the possible user codes. By designing the code sequences to have relatively small cross-correlations, the crosstalk inherent in the demodulation of the signals received from multiple transmitters is minimized.



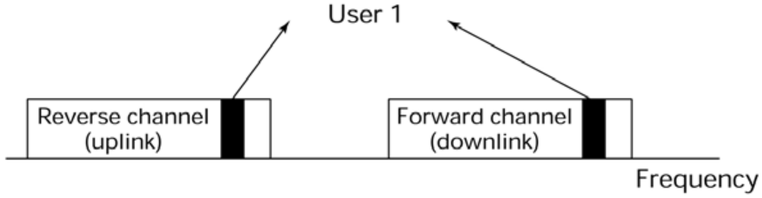
(a) (b) (c)

FDMA TDMA CDMA

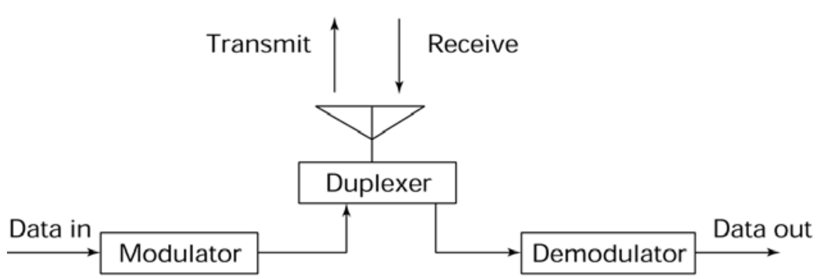
CHANNELIZATION FOR Tx & Rx OPERATION (DUPLEXING)



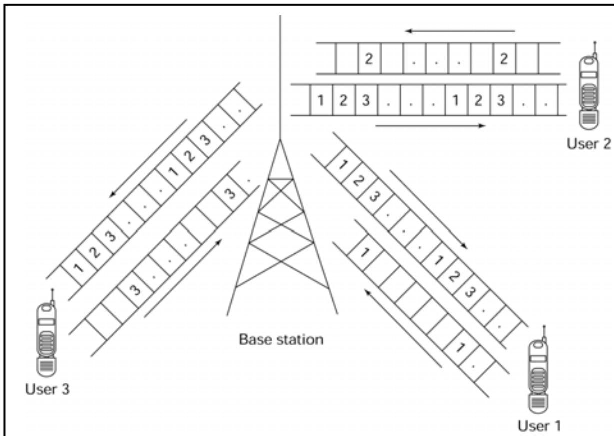
TIME-DIVISION DUPLEXING (TDD)



FREQUENCY-DIVISION DUPLEXING (FDD)



TRANSCEIVER (Tx&Rx)



Example of
TDM (downlink)/TDMA (uplink)

CAPACITY OF MULTIPLE ACCESS TECHNIQUES

Consider an AWGN channel of bandwidth W shared by K users.

FDMA: each user is allocated a bandwidth B_u=W/K. B_u includes guard band. Its normalized capacity is

$$\frac{C_K}{B_u} = \log_2\left[1 + \frac{C_K}{B_u}\frac{E_b}{N_o}\right] \rightarrow \frac{C_K}{W} = \frac{1}{K}\log_2\left[1 + K\frac{C_K}{W}\frac{E_b}{N_o}\right]$$

TDMA: each user is allocated a bandwidth W for a time fraction of T_u=1/K. T_u includes guard time. Its normalized capacity is identical to that of FDMA.

$$C = KC_K, \frac{C}{W} = \log_2\left[1 + \frac{C}{W}\frac{E_b}{N_o}\right] \rightarrow \frac{C_K}{W} = \frac{1}{K}\log_2\left[1 + K\frac{C_K}{W}\frac{E_b}{N_o}\right]$$

CDMA: The capacity of the system depends on the level of cooperation among the K users. In non-cooperative CDMA each user's PN waveform is assumed to be a Gaussian process, then each user's signal is corrupted by Gaussian noise of power (K – 1) P from other users and WN_o from the thermal noise. The normalized capacity per user is

$$P = C_K E_b, \frac{C_K}{W/K} = \log_2\left[1 + \frac{C_K E_b}{\left[(K-1)P + WN_o\right]/K}\right]$$

$$\rightarrow \frac{C_K}{W} = \frac{1}{K}\log_2\left[1 + K\frac{C_K}{W}\frac{E_b}{N_o}\left(1 + (K-1)\frac{C_K}{W}\frac{E_b}{N_o}\right)^{-1}\right]$$

For a large number of users, K, for non-cooperative CDMA

$$C = K\frac{C_K}{W} \leq \log_2 e - \left(\frac{E_b}{N_o}\right)^{-1} < \log_2 e = 1.44$$

CDMA is efficient in power-limited applications from J.G. Proakis, *Digital Communications* , (3rd Edition), McGraw-Hill, 1995.

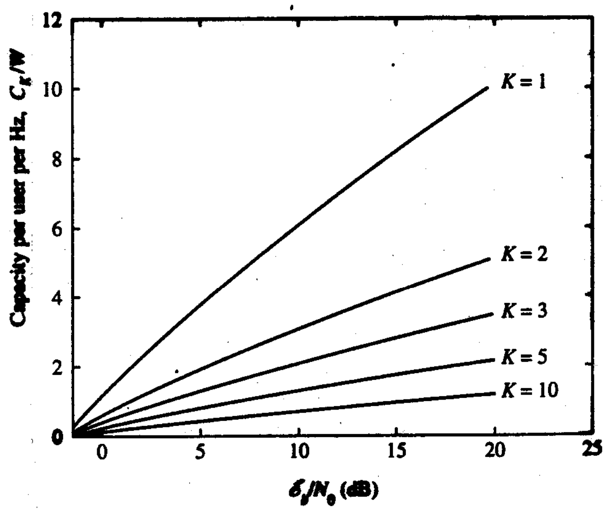


FIGURE 15-2-1 Normalized capacity as a function of $\mathscr{E}_b/N_0$ for FDMA.

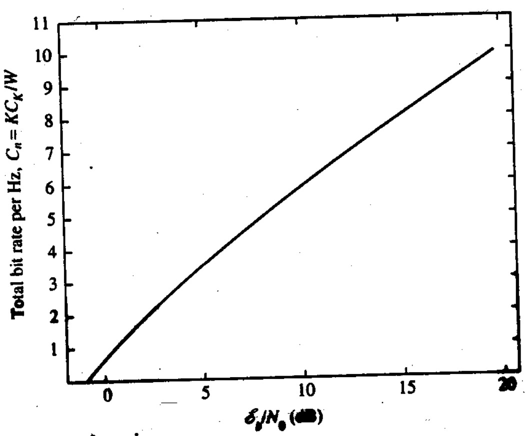


FIGURE 15-2-2 Total capacity per hertz as a function of $\mathscr{E}_b/N_0$ for FDMA.

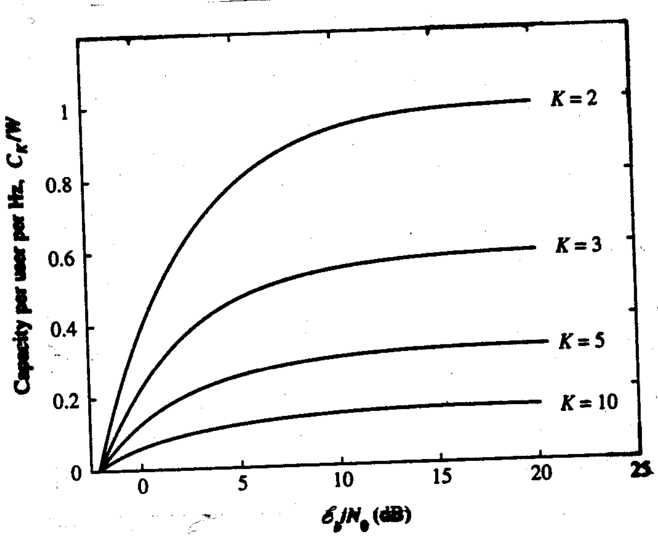


FIGURE 15-2-3 Normalized capacity as a function of $\mathscr{E}_b/N_0$ for noncooperative CDMA.

COOPERATIVE CDMA

In cooperative CDMA, K users simultaneously transmit their codewords, X_i's, one from each user codebook, simultaneously in time. The multiuser receiver knows the spreading waveforms (or codebooks) of all users. The optimum receiver observes

$$Z=(X_1+X_2+\ldots+X_K)+\text{noise}$$

and looks for K codewords, one from each user codebook, that have a vector sum closest to Z in Eudidean distance.

For K users with equal power P and rates, R_i's, in cooperative CDMA, we have the set of following rate constraints

$$R_i < W\log_2\left[1+\frac{P}{WN_o}\right],\ R_i+R_j < W\log_2\left[1+\frac{2P}{WN_o}\right],\ldots,\sum_{i=1}^{K} R_i < W\log_2\left[1+\frac{KP}{WN_o}\right]$$

For the equal rate case, the rate constraint is identical to that in TDMA/FDMA.

For the unequal rate case, it is possible to find the points in the achievable rate region such that $(R_1+R_2+\ldots+R_K)$ exceeds the capacity of FDMA and TDMA.

RADIO CAPACITY IN A SINGLE-CELL SYSTEM

TDMA or FDMA: Each time or frequency slot (channel) is assigned to one call.

- The effective bandwidth of a channel is $W=f_b/e_M$ where f_b is the channel effective bit rate and e_M is the modulation efficiency.
- For a total bandwidth of B, the number of channels per cell (or radio capacity) is $m_{TDMA} \approx m_{FDMA} \approx M = B/W = (B/f_b)\, e_M$
- The capacity can be increased by using bandwidth-efficient modulation techniques.
- Hard capacity: number of channels is fixed.

CDMA: Each spreading code (channel) is assigned to one call. For $m_{CDMA}=M$ simultaneous calls of equal power C, the effective noise power spectral density is I_o+N_o where $I_o=(M-1)C/B$ and N_o is the thermal noise power spectral density. Effective $E_s/(I_o+N_o)$ after despreading is

$$E_s/(I_o+N_o)= e_M(B/f_b)[(M-1)+N_oB/C]^{-1}$$

for $M>>1$ and $M>>C/(N_oB)$, $m_{CDMA}=M\approx e_M(B/f_b)[E_s/(I_o+N_o)]^{-1}$

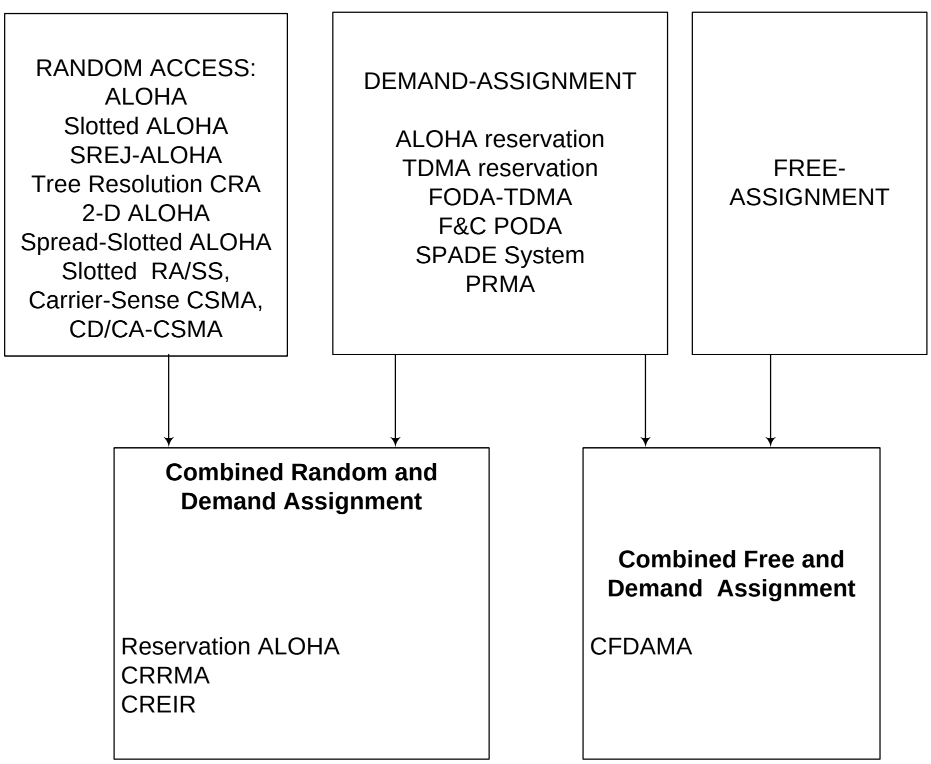
- In a single-cell system, the capacity of the CDMA system is smaller than that of TDMA/FDMA by a factor of $E_s/(I_o+N_o)$, i.e.,

$$[m_{CDMA}/\, m_{FDMA}\,]\approx[E_s/(I_o+N_o)]^{-1}$$

- It is important to **minimize** the required $E_s/(I_o+N_o)$ in order to increase the capacity of CDMA systems. This can be done by using strong error correction codes.
- Signal power, C, must be high enough so that the system is **not limited by thermal noise**.
- **Soft capacity:** “number of channels” is flexible, depending on the required operating $E_s/(I_o+N_o)$

CHANNEL ACCESS TECHNIQUES & DYNAMIC RESOURCE ALLOCATION

- Given that the resource is divided into channels, the next thing to deal with is how to distribute these channels to the terminals.
- Performance/complexity trade-offs depend heavily on the environment, e.g., cellular, or satellite (on-ground hub or on-board processing), and traffic supported, e.g., voice, video, and data, multimedia:
    - real-time, e.g., voice, video, cannot tolerate delay but can tolerate some packet loss, high error rates
    - non-realtime, e.g., data, multimedia, is bursty, -cannot tolerate loss, but -can tolerate some delay
- Dedicated channels: wasteful for data, multimedia traffic
- Dynamic capacity allocation uses statistical multiplexing to support different bursty traffic types with various quality of service requirements (typically in terms of delay and loss)
- Classification of Access Techniques & Dynamic capacity allocation:

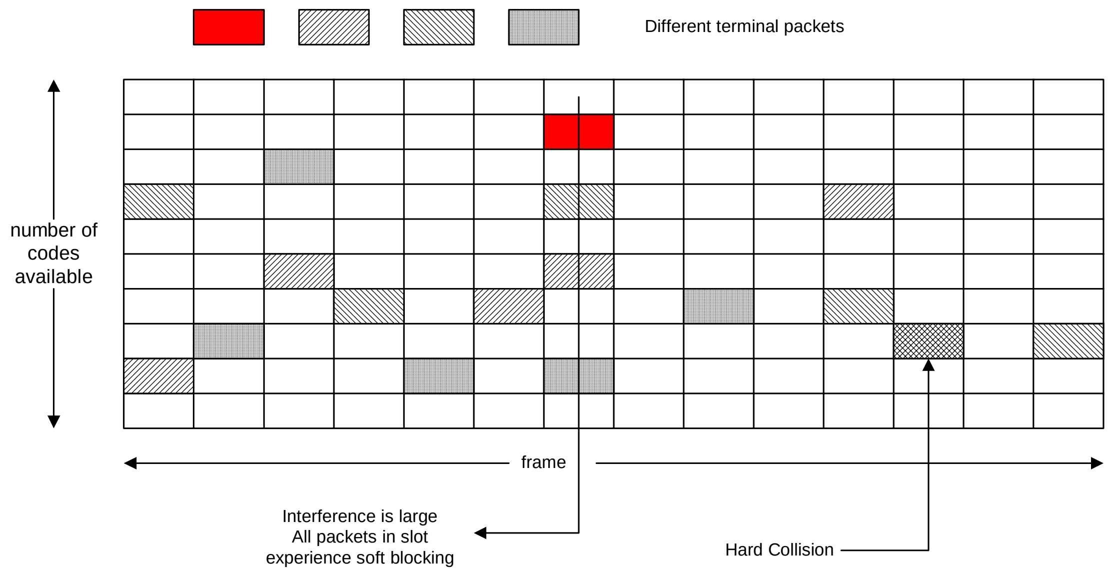


Random Access:

- Most channel oriented random techniques are based on slotted ALOHA.
- Basically all channels are up for grabs.
- Any terminal can transmit in any one of the channels.
- Due to random nature, two or more users can transmit in the same channel. In such a case, the central station would see the collision, and request a retransmission.
- This implies that the sending terminal must keep a copy of the current transmitted packet, until reception of a positive acknowledgment from the central station.
- No other packet can be sent, until the current packet is positively acknowledged.
- Basic operation:
  1. Packets are received and queued at the terminal.
  2. Terminal randomly selects a channel for transmission, and then waits for an acknowledgement
     a. Positive: Next packet becomes ready for transmission and we repeat step 2.
     b. Negative: Implies packet has collided and therefore requires retransmission.
        We could retransmit the packet in the next available channel after receiving the acknowledgement. However, chances are high that the other terminal(s) involved in the collision will receive their negative acknowledgment at about the same time. If they too select the next available channel, we would get another collision
        As a result, once a terminal receives a negative acknowledgement, the terminal waits a random amount of time and then retransmits the copy of the collided packet and again listens for an acknowledgement (step 2).
        This random wait reduces the probability of subsequent collisions.
- Drawbacks:
  - Collisions and retransmissions are not suited for real-time traffic.
  - As the load (Number of terminals or Information rate generated per terminal) in the system increases, collisions become more probable.
  - The collisions require retransmissions, and eventually a point is reached where the network is flooded with retransmitted traffic and is unstable.
  - A typical slotted ALOHA system has a maximum throughput of 36%.

Spread Slotted ALOHA:

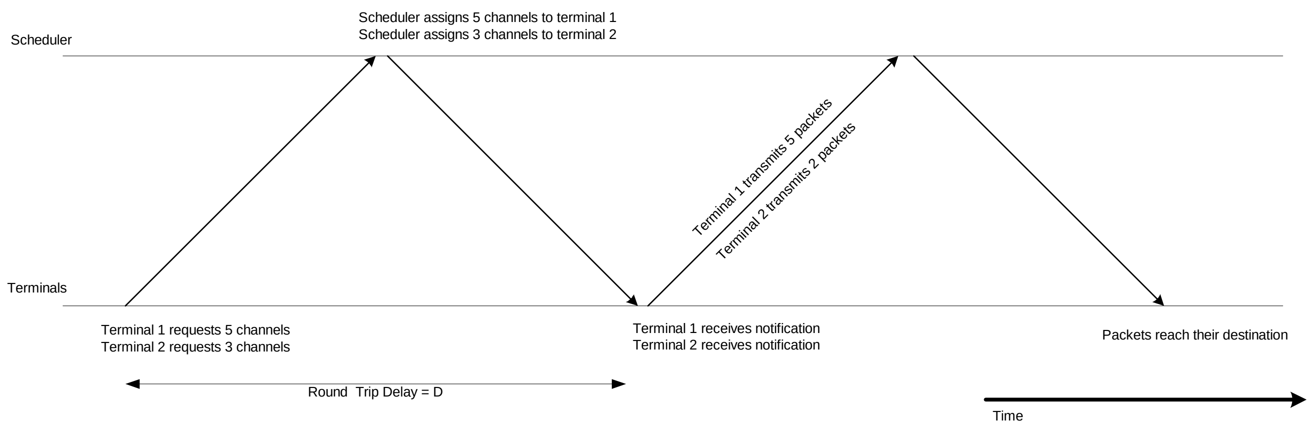
- Random access technique combined with a hybrid CDMA/TDMA.



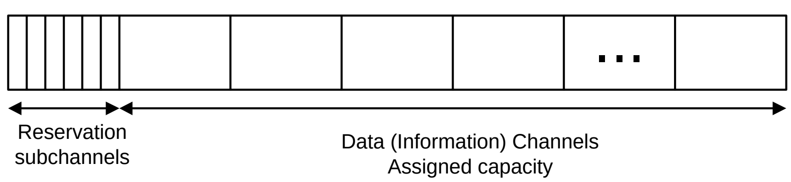
- Each terminal is assigned a set of spreading codes from which to choose.
- When a terminal receives a packet, it immediately transmits this packet on one of the allocated spreading codes.
- All terminals do the same
- Note:
  - Two or more terminals can transmit in the same time slot and on the same spreading code. This is referred to as a hard collision and requires a retransmission
  - Number of terminals transmitting on the same time slot can be very high. This leads to excessive interference. This condition is known as a soft collision. Information is not lost, but the received BER will be worse.

Demand (Reservation) Assignment:

- No possibility of collision
- Terminals make requests (reservations) for capacity, and the centralized station schedules or honors these requests – the device which does the scheduling is often referred to as the scheduler.
- Typical example:

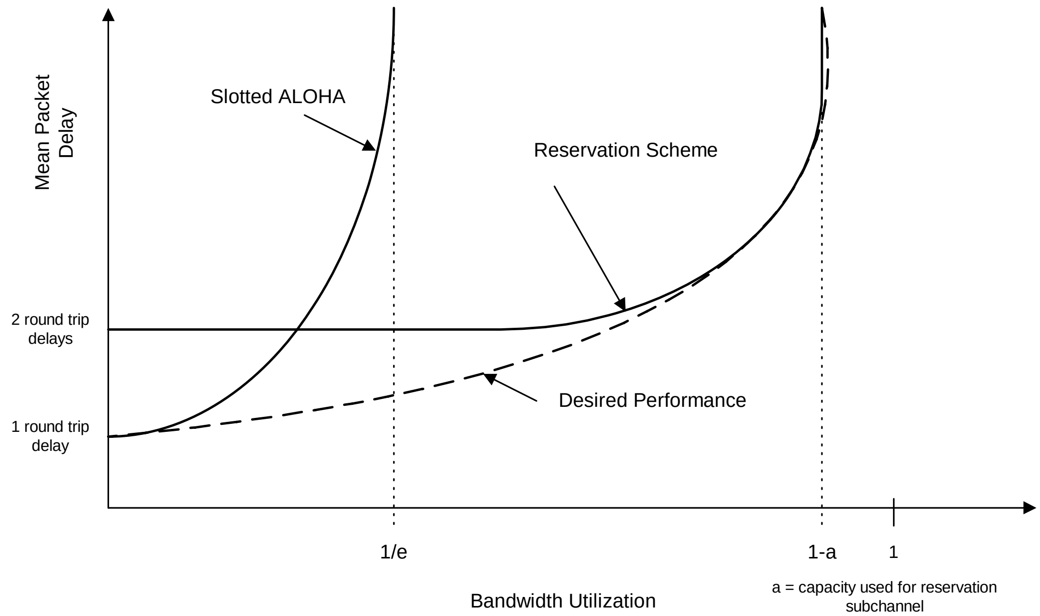


- o Demand assignment can operate on different time scales
  - Call: The capacity (channels) is assigned per call.
    These channels belong to the terminal for the entire duration of the call
    Very similar to fixed assignment
  - Burst: Terminals make explicit requests and the scheduler holds these requests until they are released.
  - Cell: This is the example shown above.
    A terminal periodically makes requests for the number of channels it needs.
- o Note that the minimum delay is two round trips (~*2D*). (one round-trip to have the request honored, and one round-trip to actually transmit the packet).
- o How does the terminal make requests?
  - Typically, a portion of the resource is set aside for making requests. For instance in TDMA, one channel can be used for this – this channel is referred to as the reservation channel.



  - In the simplest case, the reservation channel is split into a number of mini-channels and these are used for making reservations, e.g.,
    - ALOHA Reservation: mini-channels are shared using slotted ALOHA
    - TDMA Reservation: mini-channels are pre-assigned to terminals

Combined Random / Reservation Assignment:

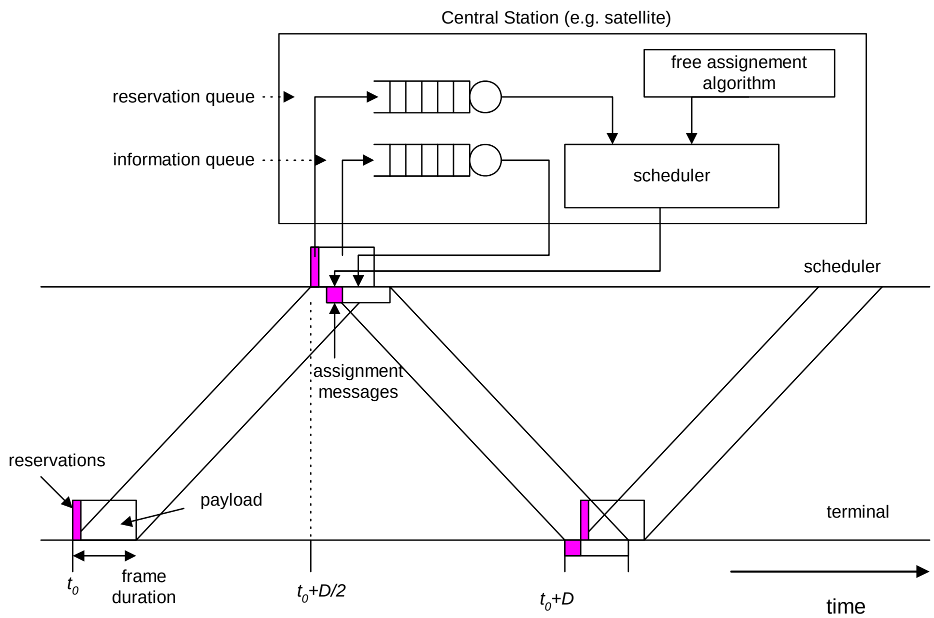


- Random access is very good at low loads, but its max throughput is very low
- Reservation access is good at high loads, but has a minimum delay of *2D* (even at low loads)
- Objective is to combine both schemes into a hybrid, which takes advantage of the best features of both, e.g., Reservation ALOHA
  - Terminals contend for channels in a random access manner (like slotted ALOHA)
  - If a terminal successfully transmits in a channel, the scheduler will hold this channel for this terminal in subsequent frames – essentially the initial successful transmission acts like a request.
  - When a terminal no longer needs the channel, it informs the scheduler to release the hold. The channel is then open for contention.
  - Very similar to the scheme Packet Reservation Multiple Access (PRMA) which has been proposed for the next generation cellular standard.

Combined Free / Demand Assignment:

- Most popular scheme is CFDAMA in SATCOM
- gained some acceptance in the satellite industry (and is currently being standardized in Europe)
- Very efficient in large propagation delay environments – but can also be used in terrestrial networks.

Basic dynamics:



- Scheduler has a queue to store requests (reservation queue) and continually runs a free assignment algorithm.
- Each frame has a mini-channel section, used by terminals for making reservations.
- At time t_0, terminals with traffic make requests.
- Requests arrive at the scheduler at time $t_0 + D/2$ (One way propagation delay)
- Requests are stored in the reservation queue.
- At the start of the next frame, the scheduler looks at the reservation queue and begins assigning channels.
- Say it has honored all the reservations and there are still empty channels. This capacity is basically unused.
- The assignments made at time $t_0 + D/2$ will only be known at the terminals at time $t_0 + D$.
- Owing to this propagation delay, the assignments are always based on requests made D seconds earlier.

- Consequently, the scheduler may have left some channels unassigned even though some terminals are waiting for capacity – Inefficient!
- Consider that the scheduler decides to make free assignments at time $t_0+D/2$. That is, after satisfying all requests, it freely assigns the remaining channels to terminals. These terminals get channels, even though they had not made explicit requests for them.
- The actual algorithm for the free assignment is quite flexible:
  - Simplest case would use a round-robin approach. That is, assign 1 channel to every terminal until all channels are assigned.
  - A more advanced approach would be to keep track of a terminal's activity, and assign the free traffic based on this activity – active terminals would get a larger portion of the free assignment.
- It is possible that channels would still go unused – a terminal may be given a free channel but have no packets to transmit.
- However, if a terminal does have traffic, these packets would be transmitted without having to make a request – notice that this results in a performance that is very similar to the random access approach.

Summary:

Fixed Assignment	Description	▪ Channels permanently assigned to terminals
	Advantages	▪ Very simple scheduler ▪ Well suited for constant bit rate type sources ▪ Channel use is contention-free
	Disadvantages	▪ Lacks flexibility when operating with terminals with variable bit rates.
Random Assignment	Description	▪ Channels are up for grabs ▪ Terminals randomly select a channel for transmission. ▪ Randomness leads to collisions, requiring a collision resolution algorithm.
	Advantages	▪ Very low access delay at low load. ▪ Very simple to implement at terminals ▪ Can support a very large population of bursty terminals
	Disadvantages	▪ Can lead to instability. ▪ Maximum load much less than 1.0 (0.36 for slotted ALOHA). ▪ Retransmission of collided packets leads to jitter (inappropriate for real-time traffic).
Demand Assignment	Description	▪ Terminals dynamically request capacity from a scheduler, which assigns channels based on these requests.
	Advantages	▪ Stability guaranteed. ▪ Utility can be maximized. ▪ Technique is fair to all terminals (fairness is guaranteed by the scheduler)
	Disadvantages	▪ Some capacity is lost due to overhead of the reservation mini-channels. ▪ Can require a fairly complex scheduler. ▪ Experiences high delay for low loads (due to the need to wait for requests to be honored).
Free Assignment	Description	▪ Channels are freely assigned to terminals based on some heuristic information. ▪ For pure free assignment, the scheduler uses a round-robin approach to distribute capacity to terminals. This approach resembles fixed assignment.
	Advantages	▪ Very simple to implement.
	Disadvantages	▪ Pure free assignment leads to inefficiency (same as with fixed assignment)
Hybrid Random/ Demand Assignment	Description	▪ Normally, channels are divided into those used in contention mode and those used in reservation mode. ▪ Terminals contend for the former using random access, while the latter are assigned by the scheduler, based on requests.
	Advantages	▪ Delay approaches that of random access at low load and demand assignment at high loads.
	Disadvantages	▪ Contention channels can still lead to collisions and jitter.
Hybrid Free/ Demand Assignment	Description	▪ Channels are assigned based on terminal requests. ▪ Any channels which remain unassigned are then freely assigned to terminals based on some heuristic information (in the simplest case, this assignment can be round-robin).
	Advantages	▪ Inherent use of long propagation delay. ▪ Performance approaches that of the combined random/reservation schemes, but does so without contention.
	Disadvantages	▪ Requires some additional scheduler processing to perform the free assignment.