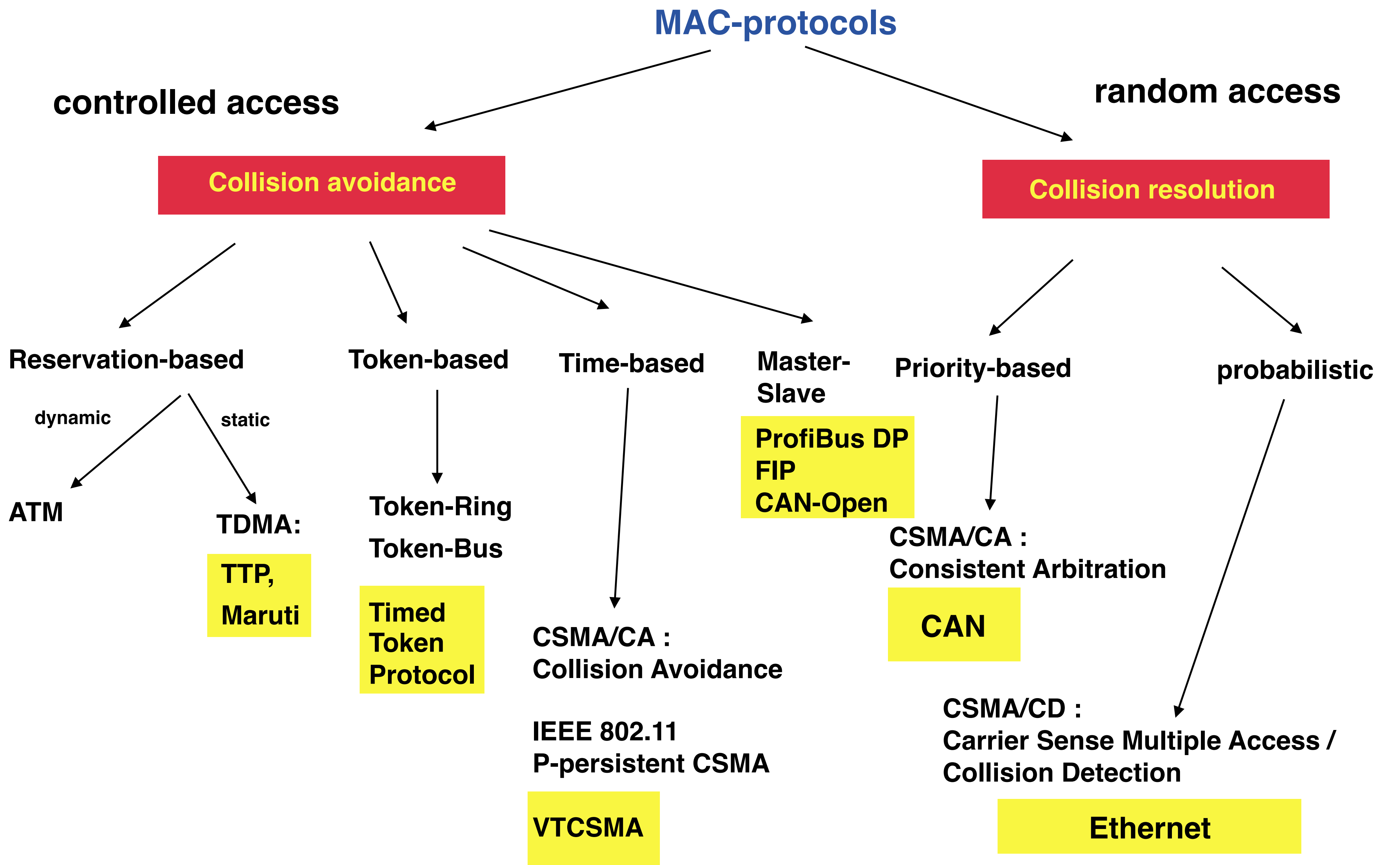

MAC-protocols
controlled access
random access
Collision avoidance
Collision resolution
Reservation-based
dynamic
static
ATM
TDMA:
TTP,
Maruti
Token-based
Token-Ring
Token-Bus
Timed
Token
Protocol
Time-based
CSMA/CA :
Collision Avoidance
IEEE 802.11
P-persistent CSMA
VTCSMA
Master-
Slave
ProfiBus DP
FIP
CAN-Open
Priority-based
CSMA/CA :
Consistent Arbitration
CAN
probabilistic
CSMA/CD :
Carrier Sense Multiple Access /
Collision Detection
Ethernet

Token based Protocols

Token-Protocols

Token Passing:

Multiple Masters circulate a token.

Token Ring: physical ring (IEEE 802.5)
Token Bus: logical ring (IEEE 802.4)

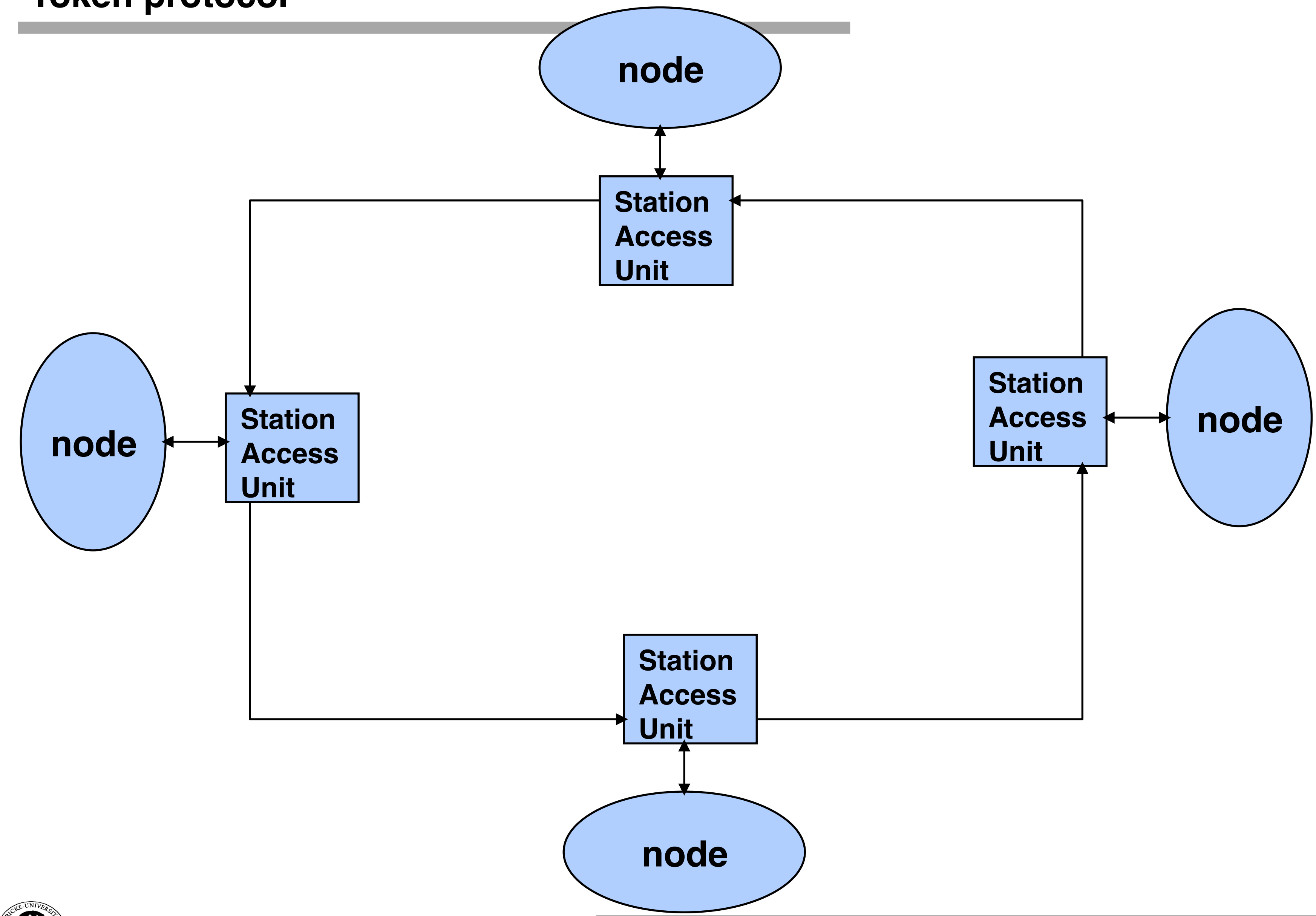
Delegated Token:

connection oriented: Central busarbiter grants a token to a participant to send one or more messages.

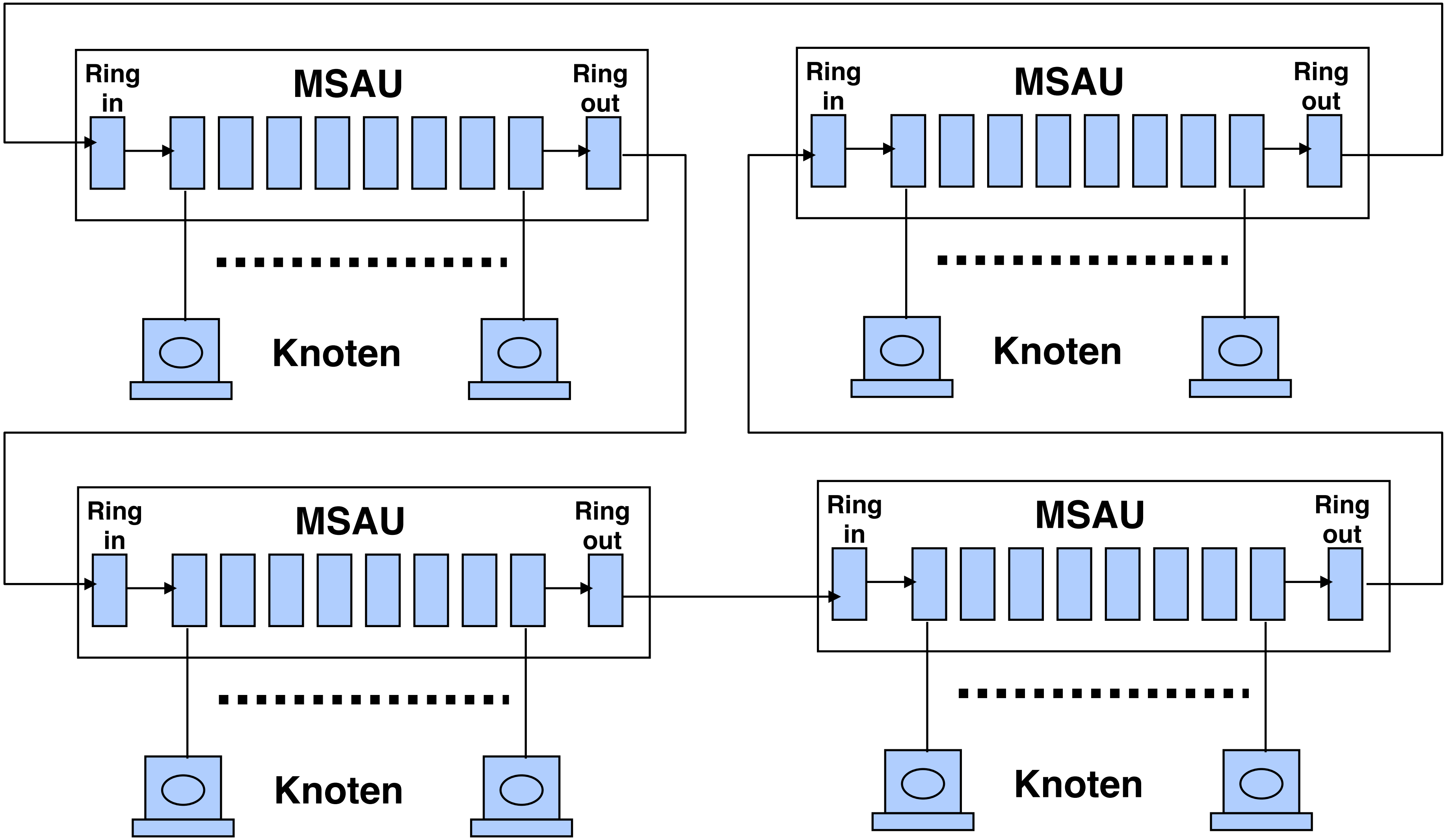
message oriented: The central busarbiter requests a participant to send a message by sending the token to this participant. Centrally controlled message dissemination.

Examples: Connection oriented: Profibus (Token Passing (logical Ring)
message oriented: FIP (Factory Instrumentation Protocol)

Token protocol

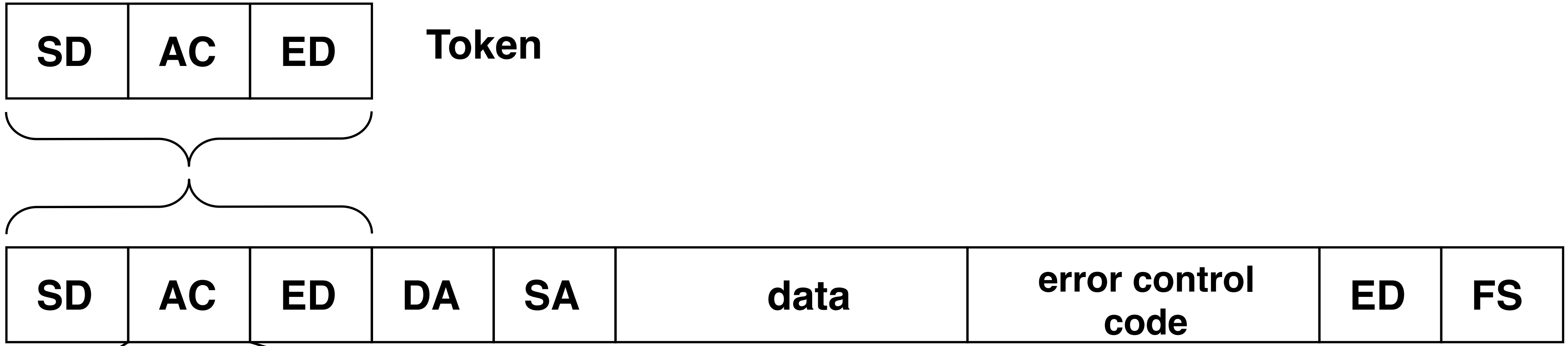


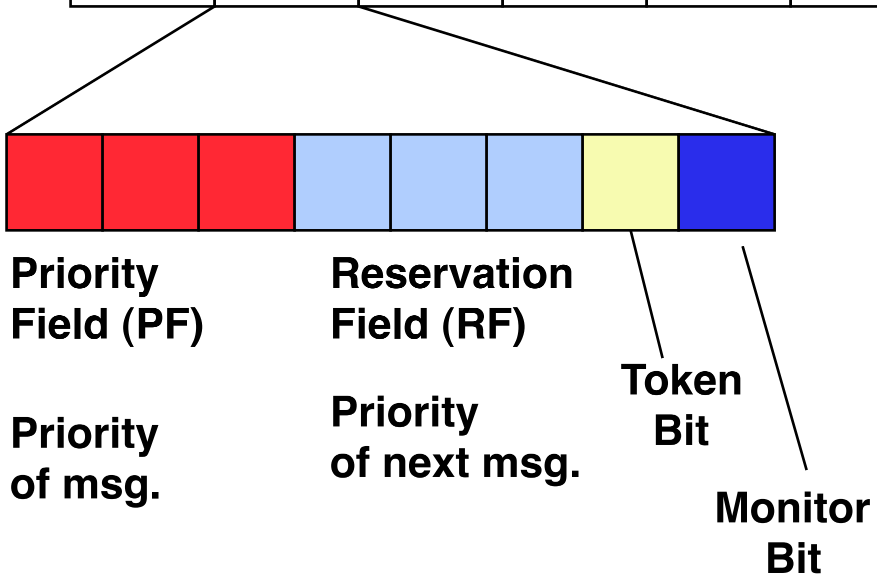
Token network topology



MSAU: Multi Station Access Unit

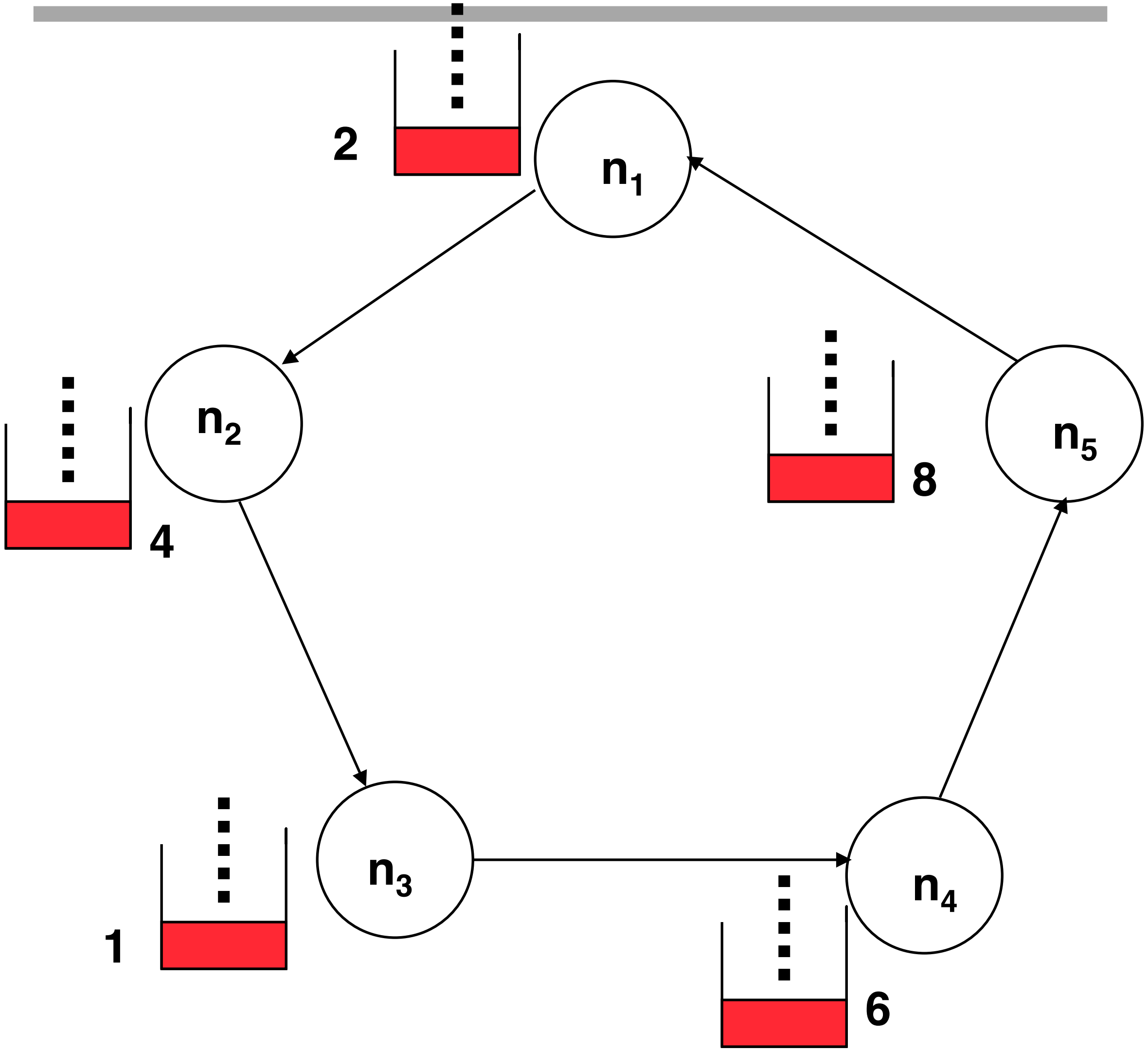
802.5 Token Ring Frame Format





SD: Start Delimiter
AC: Access Control
ED: Ending Delimiter
SA: Source Address
DA: Destination Address
FS: Frame Status
- FS = 00: Station not available
- FS = 10: Frame not delivered although station was available
- FS = 11: successfully received

Priority based reservation of messages



Round n:
node n_4 sends packet with priority x. RF is RF=6.
- **n_1 changes RF = 2**
- **n_2 and n_5 don't change**
- **n_3 changes RF into RF = 1**

Round n+1:
- **n_4 generates Token with PF = 1 and sends token on the ring.**
- **node node except n_3 is able to use the token because lower priorities.**
- **n_3 detects a message with the respective priority is in its local send queue and appends this msg to the token. Node n_3 also resets the token to the original value (=2).**

Token Ring/IEEE 802.5

Priority System

Token Ring networks use a sophisticated priority system that permits certain user-designated, high-priority stations to use the network more frequently. Token Ring frames have two fields that control priority: the *priority* field and the *reservation* field.

Only stations with a priority equal to or higher than the priority value contained in a token can seize that token. After the token is seized and changed to an information frame, only stations with a priority value higher than that of the transmitting station can reserve the token for the next pass around the network.

When the next token is generated, it includes the higher priority of the reserving station. Stations that raise a token's priority level must reinstate the previous priority after their transmission is complete.

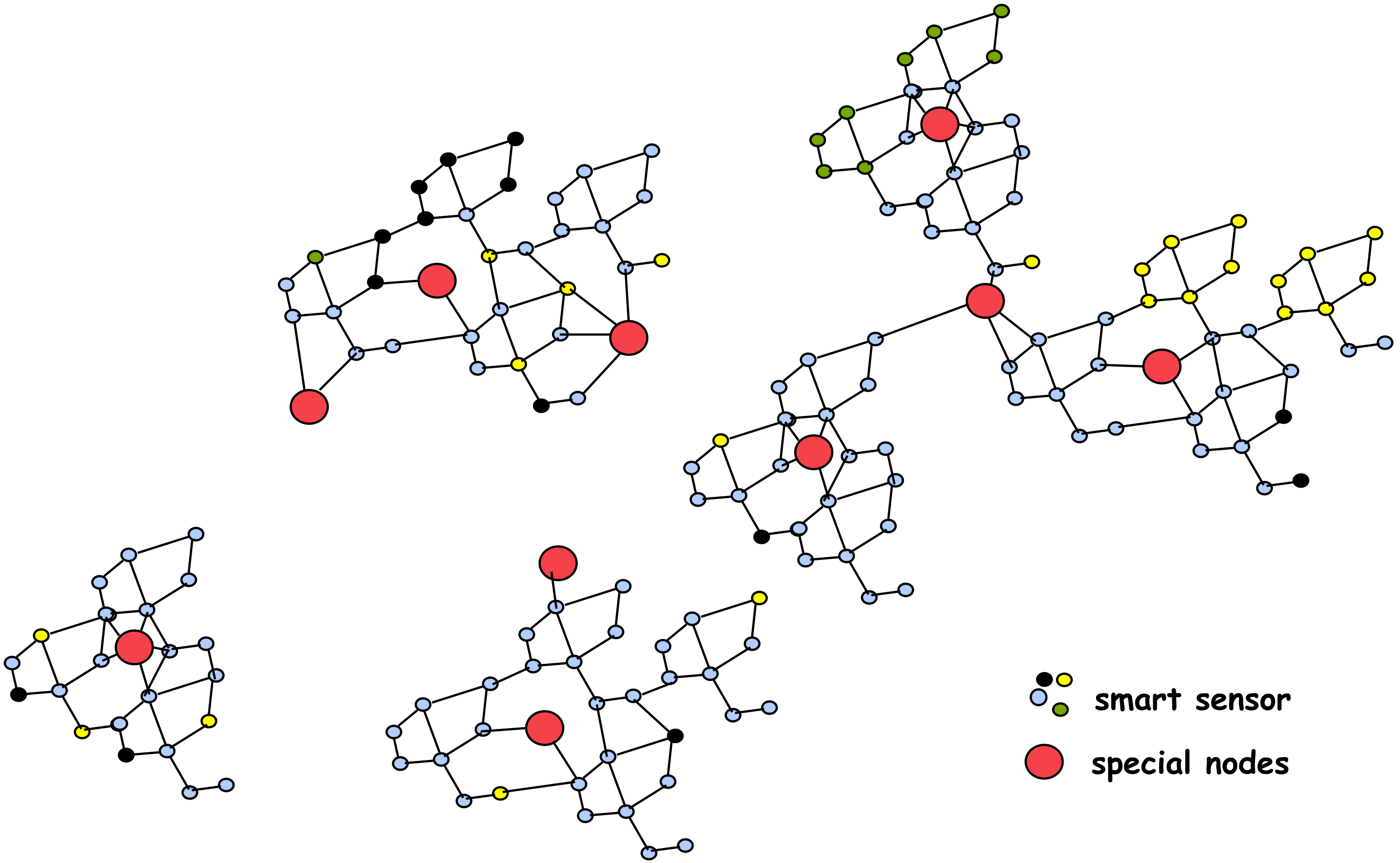
Predictability of various Networks*

Worst Case Times of Inaccessibility*	t_{inacc} (ms)	
ISO 8002/4 Token Bus (5 Mbps)	139.99	Token-based Protocols
ISO 8002/5 Token Ring (4 Mbps)	28278.30	
ISO 9314 FDDI (100 Mbps)	9457.33	
Profibus (500 kbps)	74.80	
CSMA/CD	unbounded	CSMA Protocols
CSMA/CA	stochastic	
CAN-Bus (1Mbps)	2.48	

The worst-case-delay of the Timed-Token-Protocol is 2•TTRT (Target Token Rotating Time)**

* P. Verissimo, J. Ruffino, L. Ming:” How hard is hard real-time communication on field-busses?”

Sensornets for a wired physical world



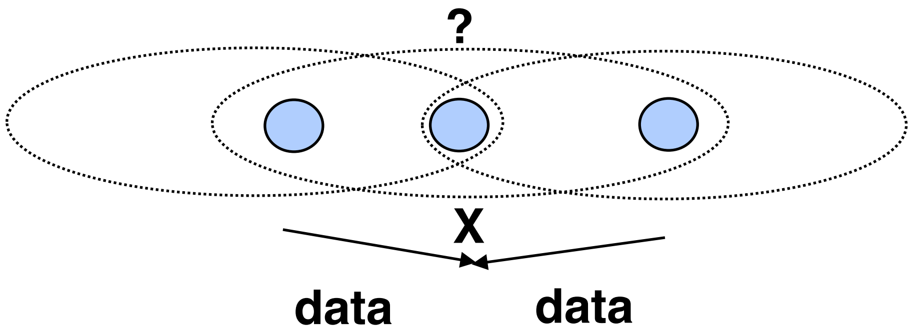
MAC-principles

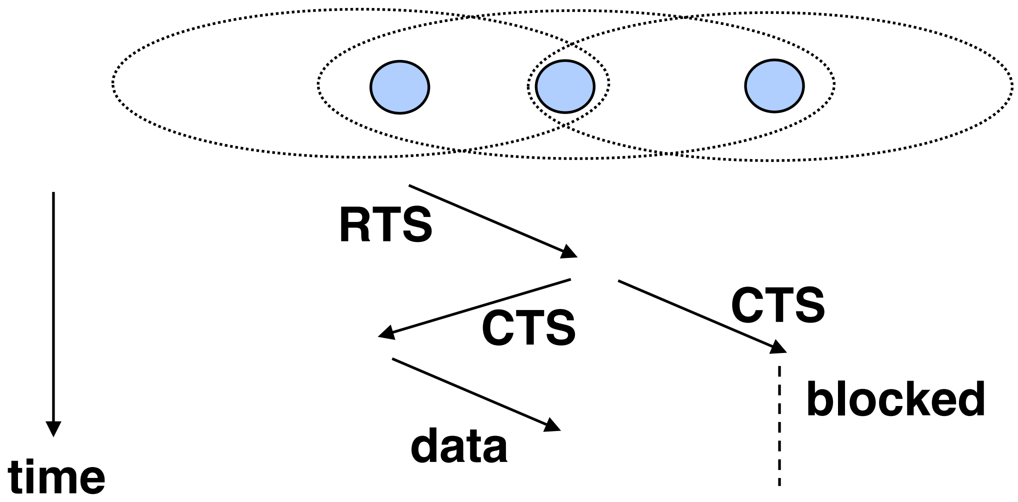
	trigger to send	Start time	channels
(simple) Aloha	data availability	arbitrary	1
Slotted Aloha	time slots	start of a time slot	1
MACA	RTS/CTS	dyn. reservation	1
MACAW	MACA + Acknowledge	same as MACA	1
CSMA	medium free	arbitrary	1
CSMA/CA	medium free	after waiting time or dyn. reserv.	1
TDMA	acc.schedule	preplanned	1
FDMA	multiple frequencies	arbitrary	m
CDMA	orthogonal codes	arbitrary	m

Problems

Multiple Access with Collision Avoidance (MACA)

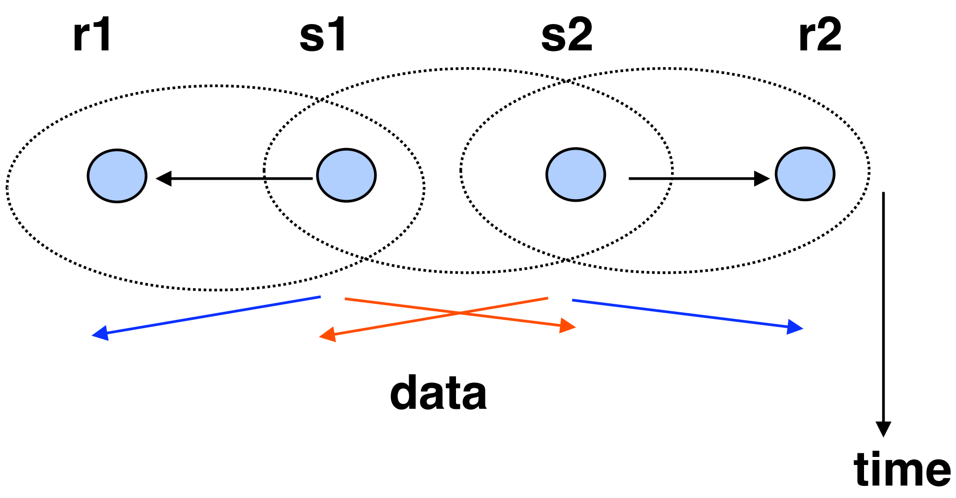
Hidden Terminal Problem

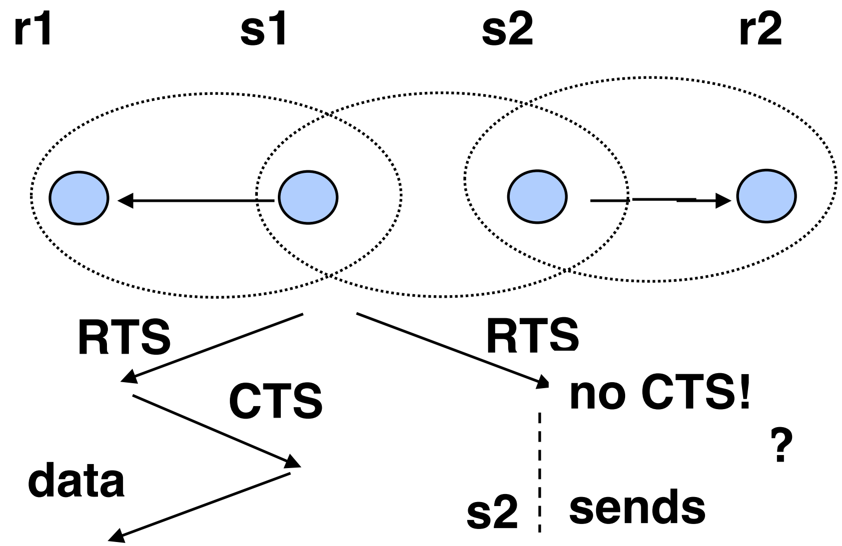




More problems

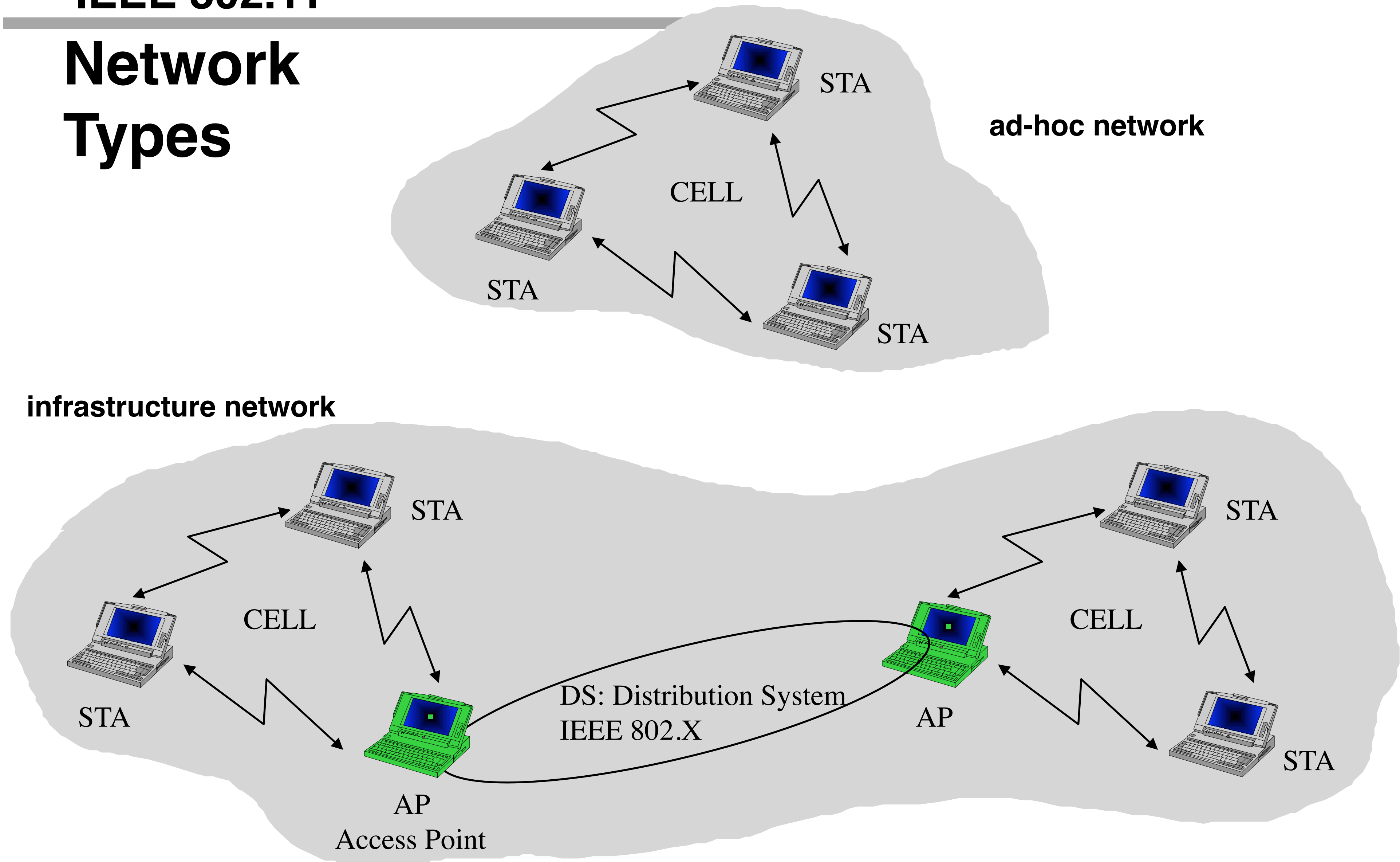
Exposed Terminal Problem





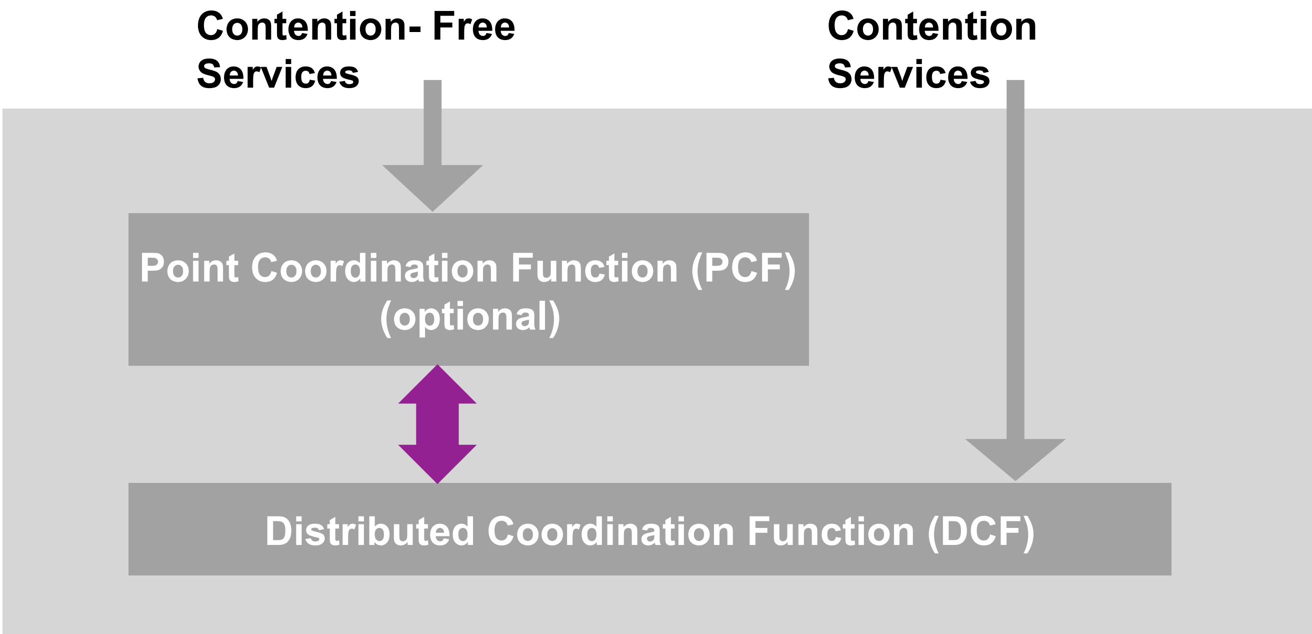
RTS/CTS to improve throughput

Network Types



IEEE 802.11 MAC Layer

MAC Architektur:

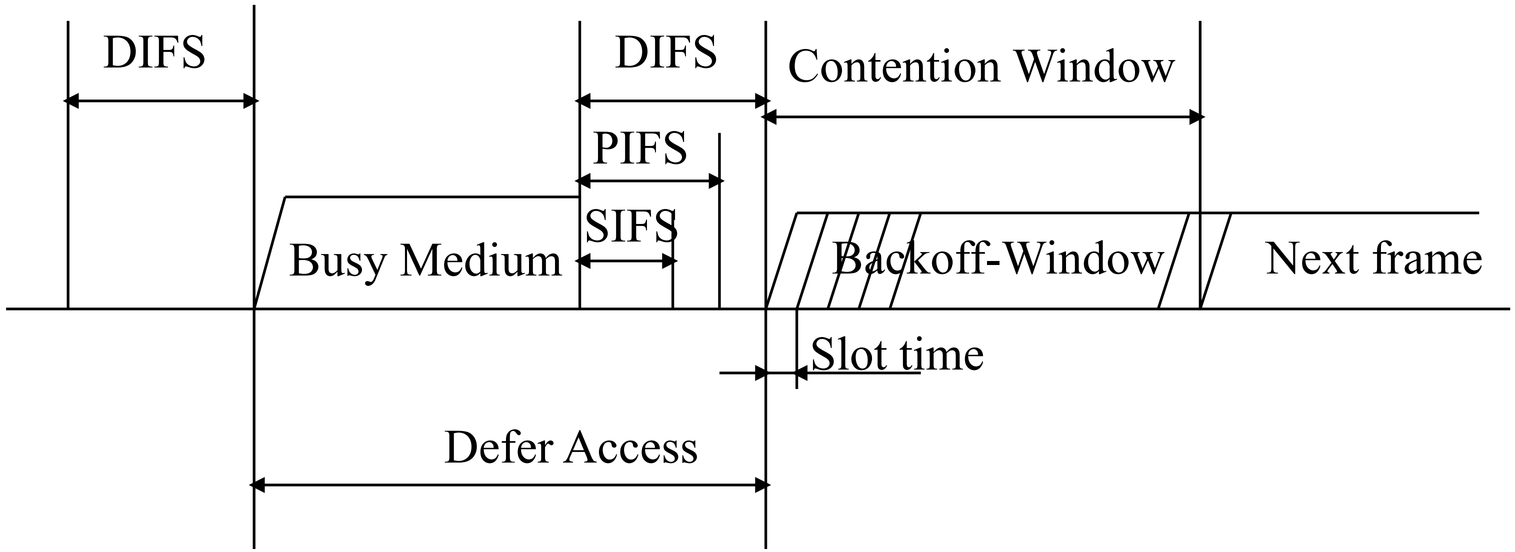


Distributed Coordination Function (DCF)

- CSMA/CA Protocol
- Collision Avoidance by random backoff procedure (p-persistent)
- All Frames are acknowledged, lost Frames are resend
- Priority Access by Interframe Space (IFS)

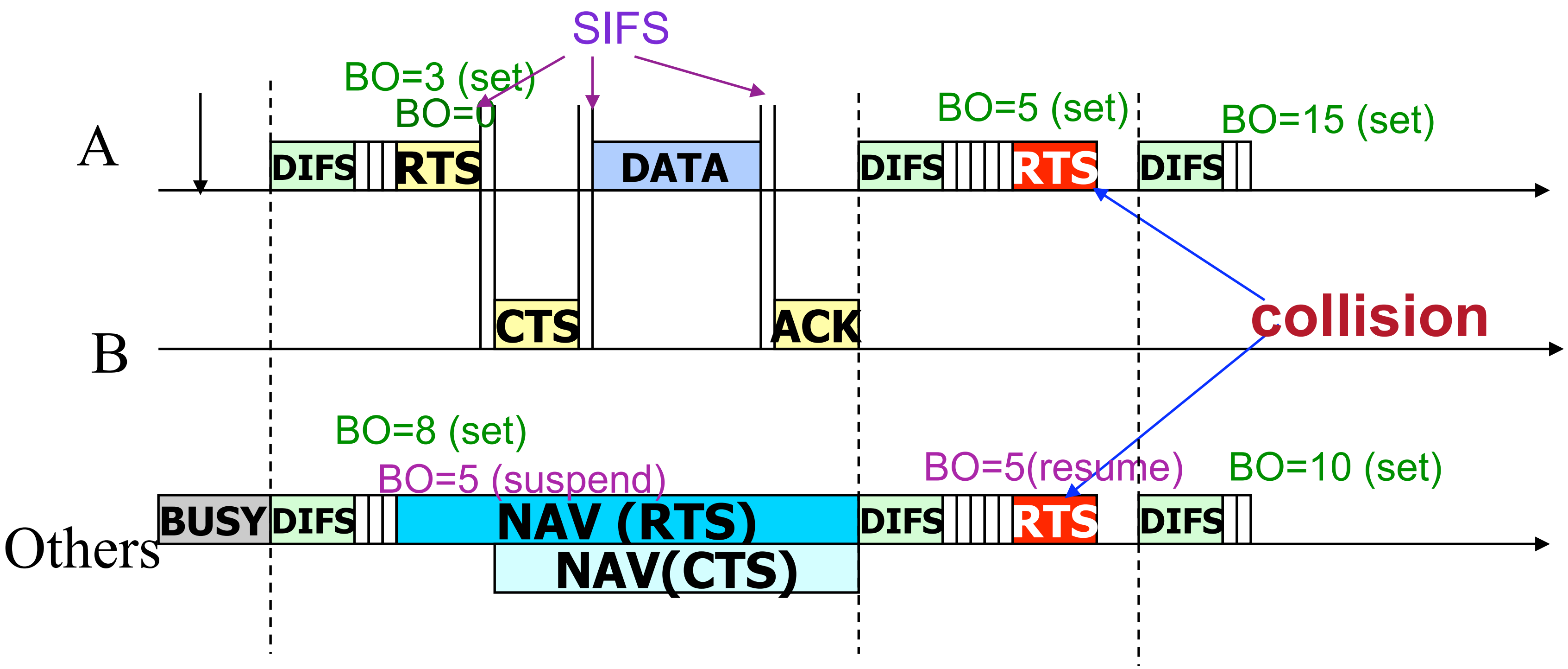
=> fair arbitration but no real-time support

Relationship of different IFSs in 802.11



DIFS: DCF Interframe Space
PIFS: PCF Interframe Space
SIFS: Short Interframe Space

Example of 802.11 RTS/CTS/DATA/ACK Scheme



BO: backoff

Key parameters for wireless networks

	EasyRadio	RFMonolitics TR 1001	ChipCon CC1000	Lucent WLAN PC "Silver"
Frequency	868 MHz	868 MHz	868 MHz	2,4 GHz
Bit rate (Kbps)	19	115,2	76,8	11.000
Energy consumption				
send (mA)	17	12,0	25,4	284,0
receive (mA)	8	3,8	11,8	190,0
standby(μA)	--	0,7	30,0	10.000,0
switching time (μs)				
standby-transmit		16	2000	
receive-transmit		12	270	
standby-receive		518	2000	
transmit-receive		12	250	
transmit-standby		10		
receive-standby		10		

Sources of increased energy consumption:

active wait:	If a node does not know when to expect a message, it must always remain in receive state.
overhearing:	A node receives a message for which it is not the destination. Better: switch off the node during this time.
collisions:	Energy which is used by sending a message during a collision is lost. The respective packet has to be resent completely. Collisions cannot be detected during sending.
protocol overhead :	Every additional measure like RTS/CTS or an acknowledge scheme increase the protocol overhead.
Dynamic behaviour:	Unbalanced load increases the probability of collisions (Thrashing).

Big Problem: idle listening

- **Rx active power is often greater than Txactive power**, due to the larger number of signal processing circuits that must be active

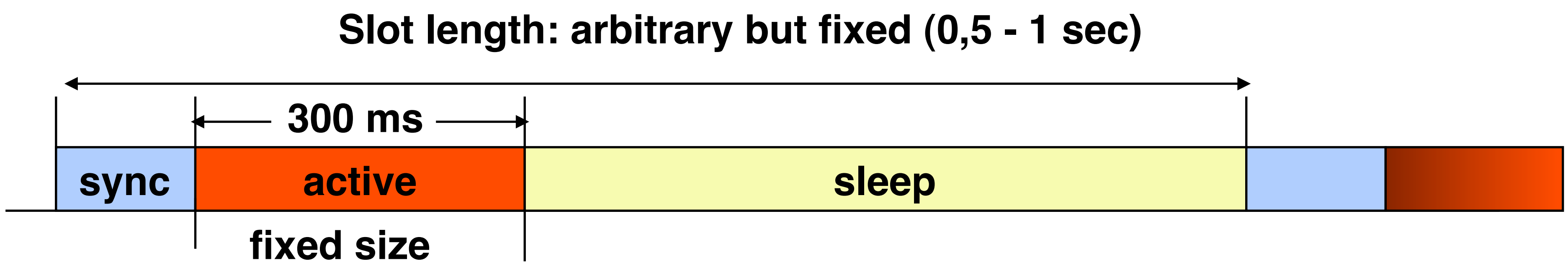
- **It's more power-efficient to blindly transmit than to blindly receive**

Energy efficient protocols try to minimize the time of active listening!

Approaches:

- **Scheduling (TDMA)**
- **activation channel (narrow band additional channel)**
- **Preamble**
- **Adaptive schemes**

Slotted protocols

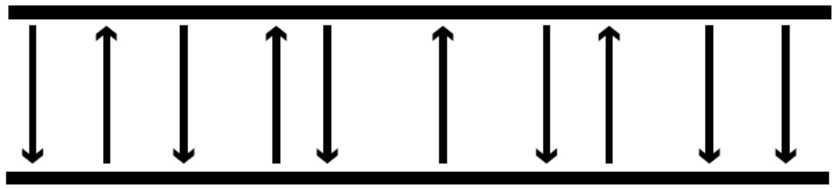


Example: S-MAC (Sensor -MAC) (Ye, Heideman, Estrin)

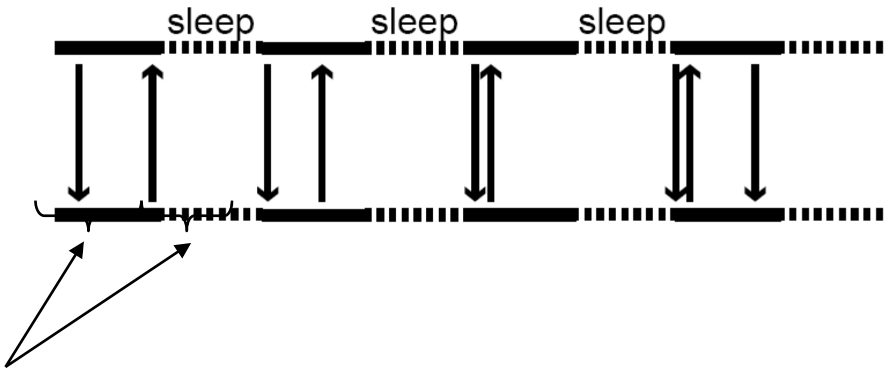
Nodes are organized in (virtual) clusters, which adopt a common slot format.

Variation T-MAC (Time-out MAC): Adaptively determining the relation between active and sleep perods. If the medium is idle the node can switch to sleep after a short interval.

CSMA



S-MAC

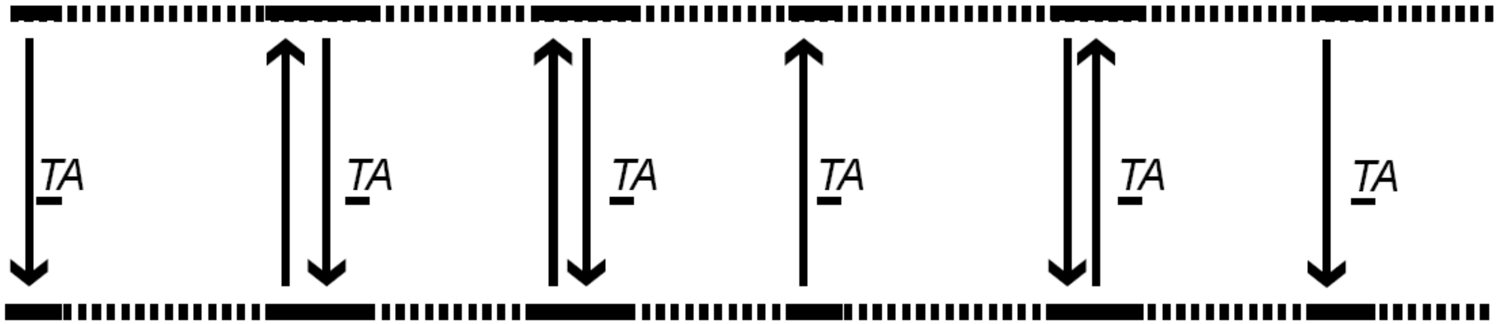


a priori fixed active and sleep intervals

During the activity periods the node must transmit local data + the messages which are relayed in the multi-hop network.

Problem with S-MAC: fixed periods

T-MAC: Time-Out-MAC

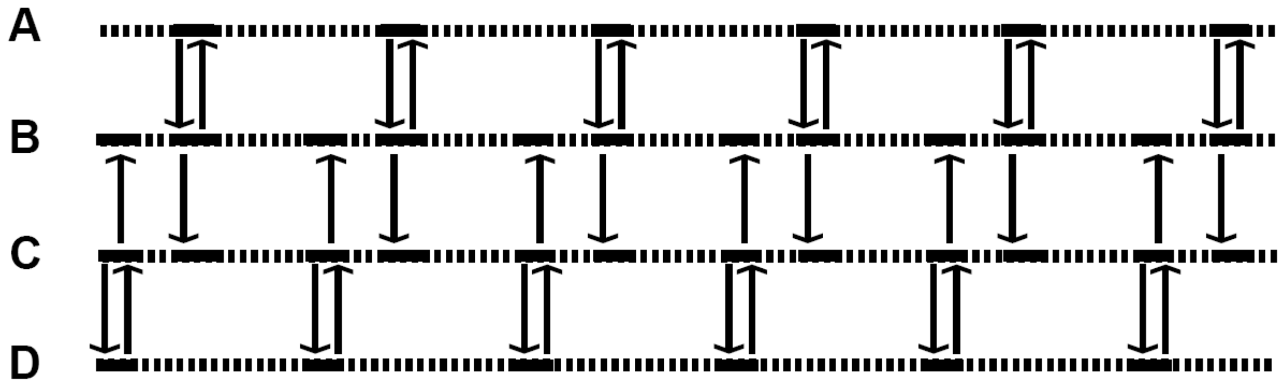


Determine the activity and sleep periods adaptivly.

An activation event is given by:
- Alarm of a periodic timer;
- Reception of a message;
- Detection of some communication (also collisions are such events);
- Termination of the own transmision or of an ack.
- The knowledge that a communication by some neighbors has been terminated. (detected by overhearing)

All communication is performed in "bursts" at the start of the aktive period.

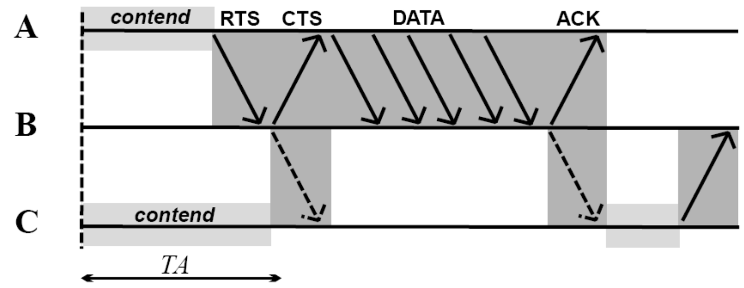
T-MAC: Communication over multiple clusters



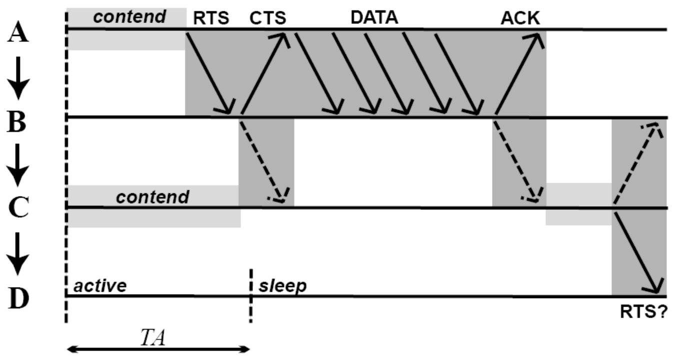
Communication between "virtual clusters" in T-MAC

Messages to relay will be buffered. The size of the buffer determines the upper bounds of activity and sleep periods.

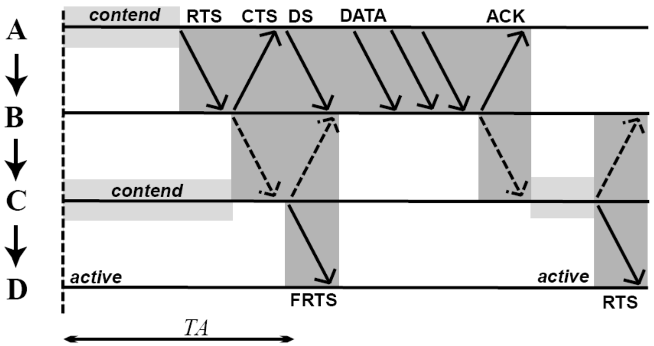
Further improvements: Eraly Sleeping Problem



Basic Cycle



**Early Sleeping Problem.
Node D goes to sleep before
node C can send the RTS.**



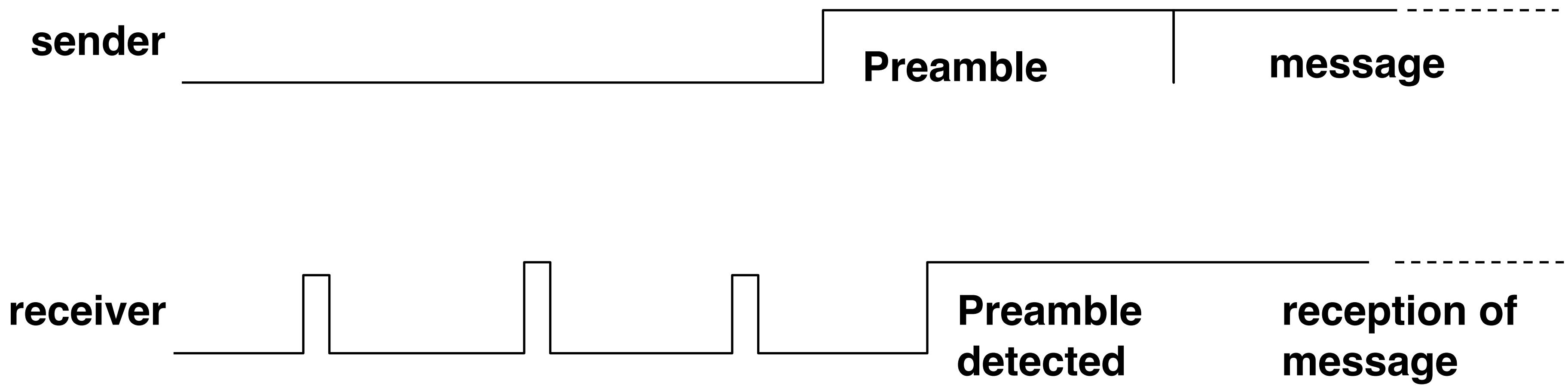
Future Requests to Send (FRTS)

As the FRTS packet would disturb the data packet that follows the CTS, the data packet must be postponed for the duration of the FRTS packet. To prevent any other node from taking the channel during this time, the node that sent the initial RTS (node A in Figure 3.5) transmits a small Data-Send (DS) packet. After the DS packet, it must immediately send the normal data packet. Since the FRTS packet has the same size as a DS packet, it will collide with the DS packet, but not with the following data packet. The DS packet is lost, but that is no problem: it contains no useful information.

J.M. van Dam: An Adaptive Energy-E cient MAC Protocol for Wireless Sensor Networks June, 2003

Variations: Low Power Listening

1.)



2.) Sender knows when the receiver is ready. Temporal coordination!

J. Hill, D. Culler: MICA: A wireless platform for deeply embedded networks. IEEE Micro 22(6), Nov. 2002

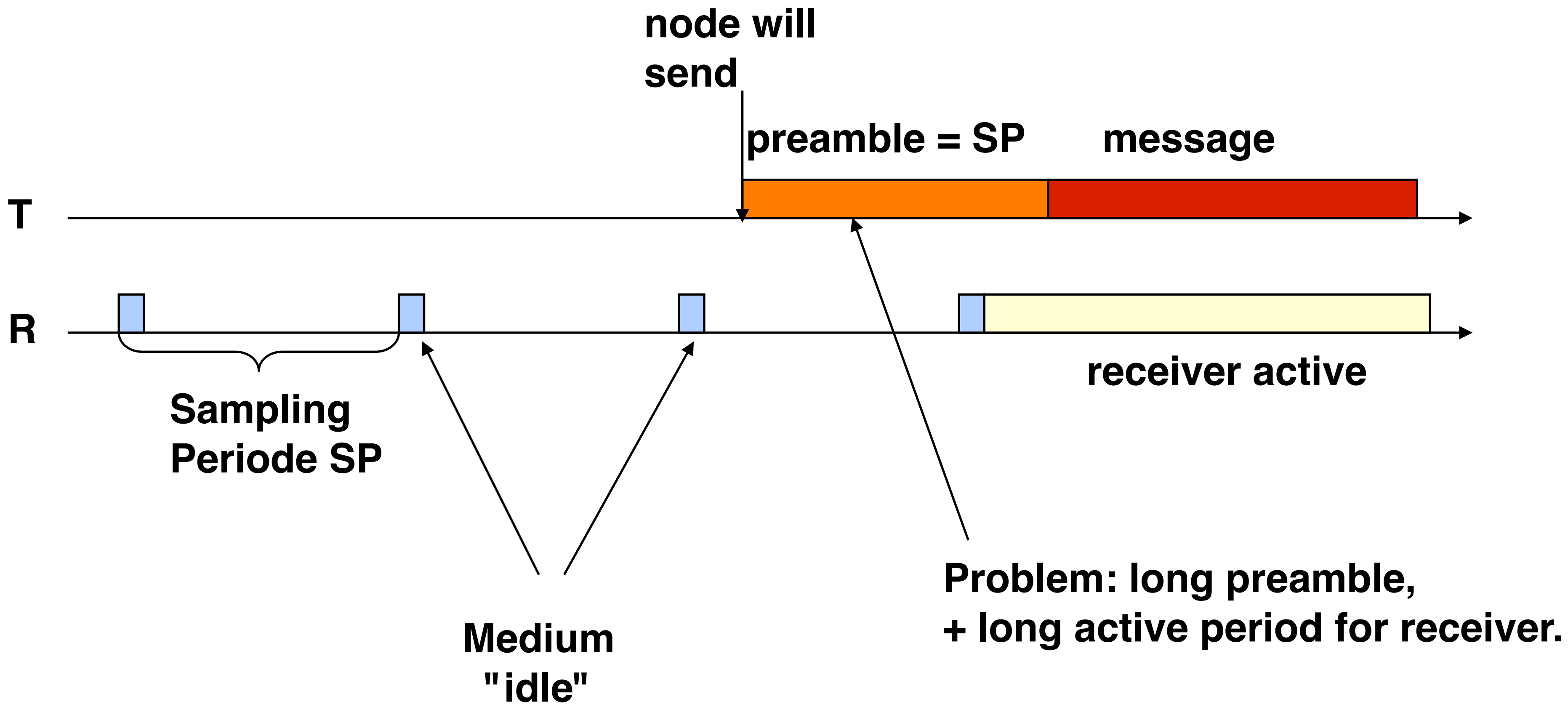
A. El-Hoiyi: Aloha with preamble sampling for sporadic traffic in ad-hoc wireless sensor networks, IEEE Int. Conf. on Comm. (ICC) New York, Apr. 2002

Low Power protocol: WiseMAC

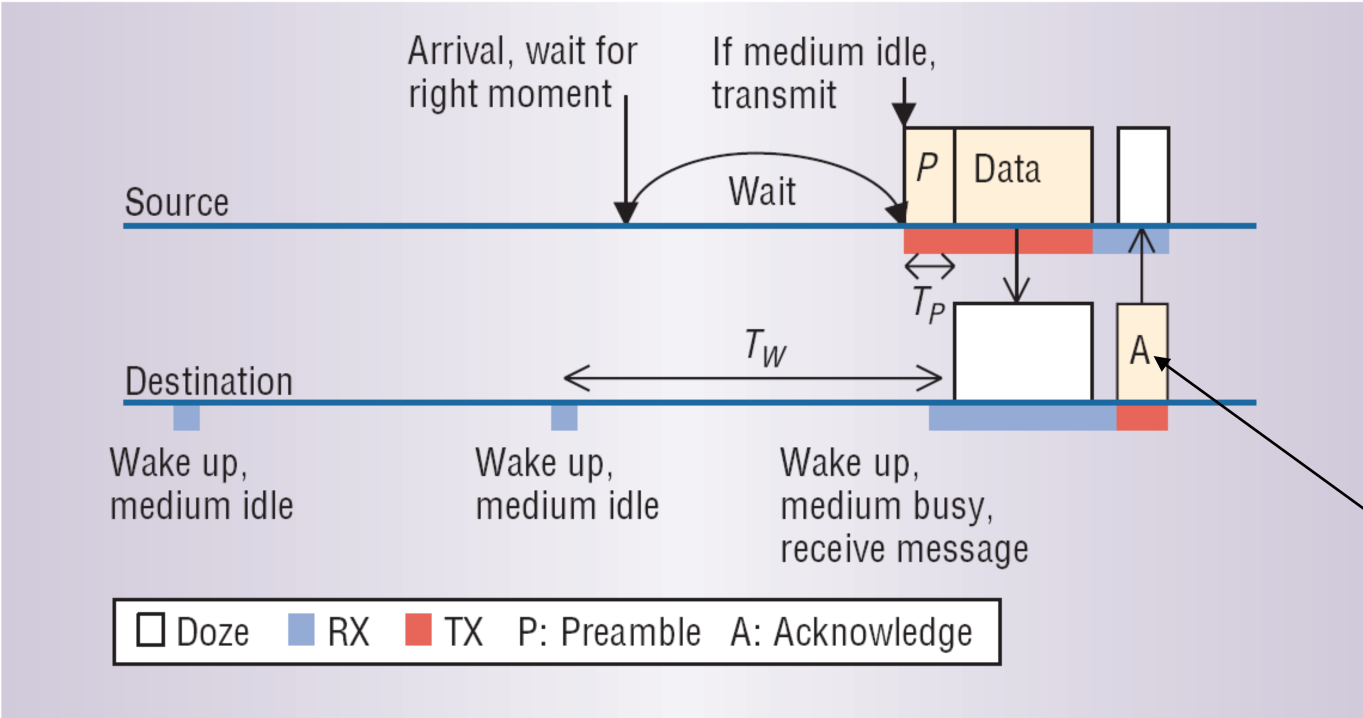
Christian C. Enz, Amre El-Hoiydi, Jean-Dominique Decotignie, Vincent Peiris (Swiss Center for Electronics and Microtechnology):
WiseNET: An Ultralow-Power WirelessSensor Network Solution, IEEE Computer, August 2004

WiseMac exploits an optimized form of "Preamble Sampling"

Standard Preamble Sampling



Low Power protocol: WiseMAC

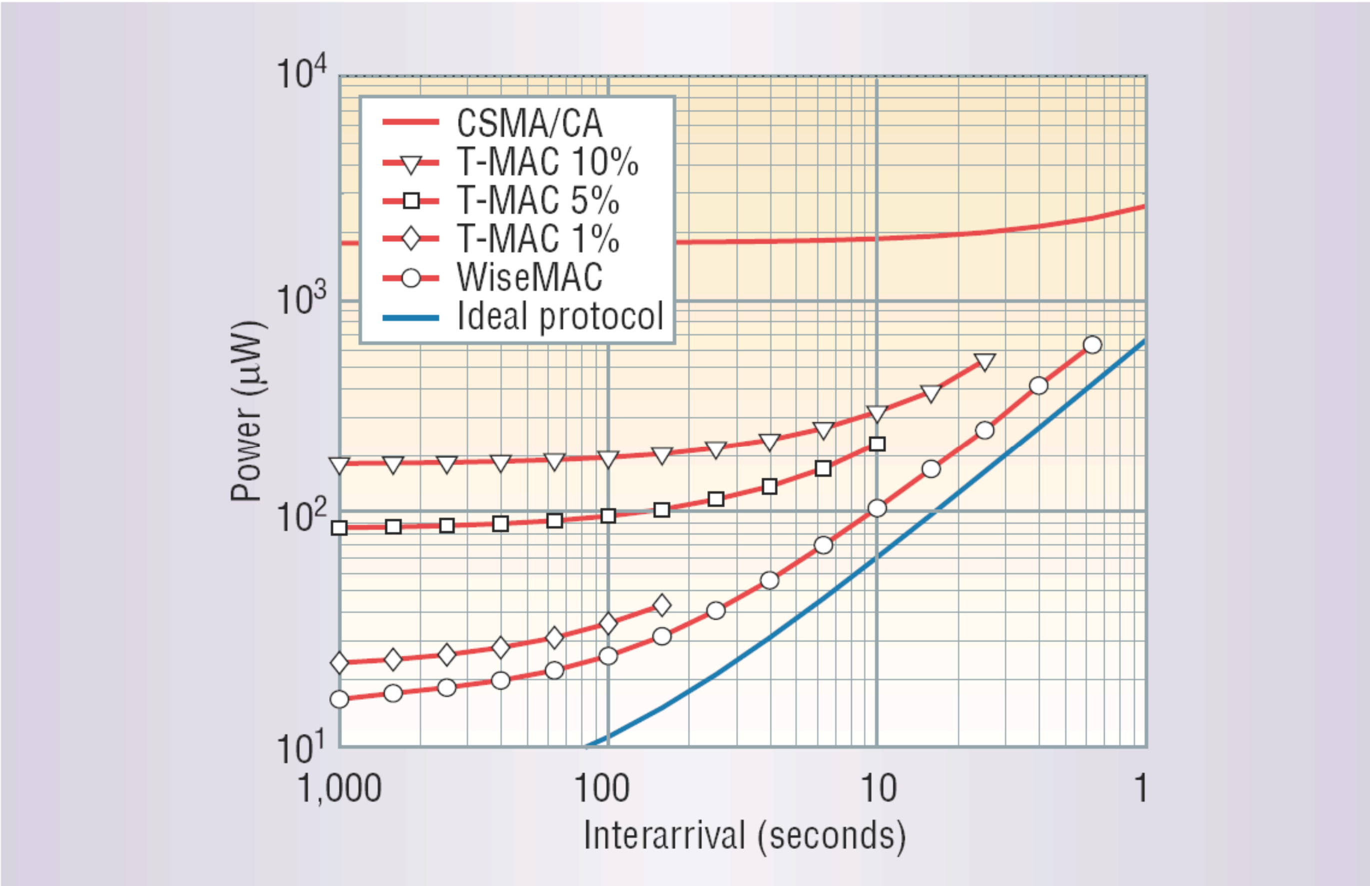


sampling period is piggy-backed in the ack.

In WiseMAC the sender adapts to the receiver's sampling period.

Christian C. Enz, Amre El-Hoiydi, Jean-Dominique Decotignie, Vincent Peiris (Swiss Center for Electronics and Microtechnology): WiseNET: An Ultralow-Power WirelessSensor Network Solution, IEEE Computer, August 2004

Comparing Low Power Protols; every node has 8 neighbors.



T-MAC:
% of packet loss because of collisions.

WiseMAC:

"With an interarrival time of 100 seconds, the power consumption amounts to as little as 25 microwatts—which translates into more than a five-year lifetime for a single AA alkaline battery."

Christian C. Enz, Amre El-Hoiydi, Jean-Dominique Decotignie, Vincent Peiris (Swiss Center for Electronics and Microtechnology):
WiseNET: An Ultralow-Power WirelessSensor Network Solution, IEEE Computer, August 2004

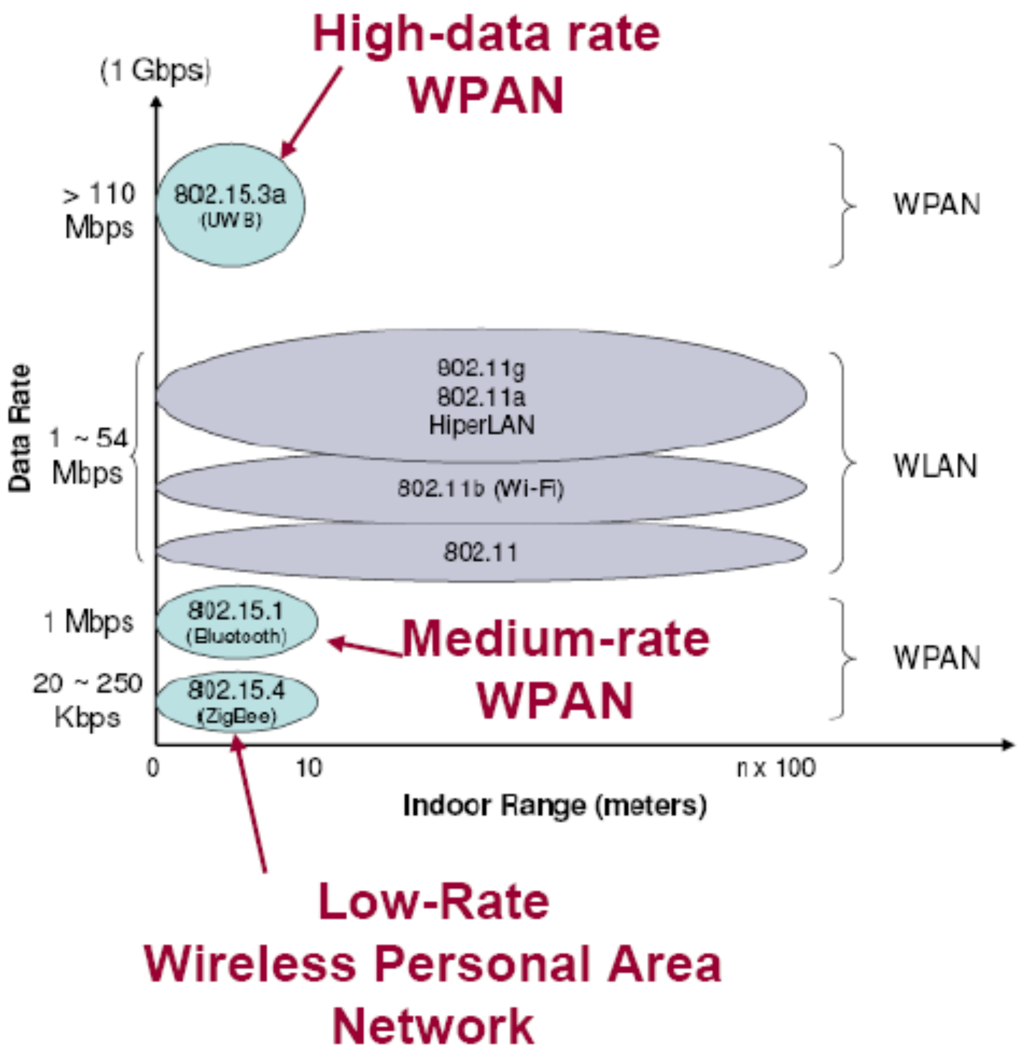
IEEE 802.15.4 WPAN

- 2 types of WPAN devices
- Network Topologies
- Architecture

Standard specifies:

- IEEE 802.15.4 PHY Layer
- IEEE 802.15.4 MAC Layer

ZigBee Alliance:
provides for upper layer services



References:

- IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks
Specific requirements—Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY), Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)
Sponsor: LAN/MAN Standards Committee of the IEEE Computer Society
Approved 12 May 2003. IEEE-SA Standards BoardJoe

- Dvorak, Motorola, IEEE 802.15.4 and Zigbee Overview, 27.09.05

- Steven Myers, Electrical and Computer Engineering University of Wisconsin Madison, ZigBee/IEEE 802.15.4

- Jose Gutierrez “IEEE 802.15.4 Tutorial” , Eaton Corporation, Jan. 2003.

- Marco Naeve “IEEE 802.15.4 MAC Overview” Eaton Corporation, May 2004.

ZigBee

– Small packets over large network
– Data rate 250 kbps @2.4 GHz
– Allows up to 254 nodes
– Simplified protocol stack
– Used in time critical applications (15msec wake up time)
– Allows guaranteed transmission of critical messages
– Mostly Static networks with many, infrequently used devices

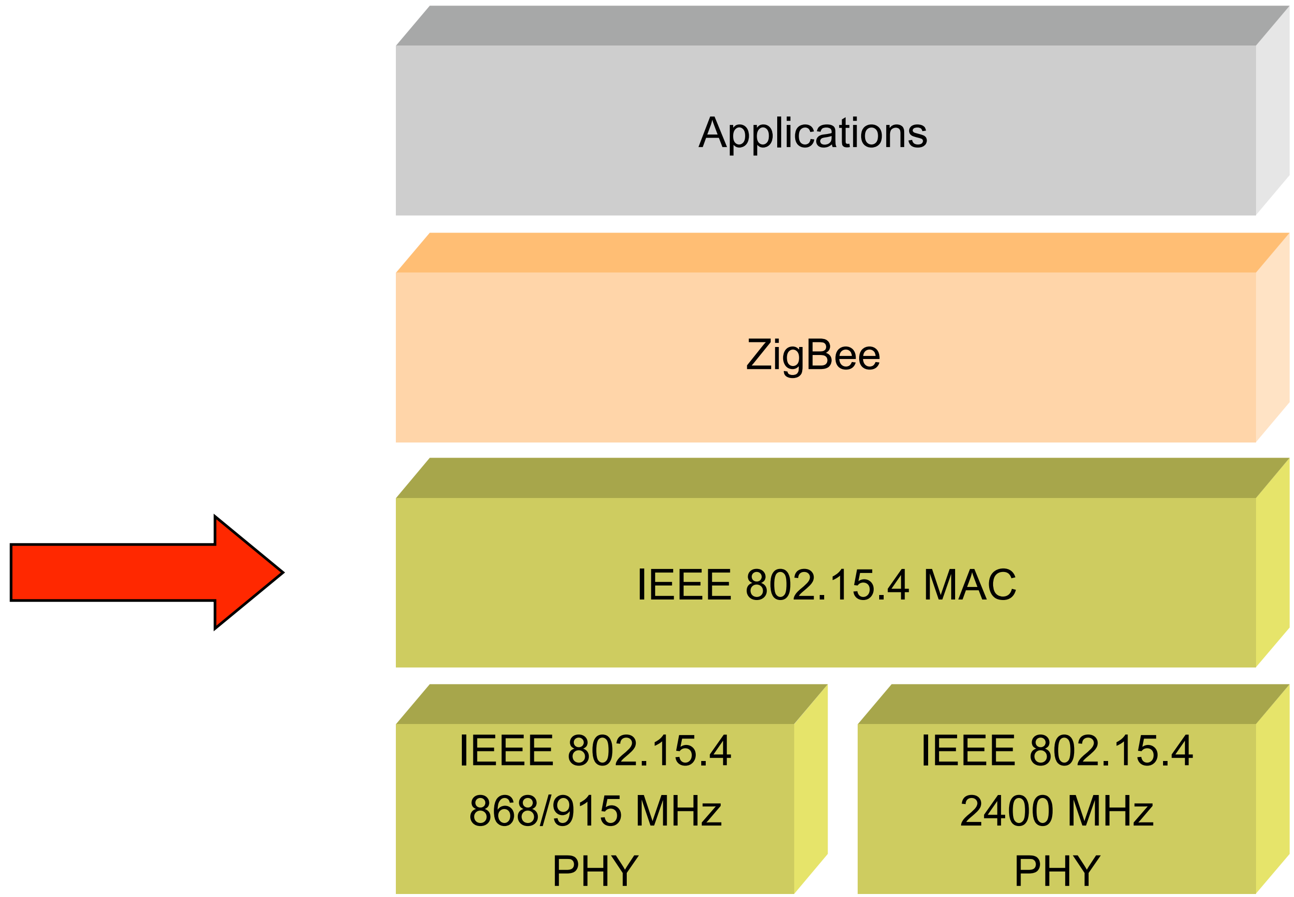
Bluetooth
– Large packets over small network
– Data rate is 1Mbps @2.4 GHz
– Allows up to 8 nodes in piconet setup
– More complex protocol stack
– Not so time critical (3sec wake up time)
– Ad-hoc networks
– File transfer

Wireless Technology Comparison Chart

Standard	Bandwidth	Power Consumption	Protocol Stack Size	Stronghold	Applications
Wi-Fi	Up to 54Mbps	400+mA TX, standby 20mA	100+KB	High data rate	Internet browsing, PC networking, file transfers
Bluetooth	1Mbps	40mA TX, standby 0.2mA	~100+KB	Interoperability, cable replacement	Wireless USB, handset, headset
ZigBee	250kbps	30mA TX, standby **356 μA**	**34KB /14KB**	Long battery life, low cost	Remote control, battery-operated products, sensors

Joe Dvorak, Motorola

802.15.4 Architecture

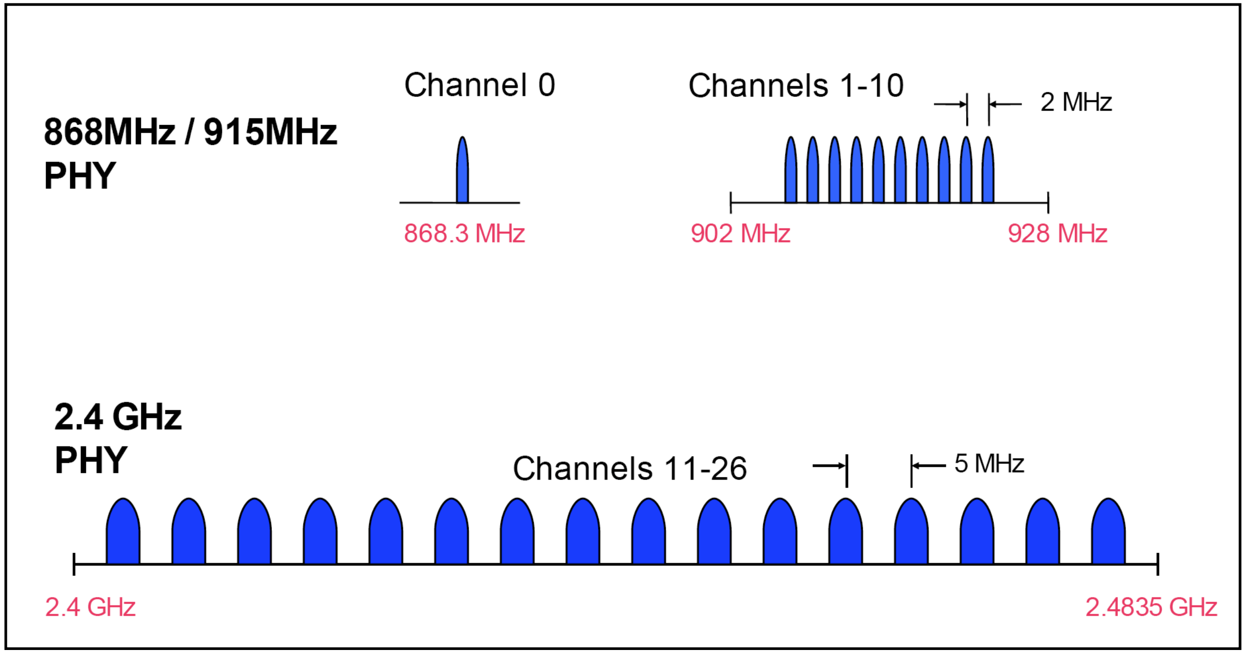


- Network Routing
- Address translation
- Packet Segmentation
- Profiles

Provides two services to physical layer management entity (PLME)

– ***PHY data service***
- **exchange data packets between MAC and PHY**

– ***PHY management service interface***
- **Clear channel assessment (CCA)**
  - **– 3 methods:**
    Energy above threshold,
    Carrier sense only, or
    Carrier sense w/ energy above threshold
- **Energy detection (ED)**
  - **– Used by network layer (channel selection)**
- **Link Quality Indication (LQI)**
  - **– Used by higher layers**
  - **– Uses ED and/or SNR estimate**

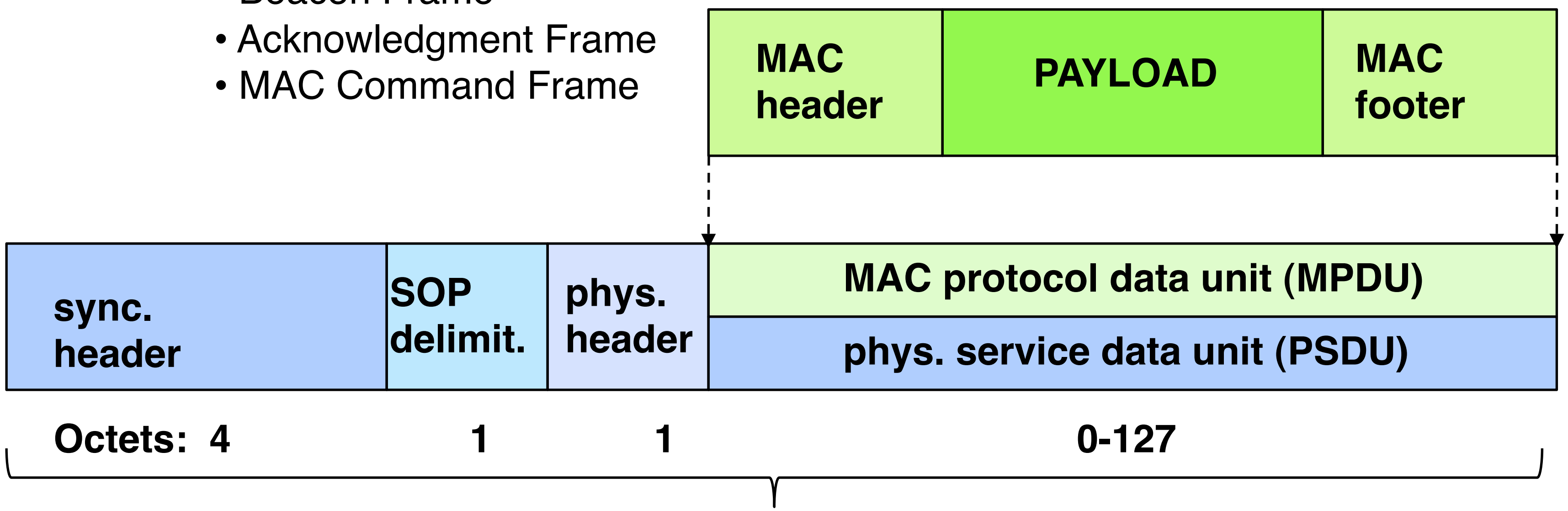


802.15.4 Channel Assignment

Steven Myers
Electrical and Computer Engineering
University of Wisconsin Madison

PHY packet format and MAC frame format

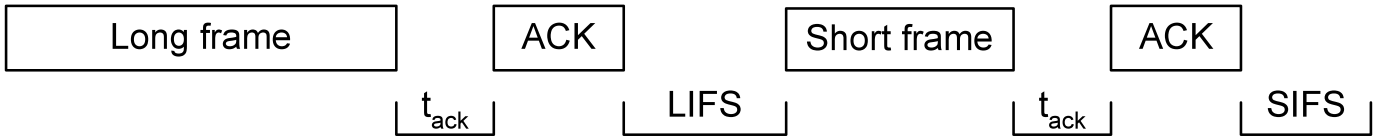
Types of MAC Frames:
- Data Frame
- Beacon Frame
- Acknowledgment Frame
- MAC Command Frame



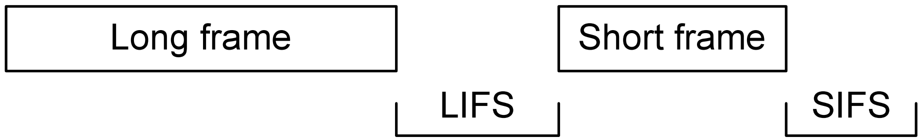
PHY Packet Fields:
- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field

Interframe Spacing

Acknowledged transmission



Unacknowledged transmission



aTurnaroundTime ≤ t_{ack} ≤ (*aTurnaroundTime* (12 symbols) + *aUnitBackoffPerio*d (20 symbols))
LIFS > *aMaxLIFSPeriod* (40 symbols)
SIFS > *aMacSIFSPeriod* (12 symbols)

For frames ≤ *aMaxSIFSFrameSize use short inter-frame spacing (SIFS)*
For frames > *aMaxSIFSFrameSize use long inter-frame spacing (LIFS)*

802.15.4 MAC Layer

Provides two services to the MAC sublayer management entity (MLME)

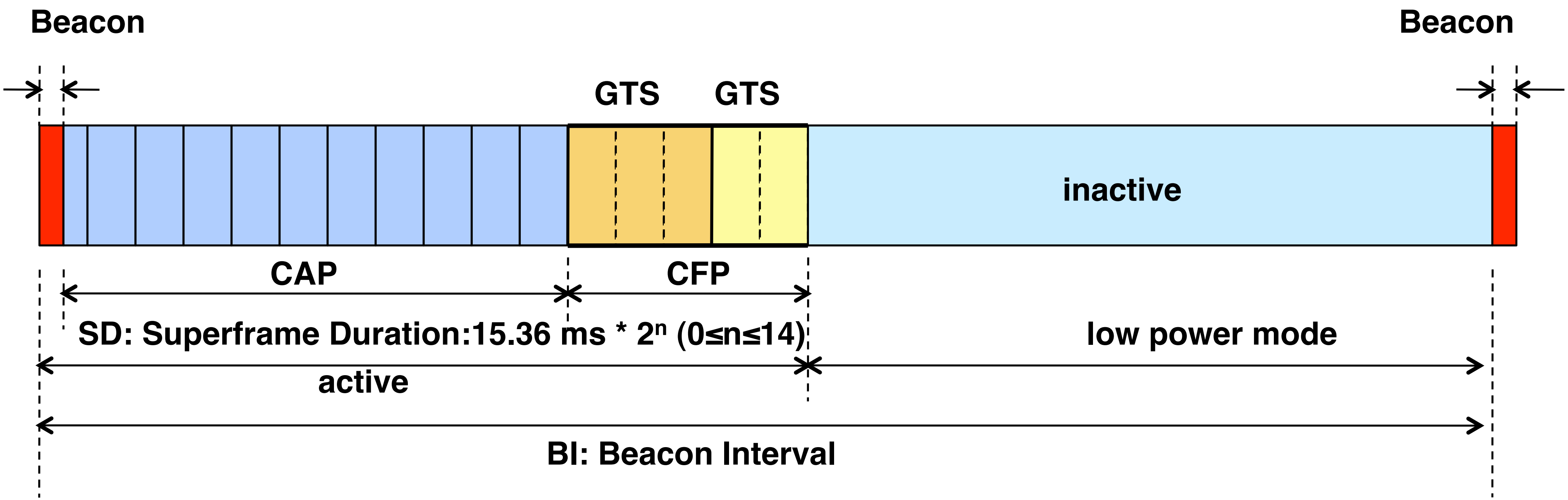
MAC data service

- **Enables transmission and reception of MAC protocol data units (MPDU) across PHY data service**

MAC management service

- **Beacon management**
- **Channel access**
- **GTS management**
- **Frame validation**
- **ACK frame delivery**
- **Association and disassociation**

Optional Superframe Structure



Beacon: sent by PAN coordinator in the first slot of the superframe. Contains network information, frame structure and notification of pending node messages.

Contention Access Period (CAP): Communication using slotted CSMA-CA

Contention Free Period (CFP): Guaranteed time slots (GTS) given by coordinator (no CSMA)

Beacon Order (BO): Describes the interval at which the coordinator shall transmit its beacon frames.

Superframe Order (SO): Describes the length of the active portion of the superframe.

Arbitration

Slotted CSMA-CA:

Used in superframe structure
Backoff periods are aligned with superframe slot boundaries of PAN coordinator

Used in CAP, must locate boundary of the next backoff period to transmit data

Un-slotted CSMA-CA:

Non beacon enabled network
Backoff periods are not synchronized between devices

Collision Avoidance

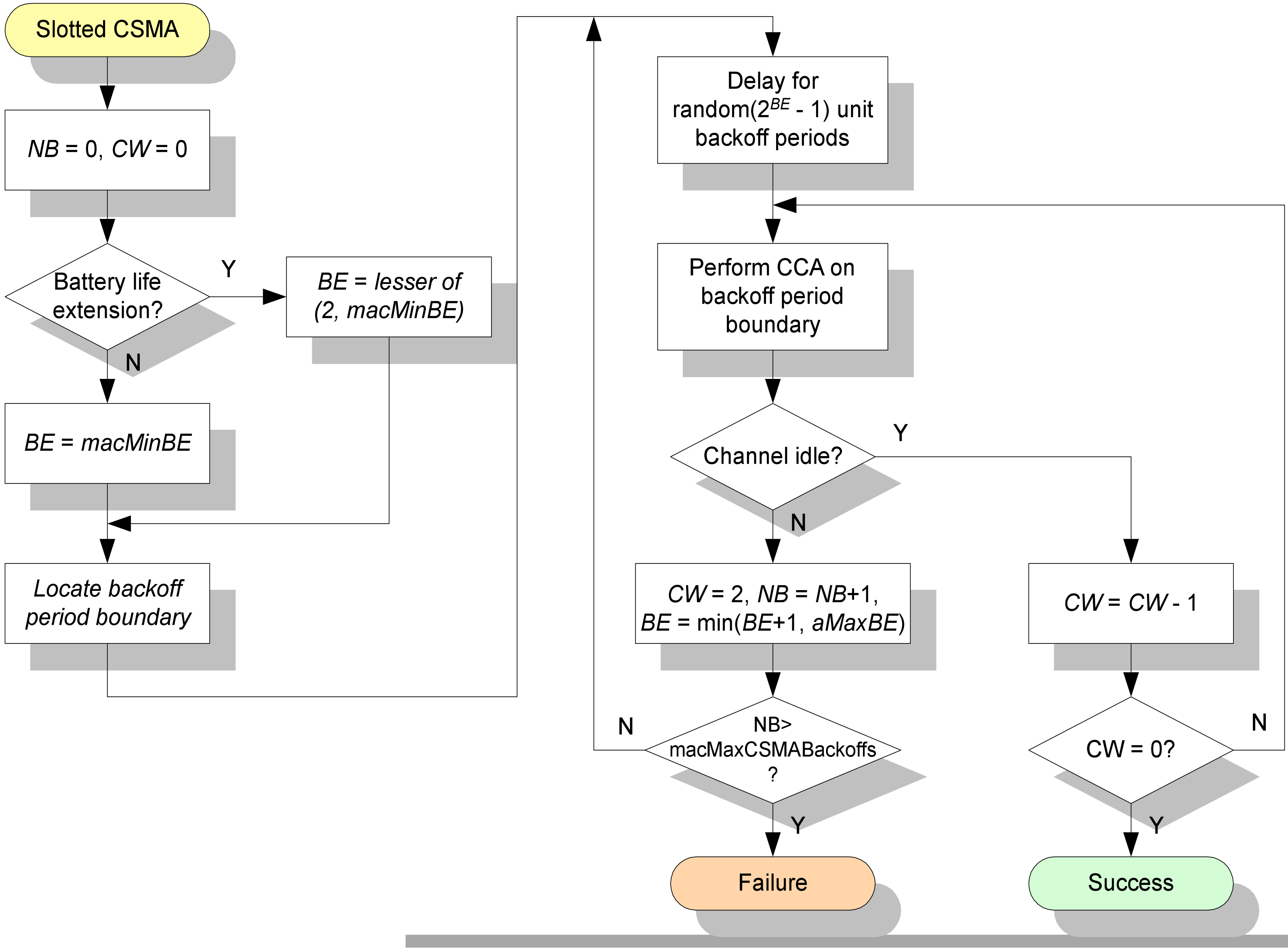
Each device has three variables:

NB is the number of times the CSMA-CA was required to backoff while attempting a current transmission.

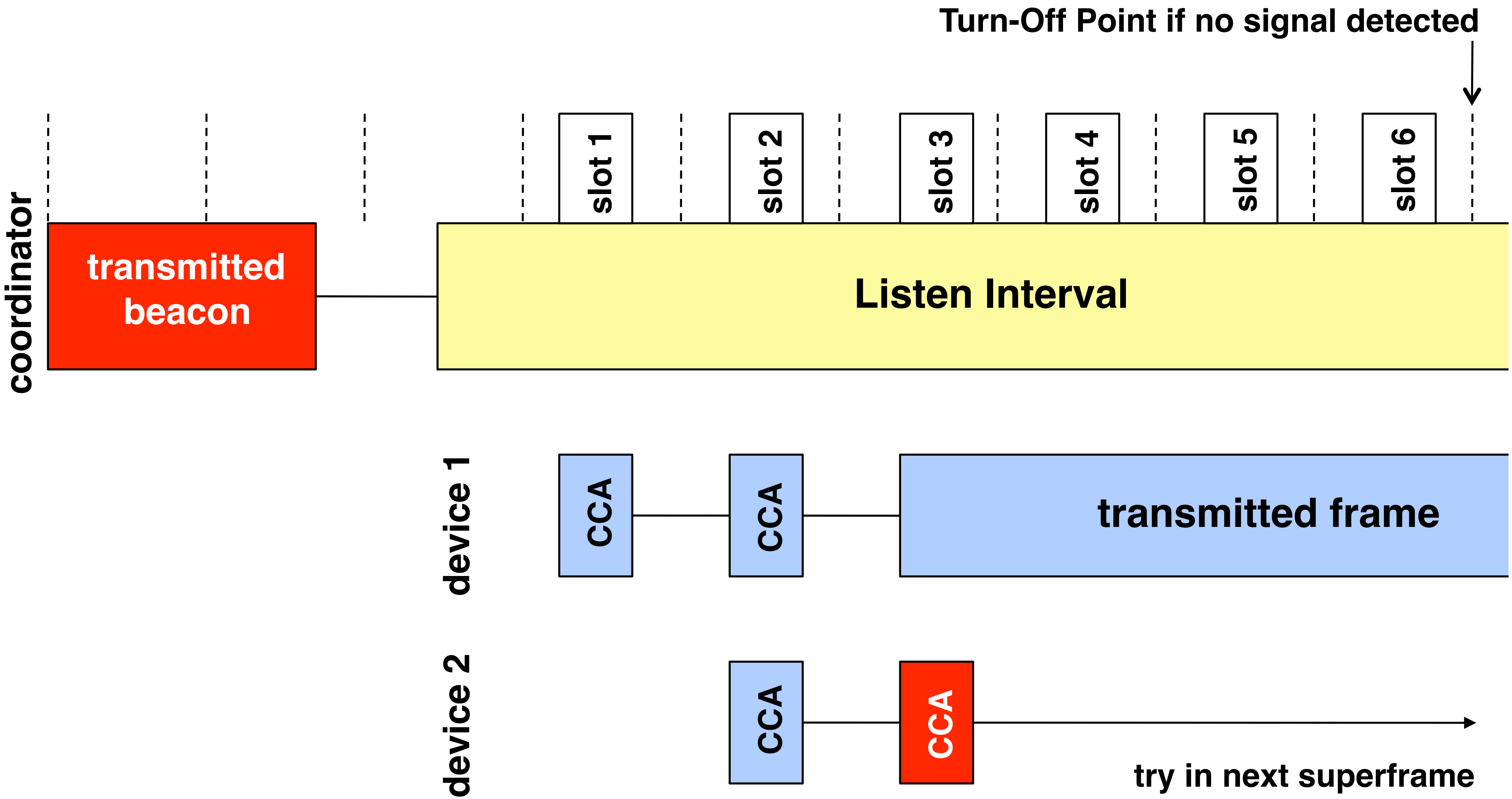
CW is the contention window length, which defines the number of backoff periods that needs to be clear of activity before a transmission can start.

BE is the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to assess the channel.

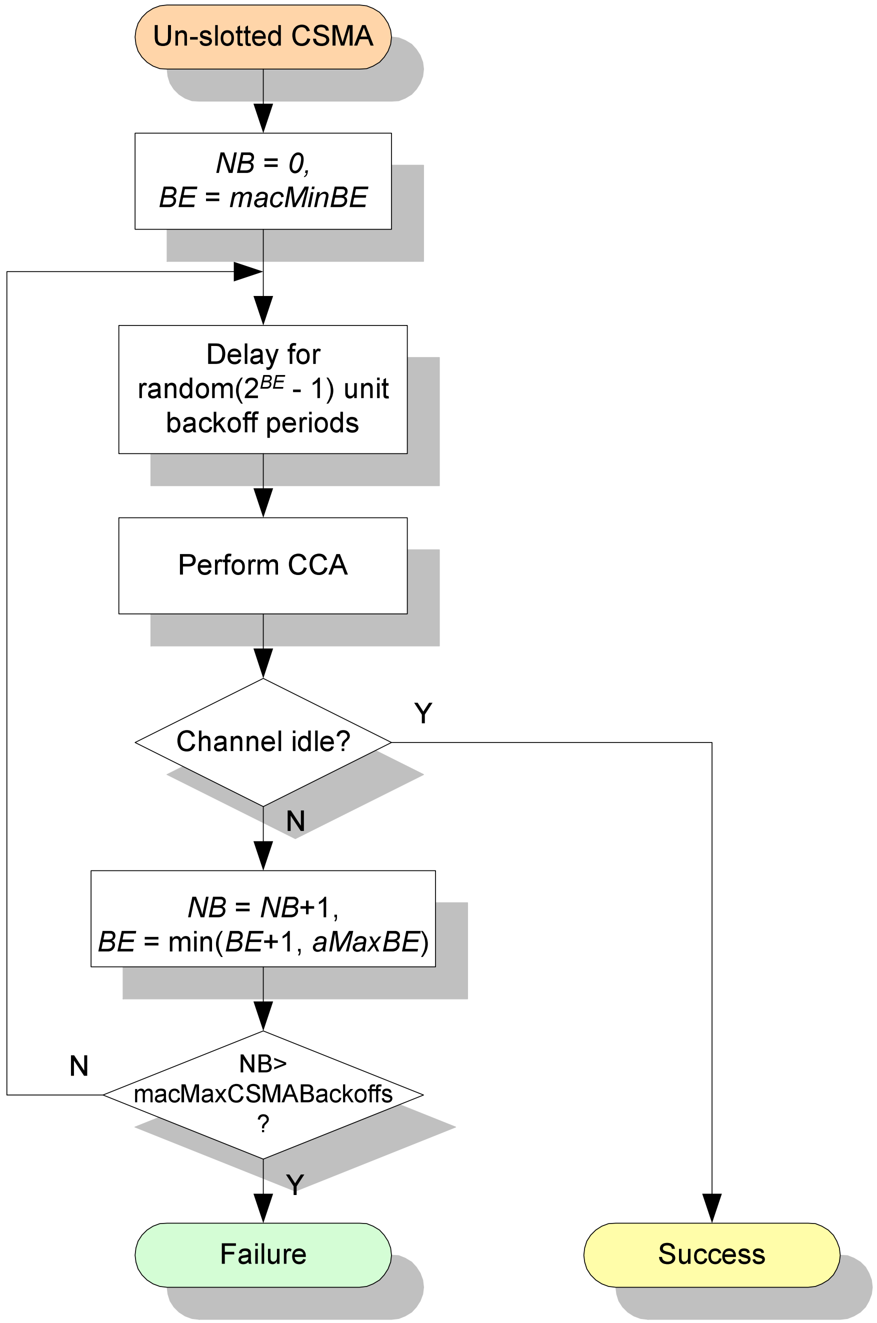
Arbitration in Slotted CSMA



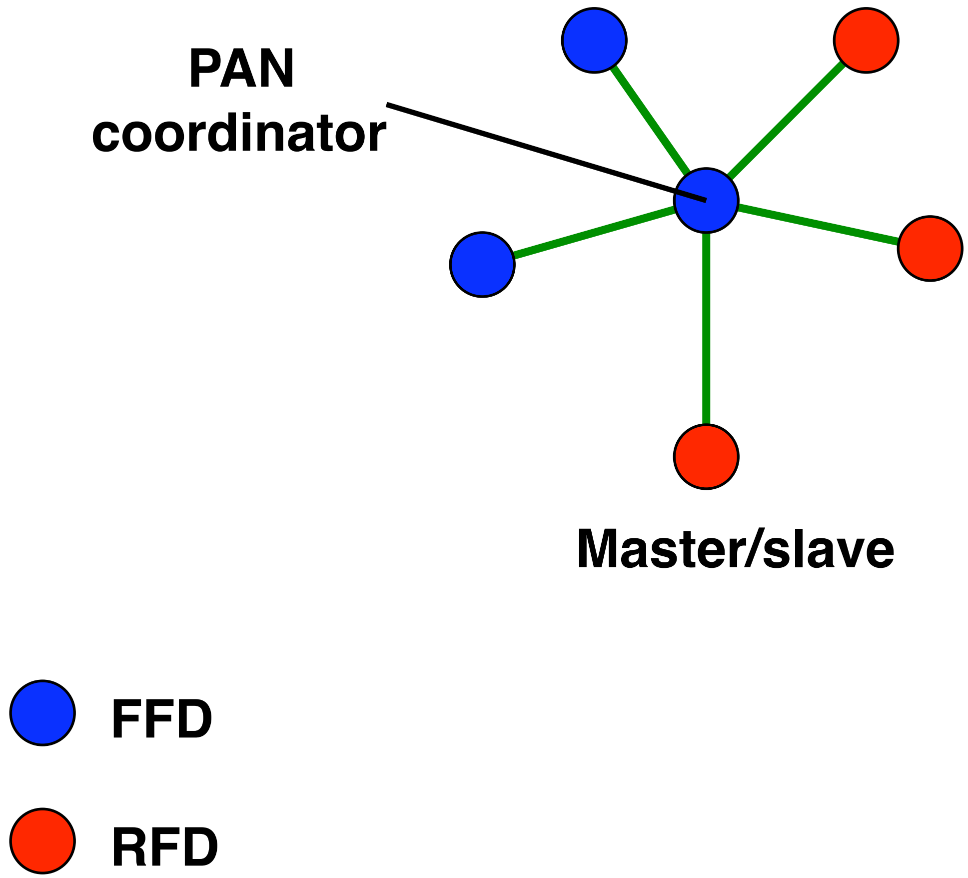
Battery Life Extension (BLE)



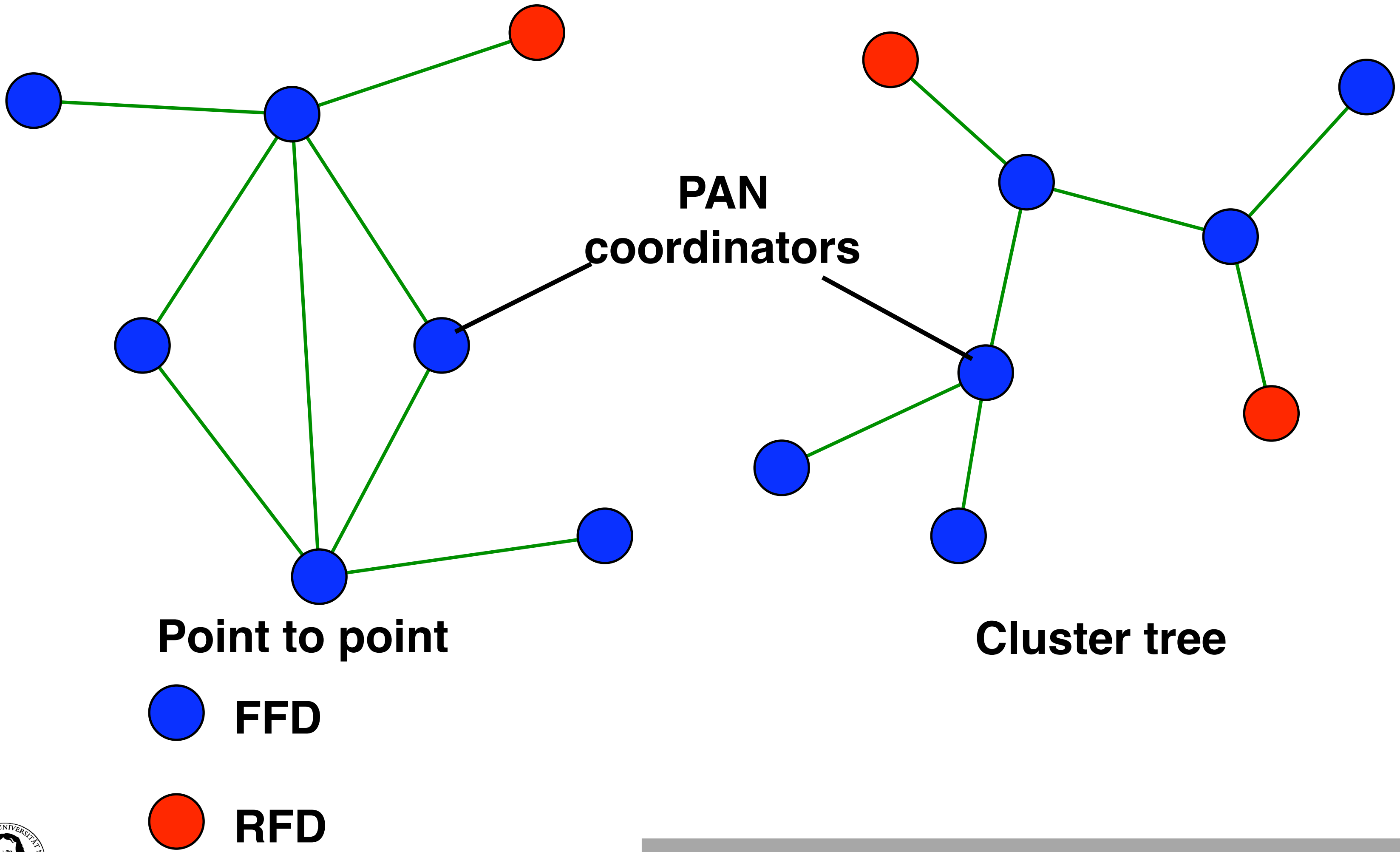
Arbitration in Unslotted CSMA



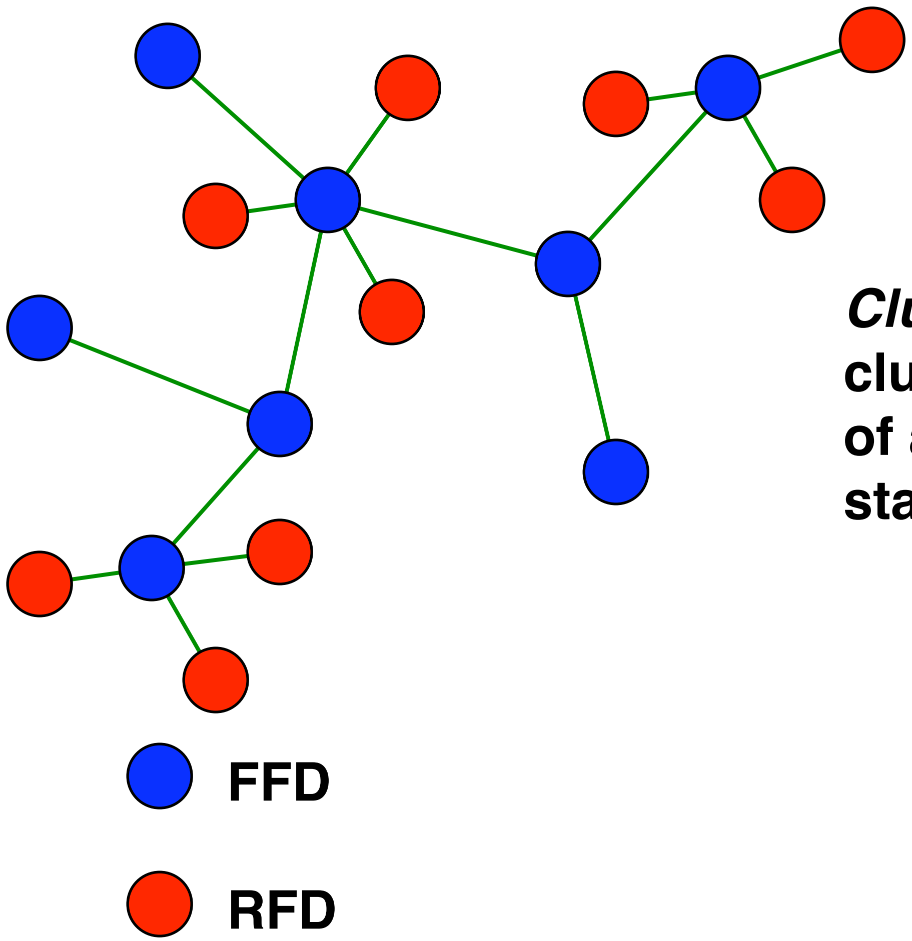
Star Topology



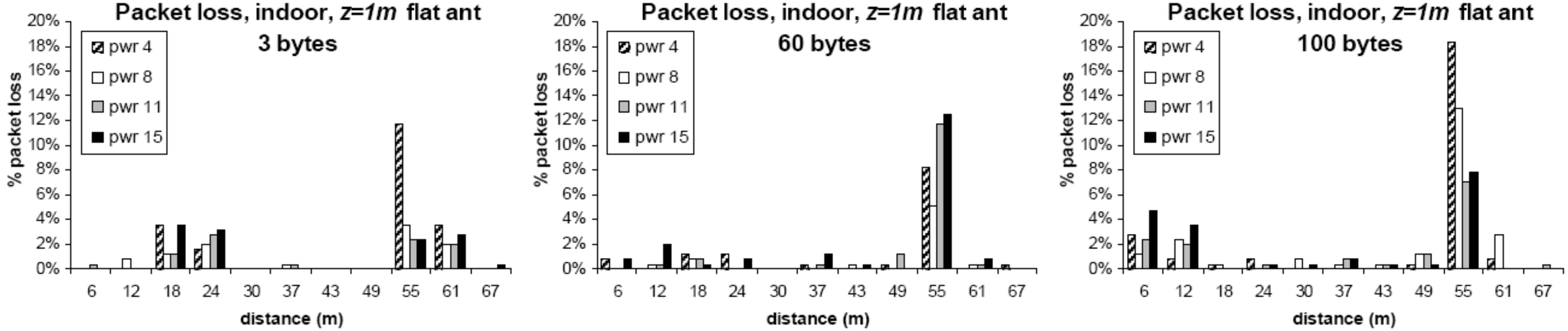
Peer-Peer Topology



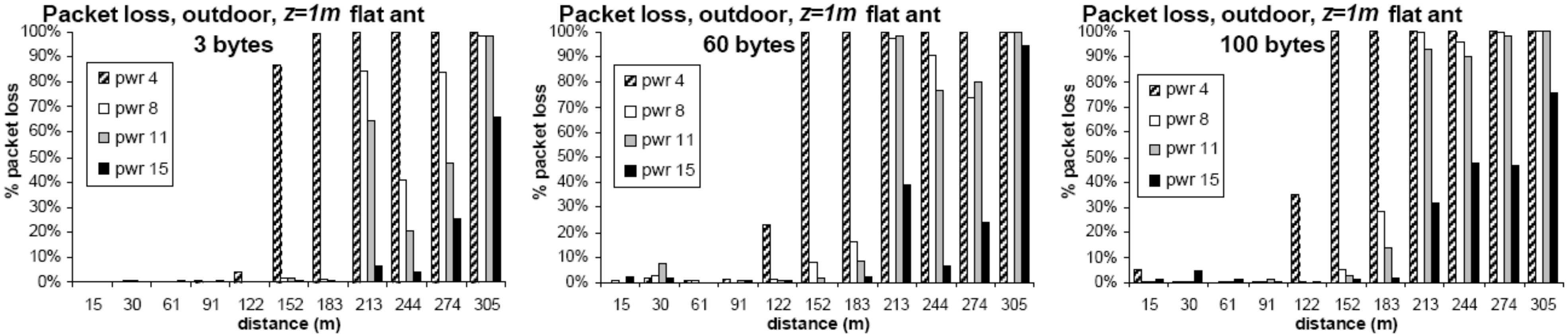
Clustered stars



Clustered stars **- for example, cluster nodes exist between rooms of a hotel and each room has a star network for control.**



Indoor range test, 1m node height, flat antenna orientation, three packet sizes



Outdoor range test, 1m node height, flat antenna orientation, three packet sizes

Steven Myers, Suman Banerjee, Seapahn Megerian, and Miodrag Potkonjak
Experimental Investigation of IEEE 802.15.4 Transmission Power Control and Interference Minimization
4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2007. SECON '07, San Diego, CA, June 2007

Embedded Networks

- o Introduction
- o Models of communication
- o Dependability and fault-tolerance
  - * Attributes and measures of Dependability
  - * Basic techniques of Fault-Tolerance
- o Time, Order and Clock synchronization
- o The physical network layer
- o Protocols for timely and reliable communication
  - * Controller Area Network (CAN-Bus)
  - * Time Triggered Protokoll (TTP/C)
  - * Byteflight, Flexray
  - * LIN, TTP/A
  - * Token protocols
- o Sensornets
  - * Protocols for wireless communication
  - * Energy-efficient MAC-protocols