CAMBRIDGE

Chapter 3 Medium Access Control

Email list: https://groups.google.com/forum/#!forum/mobile-miao

CAMBRIDGE
UNIVERSITY PRESS

Overview

- Multiple terminals need to communicate at the same time
- MAC protocols
  - Share channel
  - Multiplex several data streams of different terminals
- MAC design
  - Initially for wired communications (copper fiber optics)
    - Reliable channel with abundant bandwidth
      - BER<10e-6
    - Packet loss in wired networks is mainly due to collisions and the MAC designs are relatively simple.

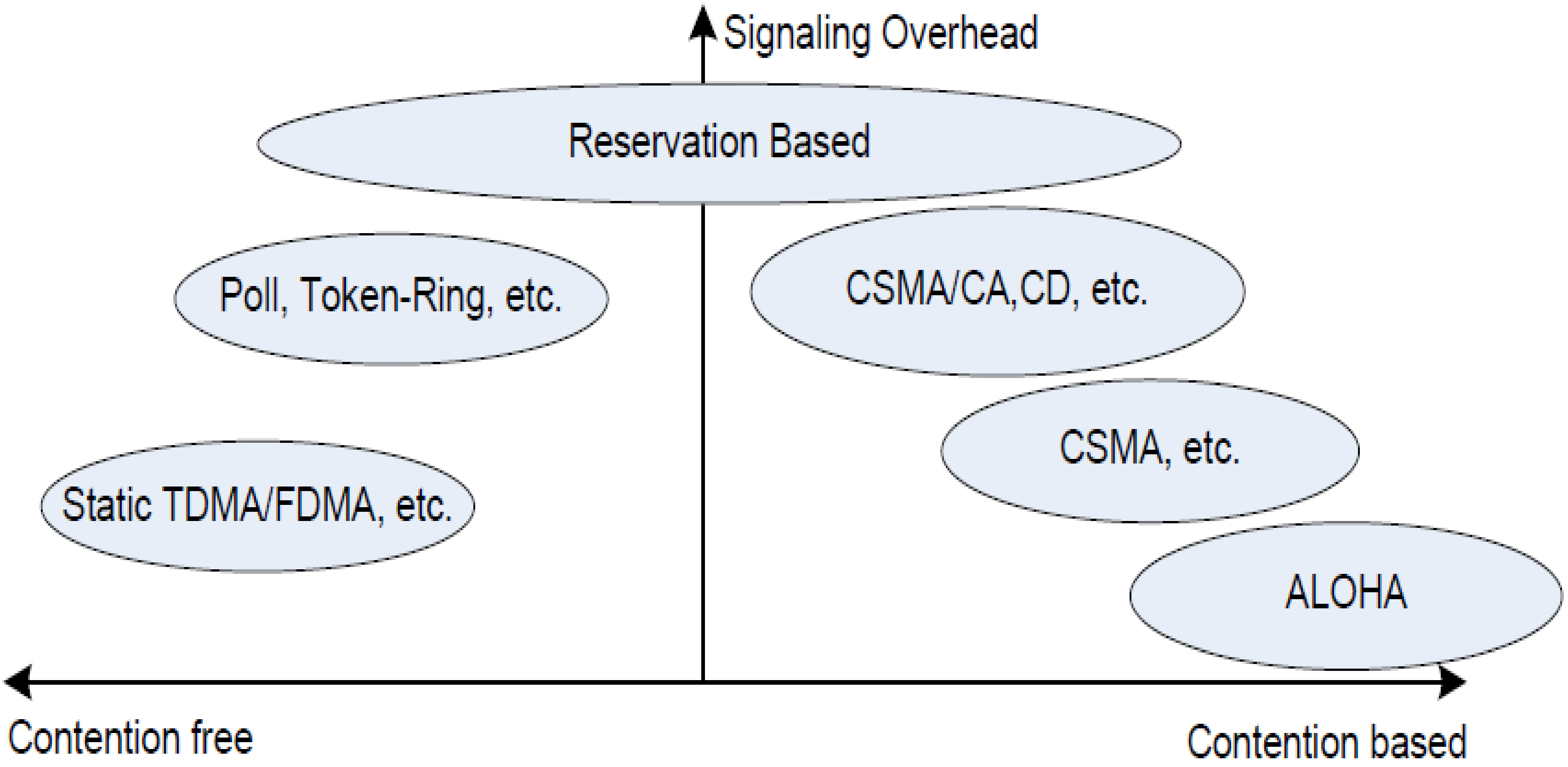
Challenges for Wireless Networks

- A radio signal may experience reflection, diffraction, or scattering before reaching its receiver.
  - Fading deteriorates the signal and incur the variation of signal quality in time, frequency, and space.
  - BER>10e-3
- Broadcast nature of wireless channels.
  - The stronger the transmission power or the closer the neighbor terminals, the stronger the interference will be.
- Half-duplex

MAC Types

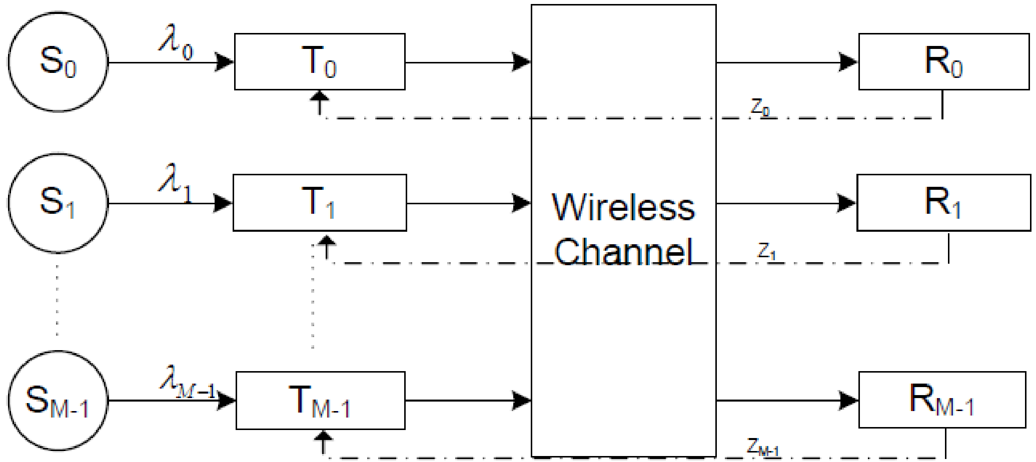
- Contention free
  - Efficient in QoS guarantee
  - Improve network throughput and reduce network response for heavily loaded networks
  - Dynamic schemes have high complexity
- Contention based
  - Inevitable packet collisions
  - Good performance in low-traffic networks
  - Low complexity

MAC Types


Signaling Overhead
Reservation Based
Poll, Token-Ring, etc.
CSMA/CA,CD, etc.
CSMA, etc.
Static TDMA/FDMA, etc.
ALOHA
Contention free
Contention based

Communications Model

- Bursty data traffic, depending on traffic types
- Message model: deterministic arrival, random Poisson arrival.



Performance Measures

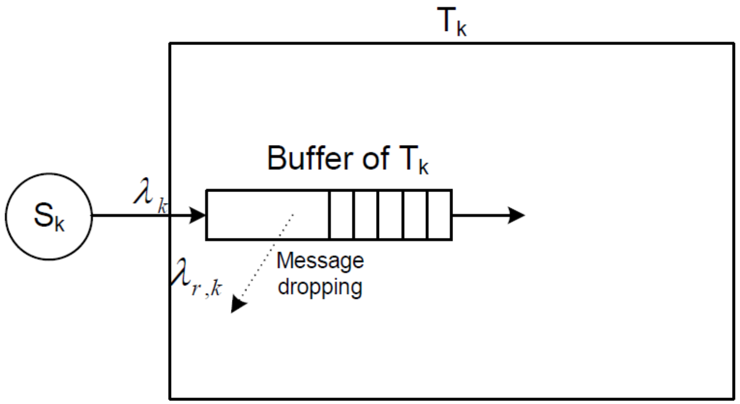
- Delay
  - Delay between arrival time and time the message sent to receiver.
  - $D_i = b_i - a_i$.
- Quality of data received:
  - BER
    - Send msg: 1 1 0 0 1 0 0 1
    - Receive msg: 0 1 0 1 1 0 1 1
    - Number of bit errors: 3.
    - BER: 3/8=37.5%
    - In practice, bit error probability, p_{BER}.
    - Factors: noise, interference, synchronization problems, fading, and so forth.
    - Improvement: higher power, lower modulation order, more robust channel coding

Performance Measures

- Quality of data received:
  - PER

$$p_{PER} = 1 - (1 - p_{BER})^N$$

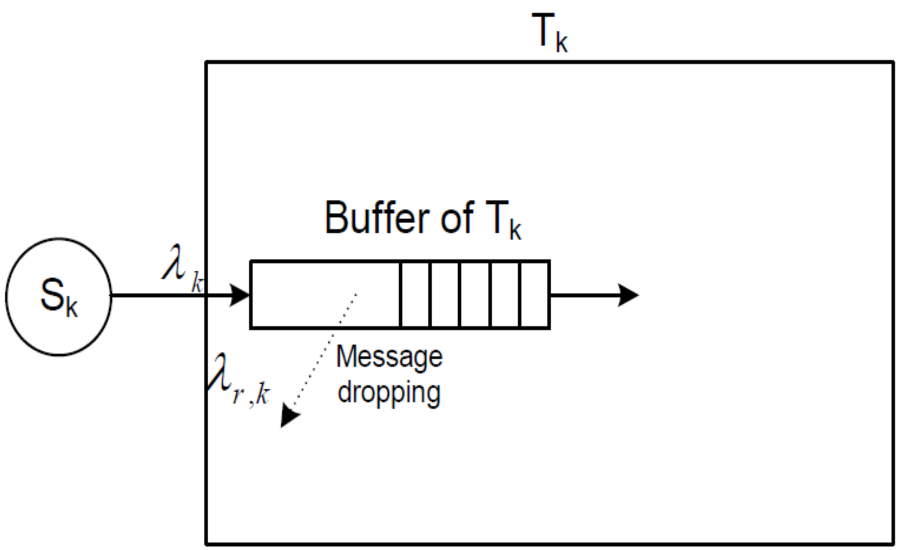
  - Packet dropping



Performance Measures

- Throughput: expected number of messages delivered to the receiver per unit time
- Individual: $S_k = \lambda_k - \lambda_{r,k}$
- System throughput:

$$S = \sum_k S_k$$



Performance Measures

- Throughput:
  - An alternative definition

File size

$$\tilde{\Lambda}(N) = E\left[\frac{N}{b_N - a_1}\right]$$

Time to send all bits

  - Normalized link delay

$$\tilde{D}(N) = \frac{1}{\tilde{\Lambda}(N)}$$

CONTENTION-FREE ACCESS PROTOCOLS

Contention-Free Access Protocols

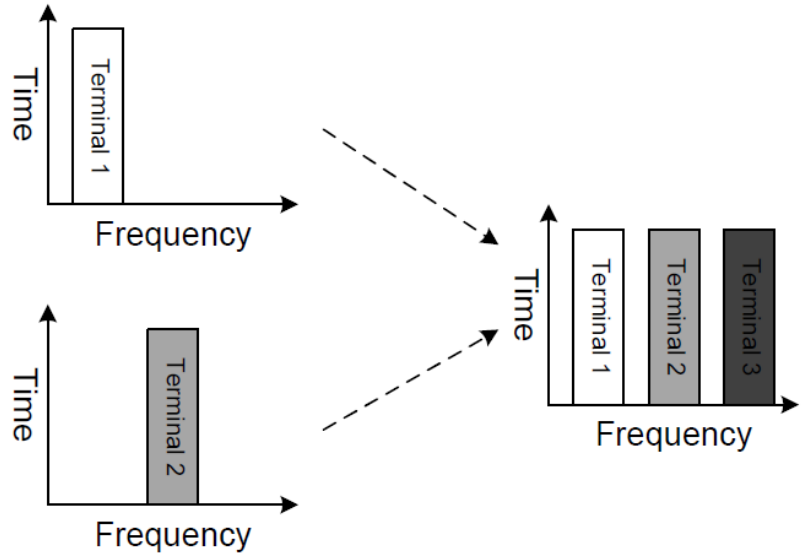
- Contention-free access protocols
  - Each terminal sends packets using predetermined time slots, frequency bands, or codes.
  - A central scheduler coordinates the transmissions of different terminals, and there will be no collisions in the network.
- Types:
  - Static access protocols
  - Dynamic access protocols

Resource Assignment Techniques

- Wireless resources can be divided into orthogonal partitions called channels and these channels can be assigned to different terminals.
- Fundamental resource partitioning techniques
  - TDMA
  - FDMA
  - OFDMA
  - CDMA
  - SDMA
- Illustration assuming static resource allocation:
  - Each link is assigned some fixed channels throughout its communication session.

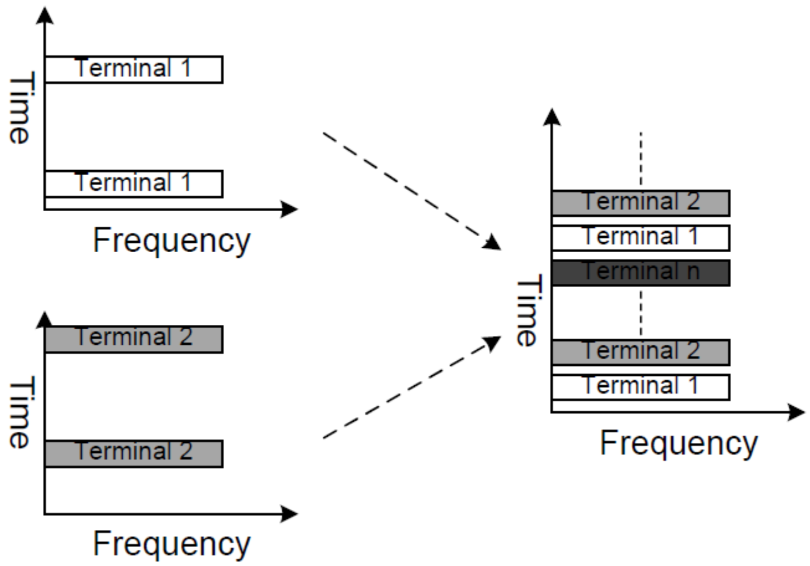
FDMA

- Oldest way of static resource allocation
- Not efficient for traffic with different rate requirements



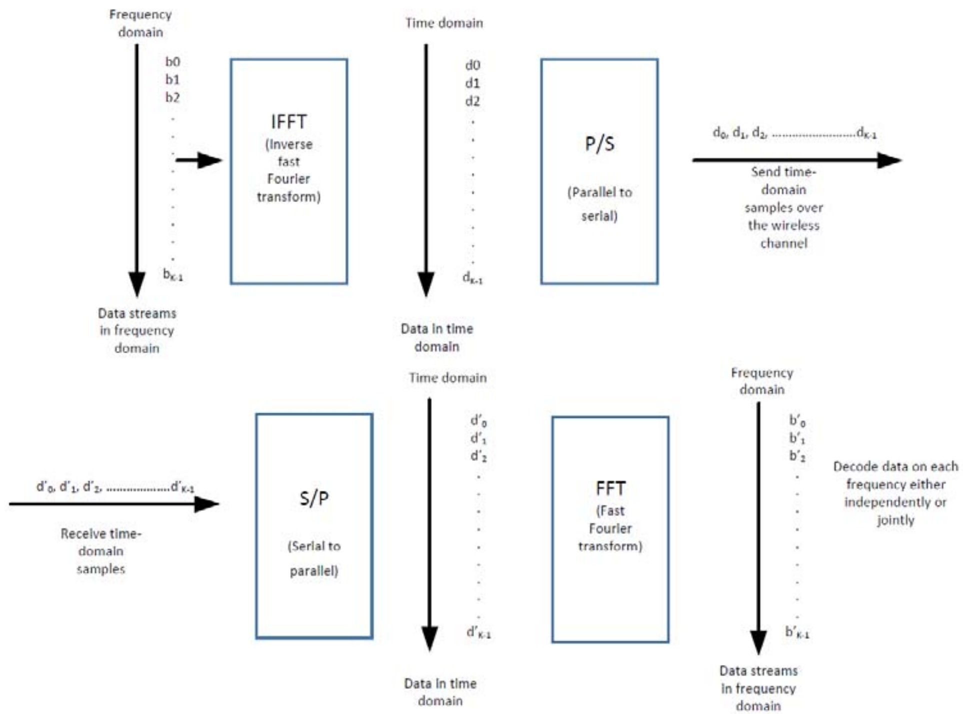
TDMA

- All terminals are synchronized
- More flexible in handling different rate requirements



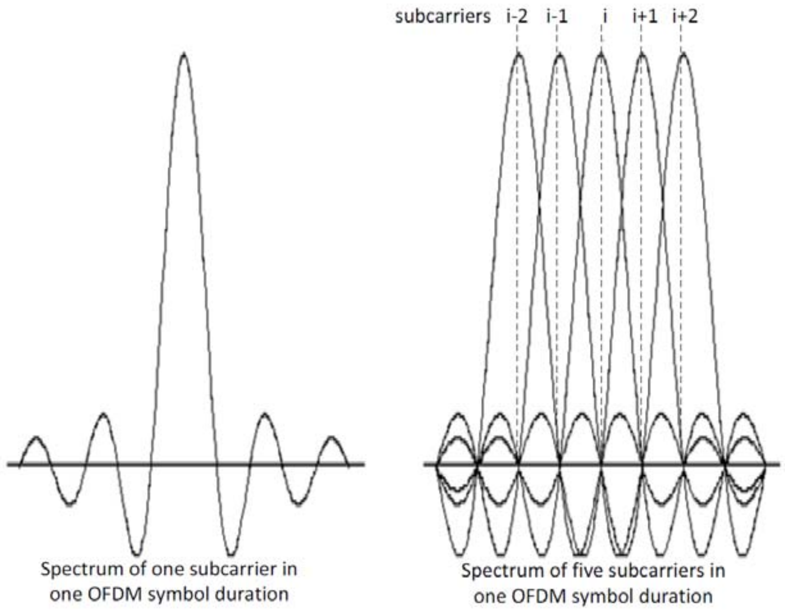
OFDMA

- Based on orthogonal frequency division multiplexing (OFDM).



OFDM Spectrum

– Orthogonal subcarriers to send multiple data symbols in parallel and achieves high spectral efficiency.



OFDM Properties

Pros

- Easy implementation
- Robust against multi-path fading and inter-symbol interference.
- Low sensitivity to time synchronization errors.

Cons

- Very sensitive to frequency-domain errors like Doppler shift and frequency synchronization problems.
- High PAPR

OFDMA

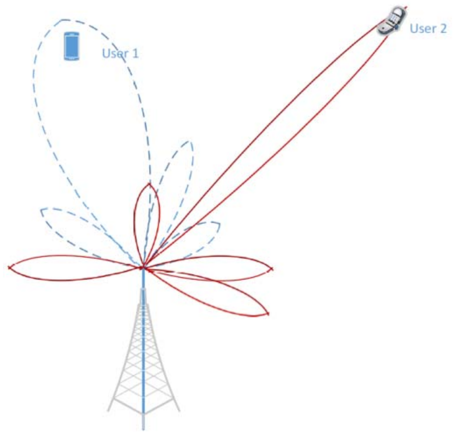
- Multiple access is achieved in OFDMA
  - Assign subsets of subcarriers to individual users.
  - For example a subcarrier can be allocated to the user with relatively the best channel condition.
- Scheduling flexibility in another dimension, the frequency domain.
  - By assigning different numbers of subcarriers to different users, differentiated qualify of service can be easily supported.
- A kind of FDMA in a wide sense.
  - OFDMA incorporates the orthogonality without guard bands, allows overlapping adjacent spectrum bands and therefore is much more spectrum efficient.

SDMA

- Mobile users are located far away.
- Uses the spatial separation to reuse the frequency spectrum for higher network capacity.
- The simplest form of SDMA
  - Reusing the same frequency in different cells
  - Cells with the same frequency should be sufficiently separated in space.
  - Limit how many cells a region may be divided into and network reuse factor

SDMA

- More advanced SDMA:
  - Frequency reuse within each cell
- Use smart antenna arrays and intelligent signal processing techniques to steer the antenna beam to the desired users and places nulls in the direction of other users.

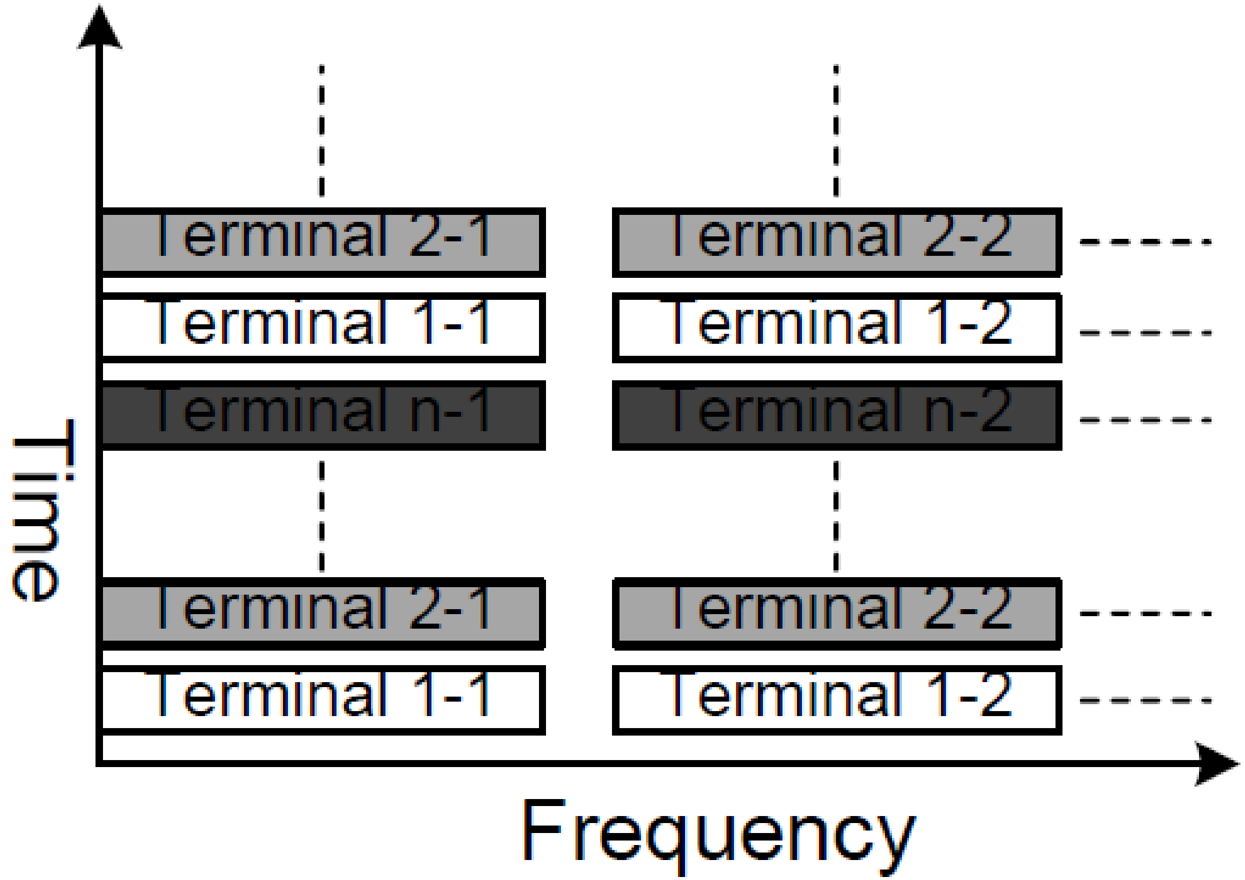


SDMA

- SDMA differs from FDMA, TDMA, and OFDMA in that a perfect spatial separation of users can not be guaranteed in general.
- The orthogonality of different users depends on the spatial correlation among the channels of the users.
  - When spatial sub-channels are not close to orthogonal, it may result in excessive co-channel interference and degraded performance.
- SDMA algorithms
  - cope with correlated subchannels and multiplex data streams of different users only when their channels are sufficiently uncorrelated.
- The number of available spatial channels
  - depend on the environment and the number of transmit and receive antennas.

CAMBRIDGE

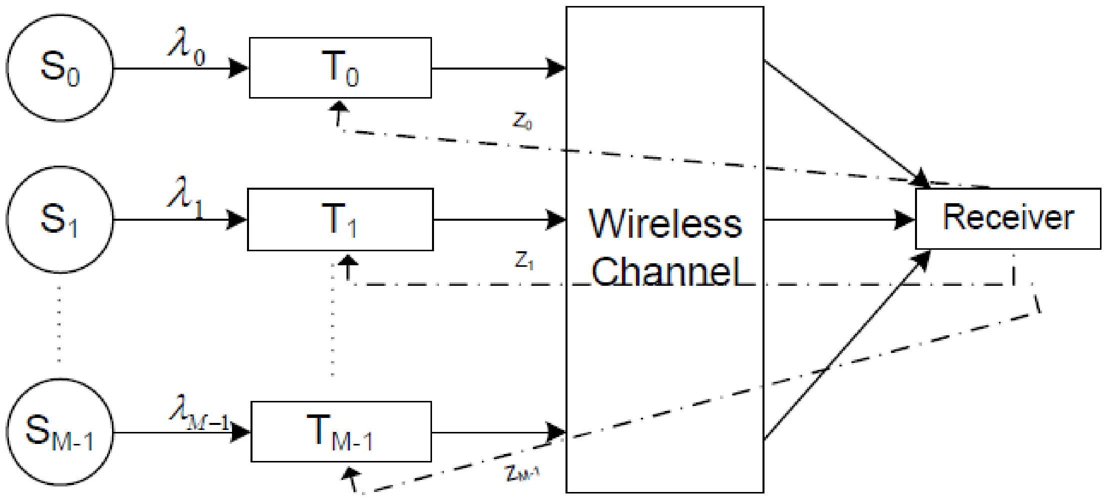
Hybrid Access



CAMBRIDGE UNIVERSITY PRESS

Resource-Sharing Conflicts (1)

- Use FDMA
- Symbols are transmitted at a rate $\frac{1}{T_b}$



Resource-Sharing Conflicts (2)

- Only one user
  - Each message has N_m symbols and the message duration is

$$T_m = N_m T_b$$

  - System throughput: # of messages per unit time

$$S = \frac{1}{T_m}$$

- M_o users
  - Split the bandwidth into M_o identical channels
    - Symbol duration of each channel: $M_o T_b$
  - Message duration: $T'_m = T_c N_m = M_0 T_b N_m = M_0 T_m$
  - Throughput of a user: $S' = \frac{1}{T'_m} = \frac{S}{M_0}.$

Dynamic Access Protocols

- Network resources can be dynamically allocated using a central scheduler to achieve better network performance.
- Good performance in heavy traffic
- QoS guarantee
- Higher complexity and cost
- Not scalable.
- Examples:
  - Poll-based access protocols
  - Token-based access protocols

Poll-based Access Protocols

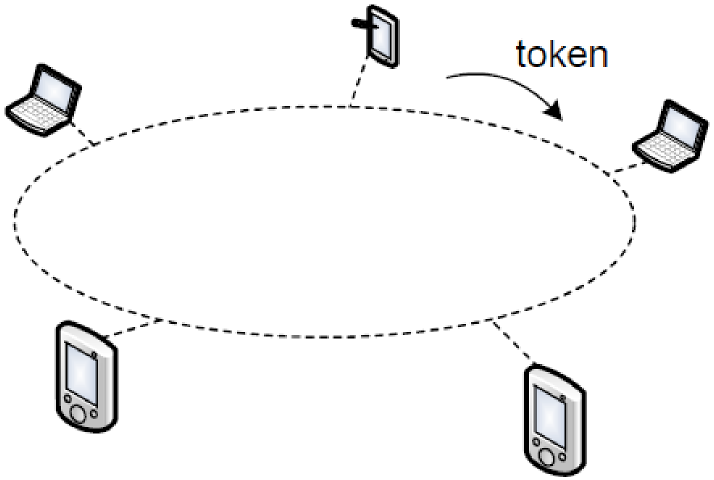
- Designate device as a channel access administrator, i.e. the central controller
  - Example: base station in cellular networks, access point in WLAN.
- To get data from a terminal
  - The controller sends a request for data to the terminal and then receives the data from what the terminal sends, if any.
  - The controller then polls another terminal and receives the data from that one, and so forth.

Poll-based Access Protocols

- Terminals linked to the controller in many different configurations.
  - For example a star topology, where the controller is the hub and all other terminals are the points of the star.
- The network configuration limits how long each terminal can transmit on each poll.
- Higher overhead as polling consumes a lot of bandwidth and turnaround time increases time overhead

Token-Ring Based Access Protocols

- A small frame, called token, is passed in an orderly fashion from one terminal to another
  - The terminal holding the token has the channel access

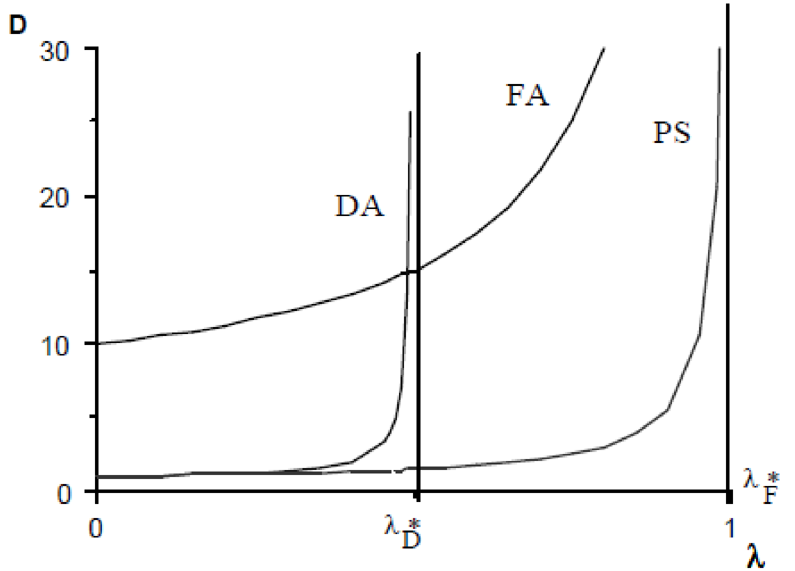


Reservation schemes.

- In almost all modern communication systems, one tries to emulate a dynamic assignment schemes, i.e. striving for some type of adaptation of the resource allocation to the present demand
- A part of the resources
  - collect information about the communication demands of the terminals
  - Can be done on separate channels or on dedicated time slots.
  - Overhead
- The rest of the resources
  - perfectly scheduled transmissions of the messages.
- Long messages/big data packets: negligible overhead
- Short packets: low throughput, higher overhead

Performance Comparison

- Fixed assignment(FA), dynamic assignment (DA), and perfect dynamic assignment (PS)



CONTENTION-BASED ACCESS PROTOCOLS

Contention-Based Access Protocols

- Contention-based access protocols allow terminals to access channel randomly when they have packets to send.
- With random access or contention-based methods, no terminal is superior to another station and none is assigned the control over another
- At each instance, a terminal that has data to send uses a procedure defined by the protocol to make a decision on whether or not to send.
- Examples: Aloha, CSMA, CSMA/CA/CD, reservation, etc.

Pure ALOHA(1)

- In the late 1960s, the ALOHA protocol was developed at the University of Hawaii.
  - Algorithm devised for a VHF-radio system to connect remote terminals on the many islands with a central computer site.
  - Control signaling, i.e. ACK, is sent on an independent control channel.
- Not synchronized

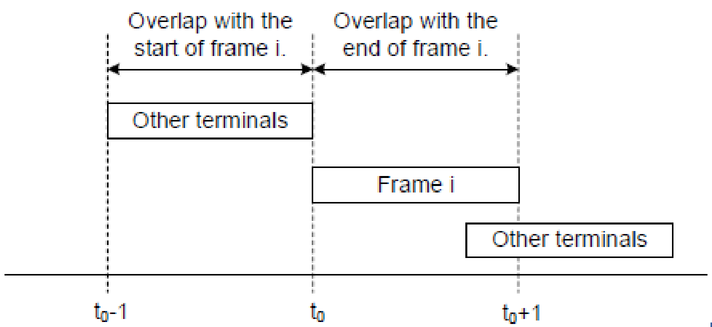
● Step 1: If there is a message to send, send it;

● Step 2: If the transmission succeeds, remove the message from the queue and go to Step 1.

If the transmission fails, wait a random time interval, i.e. backoff randomly, and go to Step 1.

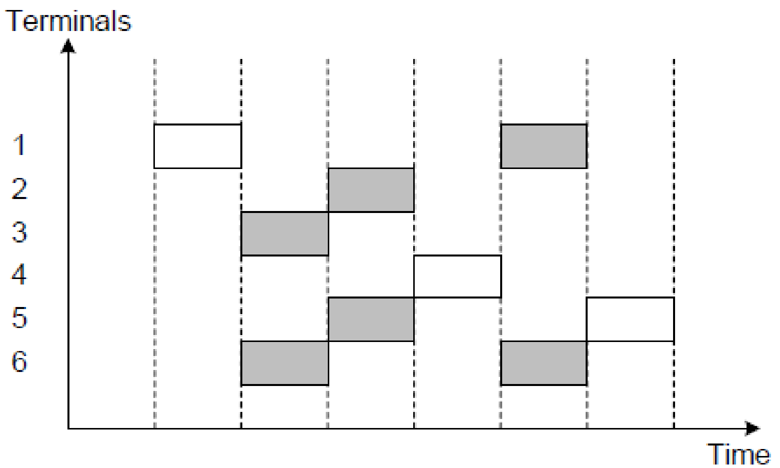
Pure ALOHA(2)

- Transmission failure due to a collision.
  - Paramount importance that the terminals do not wait identical time intervals after a collision, otherwise, another collision.
  - Backoff scheme determines the efficiency of pure ALOHA.
  - When the total traffic is low, pure ALOHA works well; otherwise, the performance is poor
- 2 consecutive frame durations needed to send one frame



Slotted ALOHA

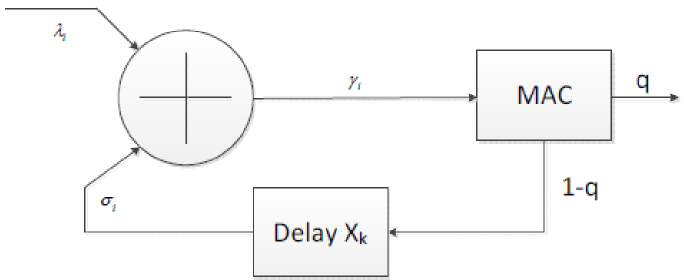
- All terminals are synchronized and time is assumed to be slotted
- Terminals can send packets only at the beginning of slots
- One frame duration needed and efficiency doubles.



Performance of Slotted ALOHA (1)

- M terminals, each with Poisson arrival messages λ_i
- Success probability: q
- Collided messages will be stored and sent out later, approximated by Poisson arrival with rate σ_i

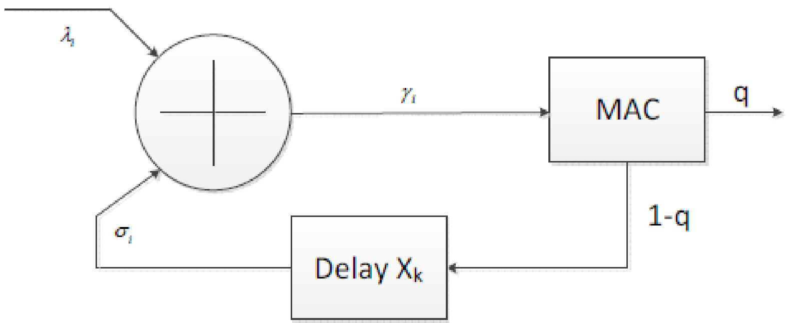
$$\gamma_i = \lambda_i + \sigma_i$$



Performance of Slotted ALOHA (2)

- The system is in a stable equilibrium
  - the average number of messages arriving to the system has to be equal to the average number of departing messages. Otherwise the system will either contain an ever-increasing number of packets or become empty.

$$q\gamma_i = \lambda_i$$



Performance of Slotted ALOHA (3)

$$q = (1-p)^{M-1} \approx (1-p)^M$$

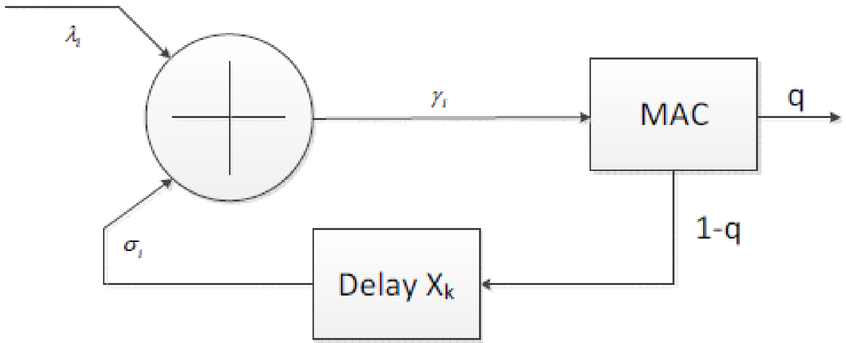
$$q \approx (1-p)^M = e^{-M\gamma_i} = e^{-\gamma}$$

$$\lambda_i = q\gamma_i = \gamma_i e^{-\gamma}.$$

$$\gamma = M\gamma_i$$

$$\begin{aligned} p &= Pr\{\text{at least one arrival in the slot}\} \\ &= 1 - Pr\{\text{no arrival in the alot}\} \\ &= 1 - e^{-\gamma_i}. \end{aligned}$$

$$\lambda = \sum_i^M \lambda_i = M\gamma_i e^{-\gamma} = \gamma e^{-\gamma}$$

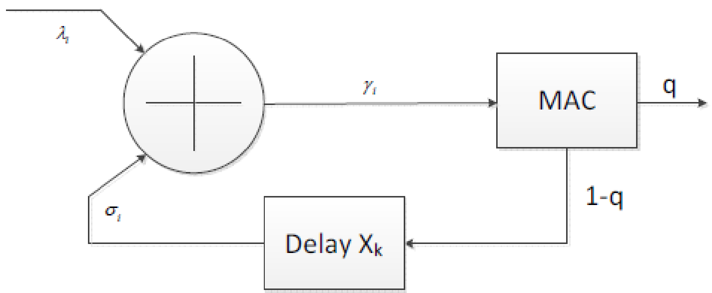


Performance of Slotted ALOHA (4)

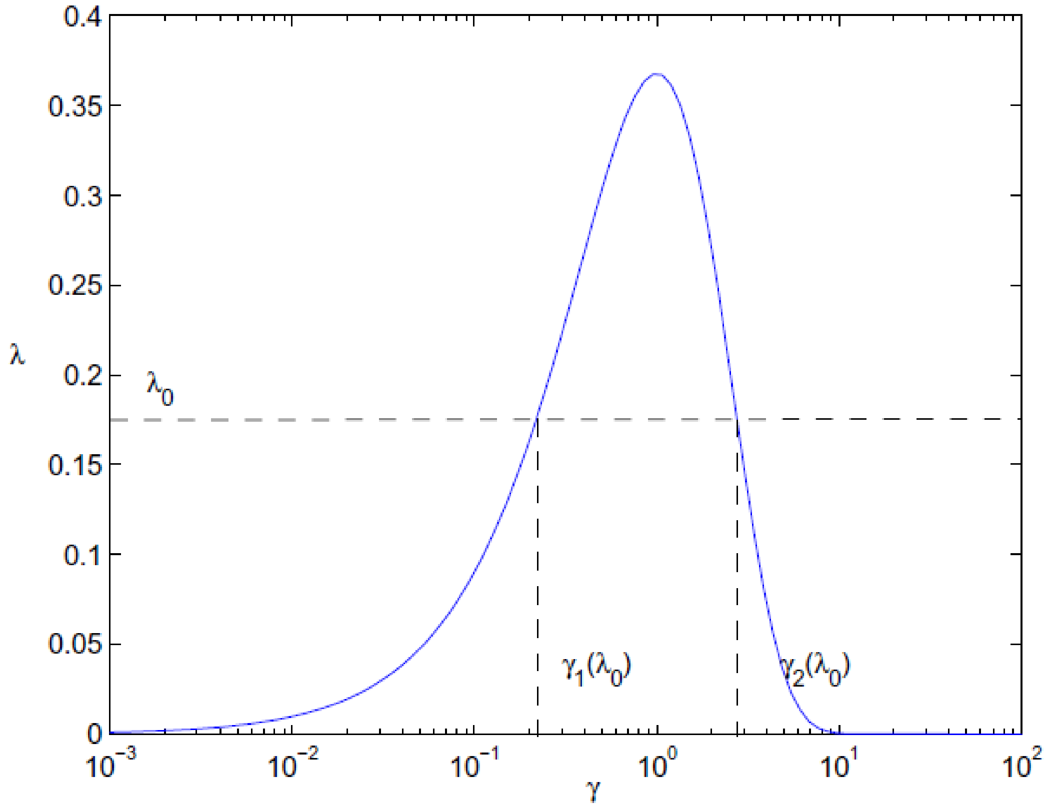
- The relationship between total message arrival rate, i.e. network throughput, and the total rate of attempts.

$$\lambda = \sum_{i}^{M} \lambda_i = M\gamma_i e^{-\gamma} = \gamma e^{-\gamma} \quad \lambda \leq \max \gamma e^{-\gamma} = e^{-1}$$

$$\lambda^* = e^{-1} \approx 36.8\%.$$



Performance of Slotted ALOHA (5)



Carrier Sense Multiple Access (CSMA)

- We can abort transmissions as soon as a collision is detected.
  - Once two packets start colliding, it is useless to continue their following transmissions
  - Otherwise, it will lead to a waste of bandwidth and energy.
- Detect collision while transmitting a packet.
- Carrier Sense Multiple Access (CSMA)
  - popular in asynchronous (non-slotted) wireless networks with low propagation delays.
  - Terminals measure the signal level to detect transmission
    - Existing transmission: defer its transmission attempt
    - Otherwise, transmit data

Different CSMA Algorithms

- Non-persistent CSMA

● Step 1: If the channel is sensed idle, transmit a packet immediately;
● Step 2: If the channel is sensed busy, wait a random amount of time and go to Step 1.

- 1-persistent CSMA

● Step 1: If the channel is sensed idle, transmit a packet immediately;
● Step 2: If the channel is sensed busy, continue sensing until the channel is idle; then transmit a packet immediately.

Different CSMA Algorithms

- p-persistent CSMA (p determines the performance)

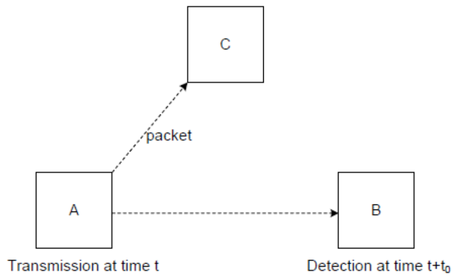
• Step 1: If the channel is sensed idle, transmit a packet with probability *p*; With probability 1 − *p*, delay its transmission by one time slot and repeat this Step.
• Step 2: If the channel is sensed busy, continue sensing until the channel is idle; then go to Step 1.

  – How to choose p?

CAMBRIDGE

Effect of Detection Delay

- Detection delay: time span between transmission time, t, and detection time, $t+t_o$.
- With large detection delay compared to the message size,
  - Useless carrier sensing information since it is only able to describe the state of the channel some time ago.
  - Two terminals may both sense that the channel is empty and start their respective transmissions.



CSMA w/ Collision Detection

- With CSMA, if a terminal decides to send a packet, it will send the whole packet.
  - It there is a collision, the resources, time, frequency, and energy, sending the whole packet are wasted.
- CSMA/CD is designed to reduce these wastes.
  - Each transmitting terminal will also monitor its own transmission.
  - If it detects a collision, it stops transmission immediately and instead sends a jam signal to indicate that there has been a collision.
- CSMA/CD widely used in wired networks

Backoff in CSMA-CD

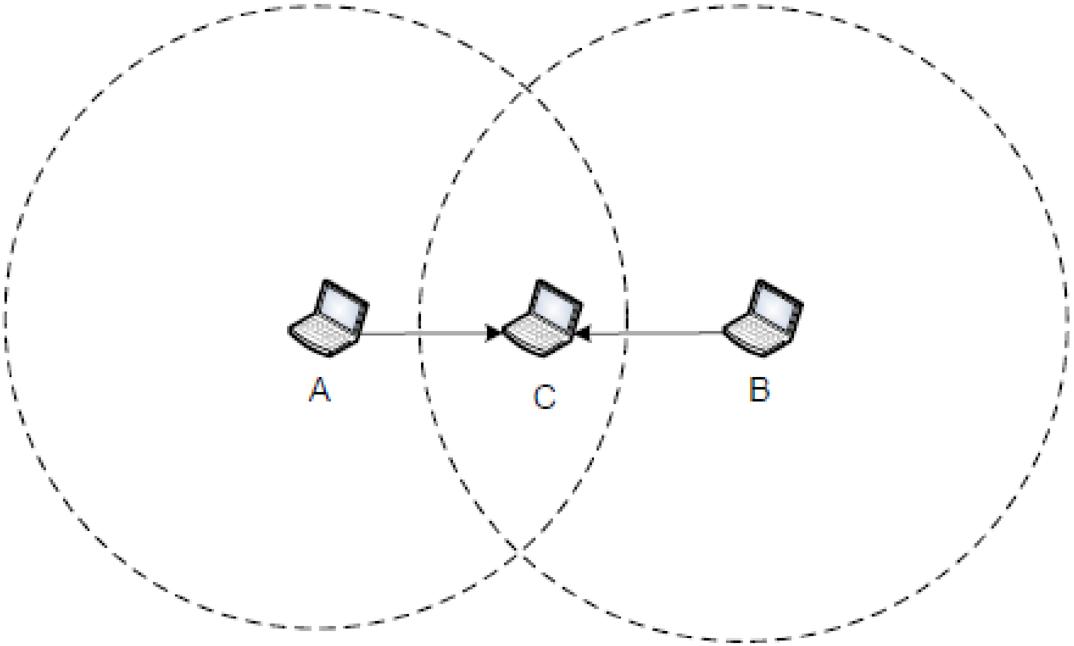
- Backoff grows to reduce collision probabilities
  - After a collision, a terminal involved in the collision will retransmit its packet after waiting for a random time period.
  - If another collision occurs, the time window from which the random waiting time is selected is increased step-by-step.
- Exponential back off:
  - In the first backoff, random backoff time is chosen randomly between [0; t];
  - In the Nth collision, the random backoff time is chosen randomly between [0, t_N], where $t_N = \min(2^{N-1}\, t;\ t_{Max})$, where t_{Max} is the maximum window size

Challenges of in Wireless Networks

- CSMA/CD not appropriate for wireless networks
  - CSMA/CD detects collisions at senders not receivers.
    - The signal strength is almost the same for wired networks but varies dramatically in wireless networks.
    - In wireless networks, the transmission power is usually much higher than the reception power and collision detection by the sender is very difficult and not possible in practice.
    - The collision at the receiver will not be detected by the sender.
- In wireless networks
  - A signal should reach the receiver without any collision
    - The receiver needs to detect collision.

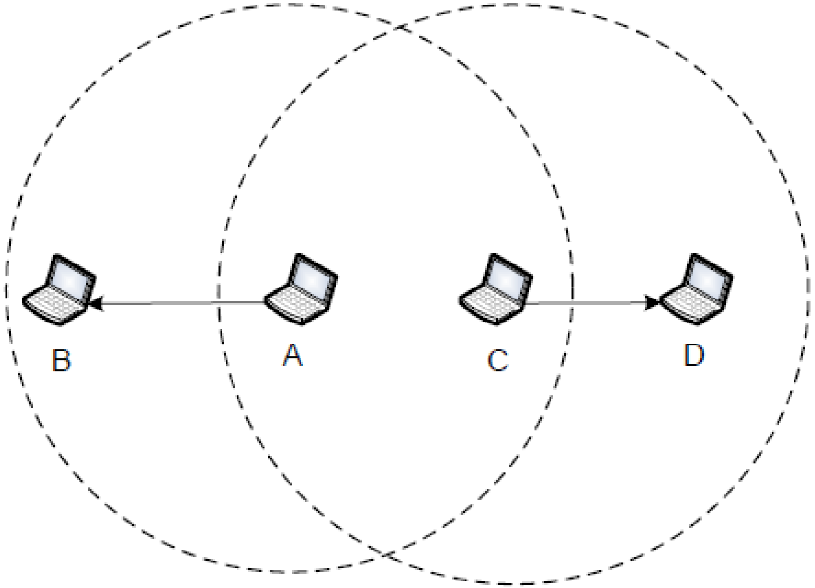
Hidden Terminal Problems

- Both A and B sense the channel idle and send.



Exposed Terminal Problem

- A and C can send packets to B and D at the same time
  - But they won't because C will sense channel busy and not transmit



CSMA w/ Collision Avoidance

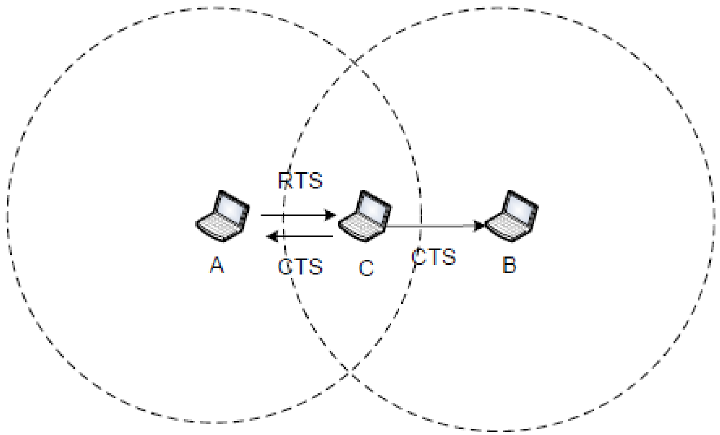
- CSMA/CA
  - Avoid collisions

Step 0: For each new transmission, choose a backoff counter randomly between [0, w-1].
Step 1: Sense the channel: idle for a DIFS period, go to step 2; otherwise, continue sensing until it is idle for a DIFS period.
Step 2: The backoff counter counts down as long as the channel remains idle. If the channel is sensed busy, go to Step 1. If the counter is zero, transmit data immediately.

  - w: exponential back off after each transmission failure

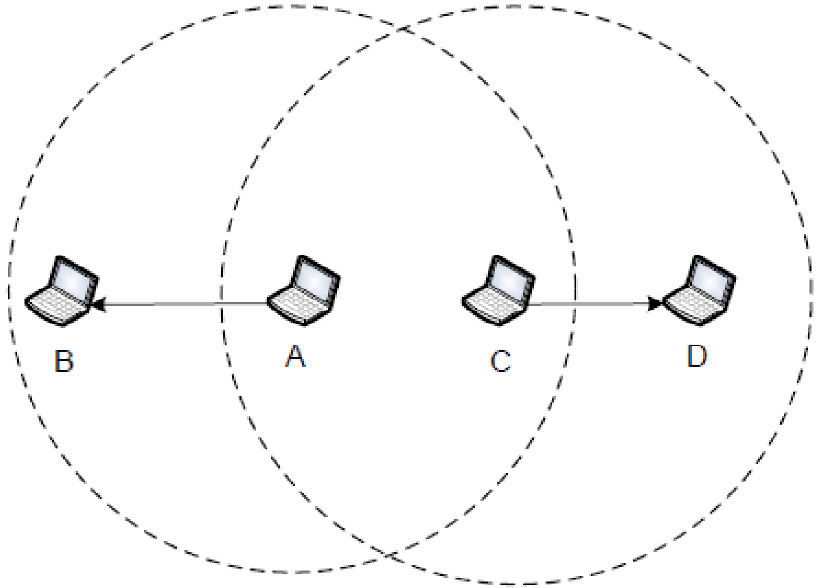
CSMA/CA

- Request To Send/Clear To Send (RTS/CTS) in CSMA/CA
  - Both RTS/CTS carry the time length for data transmission
  - Solves hidden terminal problem.



CSMA/CA

- RTS/CTS also solves the exposed terminal issue.



Example- *Another way to solve the hidden-node problem*

- *Assume an independent control channel. Time is slotted.*
  - *Sense: When the transmitter wants to send a packet to the receiver, the transmitter checks if the control channel is idle for one slot, defined as slot t.*
  - *Request: If so, in time slot, $t + 1$, it sends a request on the control channel to the receiver.*
  - *Busy announcement: After receiving the request, the receiver sends the busy signal on the control channel continuously until the transmitter finishes its packet transmission.*
  - *Transmission: After receiving the busy signal, the transmitter starts sending data at time $t + 2$ on the data channel. All other transmitters hearing the busy signal keep silent.*
- *Question: Assume two transmitters are sending data to an access point. In each idle slot, each transmitter would like to send a packet with probability p. Each packet transmission lasts M slots. What is the throughput of the network?*

Example- *Another way to solve the hidden-node problem*

- For each transmitter, the throughput is

$$S = \frac{E}{B + I}$$

E: expected time for successful packet transmissions

B: expected busy time, including both collisions and successful transmissions.

I: expected idle time.

Example- *Another way to solve the hidden-node problem*

$$Pr(I = k) = Pr(\texttt{no arrivals in the first k-1 slots}) * \\ Pr(\texttt{at least one arrival in the last slot}) \\ = [(1-p)^2]^{k-1}(1-(1-p)^2).$$

- The expected idle time is

$$I = \sum_k k[(1-p)^2]^{k-1}(1-(1-p)^2) = \frac{1}{1-(1-p)^2}.$$

Example- *Another way to solve the hidden-node problem*

- Busy transmission: either transmit or collision in a slot

$$
\begin{aligned}
& Pr(k \ \mathtt{busy\ transmissions}) \\
=& Pr(\mathtt{At\ least\ one\ arrival\ in\ the\ first} \\
& \mathtt{k\text{-}1\ slots}) * Pr(\mathtt{no\ arrival\ in\ the\ last\ slot}) \\
=& [1-(1-p)^2]^{k-1}(1-p)^2.
\end{aligned}
$$

- The expected number of busy transmissions is

$$B_N = \sum_k k[1-(1-p)^2]^{k-1}(1-p)^2 = \frac{1}{(1-p)^2}$$

Example- *Another way to solve the hidden-node problem*

- Each failed transmission:
  - Need two slots for the signaling exchange
- Each successful transmission:
  - Need M+2 slots: data + signaling
- The expected busv time is

$$B = B_N(2 * (1 - p_s) + p_s(M + 2))$$

where the success probability is

$$p_s = Pr(\mathtt{only\ one\ transmitter\ has\ a\ packet} \mid \mathtt{at\ least\ one\ transmitter\ has\ packet\ arrivals}) = \frac{2p(1-p)}{1-(1-p)^2}.$$

Example- *Another way to solve the hidden-node problem*

- The expected time for successful packet transmissions is

$$E = B_N p_s M = \frac{2p}{(1-p)(1-(1-p)^2)} M$$

- Network throughput:

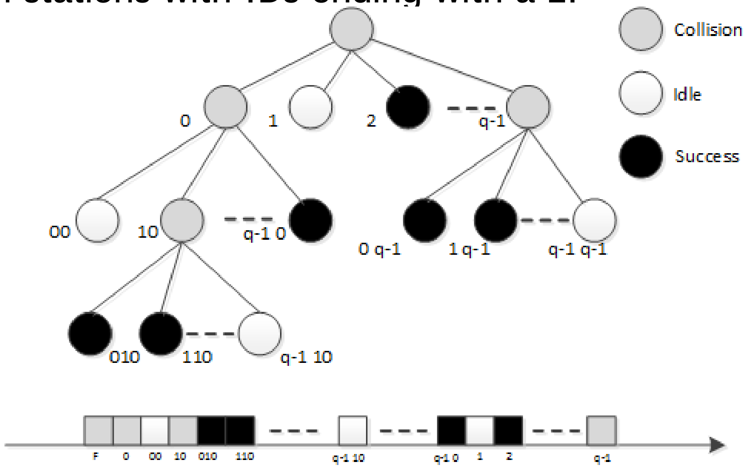
$$S = \frac{E}{B + I}$$

Conflict Resolution Algorithms

- CSMA defers data transmission when the channel is busy
- CRA: resolves conflicts and users are scheduled using a distributed algorithm.
- Example: tree-search algorithm
  - Each terminal is numbered with a unique integer with base q.
  - As soon as a conflict occurs, the system enters the conflict resolution mode and remains in this mode until the conflict has been resolved. Then it returns to the free access mode.

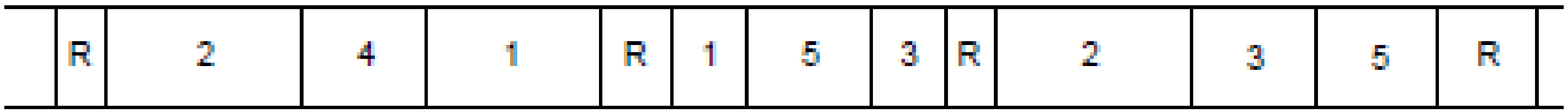
Conflict Resolution Algorithms

- In the first time slot after the collision, only stations having a zero as the final digit in their station IDs are allowed to transmit
- If another collision occurs, the station with final digits equal to 00 is enabled to transmit.
  - However, if the next slot is empty, or if it contains a successful transmission, we proceed with stations with IDs ending with a 1.



Reservation-Based Protocols

- Costly to lose one long data packet if a collision happens
- Reservation-based protocols
  - Reserve resources, time slots, frequency, etc., for data transmission without conflicts
  - Two phases:
    - Reservation phase
    - Data phase

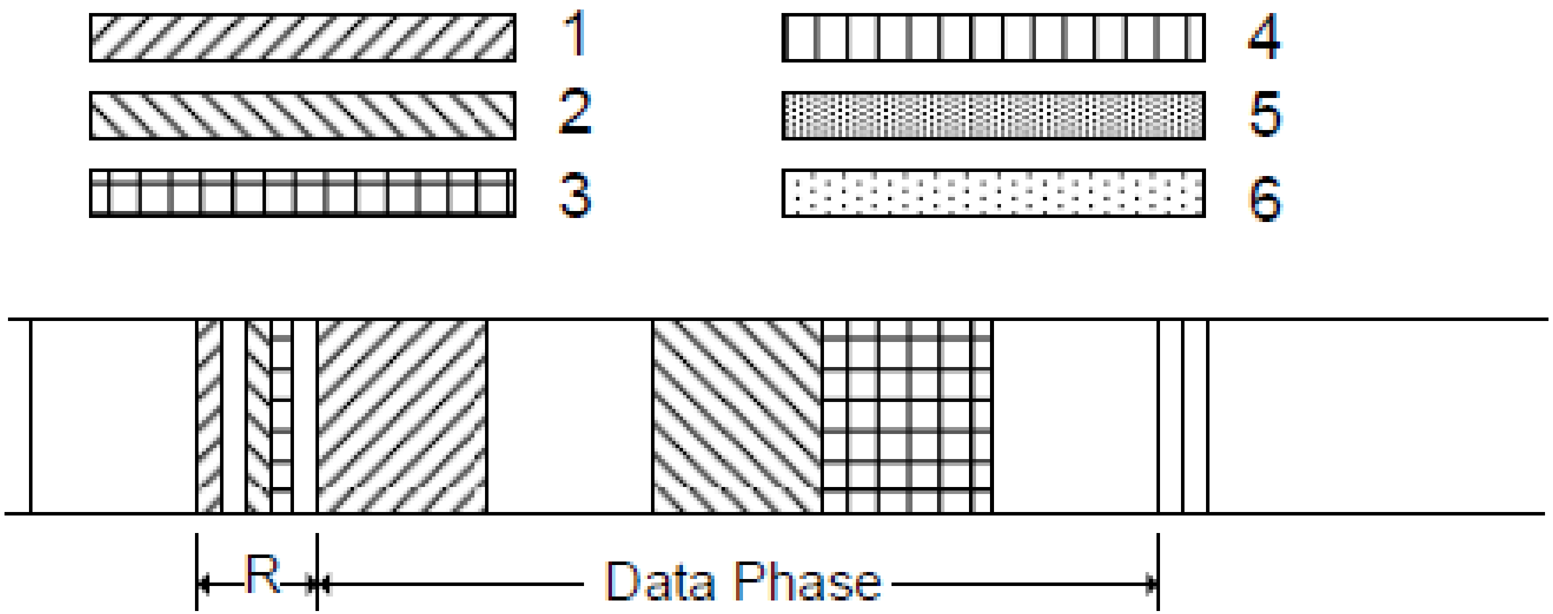


Reservation-Based Protocols

- Two categories
  - Scheduling based
    - In the contention phase, a central scheduler collects network information and then schedule the resources for all users to transmit in the data phase.
    - Discussed in more detail in the Chapter 5 Scheduling.
  - Contention based
    - Use short reservation packets to contend for resource allocation
      - Packets as small as possible
      - ALOHA, CRA, and other random access protocols can be used to decide resource reservation

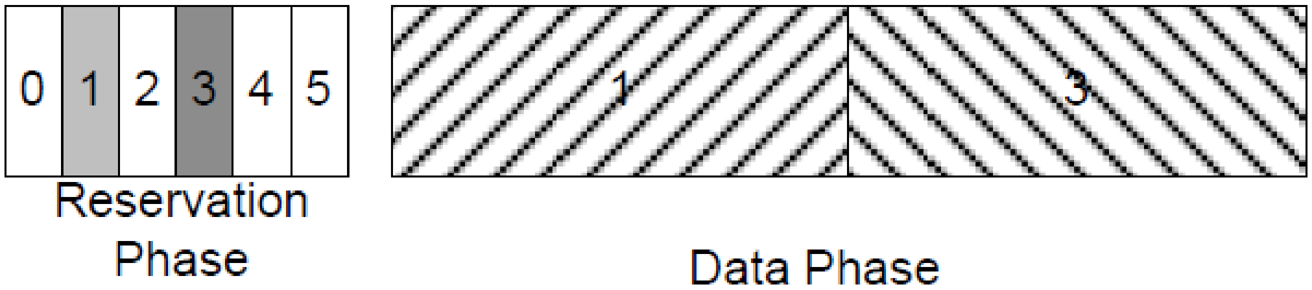
Reservation ALOHA

- Use slotted ALOHA in the reservation phase



Bit-Map Protocol

- Terminals numbered from 1 to N
- Send a short packet in the corresponding slot if a terminal has data to send
- Send data in the data phase following the order in reservation phase

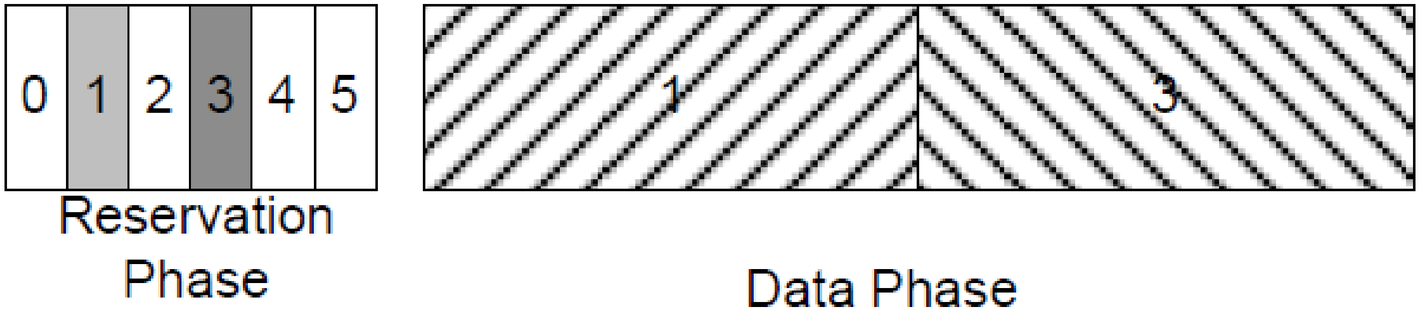


Efficiency of Bit-Map Protocol

- Low load, only one user has a packet in each data phase

$$\frac{d}{d+N}$$

d: number of bits in the packet; N: number of terminals. One bit in each reservation packet.

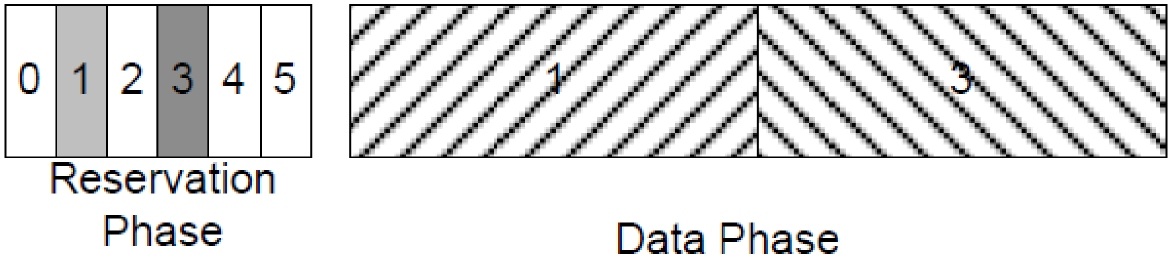


CAMBRIDGE

Efficiency of Bit-Map Protocol

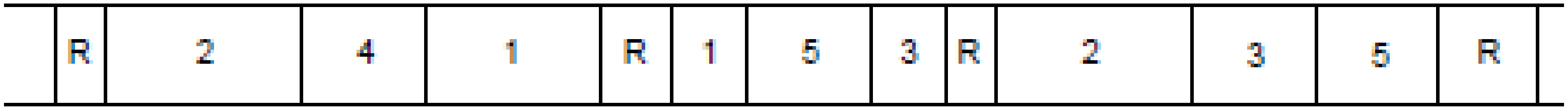
- High load, all terminal have packets

$$\frac{Nd}{Nd+N} \Rightarrow \frac{d}{d+1}$$



Efficiency Improvement

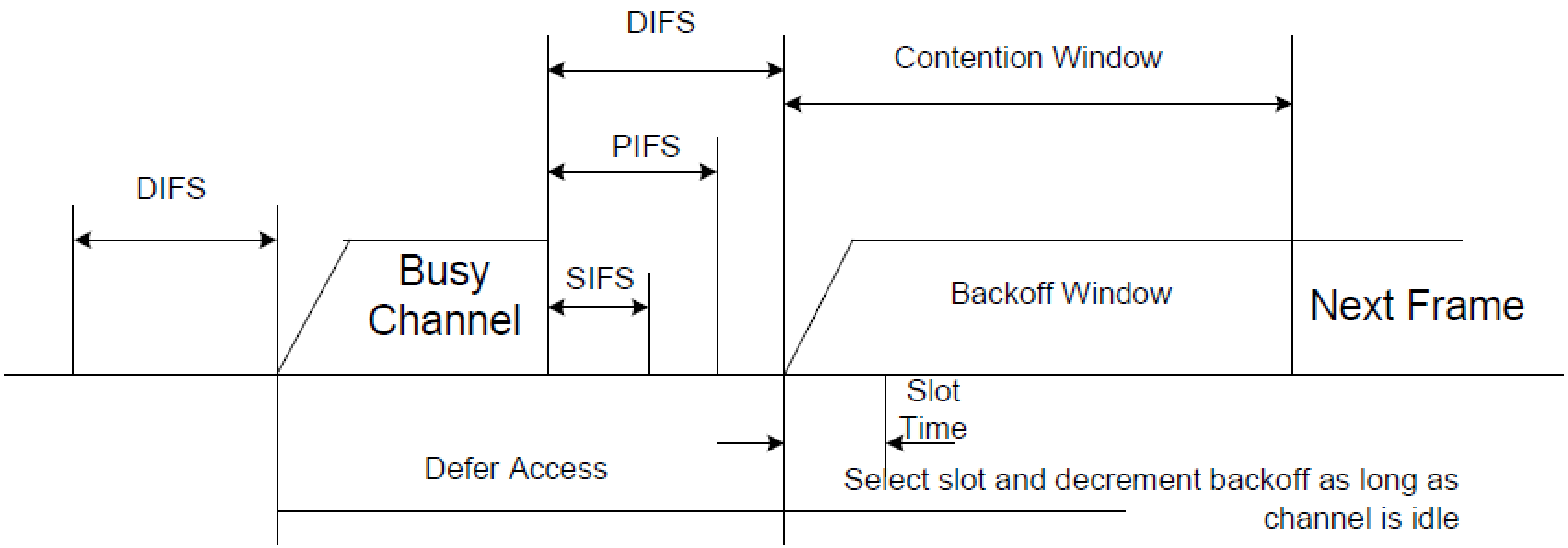
- Each reservation slot as small as possible
  - Limited by sync capability, necessary amount of information, channel capacity, etc.
- Number of reservation slots as small as possible
- Allow as many data transmission as possible.
- With ideal synchronization [G. W. Miao et al., 2012]:
  - The efficiency for networks of any type or size can approach 1 using proper reservation designs in practice.



System Examples: WiFi

- IEEE 802.11 Wireless Local Area Network (WLAN)
  - Also called WiFi
- Asynchronous, best effort, connectionless
- Access: CSMA/CA
- Carrier sensing: measure the RF energy at the antennas and determining the strength of the received signal
  - Signal strength below a threshold-> channel available

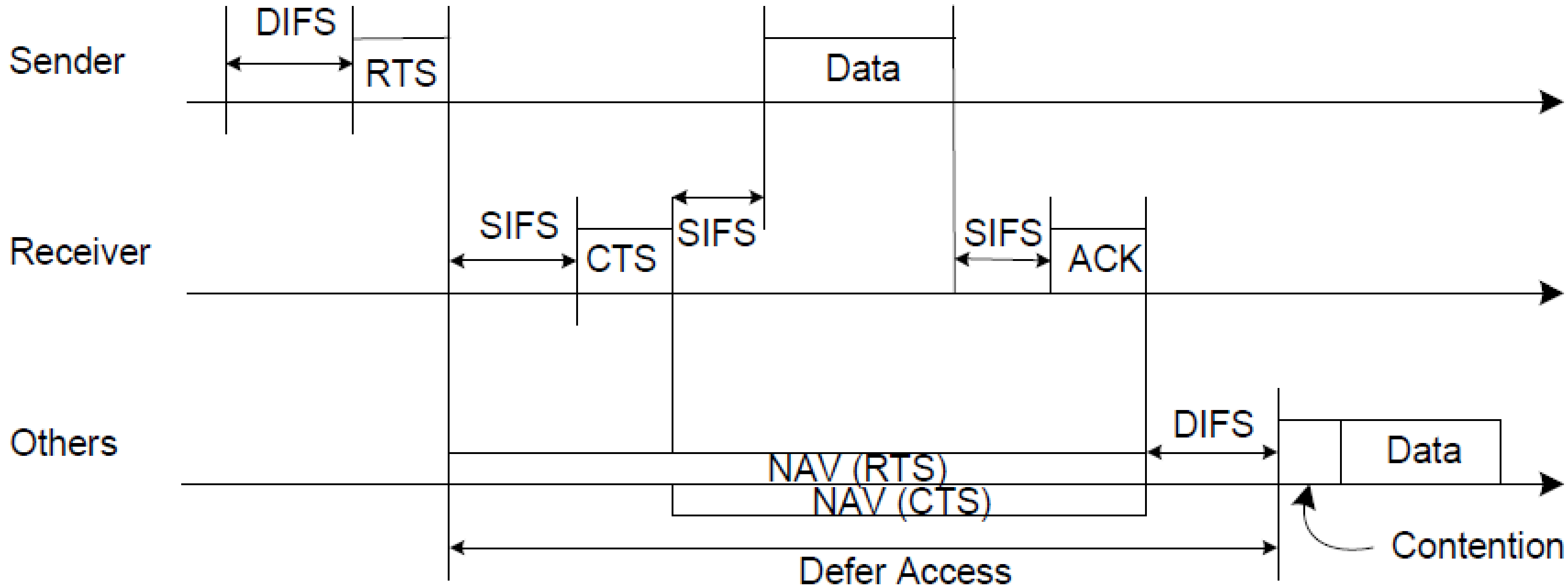
System Examples: WiFi



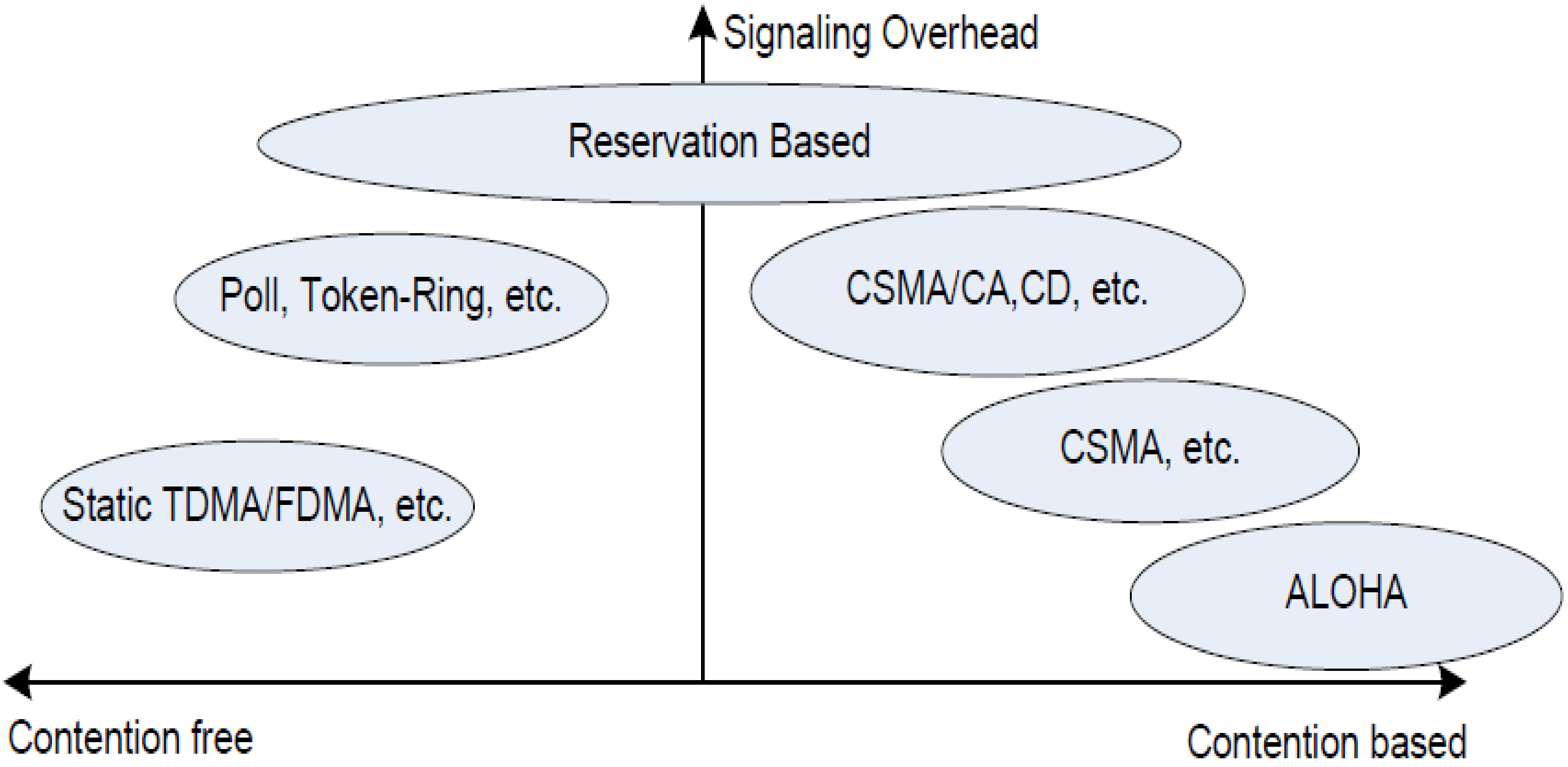
System Examples: WiFi

- To further avoid collisions:
  - virtual carrier-sense mechanism
  - network allocation vector (NAV)
    - limits the need for physical carrier sensing to save power.
    - A counter
    - Predicts future traffic and busy channel, and thus avoid channel sensing
    - Can be exploited by using RTS, CTS, ACK, and data transmission frames sequentially.

System Examples: WiFi



MAC Types


Signaling Overhead
Reservation Based
Poll, Token-Ring, etc.
CSMA/CA,CD, etc.
CSMA, etc.
Static TDMA/FDMA, etc.
ALOHA
Contention free
Contention based