ΕΠΛ 427:
ΚΙΝΗΤΑ ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ
(MOBILE NETWORKS)

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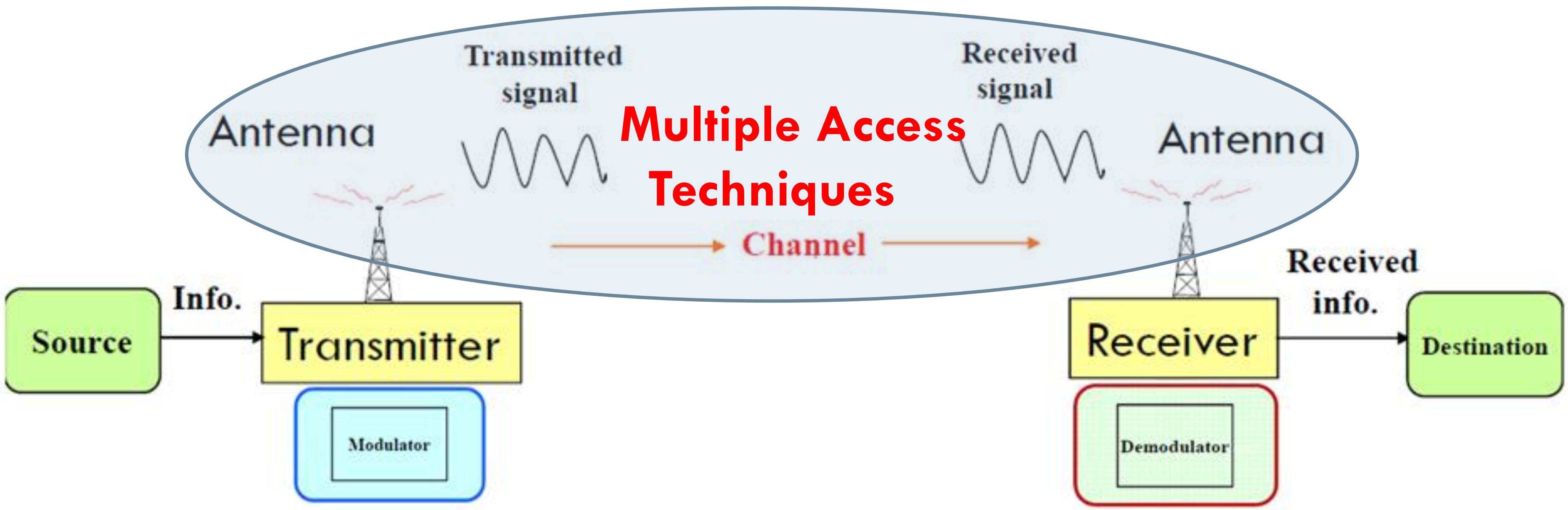
Πανεπιστήμιο Κύπρου - Τμήμα Πληροφορικής

Multiple Access Techniques

Τεχνικές Πολλαπλής Πρόσβασης

Recall (Process and Elements of Radio Transmission)



Topics Discussed

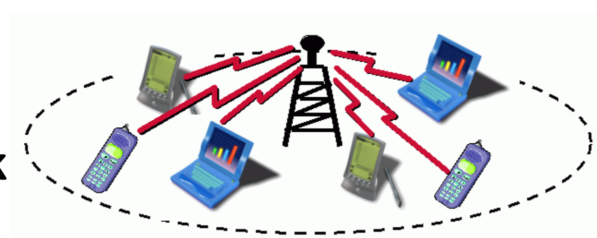
- What is Multiple Access Control
- Classification of Multiple Access Protocols
- Random Access Protocols (ALOHA, CSMA and variants)
- Hidden Terminal Problem and solution
- Duplex Communication (TDD, FDD)
- Channelization Protocols – Multiple Division Techniques for Traffic Channels (FDMA, TDMA, CDMA)
- Comparison of FDMA, TDMA, CDMA

Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

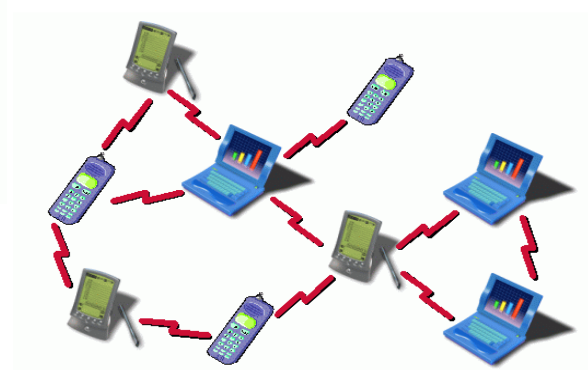
- In general wireless systems (either infrastructure or infrastructure-less based) are **multi-users systems,** while **radio resources** are **limited.**
- **Thus**, the **radio resources must be shared among multiple users.**

Infrastructure based

Wireless LAN,
Cellular Network



Infrastructure-less based



Ad Hoc
Network

Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

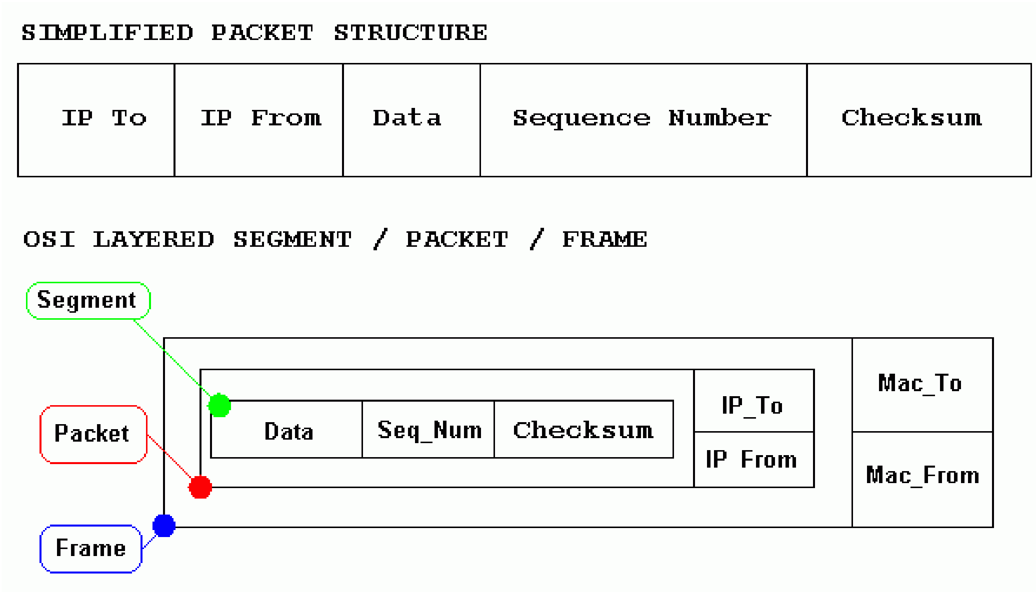
- **Problem**: When two or more stations **using the same radio resources (i.e., frequency band or bandwidth or channel)**, **transmit their frames at the same time**, their **frames will collide** and the **radio resources will be wasted during the time collision** (Όταν δύο ή περισσότερα stations που χρησιμοποιούν τους ίδιους ασύρματους πόρους στείλουν τα frames τους την ίδια ώρα, τα frames των stations θα συγκρουστούν με αποτέλεσμα το διαθέσιμο εύρος ζώνης εκείνη τη χρονική περίοδο της σύγκρουσης να πάει χαμένο).
  - How to **coordinate the access** (Πώς να γίνει ο συντονισμός πρόσβασης) of multiple sending/receiving stations to the shared channel in **order to avoid collisions** and thus **avoid waste of the radio resources**???

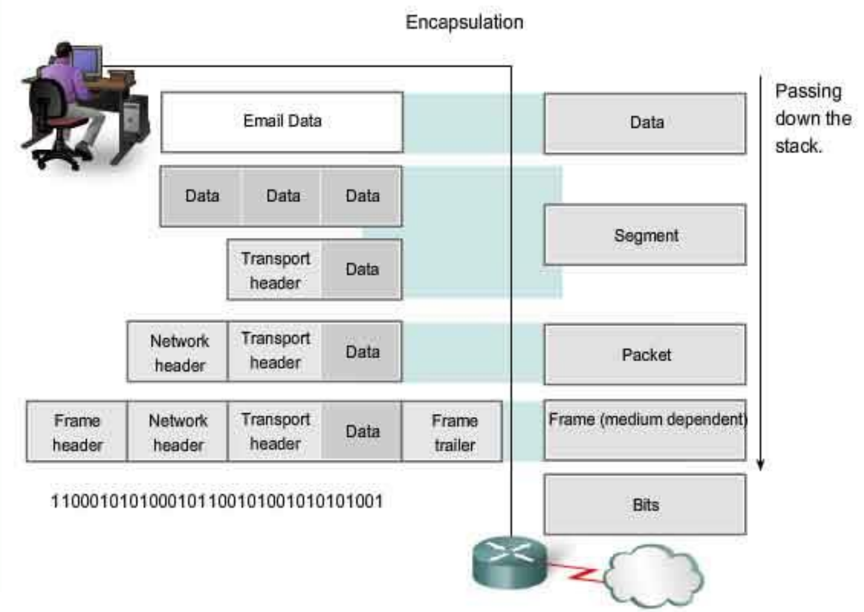
Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

- **Solution:** We need a **protocol** to **coordinate the frame transmissions** of the active stations (Χρειαζόμαστε ένα πρωτόκολλο για να συντονίσει τις εκπομπές των active stations - **active stations** είναι αυτά που **έχουν frames έτοιμα να σταλούν**).
  - These protocols are called **Medium or Multiple Access Control (MAC) Protocols.**

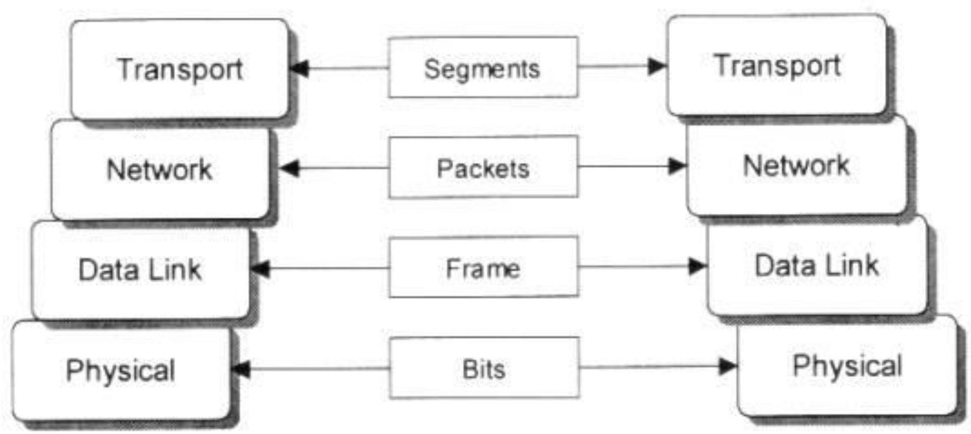
Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

Remember what a frame is?

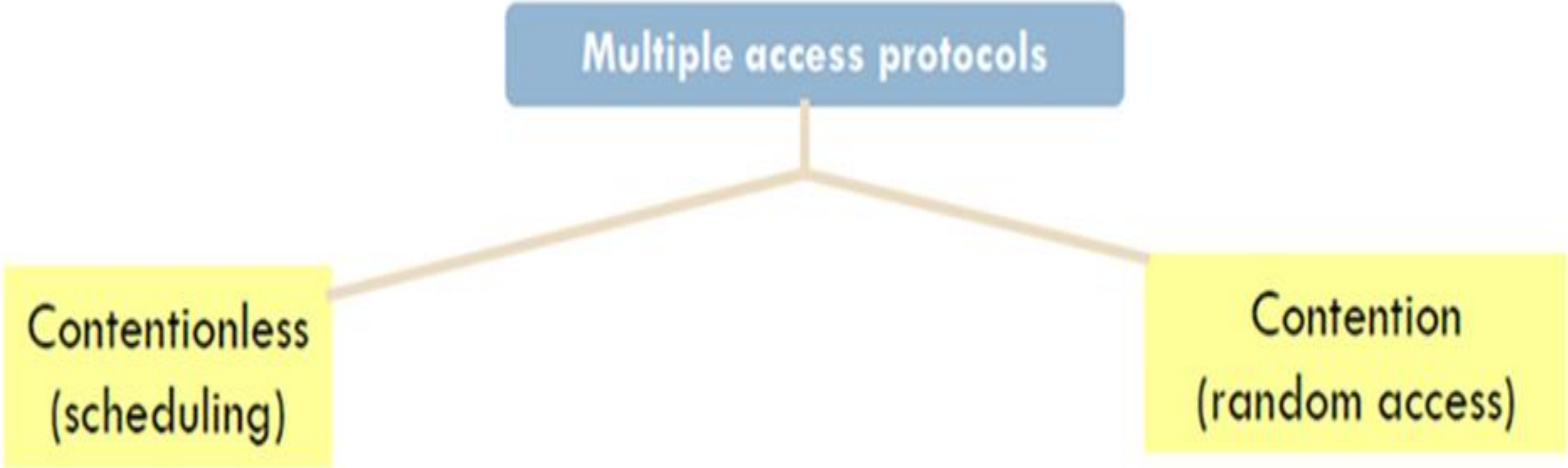




__MAC address__ is a __unique identifier assigned to network interfaces__ for communications at the data link layer of a network segment. MAC addresses are most often __assigned by the manufacturer__ of a __Network Interface Controller__ (NIC; the hardware component that connects a computer to the network) and are __stored in its hardware__. A network node may have multiple NICs and __each NIC must have a unique MAC address__.



Multiple Access Protocols Classification



Μη Ανταγωνιστικά

Ανταγωνιστικά

Multiple Access Protocols Contentionless-based

- **Contentionless-based (Μη Ανταγωνιστικά) Protocols:**
  - A **central controller** (Base Station or Access Point) **is needed** to **coordinate (**να συντονίσει**) the transmissions** of **all the stations.**
  - The **controller informs each station when** and **on which channel** it can **transmit its data.**
    - **So, each station has its own channel.**
    - **By doing this collisions can be avoided entirely**
  - With **Contentionless-based Protocols**, the stations transmit in an **orderly scheduled manner (**Τα stations εκπέμπουν με ένα μεθοδικό προγραμματισμένο τρόπο**)** so **every transmission** will **be successful (No collisions)**.

Multiple Access Protocols Contentionless-based

- **Contentionless-based (Μη Ανταγωνιστικά) Protocols:**
  - **Examples (Basic Channelization Protocols):**
    - **FDMA** (Frequency Division Multiple Access),
    - **TDMA** (Time Division Multiple Access),
    - **CDMA** (Code Division Multiple Access)
    - ***OFDMA*** *(Orthogonal Frequency Division Multiple Access)*
  - **Typically used in Infrastructure based Networks (e.g., WLANs, Cellular Networks, etc.)**

Multiple Access Protocols
Contention-based

- **Contention-based (Ανταγωνιστικά) Protocols:**
  - **No central controller** (No Base Station or Access Point) is **needed to coordinate** the transmissions of the stations.
  - **All stations transmit using the same channel, without having a central controller** to **coordinate** them.
  - If several stations **start their transmissions** more or less at the **same time, all of the transmissions will fail**.
  - These **contention-based protocols resolve the contention (επιλύουν τον ανταγωνισμό)** that occur **when several users want to transmit simultaneously** and a **central controller is not present**.

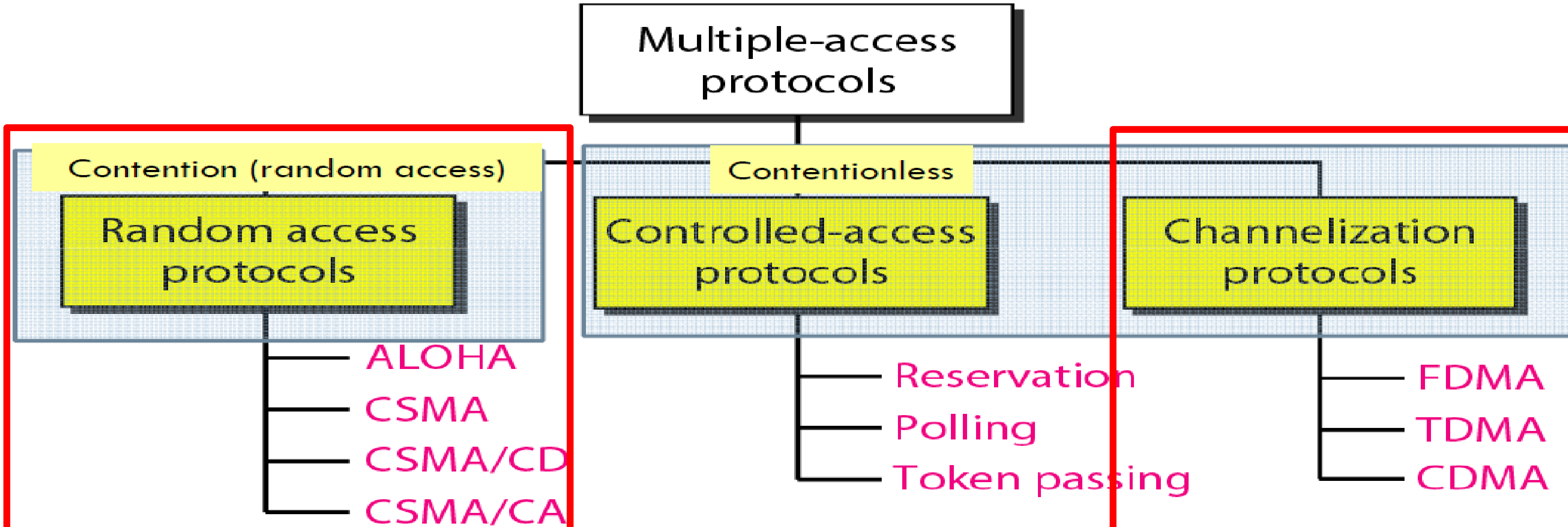
Multiple Access Protocols Contention-based

- **Contention-based (Ανταγωνιστικά) Protocols:**
  - The aim is to **minimize collisions** and **better utilize the bandwidth by determining**:
    - **When** a station **can use the channel**.
    - **What** a station **should do** when the **channel is busy.**
    - **What** a station **should do** when is **involved in a collision.**
  - Examples of Contention-based protocols are the **Random Access Protocols (Πρωτόκολλα Τυχαίας Πρόσβασης)**:
    - Pure (P) - ALOHA,
    - Slotted (S) - ALOHA,
    - Carrier Sense Multiple Access (CSMA) & its variants (και οι διαφορετικές εκδοχές του)

Multiple Access Protocols Contention-based

- **Contention-based (Ανταγωνιστικά) Protocols:**
  - Typically used in **Infrastructure-less based Networks (e.g., Ad Hoc Networks),** where all the stations transmit using **the same channel**.
  - Also can be used **in an infrastructure based network** (i.e., Cellular Network), for **exchanging control information** between a Mobile Station and the Base Station **before a (control and traffic) channel is established between them.**
    - **Note that, in infrastructure-based networks, before a control channel is established between the Base Station and the Mobile Station, the Base Station is not aware about the existence of the Mobile Station and thus have no control over it.**

Multiple Access Protocols



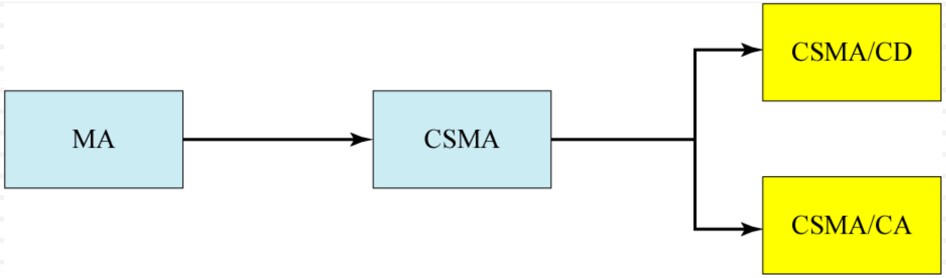
No station is superior to another station **and none is assigned the control over another**. A **station with a frame to be transmitted** can **use the channel directly** based on a **procedure defined by the protocol** to make a **decision** on **whether or not to send**.

Stations consult each other to **find which station has the right to send**. A station **cannot send unless** it has **been authorized** by **other stations** or station.

The **available radio resources (i.e., bandwidth)** is **shared in time, frequency, or using a (spreading) code**, **between different stations**.

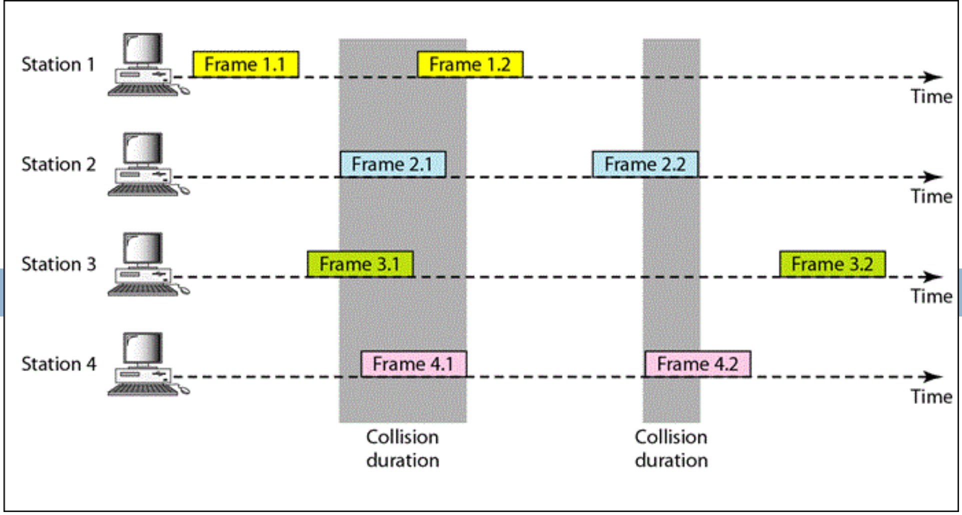
Random Access Protocols

- **ALOHA**
  - **Pure (P)-ALOHA**
  - **Slotted (S)-ALOHA**



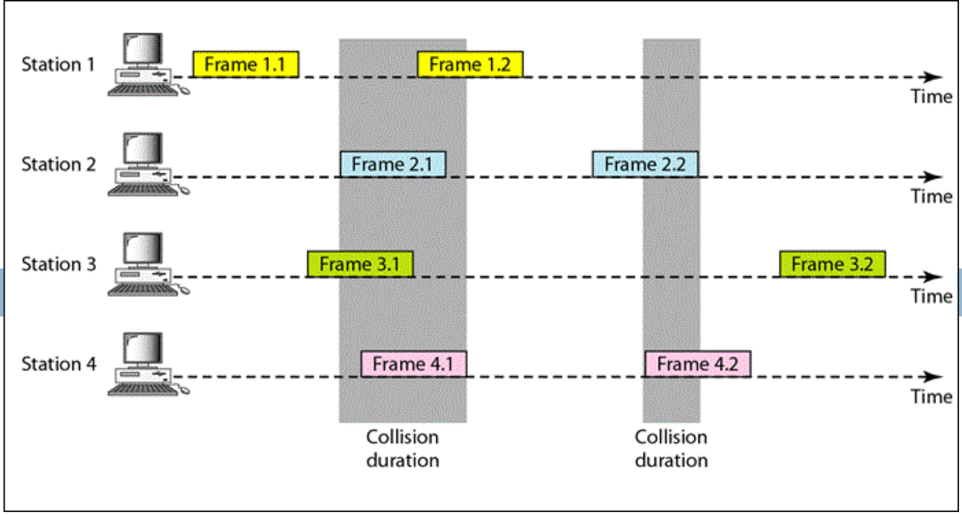
- **CSMA (Carrier Sense Multiple Access)**
  - **CSMA**
  - **CSMA/CD (CSMA with Collision Detection)**
  - **CSMA/CA (CSMA with Collision Avoidance)**

ALOHA
Pure ALOHA



- *Developed in the 1970s for a packet radio network by Hawaii University.*
- With Pure ALOHA **each station sends a frame whenever it has a frame to send (without requesting any permission)**.
- However, since there is **only one channel to share**, there is the **possibility of collision between frames from different stations**.
- The pure ALOHA protocol **relies on acknowledgments (ACK) from the receiver, to indicate if the frame have been received successfully.**
    - If the **acknowledgment does not arrive after** a **time-out period**, the **station assumes** that the **frame** has **been destroyed.**

ALOHA
Pure ALOHA



- A **collision involves two or more stations**.
- If all the stations that were involved in a collision try to **resend their frames after the time-out period**, the **frames will collide again**.
- Thus, **when the time-out period passes**, **each station waits a Random Amount of time** before resending its frame.
  - The **randomness will help avoid more collisions**. We call this time the **Back-off time** (**T_B**)
  - After a **maximum number of retransmission attempts** (**Kmax**) a **station must give up and try again later → Prevents congesting the channel** with retransmitted frames - αποφεύγει την συμφόρηση του καναλιού.

ALOHA
Pure ALOHA – Procedure used

- **With Pure ALOHA, all frames from any station** are **equal in size** and of a **fixed length** (**L bits**)
- Since **all stations produce frames with equal frame lengths**, all the stations need **equal *Transmission Time* (*T_{fr}*)*** to **transmit their frames.**
- A **station that has a frame ready to be send,** can **transmit at any time.**

Transmission Time (T_{fr}): *The time **from the first bit** until the **last bit of a frame** has **left** the **transmitting node**.*

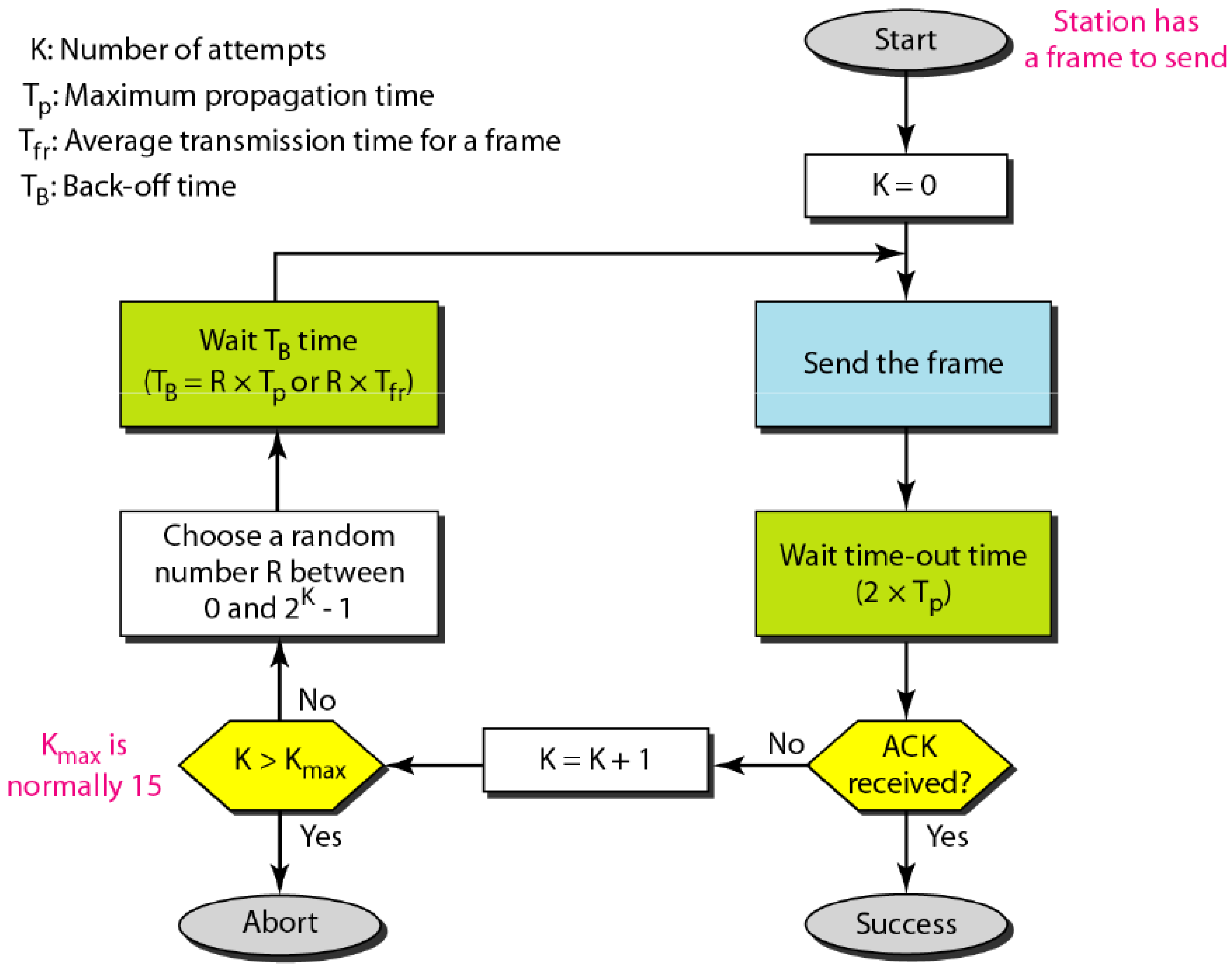
$$T_{fr} = \text{Frame Size (in bits) / Bit Rate of the Channel (in bits/sec)}$$

ALOHA
Pure ALOHA – Procedure used

- **After transmitting a frame**, the sender **waits** for **an acknowledgment (ACK)** for an **amount of time equal to** the **maximum Round-Trip *Propagation Delay**** = 2 x T_p
- If **no ACK** is received, the **sender assumes that the frame has been destroyed.**
- Then**, it waits for a Random amount of time (Back-off time)** and **resends that frame.**
- If the station **fails to receive an ACK after** a specific number of **repeated transmissions** (K_{Max}), it **gives up and tries again in a later time.**

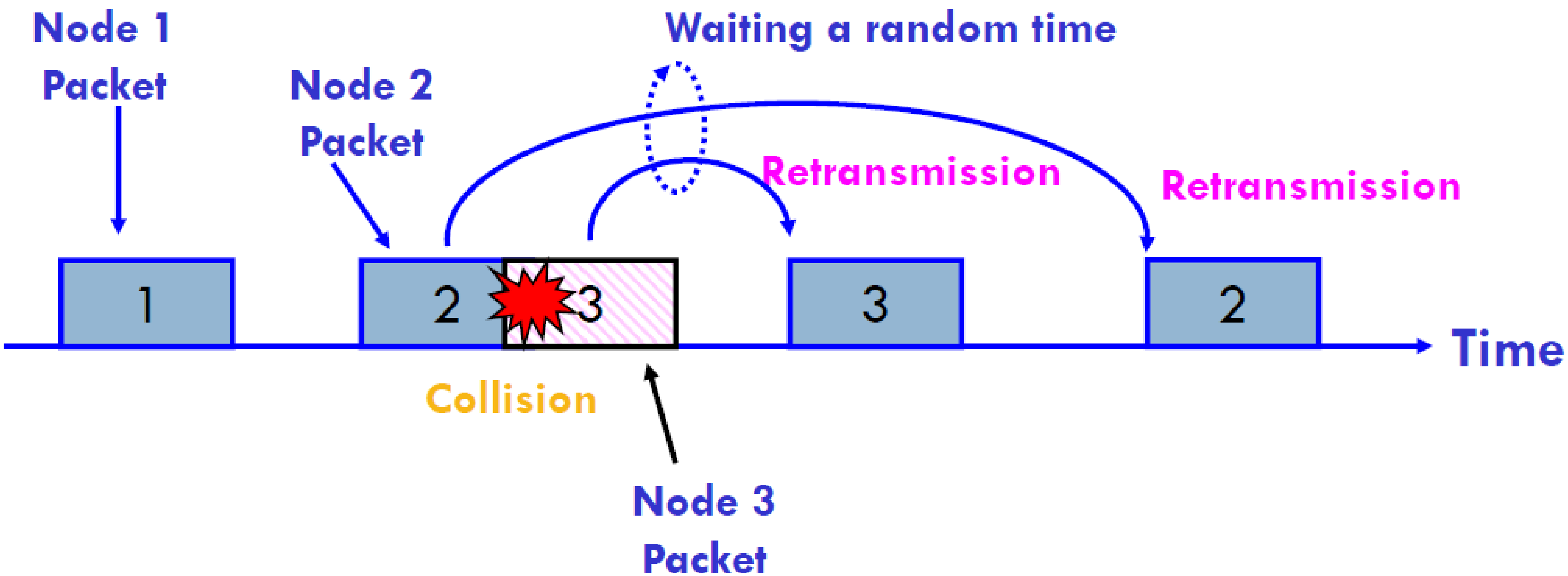
Propagation Delay(T_p): *The Time it takes for a bit of a frame to travel between two separated stations.* T_p ***= Distance / Velocity of signal (speed of light)***

ALOHA
Pure ALOHA – Procedure used



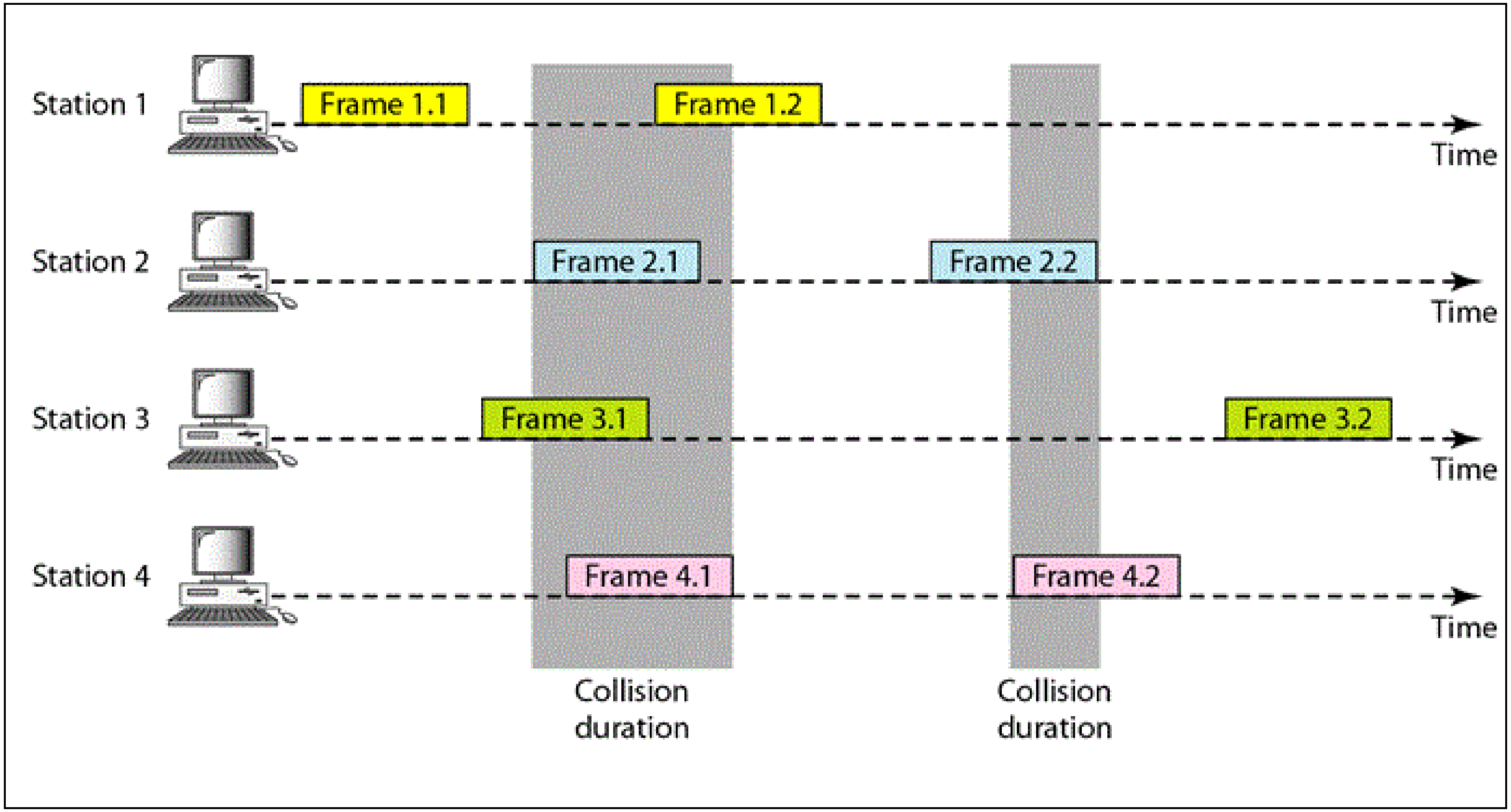
ALOHA
Pure ALOHA

- Collision avoidance mechanism
  - The stations (nodes) involved in a collision **retransmit their frames after a Random Period of time.**



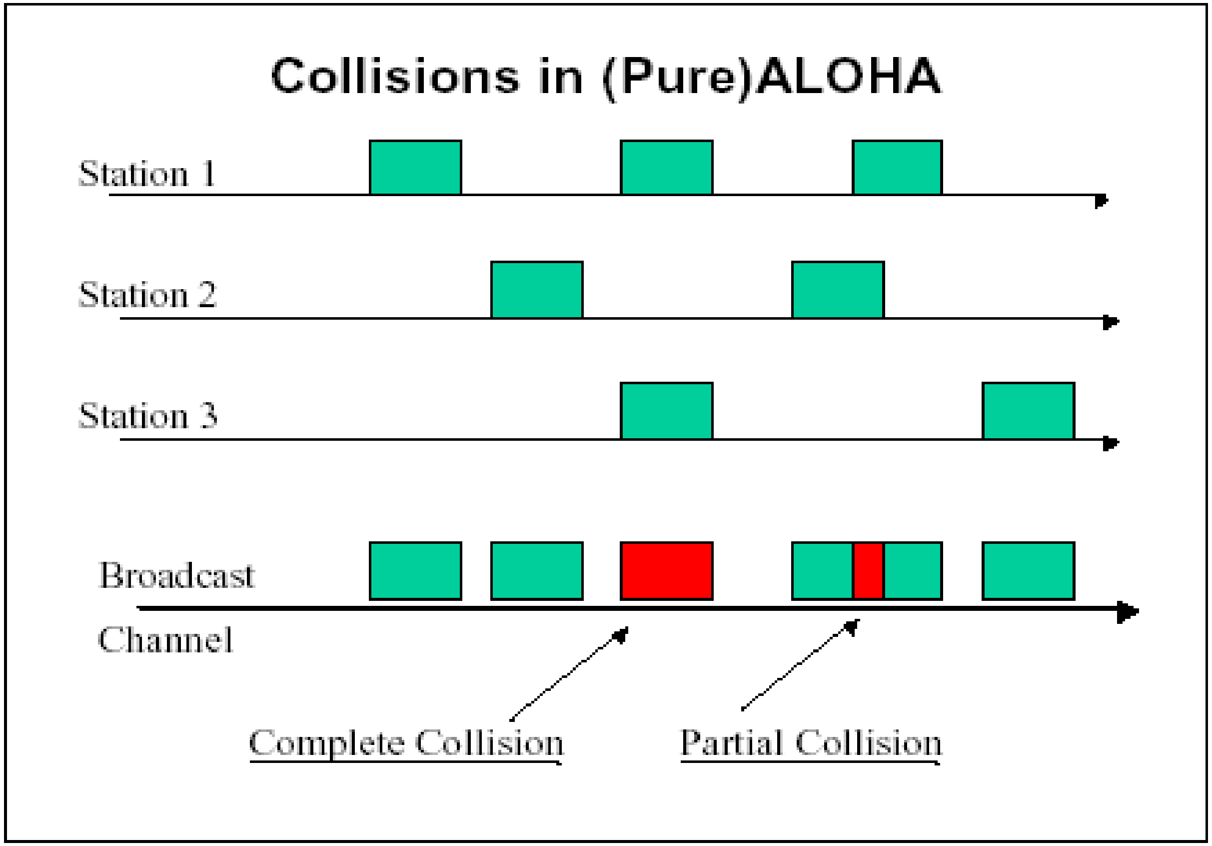
ALOHA
Pure ALOHA

- Frames transmission in a Pure ALOHA Network
  - **Collision involves two or more stations**



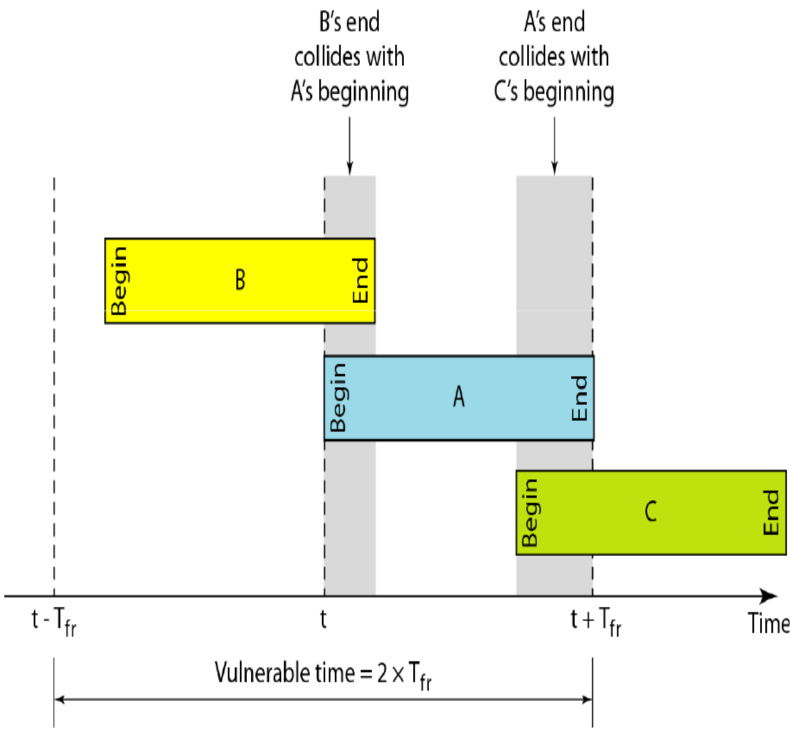
ALOHA
Pure ALOHA

- Collisions in Pure ALOHA (Complete and Partial)



ALOHA
Pure ALOHA – Vulnerable Time

- Let **t** be **the time at which the sender A wants to send a frame** and T_{fr} is the **frame time** *(Number of Bits in Frame / Bit Rate of the Channel).*
- In order to avoid any collisions, if the sender A starts transmission **at time t,** it **needs all other stations (e.g., sender C) to refrain from transmitting** during the time **from t to t +** T_{fr}.
- Also it **needs all other stations (e.g., sender B)** to **refrain from transmitting within one frame time (**T_{fr}**)** before its start. Thus **all other stations should refrain from transmitting during the time from t –** T_{fr} **to t**, otherwise they will collide.
- Thus, the **vulnerable period (η ευάλωτη περίοδος για συγκρούσεις)** for the frame of A's is **2 x** T_{fr}**. (from t -** T_{fr} **to t +** T_{fr}**)**



ALOHA
Pure ALOHA – Vulnerable Time Example

- **Example: A pure ALOHA network transmits 200-bit frames on a shared channel of 200 kbps. What is the Vulnerable time? Assuming that a station is sending a frame at time *t*, what is the requirement in order to make the frame collision-free?**

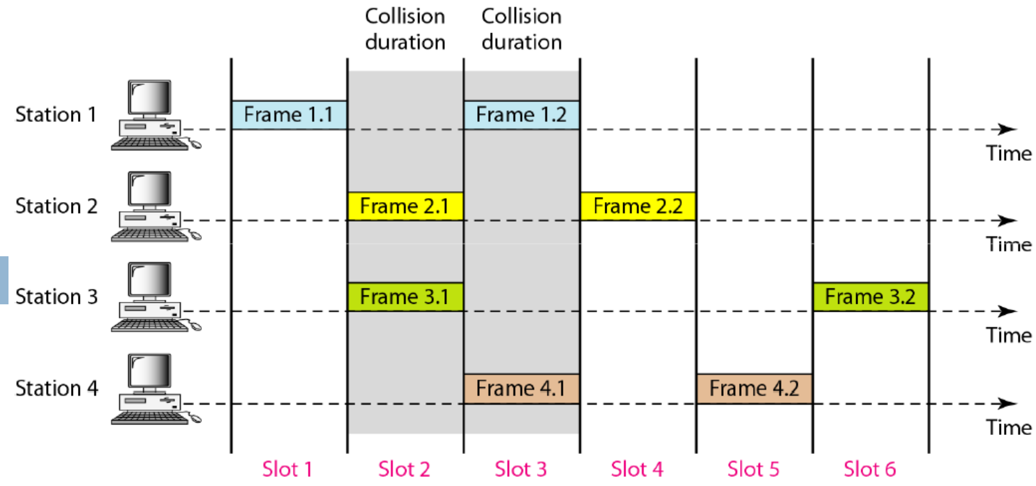
- **Solution:**
  - **Frame Transmission Time (T_{fr})** = 200 bits/200 kbps = 1 ms.
  - The **Vulnerable Time** is 2 × 1 ms = **2 ms**.
  - Assuming that **a station is sending a frame at time t,** this means that **no other station should send a frame within the period** of **t – 1 ms** and **t + 1 ms**.

ALOHA
Pure ALOHA – Efficiency of Throughput

- **Efficiency of Throughput** is the **percentage of the transmitted frames that arrive successfully** (**without collisions**).
- Pure ALOHA maximum efficiency of Throughput is ~18%. More specifically:
  - If we transmit **F** frames/s, then on average **0.18 * F frames** will **arrive successfully**, without the need of retransmission.

Throughput *or* ***network throughput*** *is the rate of successful message delivery over a communication channel. A typical method of performing a measurement is to transfer a 'large' file from one system to another system and measure the time required to complete the transfer or copy of the file. The* ***throughput is then calculated*** *by* ***dividing*** *the* ***file size*** *by the time required to complete the transfer. Then the throughput can be* ***measured*** *in* ***megabits***, ***kilobits***, *or* ***bits*** *per* ***second***.

ALOHA
Slotted ALOHA



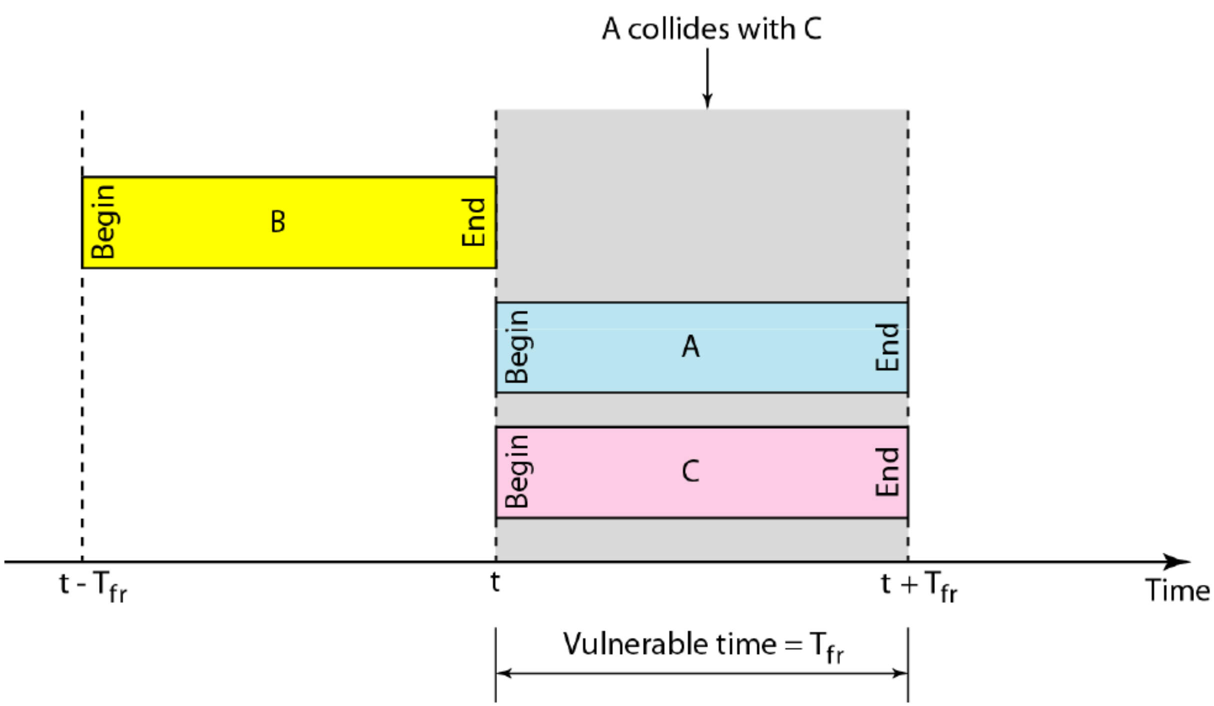
- **Was invented to improve the efficiency of throughput of Pure ALOHA, by reducing the vulnerable time of** Pure ALOHA (Pure Aloha has a **vulnerable time** of **2 x T_{fr})**
- To achieve the aforesaid, in slotted ALOHA the **time is divided into slots** (**each slot of period equal to T_{fr}**) and **force the station** to **send only at the beginning of the time slot**.
- A **central clock** or a **station, informs** all stations **about the start of a each time slot**.
- Because a station is **allowed to send** only at the beginning of the **synchronized time slot**, **if a station misses this moment**, it must **wait until the beginning of the next time slot**.

ALOHA
Slotted ALOHA

- Of course, there is **still the possibility of collision** if two stations **try to send at the beginning of the same time slot**.
- However, **the vulnerable time is now reduced to half (**equal to **T_{fr})**.
  - **By reducing the Vulnerable time from $2xT_{fr}$ to T_{fr}, Slotted ALOHA managed to increase** the **maximum channel throughput to ~37%**

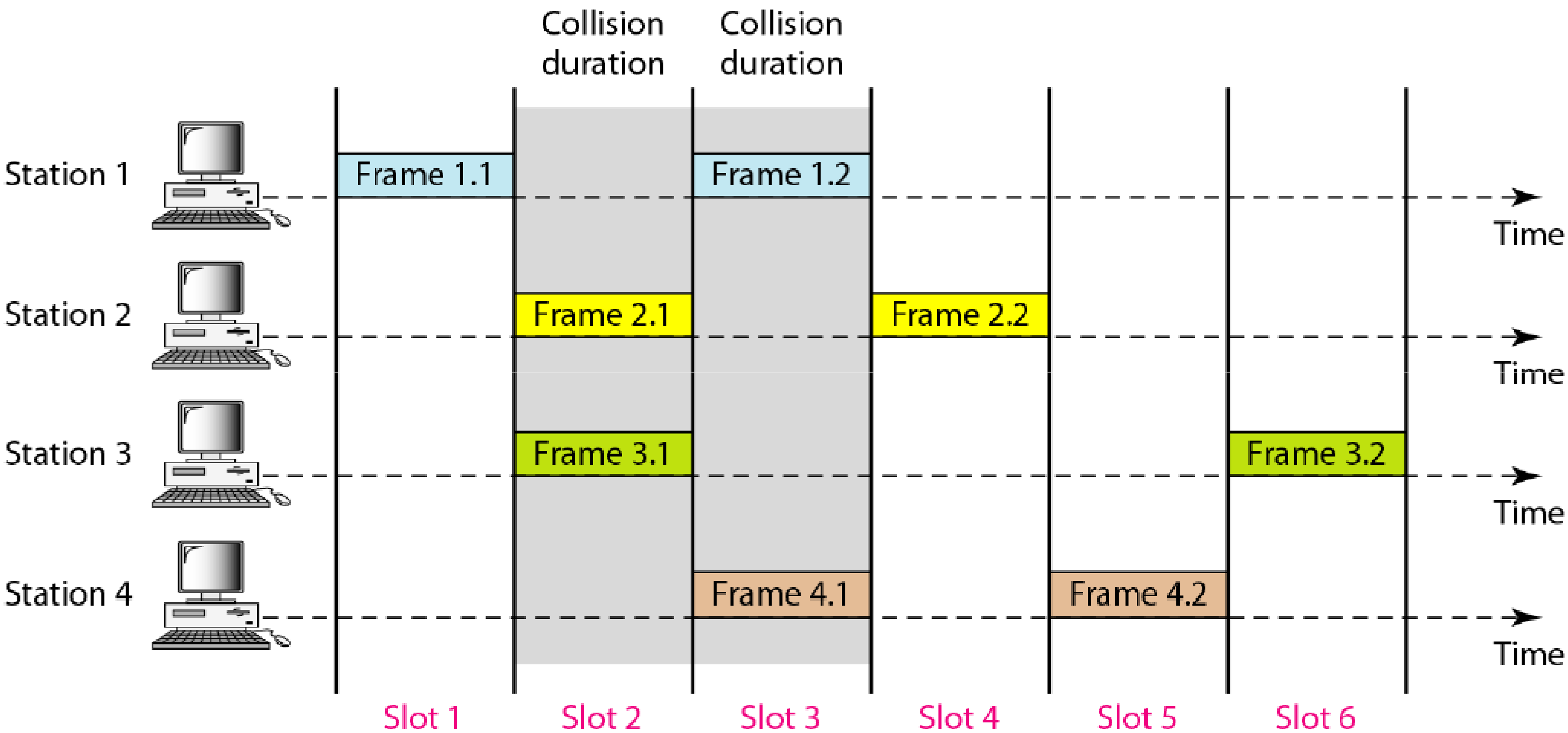
ALOHA
Slotted ALOHA – Vulnerable Time

- The only case that frames of two or more stations can collide is only when the stations transmit their frames using the same time slot → Vulnerable time = **T_{fr}.**



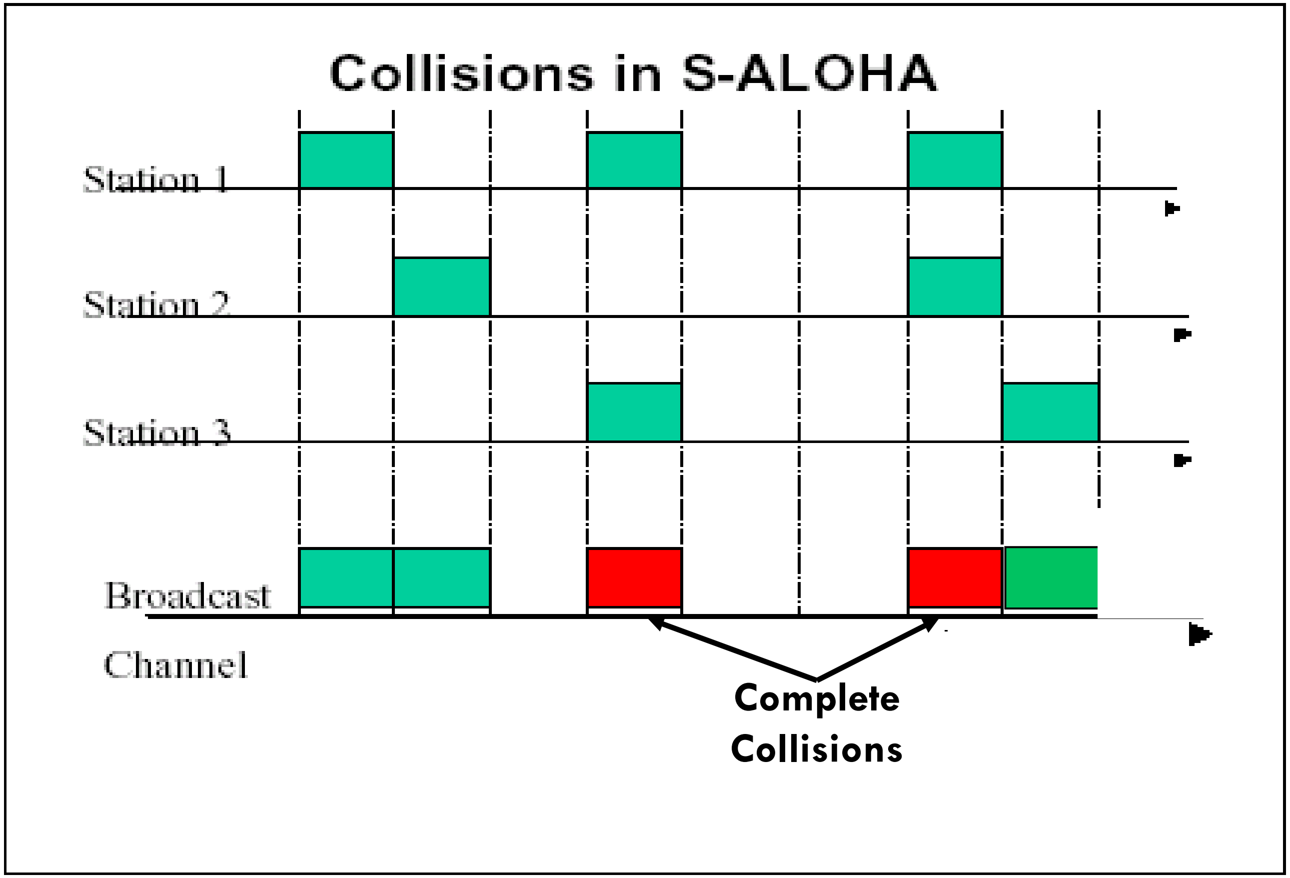
ALOHA
Slotted ALOHA

- Frames transmission in a Slotted ALOHA Network



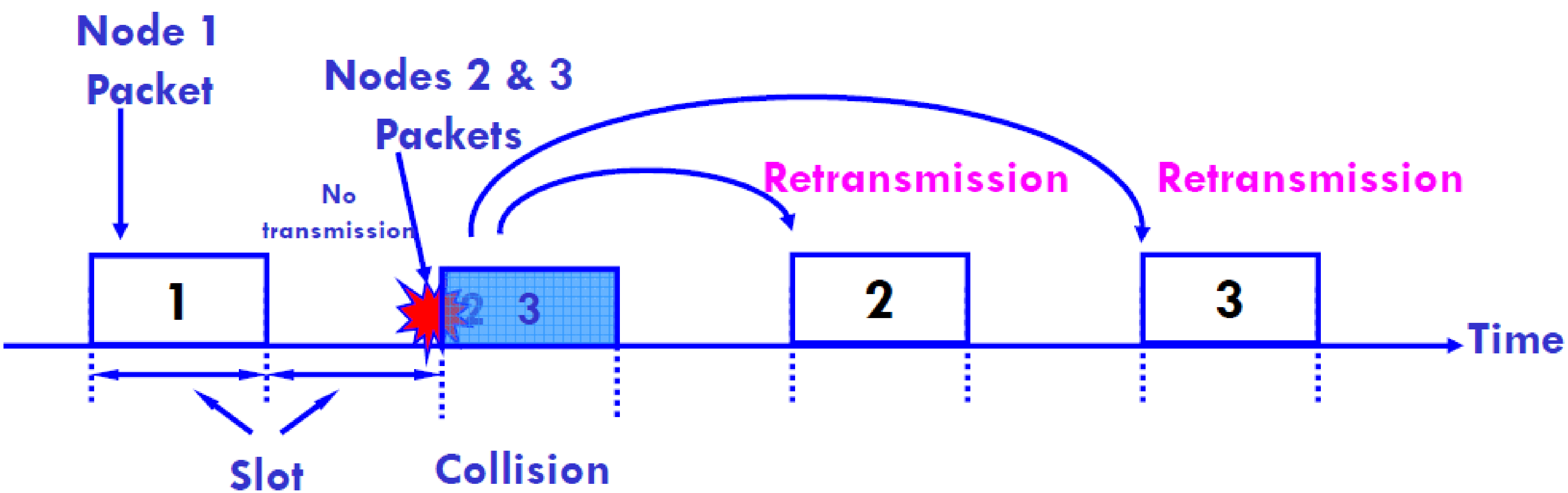
ALOHA
Slotted ALOHA

- Collisions in Slotted ALOHA (Only Complete Collisions)



ALOHA
Slotted ALOHA

- Collision avoidance mechanism
  - Similar to the Pure Aloha. **Retransmission takes place in random selection of a slot time.**



ALOHA
Advantages and Disadvantages

- **Advantage of ALOHA protocols**
  - A station that has frames to be transmitted (i.e., an active station) **can transmit continuously** at the **full rate of channel** (R bps), **if it is the only station with frames**.
  - **Very simple to be implemented**
  - **No master station** is **needed** to control the medium
- **Disadvantage of ALOHA protocols**
  - If the **number of active stations increases**, the **possibility of collisions** is also **increased**.
    - This causes **low channel utilization (i.e., low throughput)**

CSMA (Carrier Sense Multiple Access)

- **CSMA Basic**
  - **Improvement compared to ALOHA protocols:** Stations **does not** just **transmit immediately** when they have a frame to send. **First they sense the channel** and start frame transmission only **if no other transmission is ongoing**.
- **CSMA/CD (CSMA with Collision Detection)**
  - **Improvement**: Stop ongoing frame transmission if a collision is detected. → *Cannot be used with Wireless Transmissions*
- **CSMA/CA (CSMA with Collision Avoidance)**
  - **Improvement**: Senses both the medium and the "possibility of collision" before start transmitting a frame, in order to avoid collisions.
  - **CSMA/CA with ACK:** Enhances reliability of the Acknowledgements
  - **CSMA/CA with RTS/CTS:** Solves the Hidden Terminal Problem

CSMA (Carrier Sense Multiple Access)

- The maximum throughput achievable by Slotted ALOHA is only **36.8%.**
  - Thus, with Slotted ALOHA if we transmit **F** frames/s, then **0.368 * F frames** will **arrive successfully** on average without the need of retransmission)
- **We need to find another way** of **improving throughputs** and **supporting high-speed communication networks.**
- **CSMA** gives **improved throughput** **compared** to **ALOHA** protocols.
  - **Significantly minimizes potential collision** in a shared channel **by simply having the terminals listening (sensing) to the channel before transmitting a frame!!!**

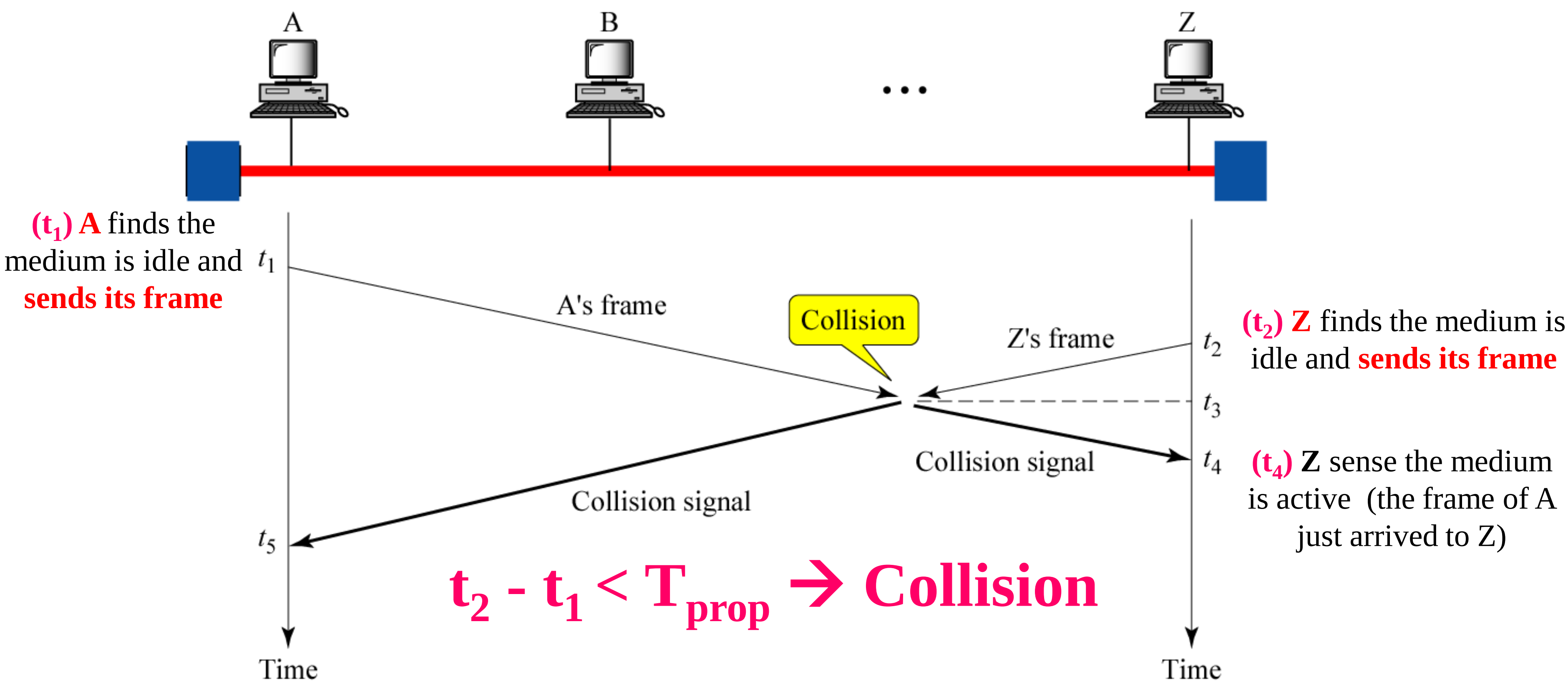
CSMA (Carrier Sense Multiple Access)

- CSMA protocols are **based on the fact** that **each station on the network is able to monitor the status of the channel before transmitting information**.
  - **Listens to the channel before transmitting a frame** (avoid avoidable collisions – αποφεύγει συγκρούσεις που θα μπορούσαν να αποφευχθούν).
  - Can **reduce the possibility** of **collision but cannot eliminate it.**

Question: Why may there be a collision, if each station listens to the channel before transmitting a frame?

Answer: Possibility of collision still exists because of Propagation Delay. When a station sends a frame, it takes time (T_p) for the first bit to reach every station and for every station to sense it.

CSMA (Carrier Sense Multiple Access) Collisions



$$t_2 - t_1 < T_{prop} \rightarrow \text{Collision}$$

Vulnerable period for CSMA: Equals to the Propagation Time

($T_{prop;}$ the time needed for the signal to propagate from one end of the channel to the other)

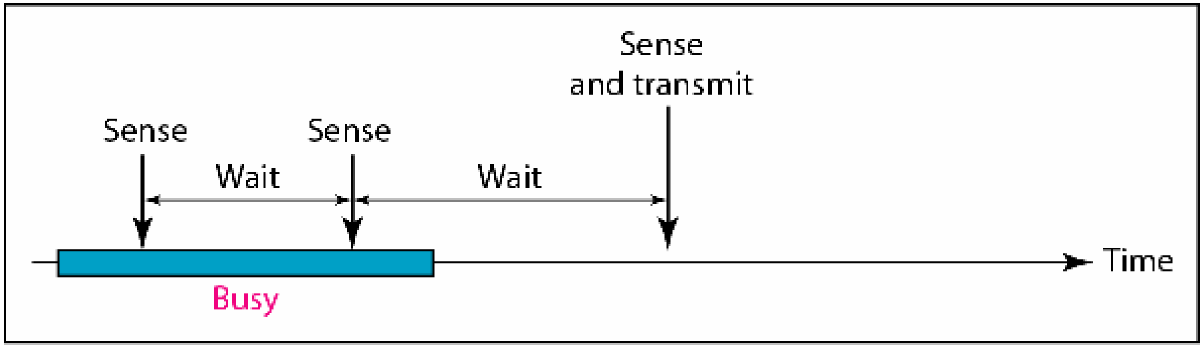
CSMA (Carrier Sense Multiple Access) Types of CSMA Protocols

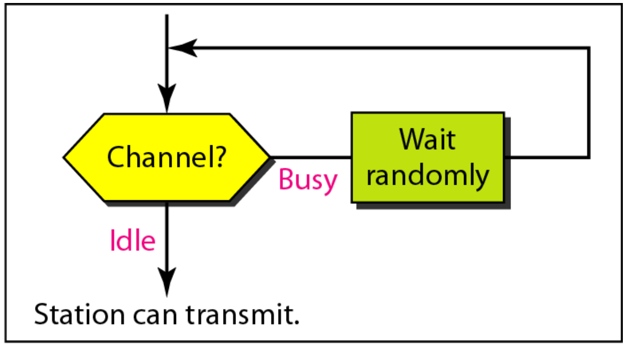
- **Types of CSMA**
  - Non-Persistent CSMA
  - Persistent CSMA
    - 1-Persistent CSMA
    - p-Persistent CSMA

- Different types of CSMA protocols that **determine**:
  - **What** a station **should do** when **channel is idle**?
  - **What** a station **should do** when **channel is busy**?

CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

- The station **senses the channel first whenever it has a frame to send**.
  - If the channel is **busy**, the station **waits for a random amount of time** and **senses the channel again**.
  - If the channel is **idle**, the station **transmits the frame immediately**.
  - If a **collision** occurs, the station **waits for a random amount of time** and **starts all over again**.
- Non-persistent Stations are **deferential (respect others)**



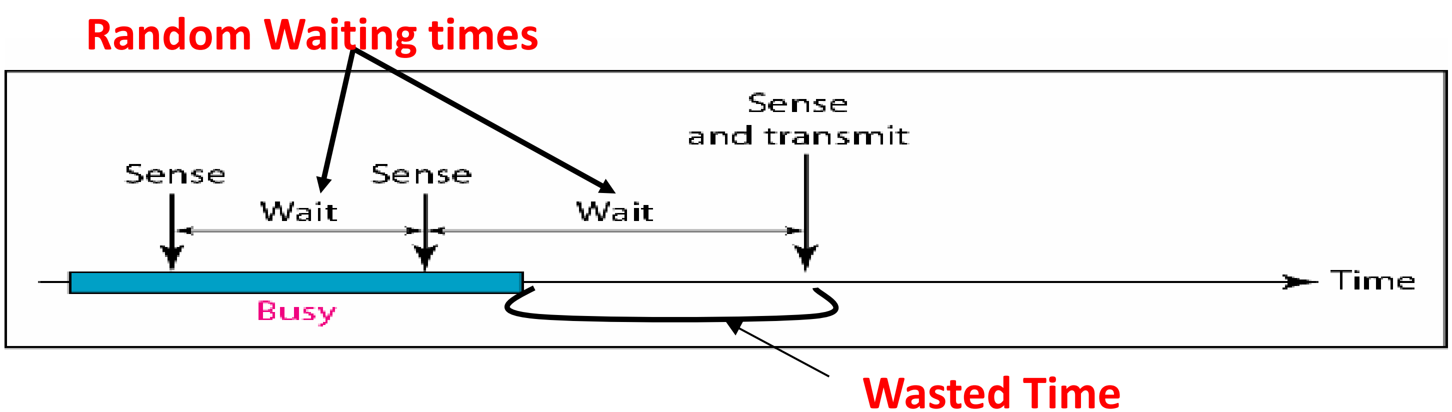


CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

- **Performance**:
  - By having the station **sensing the channel before transmitting** **its frames, the possibility of a collision is highly reduced (since the vulnerable time is Reduced to T_{prop}) and thus the throughput is increased.**
  - **Random selection of waiting time (when the medium is found busy) reduces probability of collisions** because two stations with frames to be transmitted, will **wait for different amount of times**.

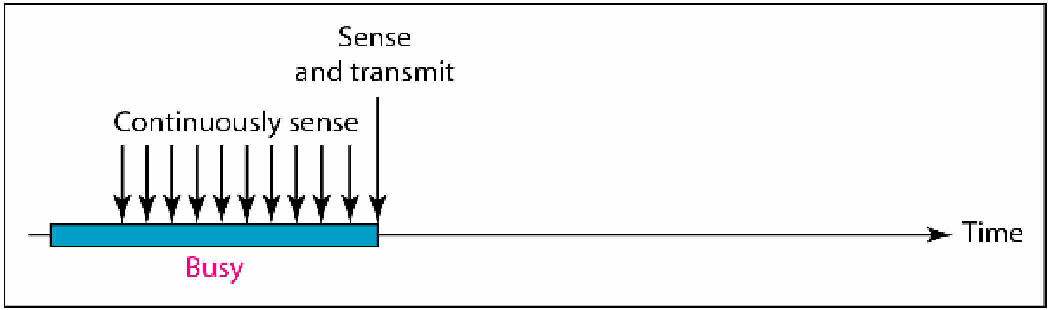
CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

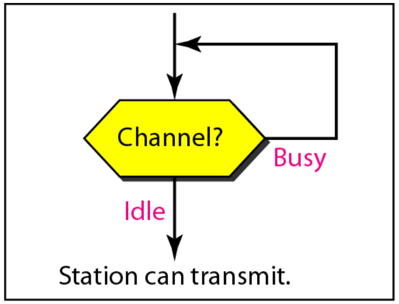
- **Performance**:
  - However, **Bandwidth is wasted** if the **waiting time** selected is **large**.
    - This is because **following an end of a transmission**, the **channel will remain idle**, **even if one or more stations have frames to send** (reduces spectral efficiency)



CSMA (Carrier Sense Multiple Access)
1-Persistent CSMA

- **1-Persistent CSMA** is used to **avoid idle channel time.**
- The **station continuously senses the channel** when it has a frame ready to send.
  - If the channel is **idle** the station **transmits immediately**;
  - If the channel is **busy**, the station **keeps listening to the channel** and **transmits** the frame **immediately after the channel becomes idle**
  - If a **collision** occurs, the station **waits for a random amount of time** and **starts all over again**.



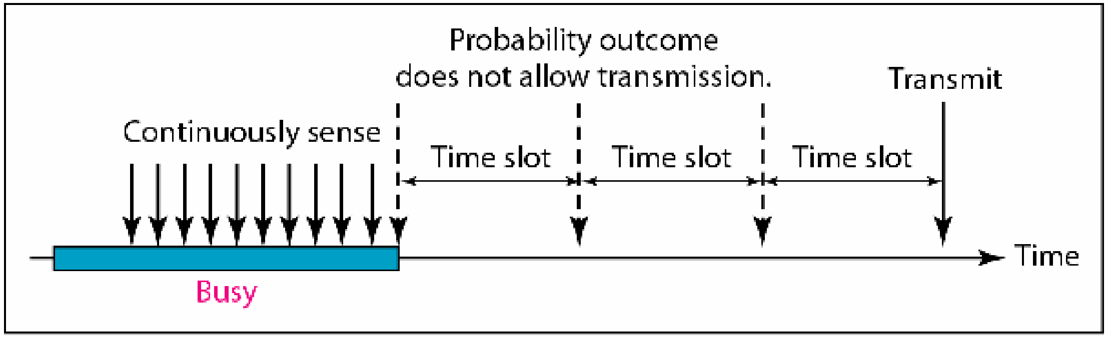


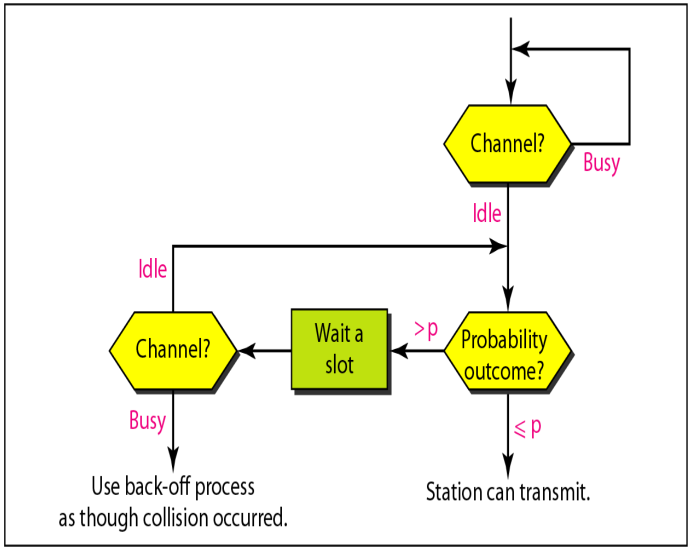
CSMA (Carrier Sense Multiple Access) 1-Persistent CSMA

- **Performance:**
  - 1-persistent stations are **selfish**
  - Is called 1-persistent because the station **transmits with a probability of 1** whenever **it finds the channel to be idle**.
  - **Increases** the **chance of collisions if two or more stations** have **ready frames** to be **transmitted** at the **same time**
  - **They will both wait for the channel to become free,** and thus they will **start transmitting their frames at the same time → Collision is Guaranteed**!

CSMA (Carrier Sense Multiple Access)
p-Persistent CSMA ($0 \le p \le 1$)

- **Time is divided into slots** where each time slot typically equals to the **Round Trip Propagation delay time (2 x T_{prop})**.
- The **MS senses** the channel **when it has a frame to send**.
  1. If the **medium is idle**, then the station **estimates a random number (P_r)** between 0 and 1.
     - **If** ($P_r \le p$) then the station will **transmit the frame, OR**
     - **If** ($P_r > p$) **the station refrains (αναβάλει) transmission** until the **next slot**, then repeat from 1**.**

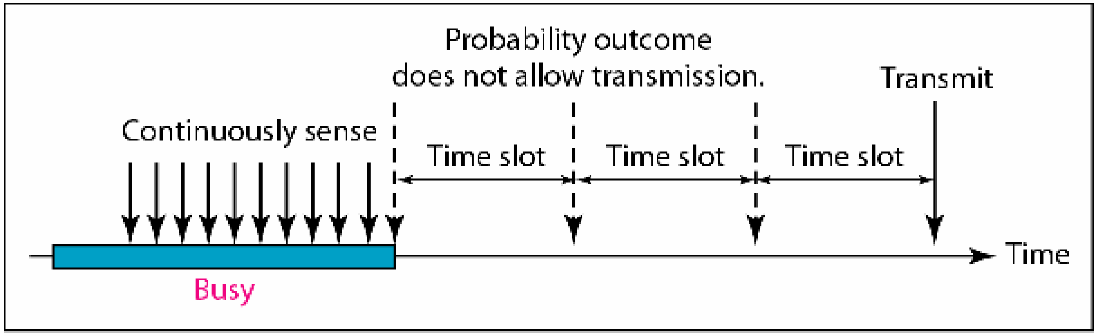


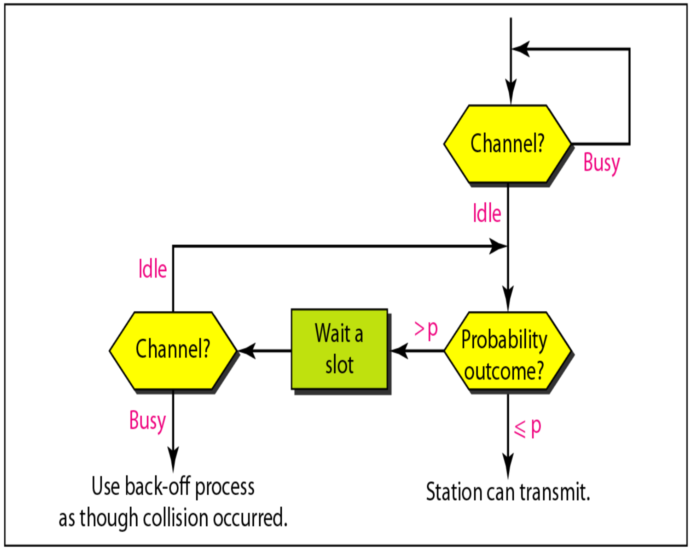


CSMA (Carrier Sense Multiple Access)

p-Persistent CSMA ($0 \le p \le 1$)

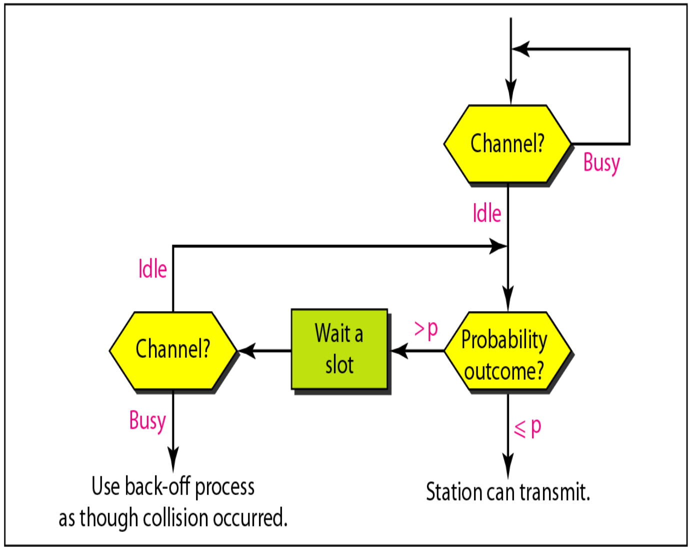
2. If the **channel is busy**, the station will **continuously listen** to the channel **until** the channel **becomes idle**, and then repeat from 1.
3. If a **collision occurs**, the MS **waits for a random amount of time** and **starts all over again by sensing the channel**.





CSMA (Carrier Sense Multiple Access)
p-Persistent CSMA

- **Performance**
  - **Reduces** the **possibility** of **collisions**
  - **Reduces channel idle time**



- **p has to be selected with care**
  - If **p small**, then **more wasted time**
    - Because if **p** small, the **possibility to have**, in some cases, **all stations refraining from transmission** will be **higher**. **No station** will **use the channel** at some periods of time.
  - If **p large, more collisions**
    - Because if **p** large, the **possibility to have more than two stations transmitting** at the **same time** be higher and thus **more collisions will occur**.

CSMA (Carrier Sense Multiple Access) Comparison of Random Access Protocols

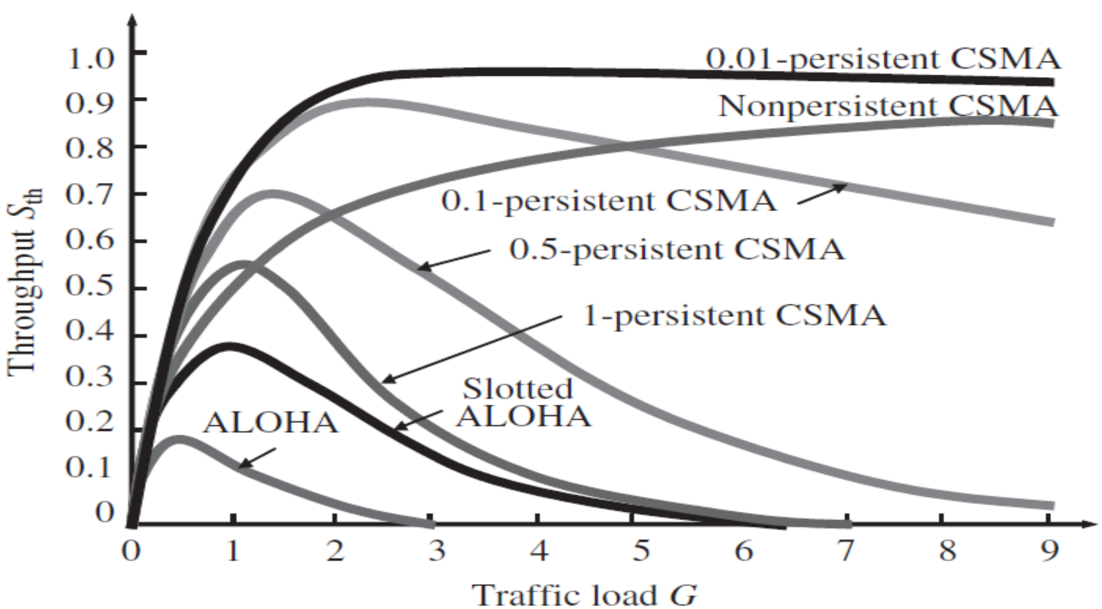
- Comparison of the channel utilization versus load for various Random Access Protocols

S: Throughput in frames per time slot

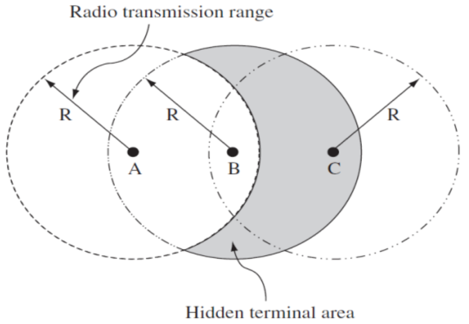
G: Is the traffic load → **G = gT**

T: duration of frame transmission

g*: Rate of packets per sec* (offered load to the channel*)*



Hidden Terminal Problem

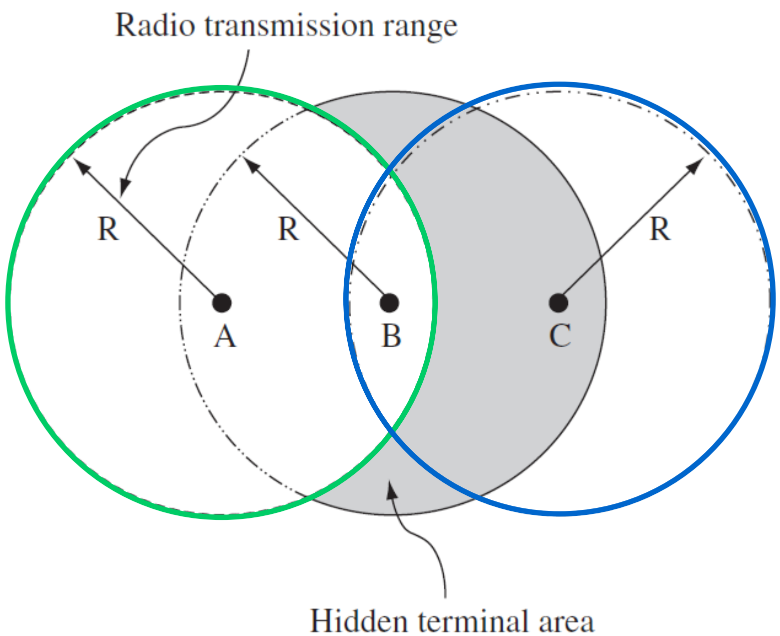


- CSMA protocol and its variants can reduce collisions drastically, however it **still suffers** from a **problem** called **Hidden Terminal.**
- **Hidden Terminals** refer to the stations that are **out of each others' radio transmission and sensing range** **(for example A and C)**.
  - For example this can occur in an **ad hoc (i.e., infrastructure-less) wireless network** where the stations are **randomly distributed** (τυχαία διασκορπισμένα).
  - Wireless stations **have limited transmission ranges** and **not all stations are within the radio range of each other (and thus cannot sense their transmissions)**.
- **The Hidden Terminal Problem** occurs when two or more **Hidden Terminals (A and C)** are **sending their frames simultaneously, to a Terminal that is located in their common coverage area (B)**.

Hidden Terminal Problem

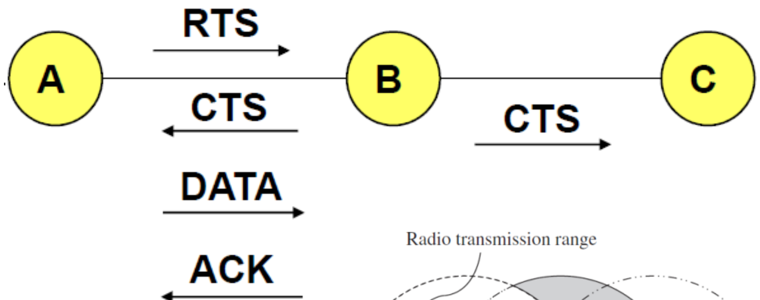
Example: Hidden Terminal Problem

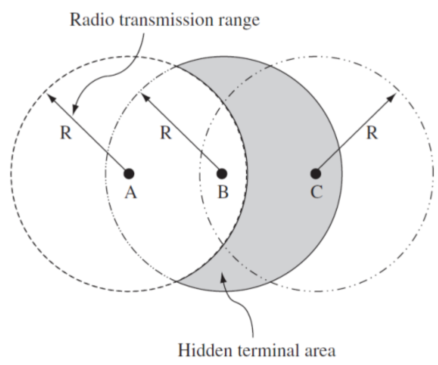
- Stations A and C can communicate with Station **B**
- But Station A and C **cannot hear each other** since they are out of each other's radio transmission/sensing range (**Hidden Terminals**).
- Station A transmits to Station **B**
- If Station C "senses" the channel, it **will not hear** Station A's transmission and **falsely conclude** that it **can begin a transmission** to Station **B**.
  - Which will **cause a collision** at Station **B**.



CSMA/CA with RTS/CTS (Request To Send/Clear to Send)

- **CSMA/CA with RTS/CTS** can overcome the Hidden Terminal Problem by **using handshake frames exchange (RTS and CTS) before starting transmitting their frame.**
- Assume that Station **A** is ready for transmission to Station **B**
  - Station **A** broadcasts a **RTS** frame to Station **B**.
  - After receiving the frame, Station **B** replies with a **CTS** frame back to Station **A**, **accepting the transmission**.
  - Hidden Station **C** which is in the transmission range of Node **B**, **receives** (senses) the **CTS** frame.
    - Therefore, Node **C knows that** Node **B is in communication with another station** and it **will refrain** (enter a delayed access state) **from any transmission.**





Channelization Protocols - Multiple Division Techniques for Traffic Channels

- **FDMA (Frequency Division Multiple Access)**
- **TDMA (Time Division Multiple Access)**
- **CDMA (Code Division Multiple Access)**
- **OFDMA (Orthogonal Frequency Division Multiple Access)**

Introduction

- The Random Access Protocols discussed in the previous slides **coordinates access of multiple sending/receiving stations using the same channel** (i.e., **only one station is allowed to transmit at given point in time** otherwise their **frames will collide**)

- **These Random Access Protocols can be used in Infrastructure-less based Networks (Ad Hoc networks)** for **exchanging data** between the Mobile Stations (MSs).

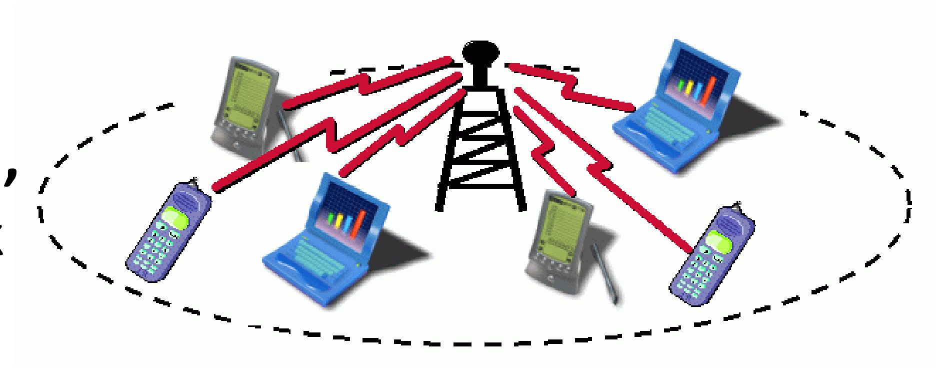
Introduction

- **They can also be used in Infrastructure based networks**, for **exchanging control information between a MS and the BS**, **before a dedicated channel is allocated to them.**
  - ***Note that, before a connection is established between the BS and the MS (e.g., just when the MS is switched on), the BS is not aware about its presence in its coverage area and thus have no control over the MS.***
  - *The* ***MS makes itself known to the BS*** *by sending to it a* ***control message*** *indicating* ***its readiness to send information to the BS.***
  - ***The channel used to send this control message is the same for all MSs in the BS's coverage area → A Random Access Protocol is used, to coordinate the transmissions of all the new MS requesting access to connect.***
  - ***The BS****, in turn,* ***advises the MS which particular traffic channel*** *is to* ***be used exclusively by that MS*** *for* ***actual information exchange****.*

Introduction

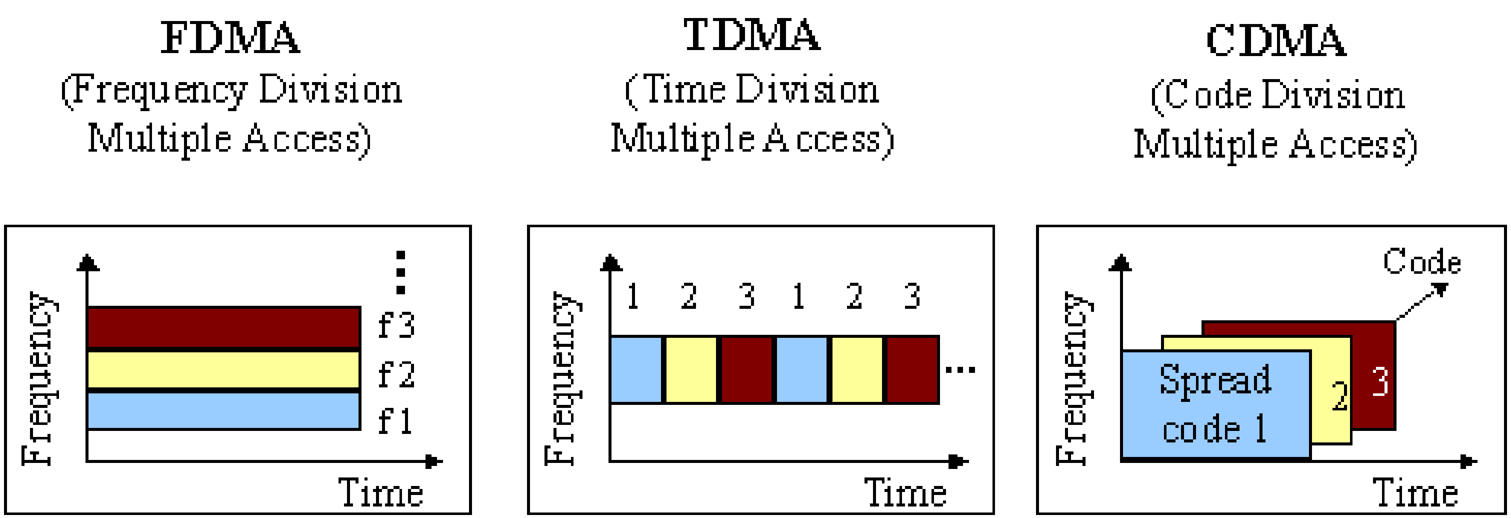
- In a wireless infrastructure-based environment, a **BS needs to establish a radio connection for all the MSs in its transmission range**.
- Thus, there is a need to address the issue of **simultaneous multiple access by numerous MSs located in the BS's coverage area**.
- To achieve this, **many channels need to be made available**.

E.g., Wireless LAN, Cellular Network

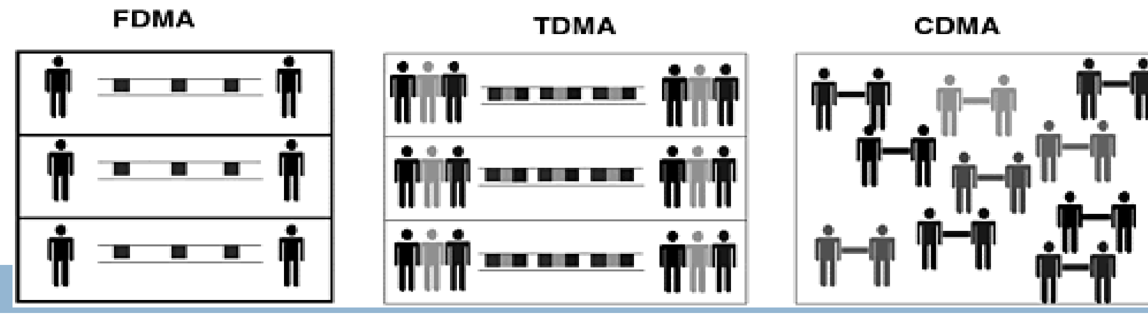


Introduction

- **Three basic ways** to **have many channels** within **an allocated bandwidth**: **Frequency**, **Time**, or **Code.**
  - **Frequency Division Multiple Access** (FDMA)
  - **Time Division Multiple Access** (TDMA)
  - **Code Division Multiple Access** (CDMA)



Introduction



FDMA, TDMA and CDMA – An Analogy:

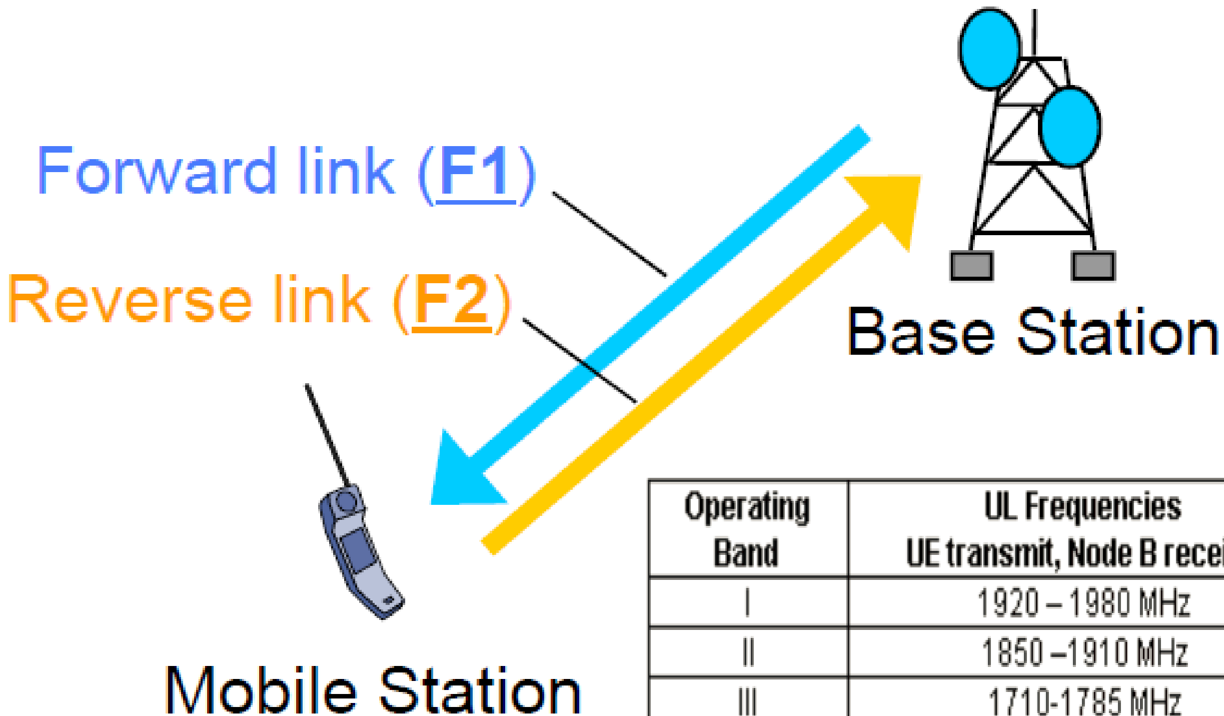
- **FDMA**: A **Large room is** divided **into small rooms** (i.e., discussion rooms). A **pair of people** that wants to communicate will **use a discussion room**. If **another pair** of people wants to speak, they **must use another discussion room**.
- **TDMA**: A **Large room can be** divided up **into small rooms** (i.e., discussion rooms). **More than one pair** of people can be **in the same room**. **Each pair** will **get 30 seconds to communicate**. **All other pairs** should **wait for their turn**. They can speak only when their turn comes.
- **CDMA**: **All people** are **in the same room**. **All pairs** can **communicate at the same time** but **each pair communicates** in **different language** that **only those two know** (i.e., different spreading codes). If **voice volume** is **minimized**, the **number of pairs that can communicate is maximized**.

Duplex Communication

- To provide **simultaneous two-way communication** (duplex communications), a **Forward link** (referred as **Downlink channel**) from the BS to the MS and a **Reverse link (**referred as **Uplink channel)** from the MS to the BS are necessary.
- **Two types** of duplex systems are utilized:
  - Frequency Division Duplexing (**FDD**)
  - Time Division Duplexing (**TDD**)
- **FDMA** mainly uses **FDD**, while **TDMA** and **CDMA** systems use either **FDD** or **TDD**

Duplex Communication - FDD

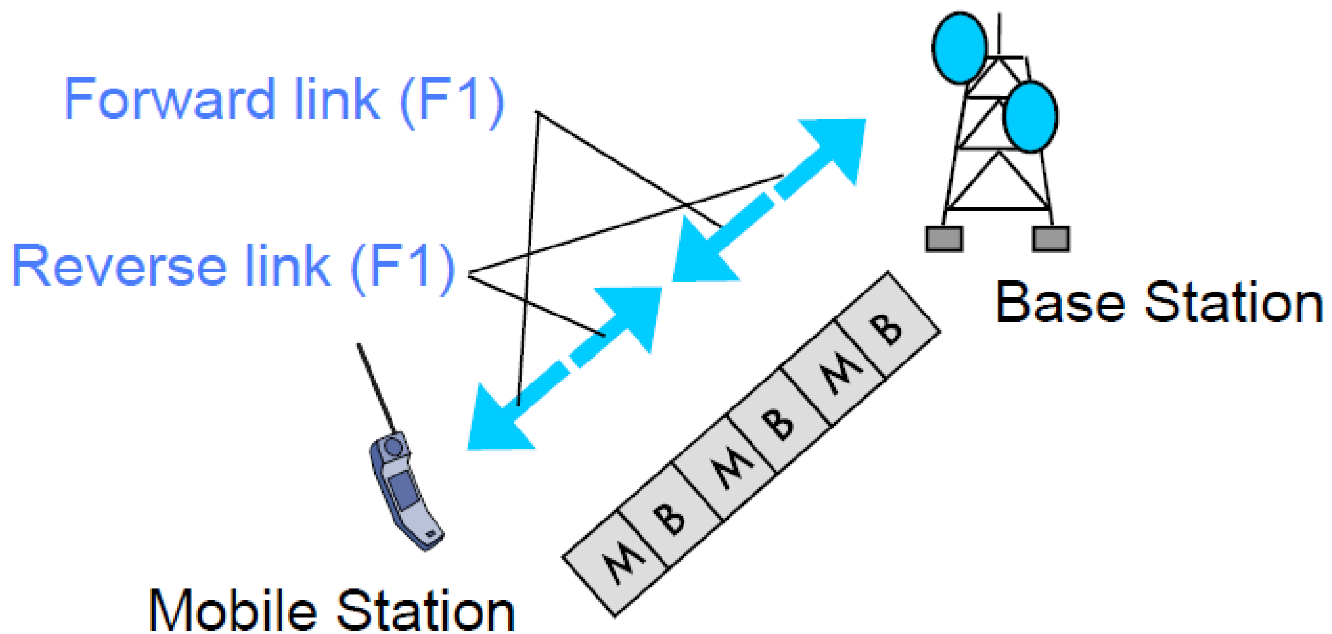
- **Forward Link** (Downlink (DL) channels) and **Reverse Link** (Uplink (UL) Channels) use **different frequency bands**.



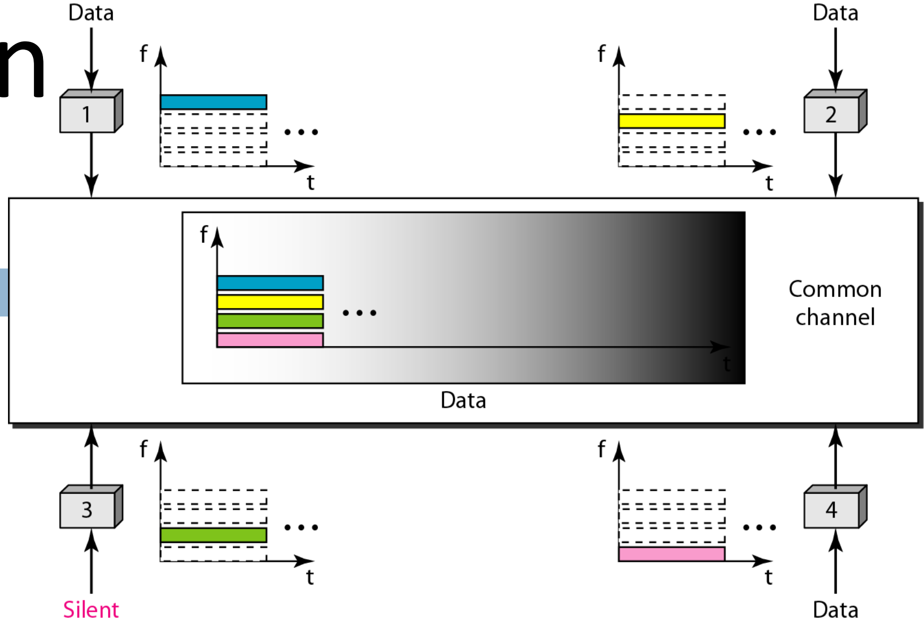
Operating Band	UL Frequencies UE transmit, Node B receive	DL frequencies UE receive, Node B transmit
I	1920 – 1980 MHz	2110 –2170 MHz
II	1850 –1910 MHz	1930 –1990 MHz
III	1710-1785 MHz	1805-1880 MHz

Duplex Communication - TDD

- **Forward Link** (Downlink channels) and **Reverse Link** (Uplink Channels) use the **same frequency band**. The Uplink and Downlink channels are **divided** into **time slots**. The **Mobile Station** and **Base Station transmit sequentially,** using the **time slots designated to them**.

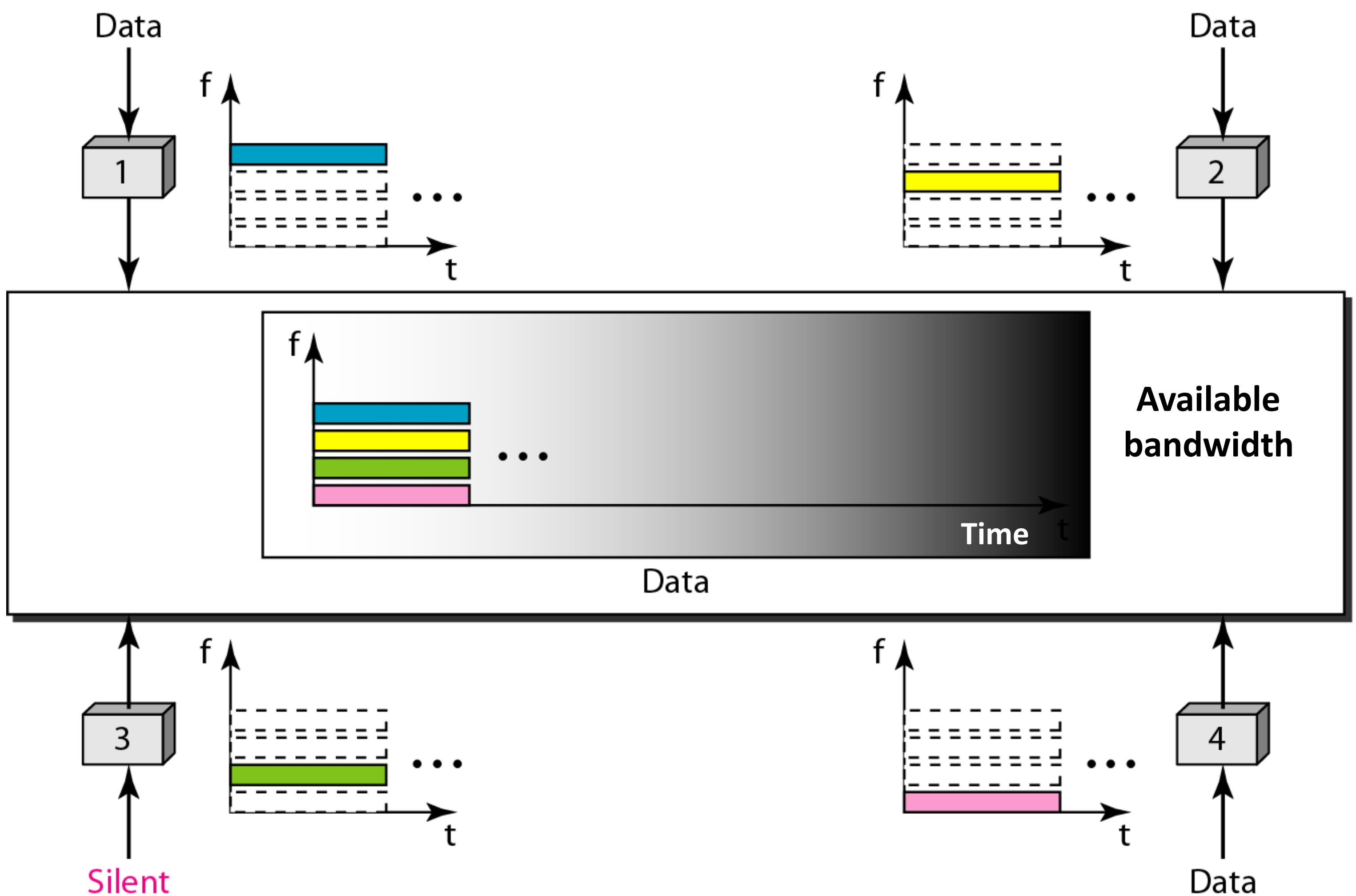


Frequency Division Multiple Access



- **Separates a large band** (i.e., the available bandwidth) **into smaller sub-bands** (frequency bandwidths) that **forms the channels.**
- The **BS dynamically assigns a different channel** (**carrier frequency**) to **each active user** (MS)
- **Guard Bands** are used to **separate channels** and **minimize adjacent channel interference**
- Uses **Frequency Division Duplexing (FDD)**

Frequency Division Multiple Access



Frequency Division Multiple Access

- **Channels** can be **assigned on-demand,** when a user needs to communicate
- **Each user** can **only be assigned one channel.**
- FDMA is used in **narrowband systems** (e.g., 30 kHz frequency bands) → E.g., FM Radio
- FDMA was the **initial multiple-access technique used in** the 1st Generation systems.
  - Used in **analog cellular phone systems** (AMPS; Advanced Mobile Phone System)

Frequency Division Multiple Access

Advantages:

- Provides **large time between subsequent symbols compared** to the **average Delay Spread.**
  - **This reduces InterSymbol Interference** (ISI) - No serious ISI is likely to occur if the **time between symbols** is **longer than, say, Ten times the Average delay spread.**
- **No need for synchronization** (network timing) required because **transmission is continuous in FDMA → Reduces Overhead**
- **Algorithmically simple and easy to implement**.

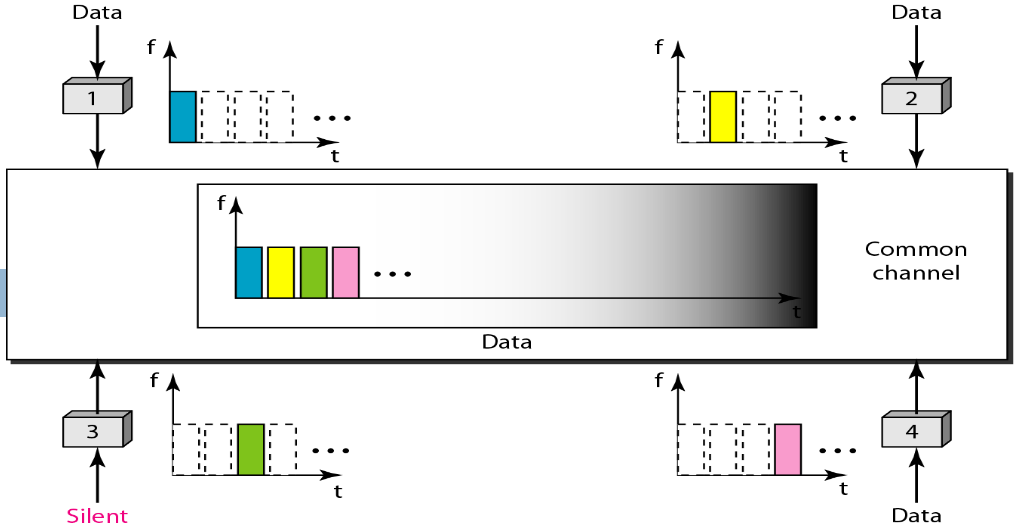
Depending on the ***propagation environment*** *and the* ***distance of the MS from the BS****, the* ***Delay Spread*** *can be in the* ***range from some nanoseconds (***10^{-9} ***seconds) to some microseconds(***10^{-6} ***seconds))***

Frequency Division Multiple Access

Disadvantages:

- If there are **not enough users** **for the number of available channels**, the **channels that are not used**, **will** **remain idle** → **the radio spectrum is wasted** **(spectral inefficient)**
- **Channel bandwidth** is relatively **narrow** (30KHz) → **Low data rates** **achieved in FDMA based systems.**
- **Presence of** **guard bands** **(idle unused frequency bands – 500 Hz on each side of the channel)** between adjacent channels **are needed** → **Reduces spectral efficiency**
- A Channel (frequency band) allocated to a user is **reserved for the whole call duration** (even when silent)→ **Reduces spectral efficiency**
- The **maximum bit rate** per channel **is fixed**.
- **Requires** **expensive narrowband filters** to **reduce adjacent channel interference** **(i.e., interference from channels that uses adjacent frequencies)**

Time Division Multiple Access



- In TDMA, the **available bandwidth** is **timeshared between the users** → TDMA **splits the time** into **several time slots** and **assigns the slots among multiple users**.
  - **Only one user** can **transmit or receive data per slot**
- The **users are synchronized in time** using a **network-wide clock** and **each of the users takes turn in transmitting and receiving** data in its assigned time slot in a **Round Robin fashion**.
- There is a **Guard Time between** the subsequent **time slots so that interference caused due to multipath propagation delays (i.e., due to delay spread)**, can be **minimized.**

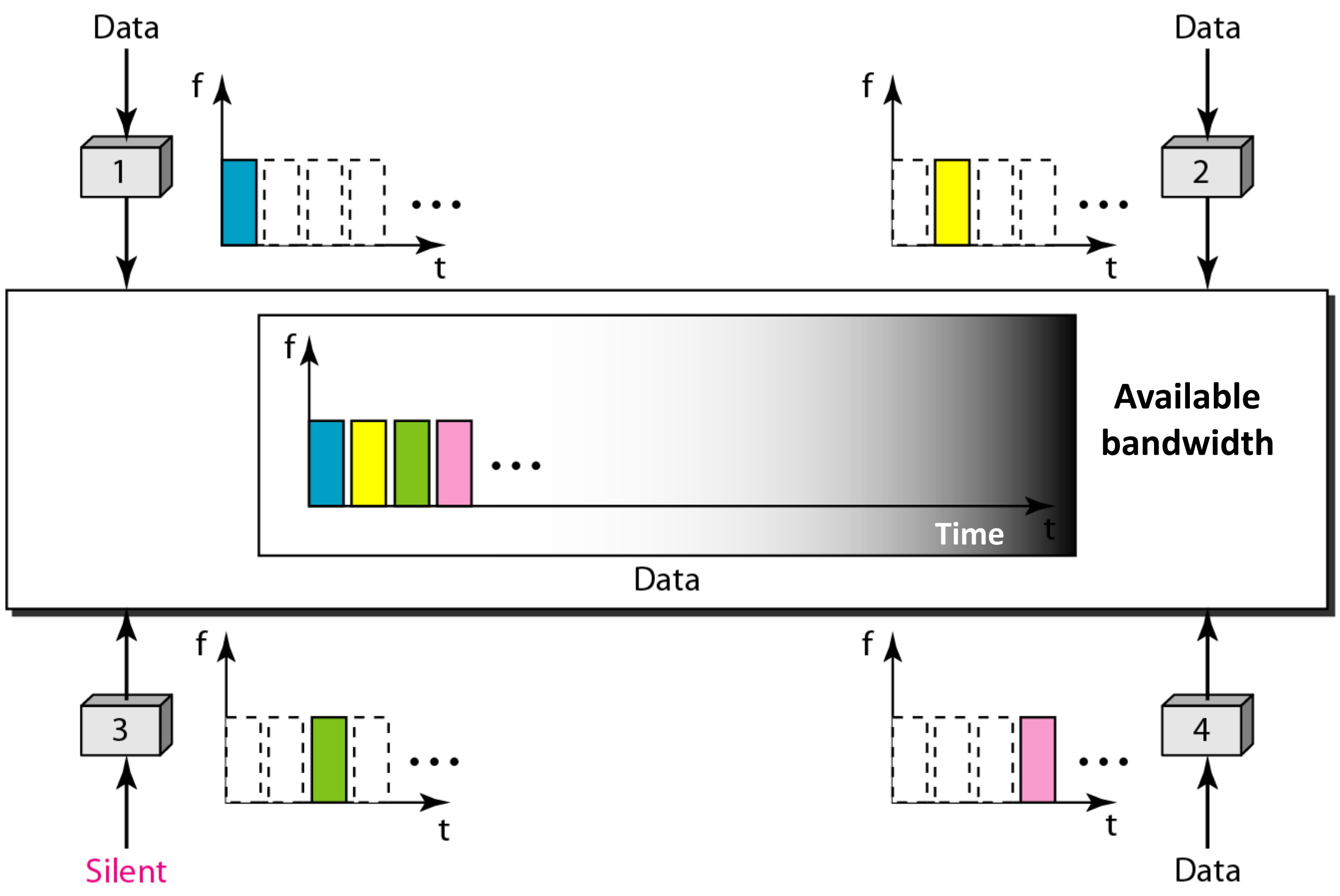
Time Division Multiple Access

- The **Guard Time used between subsequent time slots** is usually **estimated by considering**:
  - **Time inaccuracies due to clock** (synchronization) **instability**
  - **Delay Spread** of transmitted symbols (so as to avoid Intersymbol Interference between the different users)
  - **Transmission Time Delay** (the time **from the first bit** until the **last bit of a packet** has **left** the **transmitting station**) → **Depends on the bit rate of the channel**.
- Uses **Time Division Duplexing (TDD)**
- **Channels can be assigned on-demand** when a **user needs to communicate**.

Time Division Multiple Access

- Widely used in the field of mobile telephones (GSM) and mobile satellite communication systems
- In radio systems, **TDMA is usually used alongside with FDMA**. This is the case for GSM (**Global System for Mobile** Communications).

Time Division Multiple Access



Time Division Multiple Access

Advantages:

- **No Guard Band required → Enhances spectral efficiency** as all frequencies of the available bandwidth are utilized
  - **Higher bit rates** achieved and **more users** can be **supported using the same bandwidth**, than FDMA.
- **Extended battery and Talk time:**
  - **Mobile Devices** can **save battery power** by **turning off Transmitter/Receiver, during time slots they are not transmitting or receiving data.**
- **Can support Flexible Bit Rates** → Can **allocate multiple time slots to a user, if needed,** to provide **increased data rate.**

Time Division Multiple Access

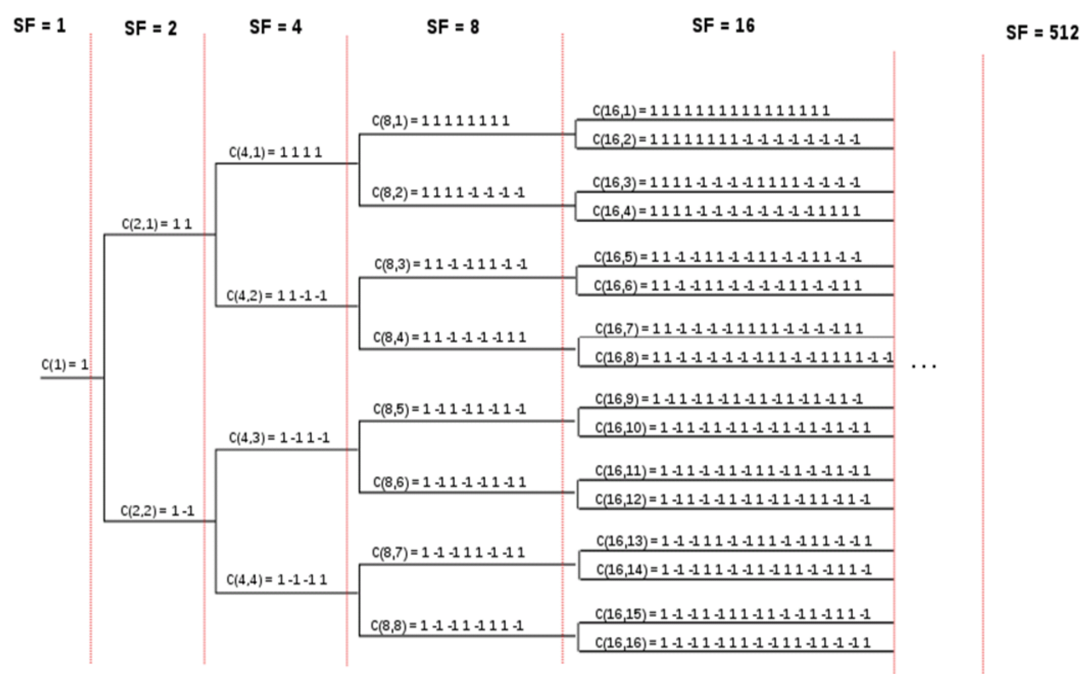
Disadvantages:

- Requires **network-wide timing synchronization →** **Increases complexity and signaling overhead**
- **Guard Time (10 x average delay spread) between time slots have to be considered** to **separate users → Spectral Inefficiency, as the available bandwidth remains idle between subsequent time slots**
  - **However, these Guard Times are minor (some nano- or micro-seconds, depending on the environment)**.
- **Too few users** result in **idle channels**
- A Channel (time slots) allocated to a user is **reserved for the whole call duration** (even when silent)→ **Reduces spectral efficiency**
- **Higher costs** due to **greater equipment sophistication**

Code Division Multiple Access

***For further info see Slides of Spread Spectrum Techniques**

- Divides up a radio channel **not by frequency** (as in FDMA), **not by time** (as in TDMA), but instead by using **Code Sequences (Spreading Codes)** for **each user**.
- **Guard Spaces** are realized **by using codes** with the necessary 'distance' in code space, e.g., **Orthogonal Codes**.
- These codes are derived from an **Orthogonal Variable Spreading Factor (OVSF)** code tree, and **each user is given a different, unique code**.



Code Division Multiple Access - Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users →**
  - "**Sender 1**" has a
    - Spreading Code (C_1) = (1, 1, 1, 1), Data (D_1) = (0, 0)
  - "**Sender 2**"
    - Spreading Code (C_2) = (1, -1, 1, -1), Data (D_2) = (0, 1)
  - "**Sender 3**"
    - Spreading Code (C_3) = (1, 1, -1, -1), Data (D_3) = (1, 0)
  - "**Sender 4**"
    - Spreading Code (C_4) = (1, -1, -1, 1), Data (D_4) = (1, 1)
  - All senders **transmit simultaneously**

Code Division Multiple Access - Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users,**
  - **“Sender 1” Spread Signal**:
    - (-1, -1, -1, -1, -1, -1, -1, -1)
  - **“Sender 2” Spread Signal:**
    - (-1, 1, -1, 1, 1, -1, 1, -1)
  - **“Sender 3” Spread Signal:**
    - (1, 1, -1, -1, -1, -1, 1, 1)
  - **“Sender 4” Spread Signal:**
    - (1, -1, -1, 1, 1, -1, -1, 1)

  - **Interference Pattern (We add all the signals together)**
    - **(0, 0, -4, 0, 0, -4, 0, 0)**

Code Division Multiple Access -
Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users (Interference Pattern: (0, 0, -4, 0, 0, -4, 0, 0))**
-
  - **"Sender 1" Despread Signal (C_1 = (1, 1, 1, 1))**
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, 1, 1, 1) = (-4, -4) → **Data (0, 0)**
  - **"Sender 2" Despread Signal** (C_2 **= (1, -1, 1, -1)**)
    - ((0, 0, -4, 0), (0, -4, 0, 0)). (1, -1, 1, -1) = (-4, +4) → **Data (0, 1)**
  - **"Sender 3" Despread Signal** (C_3 **= (1, 1, -1, -1)**)
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, 1, -1, -1) = (+4, -4) → **Data (1, 0)**
  - **"Sender 4" Despread Signal** (C_4 **= (1, -1, -1, 1)**):
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, -1, -1, 1) = (+4, +4) → **Data (1, 1)**

Code Division Multiple Access

*For further info see Slides of Spread Spectrum Techniques

- In contrast with FDMA and TDMA which are **bandwidth and time limited**, CDMA is **interference limited**.
- Because **all users transmit on the same frequency and at the same time, internal interference generated by the users** is the **most significant factor** in **determining system capacity** and **call quality**.
  - **Each user** is a **source of interference to all the other users** in the cell.

Code Division Multiple Access

***For further info see Slides of Spread Spectrum Techniques**

- To increase capacity, the **transmit power for each user** must be **reduced to limit interference**.
- However, **the Received signal power (at the BS) should be enough to maintain the minimum required *SNIR needed by the Receiver (for allowing it to decode the signal correctly)*** for a **satisfactory call quality**.
- Thus, the goal is **all MSs' transmitted signals to reach the Base Station and received with about the same signal power (and equal to the minimum required SNIR) from the BS (**also known as Node-B**)** → **Otherwise some signals could drown others**.

Code Division Multiple Access

***For further info see Slides of Spread Spectrum Techniques**

Advantages:

- **Better Spectral Efficiency** than FDMA and TDMA → **The available bandwidth is much better utilized**.
- **No absolute limit on the number of users.**
  - **CDMA** is **interference limited**, NOT bandwidth limited.
  - **If interference is kept low, more users can be included.**
- **Flexible allocation of resources** is supported (variable bit rates supported) → Depending on the bit rate requested, a **different Spreading Code**, with a different **Spreading Factor** will be assigned.
- **Impossible for hackers to decode the signal without knowing the Spreading Code** used (Provides better security and privacy)

Code Division Multiple Access

* **For further info see Slides of Spread Spectrum Techniques**

Advantages:

- **Better signal quality** and **greater resistance to interference and noise** (due to the **Processing Gain** achieved)
- **Increased talk time** and **standby time for Mobiles** (Uses Fast **Power Control that saves battery life for MS**)
- **No sense of handovers** when a MS is changing cells (**Soft Handover** can be used; The MS can have simultaneous connection with more than one BSs)
- The **CDMA channel is 1.23 MHz wide** (**higher data bits rates can be supported** compared to FDMA and TDMA
  - Wideband – CDMA (WCDMA) supports a 5 MHz channel and thus much higher bit rates; used in UMTS networks.

Code Division Multiple Access

* For further info see Slides of Spread Spectrum Techniques

Disadvantages:

- Requires **more complex transmitter and receiver** for **spread spectrum signal generation** and **reception** (**more expensive equipment**)
- **Near-far problem arises: If all users transmit with the same power,** signals received from MSs closer to the receiver will be stronger than signals transmitted from MSs farther away.
  - **The BS requires to Power Control all the MSs in its coverage** in order to **keep their transmission power levels to the lowest possible for reducing interference to the minimum.**
  - **Power Control increases the complexity of the system**.

Summary of the various Multiple Division Techniques

Technique	FDMA	TDMA	CDMA
Concept	Divide the frequency band into disjoint subbands	Divide the time into non-overlapping time slots	Spread the signal with orthogonal codes
Active terminals	All terminals active on their specified frequencies	Terminals are active in their specified slot on same frequency	All terminals active on same frequency
Signal separation	Filtering in frequency	Synchronization in time	Code separation
Handoff	Hard handoff	Hard handoff	Soft handoff
Advantages	Simple and robust	Flexible	Flexible
Disadvantages	Inflexible, available frequencies are fixed, requires guard bands	Requires guard space, synchronization problem	Complex receivers, requires power control to avoid near-far problem
Current applications	Radio, TV, and analog cellular	GSM and PDC	2.5G and 3G

Ερωτήσεις;

Additional Slides

Pure ALOHA Versus Slotted ALOHA Throughput Achieved

- **Pure ALOHA:** Users **transmit any time they desire**.
- **Slotted ALOHA:** Users **transmit only at the beginning of a time slot.**

GREATER POSSIBILITY OF COLLISION IN PURE ALOHA, THUS REDUCING THE THROUGHPUT (S)

Pure ALOHA → $S = G \times e^{-2G}$

Slotted ALOHA → $S = G \times e^{-G}$

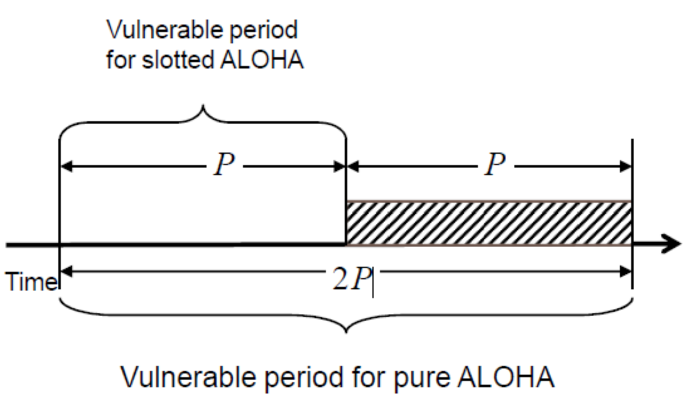
e: Mathematical constant (2.71828…)

S: Throughput in frames per time slot

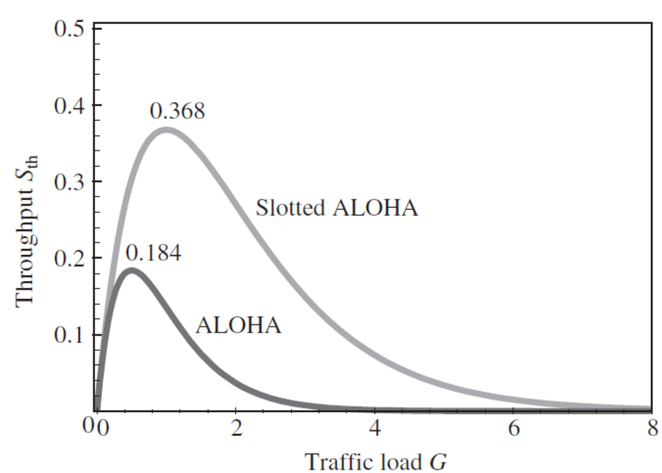
G: Is the traffic load → **$G = g \times T$**

T: Duration of frame transmission

g*: Rate of packets per sec* (offered load to the channel)



P= frame transmission time



CSMA/CD (Carrier Sense Multiple Access with **Collision Detection**)

- **The basic CSMA has an inefficiency**:
  - If **two terminals begin transmitting at the same time**, **each will transmit its complete frame**, **even though they collide**.
  - **Wastes the medium for an entire frame time(T_{fr})**
- With **CSMA/CD** the main idea is to **terminate transmission immediately after detection of a collision**
  - Aims to **reduce channel waste**

- **CSMA/CD operates as follows:**
  - **While transmitting**, the sender is **listening to the medium for collisions**.
  - If a **collision is detected** during the transmission, **the sender aborts its transmission immediately** and it attempts to transmit later **after waiting for a random amount** of time.

CSMA/CD (Carrier Sense Multiple Access with **Collision Detection**)

- CSMA/CD is widely used for **bus topology LANs** (IEEE 802.3, **Ethernet)** while **not possible in wireless radio**
  - In **wireless system**, **either** you can **transmit data** using the radio **or receive data**.
  - Hence, **both transmission and sensing is not possible by a wireless device** and **CSMA/CD cannot be used** in a wireless environment of a shared channel.
- **How does a station detects a collision?**
  - A station **monitors the channel while transmitting**.
  - If the **observed power** is **more than the transmitted power of its own signal**, it means a **collision occurred**

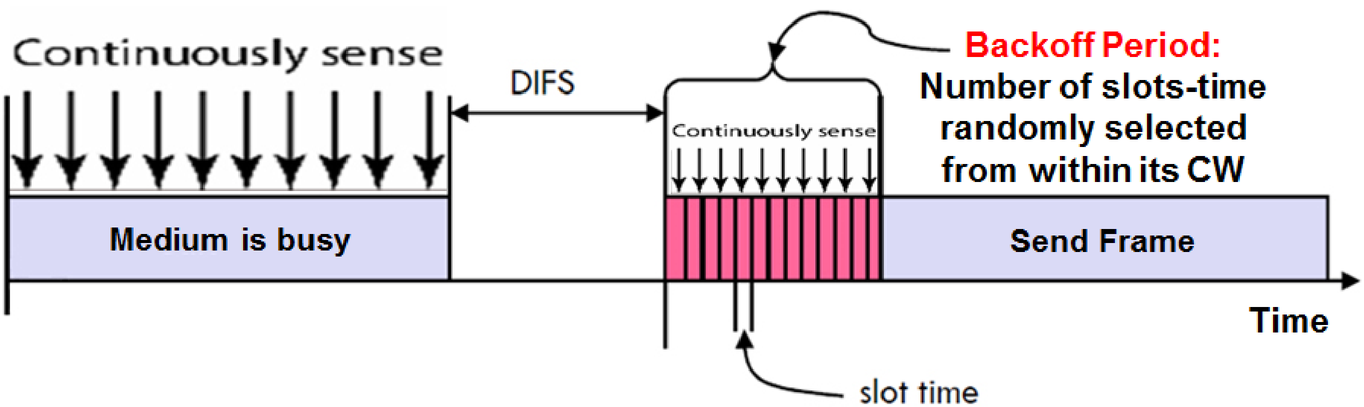
CSMA/CA (Carrier Sense Multiple Access with **Collision Avoidance**)

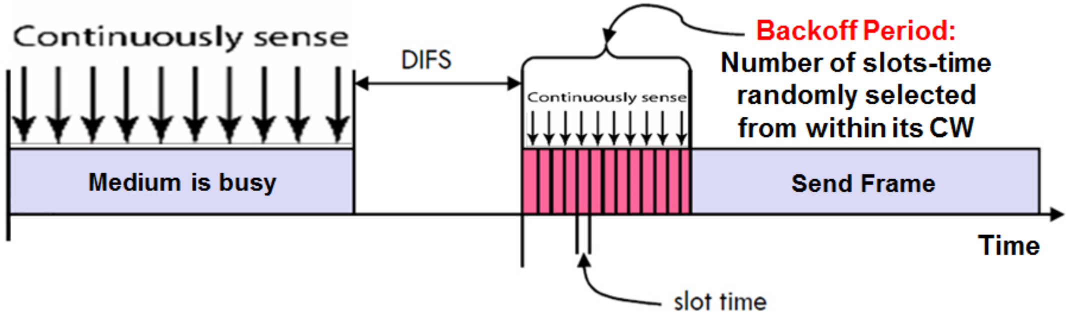
- **CSMA/CA** is based on the CSMA/CD
  - Under basic CSMA/CA technique, **all MSs watch the channel** in the **same way as CSMA/CD**
  - However with CSMA/CA a station with a frame to transmit **senses both the medium and "the collision" instead of starting traffic immediately** after the medium **becomes idle**.
    - CSMA/CA acts to **prevent collisions** before they happen
  - CSMA/CA is used to improve the performance of basic CSMA by attempting to be less "greedy" on the channel.

CSMA/CA (Carrier Sense Multiple Access with **Collision Avoidance**)

A station with a frame to transmit senses the medium:

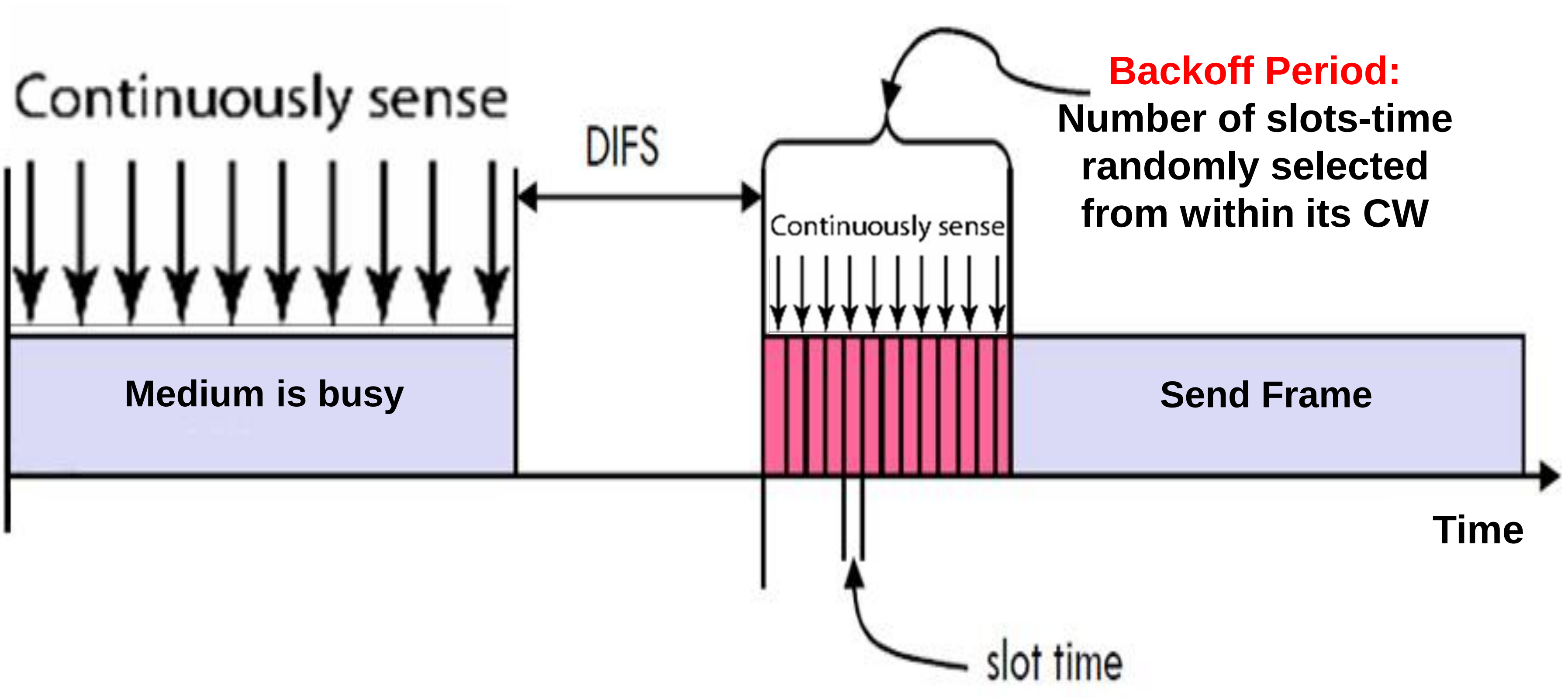
1. If the **medium is idle**, it **waits to see if the medium remains idle** for a time equal to **DIFS (Distributed InterFrame Space)**. **If so, the station may transmit immediately.**
   - **DIFS** defines **how long a channel must be idle** before a **station can attempt transmission**
2. However, if the **medium is busy**, the **station defers transmission** and continues to **monitor the medium** until **the current transmission is over**.





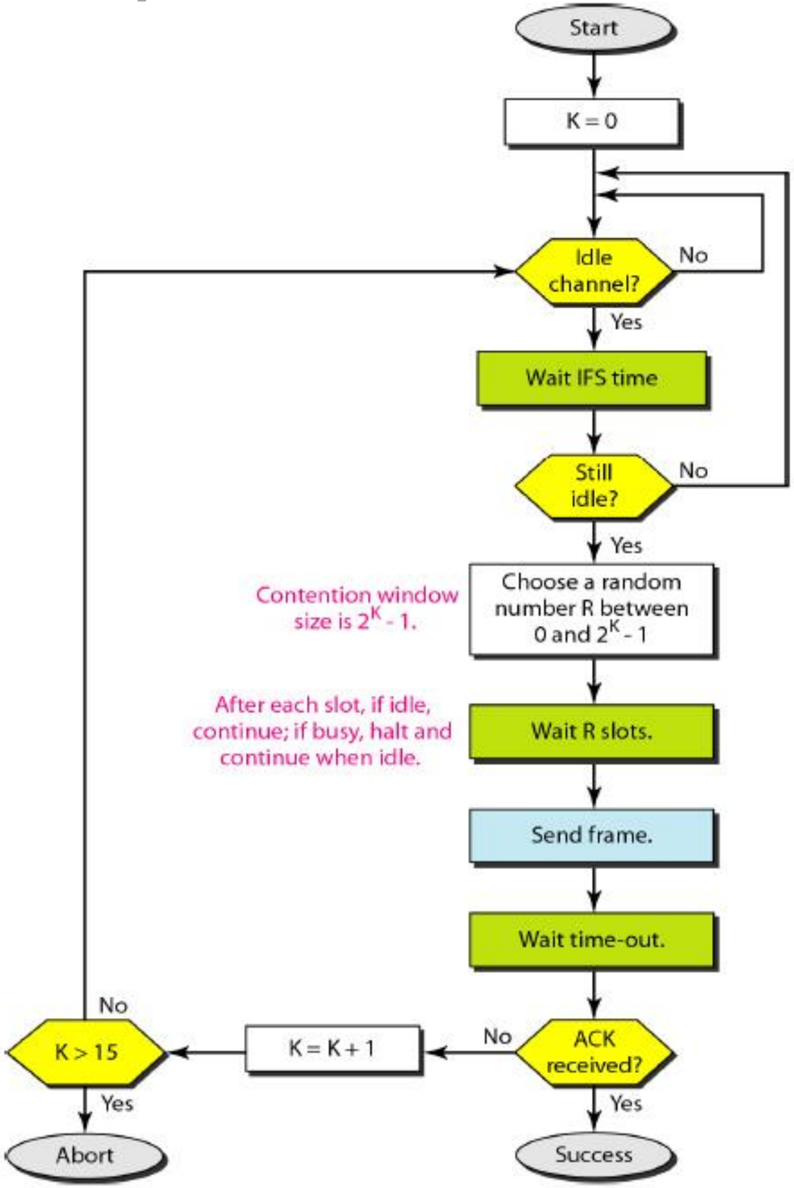
3. Once the current transmission is over, the **station delays another DIFS**.
   - If the **medium remains idle for this period**, then the station picks a random **Backoff Period** (**a number of slots-time randomly selected from** within its **Contention Window (CW)**) to **wait before transmitting its data** and **again senses the medium**.
     - The **Backoff period** is used to initialize the **Backoff Counter**
   - The MS can **start transmitting its data** when the **Backoff Counter becomes zero**.
     - The **Backoff Counter** can **count down only when the medium is idle**. It is **frozen** as soon **as the medium gets busy**.
     - **After the busy period**, **counting down** of **the Backoff Counter resumes only after the medium has been free for longer than DIFS.**
4. **If** the **transmission is unsuccessful**, which is **determined by the absence of an acknowledgement**, then it is **assumed that a collision has occurred and attempts to resend the frame**.

CSMA/CA (Carrier Sense Multiple Access with **Collision Avoidance**)

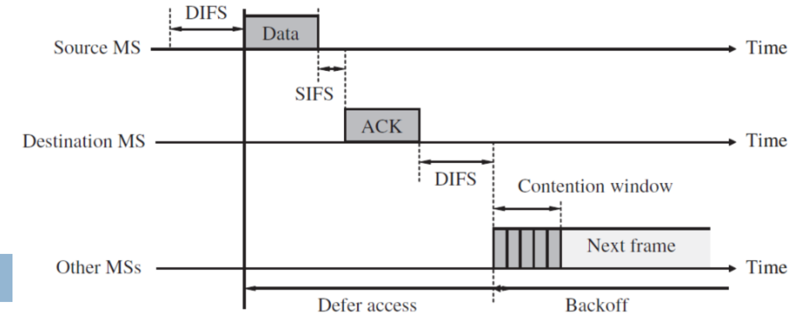


CSMA/CA (Carrier Sense Multiple Access with **Collision Avoidance**)

- **Collisions can occur** only when two or more terminals **select the same time slot in which to transmit** their frames.
- Whenever collision occurs, the **size of Contention Window (CW) is doubled** so that the **range** of the **random time delay** is increased, and reduce the probability of any future collision.
    - This process is **repeated till the transmission is successful** and **then the CW is reset to the original value**.

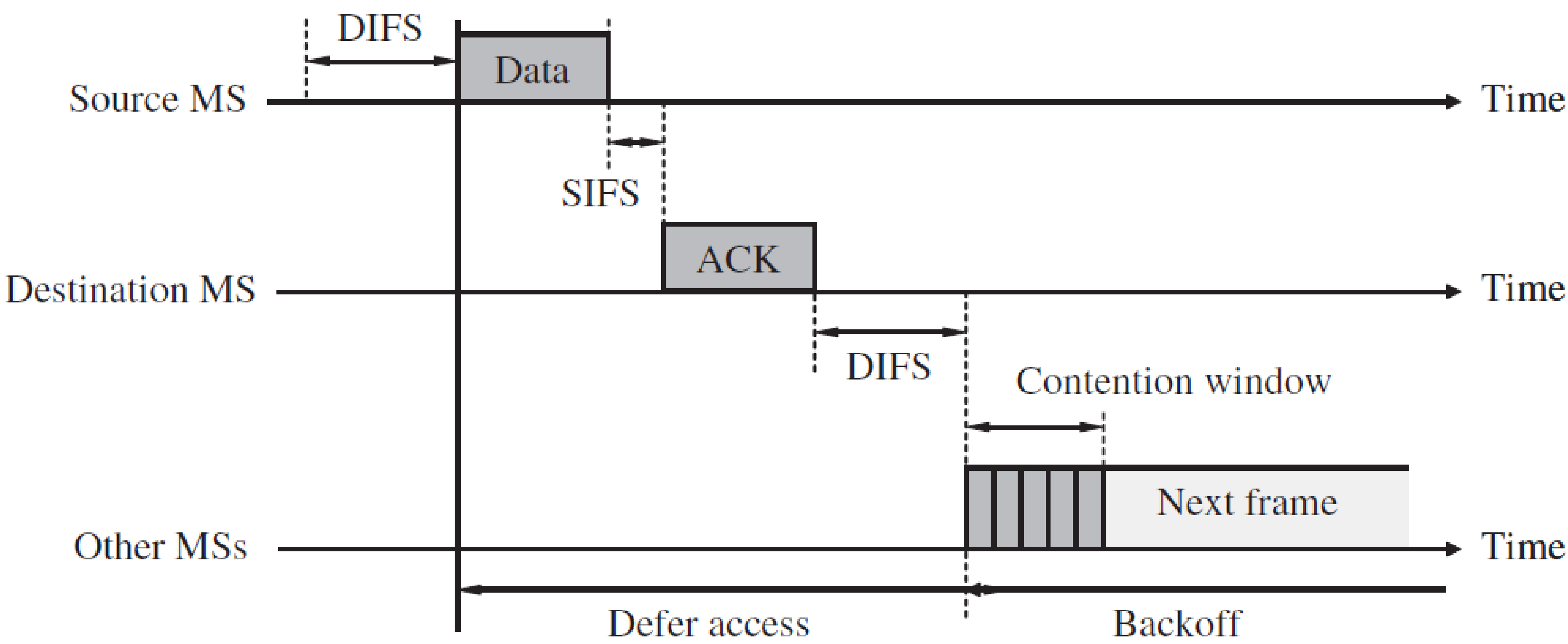


CSMA/CA with ACK

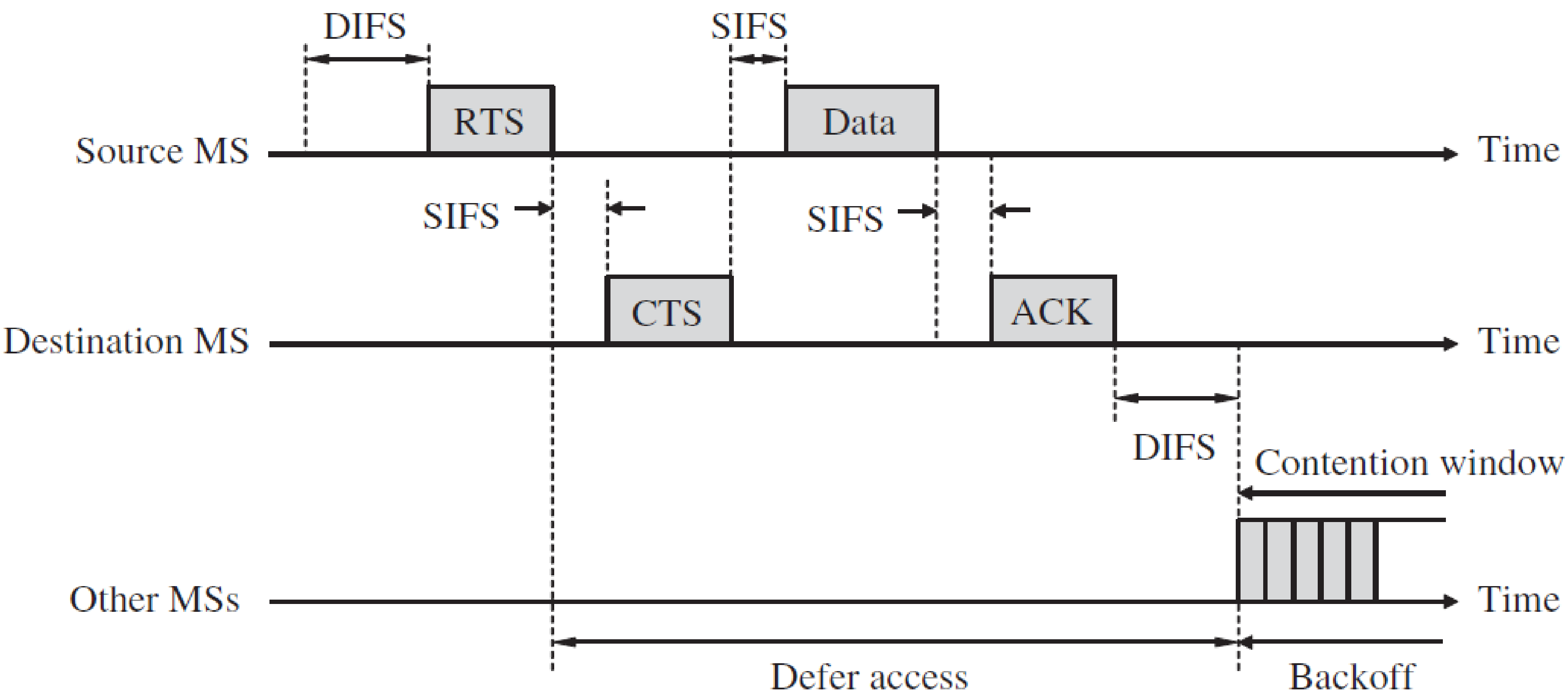


- In this scheme, an **immediate positive Acknowledgment (ACK)** is employed to **indicate a successful reception** of each **data frame**
  - **Increases the reliability of the Acknowledgements** (i.e., in case an Acknowledgement is sent it guarantees that it will not be lost due to collisions) **and thus reduces unnecessary retransmissions**.
- This is accomplished by **making the receiver send an ACK frame** immediately **after a time interval of Short InterFrame Space (SIFS)**.
  - **SIFS** (SIFS < DIFS) defines **how long a receiving station waits before sending an ACK** or other response.
  - **As SIFS < DIFS**, the receiver **transmits ACK without sensing the state of the medium**, as **no other station** or device **is expected to use the shared medium at that time**
  - In case **an ACK is not received**, the **data frame is presumed to be lost,** and a **retransmission is automatically scheduled** by the **transmitter**.

CSMA/CA with ACK

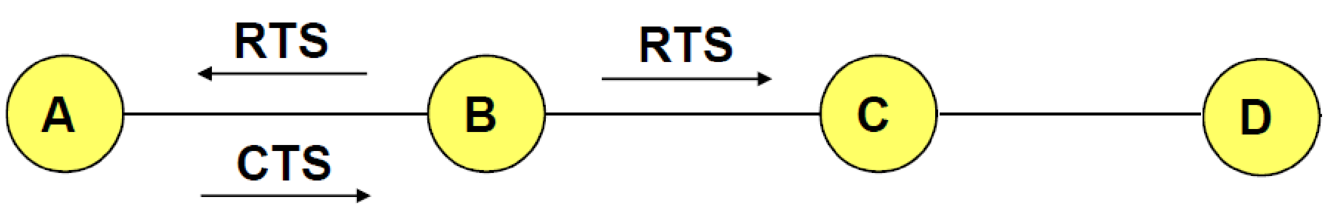


CSMA/CA with RTS/CTS (Request To Send/Clear to Send)



Exposed Terminal Problem CSMA/CA with RTS/CTS

- Although CSMA/CA with RTS/CTS can solve the Hidden Terminal problem, it creates another problem, namely **Exposed Terminal Problem.**
  - The **Exposed Terminal Problem** usually leads to **lower network throughput**.
- **Example:**
  - Station **B** broadcasts a RTS frame to Station **A**.
  - Station **C** will also receive the packet as it is within Station's **B** transmission range
  - **Problem**: Station C will enter a **delayed access state** and refrain from transmitting to Station D, although the transmission between Stations C and D will not interfere with the data reception at Station A.



Performance of Random Access Protocols

- **Simple** and **easy** to **implement**.
- It is **decentralized**. I.e., there is **no a central device that can fail** and **bring down the entire system**.
- In **low-traffic**, frame transfer has **low-delay**. However, in **heavier traffic**, **frame delay has no limit**.
- In some cases, a **station may never have a chance to transfer** its frame (**unfair protocol**).
- A station that has frames to be transmitted can **transmit continuously** at the **full rate of channel (R)** if it is the **only station with frames.**
- If the **number of stations** that want to **transmit increases**, **many collisions may occur which can** highly **reduce the throughput** of the system.

Properties of Multiple access protocols (1/2)

- **Properties that any good multiple access protocol should possess:**
  - The protocol controls the allocation of channel capacity to the users.
  - The transmission medium should be used efficiently in terms of channel throughput and the delay of transmissions.
  - Each user should receive the same allocated capacity.
  - The protocol should be flexible in allowing different types of traffic (e.g., voice and data).
  - If the system is in equilibrium, an increase in load should move the system to a new equilibrium point.
  - If one user does not operate correctly, this should affect the performance of the system as little as possible.

Properties of Multiple access protocols (2/2)

- **In the wireless mobile environment, the protocol should be able to deal with:**
  - The hidden terminal problem
    - Two terminals are out of range hidden from each other by a hill, a building, or some other physical obstacle opaque to ultra high frequency (UHF) signals but both within the range of the central or base station).
  - The near-far effect
    - Transmissions from distant users are more attenuated than transmissions from users close by
  - The effects of multipath fading and shadowing
  - The effects of co-channel interference in cellular wireless systems caused by the use of the same frequency band in different cells

Code Division Multiple Access

- **Processing Gain**
  - As illustrated in the previous example, the amplitude of the own signal **increases on average by a factor of 4**
    - The **correlation detection** has **raised the desired user signal** by the **Spreading Factor**, here 4, **from the interference (Interference Pattern) present** in the **CDMA system**.
  - This effect is termed **'Processing Gain'** and is a **fundamental aspect of all CDMA systems**, and in general of all **Spread Spectrum** systems.
    - **Spread Spectrum** systems **use a transmission bandwidth** that is **several orders of magnitude greater** than the **minimum required signal bandwidth**

Code Division Multiple Access

- **Processing Gain**
  - **Processing Gain allows the received signal power to be under the interference or thermal noise power**, and the **CDMA receiver can still detect the signal**.
  - **Detection** of a **Spread signal** is **difficult without knowledge of the Spreading Code**.
    - Spread Spectrum systems originated in military applications as it is very difficult to jam, difficult to interfere with, and difficult to identify the signal without knowing the Spreading Code.