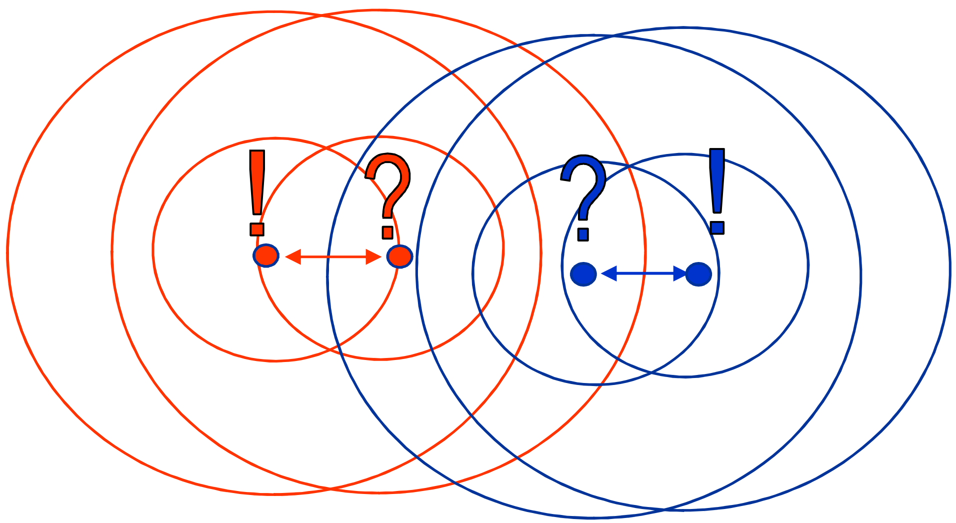
The MAC layer in wireless networks

- **The wireless MAC layer roles**
  - ***Access control to shared channel(s)***
    - **Natural broadcast of wireless transmission**
    - **Collision of signal: a time/space problem**
    - **Who transmits when? (and where)?**
      - **Avoid collisions (no Collision Detection)**
  - ***Scarce resources utilization***
    - **Channel capacity and battery power**
  - ***performance and QoS***
    - **System level and (or vs?) user level**
  - ***Frame organization, and intra-, inter-layer information management***
    - **Cross layering principles for adaptive behavior?**
    - **Risk for "spaghetti design" [Kumar2003]**

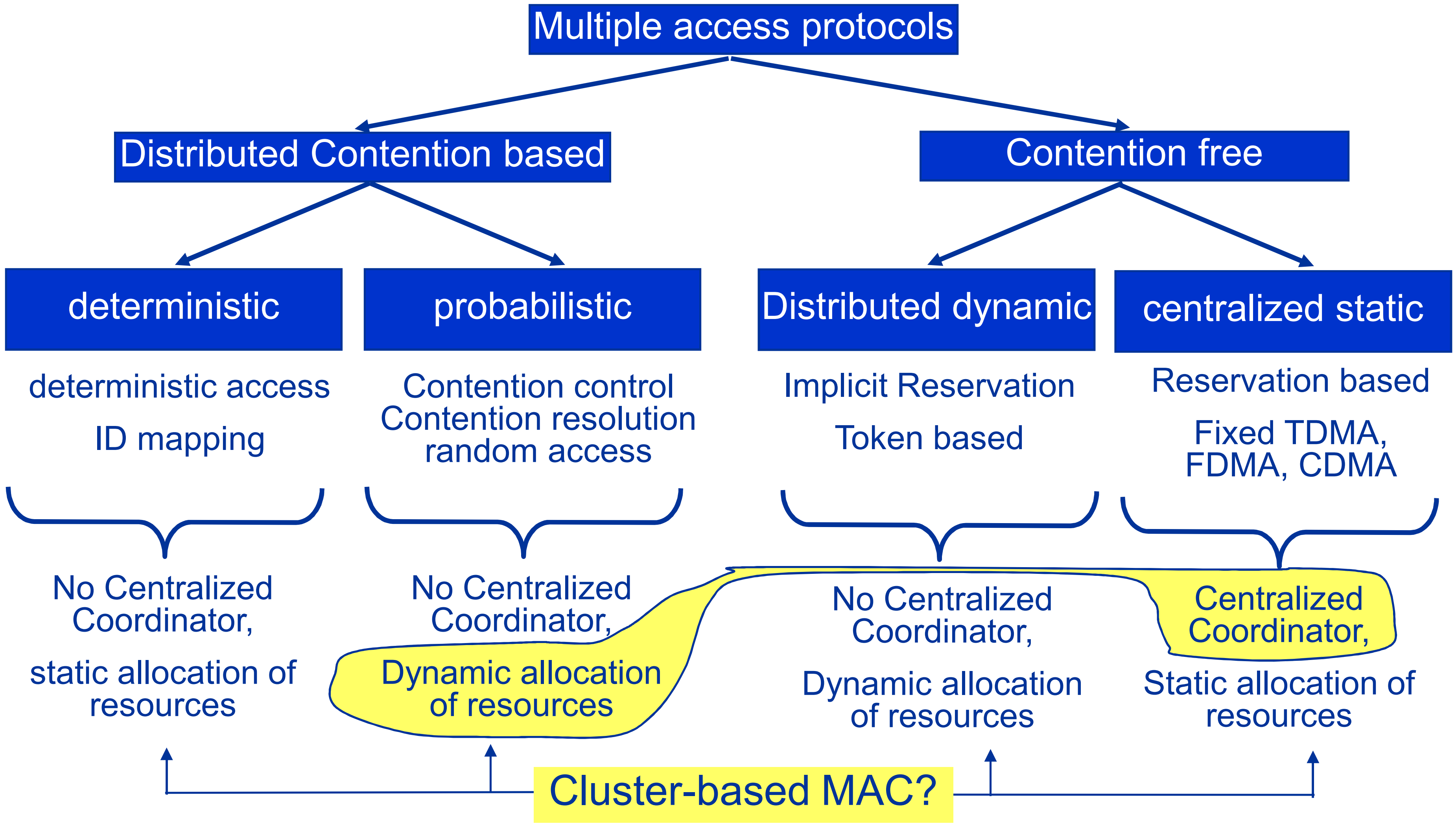
[Kumar2003] V. Kawadia, P.R. Kumar, "A Cautionary Perspective on Cross Layer Design", Submitted for publication, 2003 (http://black1.csl.uiuc.edu/~prkumar/)

Collision of wireless signals

- **Collision** has destructive effect on the receiver
  - ...causes both channel and power waste
  - Collision detection is not practical in wireless systems
  - Collision avoidance/resolution + contention control on the sender
- Capture effect is possible
  - Exploited to enhance channel reuse, if possible
- Collision domain: set of nodes sharing the same channel
  - Space splitting, transitive relation



Wireless MAC protocols' classification



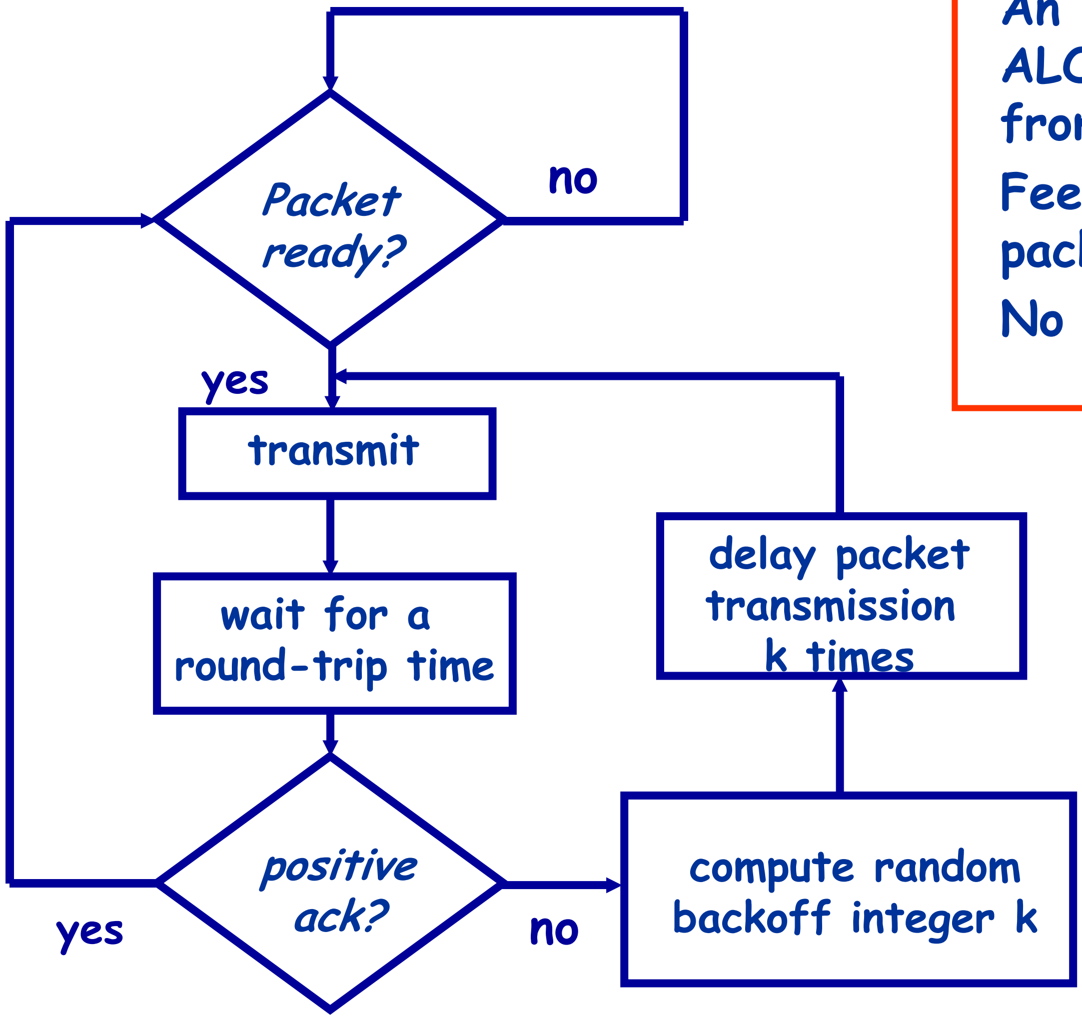
Evolutionary perspective of distributed MAC

- Distributed, contention-based wireless MAC Problem:
  - the frame vulnerability (collision risk)
  - Needs resolution in distributed way (no centralized coordinator)
- let's analyze the **time domain first**
  - Aloha [Abramson1970]: no coordination
  - Slotted Aloha
  - CSMA [Kleinrock1975]: listen before to transmit
  - Slotted CSMA
  - CSMA/CD: listen before and while transmitting
    - *(unpractical in wireless scenarios)*
    - *CSMA/CA + contention resolution (reactive resolution of collisions)*
    - *CSMA/CA + contention control (preventive/reactive reduction of risk of collisions)*

[Abramson1970]
N. Abramson, ``The ALOHA system - another alternative for computer communications'', Proc. Fall Joint Comput. Conf. AFIPS, 1970

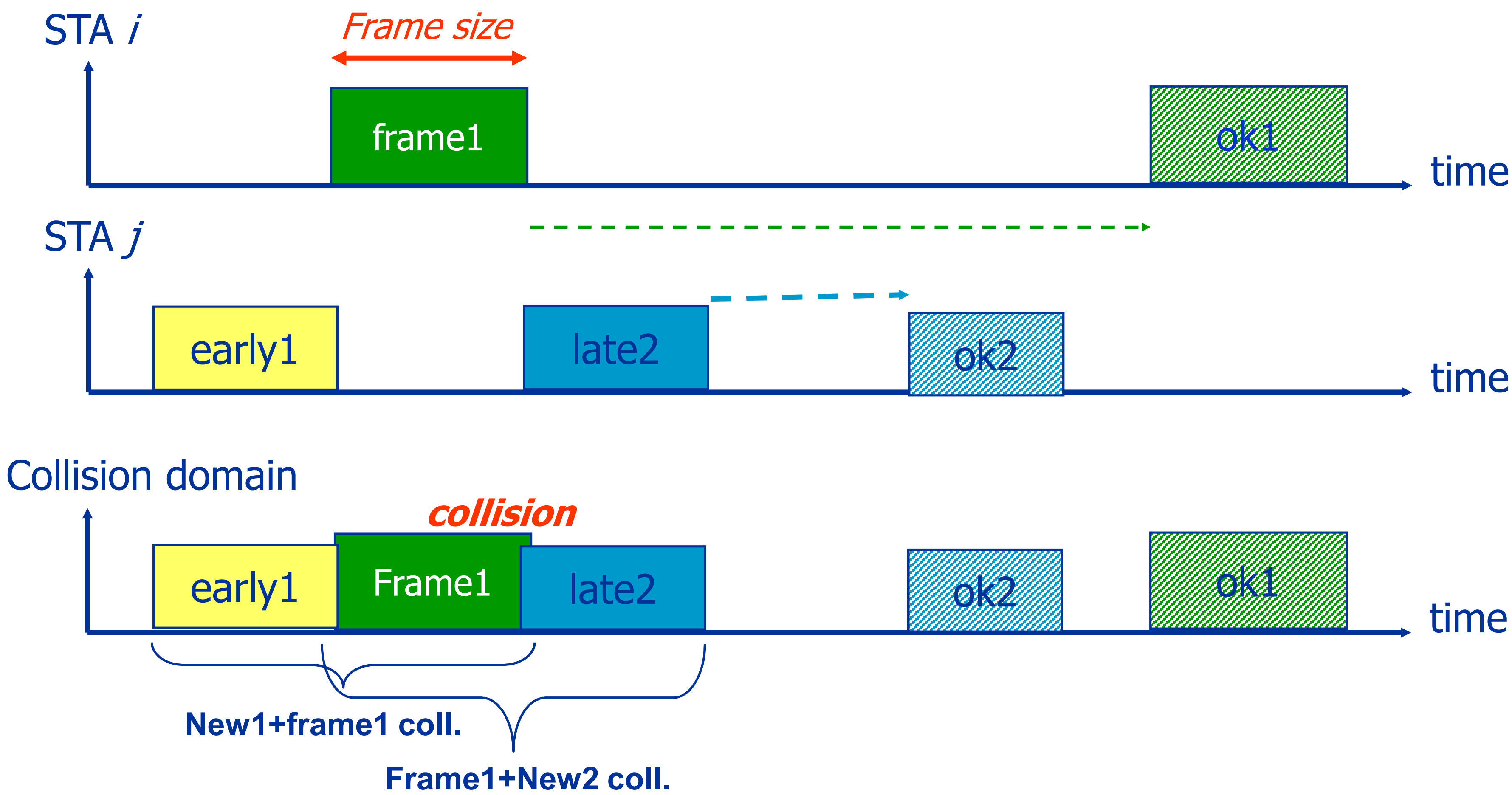
[Kleinrock1975]
L. Kleinrock, F.A. Tobagi ``Packet Switching in Radio Channels: Part I - Carrier Sense Multiple-Access modes and their throughput-delay characteristics'', IEEE Transactions on Communications, Vol Com-23, No. 12, pp.1400-1416, 1975

The ALOHA protocol



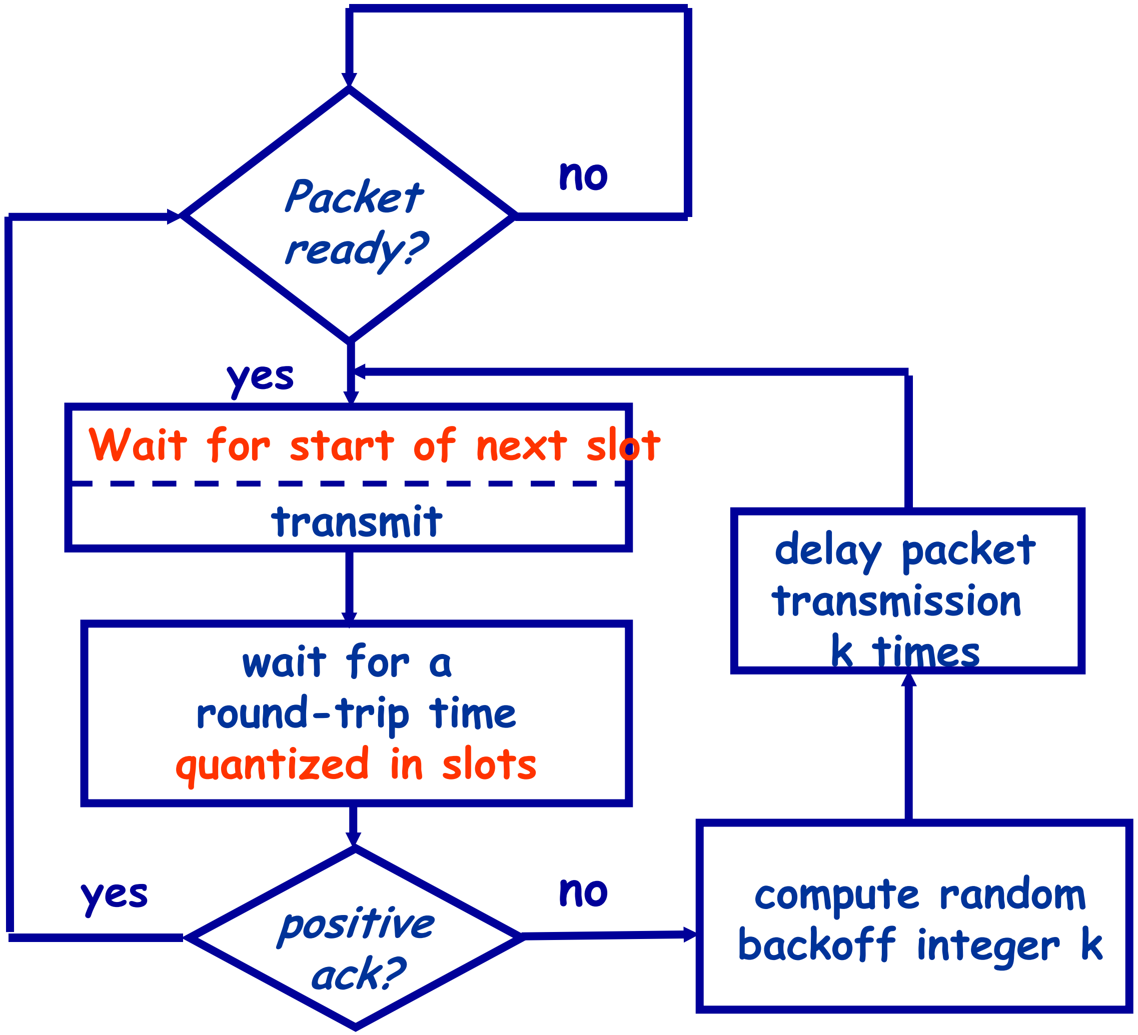
- An integral part of the ALOHA protocol is feedback from the receiver
- Feedback occurs *after* a packet is sent
- No coordination among sources

The ALOHA protocol

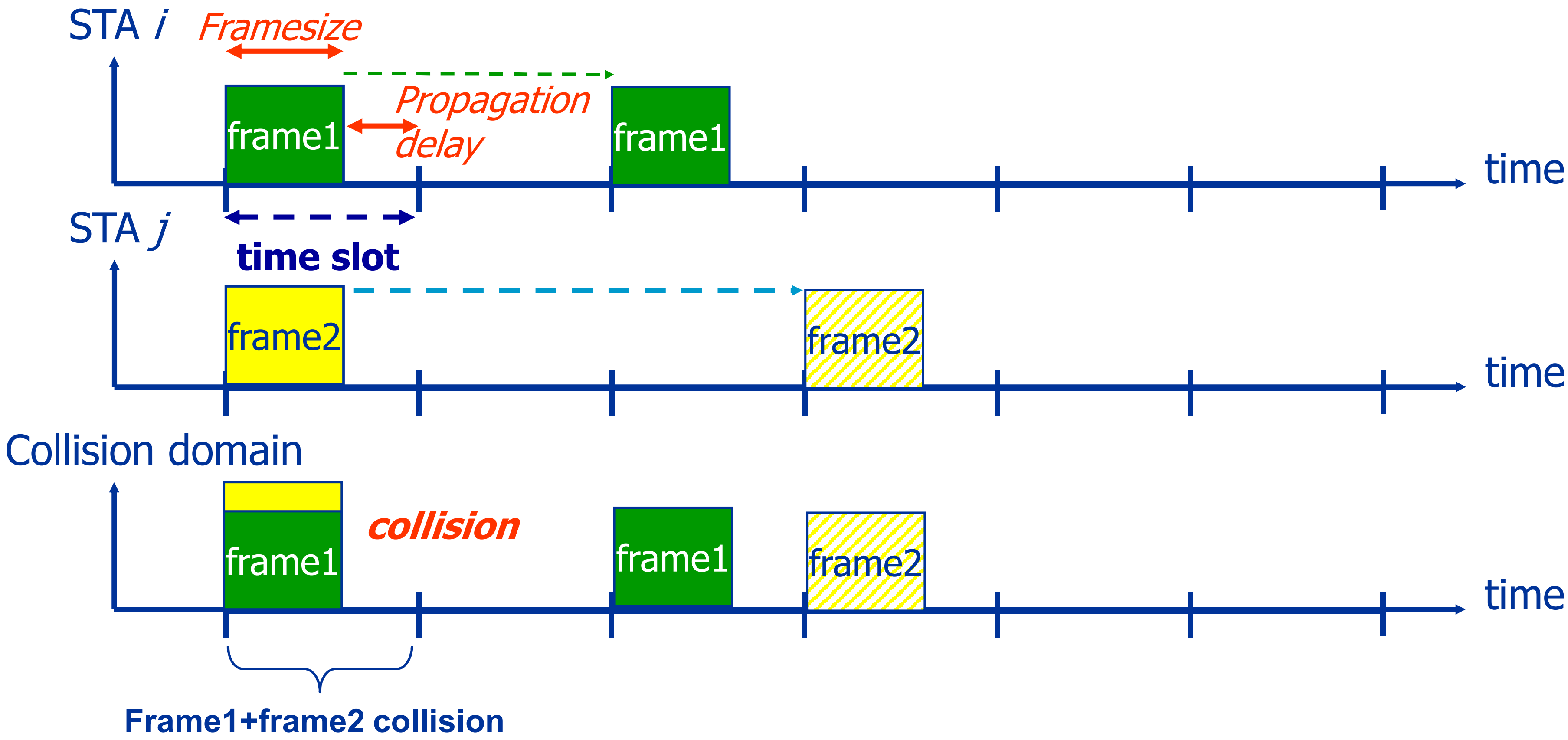


- Frame vulnerability time: twice the frame size

Slotted ALOHA

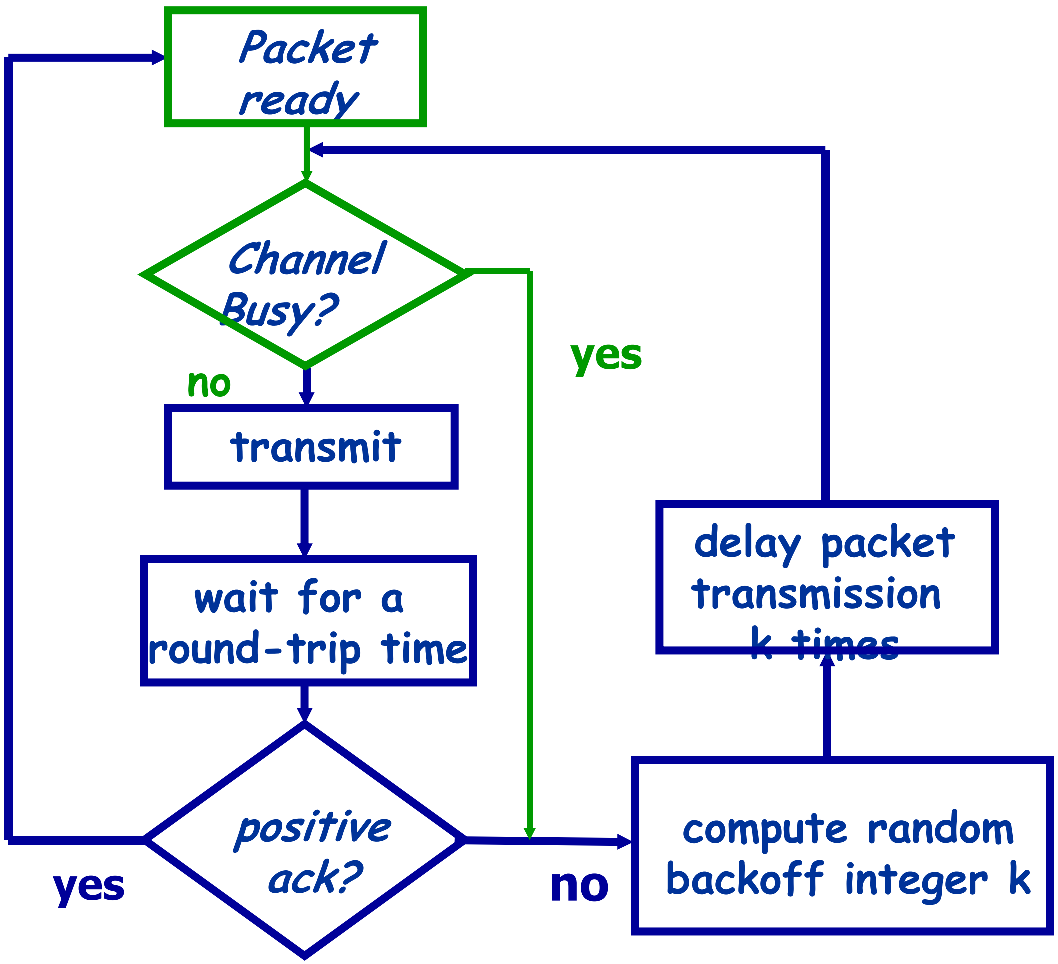


Slotted ALOHA

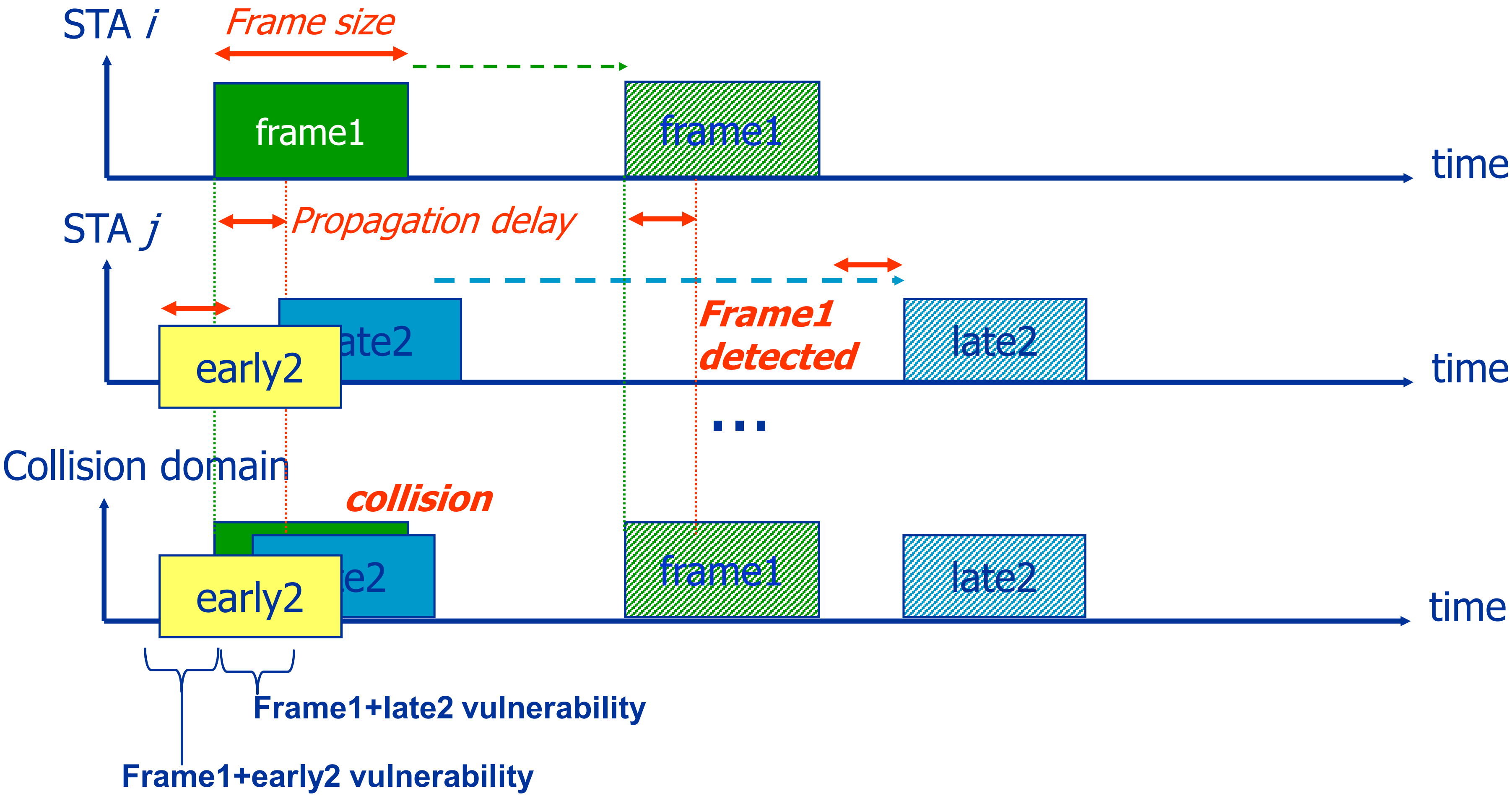


- Frame vulnerability time: the frame size (slot + propagation)

CSMA Protocol

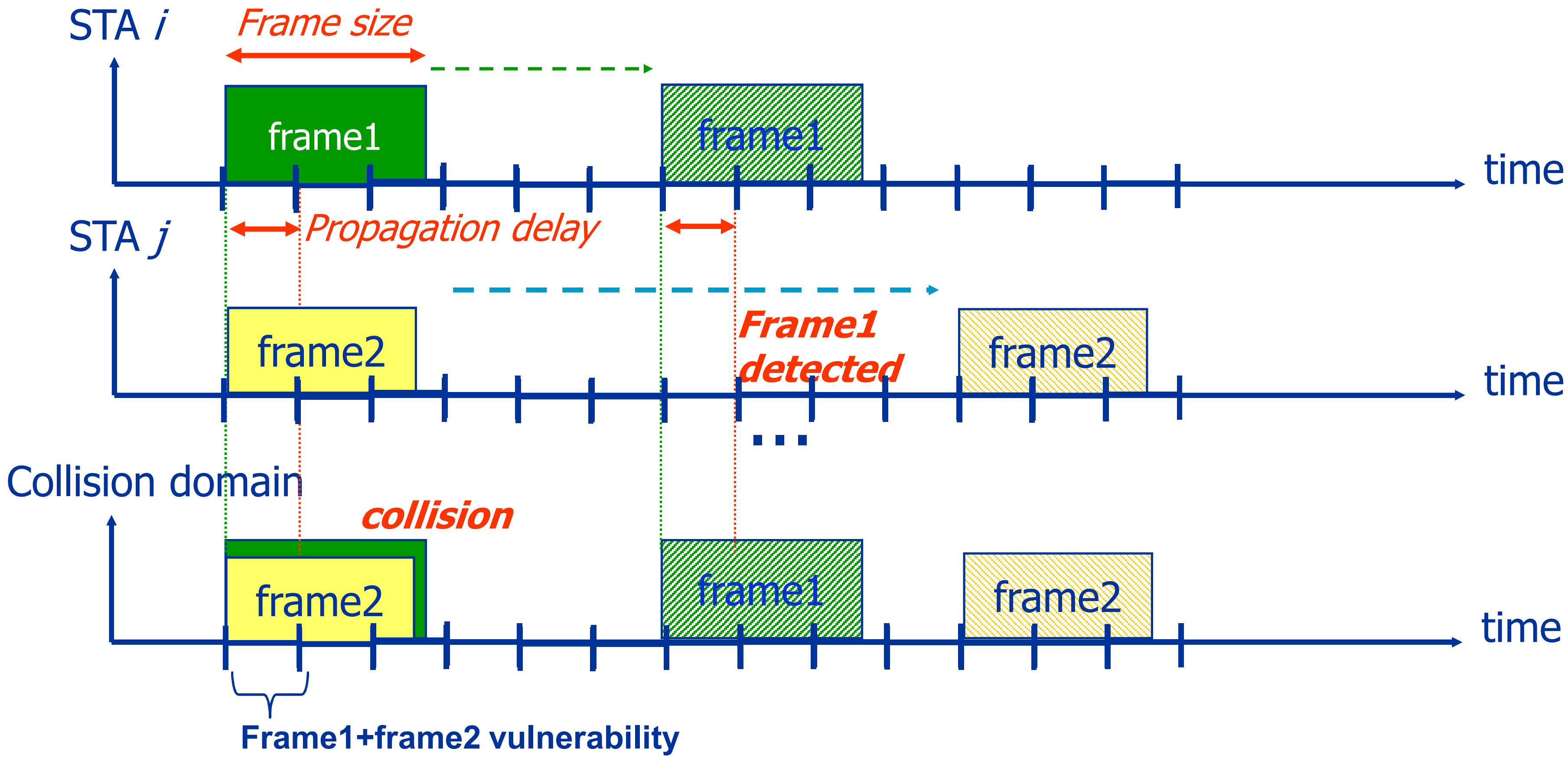


CSMA Protocol



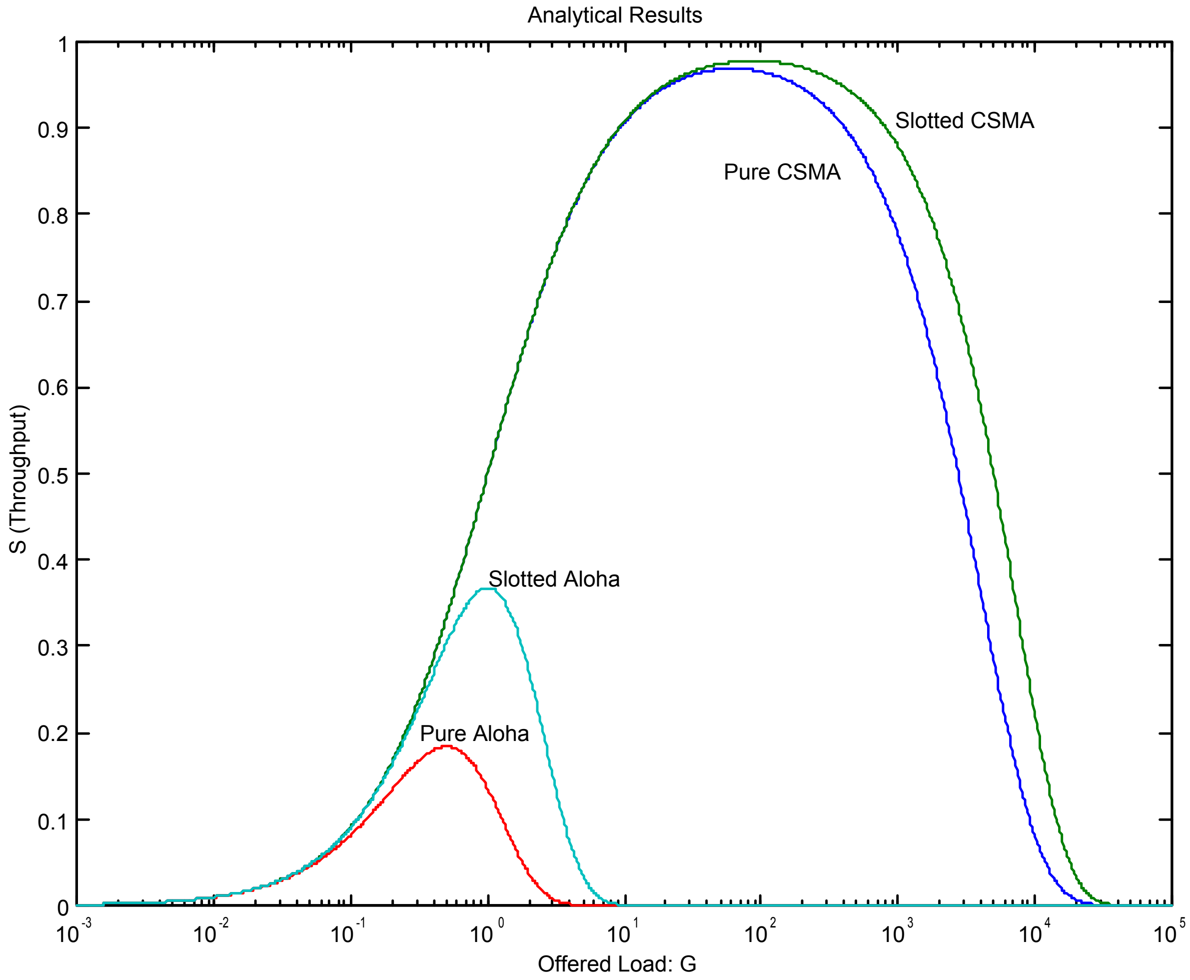
- Frame vulnerability time: twice the propagation delay

Slotted CSMA Protocol



- Frame vulnerability time: the propagation delay

Throughput comparison



CSMA/CA: the IEEE 802.11 Wireless LAN

- **1 Medium Access Control (MAC) protocol:**
  - 2 coordination functions co-exist in a superframe structure (time division)
  - **Distributed Coordination Function (DCF)**
    - *Ad-Hoc networks (peer to peer)*
    - *Distributed control (no base station)*
    - *contention based access (no QoS, no minimum delay)*
    - *CSMA/CA access protocol with Binary Exponential Backoff*
  - **Point Coordination Function (PCF)**
    - *Centralized control (Base station)*
    - *Polling based access (soft QoS, minimum delay)*
    - *minimum bandwidth guarantee*

Will be analyzed later...

Evolutionary perspective of distributed MAC

- Distributed, contention-based wireless MAC Problem:
  - the frame vulnerability (collision risk)
  - Needs resolution in distributed way (no centralized coordinator)
- let's analyze the **Space domain**
  - MACA [Karn1990]: RTS/CTS, no carrier sense (MACA-BI, RIMA...)
  - MACAW [Bharghavan et al.1994]: RTS/CTS, no carrier sense and immediate ACK (more reliable and efficient Link Layer Control)
  - FAMA [Fullmer et al.1995]: RTS/CTS, carrier sense + other stuff
- Main solution: RTS/CTS mechanism
  - Today under some criticisms

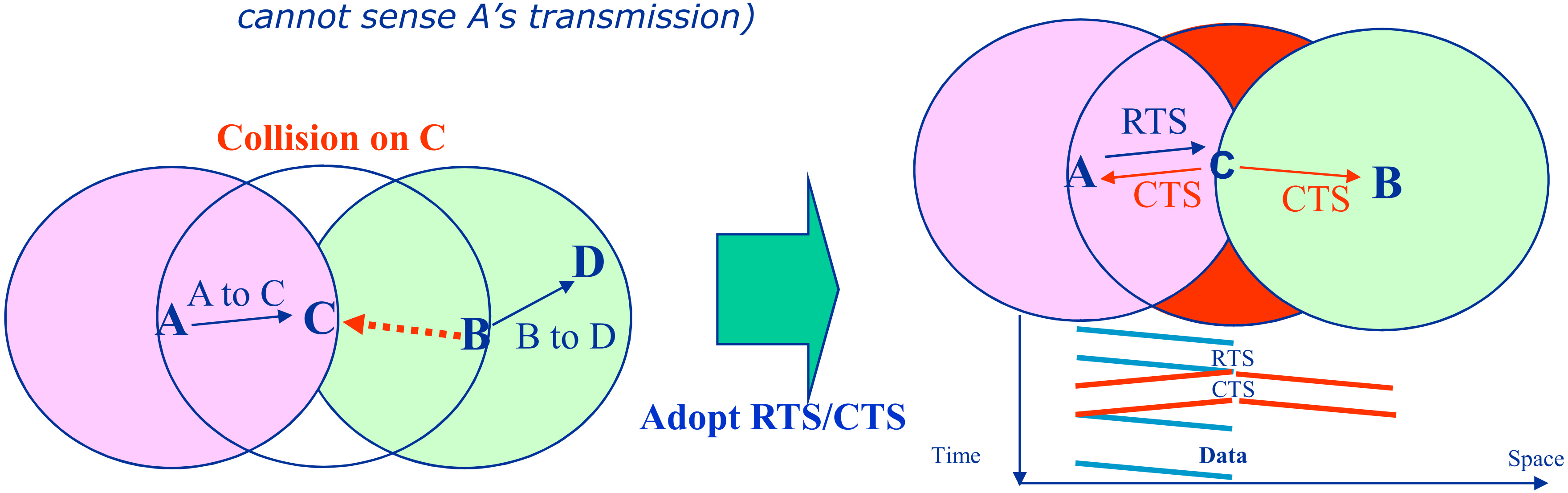
[Karn1990]
P. Karn, ""MACA - A new Channel Access Method for Packet Radio", proc. 9-th Computer Networking Conference, September 1990

[Bharghavan et al. 1994]
V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol for Wireless LAN's," proc. ACM SIGCOMM'94, pp.212-225, London, 1994

[Fullmer et al. 1995]
C.L. Fullmer, J.J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet Radio Networks", Proc. ACM Sigcomm'95 Cambridge, MA, 1995

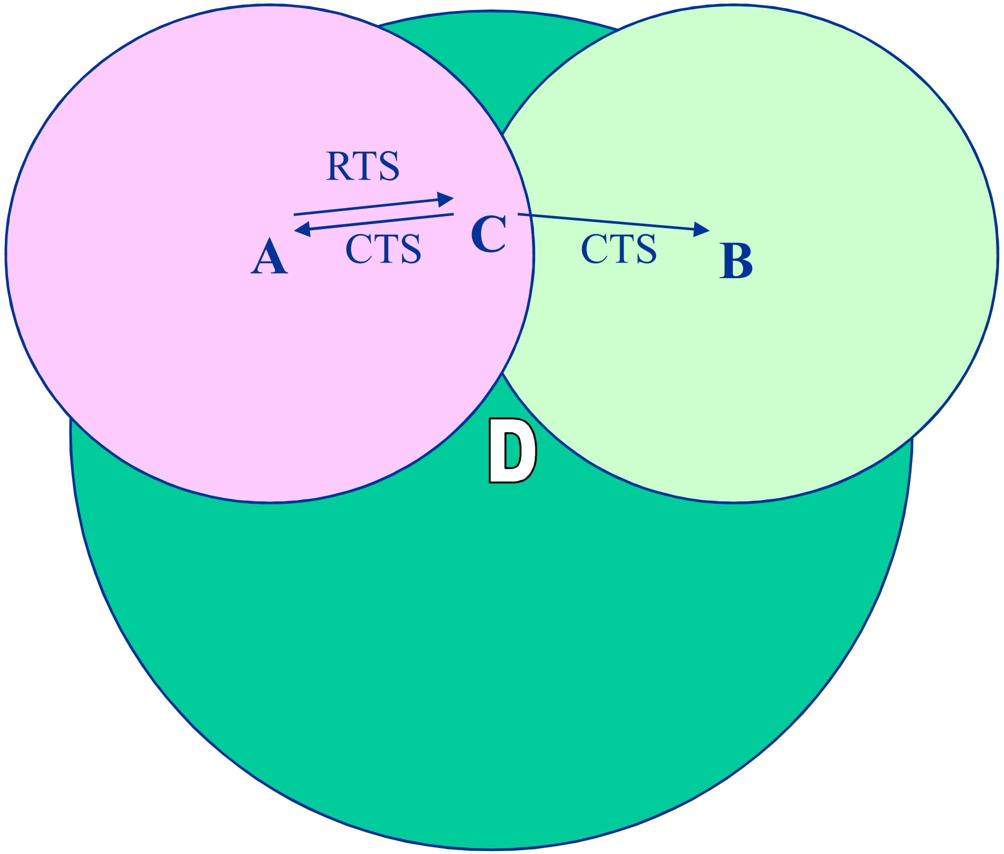
Hidden and Exposed terminals: RTS/CTS

- **The space domain:**
- Hidden and exposed terminals: space vulnerability
- RTS/CTS mechanism to contrast Hidden terminals
  - Hidden terminals: B does not sense traffic, but the receiver C cannot receive its packet due to a transmission from A to C (A hidden to B)
  - to seize the channel, according to CSMA/CA, a station transmits a short RTS (request to send) packet and waits for the CTS (Clear to Send) response.
    - *A transmit RTS to C and seizes the coverage area*
    - *C respond with CTS to A (B receive the CTS and does not transmit even if it cannot sense A's transmission)*



RTS/CTS drawbacks

- **RTS/CTS is not a “guaranteed” solution and it is additional overhead**
- Power asymmetry, detection and interference range >> transmission range

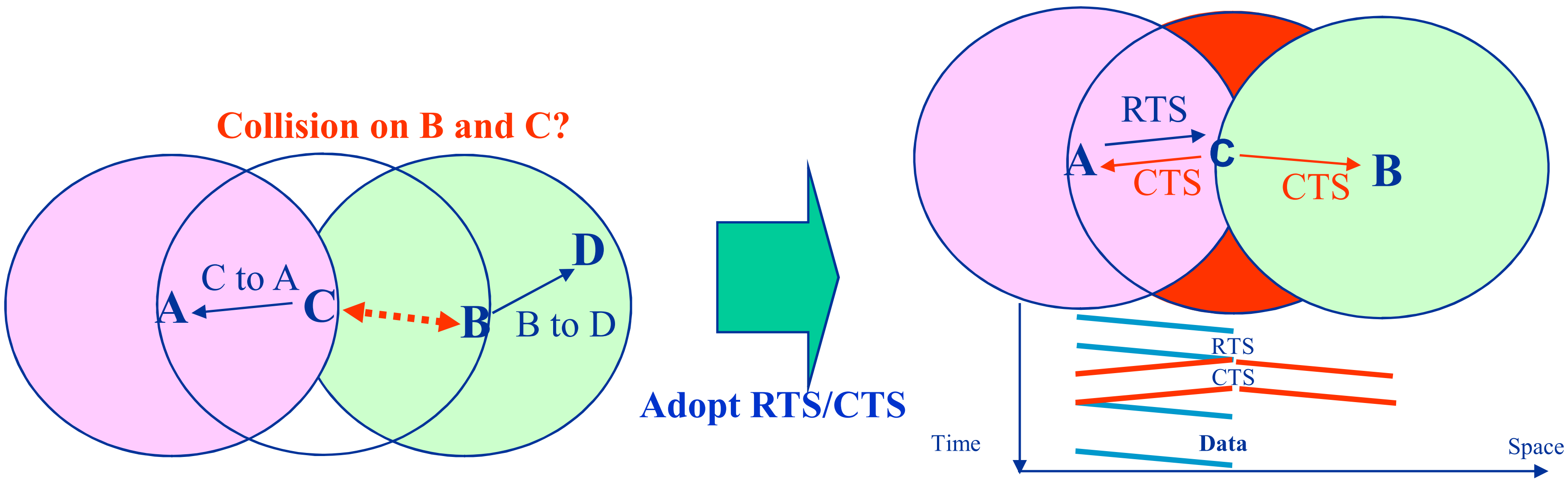


Ad hoc Multi-hop: Time/Space problems

- A bi-directional chain of MAC frames
  - TCP streams (Data + Ack)
- Self-contention (MAC layer problem)
  - Inter-stream self-contention (Data vs. Ack TCP streams)
  - Intra-stream self-contention (same TCP stream)
  - How to obtain coordination?
  - New proposed solutions
    - *Fast forward*
    - *Quick exchange*
    - *Flow numbering (pre-routing at the MAC layer???)*
    - *Frame transmission by forward invitation*

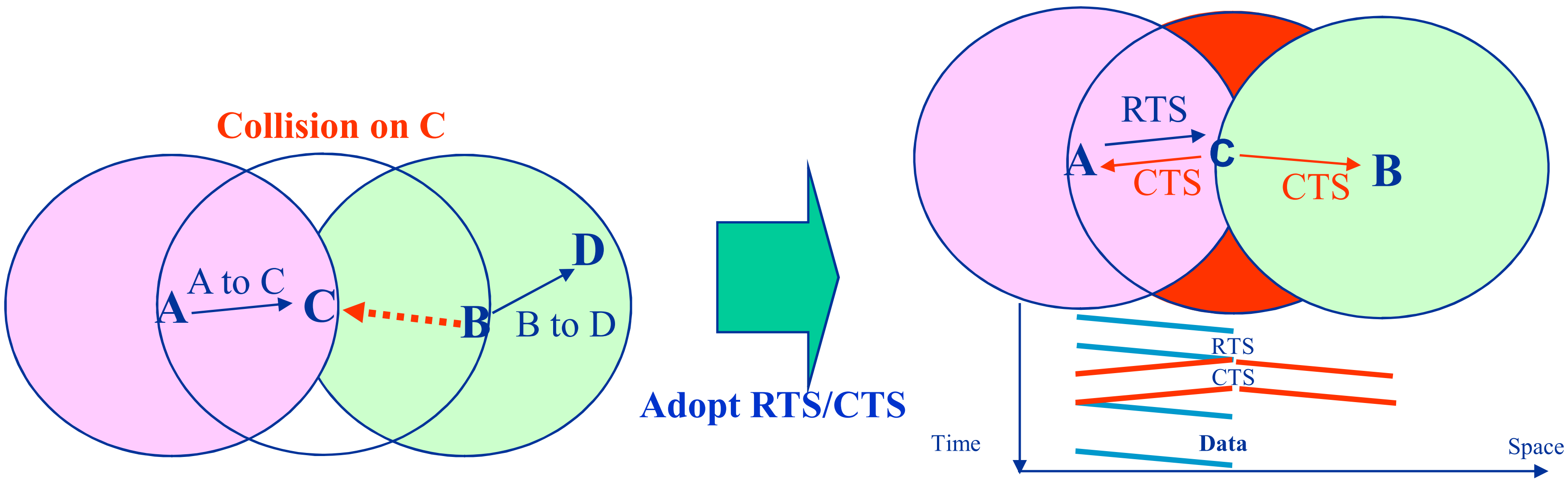
MACA: slotted RTS/CTS, no CS

- MACA: eliminates the carrier sensing
  - ...because the contention is on the receiver!
- Introduces slotted RTS/CTS (30 bytes each) and slot time equals the RTS (and CTS) duration
- Allow exploitation of concurrent spatial transmission if the receiver is not exposed to two hidden transmitter terminals
- Variations: MACA-BI, RIMA (receiver initiated)



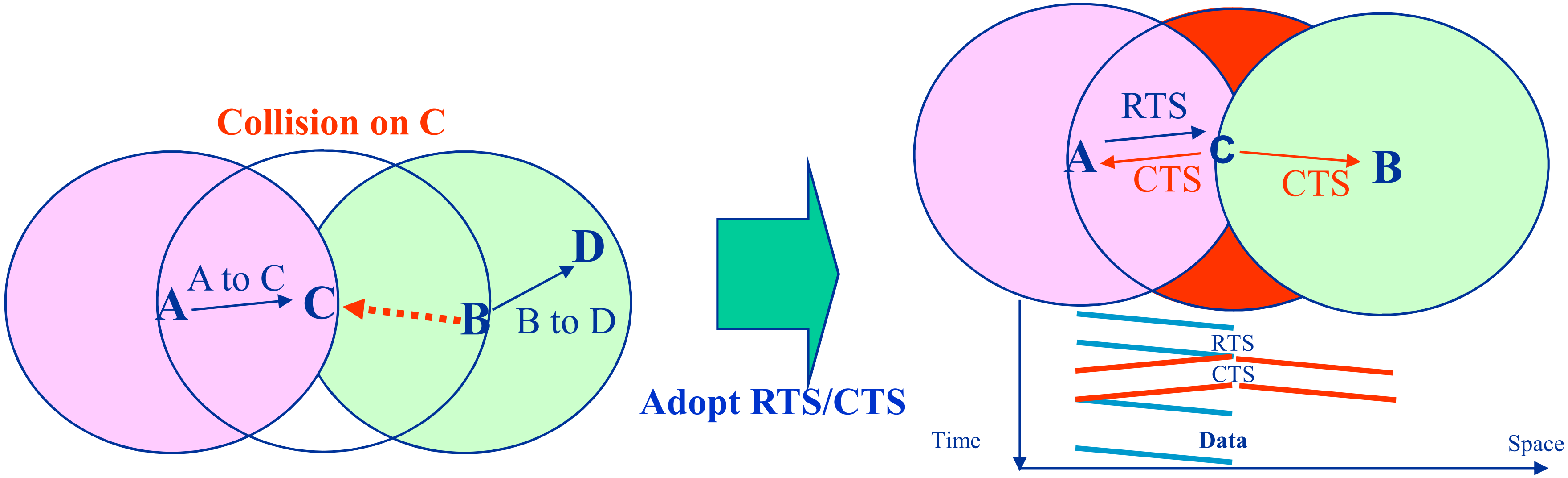
MACAW: no cs + slotted RTS/CTS + ACK

- MACAW: fairness of the backoff procedure
  - MILD + Binary Exponential Backoff
  - Cooperation-based backoff values (space-issues of contention)
- no carrier sensing before both slotted RTS/CTS
- Introduces ACK (RTS – CTS – DATA – ACK)
  - Efficient retransmission policy at Data Link layer
- Problem: both sender and receiver act as receiver during frame transmissions (no concurrent space exploitation of the channel)

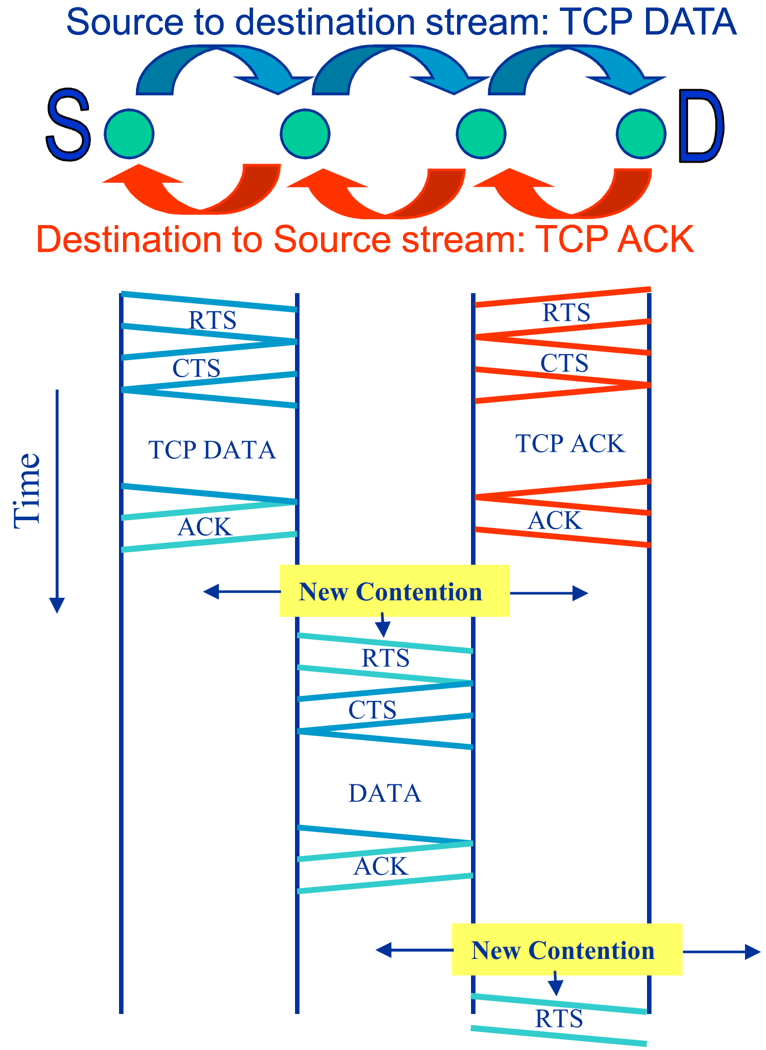


FAMA: cs + slotted RTS/CTS + ACK

- FAMA: re-introduces carrier sensing before both slotted RTS/CTS
- Introduces lower bound for size of RTS/CTS and CTS-dominance
- Floor acquisition: principle for time and space contention

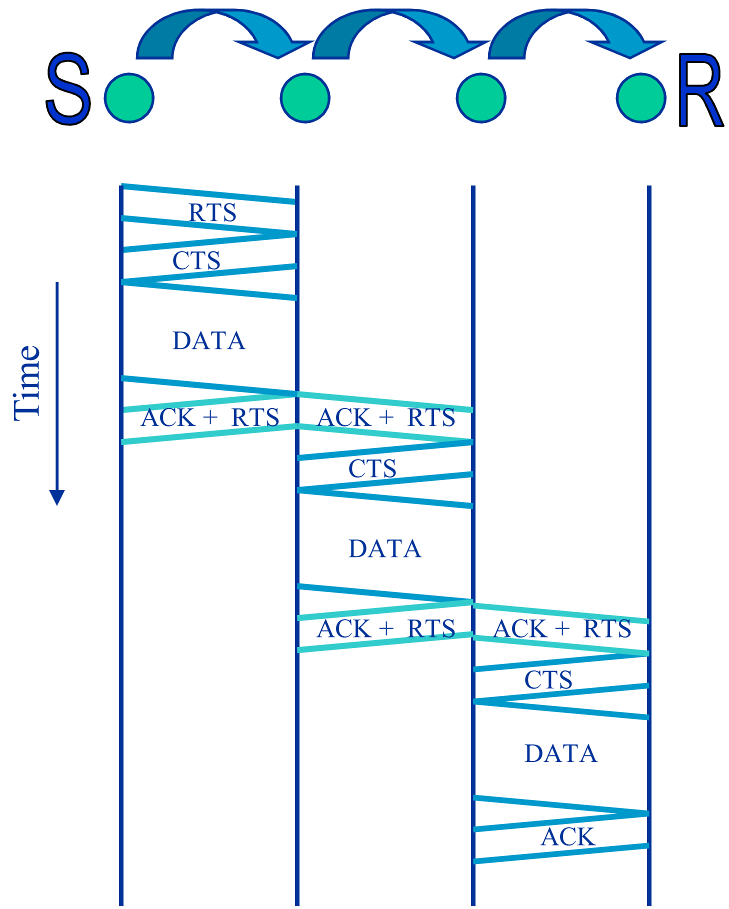


Ad hoc Multi-hop: Time/Space problems

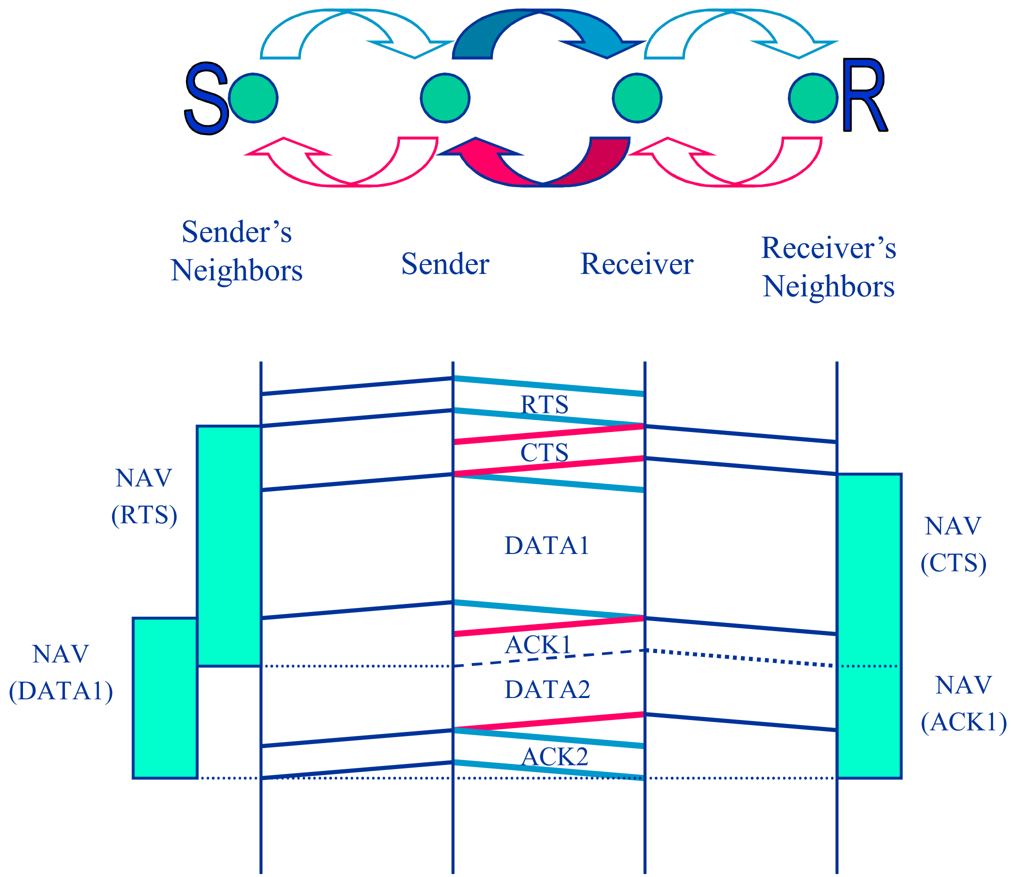


Ad hoc Multi-hop: Time/Space problems

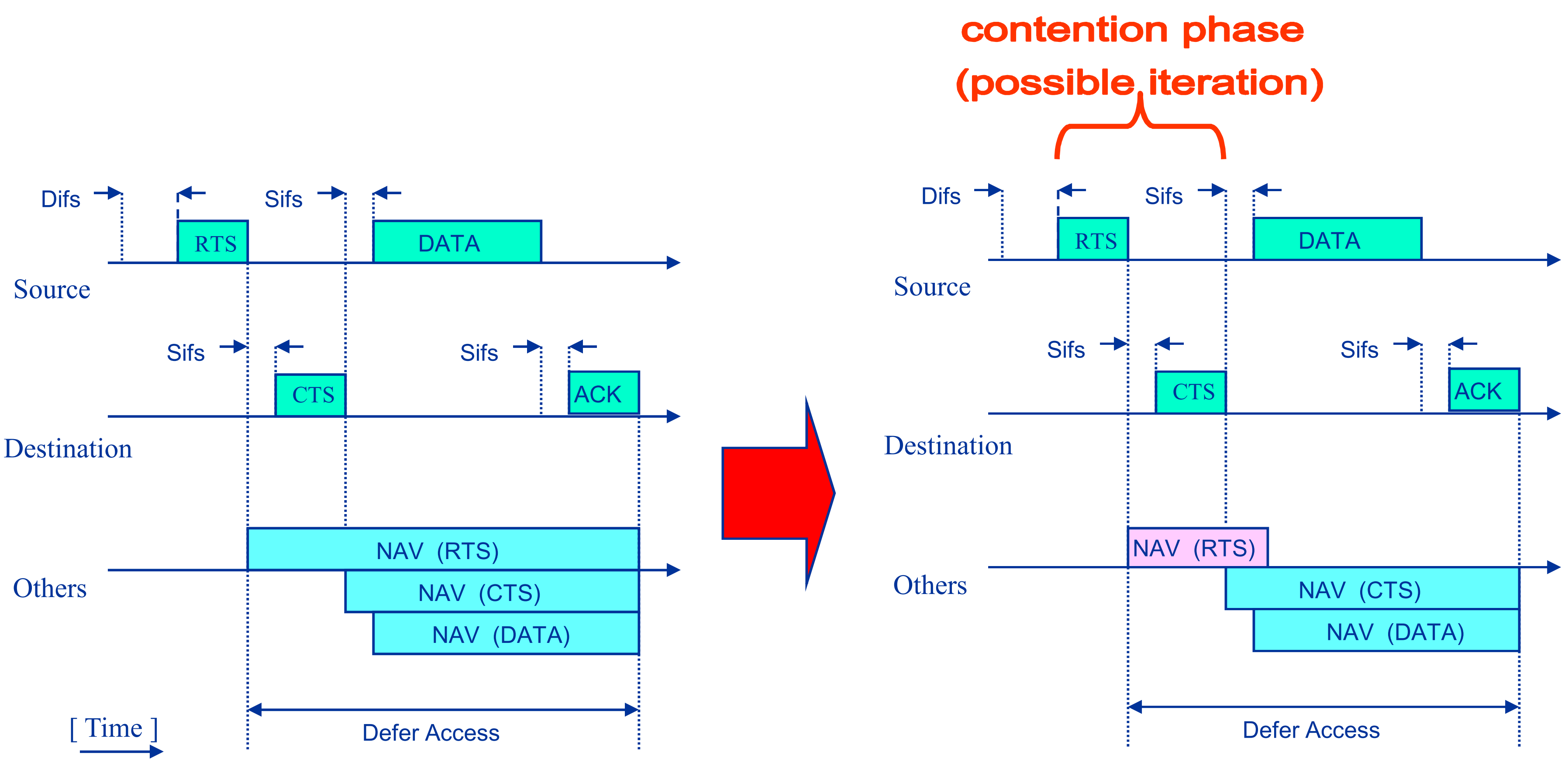
Fast Forward intra-stream



Quick Exchange inter-stream



Modified NAV policy



CSMA/CA: the IEEE 802.11 Wireless LAN

- **1 Medium Access Control (MAC) protocol:**
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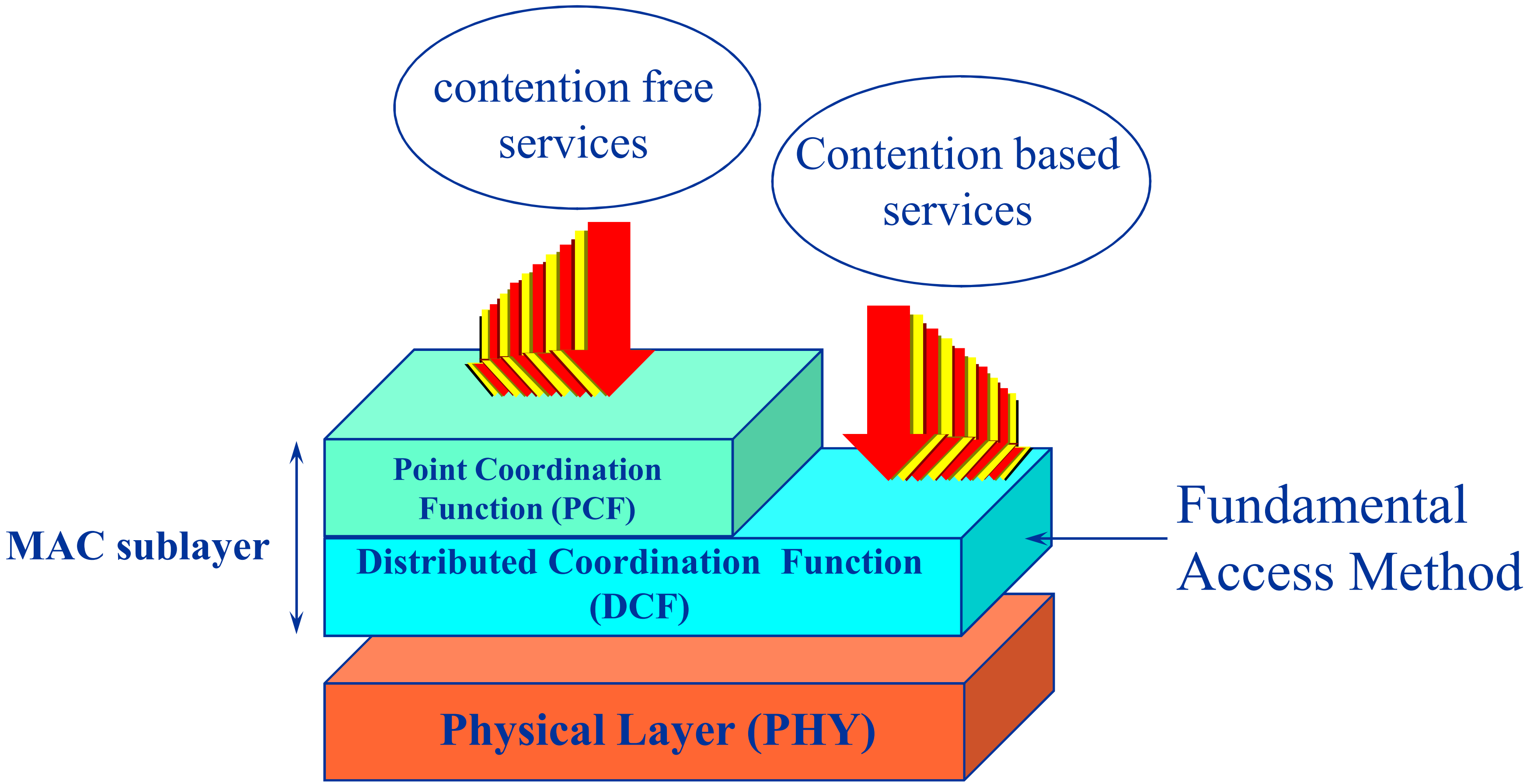
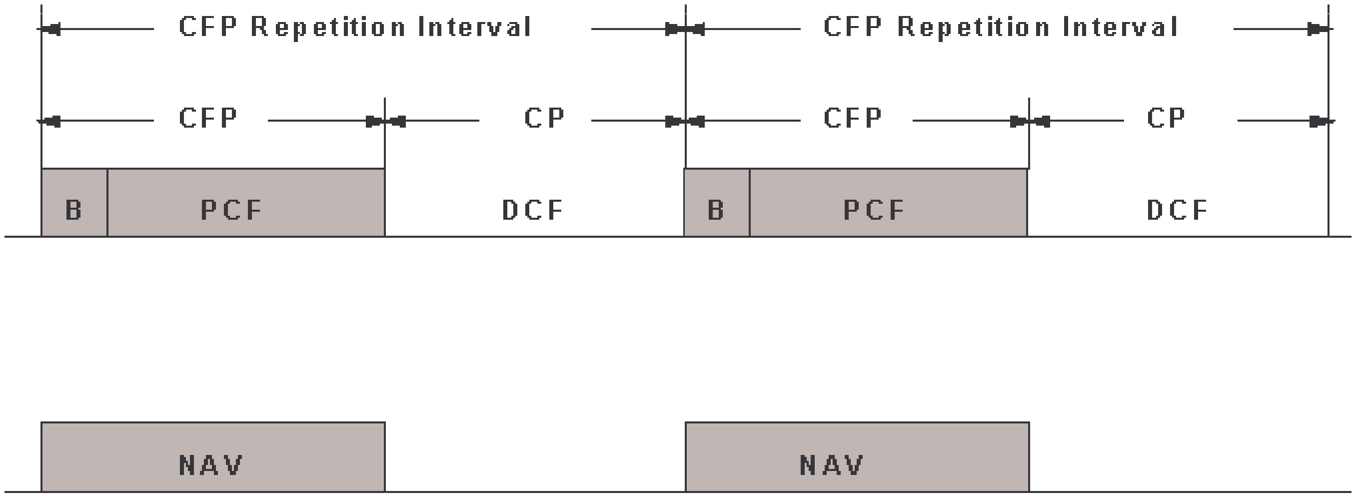
  - **Distributed Coordination Function (DCF)**
    - *Ad-Hoc networks (peer to peer)*
    - *Distributed control (no base station)*
    - *contention based access (no QoS, no minimum delay)*
    - *CSMA/CA access protocol with Binary Exponential Backoff*
  - **Point Coordination Function (PCF)**
    - *Centralized control (Base station)*
    - *Polling based access (soft QoS, minimum delay)*
    - *minimum bandwidth guarantee*

IEEE 802.11 MAC protocol architecture



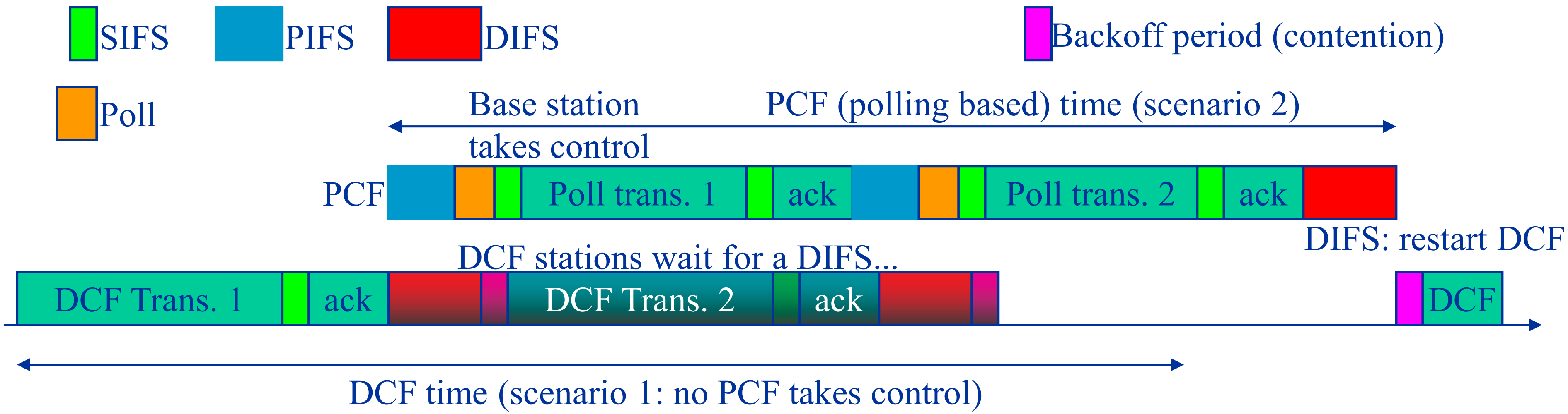
Point coordinated mode (PCF)

- point coordinated mode is a contention free, optional service
  - can co-exist with the DCF in a superframe structure.
- central coordinator, i.e. the access point
  - manages stations belonging to its access list.
  - guaranteed to access the channel in a contention-free environment.



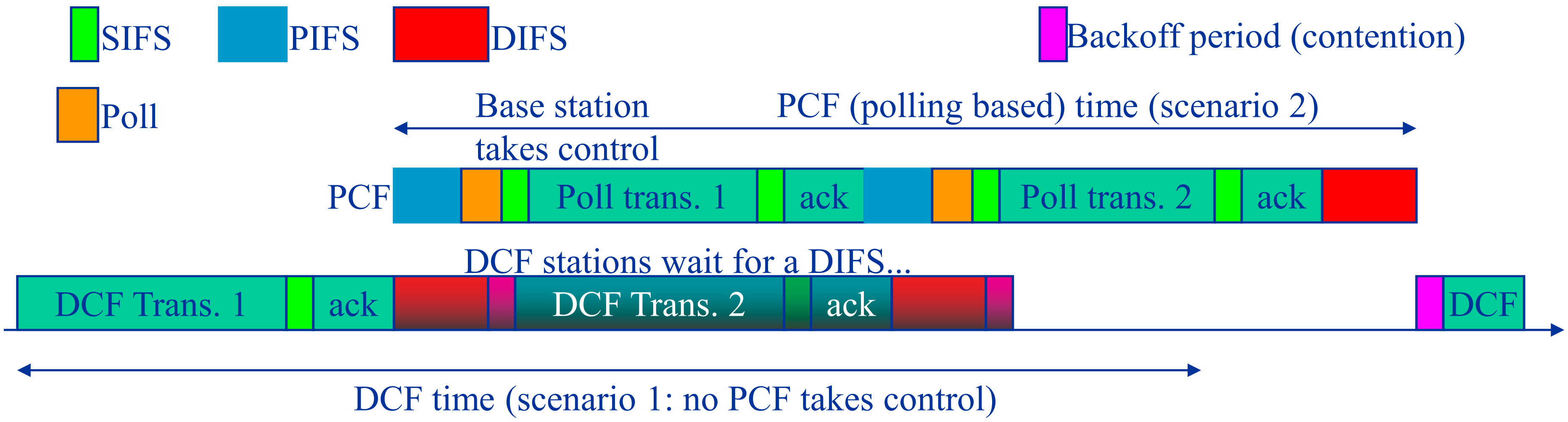
DCF and PCF control: IFS

- **Each station performs a carrier sensing activity when accessing the channel**
- **priority is determined by Interframe spaces (IFS):**
  - **Short IFS (SIFS) < Point IFS (PIFS) < Distributed IFS (DIFS)**
  - **after a SIFS only the polled station can transmit (or ack)**
  - **after a PIFS only the Base Station can transmit (and PCF takes control)**
  - **after a DIFS every station can transmit according to basic access CSMA/CA (DCF restarts)**



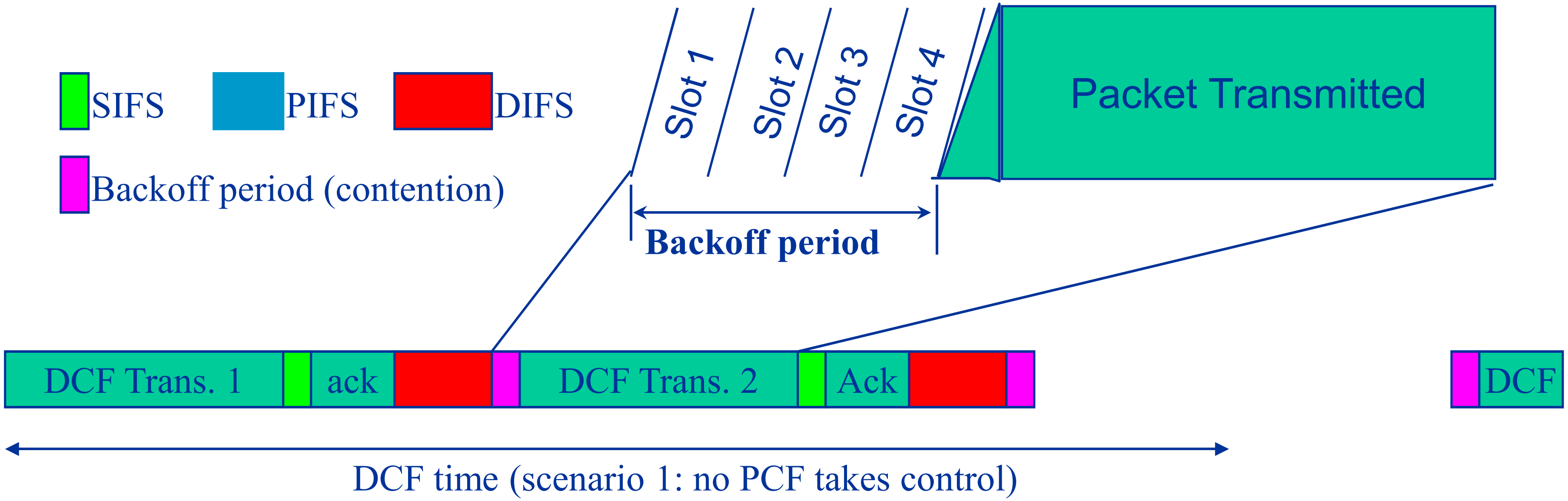
Point Coordination Function (PCF)

- during the PCF time the base station has priority in accessing the channel
  - Base Station waits for a PIFS after a transmission and takes control (DCF stations must wait for DIFS>PIFS)
  - base station polls stations that reserved the channel
  - at the end of the PCF period the Base Station releases the channel and DCF restarts (after a DIFS)

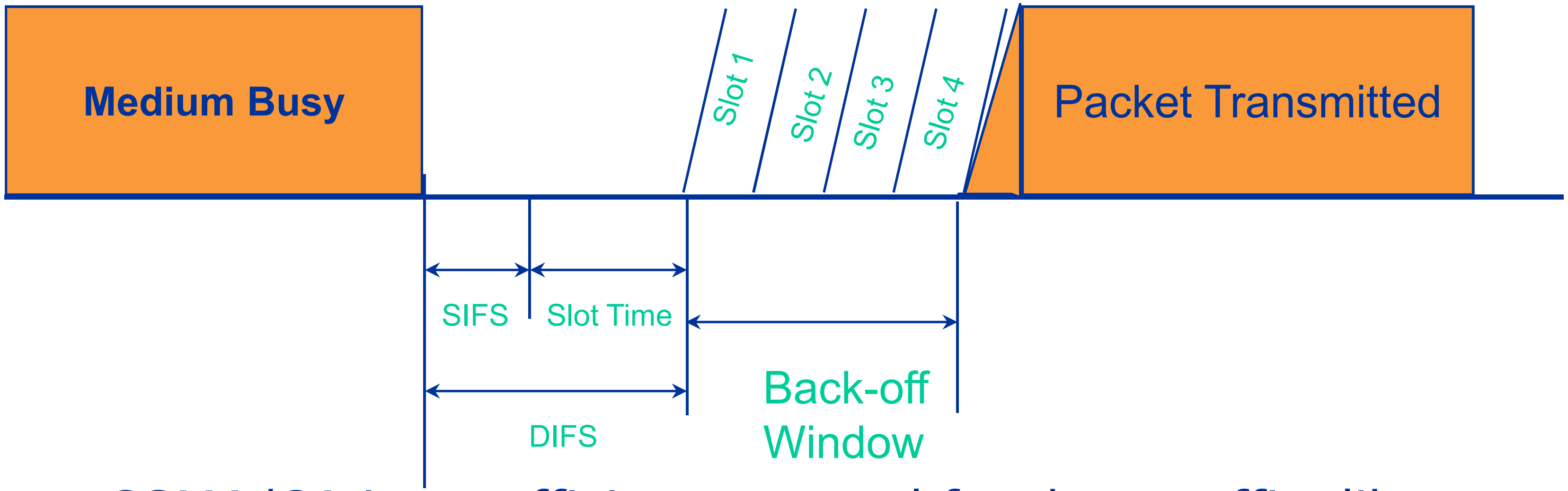


Distributed Coordination Function (DCF)

- Basic Access mode:
  - Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access scheme (listen before transmit)
  - carrier sensing performed to detect ongoing transmissions
  - Binary Exponential Backoff over slotted idle time
    - ***each station randomly selects the transmission slot in a variable sized Contention Window***
  - no Collision Detection (CD)



CSMA/CA Access Mechanism



- CSMA/CA is an efficient protocol for data traffic, like Ethernet
- Listen before transmit
- Always back-off before a transmission or retransmission
  - Designed to provide fair access to the medium

DCF Backoff procedure

• ***Selection of a random Backoff Time***

CWi=contention window size at the i-th transmission attempt. CWi is doubled after each collision experienced (to reduce the contention)

BackoffTime(i)=(Cwi*random())*SlotTime

i	1	2	3	4	5	6	7
CW_i	15	31	63	127	255	511	1023

- ***Reduction of the Backoff Time***

  After an idle DIFS period from the last transmission, a station decrements its Backoff Time by a Slot_time for each slot where **no activity is sensed on the medium.**

- ***Frozen***

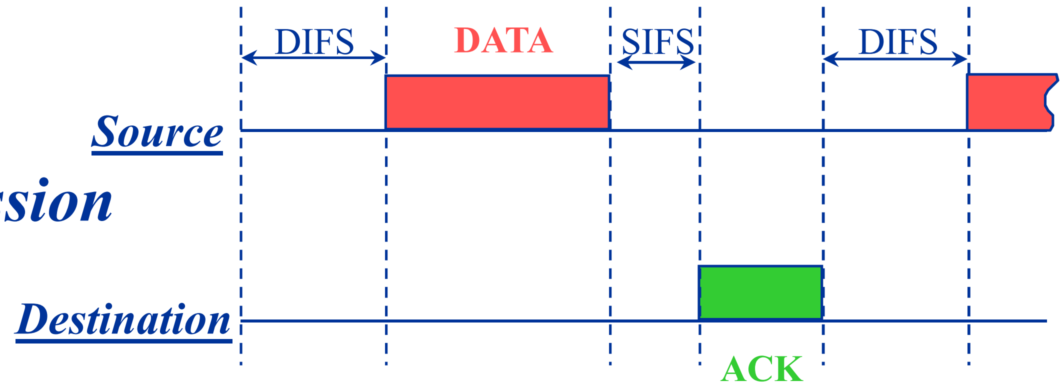
  As soon as the medium is determined to be busy, the backoff procedure is suspended**.**

- ***Transmission***

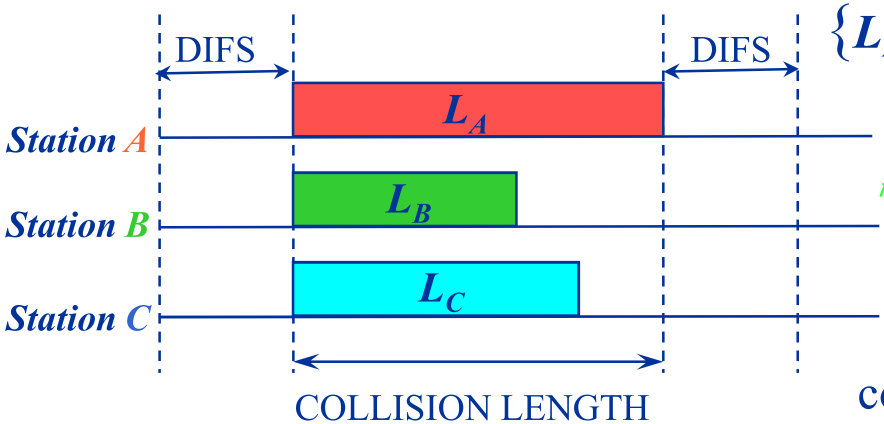
  When the Backoff Time reaches zero, the station starts the transmission.

DCF basic access: overview

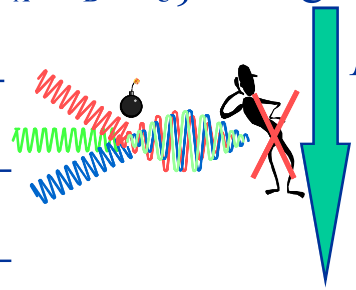
- ***Successful transmission***



- ***Collision: no CD***



$\{L_A, L_B, L_C\}$ = lengths of colliding packets



IEEE 802.11 does not implement collision detection

collision length = <u>***maximum***</u> $\{L_A, L_B, L_C\}$

IEEE 802.11 Contention Control

- Effect of high contention = many collisions

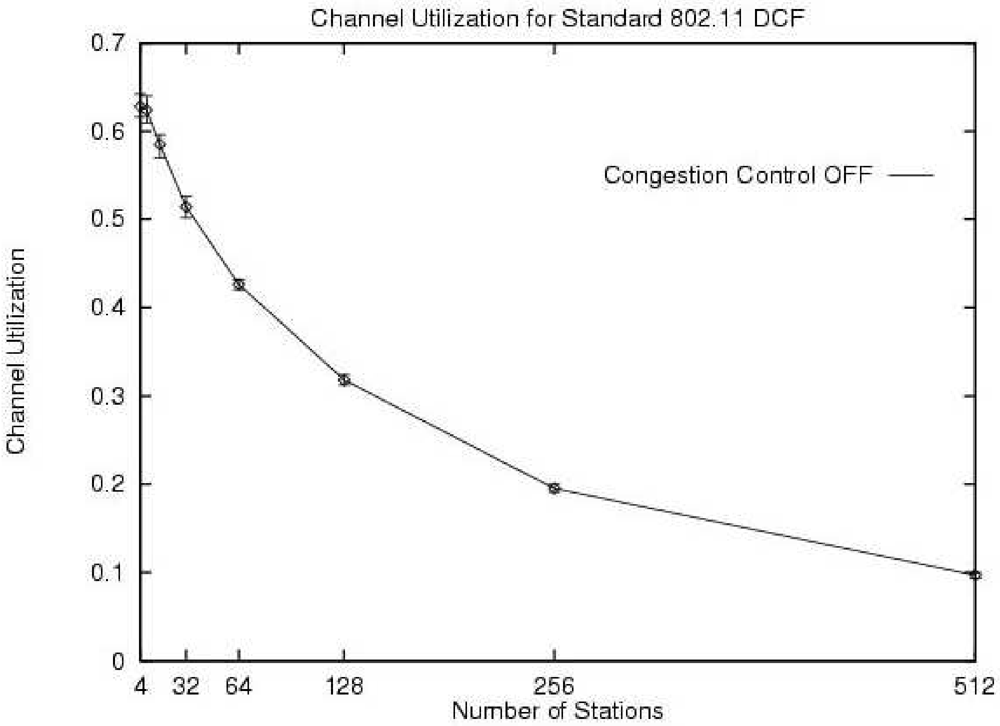


FIG. 1. Channel utilization of Standard 802.11 DCF

IEEE 802.11 Contention Control

- Information known due to carrier sense

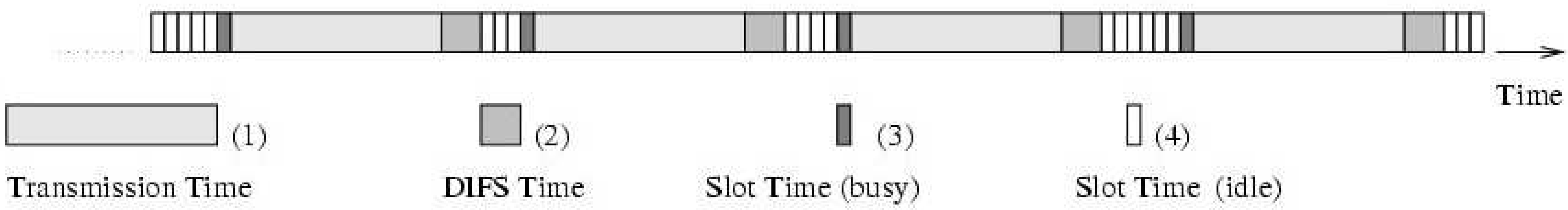


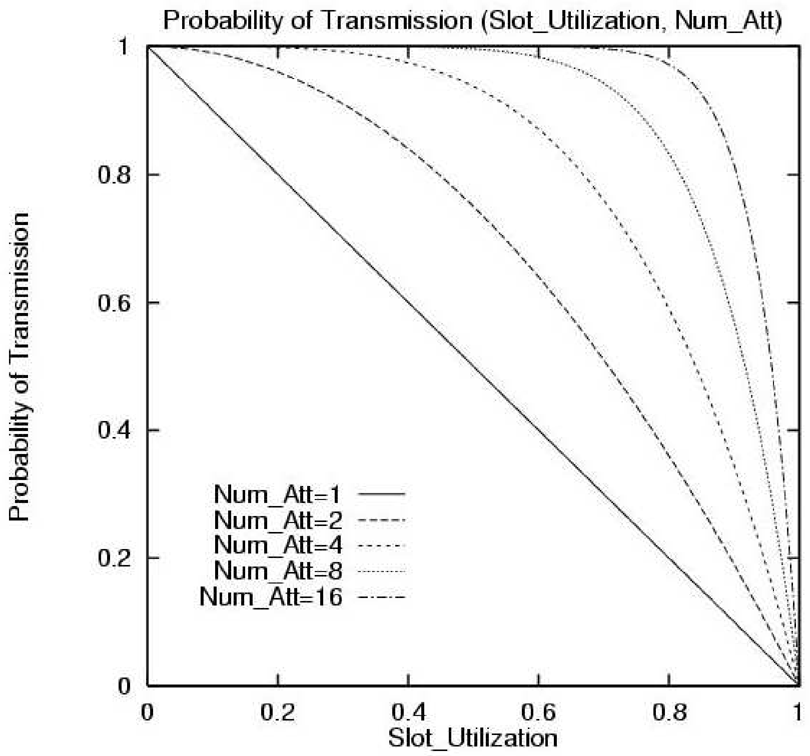
FIG. 2. A sample of the channel state observed by each station.

Slot Utilization = Num Busy Slots / Initial Backoff

Slot Utilization in [0..1]

IEEE 802.11 Contention Control

- Adoption of Slot Utilization in Distributed contention control (DCC)
- Probability of Transmission = P_T
- $P\_T = (1 - S\_U)^{Num\_Att}$



IEEE 802.11 Contention Control

- Probabilistic Distributed Contention Control

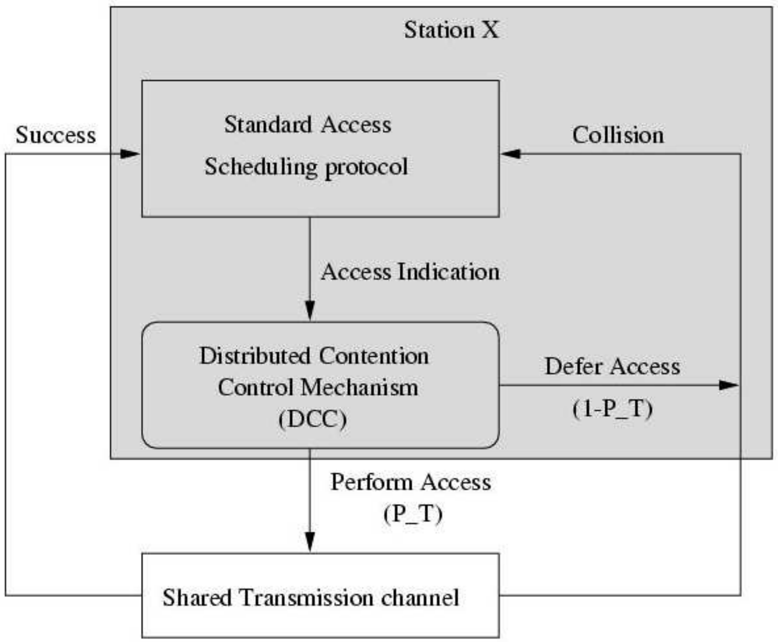
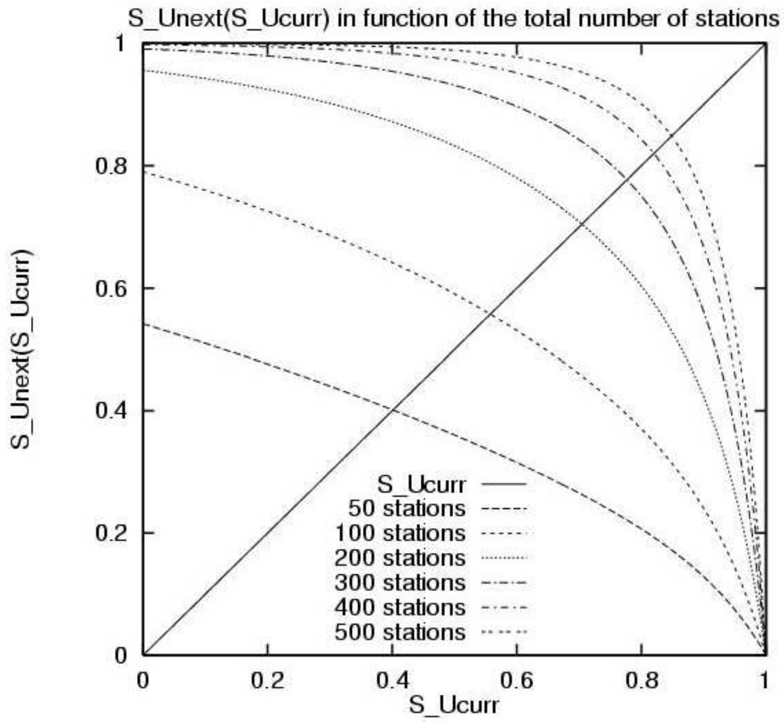


FIG. 3. Architectural collocation of DCC



Extends 802.11 MAC

Stable (avoids collapse)

IEEE 802.11 Contention Control

- DCC => better performance (no overheads)

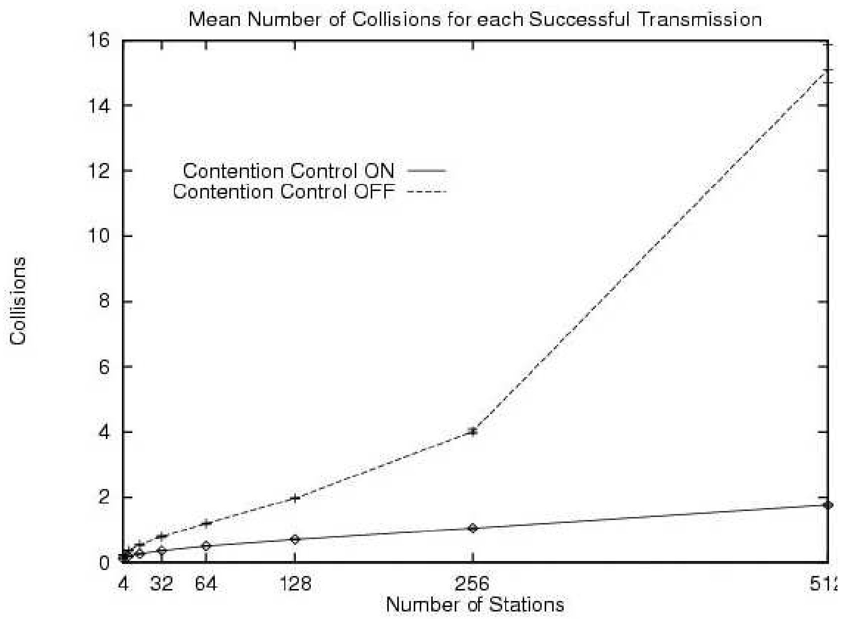


FIG. 6. Mean number of collisions for each successful transmission.

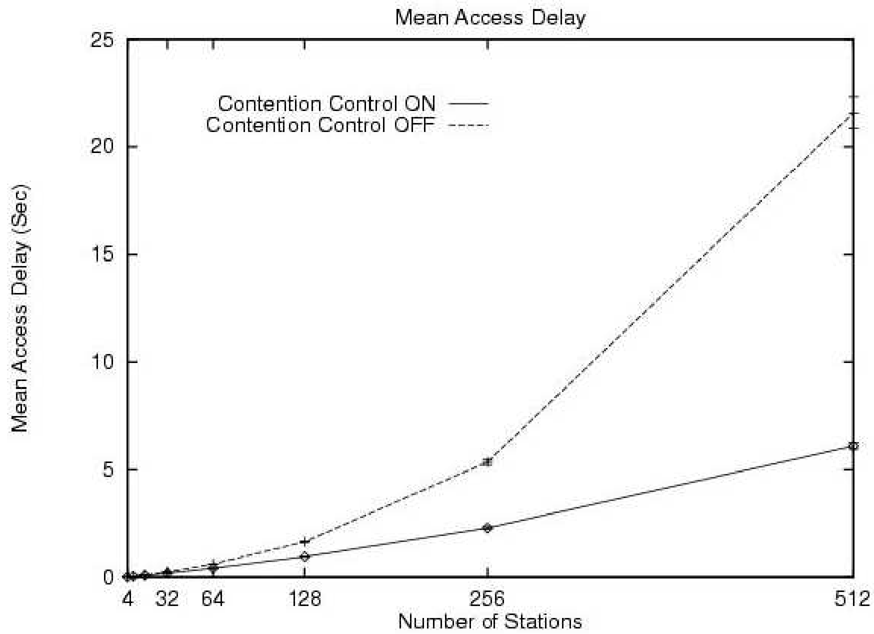


FIG. 7. Mean Access Delay

IEEE 802.11 Contention Control

- DCC => better performance (no overheads)

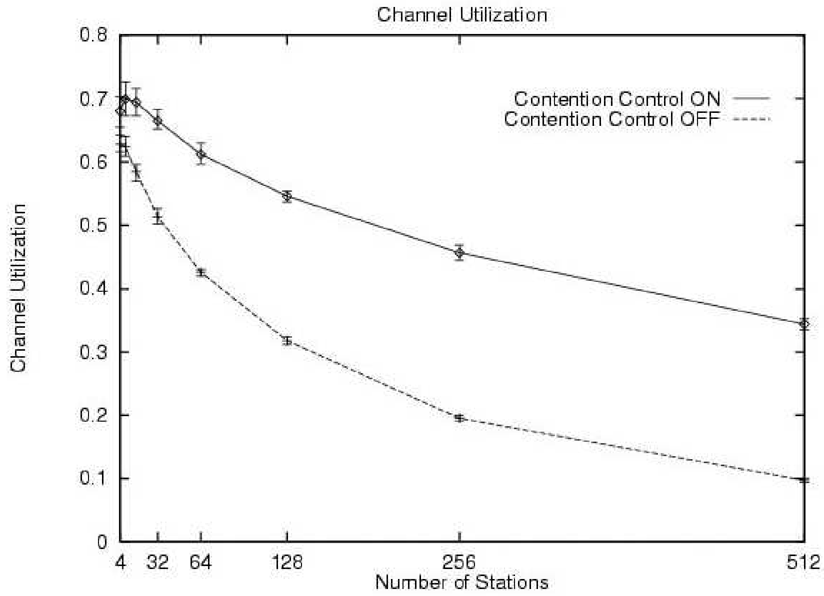
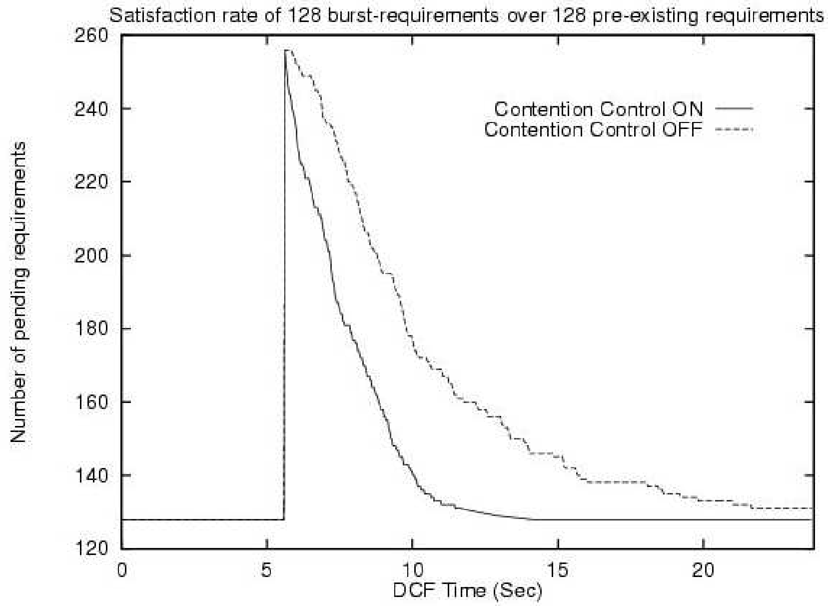


FIG. 10. Channel Utilization



IEEE 802.11 Contention Control

- DCC distributed priority mechanism

$$P\_T = (1 - S\_U)^{Num\_Att * Prior\_Lev}$$

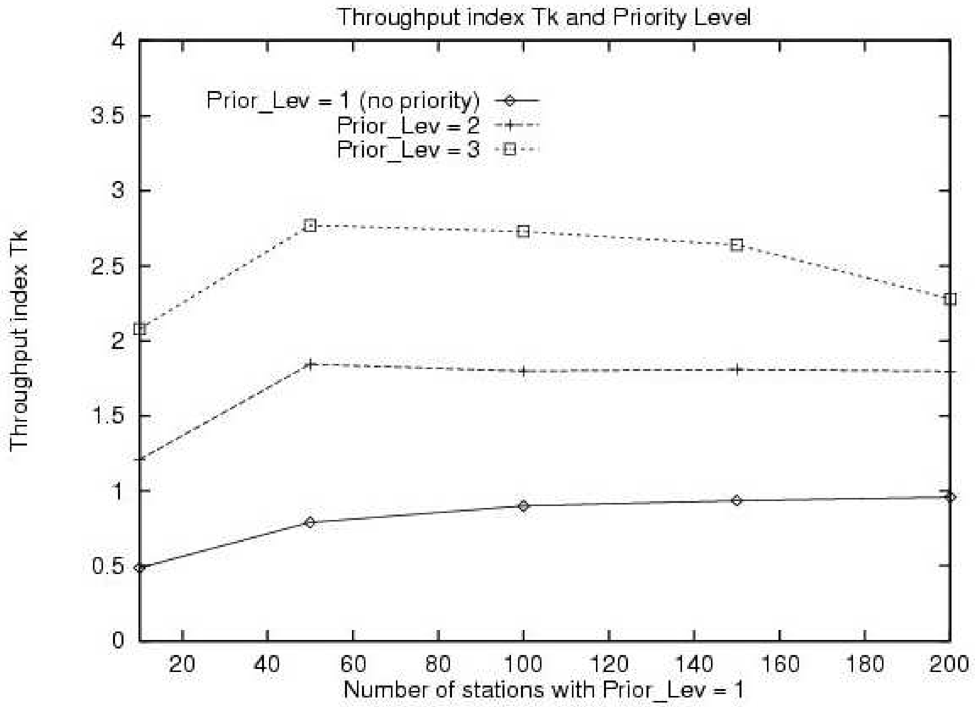


FIG. 15. Throughput index and Priority levels: system A

IEEE 802.11 Contention Control

- AOB = optimum performance
  - No need to estimate number of stations