Wireless Sensor Networks
4. Medium Access

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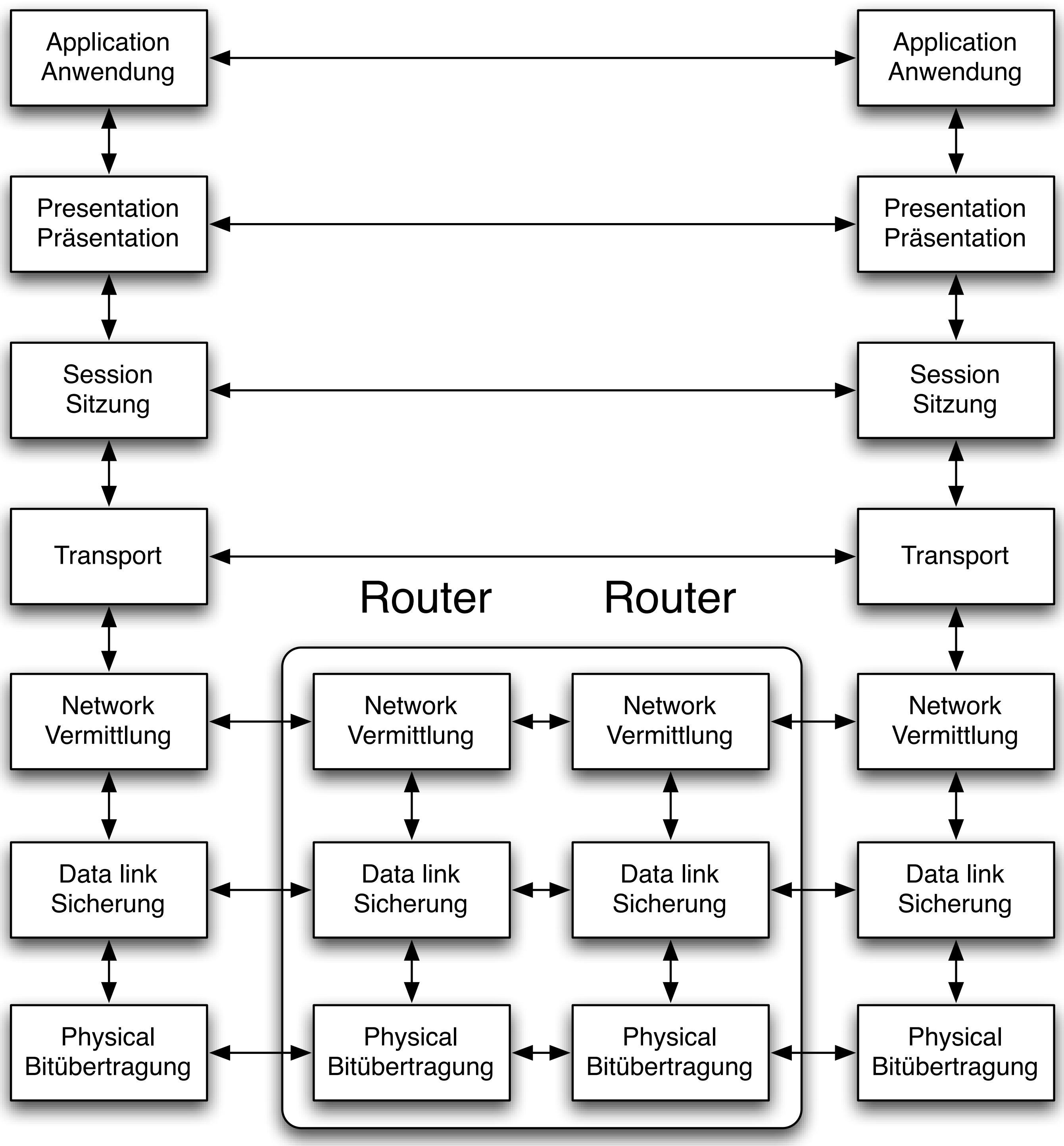
ISO/OSI Reference model

- 7. Application
  - Data transmission, e-mail, terminal, remote login
- 6. Presentation
  - System-dependent presentation of the data (EBCDIC / ASCII)
- 5. Session
  - start, end, restart
- 4. Transport
  - Segmentation, congestion
- 3. Network
  - Routing
- 2. Data Link
  - Checksums, flow control
- 1. Physical
  - Mechanics, electrics

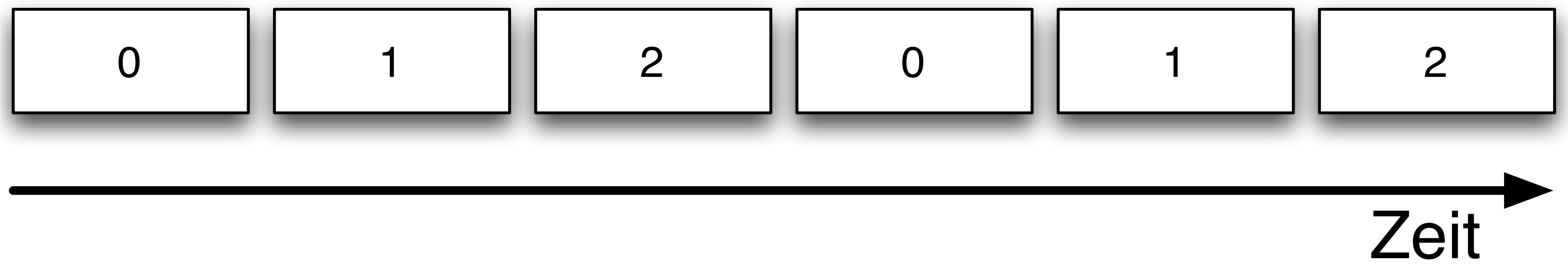


Types of Conflict Resolution

- Conflict-free
  - TDMA, Bitmap
  - FDMA, CDMA, Token Bus
- Contention-based
  - Pure contention
  - Restricted contention
- Other solutions
  - z.B. MAC for directed antennae

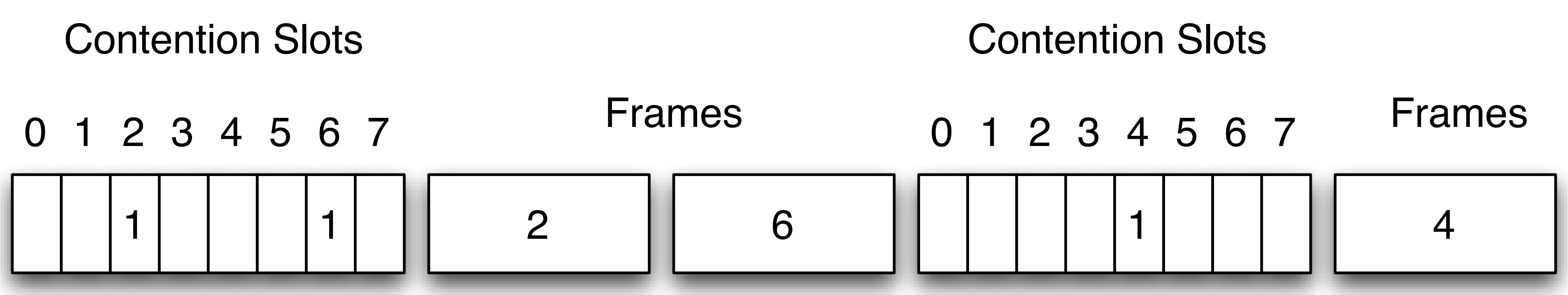
Contention Free Protocols

- Simple Example: Static Time Division Multiple Access (TDMA)
  - Each station is assigned a fixed time slot in a repeating time schedule
  - *Traffic-Bursts* cause waste of bandwidth



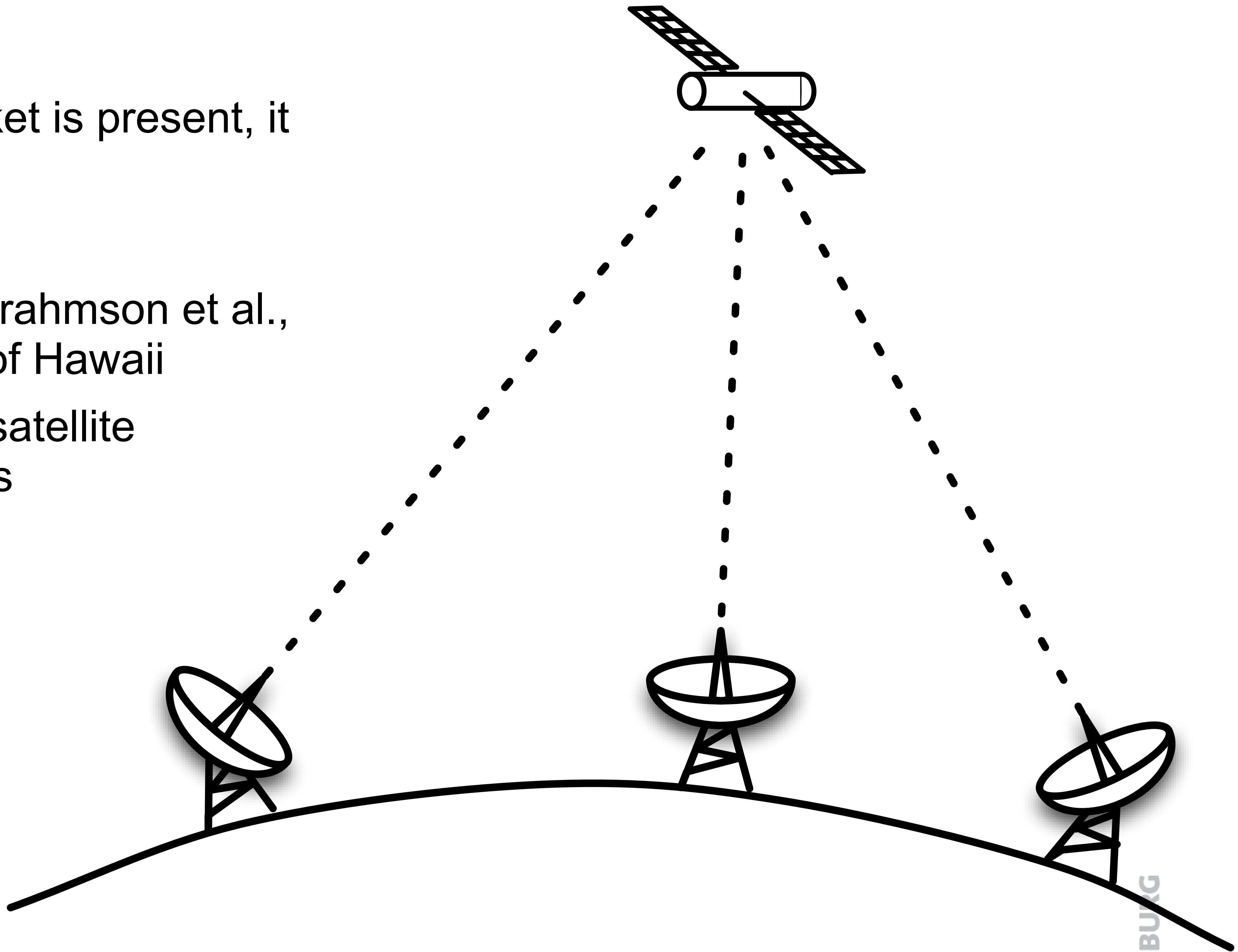
Bitmap Protokoll

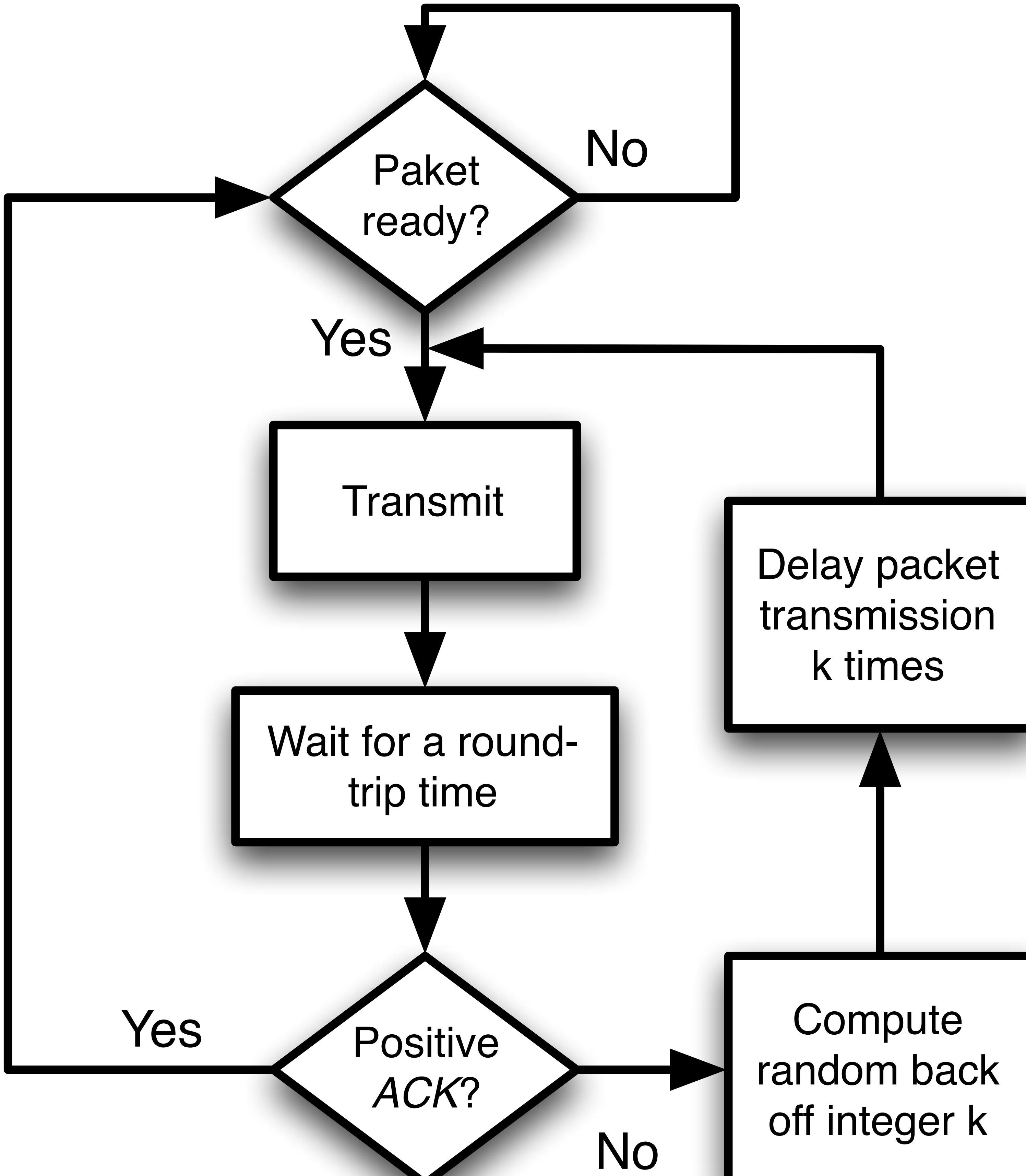
- Problems of TDMA
  - If a station has nothing to send, then the channel is not used
- Reservation system: bitmap protocol
  - Static short reservation slots for the announcement
  - Must be received by each station
- Problem
  - Set of participants must be fixed and known a-priori
  - because of the allocation of contention slots



ALOHA

- Algorithm
  - Once a paket is present, it will be sent
- Origin
  - 1985 by Abrahmson et al., University of Hawaii
  - For use in satellite connections




Paket ready?
No
Yes
Transmit
Delay packet transmission k times
Wait for a round-trip time
Yes
Positive *ACK*?
No
Compute random back off integer k

ALOHA – Analysis

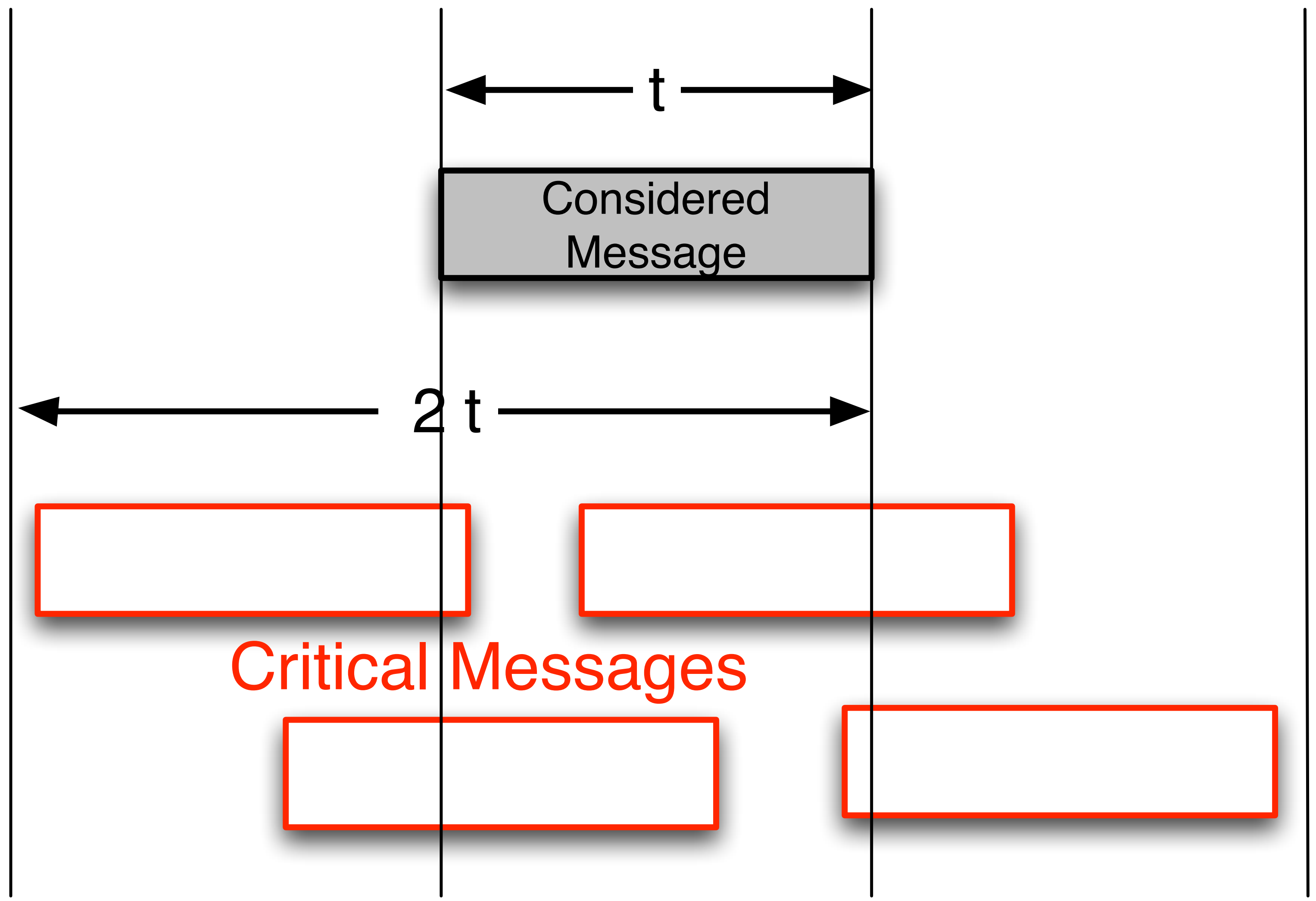
- Advantage
  - simple
  - no coordination necessary
- Disadvantage
  - collisions
    - sender does not check the channel
  - sender does not know whether the transmission will be successful
    - ACKs are necessary
    - ACKs can also collide

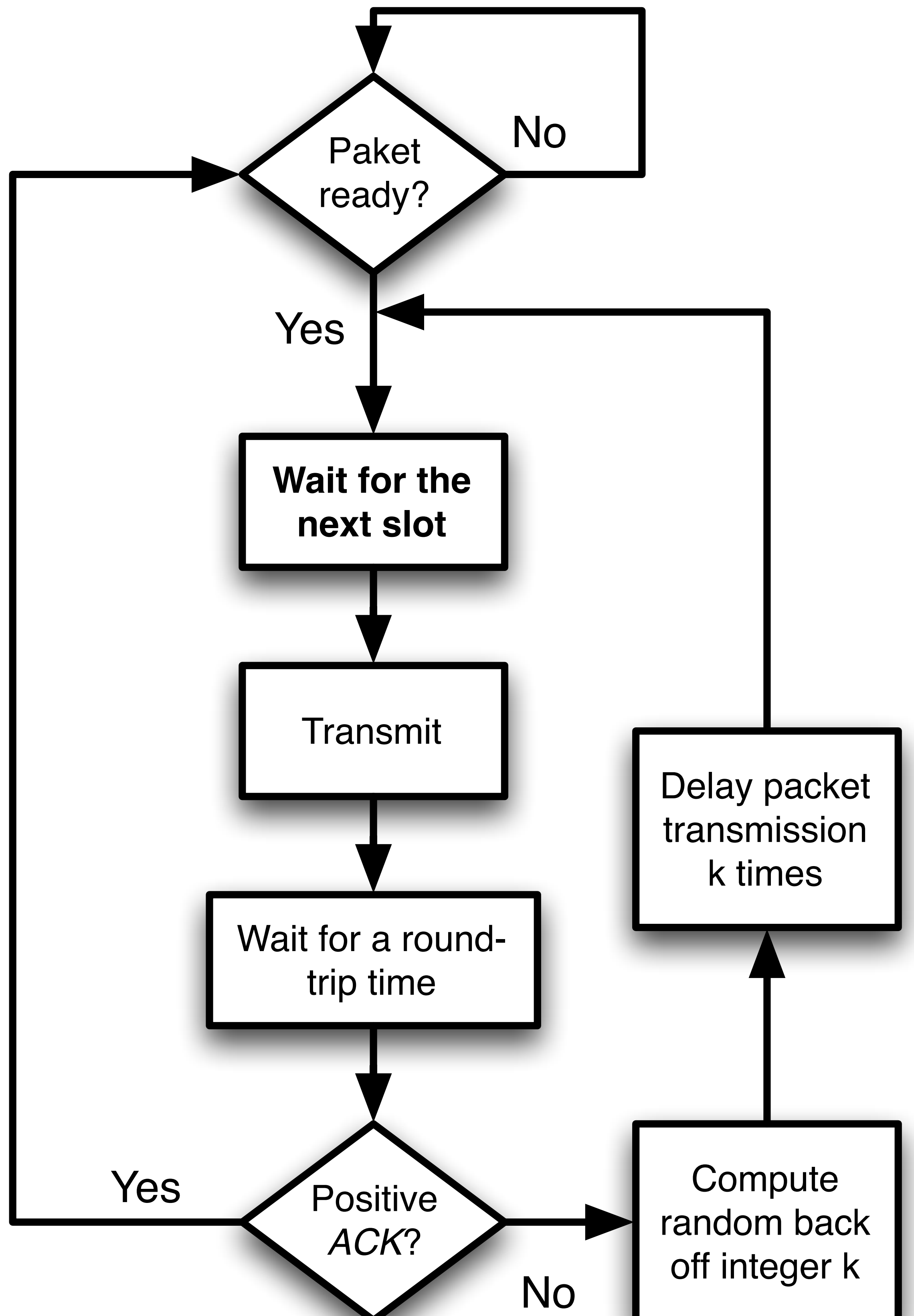
ALOHA – Efficiency

- Consider Poisson-process for generation of packets
  - describe “infinitely” many stations with similar behavior
  - time between two transmission is exponentially distributed
  - let G be the expectation of the transmission per packet length
  - all packets have equal length
  - Then we have $$P[k \text{ transmissions}] = \frac{G^k}{k!} e^{-G}$$
- For a successful transmission, no collision with another packet may happen
  - How probable is a successful transmission?

ALOHA – Efficiency

- A packet X is disturbed if
  - a packet starts just before X
  - a packet starts shortly after X starts
- A packet is successfully transmitted,
  - if during an interval of two packets no other packets are transmitted





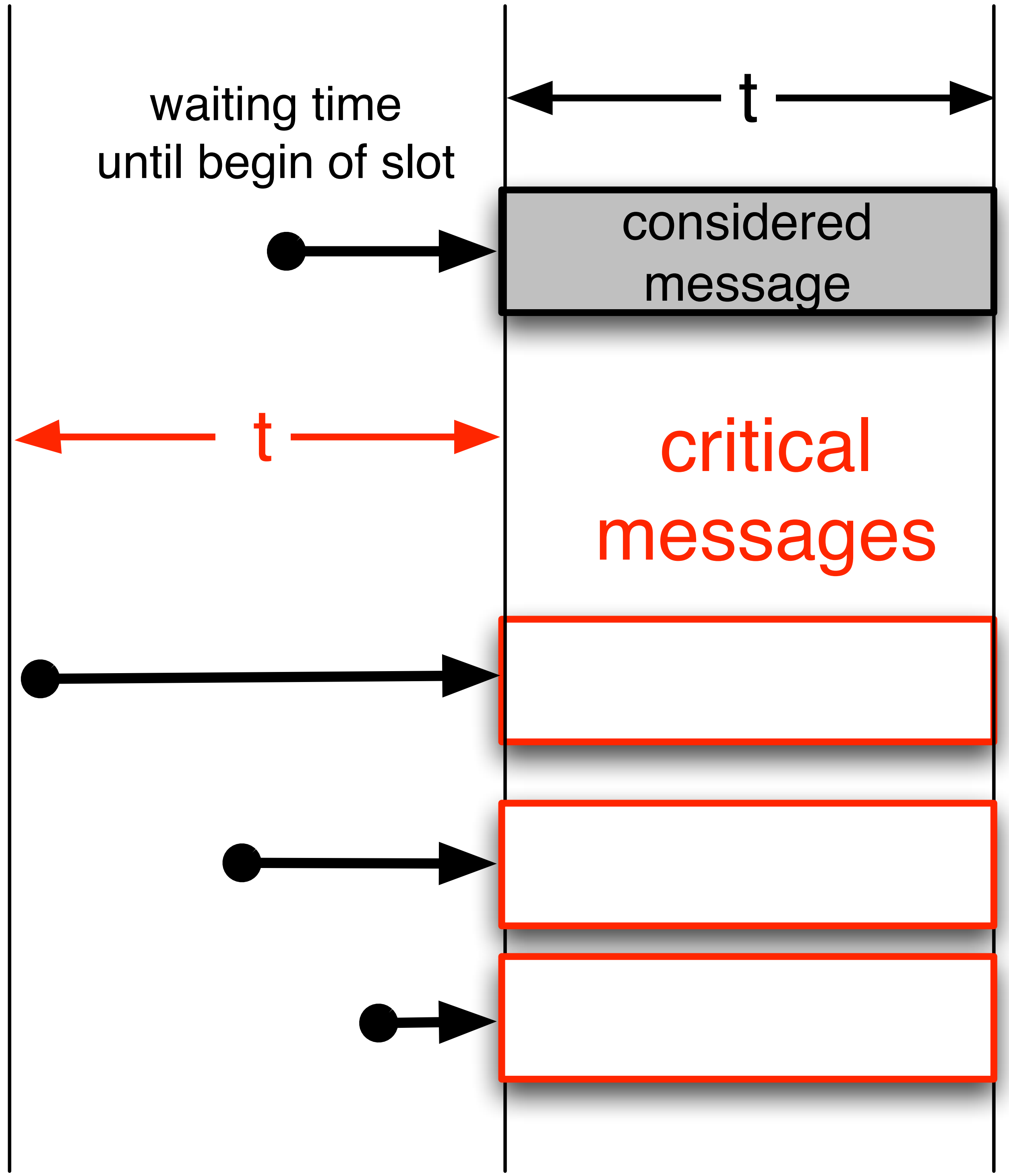
Paket ready?
No
Yes
Wait for the next slot
Transmit
Wait for a round-trip time
Positive ACK?
Yes
No
Compute random back off integer k
Delay packet transmission k times

Slotted ALOHA

- ALOHA‘s problem
  - long vulnerability of a packet
- Reduction through use slots
  - synchronization is assumed
- Result
  - vulnerability is halved
  - throughput is doubled
    - $S(G) = Ge^{-G}$
    - optimal for G=1, S=1/e

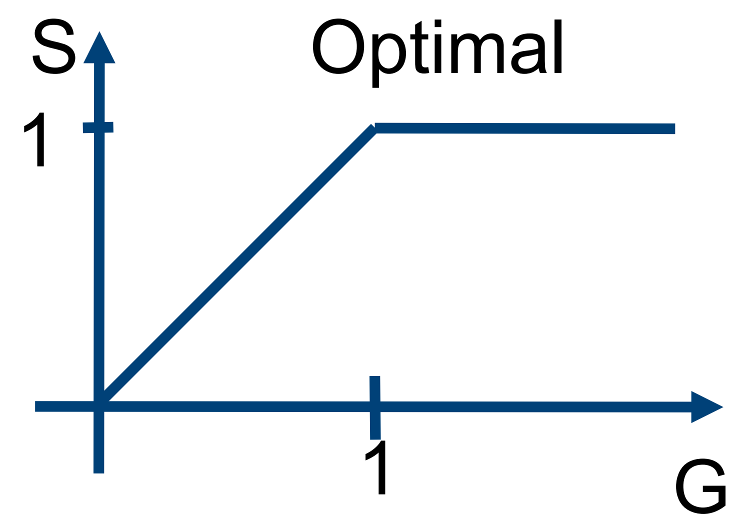
Slotted ALOHA – Effizienz

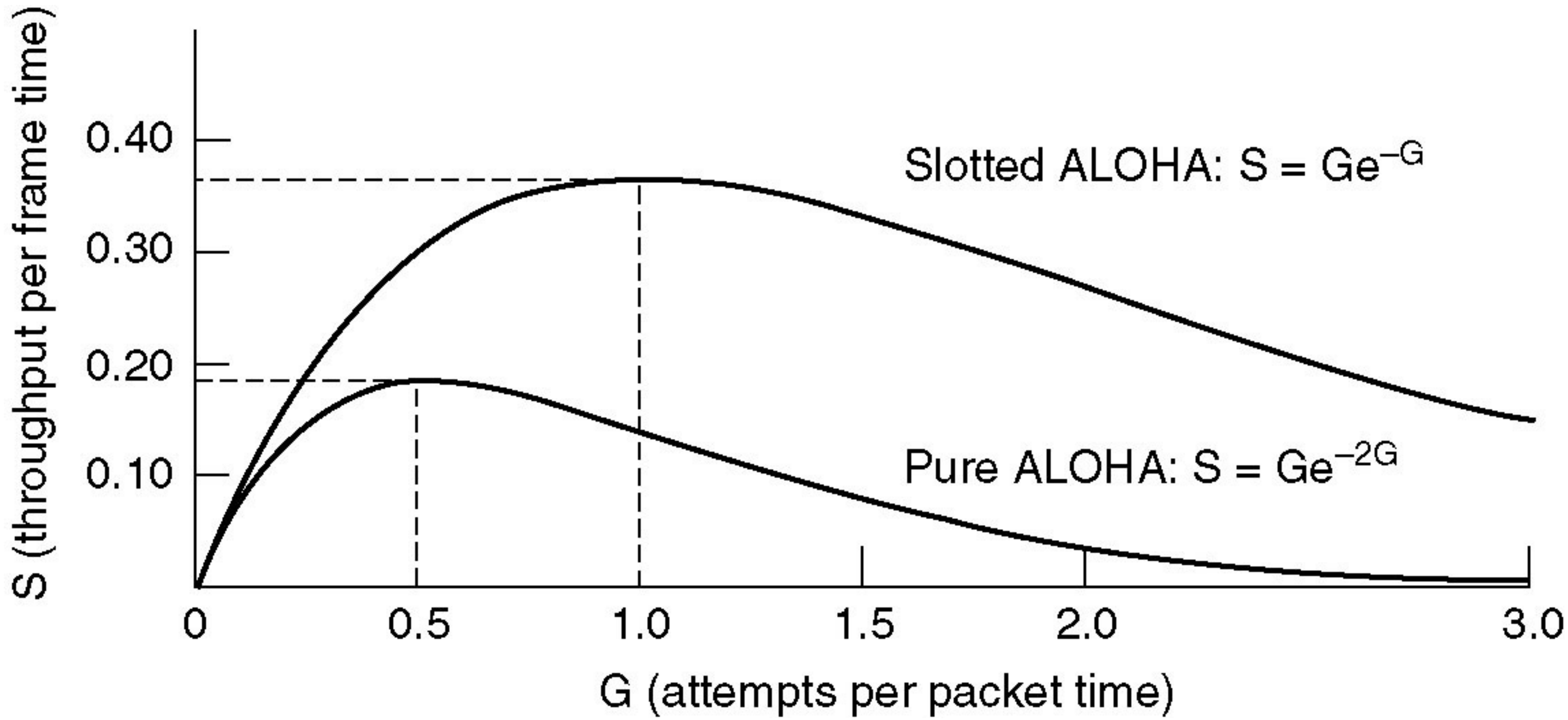
- A packet X is disturbed if
  - a package starts just before X
- The packet is successfully transmitted,
  - when transmitting over a period of **one** packets no (other) packets appears

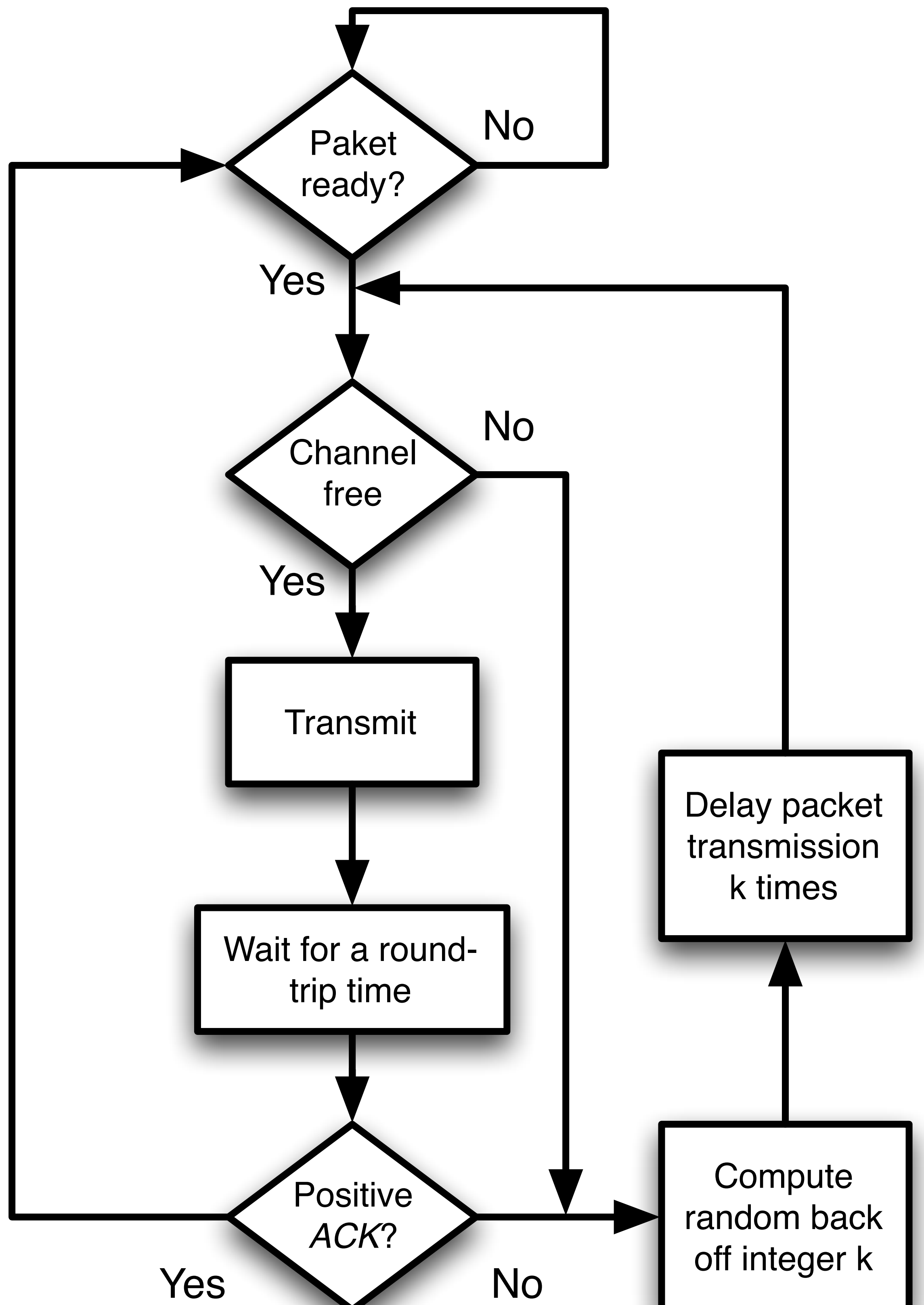


Throughput with respect to the Load

- (Slotted) ALOHA
  - not a good protocol
  - Throughput breaks down for increasing demand

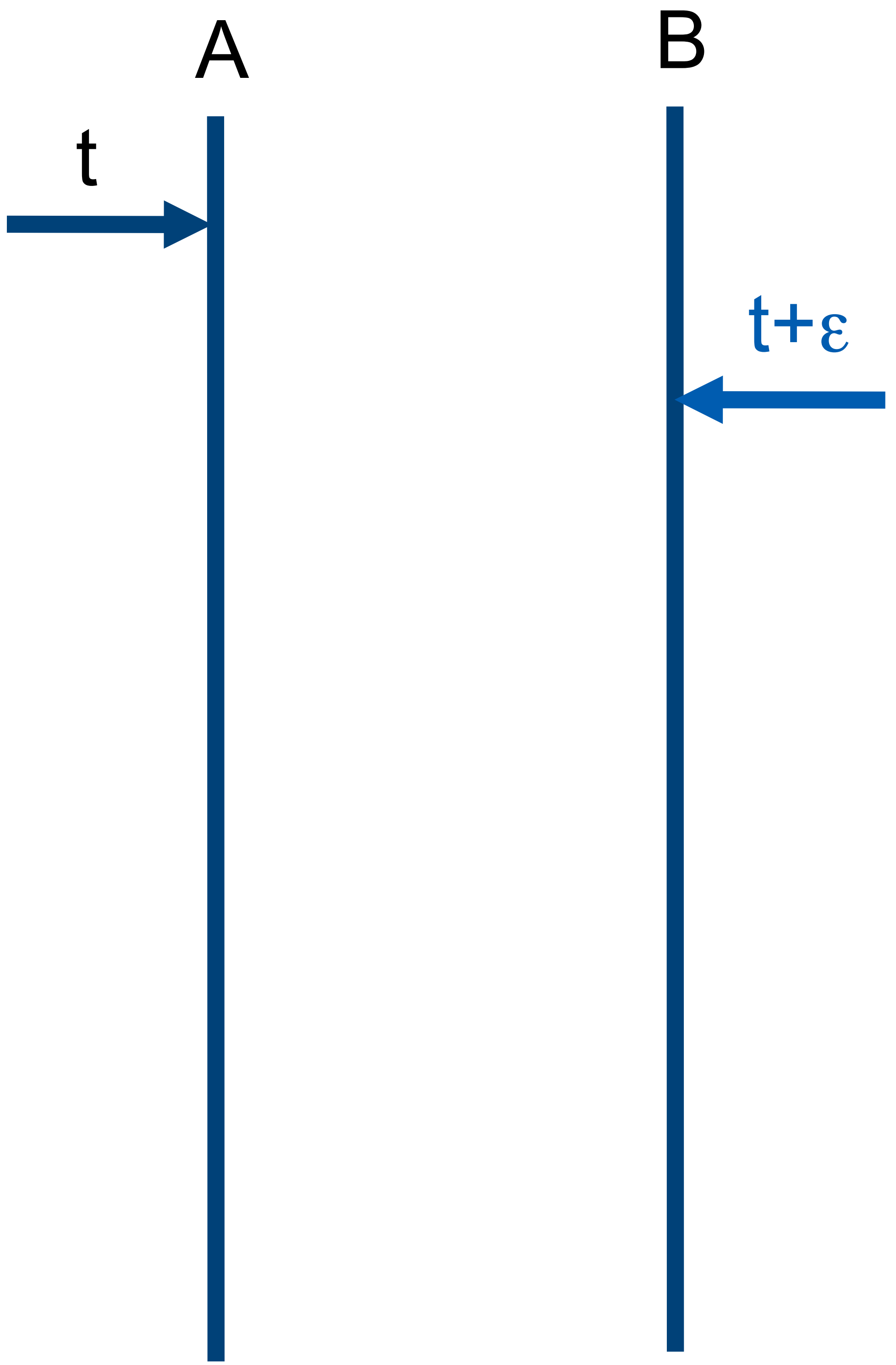





No
Paket
ready?
Yes
No
Channel
free
Yes
Transmit
Wait for a round-
trip time
Delay packet
transmission
k times
Compute
random back
off integer k
Positive
ACK?
Yes
No

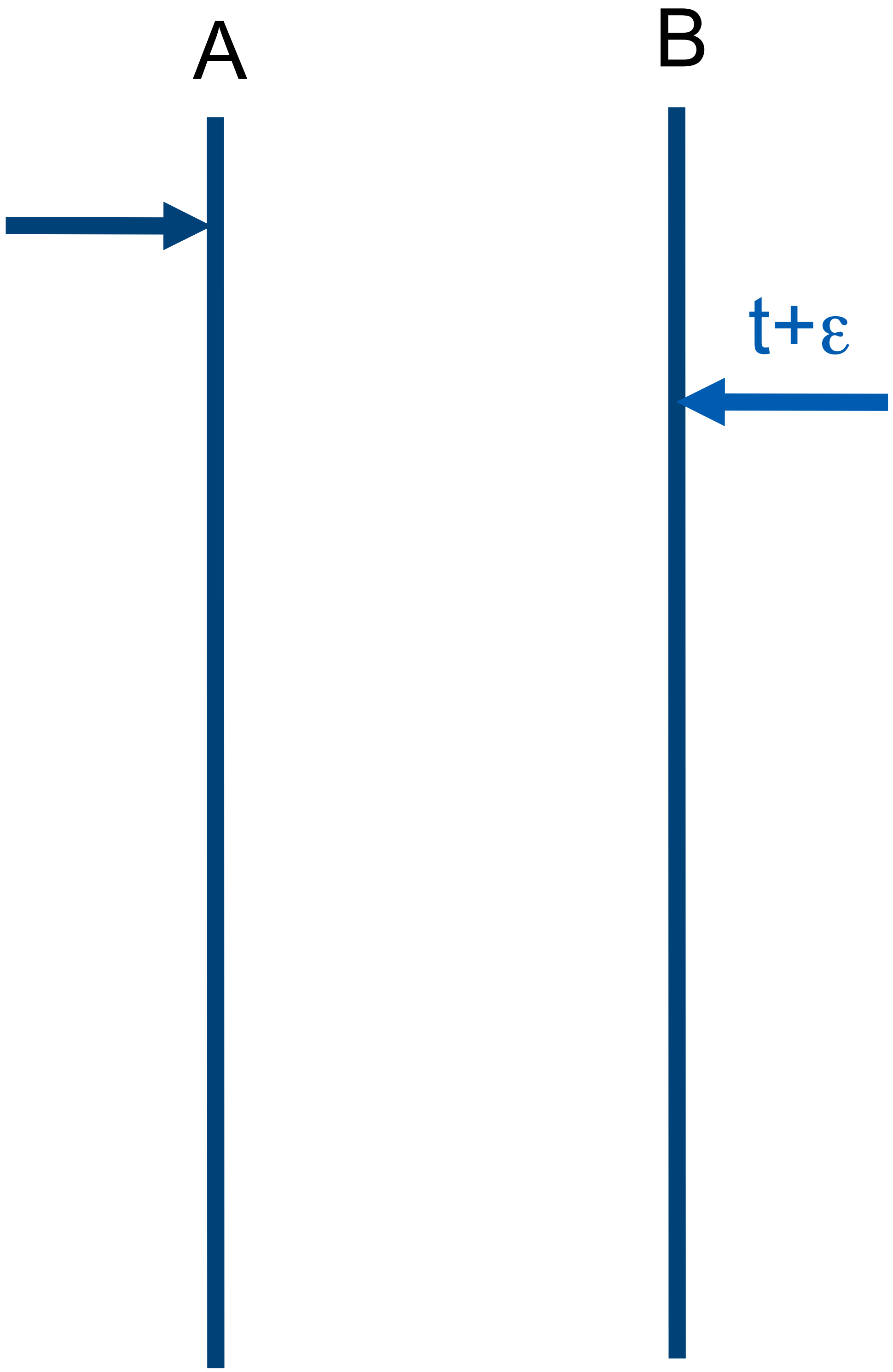
CSMA und Transmission Time

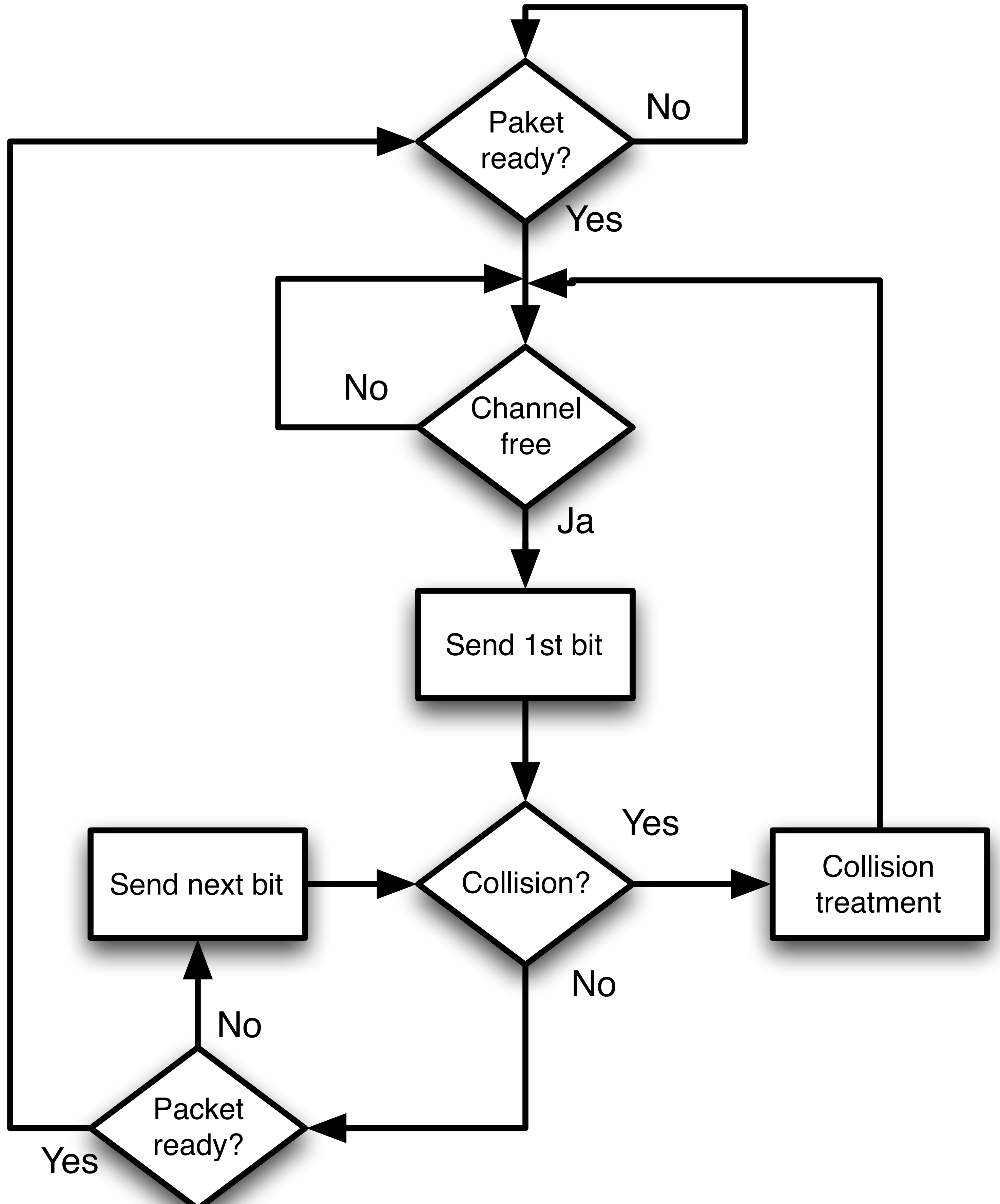
- CSMA-Problem:
  - Transmission delay d
- Two stations
  - start sending at times t and t + ε with ε <d
  - see a free channel
- 2nd Station
  - causes a collision



Collision Detection in Ethernet – CSMA/CD

- CSMA/CD – Carrier Sense Multiple Access/Collision Detection
  - Ethernet
- If collision detection during reception is possible
  - Both senders interrupt sending
  - Waste of time is reduced
- Collision Detection
  - simultaneously listening and sending must be possible
  - Is that what happens on the channel that's identical to the message?




Paket ready?
No
Yes
No
Channel free
Ja
Send 1st bit
Yes
Send next bit
Collision?
Collision treatment
No
No
Packet ready?
Yes

Computation of the Backoff

- Algorithm: Binary Exponential Backoff
  - k:=2
  - While a collision has occurred
    - choose t randomly uniformly from {0,...,k-1}
    - wait t time units
    - send message (terminate in case of collision)
    - k:= 2 k
- Algorithm
  - waiting time adapts to the number of stations
  - uniform utilization of the channel
  - fair in the long term

Problem of Wireless Media Access

- Unknown number of participants
  - broadcast
  - many nodes simultaneously
  - only one channel available
  - asymmetric situations
- Collisions produce interference
- Media Access
  - Rules to participate in a network

Aims

- Delay
- Throughput
- Fairness
- Robustness and stability
  - against disturbances on the channel
  - against mobility
- Scalability
- Energy efficiency

Methods

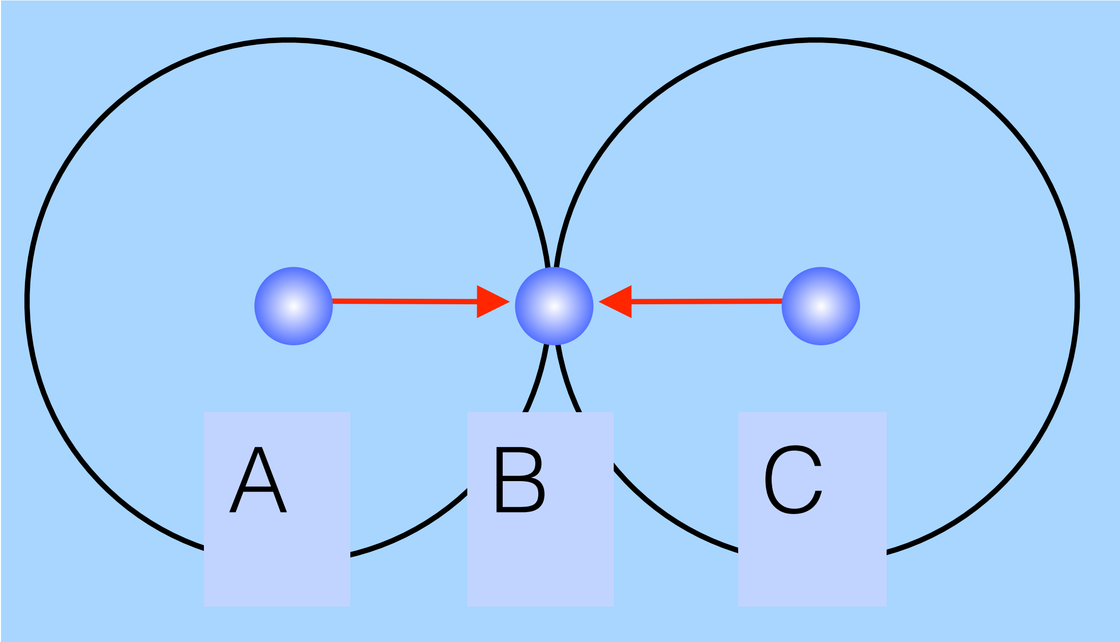
- Organisation
  - Central control
  - Distributed control
- Access
  - without contention
  - with contention

Problem of Media Access

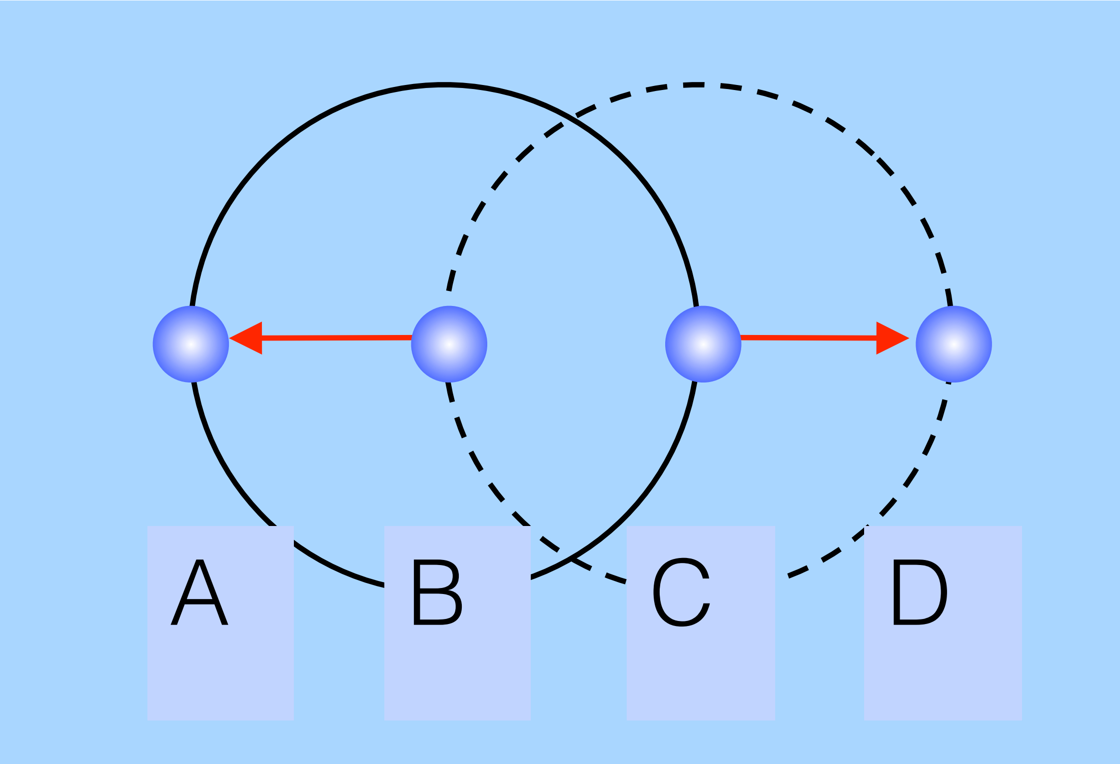
- CSMA/CD not applicable
  - Media is only locally known
  - Bounded range
- Hidden Terminal
  - Receiver collision despite *carrier sensing*
- Exposed Terminal
  - Opportunity costs of unsent messages because of c*arrier sensing*

Hidden Terminal and Exposed Terminal

- Hidden Terminal Problem



- Exposed Terminal Problem



Alternative Solutions

- Extended hardware
  - Addition carrier signal blocks and ensures transmission
- Centralized solution
  - Base station is the only communication partner
  - Base station coordinates the media access

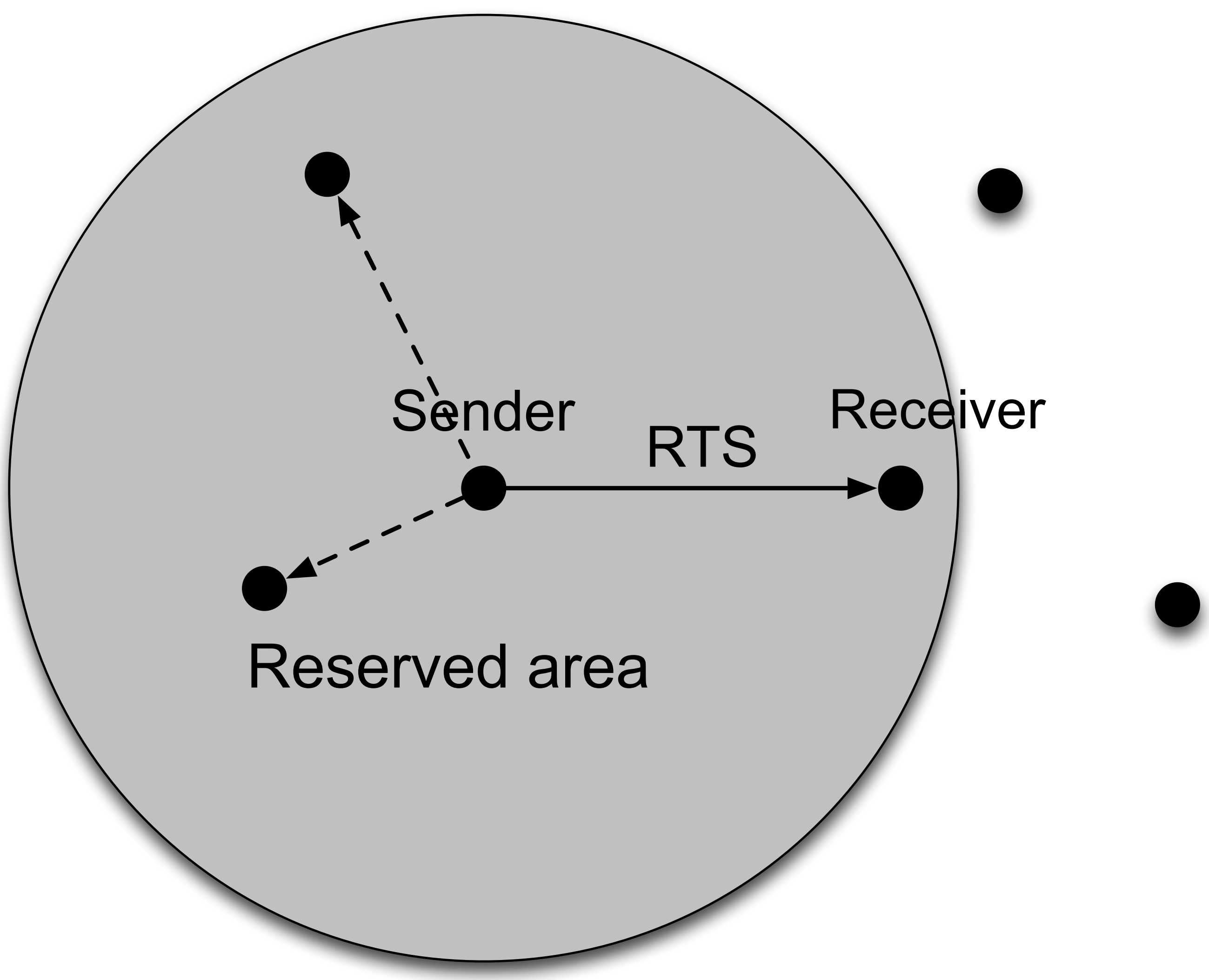
MACA

- **Phil Karn**
  - MACA: A New Channel Access Method for Packet Radio 1990
- **Alternative names:**
  - Carrier Sensing Multiple Access / Collision Avoidance (CSMA/CA)
  - Medium Access with Collision Avoidance (MACA)
- **Aim**
  - Solution of the Hidden and Exposed Terminal Problem
- **Idea**
  - Channel reservation before the communication
  - Minimization of collision cost

Request to Send

(a) A sends Request to Send (RTS)

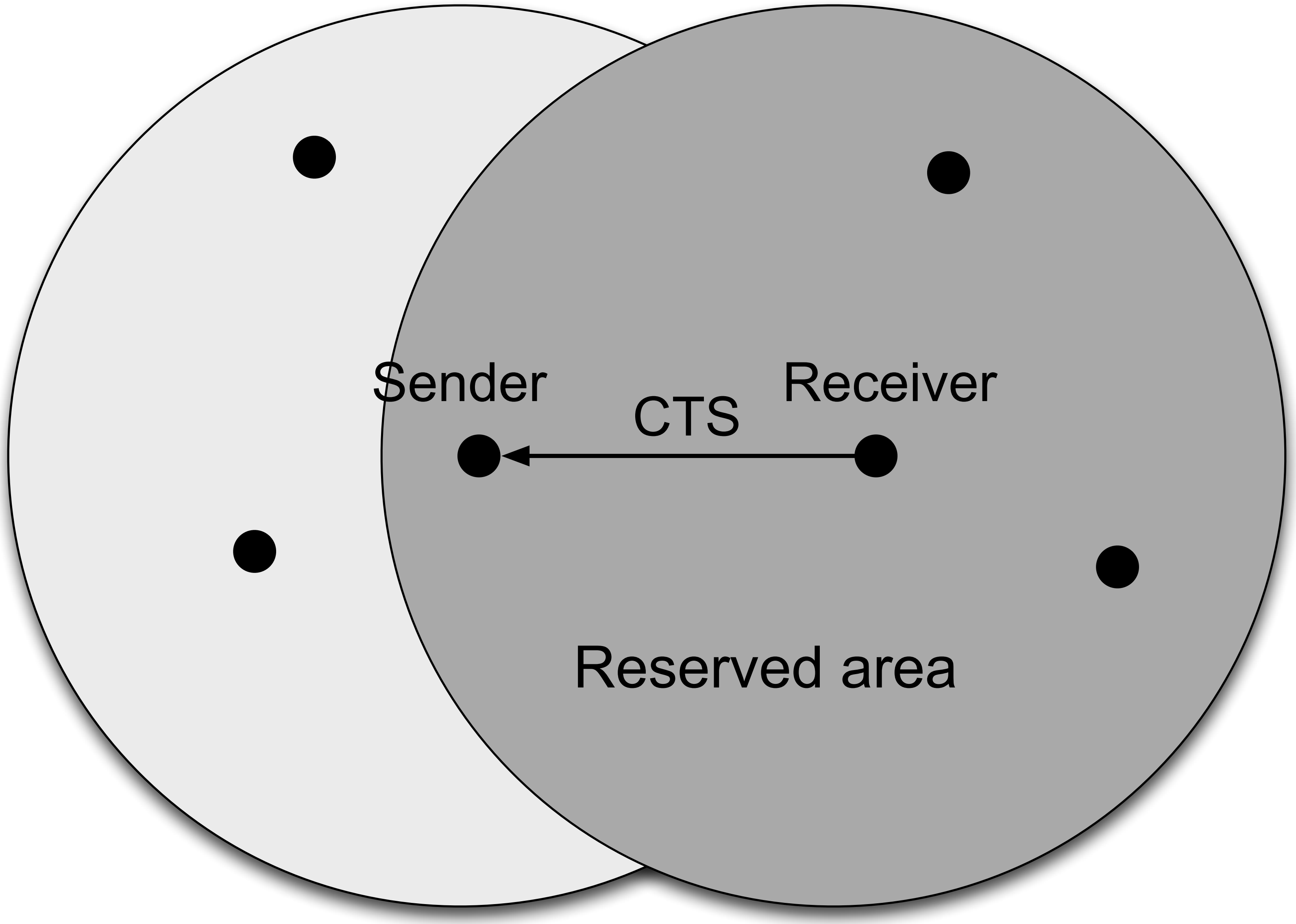
(b) B answers with Clear to Send (CTS)

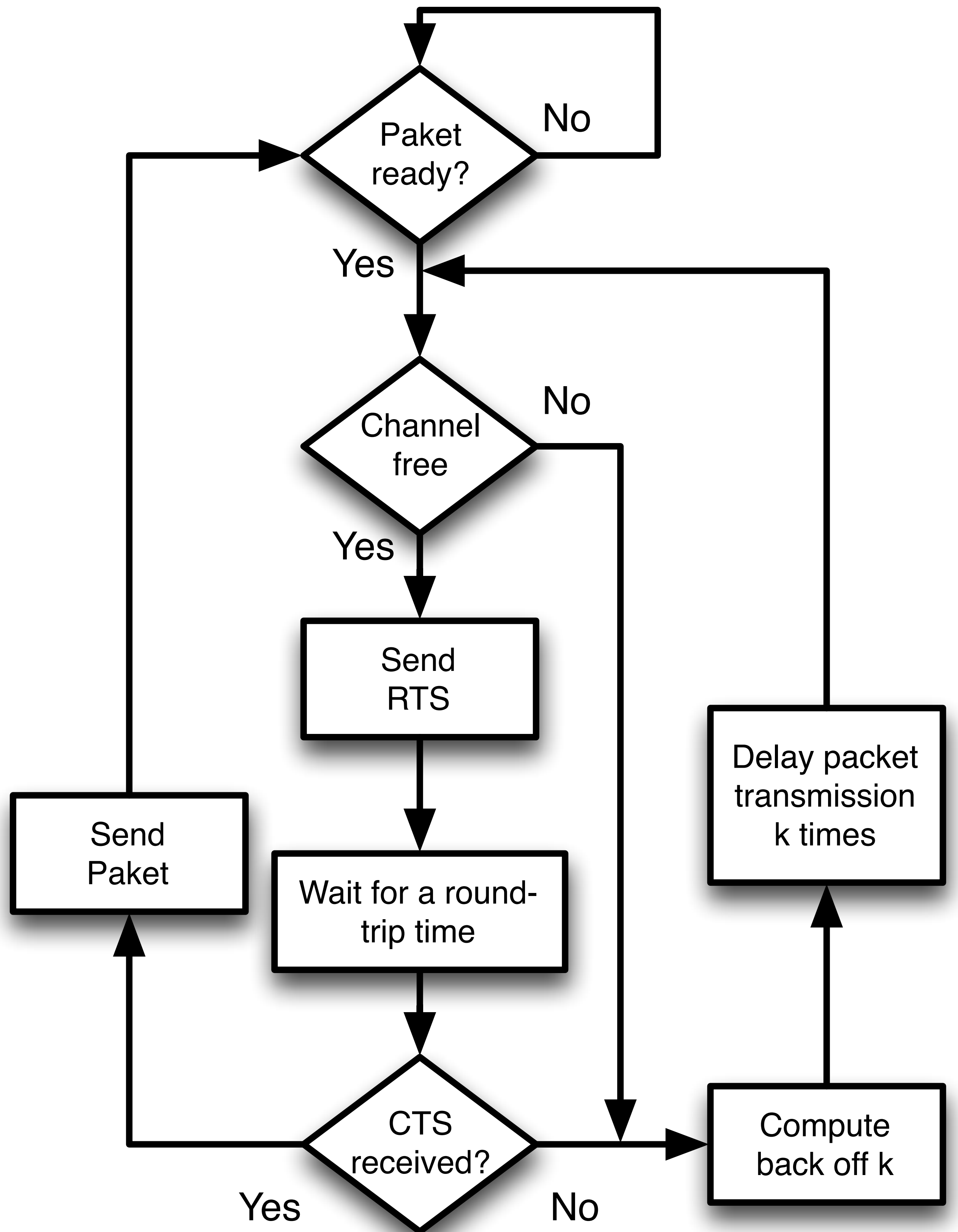


Clear to Send

(a) A sends Request to Send (RTS)

(b) B answers with Clear to Send (CTS)




No
Paket ready?
Yes
Channel free
No
Yes
Send RTS
Wait for a round-trip time
CTS received?
Yes
No
Send Paket
Compute back off k
Delay packet transmission k times

Details for Sender

- A sends RTS
  - waits certain time for CTS
- If A receives CTS in time
  - A sends packet
  - otherwise A assumes a collision at B
    - doubles *Backoff*-counter
    - and chooses a random waiting time from {1,...,*Backoff* }
  - After the waiting time A repeats from the beginning

Details for Receiver

- After B has received RTS
  - B sends CTS
  - B waits some time for the data packet
  - If the data packet arrives then the process is finished
    - Otherwise B is not blocked

Details for Third Parties

- C receives RTS of A
  - waits certain time for CTS of B
- If CTS does not occur
  - C is free for own communication
- If CTS of B has been received
  - then C waits long enough such that B can receive the data packet

Details for Third Parties

- D receives CTS of B
  - waits long enough such that B can receive the data packet
- E receives RTS of A and CTS of B
  - waits long enough such that B can receive the data packet

MACAW

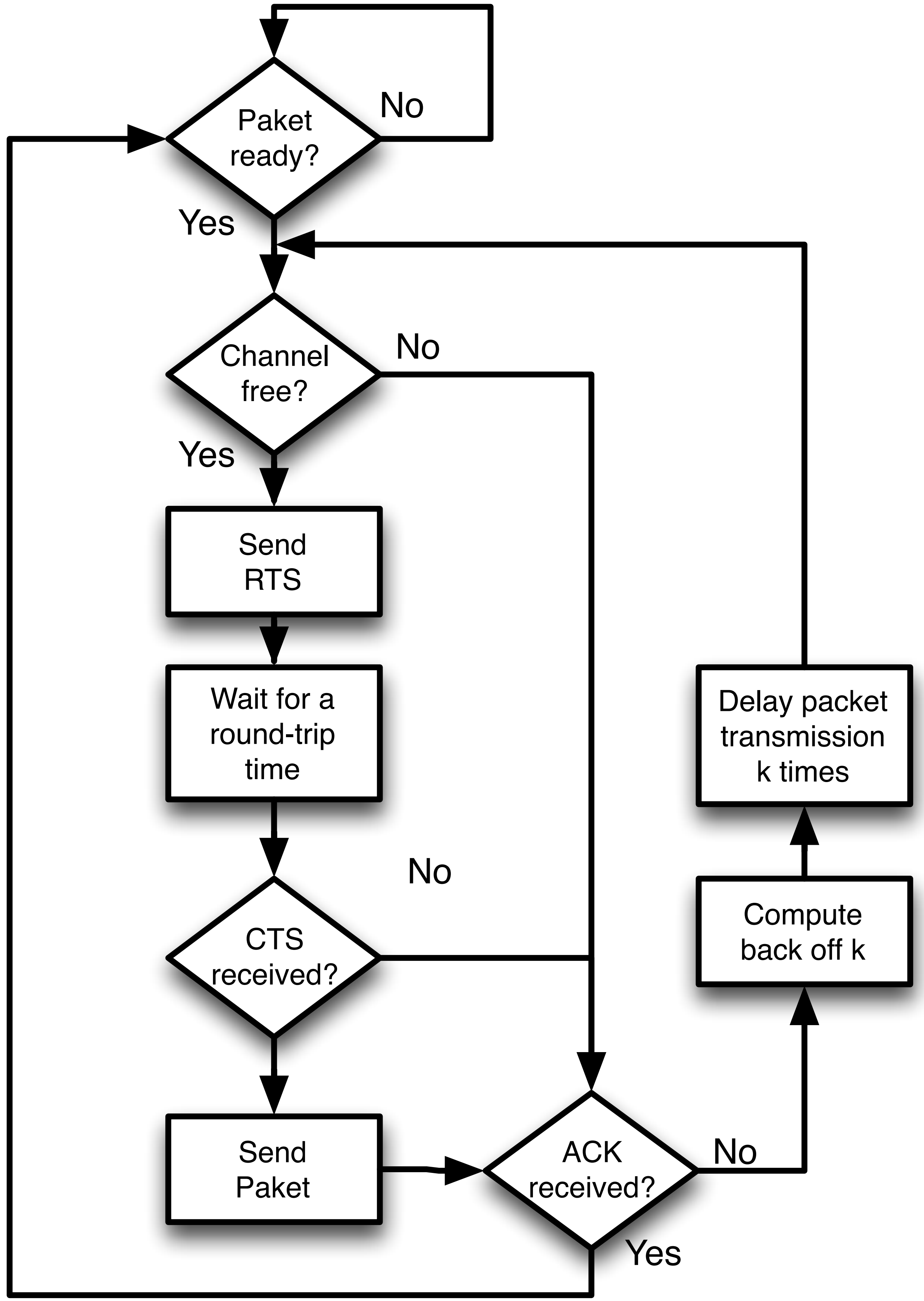
- Bharghavan, Demers, Shenker, Zhang
  - MACAW: A Media Access Protocol for Wireless LAN‘s, SIGCOMM 1994
  - Palo Alto Research Center, Xerox
- Aim
  - Redesign of MACA
  - Improved backoff
  - Fairer bandwidth sharing using *Streams*
  - Higher efficiency
    - by 4- and 5-Handshake

Acknowledgment in the Data Link Layer

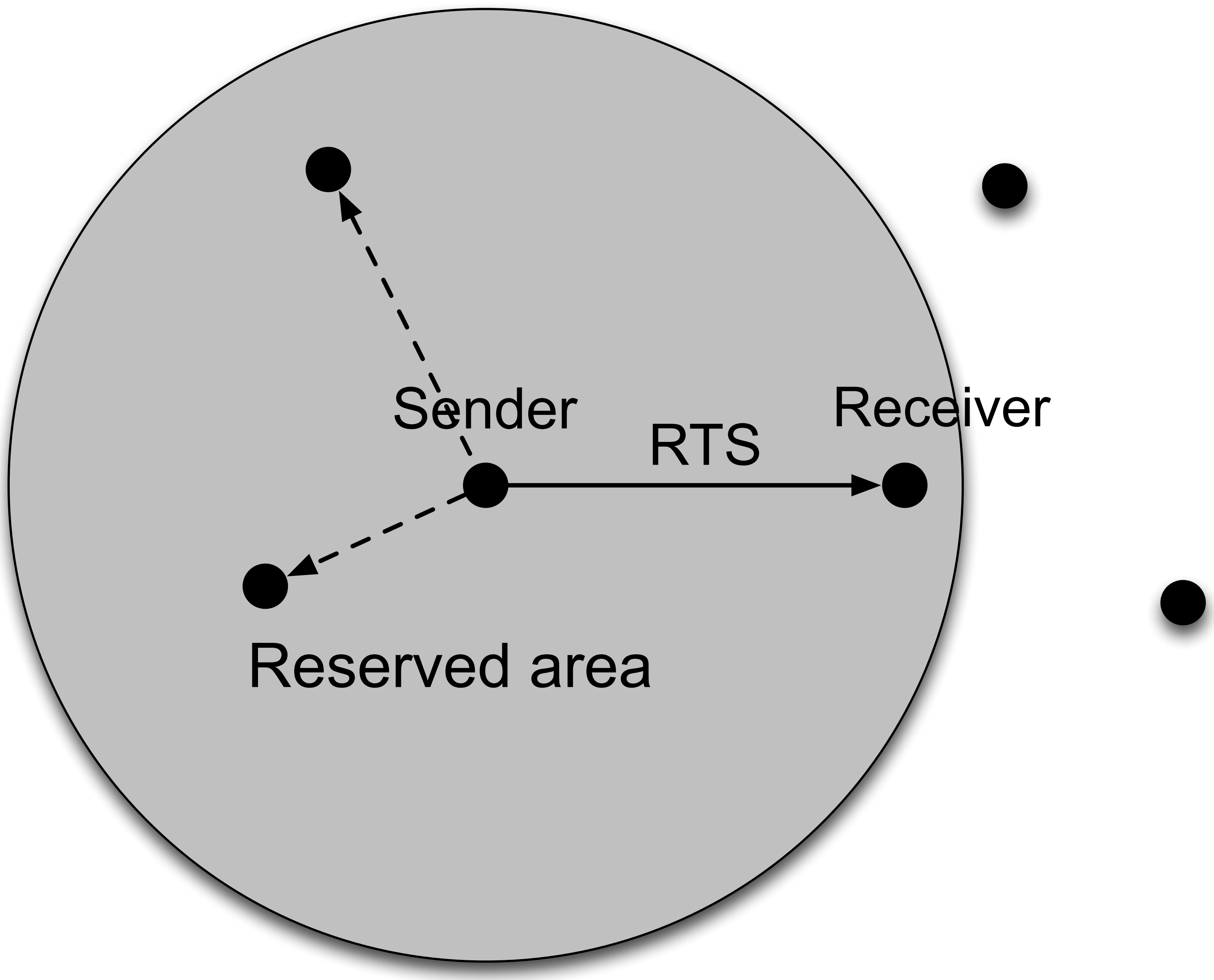
- MACA
  - does not use Acks
  - initiated by Transport Layer
  - very inefficient
- How can MACA use Acks?

MACAW
4 Handshake

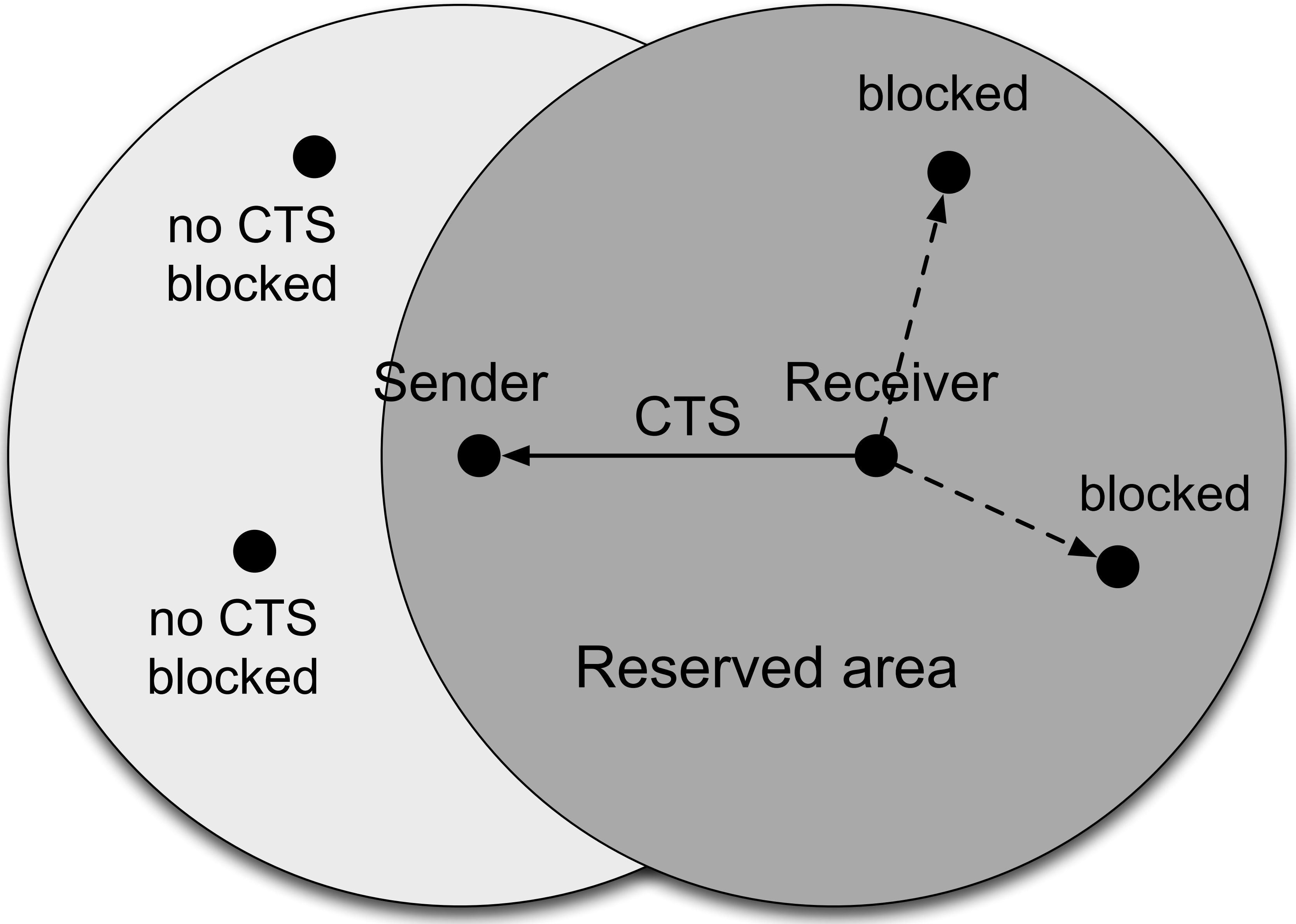
- Participants
  - Sender sends RTS
  - Receiver answers with CTS
  - Sender sends data packet
  - Receiver acknowledges (ACK)
- Third parties
  - Nodes receiving RTS or CTS are blocked for some time
  - RTS and CTS describe the transmission duration
- Sender repeats RTS, if no ACK has been received
  - If receiver has sent ACK
  - then the receiver sends (instead of CTS) another ACK


Paket ready?
No
Yes
Channel free?
No
Yes
Send RTS
Wait for a round-trip time
No
CTS received?
Send Paket
ACK received?
No
Yes
Delay packet transmission k times
Compute back off k

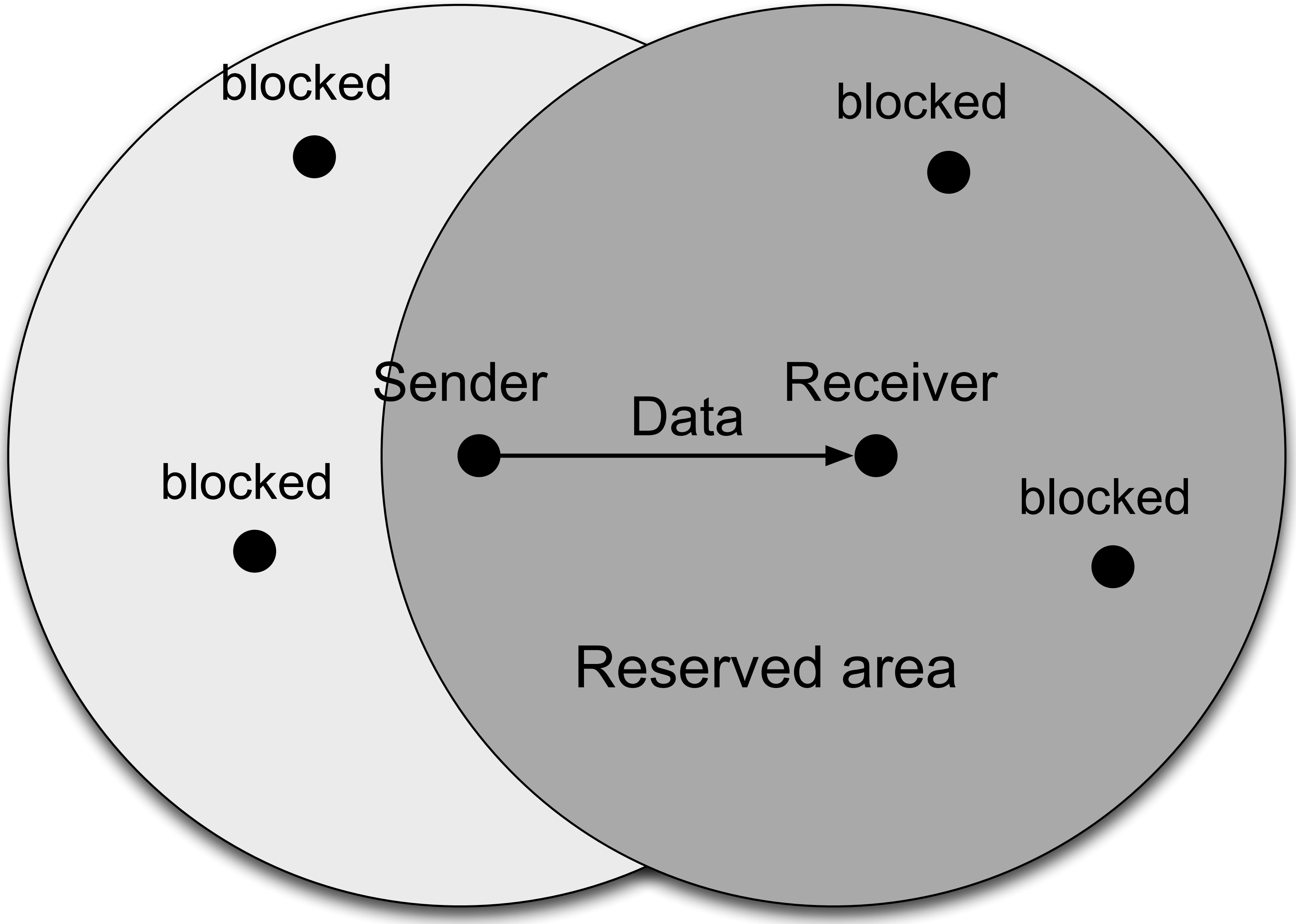
MACA 4-Handshake
RTS



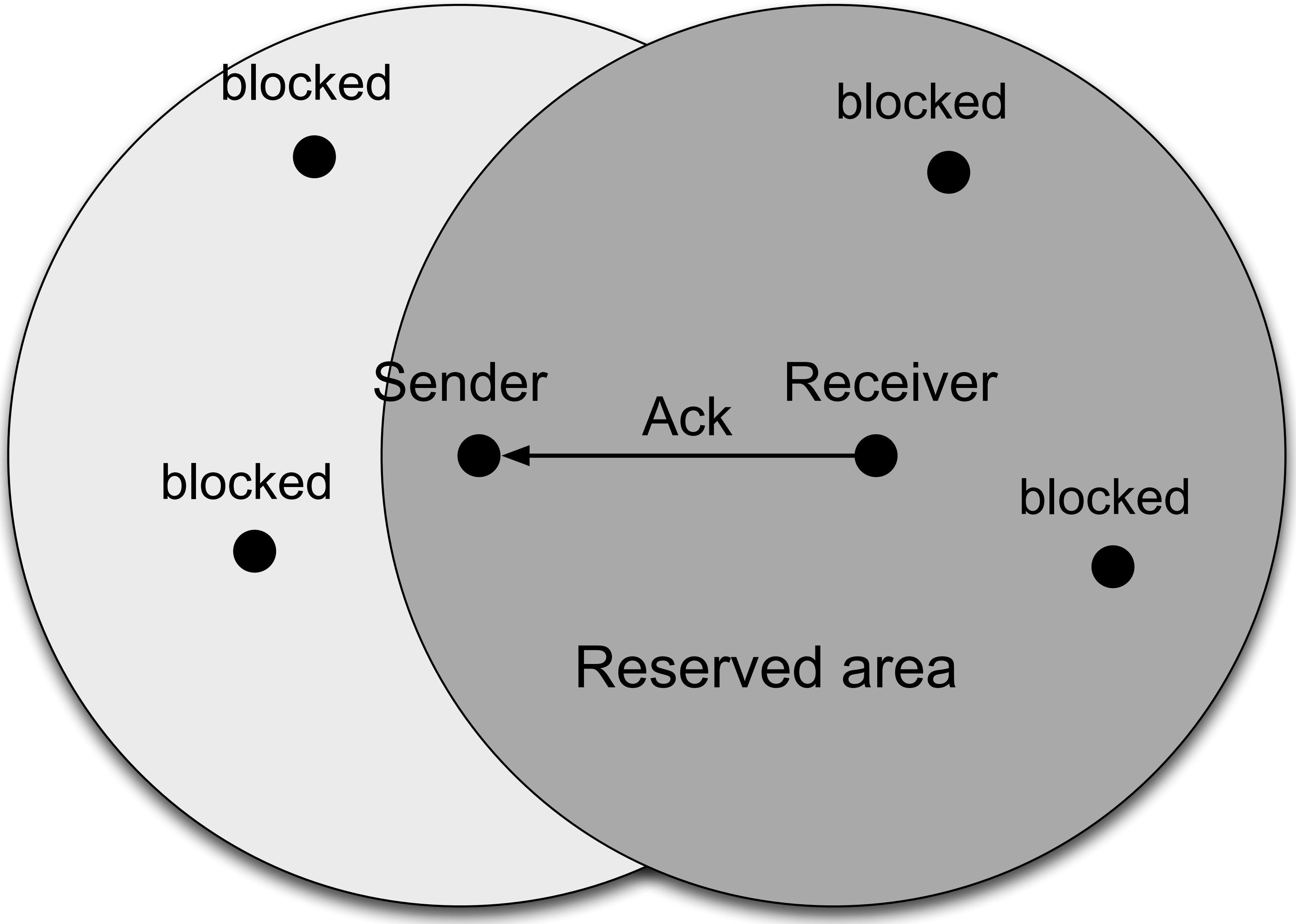
MACAW 4-Handshake CTS



MACAW 4-Handshake
Data



MACAW 4-Handshake
Ack



Acknowledgments

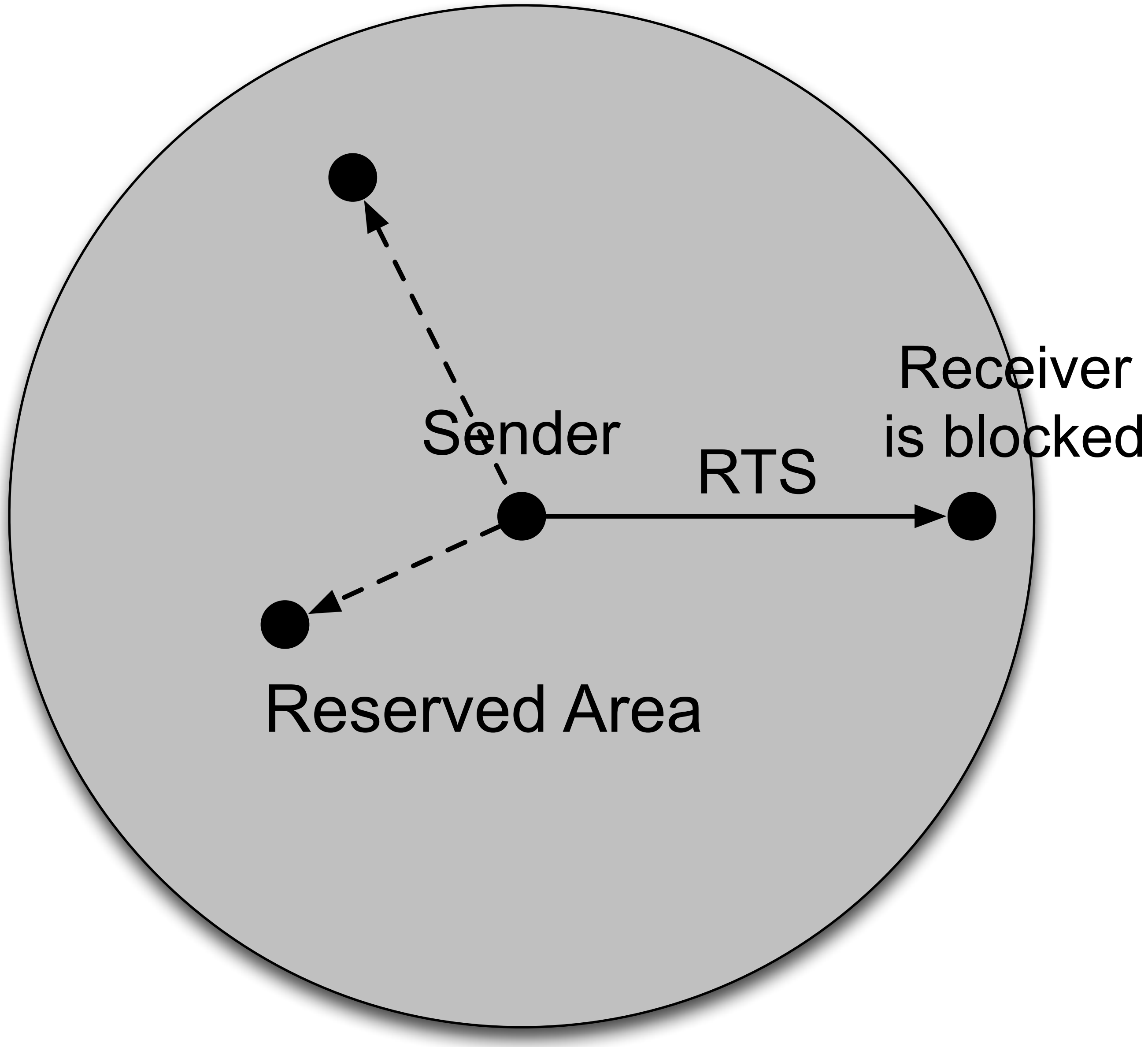
- Adding ACKs to MACA
  - In MACA done by transport layer
- leads to drastical improvements of throughput even for moderate error rates

error rate	throughput	
	RTS-CTS-DATA	RTS-CTS-DATA-ACK
0	40	37
0,001	37	37
0,01	17	36
0,1	2	10

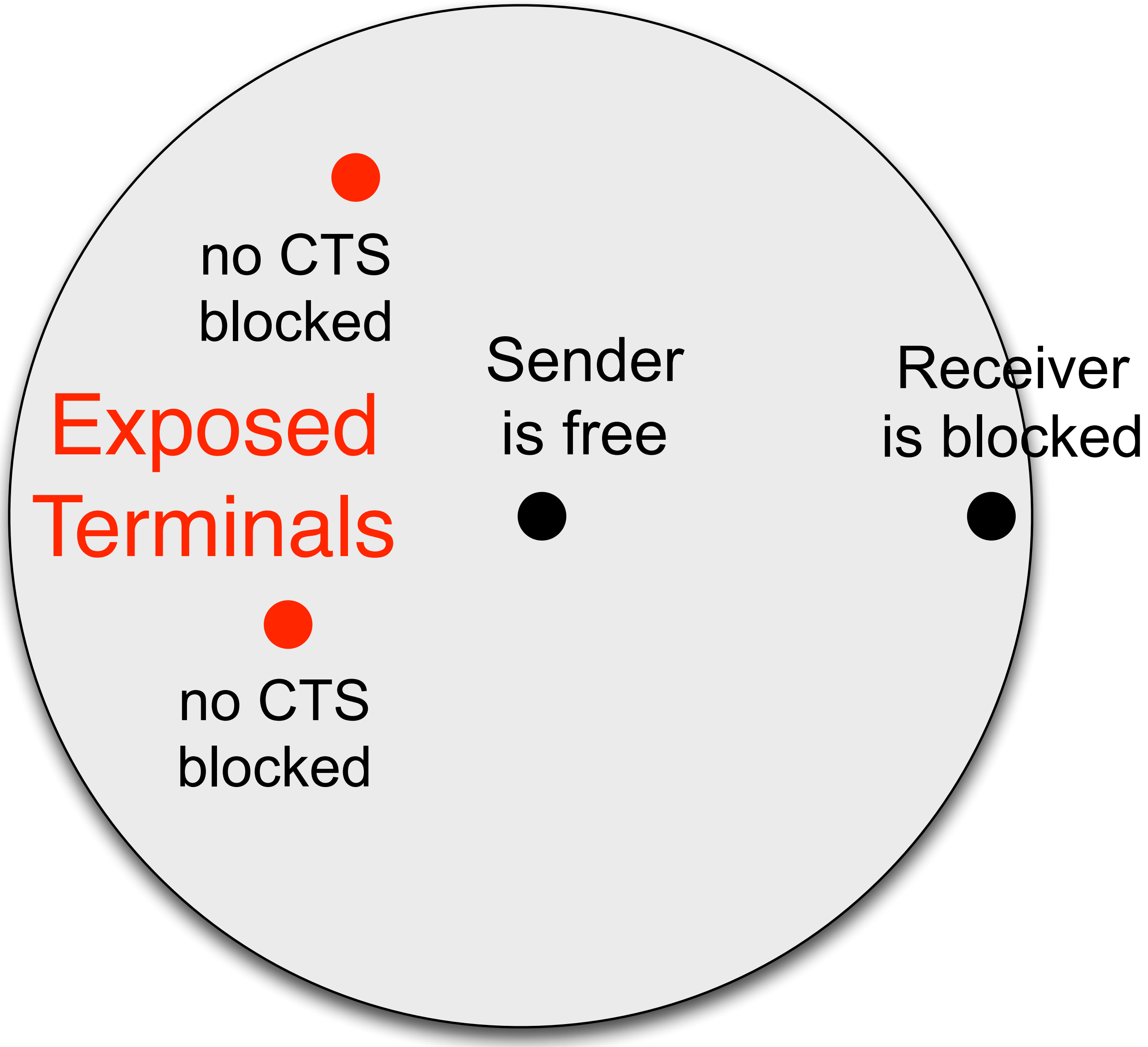
MACAW
4 Handshake

- Worst-Case blockade
  - Sender sends RTS
  - Receiver is blocked
  - Sender is free
  - But the environment of the sender is blocked

MACAW 4-Handshake
RTS



MACAW 4-Handshake
CTS is missing



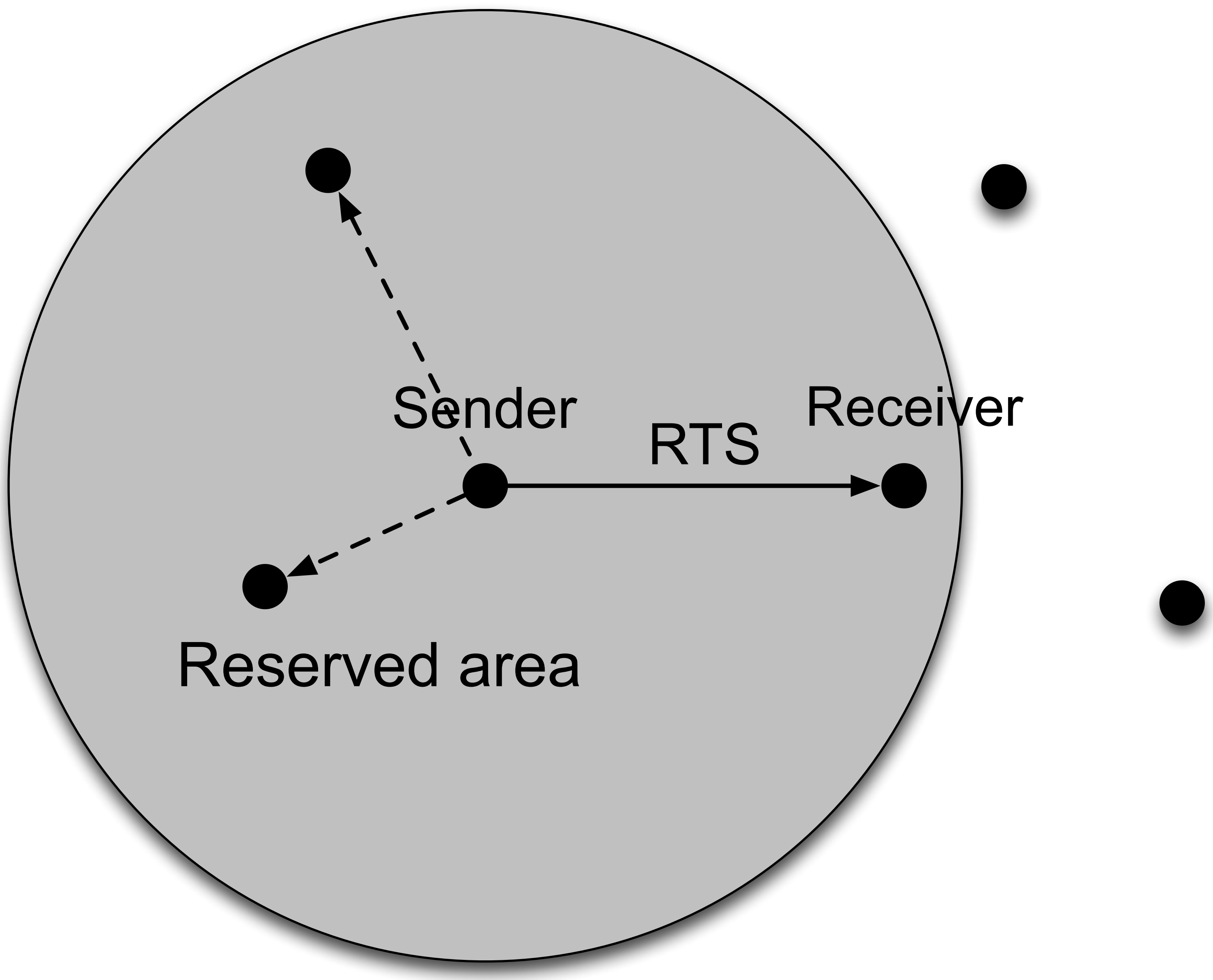
MACAW
5 Handshake

- 4-Handshake increases Exposed Terminal Problem
  - Overheard RTS blocks nodes
  - even if there is no data transfer
- Solution
  - Exposed Terminals are informed whether data transmission occurs
  - Short message DS (data send)
- 5 Handshake reduces waiting time for exposed terminals

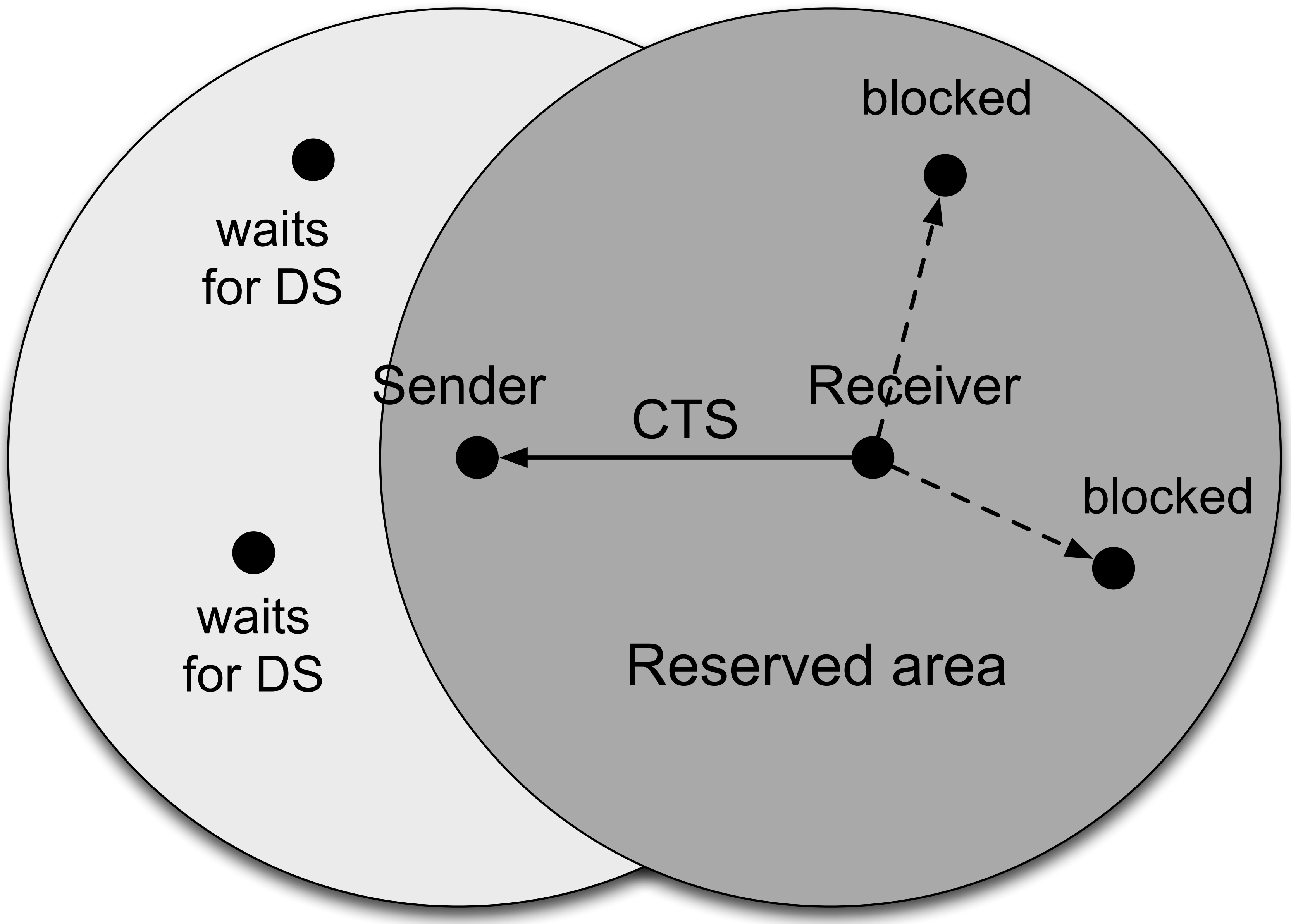
MACAW
5 Handshake

- Participants
  - Sender sends RTS
  - Receivers answers with CTS
  - Sender sends DS (Data Send)
  - Sender sends DATA PACKET
  - Receiver acknowledges (ACK)
- RTS and CTS announce the transmission duration
- Blocked nodes
  - have received RTS and DS
  - have received CTS
- Small effort decreases the number of exposed terminals

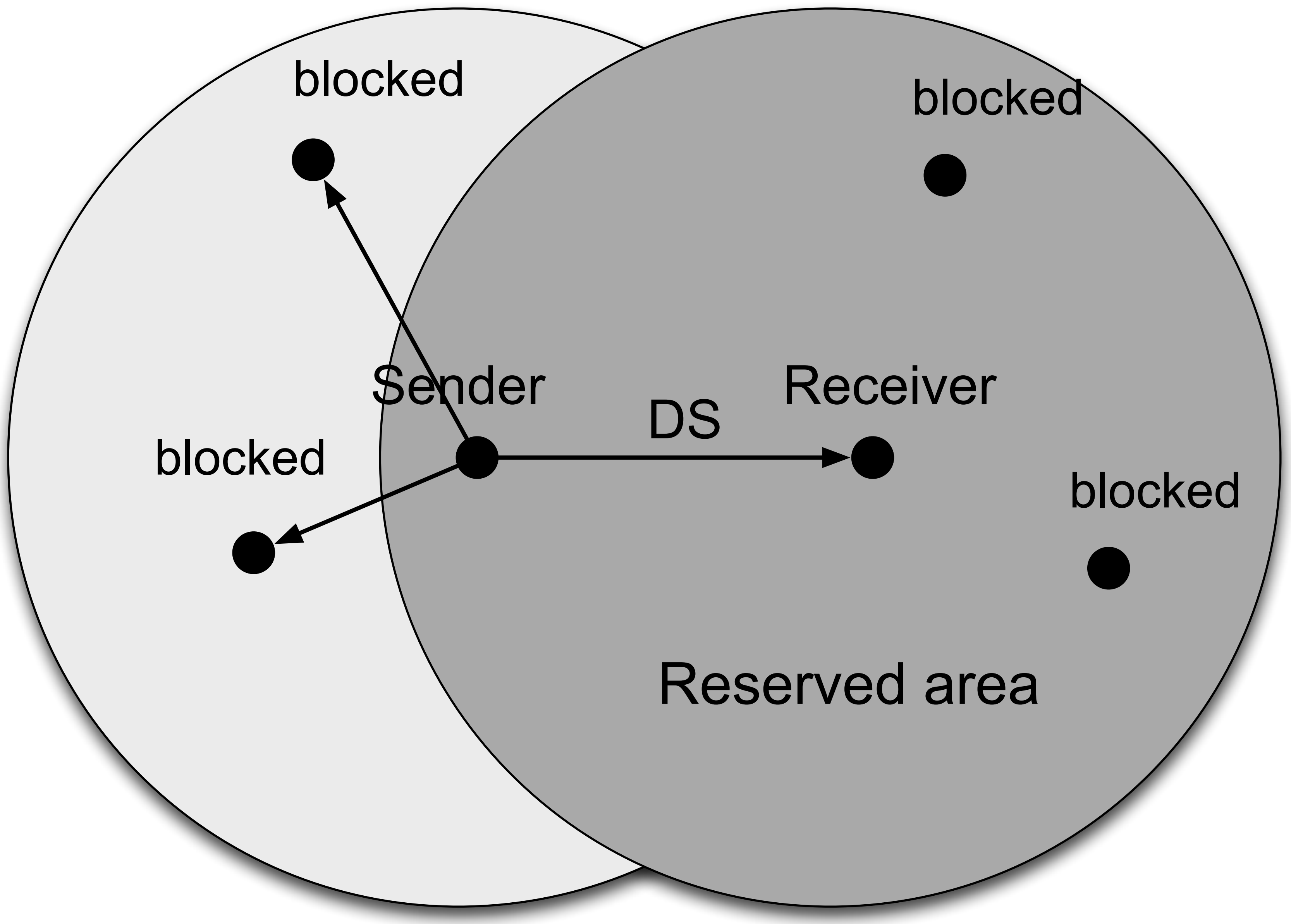
MACAW 5-Handshake RTS



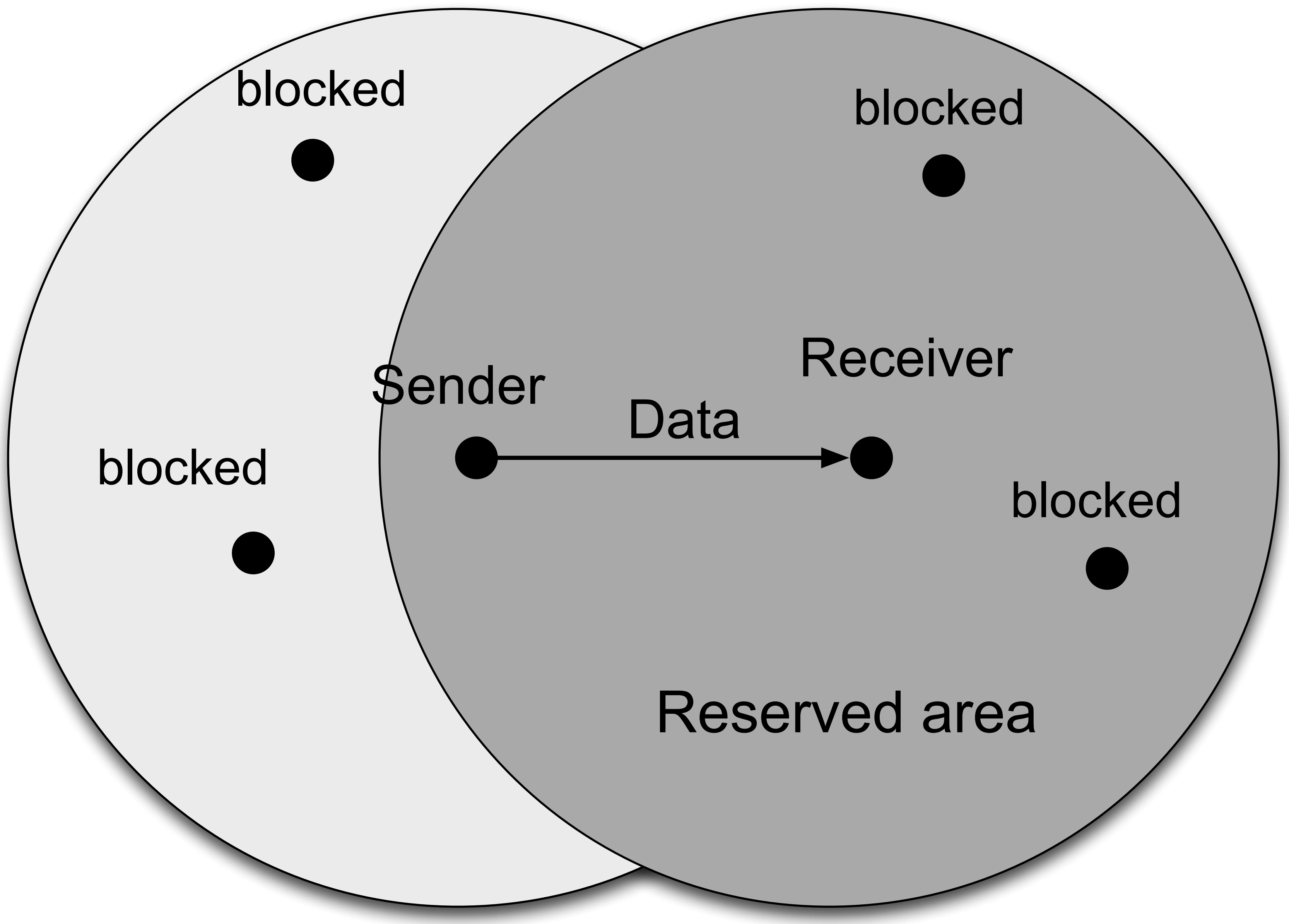
MACAW 5-Handshake CTS



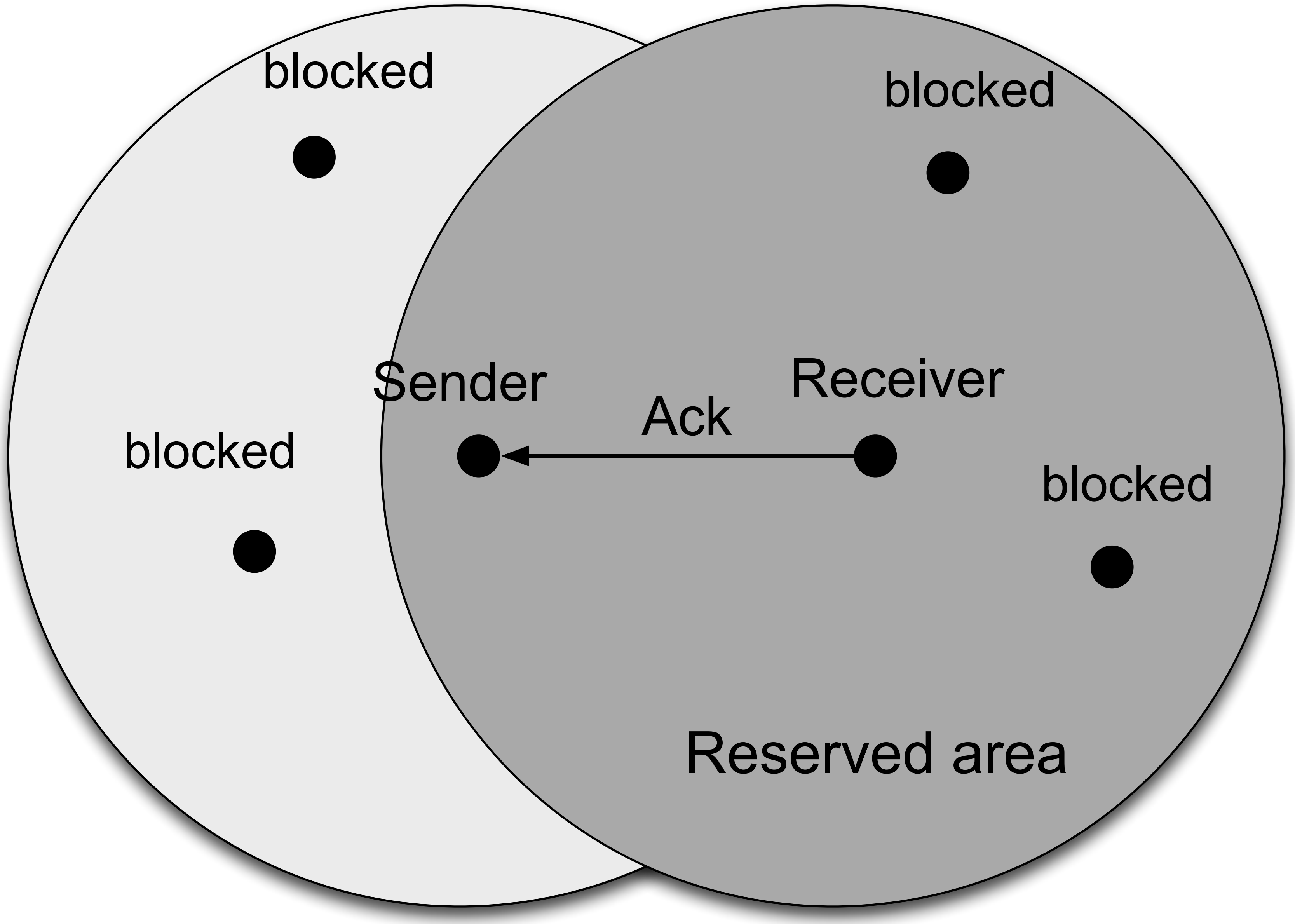
MACAW 5-Handshake DS



MACAW 5-Handshake
Data



MACAW 5-Handshake
ACK



Unfair Distribution

- 4 and 5-Handshake create unfair distribution
  - A has a lot of data for B
  - D has a lot of data for C
  - C receives B and D, but does not receive A
  - B can receive A and C, but does not hears D
- A is the first to get the channel
- D sends RTS and is blocked
  - Backoff of D is doubling
- At the next transmission
  - A has smaller backoff
  - A has higher chance for next channel access

RRTS

- Solution
  - C sends RRTS (Request for Request to Send)
    - if ACK has been received
  - D sends RTS, etc.
- Why RRTS instead of CTS?
  - If neighbors receive CTS, then they are blocked for a long time
  - Possibly, D is not available at the moment

Backoff Algorithms

- After collision wait random time from {1,.. Backoff}
- Binary Exponential Backoff (BEB) algorithm
  - Increase after collision
    - backoff = min{2 backoff, maximal backoff}
  - Else:
    - backoff = Minimal Backoff
- Multiplicative increase, linear decrease (MILD)
  - Increase:
    - backoff = min{1.5 backoff, maximal backoff}
  - Else:
    - backoff = max{backoff - 1, minimal-backoff}

Information Dissemination for Backoff-Algorithm

- Backoff parameter are overheard
  - participants adapt the parameters to the overheard backoff values
  - using MILD
- Motivation
  - if a participant has the same backoff value, then the fairness has been reached

Media ACcess MAC

- Prevention of collisions on the medium
  - Fair and efficient bandwidth allocation
- MAC for WSN
  - Regulates sleep cycles for participants
  - Reduces waiting time for active reception
- Standard protocols are not applicable for WSN
  - Energy efficiency and sleep times must be added

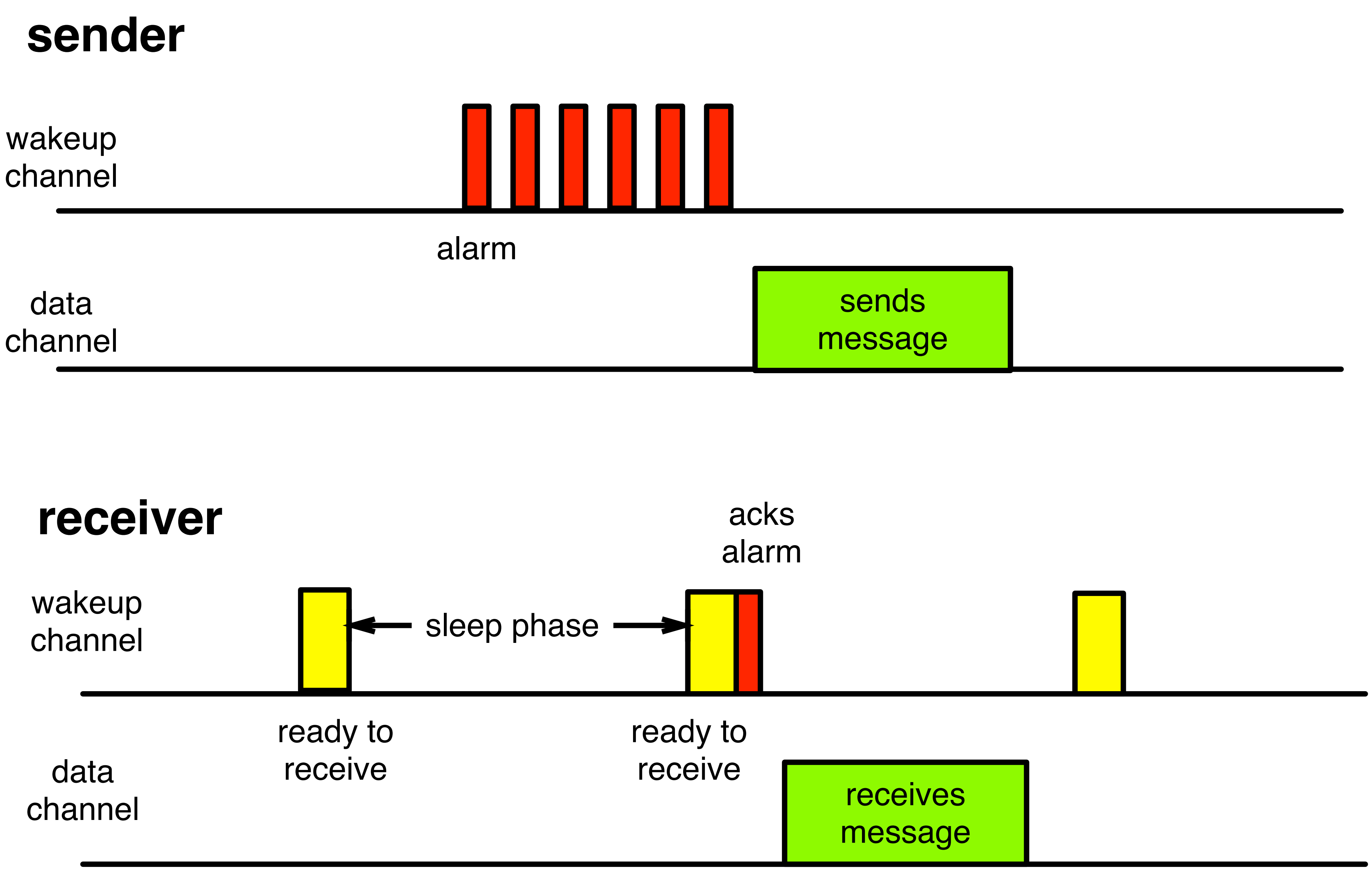
MACA and WSN

- MACA:
  - Channel must be monitored for RTS and CTS
  - Nodes waking up can disrupt existing communications
- Solution in IEEE 802.11:
  - Announcement Traffic Indication Message (ATIM)
    - prevents receiver from starting a sleep cycle
    - informs about upcoming packages
    - is sent within the beacon interval
  - When no message is pending, then the client can switch off its receiver (for a short time)

STEM

- Schurgers, Tsiatsis, Srivastava
  - STEM: Toplogy Management for Energy Efficient Sensor Networks, 2001 IEEEAC
- Sparse Topology and Energy Management (STEM)
- Special hardware with two channels
  - Wakeup channel
  - data channel
- no synchronization
- No RTS / CTS
- Suitable for decentralized multi-hop routing

STEM


sender
wakeup channel
alarm
data channel
sends message
receiver
acks alarm
wakeup channel
sleep phase
ready to receive
ready to receive
data channel
receives message

STEM

Sparse Topology and Energy Management Protocol

- Wakeup channel
  - sender announces message
  - announcement will be repeated until the receiver acknowledges
  - receiver sleeps in cycles
- Data channel
  - is used for undisturbed transmission
- No RTS / CTS
- No carrier sensing

Discussion STEM

- Sleep cycles ensure efficiency in the data reception
  - longer cycles improve energy efficiency
  - but increase the latency
- Too long sleep cycles
  - increase the energy consumption at the transmitter
  - lead to traffic congestion in the network
- Lack of collision avoidance
  - can result in increased traffic because of long waiting times
  - increase energy consumption

STEM

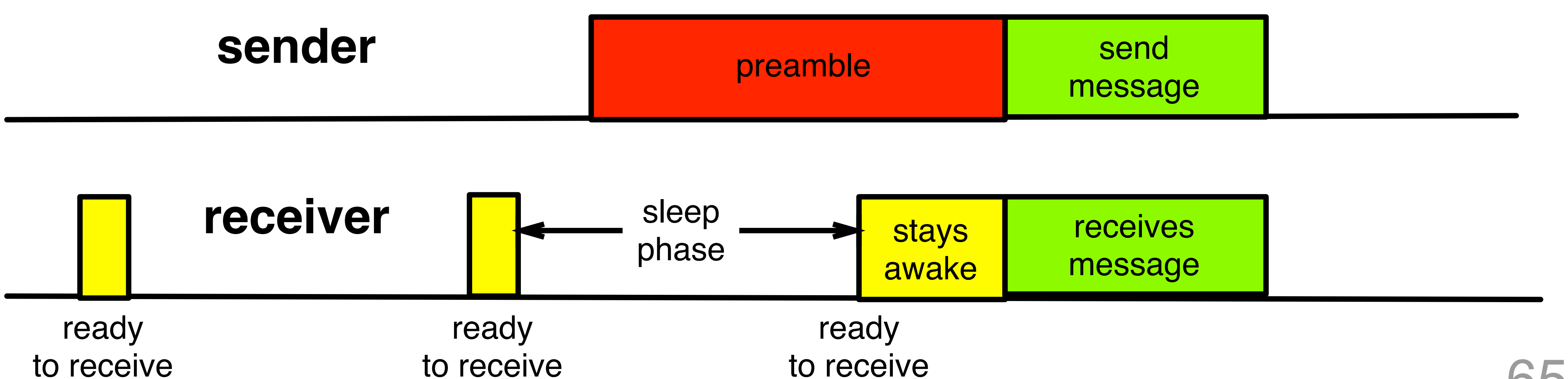
- STEM
  - can be combined with GAF (Geographic Adaptive Fidelity)
  - GAF reduces the sensor density, by allowing only the activation of one sensor in a small square
- T-STEM
  - STEM adds a busy-signal channel to wake up and to prevent communication from interruption

Preamble Sampling

- Only one channel available and no synchronization
- Receiver
  - wakes up after sleep period
  - listens for messages from channel
- Sender
  - sends a long preamble
  - and then the data packet

Preamble Sampling

- Only one channel available, no synchronization
- Receiver
  - is awake after sleep period
  - listens channel for messages from
- Transmitter
  - sends long preamble
  - and then the package



Efficiency of Preamble Sampling

- Few messages
  - Better: long sleep phases
  - Receiver consume most of the total energy
- Many messages
  - Short sleep phases
  - Sender consume most of the total energy
  - We observe for preamble time T and some positive constants c, c ', c'':

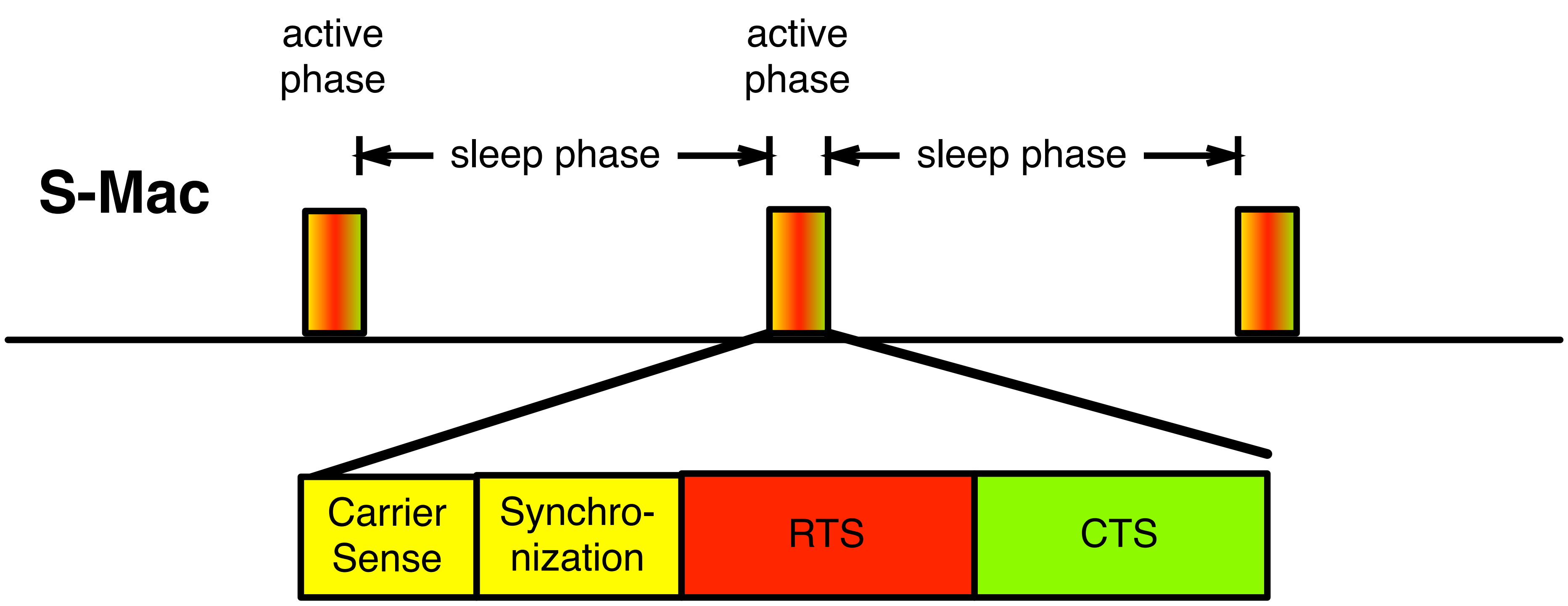
$$\text{Energy} = cT + \frac{c'}{T} + c''$$

Sensor-Mac (S-MAC)

- Ye, Heidemann, Estrin
  - An Energy-Efficient MAC Protocol for Wireless Sensor Networks, INFOCOM 2002
- Synchronized sleep and wake cycles
- MACA (RTS / CTS)
  - for collision avoidance
  - and detection of possible sleep cycles

S-MAC Protocol

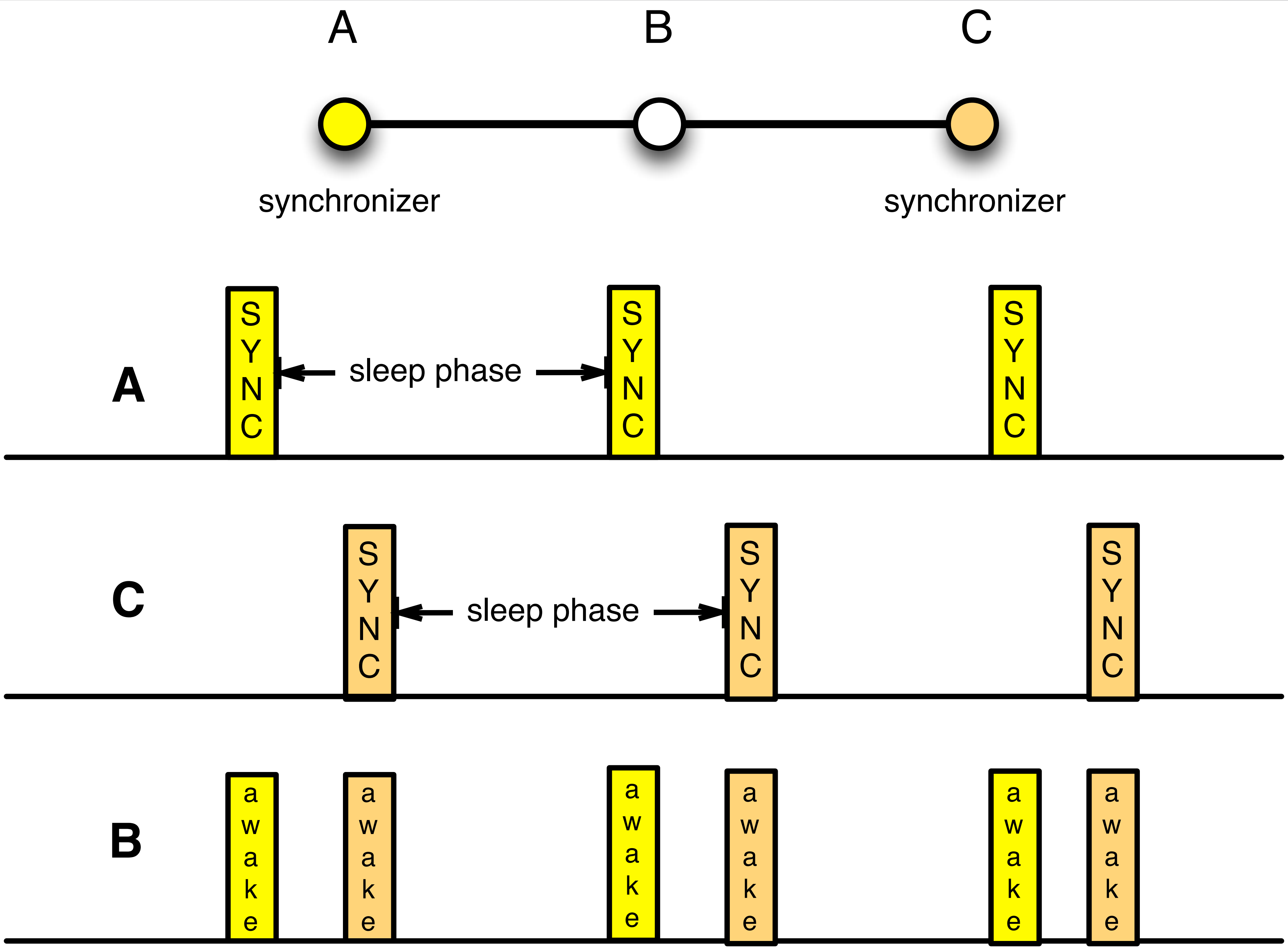
- Active phase
  - Carrier Sensing
  - Send Sync packet synchronizer short sleep duration with ID and
  - Interval for Request to Send (RTS)
  - Interval for Clear-to-Send (CTS)



Schedule

- Each node maintains Schedule Table
  - with the sleep cycles of known neighbors
- At the beginning listen to the channel for potential neighbors
  - the sender adapts to the sleep cycles of the neighbors
  - if several sleep cycles are notices, then the node wakes up several times
- If after some time no neighbors have been detected (no sync)
  - then the node turns into a synchronizer
  - and sends its own Sync packets

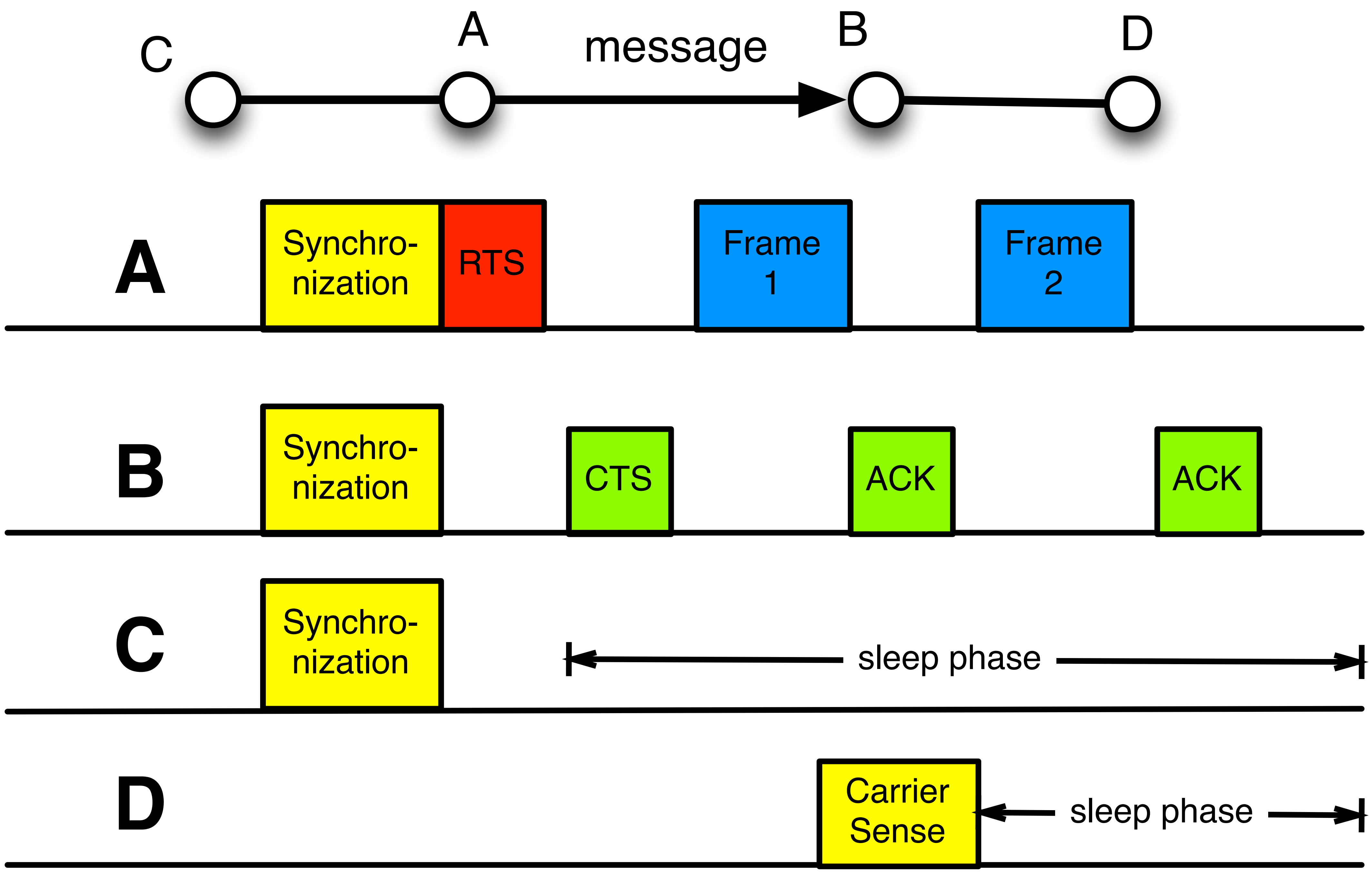
Synchronized Islands



Message Transmission

- If a node receives RTS for a foreign a node
  - then he goes to sleep for the announced time
- Packet is divided into small frames
  - be individually acknowledged with (ACK)
  - all frames are announced with only one RTS / CTS interaction
  - If ACK fails, the packet is immediately resent
- Small packets and ACK should avoid the hidden terminal problem
- All frames contain the planned packet duration in the header

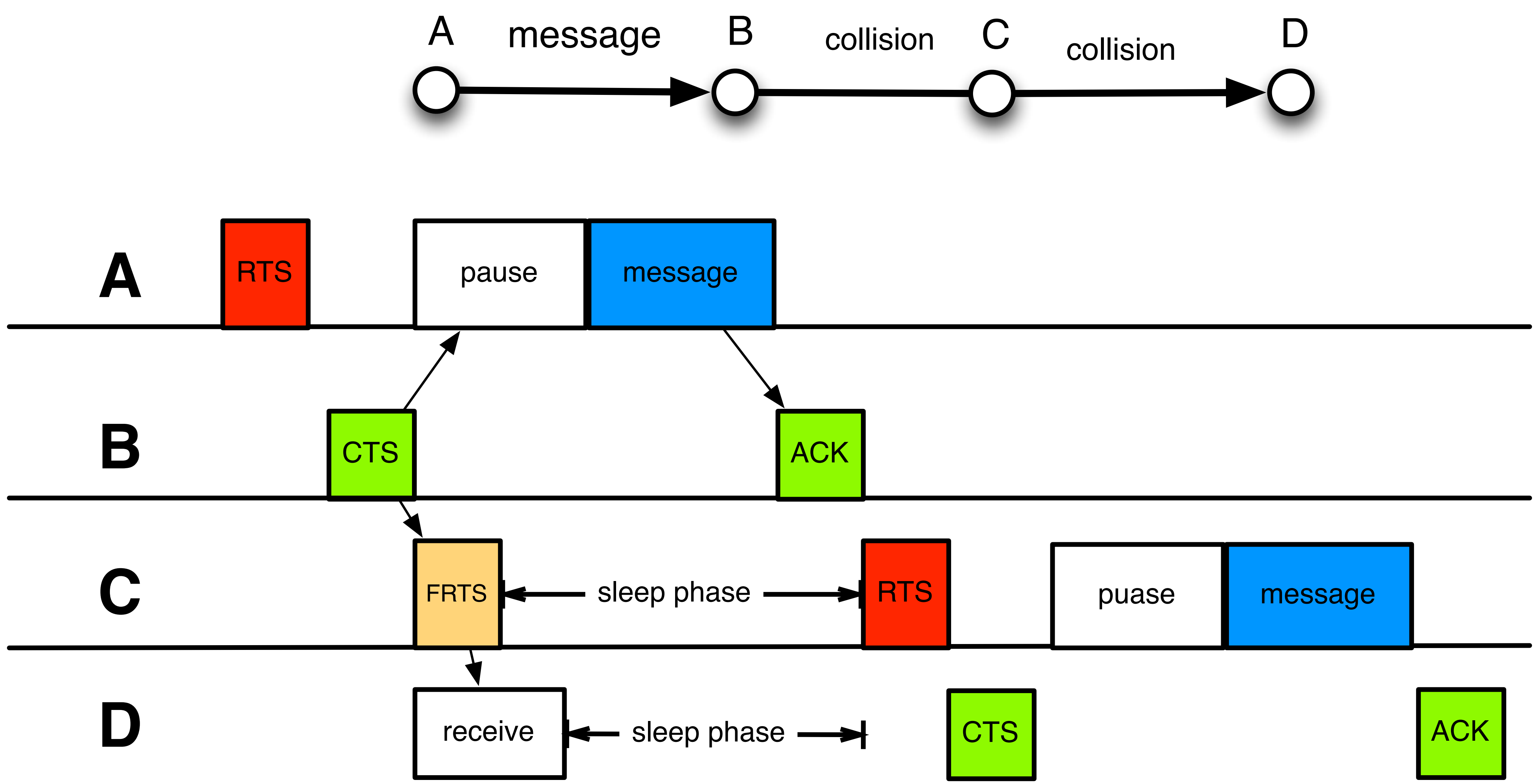
Message Transmission
S-MAC



Timeout-MAC (T-MAC)

- T. van Dam, K. Langendoen
  - An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks, SenSys 2003
- Main goal
  - extension of the MACA-protocol to save energy
- Method
  - Traffic dependent sleep cycles
  - New: FRTS-Signal (Future Request to Send)
    - informs about future message
    - Allows adapted sleep phases of the receiver

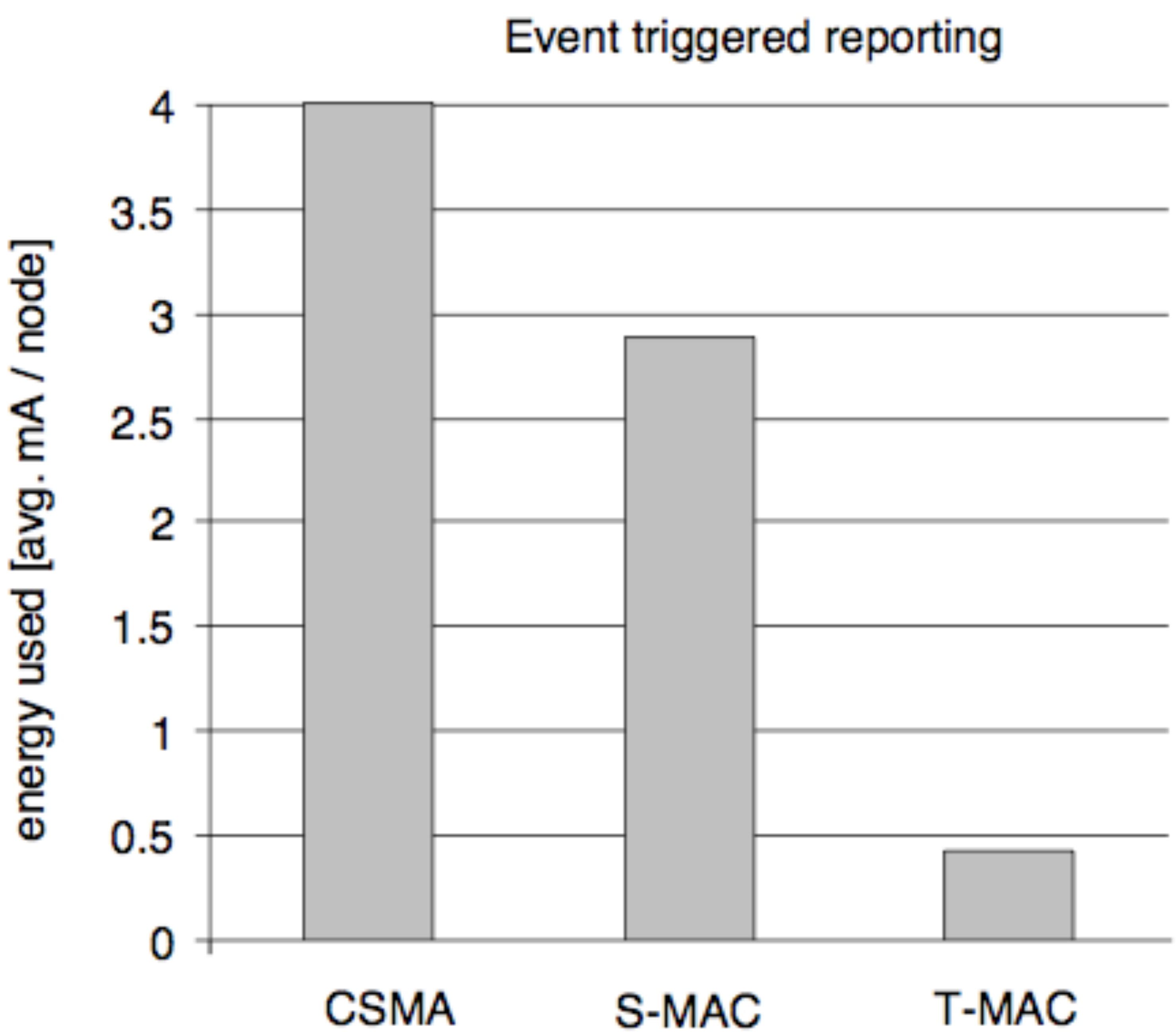
T-MAC



A
message
B
collision
C
collision
D
A
RTS
pause
message
B
CTS
ACK
C
FRTS
sleep phase
RTS
puase
message
D
receive
sleep phase
CTS
ACK

Comparison of S-MAC and T-MAC

- FRTS solves problems that are increased by adapted sleep cycles
  - e.g. Early Sleeping i.e., Falling asleep because sender is blocked by foreign CTS
- Simulation indicates significant energy reduction
  - also improve the throughput

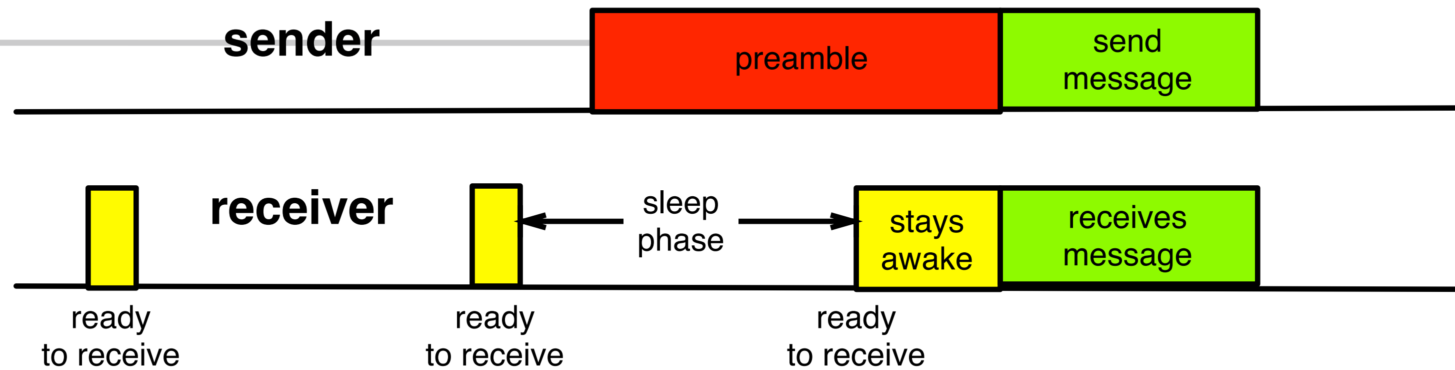


T. van Dam, K. Langendoen, An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks, SenSys 2003

B-MAC

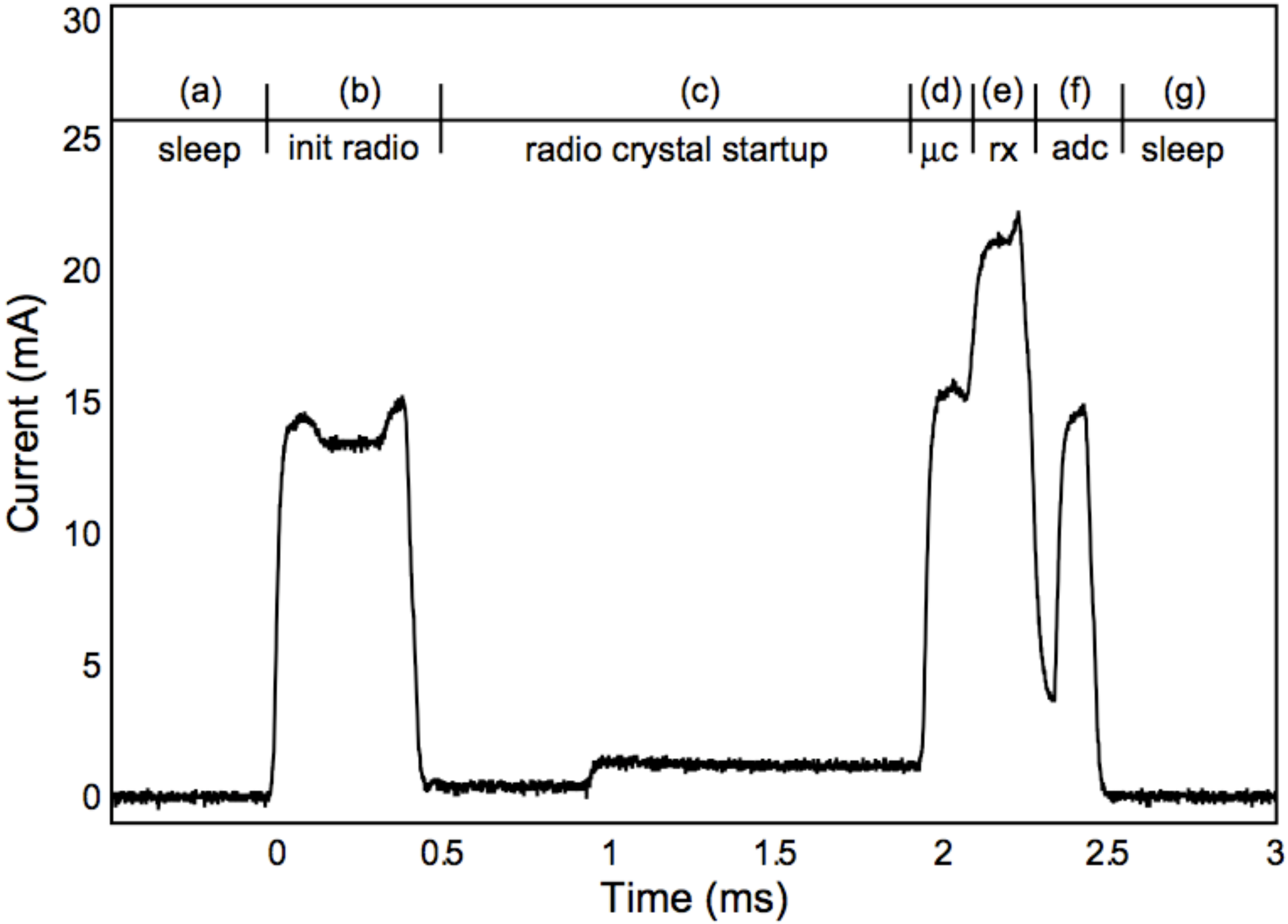
- Polastre, Hill, Culler
  - Versatile Low Power Media Access for Wireless Sensor Networks, SenSys'04, November 3–5, 2004, Baltimore, Maryland, USA.
- B-MAC (Berkeley-MAC)
  - no synchronization
  - Clear Channel Assessment
  - Evaluation of RSSI compared to noise
  - Hardware-oriented implementation
  - Very simple, low memory and power consumption

B-MAC



- Low Power Listening
  - Preamble Sampling
  - Special wake-up protocol
  - adapted to hardware with low power consumption
  - Node goes into sleep mode after test
- optional
  - RTS / CTS
  - Acknowledgments
- De-facto standard for WSN MAC Protocols

Low Power Listening



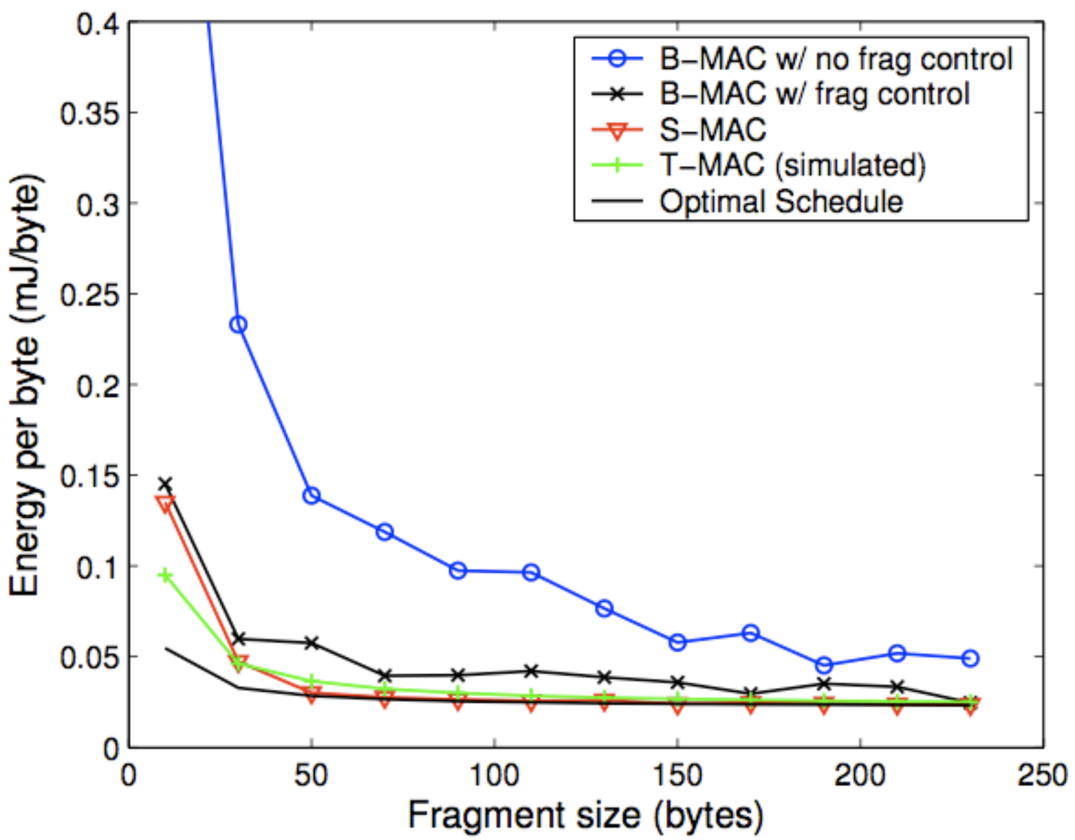
Polastre, Hill, Culler, Versatile Low Power Media Access for Wireless Sensor Networks, SenSys'04

Memory Consumption B-MAC and S-MAC

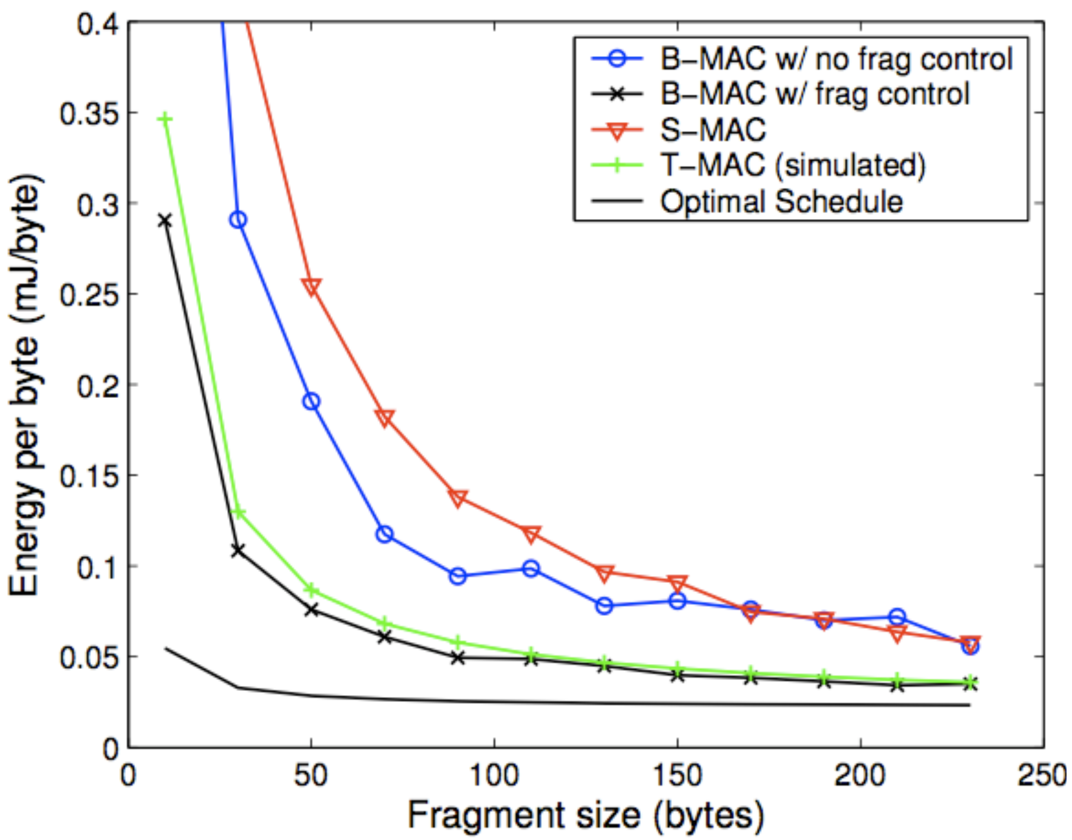
Protocol	ROM	RAM
B-MAC	3046	166
B-MAC w/ ACK	3340	168
B-MAC w/ LPL	4092	170
B-MAC w/ LPL & ACK	4386	172
B-MAC w/ LPL & ACK + RTS-CTS	4616	277
S-MAC	6274	516

Polastre, Hill, Culler, Versatile Low Power Media Access for Wireless Sensor Networks, SenSys'04

Comparison of Energy Consumption



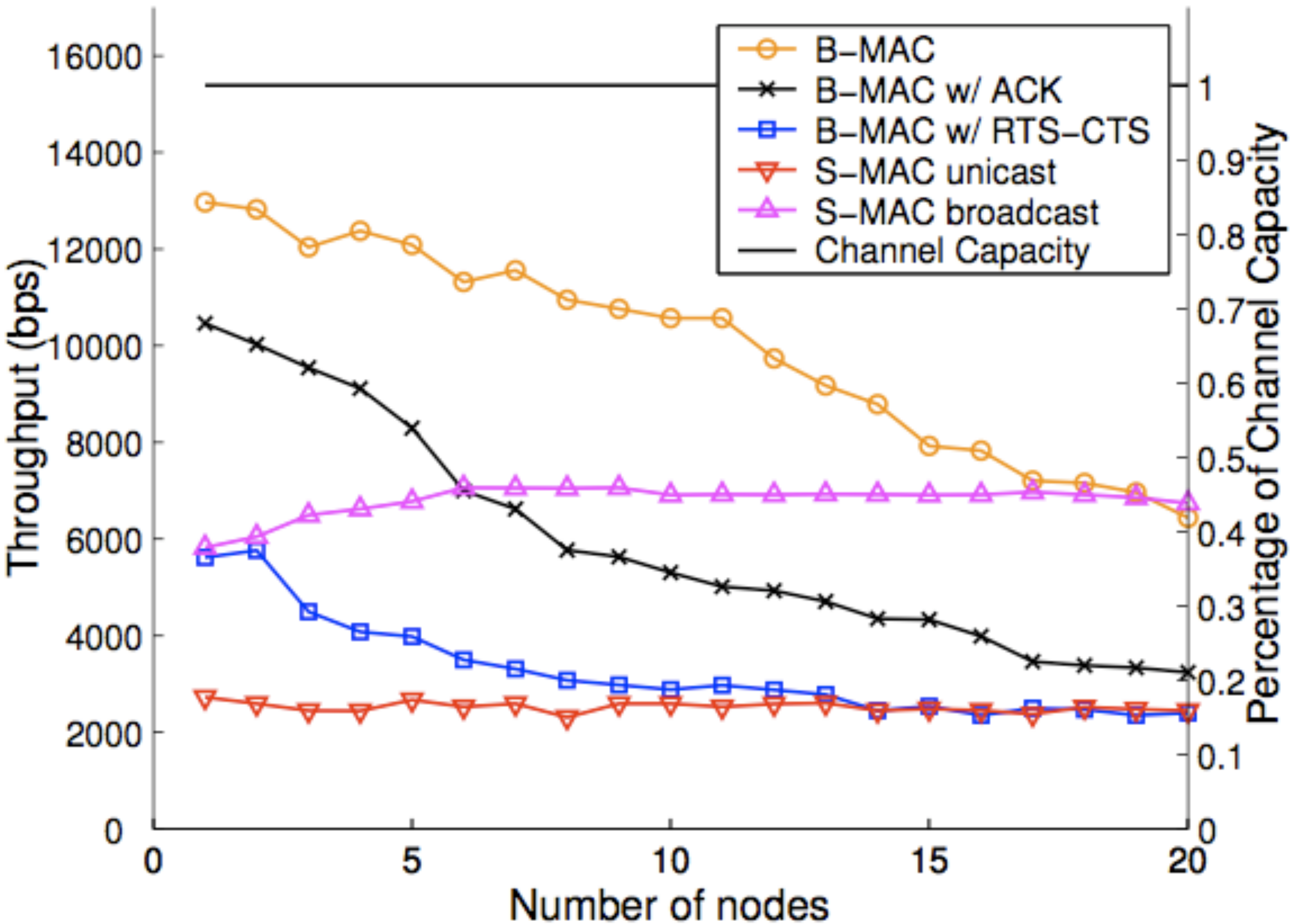
(a) 10 second message generation rate



(b) 100 second message generation rate

Polastre, Hill, Culler, Versatile Low Power Media Access for Wireless Sensor Networks, SenSys'04

Throughput



Polastre, Hill, Culler, Versatile Low Power Media
Access for Wireless Sensor Networks, SenSys'04

Outlook MAC in WSN

- Many other protocols in WSN
  - LEACH, TRAMA, PAMAS, SMACS, ...
- Very large diversity of protocols
  - very simple and very complex protocols
  - very specialized for certain hardware or not at all
  - TDMA, CDMA, clustering, multi-hop, single-hop, ...
- Further reading
  - Karl, Willig: Protocols and Architectures for Wireless Sensor Networks, Wiley, 2005

Wireless Sensor Networks
4. Medium Access

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