Embedded Systems and Wireless Communication (First Part)

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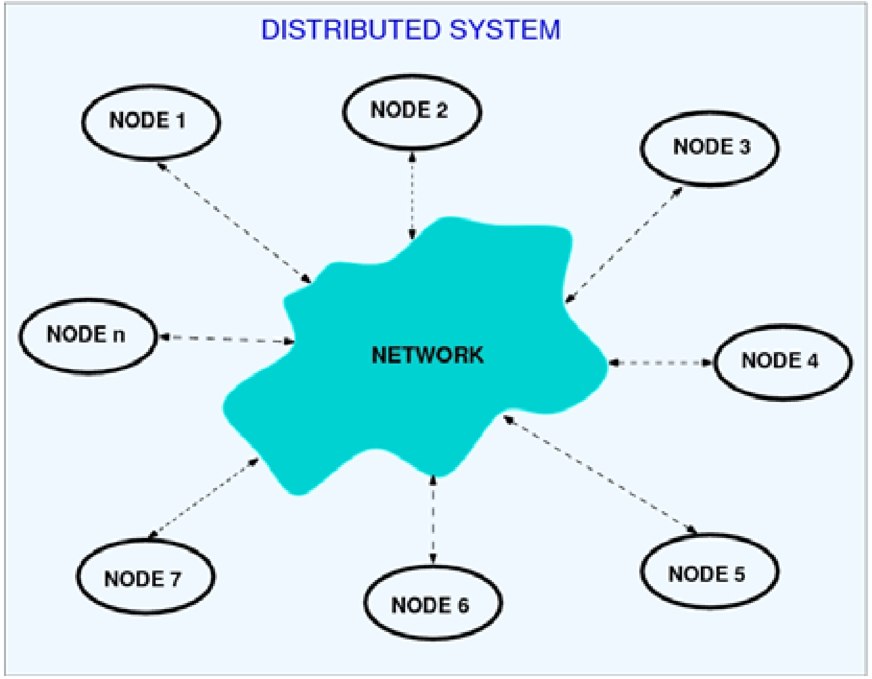
Outline

- Introduction to Distributed Embedded Systems, QoS and Real-time communication
- Wireless Networking
  - QoS Communication over a wireless channel
  - MAC protocols: CSMA/CA, TDMA (scheduling approach) and 802.15.4/ZigBee
  - Real-time MAC protocols
  - Real-Time Communication over a wireless channel, utopia or achievable goal?

Distributed System

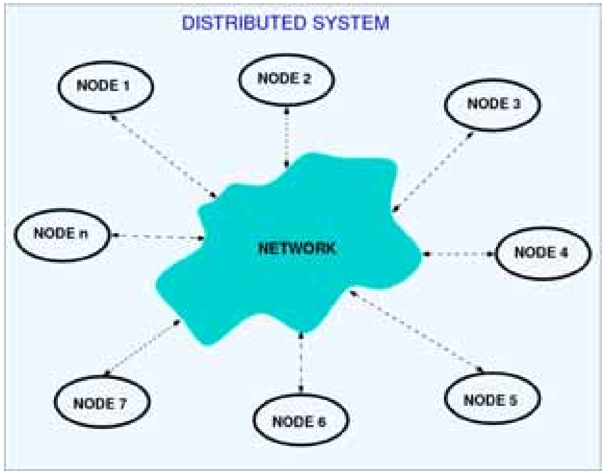


- Distributed System: is an application that executes a collection of protocols to coordinate the actions of multiple processes on a network, such that all components cooperate together to perform a single or small set of related tasks.

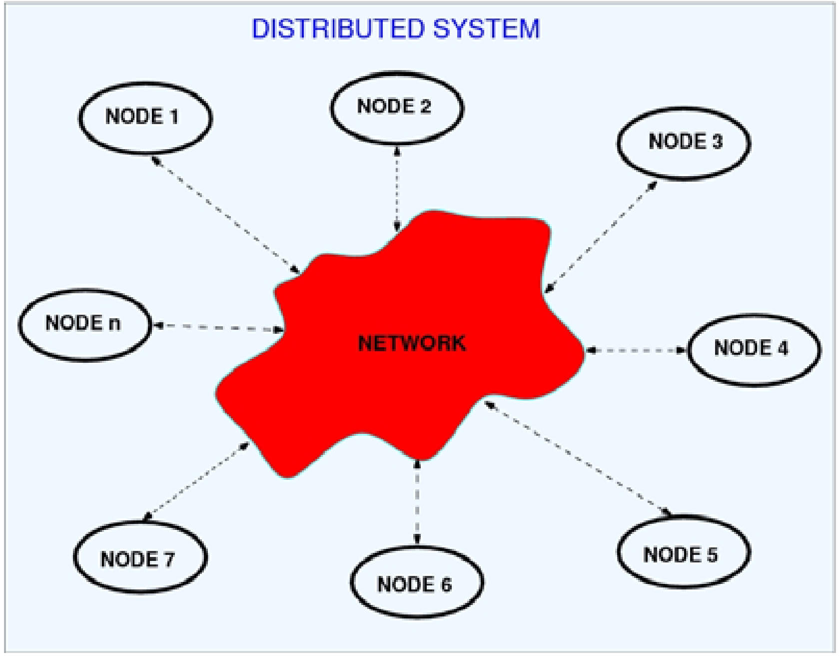
Distributed Systems

➢Why a distributed architecture is desirable?

- ➢**Composability**: the system is built by composing/integrating sub-systems
- ➢**Scalability**: a new system function can be obtained adding a new node. A system function can be replicated in the same way
- ➢**Information Processing close to data sources/sinks**: in-node data elaboration: intelligent sensors and actuators
- ➢**Dependability**:
  - ➢Robustness: a node failure does not jeopardize the system operation (no single point of failure)
  - ➢Maintainability: tanks to system modularity, a node can be replaced easily



Distributed Systems

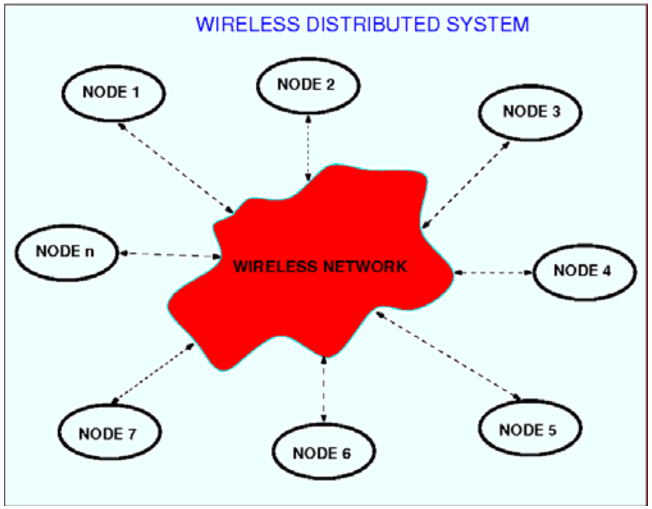


- The network is a fundamental part of a Distributed System
- In general, a node failure does not compromise system services
- In general, loss of network operation jeopardizes system services
- THE NETWORK IS THE KERNEL OF A DISTRIBUTED SYSTEM

Applications

- Wireless Sensor/Actuator Networks
  - Home automation (domotic systems)
  - Wearable WSN for health-care
  - Environment monitoring
- Multi robot team
- Control System for Cars, Airplanes, Trains etc
- Factory Automation
- Etc.

Wireless Distributed Systems

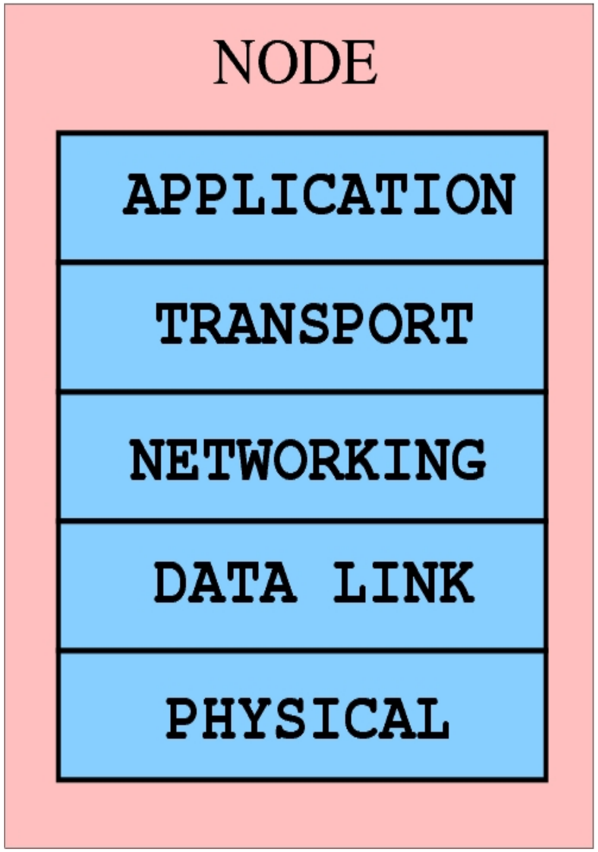


- Wireless Distributed Systems: Distributed Systems where the network is composed by wireless nodes
- With respect to a wired channel, the management of a wireless channel is **more difficult**.
- A wireless channel is characterized by:
  - High bit error rate -> e.g > 10-3
  - Asymmetric links: 

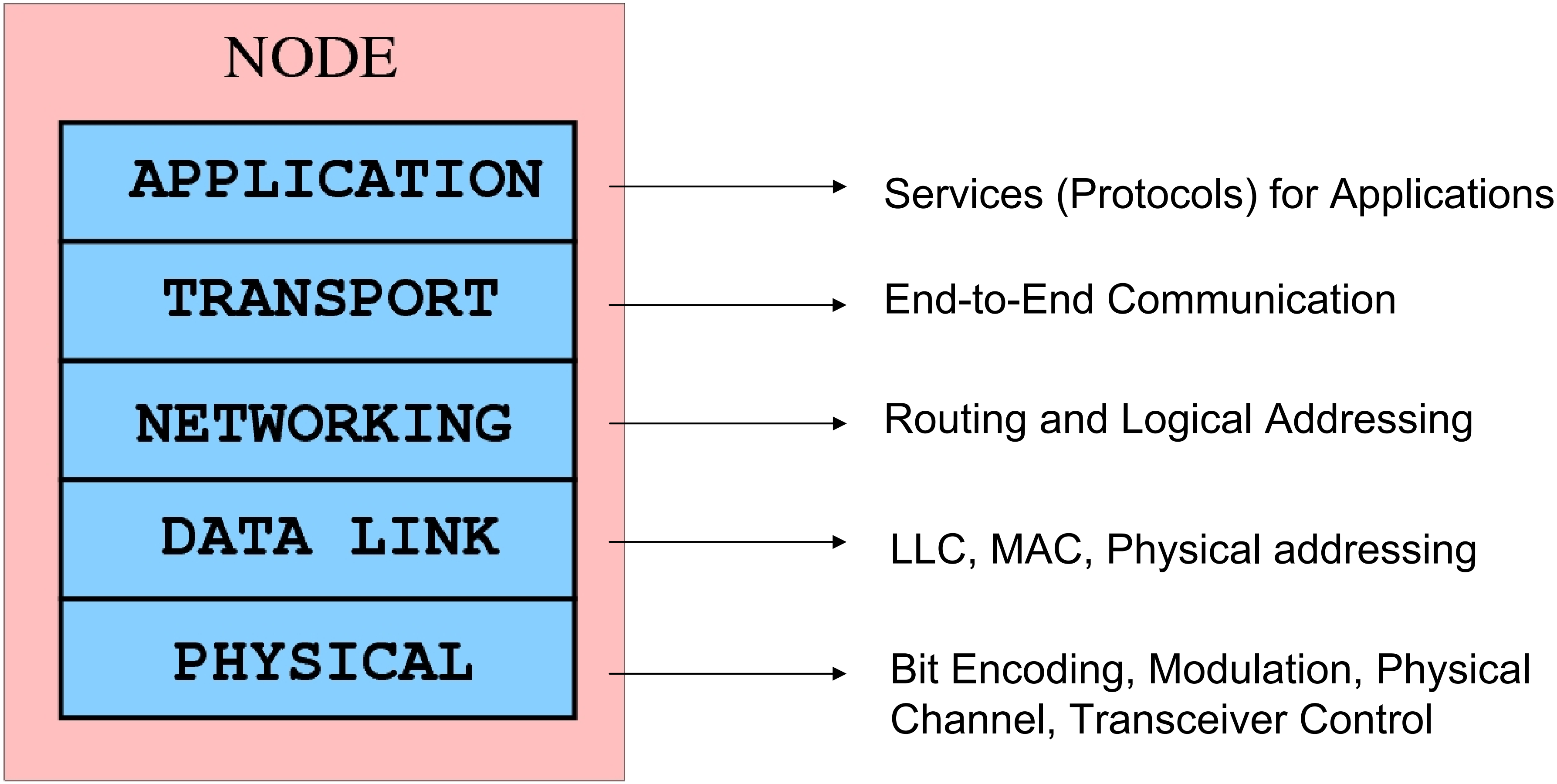
  - Variable Channel Capacity (Bandwidth) , both over the time and node by node

Communication Stack (TCP/IP Model)

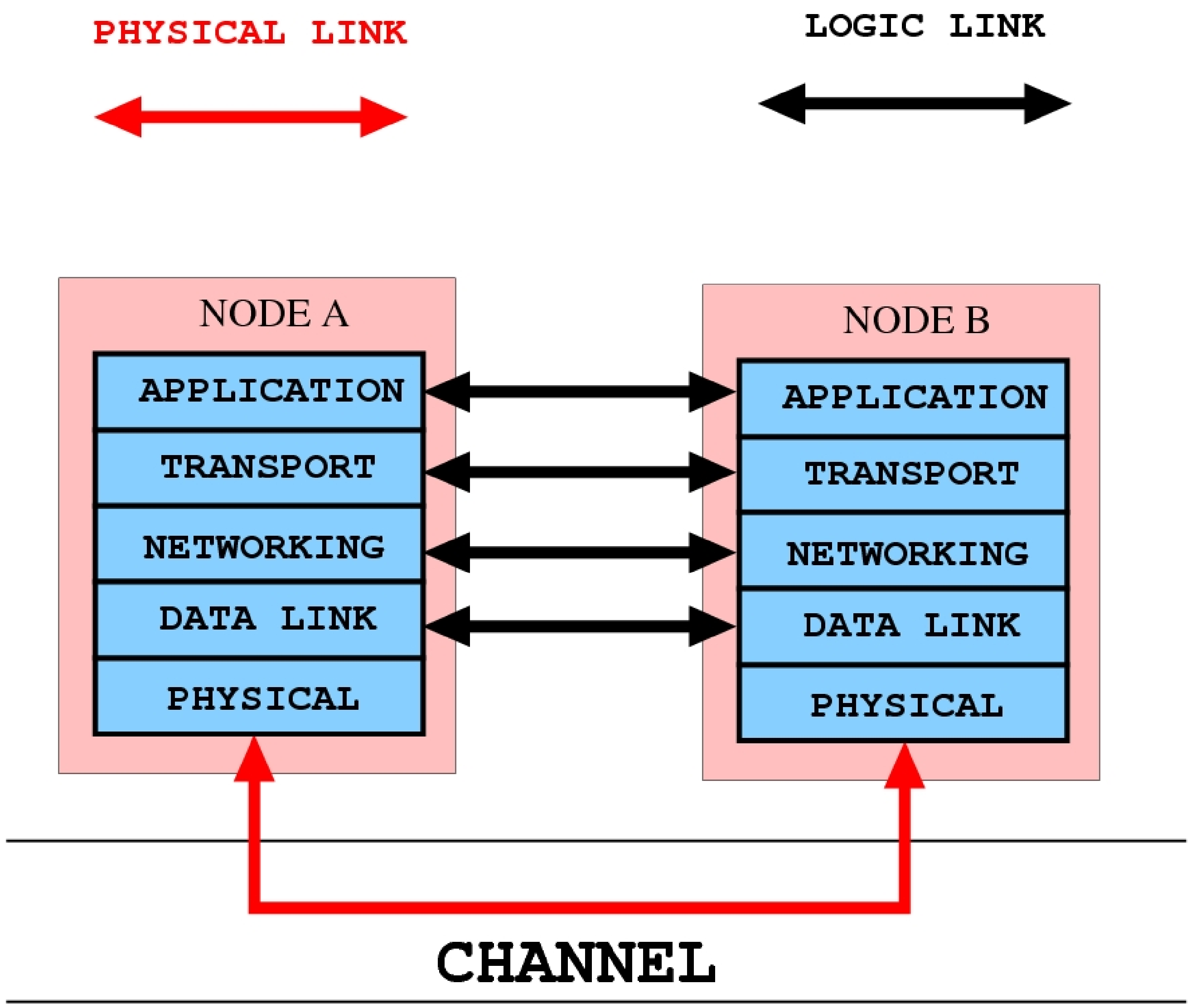
- Network systems designed by a modular methodology-> layered stack
- Each layer is delegated to specific functionalities
- Each layer implements:
  - Protocols to manage the communication with the corresponding layer in other nodes
  - Services provided to adjacent layers through service interfaces



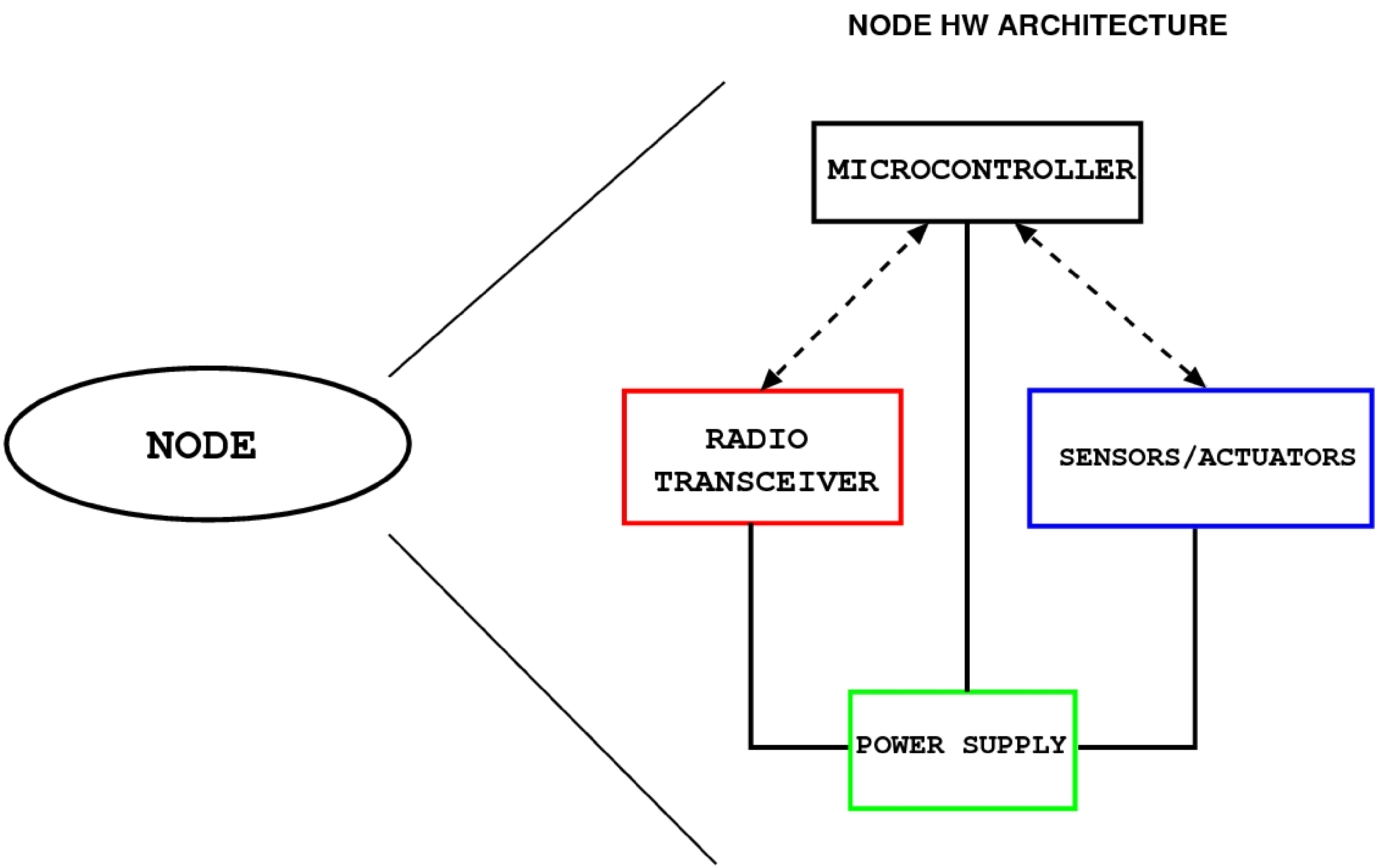
Communication Stack



Communication Stack



Node Architecture (Embedded Systems)



Real-Time Communication

- Real-time Communication:
  - Efficient communication of Short Data: Sensor Data (few bytes)
  - Periodic transmission with low Jitter: Control, Sensor and Monitoring Data: Time Triggered Transmission
  - Fast transmission of Event Data (Asynchronous Data): Event Triggered Transmission
- Mixed traffic Communication:
  - Coexistence of Best-effort traffic (non real-time traffic as log data, configuration data) and Real-Time traffic

Real-Time Communication

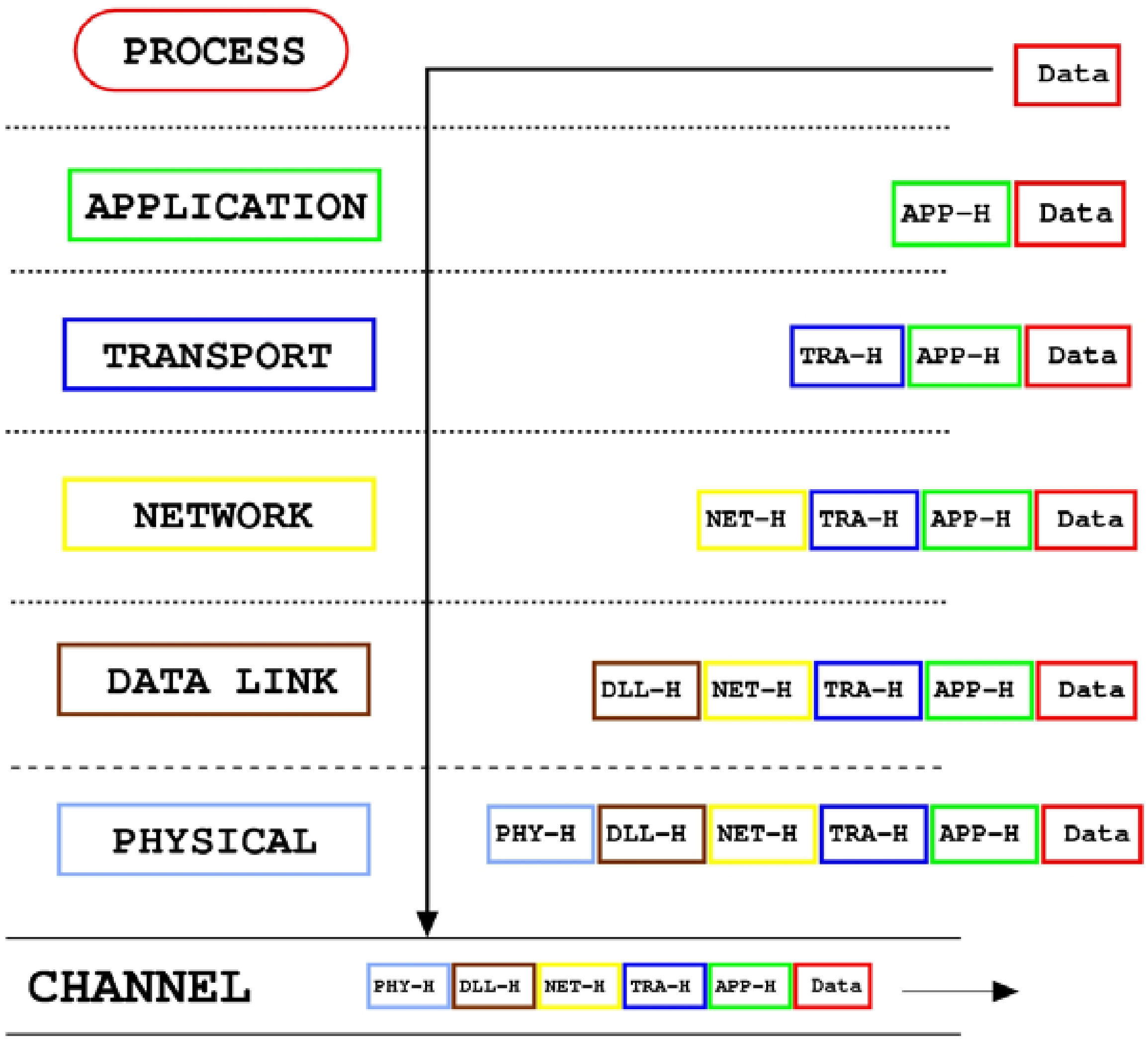
- End-to-End Communication delay must be bounded
- Each layer introduces computational and communication (header bytes) overheads
- All layer services must be time-bounded
- Thus not all stack layers are implemented:
  - Short Messages: message fragmentation/reassembly is not needed (no Transport Layer)
  - When there is only a single-hop domain, the network layer is not implemented (no routing)
  - Application Layer interfaces the Data Link Layer directly (when there is no need of the Network layer)

Communication Efficiency

- *CEff*: Communication Efficiency
- *Data_length* (payload) is the length (time unit) of data generated by the application running in the node
- *Comm_length* is the time length of the message transaction (end-to-end delay). It comprises layer services overhead plus transmission overhead due to the control characters (packet headers)

$$CEff = \frac{Data\_length}{Comm\_length}$$

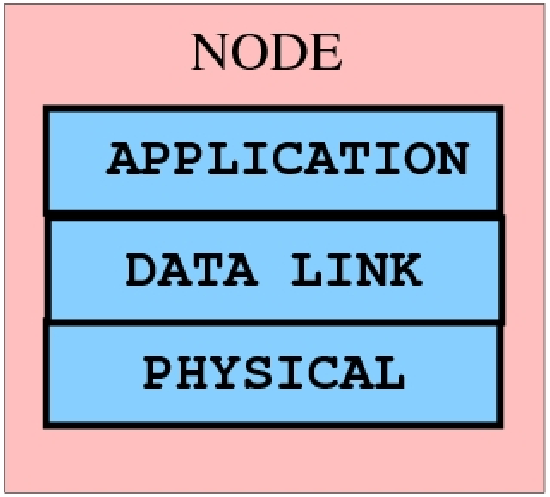
Communication Overhead



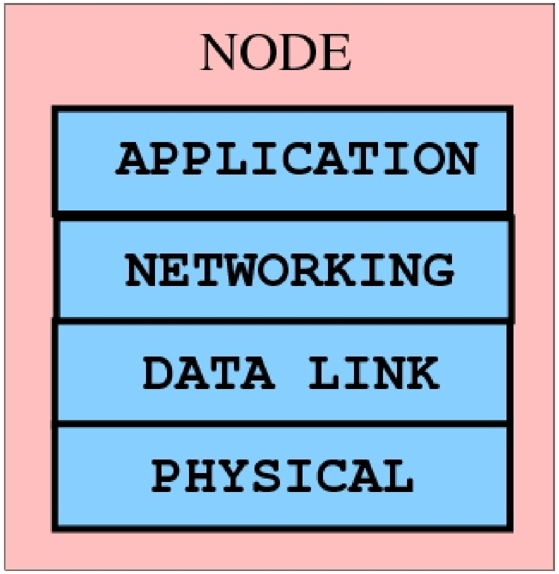
Collapsed Model

- Ex. Single-Hop Domain: Factory Automation-> Field Bus
- Ex Multi-Hop Domain: Wireless Sensor Networks

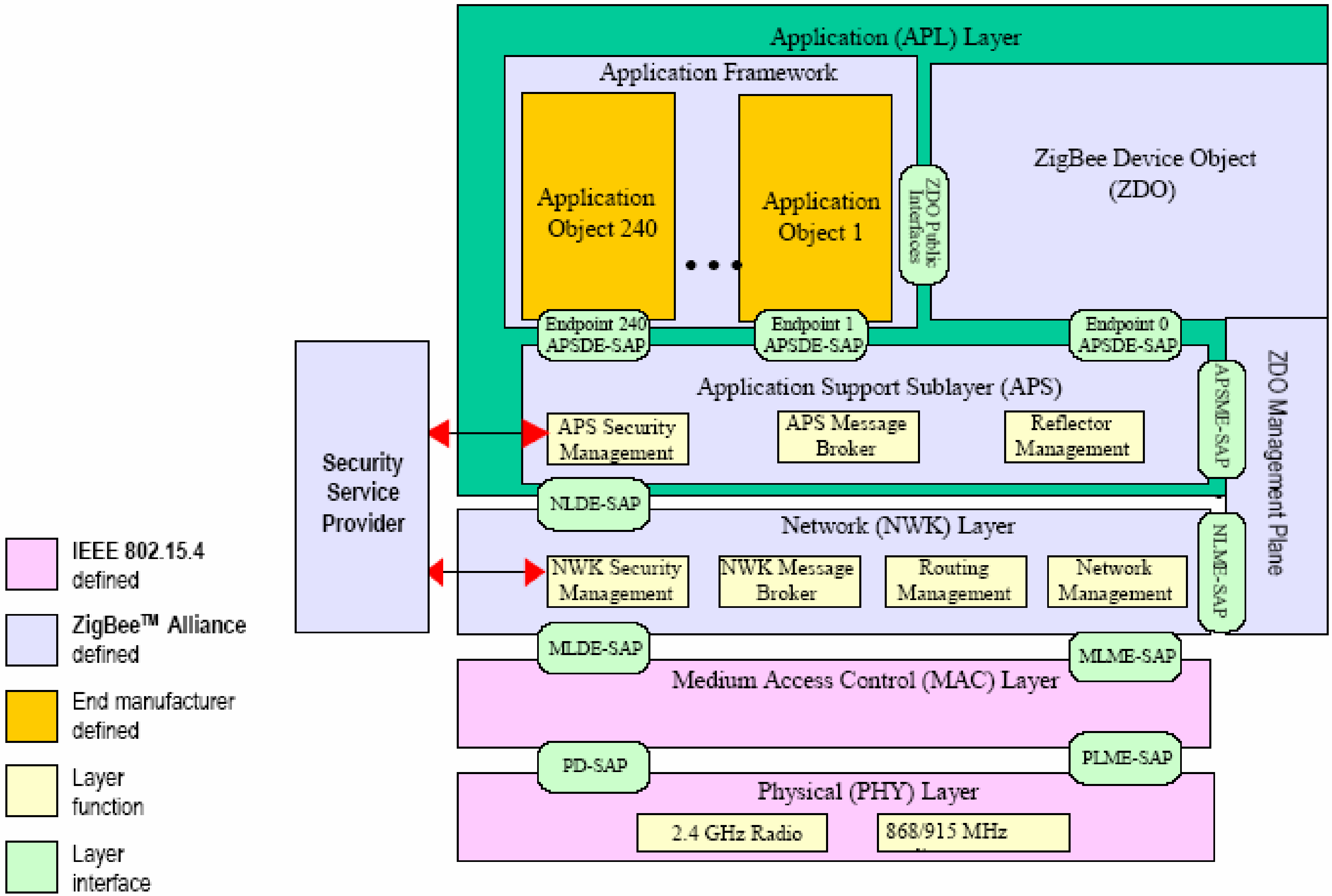
SINGLE–HOP DOMAIN



MULTI–HOP DOMAIN



ZigBee Stack



QoS definition

- QoS requirements are application dependent
- Main QoS metrics:
  - Throughput: (AvailBand - OverheadBand)/ AvailBand;
  - Maximum Delay: time-bounded transmission
  - Jitter: variability on message transmission/receiving time
  - Reliability: Integrity of messages. Guarantee that all messages will be delivered correctly.
- Other Performance Metrics:
  - Energy Dissipation: Energy wasted should be limited, either to achieve a predefined system lifetime or to maximize the system lifetime
  - Fairness: assignment of network resources in a balanced fashion among the nodes
  - Stability: the network is a dynamic system. The protocols performance should be stable under any working condition.
  - Robustness: normal network (protocols) operation should be guaranteed even under some control packet losses or node failure (e.g. coordinator node failure)

Examples on QoS requirements

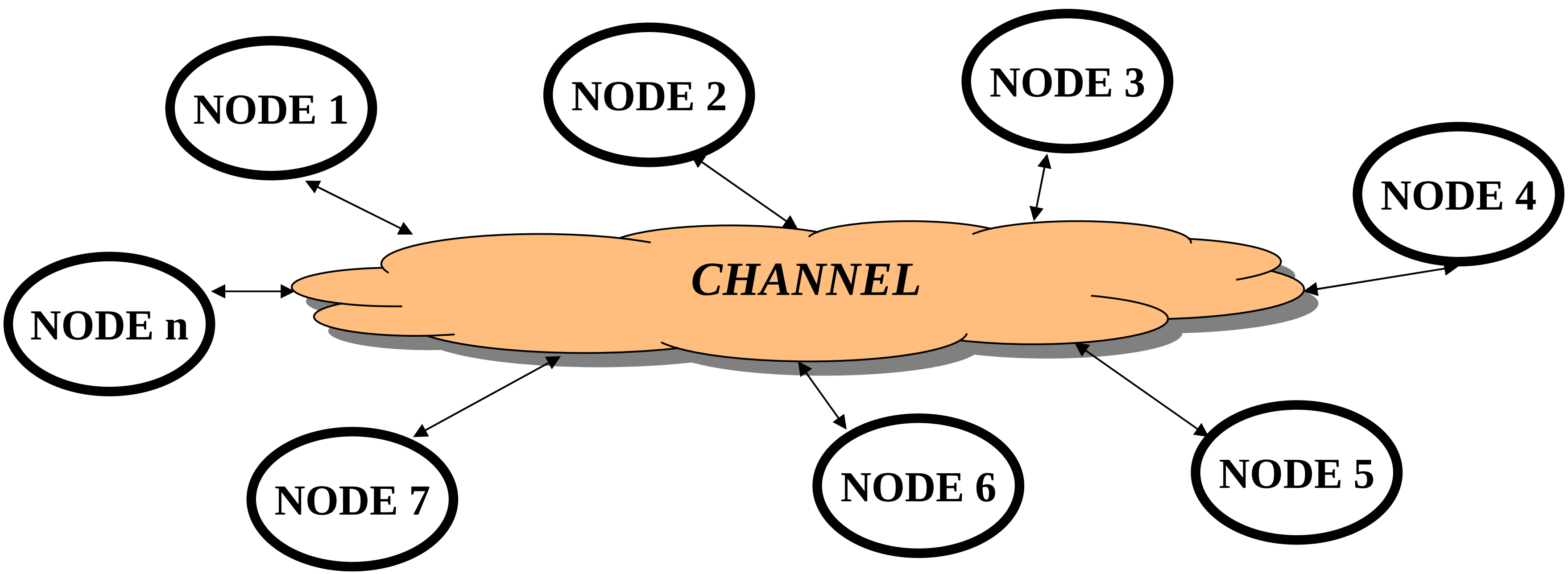
- **Multimedia streaming**:
  - High packet delivery ratio
  - Low Delay
  - Low Jitter
- **Control Applications**:
  - Low Jitter
  - Periodic Message Delivery
- **Distributed Information Systems (data base)**:
  - Integrity of messages exchanged -> the system should guarantee the integrity of data retrieved (data without errors)

Data Link Layer

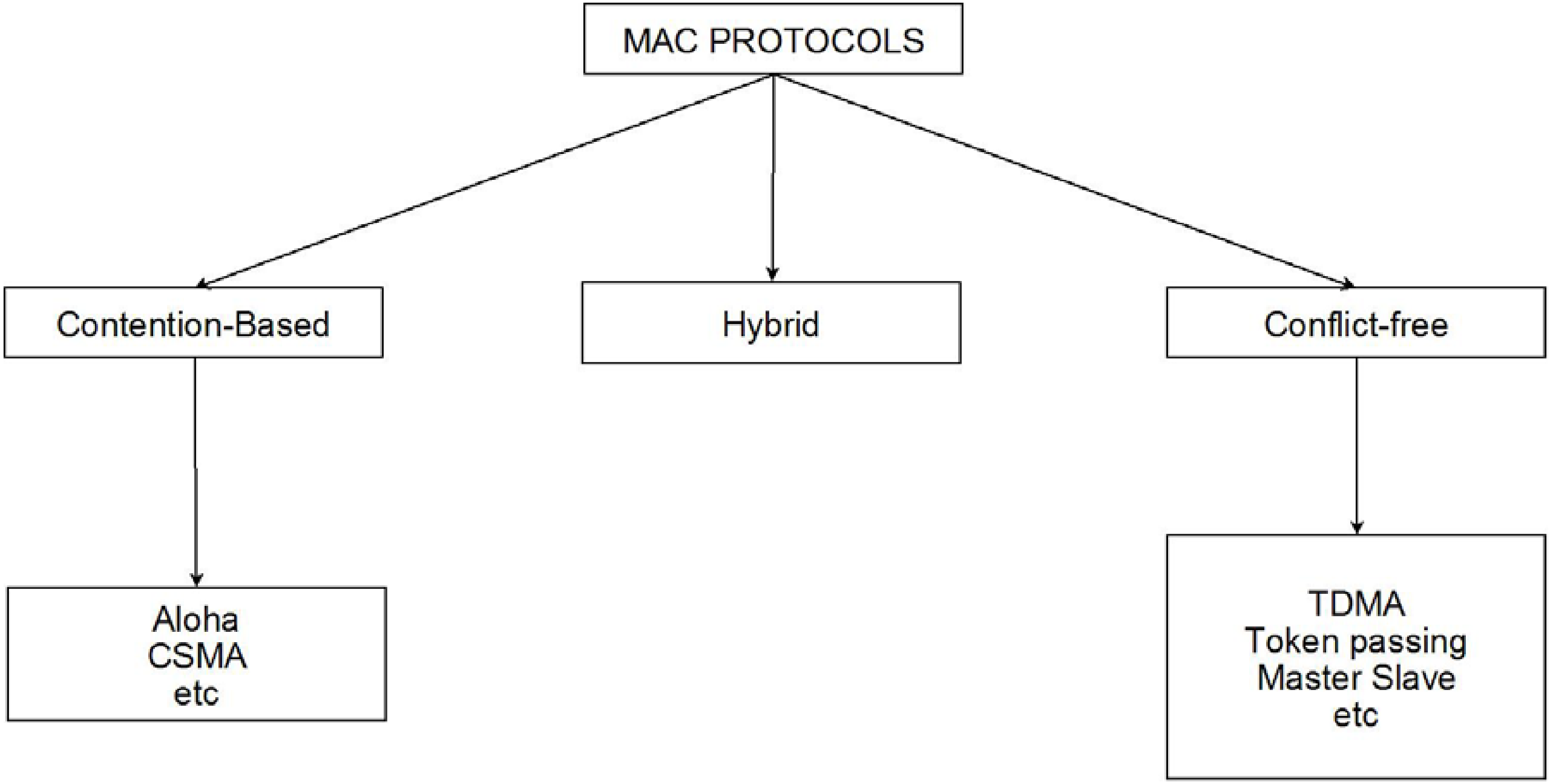
- Data Link Layer (It is of paramount importance for Real-time Communication)
  - Logic Link Control (LLC)
  - Medium Access Mechanism (MAC)
- LLC:
  - Formation and maintenance of links between one-hop neighbors nodes
    - Link discovery, setup, maintenance, link quality estimation
  - Reliable and Efficient information (packets) transmission over the established links
    - Addressing and Flow Control
    - Admission Control
    - Error Control
      - Acknowledgement (ACK)
      - Automatic Repeat reQuest (ARQ)
      - Forward Error Correcting (FEC) (**Preferred for Real-Time Comm.)**
- MAC:
  - Management of medium (channel/link) access

MAC protocols

- The task of a MAC protocol is to manage the channel access by nodes
- From the point of view of a MAC sub-layer, the network is composed by n nodes sharing a common channel (medium)
- It determines the order of the channel access by contending nodes. Hence it determines the network access delay
- The MAC protocol is fundamental for the real-time performance of a network that uses a common medium



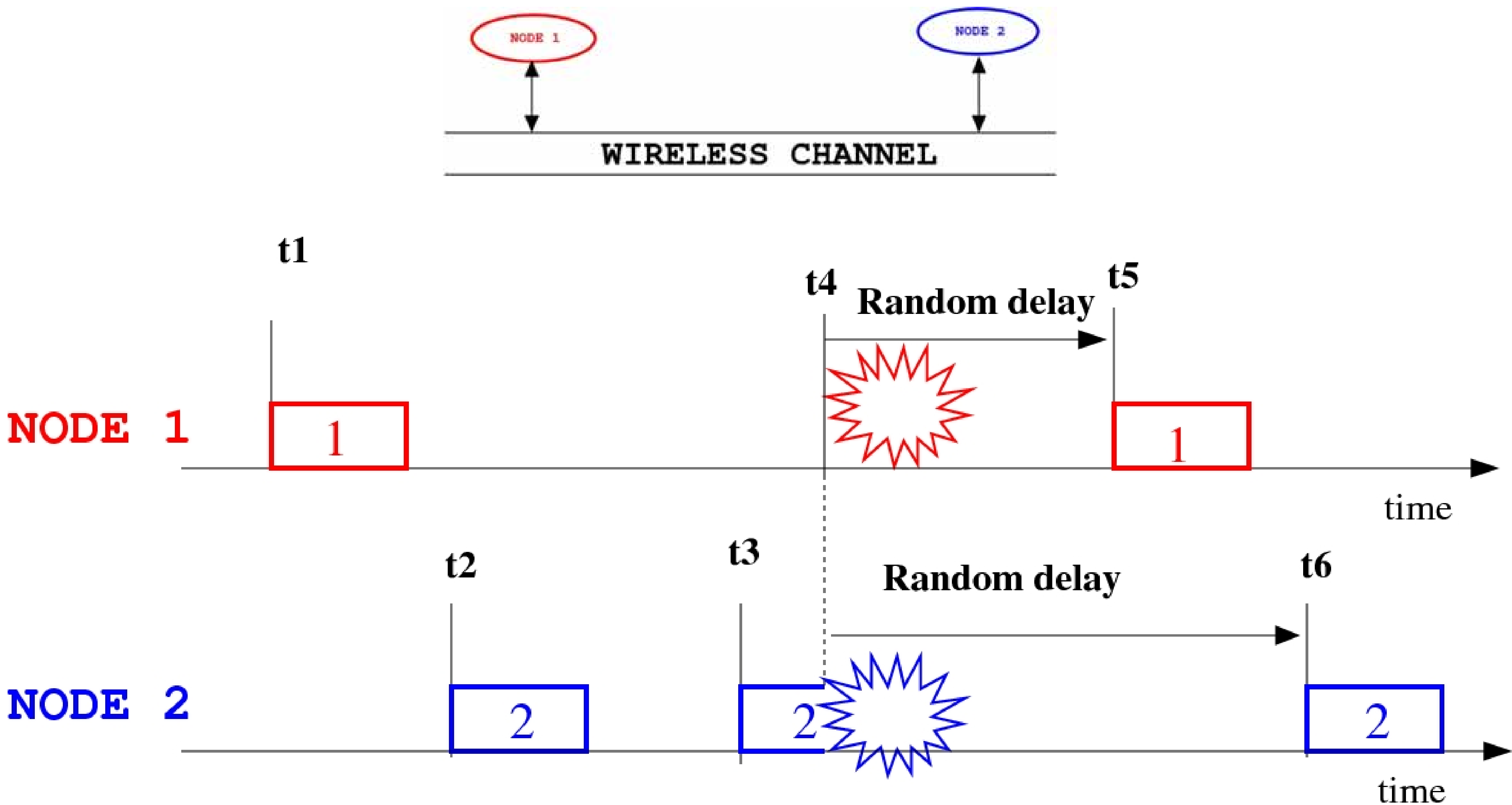
Wireless MAC protocols



Aloha

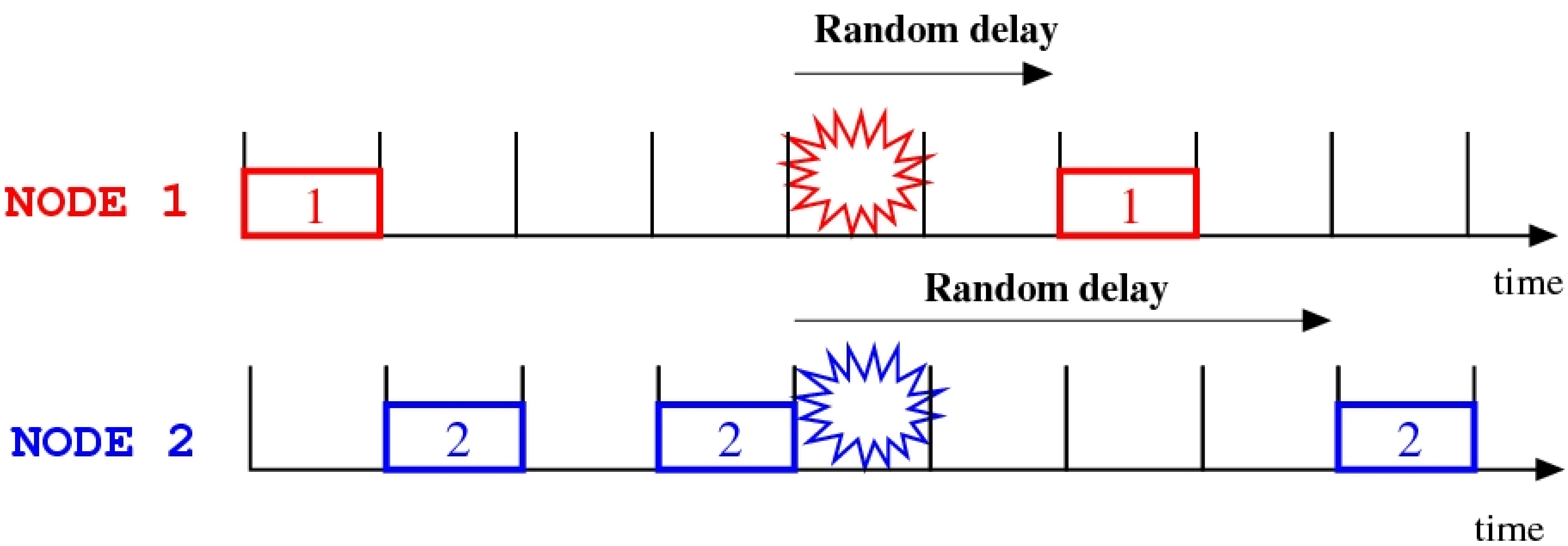
- Designed by Norman Abramson at University of Hawaii in 1970s.
- The base algorithm is simple:
  - Whenever you have a packet to transmit, send the packet
  - If the packet collides with an other transmission, wait for a random interval and then try to send the packet
- It is assumed that a node can be aware of a collision either by listening to the channel while transmitting, or by some feedback mechanism (e.g. ACK)

Aloha


NODE 1
NODE 2
WIRELESS CHANNEL
t1
t4
Random delay
t5
NODE 1
1
1
time
t2
t3
Random delay
t6
NODE 2
2
2
2
time

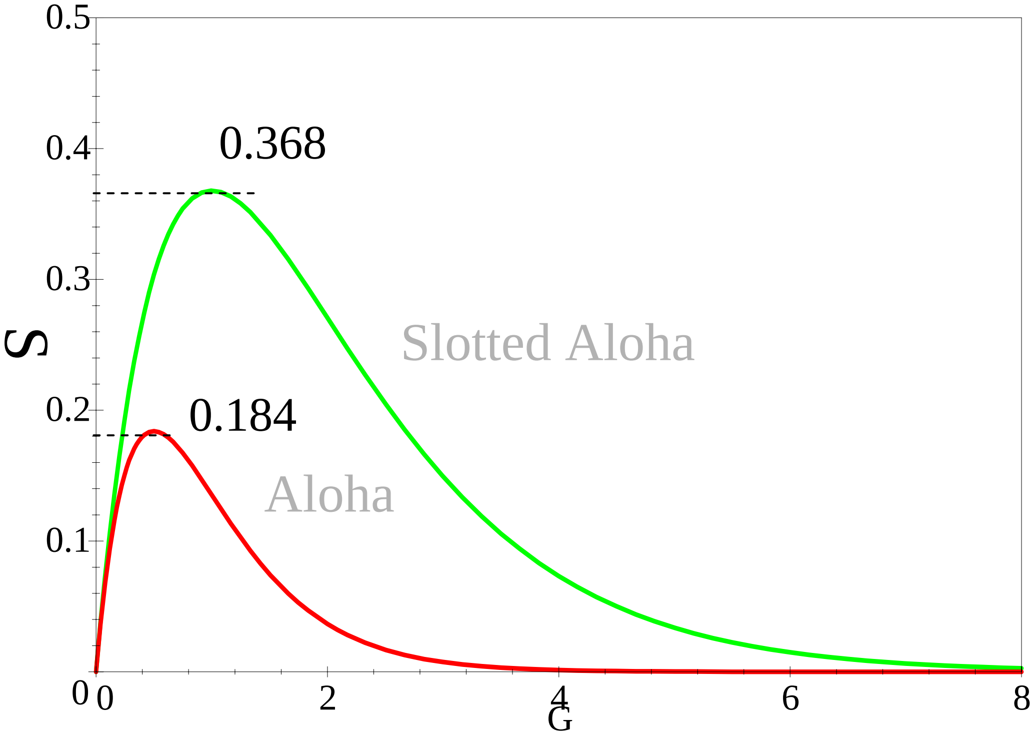
Slotted-Aloha

- Slotted-Aloha improves the basic version.
  - The time is divided in time-slots
  - A node can try to send a packet only at the beginning of every slot. A node cannot try to send a packet in the middle of a slot
  - The number of collisions is reduced
  - The nodes must be synchronized



Aloha

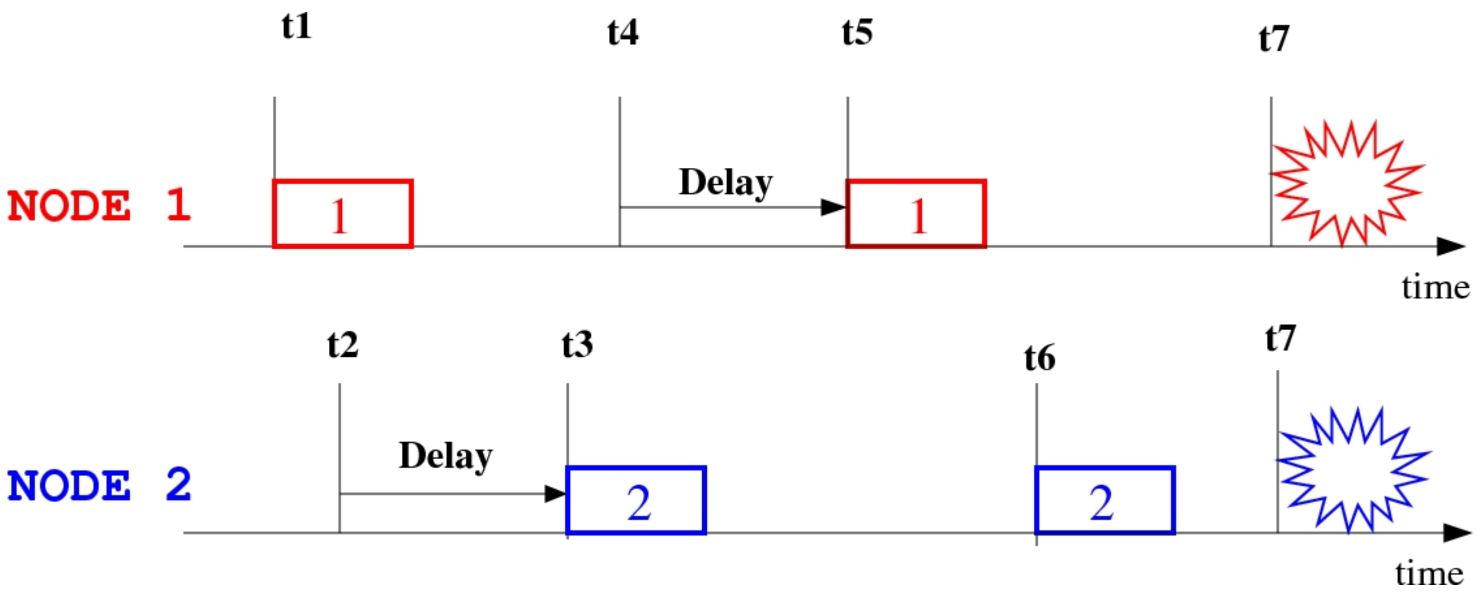
- Maximum Throughput of pure Aloha: $S_{\max} = 0.5e^{-1} = 0.184$
- Maximum Throughput of Slotted-Aloha: $S_{\max} = e^{-1} = 0.368$



- G = Offered Load.
- G is the average number of transmission attempts per packet (slot) time
- With Aloha S_{max} is for G=0.5
- With Slotted-Aloha S_{max} is achieved for G=1

CSMA

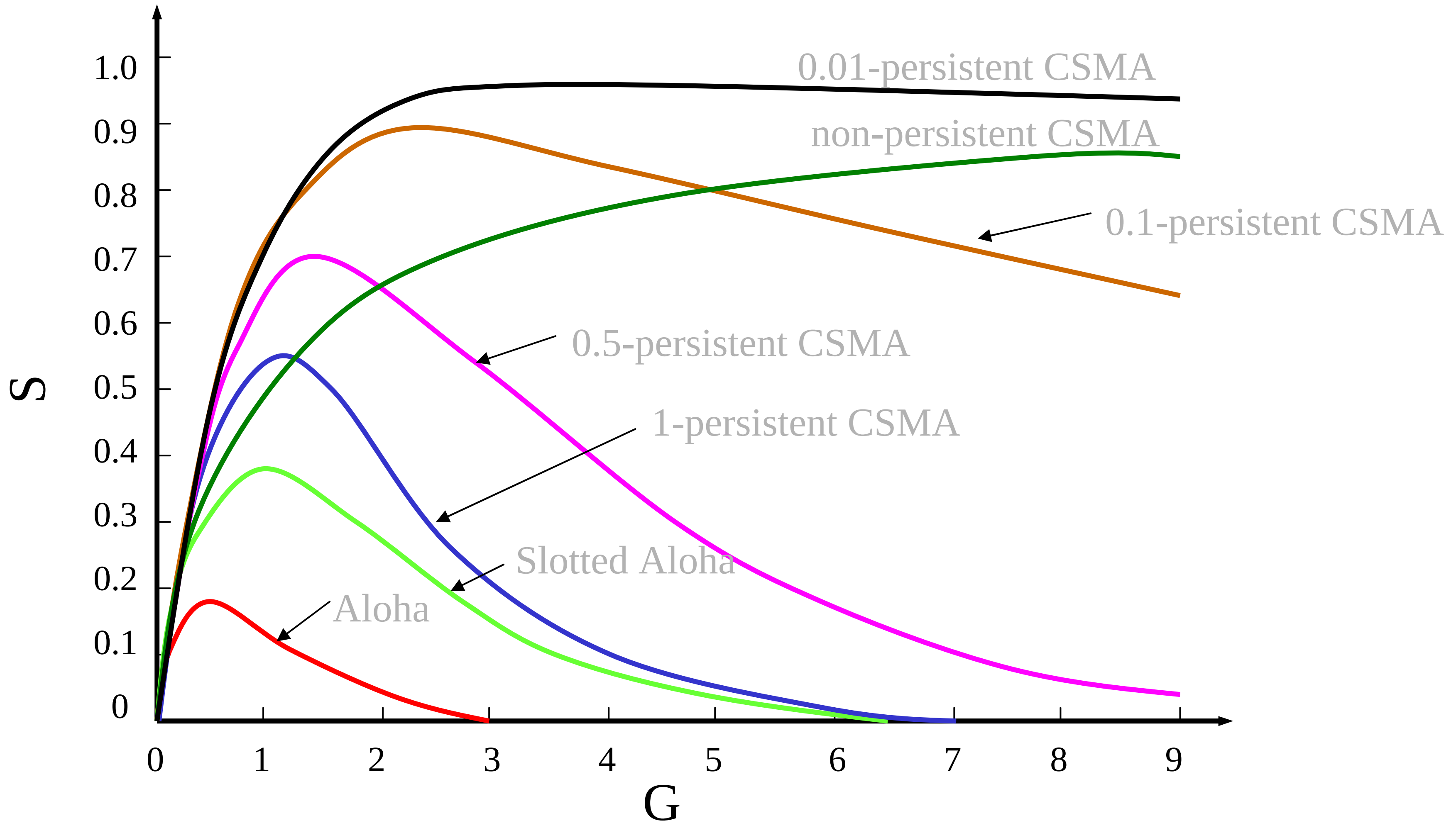
- Carrier Sense Multiple Access (CSMA):
  - Sense the channel every time you have a packet to send. If the channel is free (idle) then send your packet
  - If the channel is busy, then retry



CSMA non persistent
CSMA x-persistent

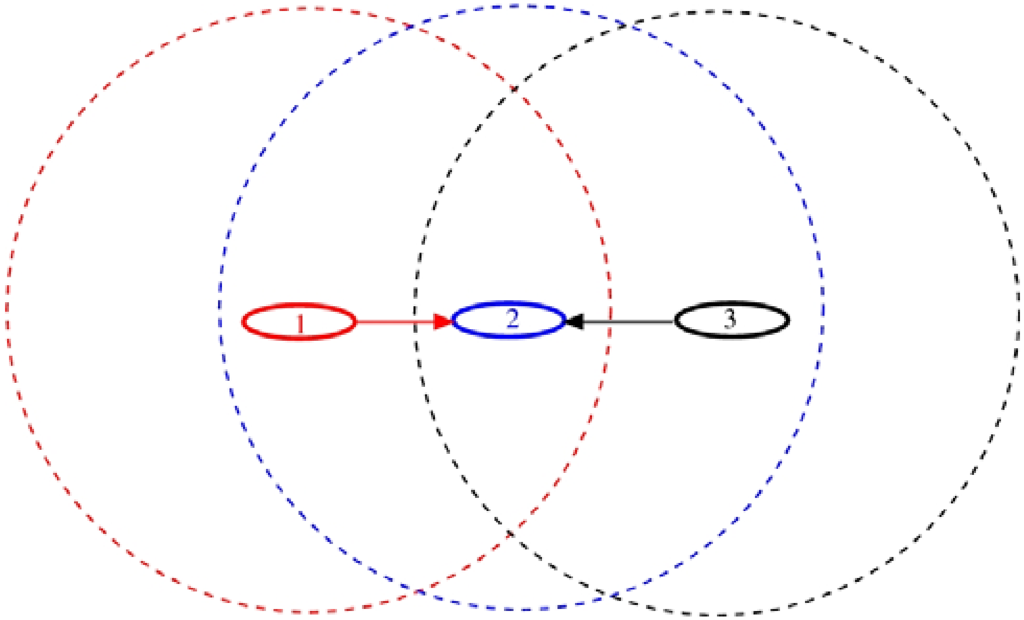
- CSMA 1-persistent
  - **Step 1**: if the channel is free, transmit the packet
  - **Step 2**: if the channel is busy, continue to listen the channel until it is free then transmit the packet
    - If two nodes are listening the channel when a third node is transmitting, when this last finished the two nodes start transmitting causing a collision
- CSMA non persistent:
  - **Step 1**: if the channel is free, transmit the packet.
  - **Step 2**: if the channel is busy, wait for a random time and repeat Step1
    - Random backoff reduces collisions probability
    - Too long backoff reduces the throughput
- CSMA p-persistent
  - This algorithm is usually used when the time is divided in slots
  - **Step 1**: if the channel is free, transmit with probability p and defer to next time slot with probability 1-p.
  - **Step 2**: if the channel is busy, continue to sense the channel. When the channel is free repeat Step 1
  - **Step 3**: if transmission is deferred by a time slots repeat Step 1
    - A tradeoff between non-persistent and 1-persistent

Throughput (S) vs Offered Load (G)



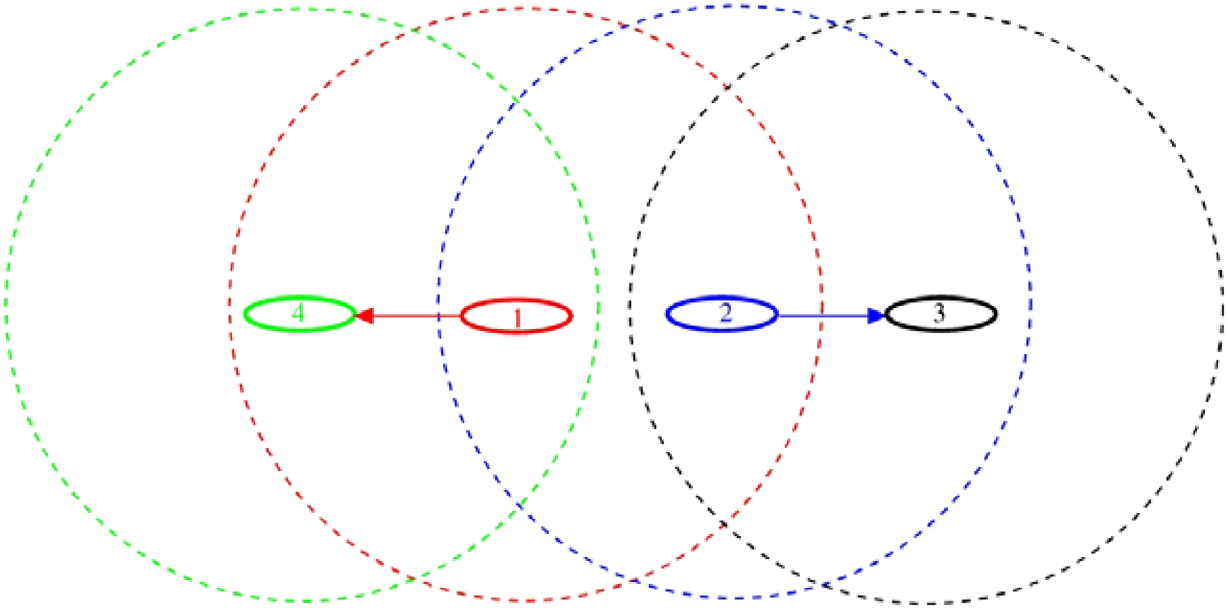
Hidden Node problems

- CSMA protocols suffers the **Hidden Node** problem
  - Node 1 wants to transmit to Node 2 , it finds the channel free and starts transmitting
  - Node 3 wants to transmit to Node 2, since Node 3 is out of range with respect to Node 1, it finds the channel free and start transmitting to Node 2
  - There is a **collision** between the transmissions of Node 1 and Node 3



Exposed Node problem

- CSMA protocols suffers the **Exposed Node** problem
  - Node 1 wants to transmit to Node 4, it finds the channel free and starts transmitting
  - Node 2 wants to transmit to Node 3, if finds the channel busy, then it blocks waiting for the channel to be free
  - Transmission from Node 1 cannot reach Node 3, transmission from Node 2 cannot reach Node 4, therefore Node 1 and 2 could **transmit simultaneously**!



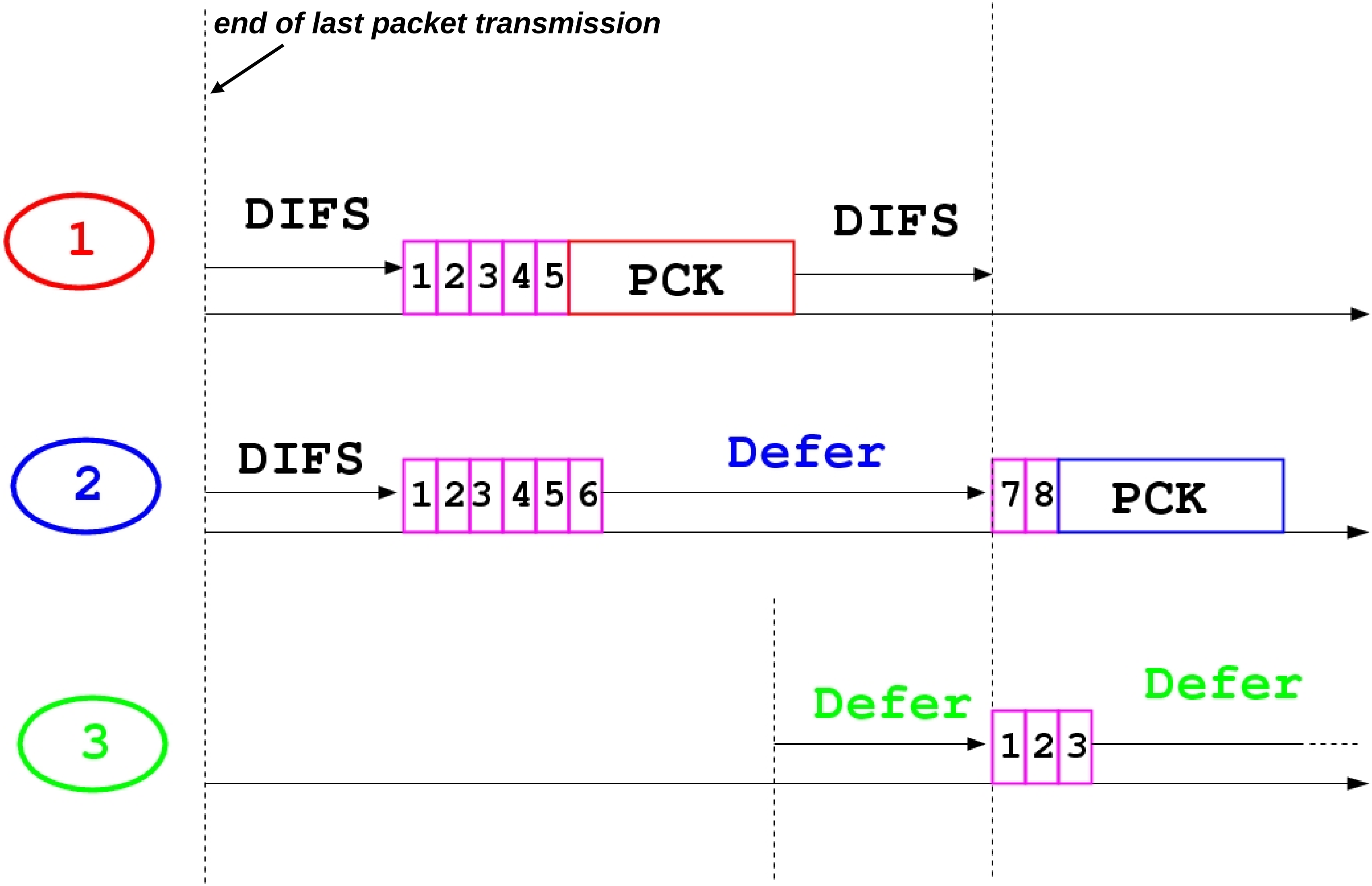
CSMA/CA

- To reduce the wasted time due to collisions, if two or more nodes transmit at the same time, hence there is a collision, it would be better that the nodes stop transmitting
- This is possible with wired networks, because a node can transmit and listen the channel at the same time (e.g CSMA/CD-Ethernet)
- With a wireless channel, to transmit and to listen at the same time is difficult or even impossible
- Solutions: CSMA/CA (Collision Avoidance)
  - The worst situation happens when the medium is busy and two or more nodes are sensing the medium waiting to transmit
  - CSMA/CA try to reduce the collision probability by a random backoff procedure :
    - if the channel is free then backoff for a random time, after that if the channel is still free transmit

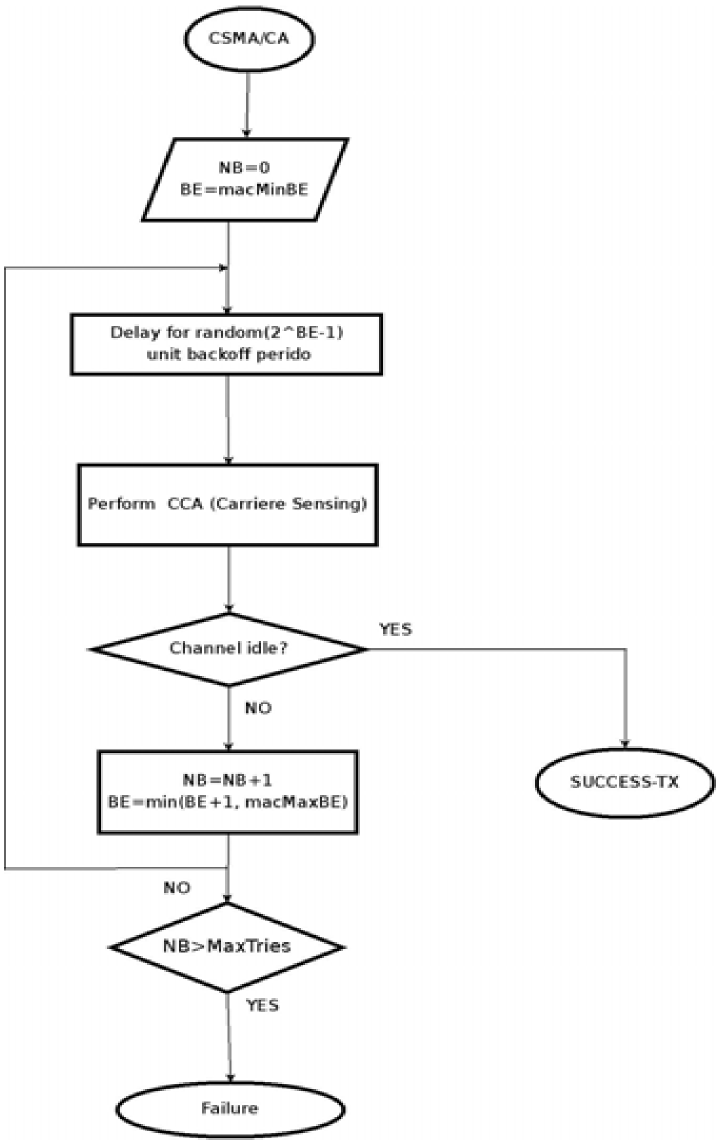
IEEE 802.11 CSMA/CA

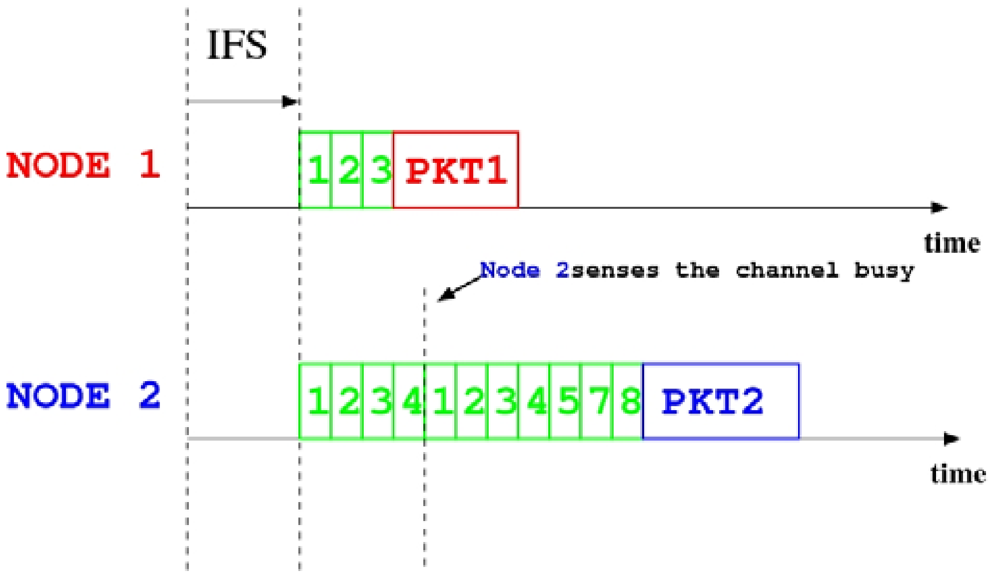
- Nodes ready to transmit sense the medium.
- If the channel is busy, wait until the end of current transmission
- Then wait for an additional predetermined time period DIFS (Distributed Inter Frame Space).
- Then pick up a random number of slots (the initial value of backoff counter) within a Contention Window to wait before transmitting its frame
  - Contention Window is defined by [0,CW], where $CW_{min} \le CW \le CW_{max}$
- If there are transmissions by other nodes during this time period (backoff time), the node stops its counter.
- It resumes count down after nodes finish transmission plus DIFS. The node can start its transmission when the counter reaches to zero
- If the channel access fails (e.g. there is a collision), then increment the CW value. ($CW = 2*CW$)
- The initial backoff makes CSMA/CA similar to p-persistent CSMA

IEEE 802.11
CSMA/CA



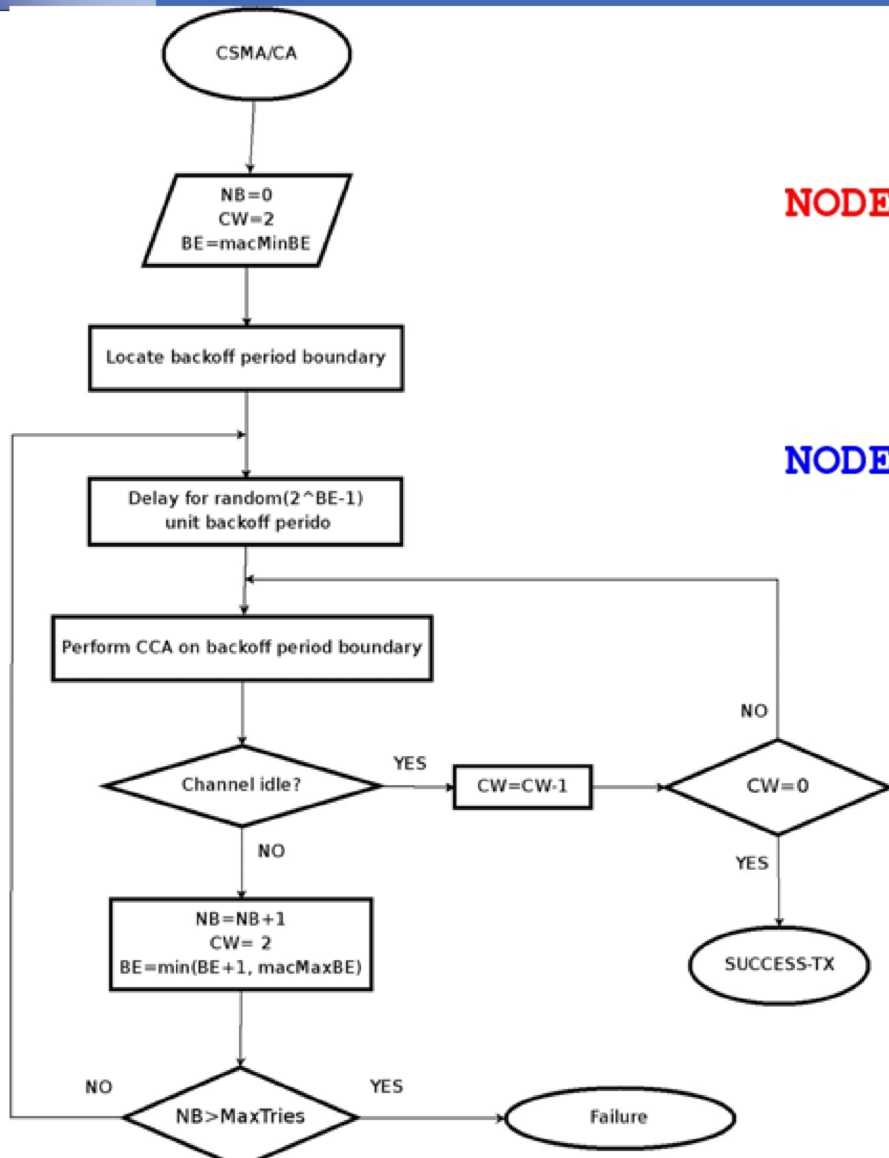
IEEE 802.15.4/ZigBee unslotted CSMA/CA

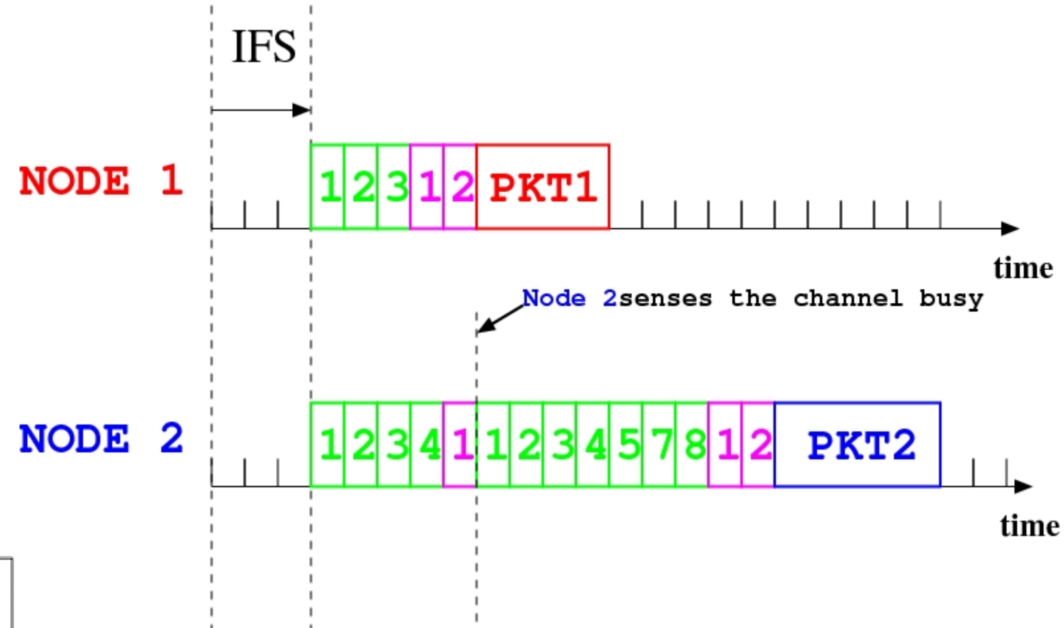




- NB: number of tries performed
- BE: backoff exponent
  - Backoff interval: (0, 2^BE -1)
- The initial backoff makes CSMA/CA similar to p-persistent CSMA

IEEE 802.15.4/ZigBee slotted CSMA/CA



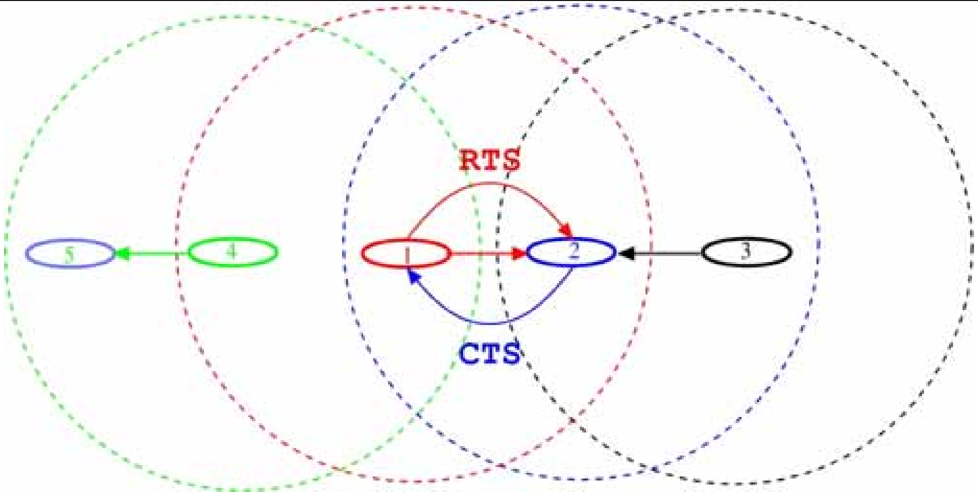


- NB: number of tries performed
- BE: backoff exponent
  - Backoff interval: $(0, 2^{BE} -1)$
- CW (Contention Window). CW=2
- The initial backoff makes CSMA/CA similar to p-persistent CSMA

Mitigating Hidden/Exposed Node Problem

- The Hidden/Exposed Node Problem can be mitigated by an handshaking mechanism
- A node that want to transmit sends a Request To Send (RTS) packet to receiver node
- The receiver replies with a Clear To Send packet (CTS)
- A node that ears a CTS packet keeps silent for duration of incoming transmission
- A node that ears a RTS packet but not a CTS, assumes to be an Exposed node, then it can transmit also whether it finds the channel busy for the duration of the incoming transmission
- Both RTS and CTS report the length of the packet being to be transmitted
- This mechanism is used, for instance, by IEEE 802.11, MACA, MACAW protocols

Mitigating Hidden/Exposed Node Problem



- Both Node 1 and Node 3 want to send a packet to Node 2
- Node 1 senses the channel free and send a RTS packet
- Node 2 receives the RTS and responds with a CTS packet
- Node 3 receives the CTS then keep silent
- Node 4 receives a RTS but not the CTS, then it assumes to be an **exposed node**
- Node 1 transmit its packet
- Node 4 being an **exposed node** might transmit a packet even if it senses the channel busy

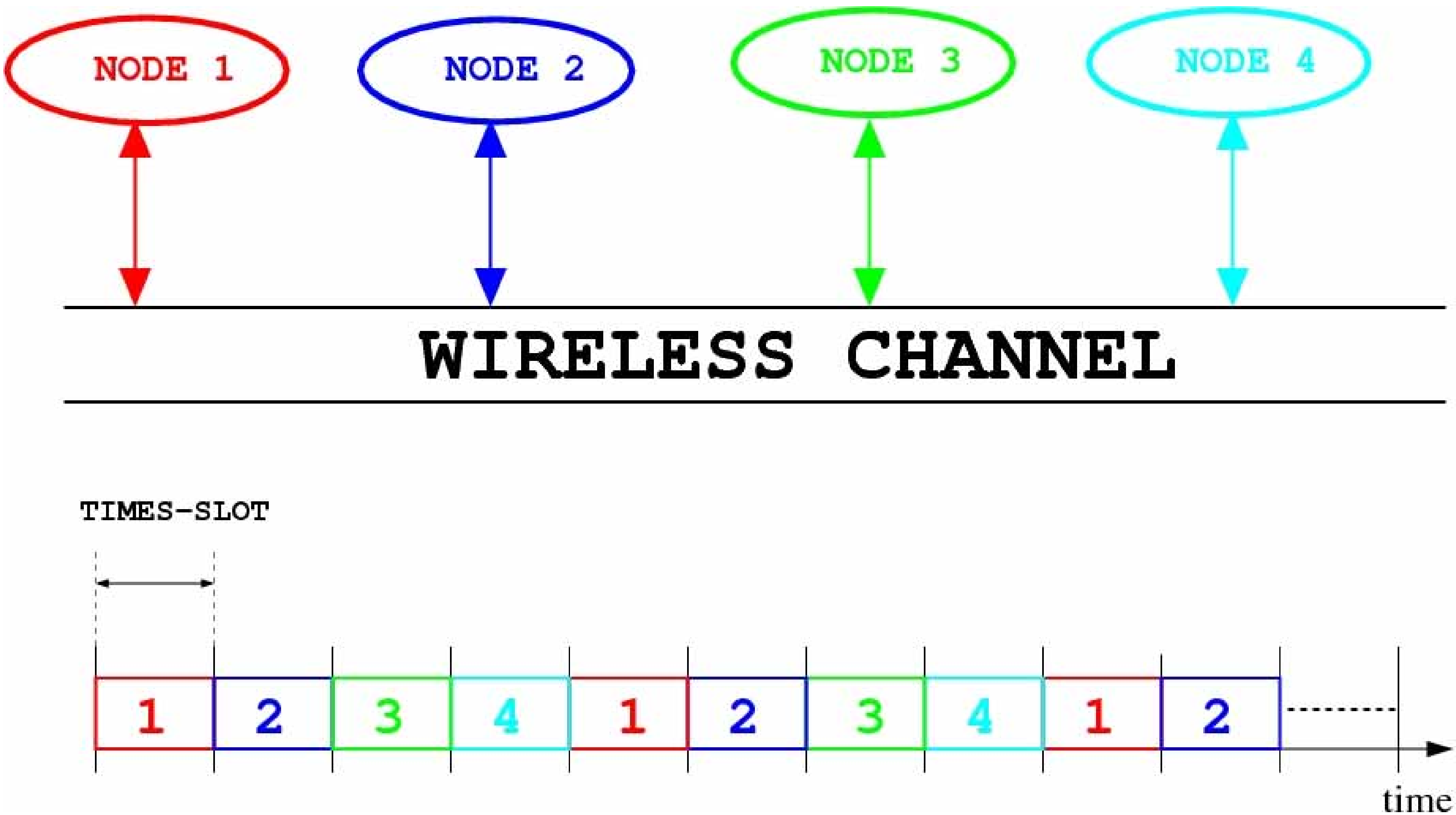
Scheduling approaches

- The time is divided in time slots
- Each time slot is reserved/dedicated to a node
- Each node has an exclusive access to its time slots: no collisions
- Different scheduling policy can be used to assign the time-slots:
  - Round Robin (RR)
  - Weighted Round Robin (WRR)
  - Rate Monotonic (RM)
  - Earliest Deadline First (EDF)
  - Etc
- Any algorithm from resource scheduling theory might be applied
- Time slot dimension is an important parameter
  - All packets have the same dimension: time-slot=time packet
  - Packets have different dimension: an important portion of bandwidth can be lost: a bandwidth reclaiming mechanism is desirable
- Nodes must be synchronized: synchronization mechanisms are needed

Fully distributed Scheduling Approaches

- In case of fully distributed approaches:
  - Each node must know/build the schedule
  - In order to build a common schedule either each node must know the traffic parameters of other nodes, or at least some common information should be shared by the nodes
- Example of such approaches: RR, Implicit EDF
- We will see some detail of Implicit EDF later

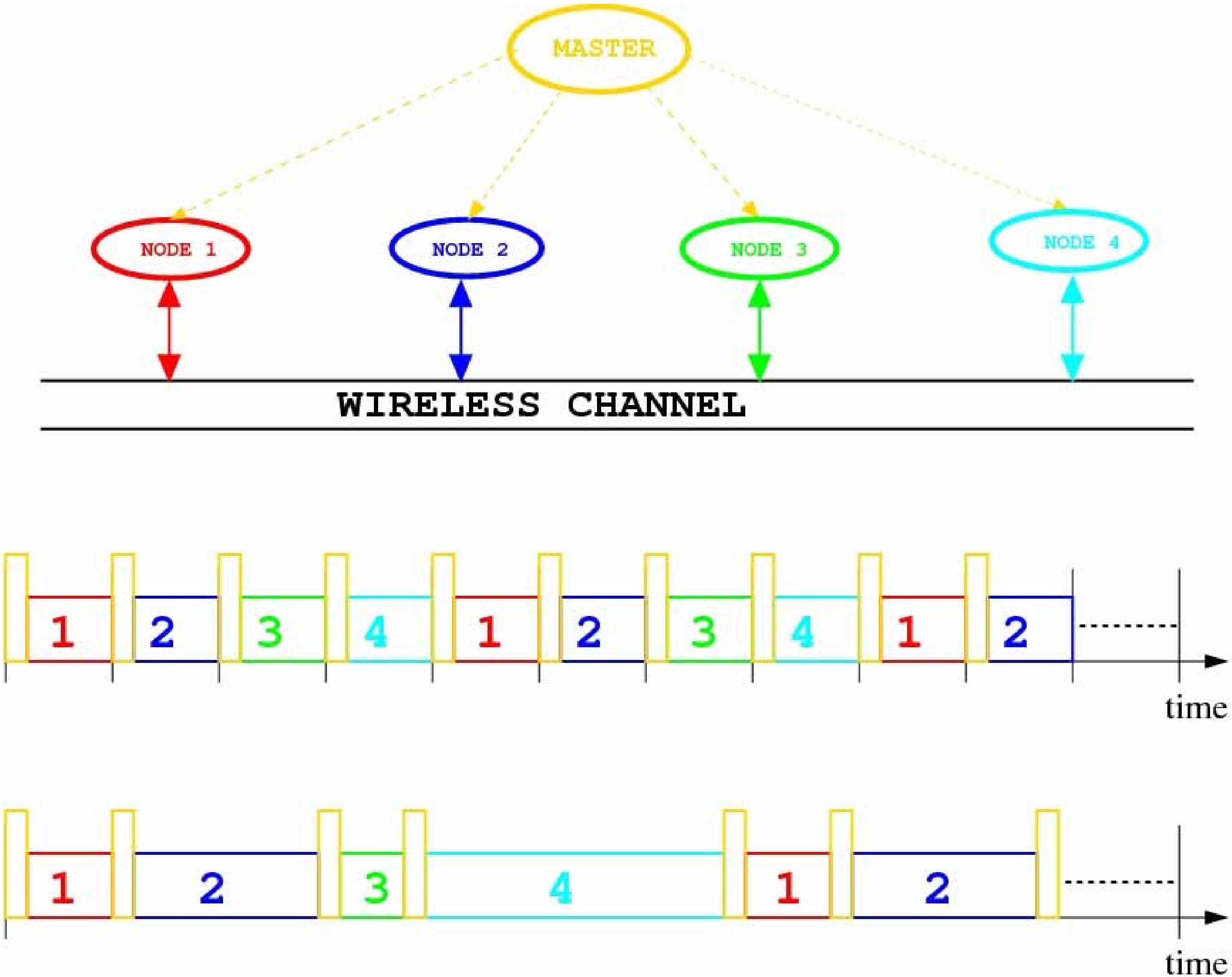
Round Robin Scheduling



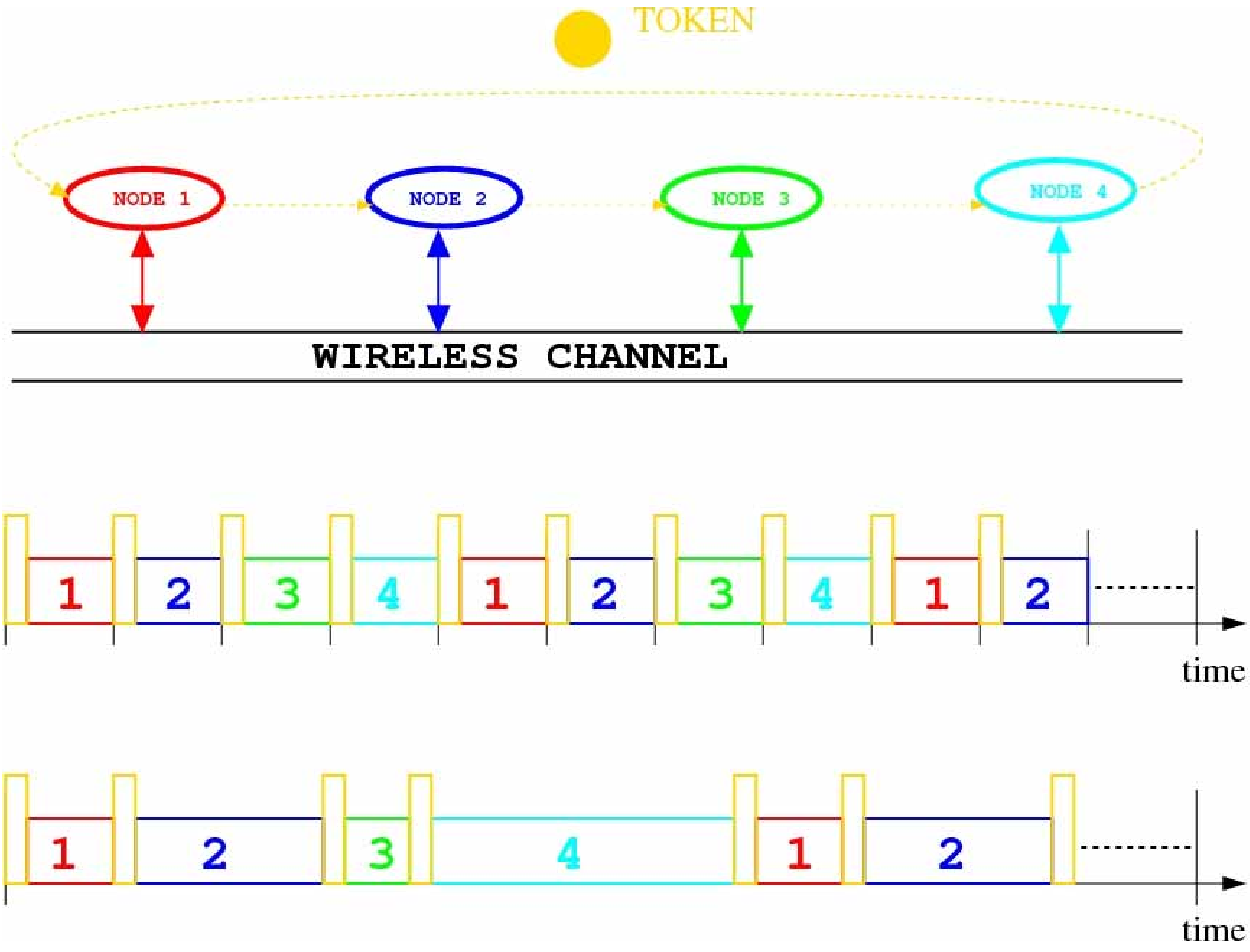
Coordinated (Centralized) Scheduling Approaches

- There is a central Coordinator node (a.k.a. Master)
- The Coordinator decides when a node can access the channel
  - Polling (Master/Slave):
    - Coordinator polls the nodes for packet transmission using some scheduling policy (Bluetooth)
  - Access Window approach :
    - Coordinator defines an channel Access Window by means of a periodic beacon transmission. The Access Window is defined by two consecutive beacon (802.15.4).
    - The Access Window is divided in time slots
    - Coordinator communicates the Access Window scheduling in the beacon packet (for instance)
- Both the poll and the beacon mechanisms synchronize the nodes
- Token passing approach
  - There is a token traveling among the nodes
  - Each node has a time budget
  - Every time a node receives the token, it can transmit its traffic for a time no greater then its budget
  - It needs a policy to exchange the token among the nodes (e.g. RR)
  - It needs a policy to assign the budgets (e.g Weighted RR)

Polling approach (MASTER SLAVE):



Token Passing

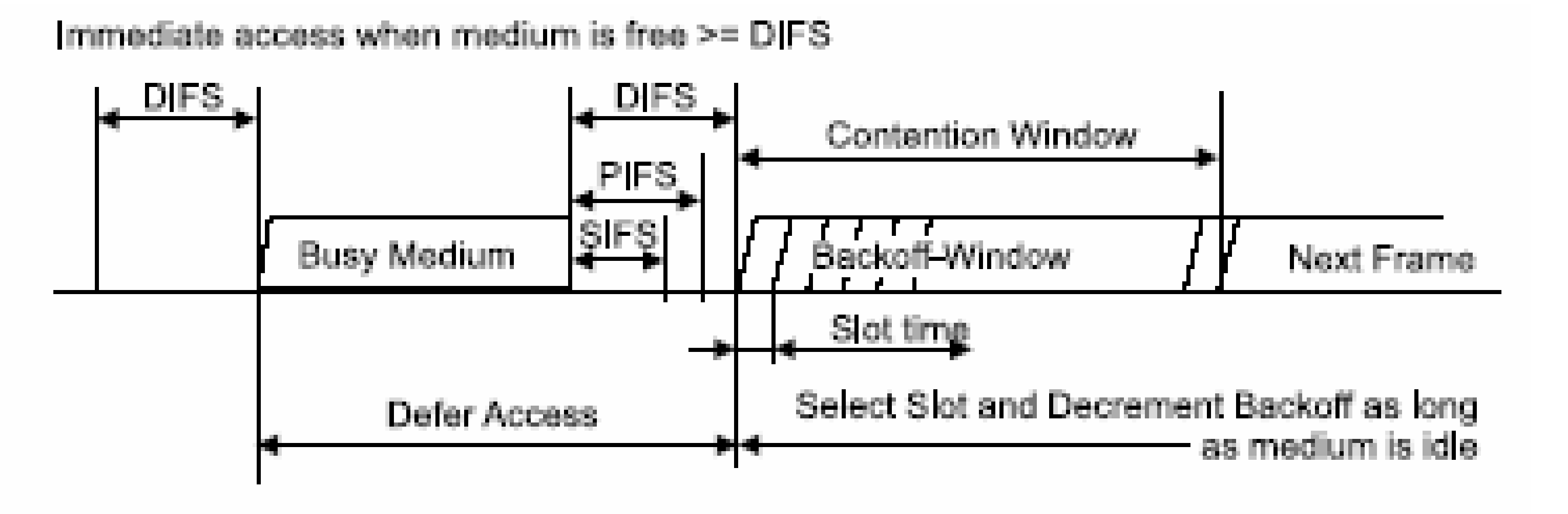


Mixed Approaches (Hybrid)

- Mixed approaches exploit both CSMA techniques and scheduling based (collision-free) techniques
- Several standard protocols use a mixed approach: e.g. IEEE 802.11 and IEEE 802.15.4
- IEEE 802.11 (Wi-Fi)
  - Distributed Coordination Function (DCF)
    - RTS/CTS + CSMA/CA + NAV (Network Allocation Vector ->Virtual Carrier Sensing)
    - Virtual Carrier Sensing: a node extracts the length of the incoming transmission from either RTS or CTS, then keep silent for the entire packet length
    - A positive ACK is used to confirm the packet has been received correctly
  - Point Coordination Function (PCF) (Polling approach)
    - Central Coordinator (Access Point)
- IEEE 802.15.4: Access Window with CSMA/CA and reserved time slots (more details later)

802.11-DCF and PCF coexistence

- Inter Frame Space (IFS): minimum space between two consecutive packets
- Distributed IFS (DIFS): between consecutive packets under DCF
- Point IFS (PIFS): PCF traffic
- Short IFS: ACK or CTS



Real-Time MAC protocols

- Contention Based Protocols
  - Differentiation Mechanisms for IEEE802.11 CSMA/CA
- Scheduling Based Protocols
  - Implicit EDF
- Mixed Contention and Scheduling Protocols
  - IEEE 802.15.4/ZigBee

Differentiation Mechanism IEEE 802.11

- IEEE 802.11 DCF fairness: DCF shares the available bandwidth among the nodes fairly, that is, each node receives the same portion of bandwidth. Each node has the same probability to access the channel
- For a timely communication (QoS in general), a node (network traffic source) should receive a portion of bandwidth proportional to its priority
- Priority traffic differentiation mechanisms:
  - Scaling the contention window according to the priority of each traffic source (node)
  - Assigning different DIFS to different priority traffic sources

Contention Window Scaling

$$CW_i = \left\lceil CW_i \left(2 + \frac{priority_i - 1}{\max\_priority} \right) \right\rceil$$

- CW is expressed in time slots, e.g. CW=4 backoff slots
- Example:
  - Network composed by n nodes
  - Each node has a periodic stream $S_i=(C_i,P_i,D_i=P_i)$
  - Node priority assigned by Rate Monotonic (or EDF)
  - $priority_i \propto P_i$ (RM)
  - $max\_priority \propto \max(P_i)$ (RM)
  - The higher the priority number, the lower the priority
  - The higher the priority, the lower CW

DIFS differentiation

$$DIFS_i = BASE\_DIFS * priority_i$$

- Example:
  - Network composed by n nodes
  - Each node has a periodic stream $S_i=(C_i,P_i,D_i=P_i)$
  - Node priority assigned by Rate Monotonic (or EDF)
  - $priority_i \propto P_i$ (RM)
  - The higher the priority number, the lower the priority
  - The higher the priority the lower DIFS

IEEE 802.11e

- IEEE 802.11e is the standard version that support QoS requirements
- It defines Enhanced DCF (EDCF) which provides service differentiation mechanisms
- It defines also a new polling base access mechanism called Hybrid Coordination Function (HCF) Controlled Access Channel (HCCA) (an enhanced PCF)
- EDCF defines four class of channel Access Categories (AC)
- Each AC has a different priority
- Service differentiation is achieved by:
  - **Contetion Window differentiation:** it assigns to each AC a different CW_{min}, CW_{max}
  - **DIFS differentiation**: Instead of using an unique DIFS, EDCF uses a different Arbitration IFS (AIFS) value for each AC. The higher the AC priority the shorter the AIFS

Black Burst

- Black Burst is a technique to guarantee a better performance for real-time traffic under IEEE 802.11
- A Real-Time (RT) node is one that has real-time traffic to deliver
- RT nodes contend to access the channel after a Medium IFS (MIFS<DIFS)
- RT nodes sort the access right by jamming the channel sending pulses of energy (BB)
- The node that sends the longest BB wins the contention and it can transmit its real-time packet

Black Burst

$$BB(t_{rt}^{i}) = (1 + t - t_{rt}^{i})t_{bbslot}$$

$$t_{rt}^{i} = t_{tx}^{i} + t_{sch}$$

$t \rightarrow$ **Current time instant**

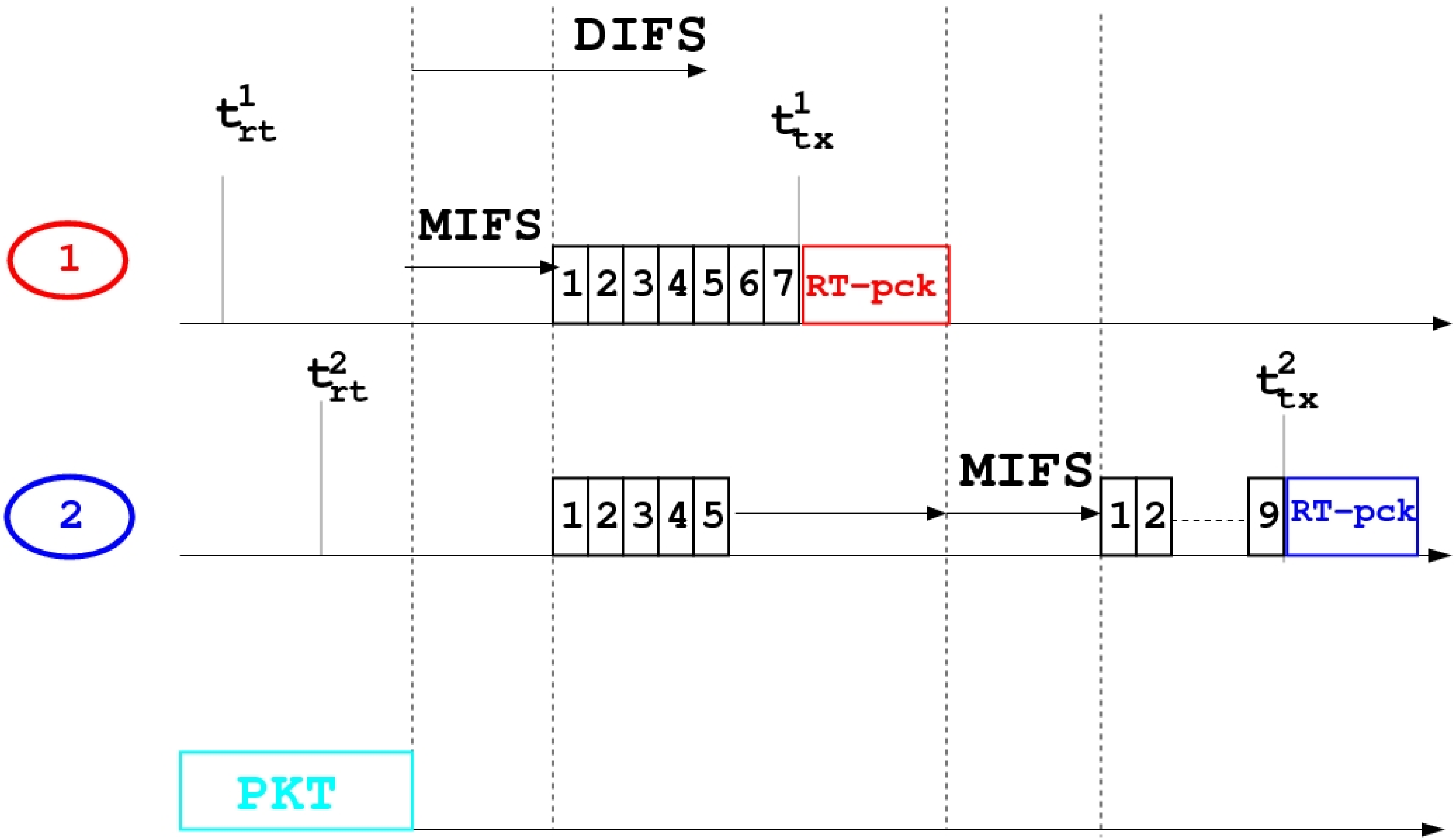
$t_{rt}^{i} \rightarrow$ **Time instant at which node *i* attempts to access the channel for transmitting**

$t_{tx}^{i} \rightarrow$ **Time instant at which node *i* transmits its real-time packet**

$t_{sch} \rightarrow$

- **Minimum interval between two consecutive real-time packet transmission attempts.**
- **Equal for all node**

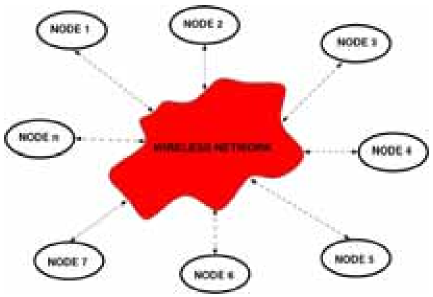
Black Burst



DIFS
t^1_{rt}
t^1_{tx}
MIFS
1
1 2 3 4 5 6 7
RT-pck
t^2_{rt}
t^2_{tx}
MIFS
2
1 2 3 4 5
1 2
9
RT-pck
PKT

Implicit EDF (IEDF)

- It uses a scheduling base channel access mechanism
- It uses the EDF algorithm to compute the transmission schedule
- Each node must know the traffic parameters of each other node
  - $S_i=(C_i,T_i,D_i=T_i)$ Traffic Parameters
    - S_i message stream
    - T_i message period
    - D_i message relative deadline
    - C_i message length (time units)

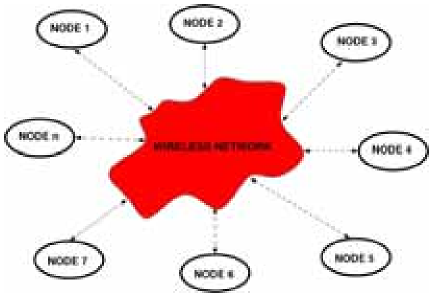


- Each node computes the schedule. The schedule is replicated at each node
  - Each node will know which one has the shortest deadline hence the right to access the channel to transmit
- Each nodes has an exclusive access to the channel

IEDF

- Nodes must by synchronized
- Unused bandwidth problem: a reclaiming bandwidth mechanism is necessary: FRASH
- Dynamic schedule update mechanism is needed when a node wants to join the network or a node leaves the network
- Under IEDF, it is possible to manage both periodic traffic and sporadic traffic (through Aperiodic Servers)
- Consider to have a message stream set M=(S_1,S_2,..S_n), a set of *s* Servers with:
  - Q_j Server Capacity
  - T_j Server Period
- **Stream set Feasibility Test (**classsic EDF+Servers test**):**

$$\sum_{i=1}^{n} \frac{C_i}{T_i} + \sum_{j=1}^{s} \frac{Q_j}{T_j}$$



IEDF

Message table

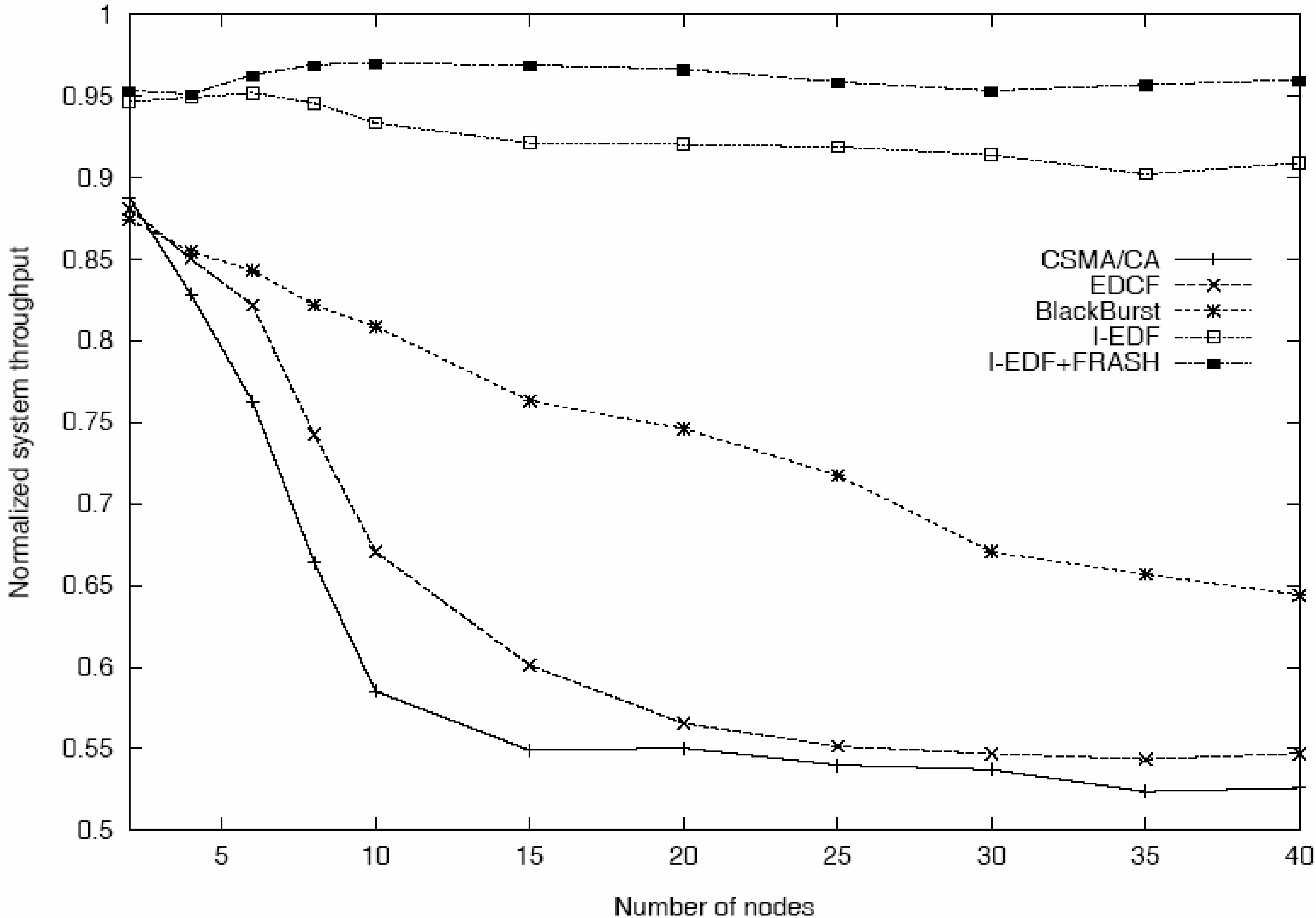
nodes rank ↑

Transmitter node	Message length	Message period
A	*3*	*8*
B	*1*	*6*
	1	*8*
C	*1*	*4*

C	B	A	A	A	B	C	B	C	A	A	A	B	C	B		C	A	A	A	B	B	C		C

0 FRAMES 10 20

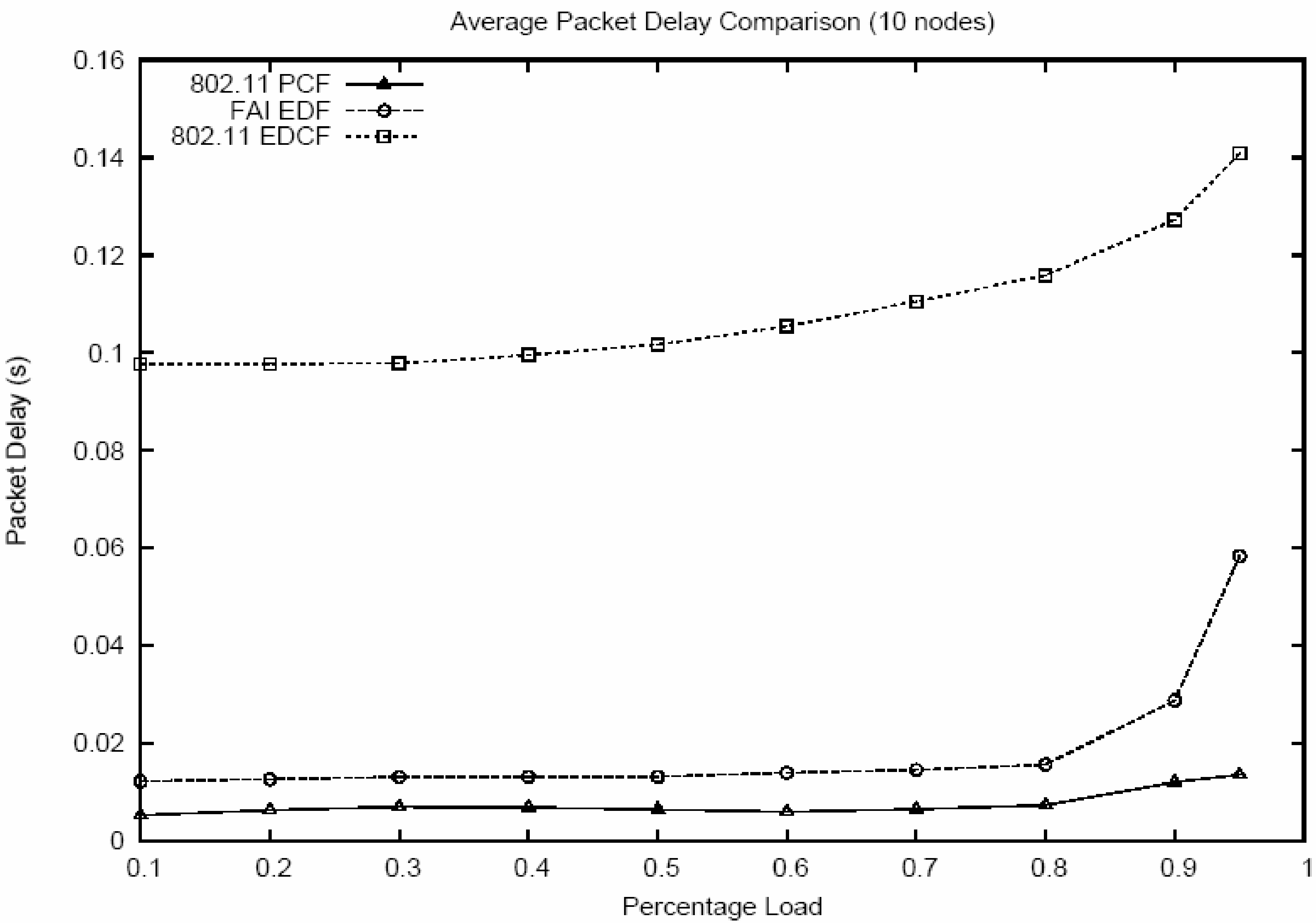
IEDF


1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
5
10
15
20
25
30
35
40
Normalized system throughput
Number of nodes
CSMA/CA
EDCF
BlackBurst
I-EDF
I-EDF+FRASH

Fault Tolerant Asynchronous Implicit-EDF
FAI-EDF

- Fault Tolerant Asynchronous Implicit-EDF
  FAI-EDF
- It is an improved version of IEDF
- It does not need clock synchronization
- The protocol is robust with respect to both packet loss and node failure
- Time budgets mechanism is used for bandwidth reclaiming

FAI-IEDF

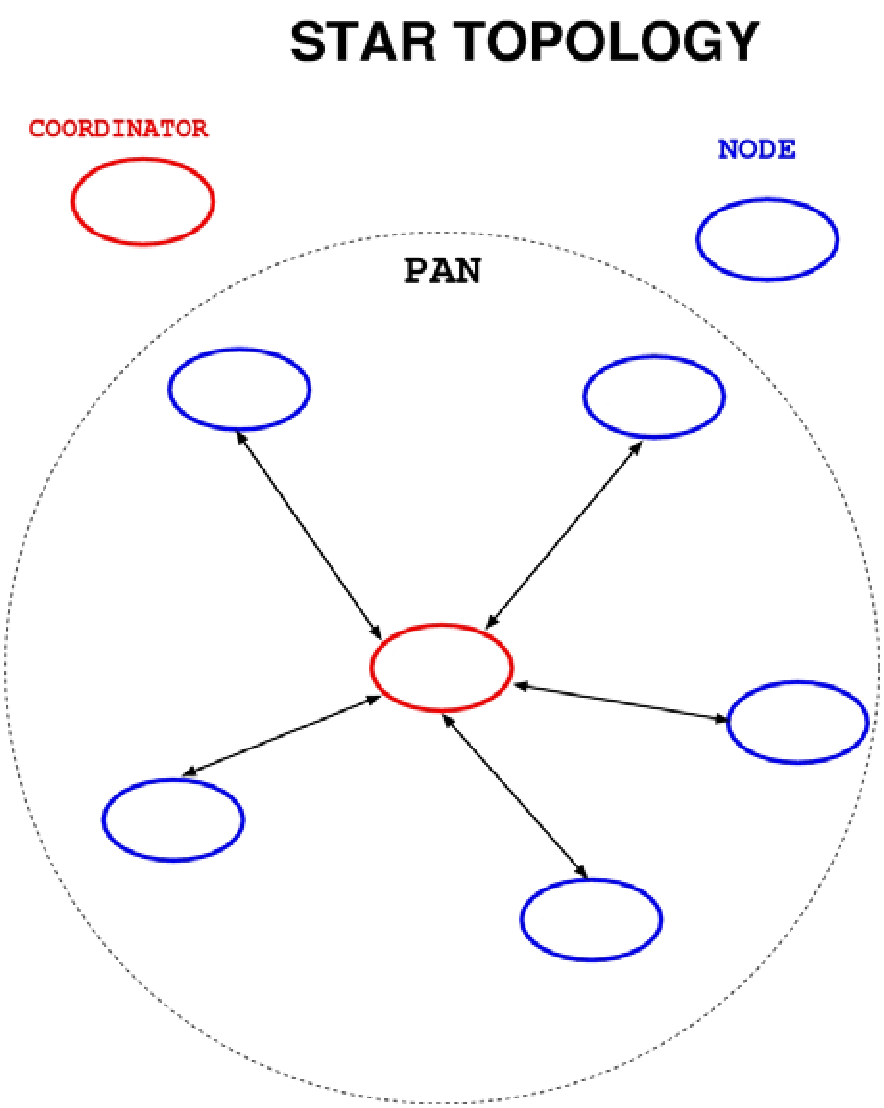


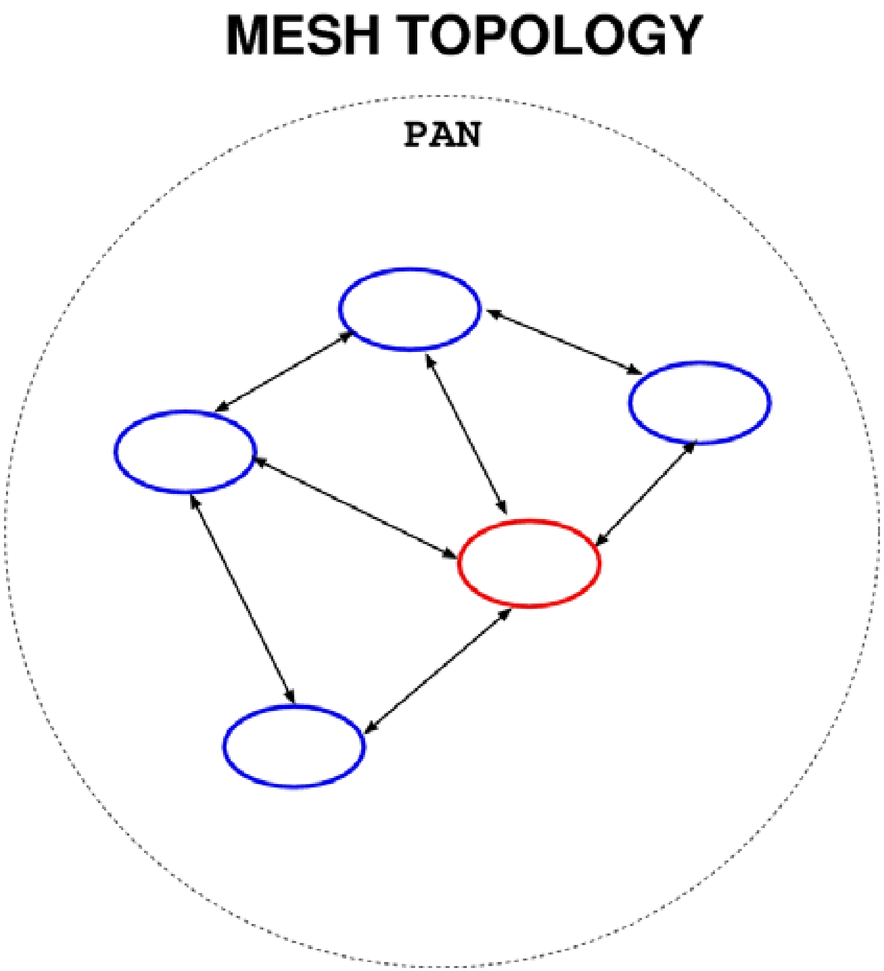
Average Packet Delay Comparison (10 nodes)
802.11 PCF
FAI EDF
802.11 EDCF
Packet Delay (s)
Percentage Load
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

802.15.4/ZigBee

- IEEE 802.15.4 defines MAC and PHY layers
- ZigBee defines the Network layer and the Application layer
- The nodes are grouped by Personal Area Network (PAN): it defines a cluster of nodes managed by a Coordinator node
- PAN Topologies: star and mesh
- IEEE 802.15.4 defines a slotted beaconed mode operation and an unslotted mode operation
- Unslotted mode (used by ZigBee):
  - whenever a node in the PAN wants to transmit, it uses the unslotted CSMA/CA algorithm (described before)
  - The task of the Coordinator is to manage the PAN
    - Es. Node association/disassociation

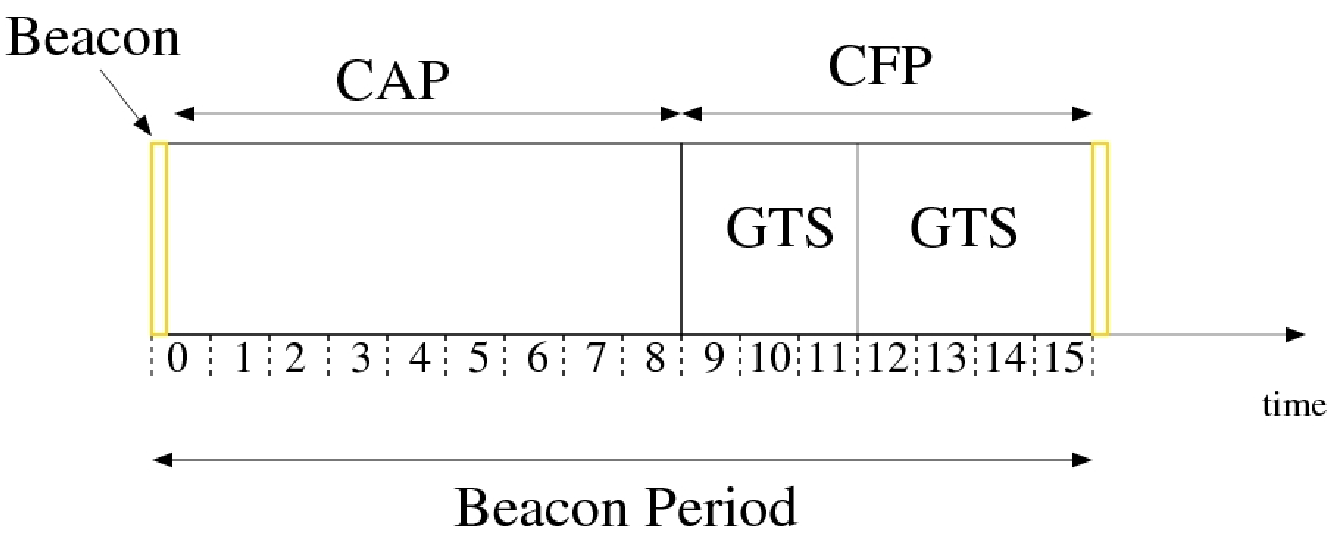
IEEE 802.15.4 topologies





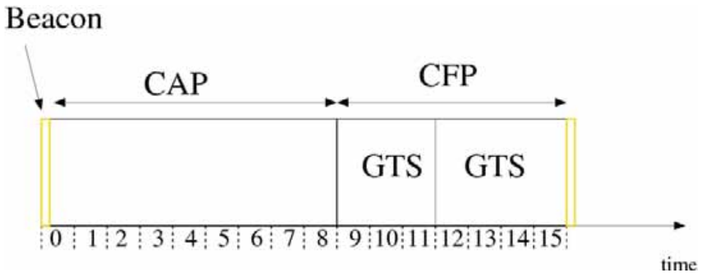
802.15.4/ZigBee

- Slotted beaconed mode (ACCESS WINDOW)
  - Coordinator bounds the channel access time by an Access Window
  - The Access Window is bounded with a periodic beacon transmitted by the Coordinator
  - Access Window contains 16 time slots
  - Access Window comprises a Contention Access Period (CAP) and a Contention Free Period (CFP)



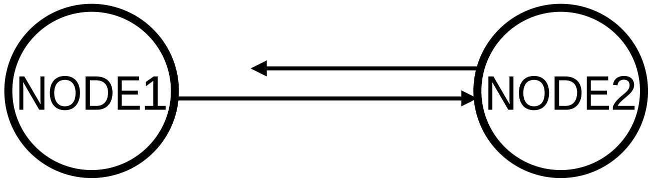
802.15.4/ZigBee

- During the CAP nodes use slotted-CSMA/CA to
  - Send data packets
  - Send GTS allocation requests
  - To join the PAN
  - Etc.
- Some nodes (max 7 nodes) can have a Guaranteed Time Slots (GTS) allocated in the CFP
- During the CFP, there are no collisions: Exclusive channel access by nodes which hold a GTS
- Scheduling of GTSs is contained in the beacon



Wireless Real Time Communication

- With respect to a wired channel, the management of a wireless channel is **more difficult**.
- A wireless channel is characterized by:
  - High bit error rate -> e.g > 10^{-3}
  - Asymmetric links:



  - Variable Channel Capacity (Bandwidth)

Wireless Real Time Communication

- Is hard real-time communication over a wireless channel just an utopia?
- The second Shannon Theorem states: a noisy channel with channel capacity *C* and information transmitted at a rate *R*, then if R<C there exists a code that allows the probability of error at the receiver to be made arbitrarily small. This means that theoretically, it is possible to transmit information without error at any rate below *C*.
- Advanced techniques such as Turbo code, come much closer to reaching the theoretical Shannon limit, but at a cost of high computational complexity.
- In general, this kind of code are not suitable for small embedded systems. They are developed either by custom IC or by FPGA.

- Apart from the code complexity, using advanced codes we can transmit with bit error probability arbitrarily small at the channel capacity.
- But the big problem is: the channel capacity, that is, the available bandwidth varies both over the time and node by node, because it depends on the signal-to-noise ratio which depends on the environmental conditions.
- **Shannon–Hartley**
  - *B* is the channel bandwidth
  - *S* is the signal power
  - *N* is the noise power

$$C = B\log_2 \frac{S}{N}$$

Wireless Real Time Communication

- Is it possible to achieve hard real-time communication over a wireless channel?
- In general the answer is negative, because the channel capacity is usually not stable.
- Only soft real-time communication could be possible. Probabilistic guarantee on message deadlines.
- But in those cases where we can guarantee a minimum signal-to-noise ratio value, using “good” codes, it could be possible to obtain hard real-time communication.
- In general, other than a smart hardware design, we need dynamic protocols to adapt the communication parameters (e.g error correction code length, stream utilizations, etc.) to the channel conditions (channel capacity).

Literature

- Downloadable version of this presentation will include literature references for the discussed topics:
  - Distributed Systems
  - Wireless MAC Protocols and techniques
  - Real-Time and QoS
  - Cross-Layer Design (Not treated in this presentation)
  - Energy Aware Communication (Not treated in this presentation)

Literature

- Distributed Systems
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- A general overview on networking
  - Andrew Tanembaum." *Computer Networks* ". Prentice Hall
- Wireless Sensor Networks (protocols and energy aware issues)
  - Holger Carl, Andreas Willing. "Protocols and Architecture for Wireless Sensor Networks". Wiley
- Real-time, QoS and resource management on Wireless Communication
  - Mihaela Cardei, Ionut Cardei, Ding-Zhu Du. "*Resource Management in Wireless Networking*". Springer
  - Bulent Tavli, Wendi Heinzelman. "*Mobile Ad Hoc Networks, Energy-Efficient Real-Time Data Communications*". Springer
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  - J. Mišic, S. Shafi, and V. B. Mišic, “The Impact of MAC Parameters on the Performance of 802.15.4 PAN”, *Elsevier Ad hoc Networks Journal*, 3(5):509–528, 2005.
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  - Anis KOUBAA, Mário ALVES, Eduardo Tovar. **“**An implicit GTS allocation mechanism in IEEE 802.15.4 for time-sensitive wireless sensor networks: theory and practice” Real-Time Systems Journal, Volume 39, Numbers 1-3, pp 169 - 204, Springer, August 2008
    - http://www.springerlink.com/content/u203825646vv811r/
  - At the following link you can find several papers on real-time communication over IEEE 802.15.4, and other similar topics
    - http://www.cister.isep.ipp.pt/asp/list_docs2.asp