Random multiple access organization in telecommunication systems with large user population

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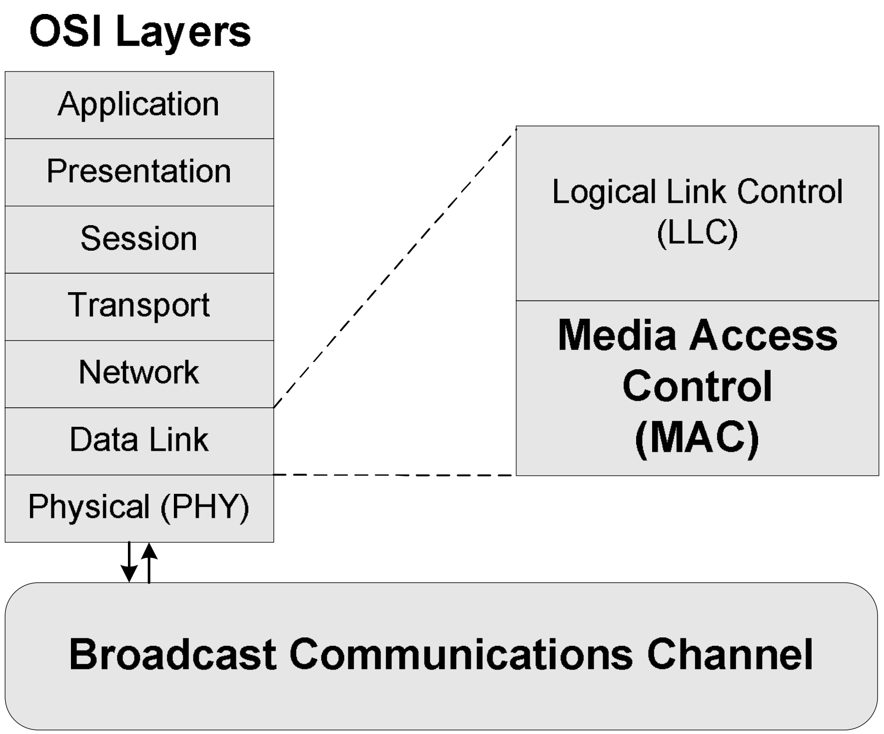
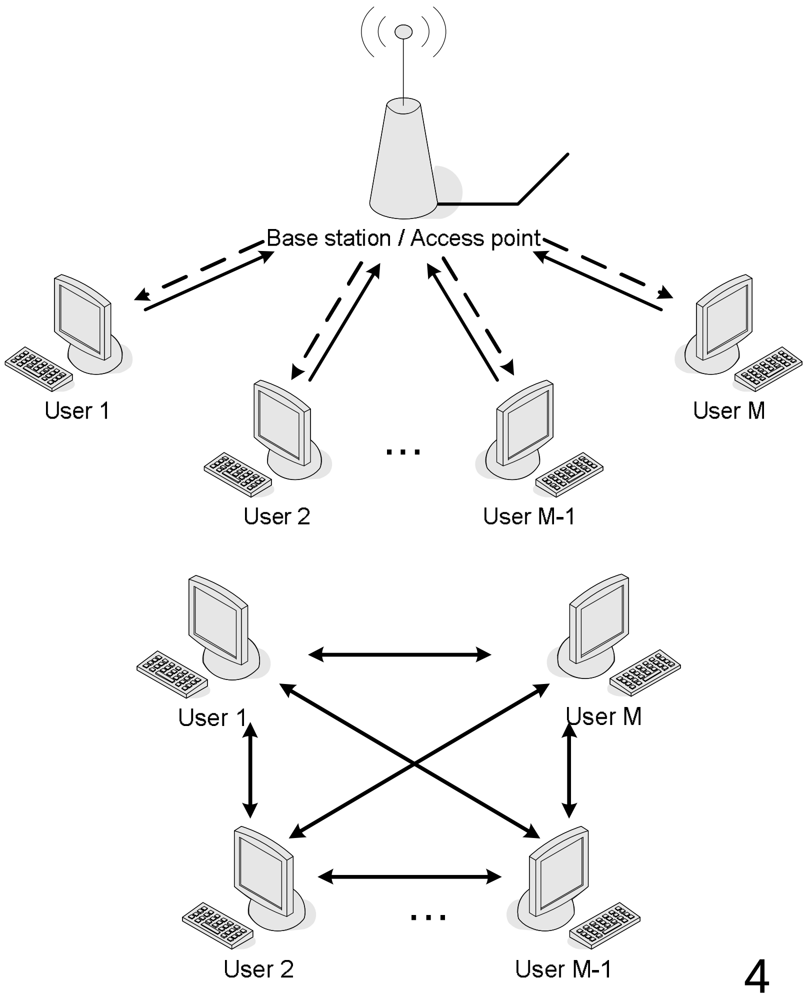
Session Agenda

- **Media access control** role for network communication
- **Reference model** of a random multiple access (RMA) system
- **Instability** of the RMA algorithms in the existing telecommunication systems
- **Tree** RMA **algorithms** as a possible solution for the instability problem
- Tree algorithms **implementation issues** and alternative proposals

Media access control role for network communication

Primary Research Focus





MAC Algorithms Classification

MAC algorithms

- Centralized
- Distributed

- Synchronous
- Asynchronous

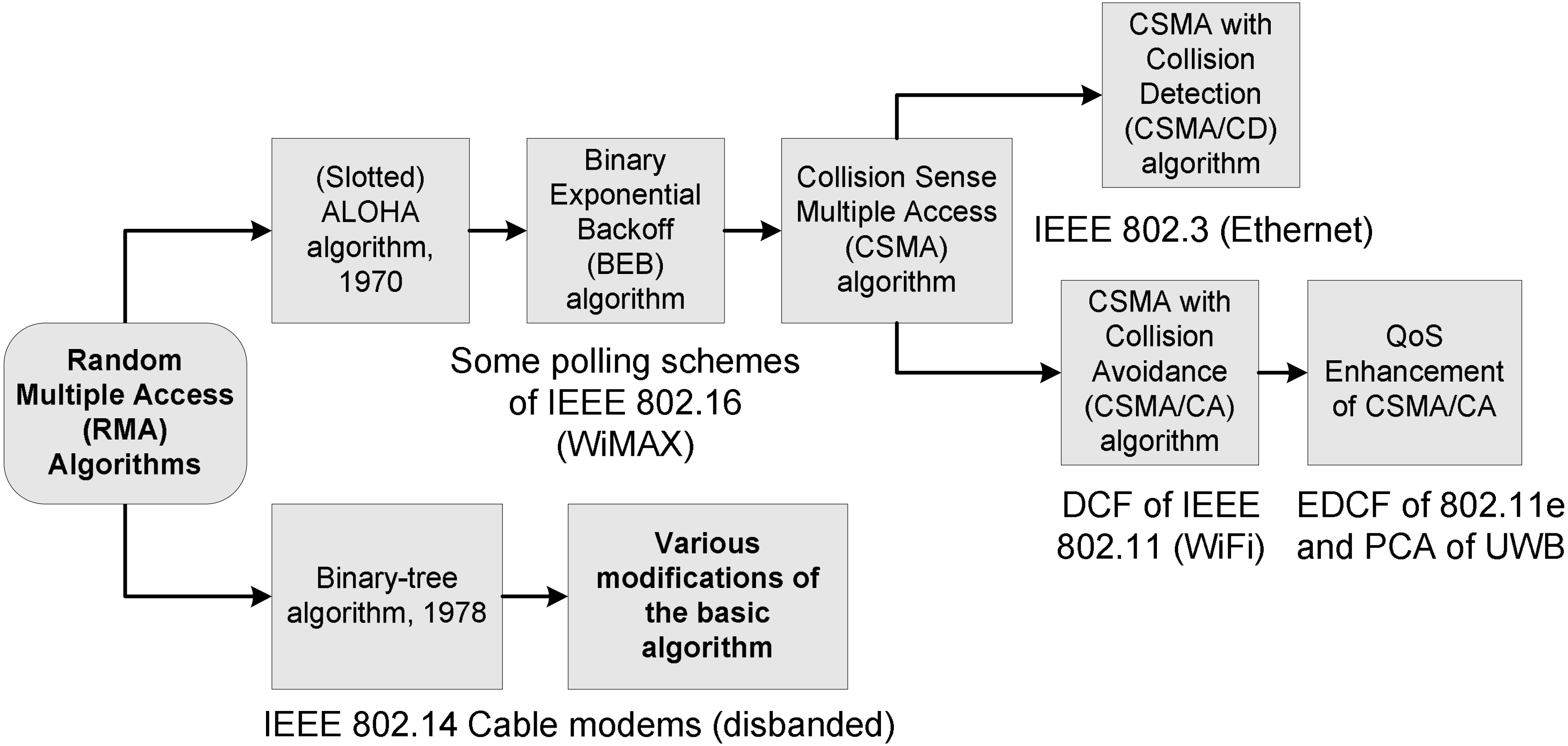
- Static
- Dynamic

- Channelization (TDMA, FDMA, CDMA)
- Reservation/Polling
- **Random (RMA)**

Examples

- IEEE 802.3 (Ethernet):
  RMA
- IEEE 802.11 (WiFi):
  RMA + Reservation/Polling
- IEEE 802.16 (WiMAX):
  Reservation/Polling + **RMA**
- IEEE 802.15.3c, ISO 26907 (UWB):
  Reservation/Polling + **RMA**

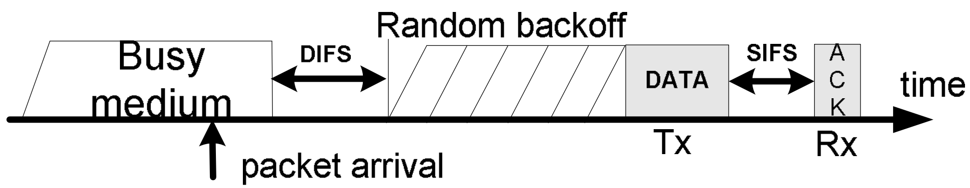
RMA Algorithms Evolution



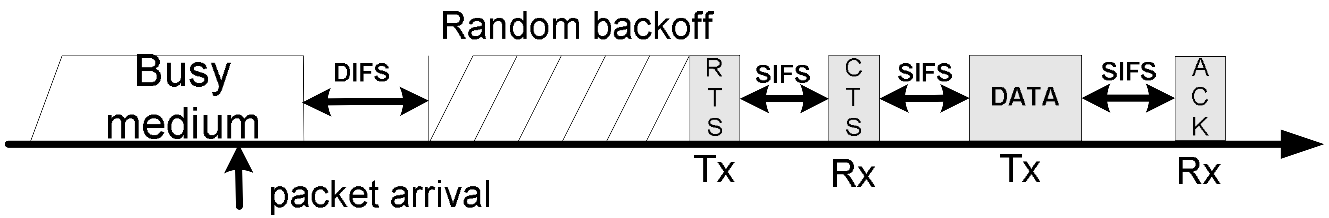
RMA Applications: IEEE 802.11 LAN

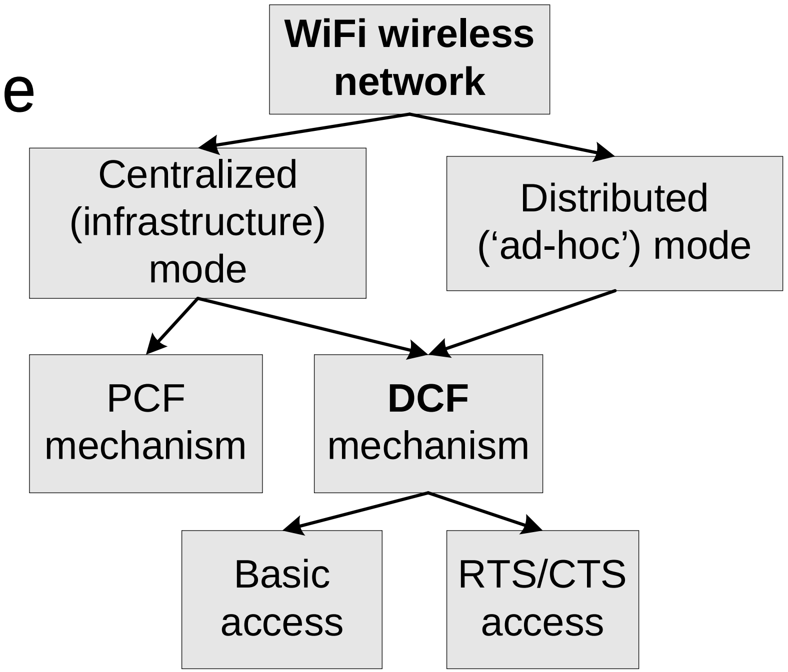
Collision Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme

Basic access snapshot



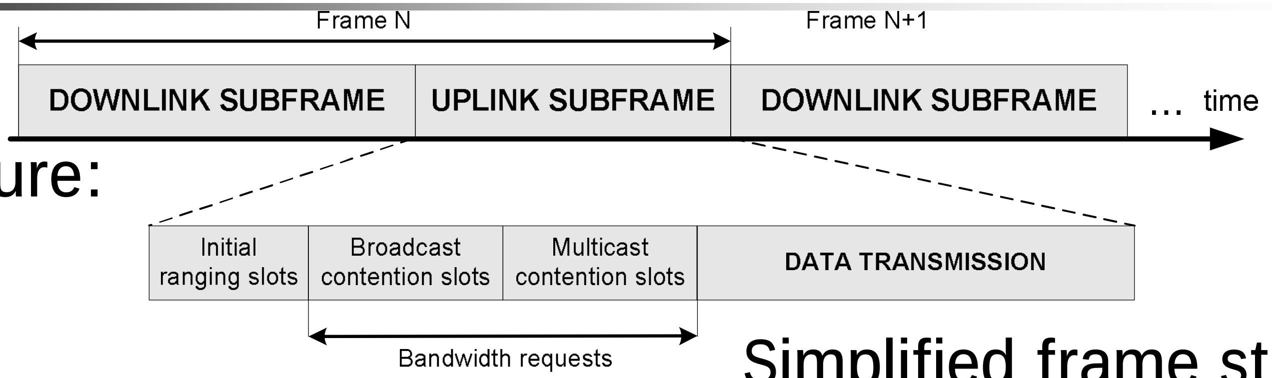
RTS/CTS access snapshot



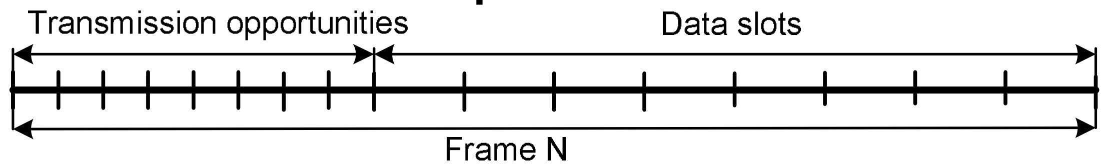


RMA Applications: IEEE 802.16 WAN

General frame structure:



Simplified frame structure:



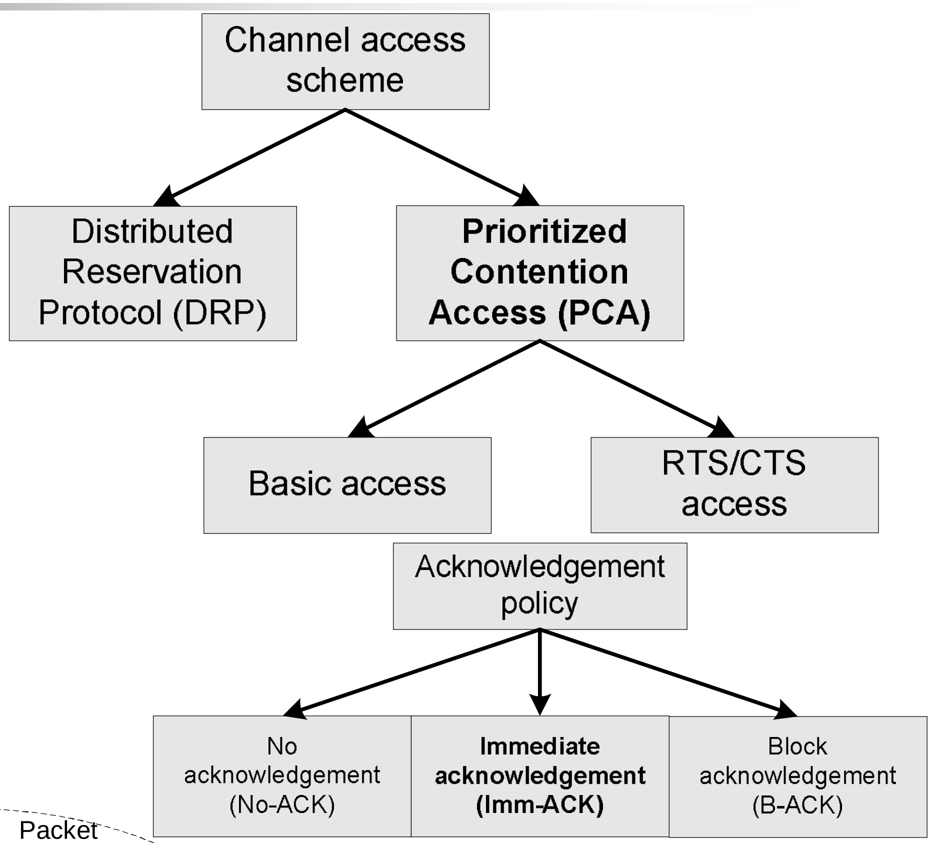
Polling schemes

- Unicast (deterministic)
- **Multicast** (for nrtPS, ertPS and BE connections only)
- **Broadcast**

Collision resolution

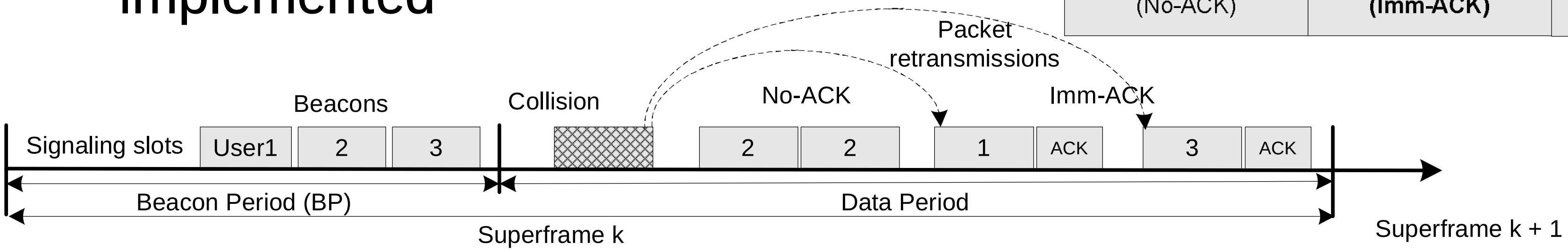
- Binary Exponential Backoff (BEB) algorithm
- Base station broadcasts BEB parameters

RMA Applications: ISO/IEC 26907 PAN

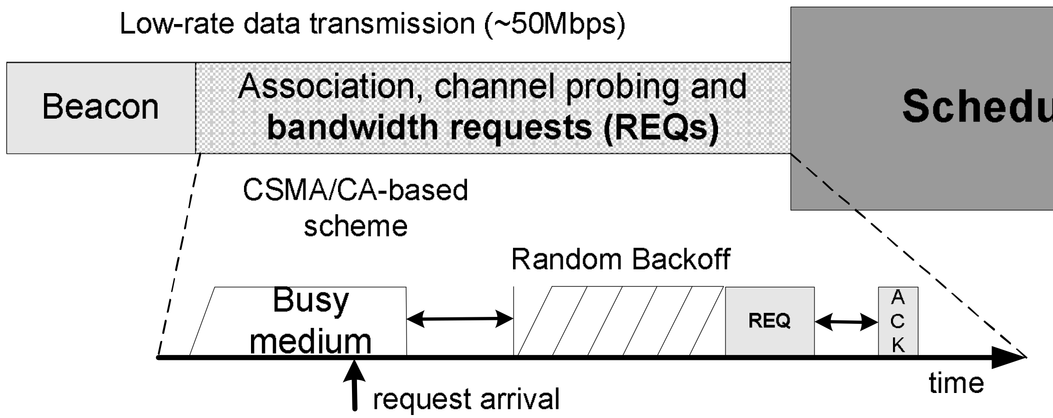


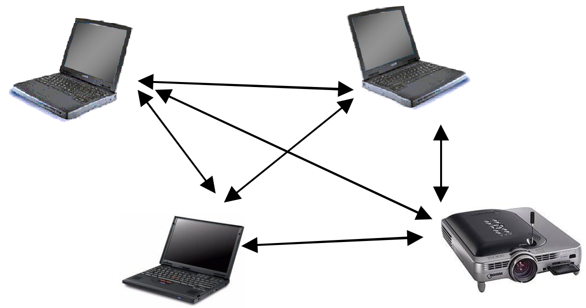
Main features

- Synchronous system
- Each user broadcasts its beacon
- Supports both RMA (PCA) and scheduling (DCF)
- PCA is a CSMA/CA-scheme with QoS support
- Several ACK policies implemented

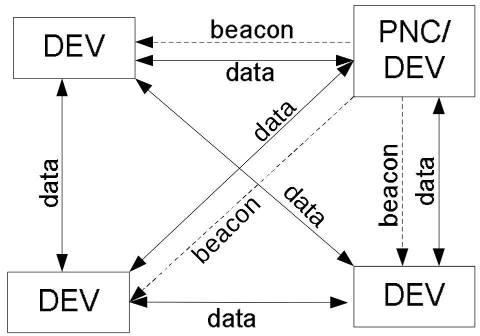


RMA Applications: IEEE 802.15.3c PAN





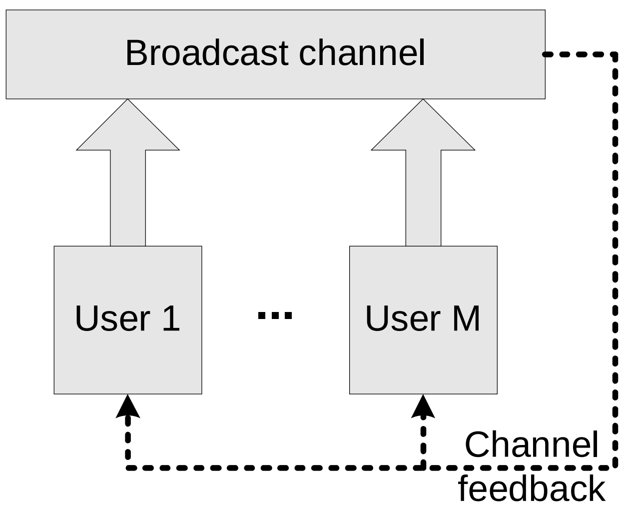
- Piconet coordinator (PNC) sends its beacon in each superframe
- Bandwidth requesting is CSMA/CA-based (low data rates)
- Data transmission is TDMA-based (high data rates)



Reference model of a random multiple access (RMA) system

Reference RMA Model

- Developed in late 70s
  by **R. Gallager**: "A perspective on multiaccess channels", 1985
  and **B. Tsybakov**: "Survey of USSR contributions to random multiple-access communications", 1985
- Discussed by D. Bertsekas and R. Gallager: "Data Networks", 1987



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

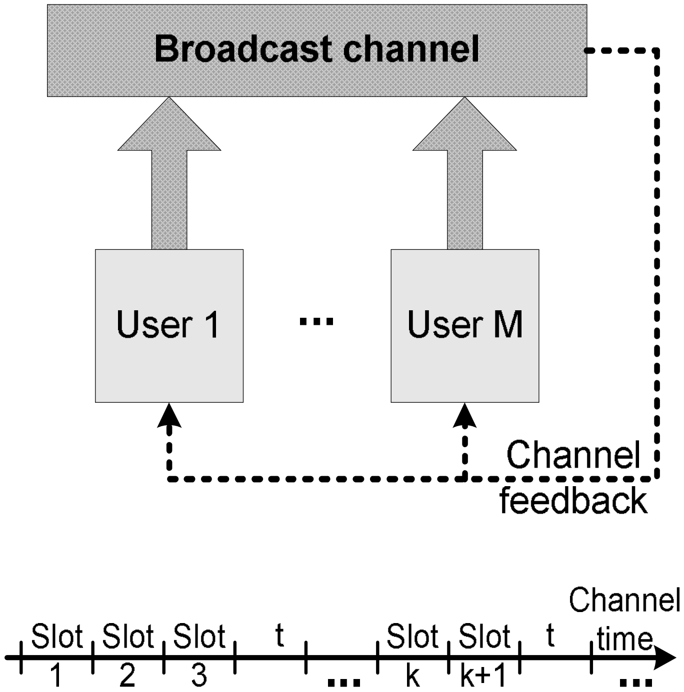
A3: Ternary channel feedback

A4: Immediate channel feedback

A5: Noise-free channel

A6: Input source probabilistic model

A1: Slotted Access



Principal assumptions:

A1: Slotted (synchronous) system

- Equal packet lengths, Tx time is ***t***
- Slotted channel time, slot duration is ***t***
- Slot borders are known
- Tx starts only on slot borders

A2: Collision or perfect reception

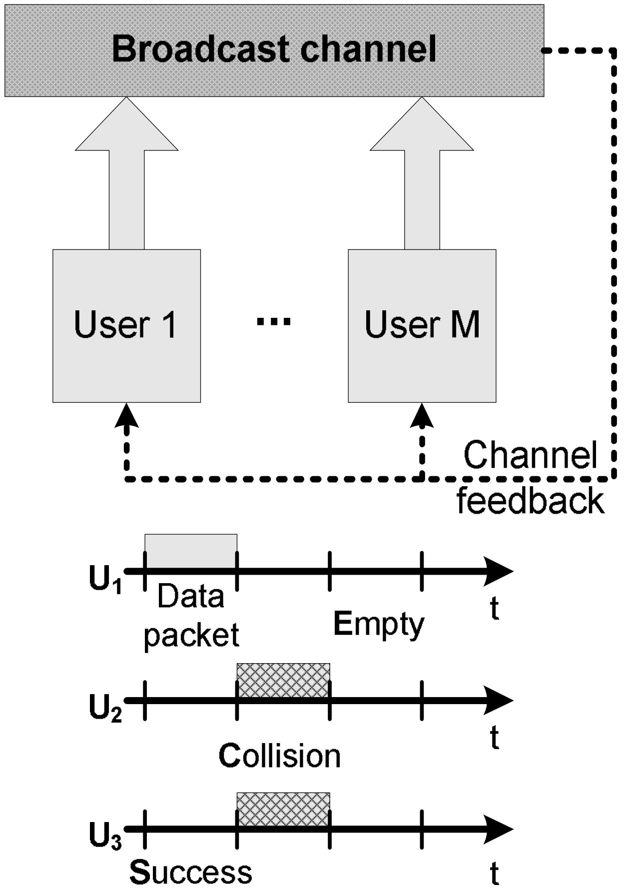
A3: Ternary channel feedback

A4: Immediate channel feedback

A5: Noise-free channel

A6: Input source probabilistic model

A2: Collision or Perfect Reception



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

- Define 3 events **in broadcast channel**:
  - 1 user Tx per slot → **S**uccess
  - ≥ 2 user Tx per slot → **C**ollision
  - 0 user Tx per slot → **E**mpty

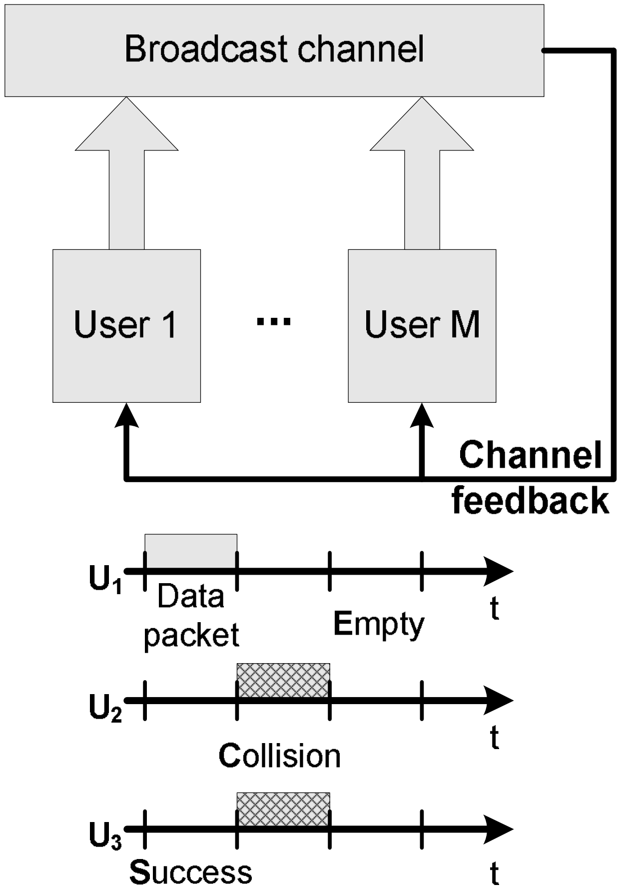
A3: Ternary channel feedback

A4: Immediate channel feedback

A5: Noise-free channel

A6: Input source probabilistic model

A3: Ternary Channel Feedback



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: Ternary channel feedback

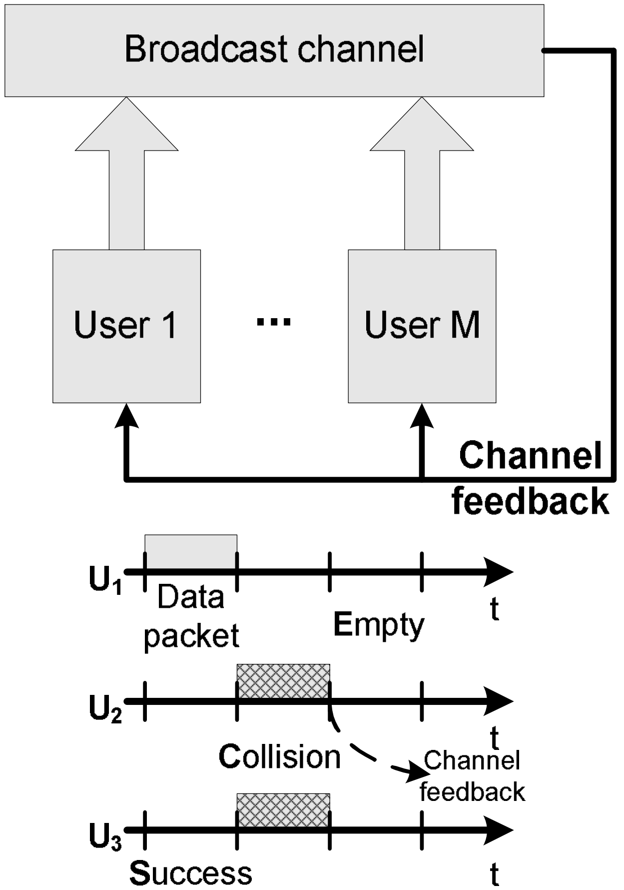
- All 3 events are distinguished **by a user**:
  - **S**uccess
  - **C**ollision
  - **E**mpty

A4: Immediate channel feedback

A5: Noise-free channel

A6: Input source probabilistic model

A4: Fast Channel Feedback



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: Ternary channel feedback

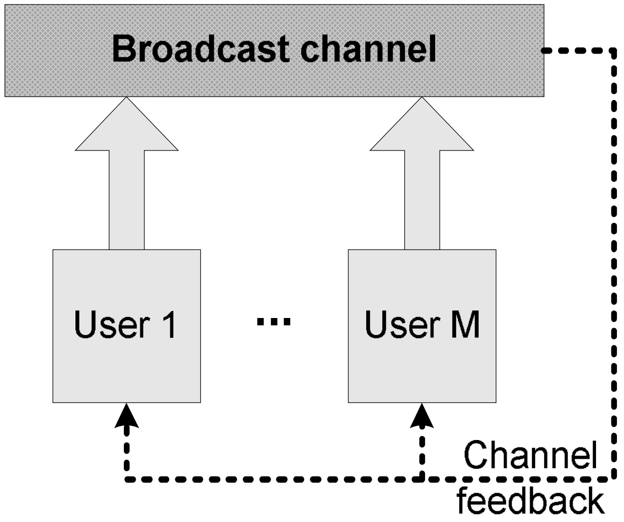
A4: Immediate channel feedback

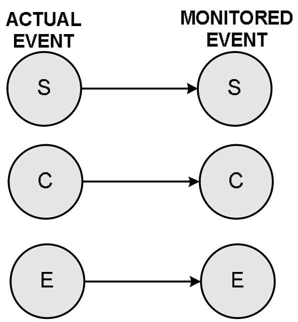
- Current slot event is known by the next slot

A5: Noise-free channel

A6: Input source probabilistic model

A5: Noise-free Channel





Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: Ternary channel feedback

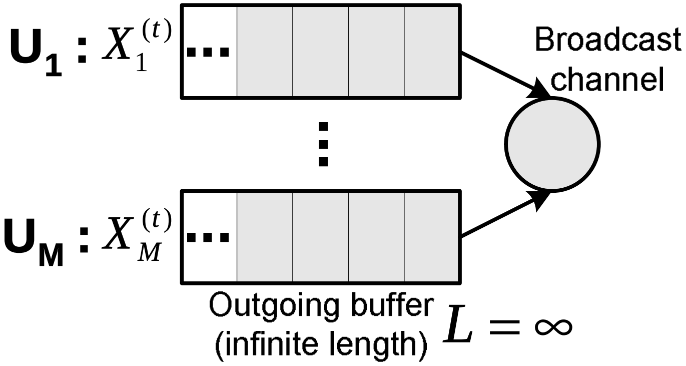
A4: Immediate channel feedback

A5: Noise-free channel

- Actual channel event coincides with monitored

A6: Input source probabilistic model

A6: Input Source Probabilistic Model



$$M - finite$$

$$X_j^{(t)} \in \{0,1\},\ j = \overline{1, M}$$

$$\Pr\{X_j^{(t)} = 1\} = z$$

$$\Pr\{X_j^{(t)} = 0\} = 1 - z$$

$$E[\sum_{j=1}^{M} X_j^{(t)}] = M \cdot z = l$$, arrival intensity

$$\Pr\{\sum_{j=1}^{M} X_j^{(t)} = i\} = \binom{M}{i} \cdot z^i \cdot (1-z)^{M-i}$$

Finite population model with Bernoulli input source $\boxed{M < \infty}$. Parameters: l, M

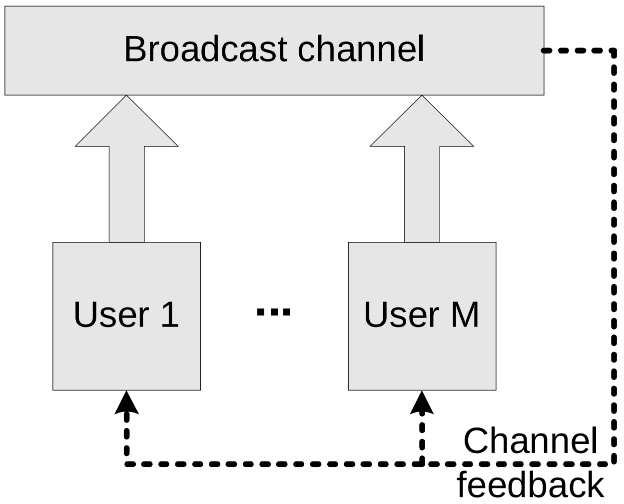
$$\begin{cases} M \to \infty \\ z \to 0 \\ M \cdot z = const = l \end{cases}$$

$$\Pr\{\sum_{j=1}^{M} X_j^{(t)} = i\} \to \frac{l^i}{i!} \cdot e^{-l}$$

User = packet

Infinite population model with Poisson input source $\boxed{M = \infty}$. Parameter: l

Reference RMA Model Summary



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: Ternary channel feedback

- Success, Collision, Empty

A4: Immediate channel feedback

A5: Noise-free channel

A6: Input source probabilistic model

- Finite population, Bernoulli source
- Infinite population, Poisson source

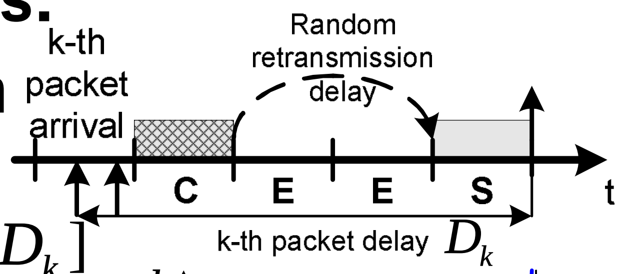
Instability of the RMA algorithms in the existing telecommunication systems

RMA Algorithm Definition

RMA algorithm **is a rule**, according to which a user decides whether **to transmit** a packet in each slot **by monitoring the channel activity**

Principal **performance characteristics:**

- Mean packet delay d_a of an algorithm
  - Enumerate arriving packets
  - In stationary conditions: $d_a = \lim_{k\to\infty} \sup E[D_k]$

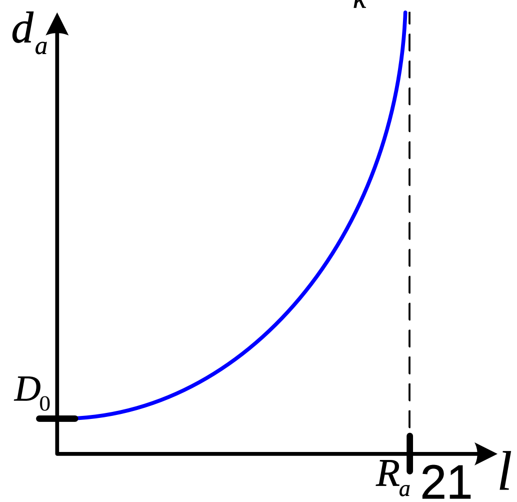


- Algorithm rate R_a

$$R_a = \sup_l \{ l : d_a(l) < \infty \}$$

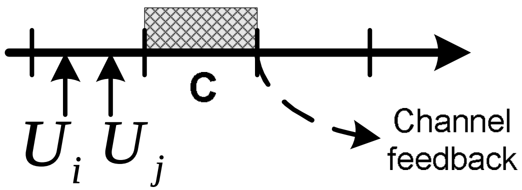
- Capacity C_{RMA} is the upper bound on R_a for all RMA algorithms A

$$C_{RMA} = \sup_{a \in A} R_a$$



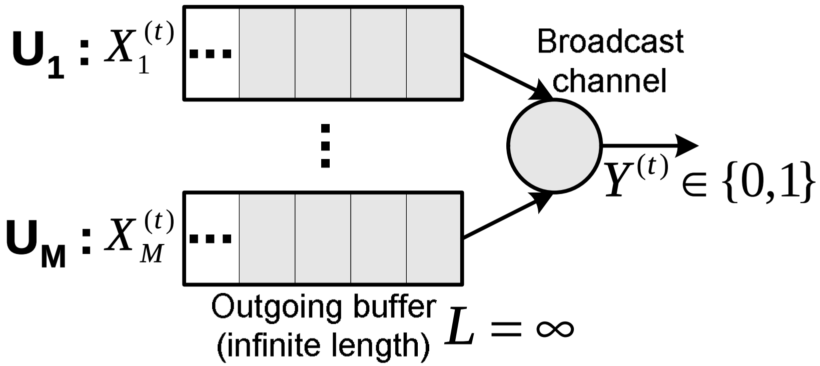
Finite Population Slotted ALOHA

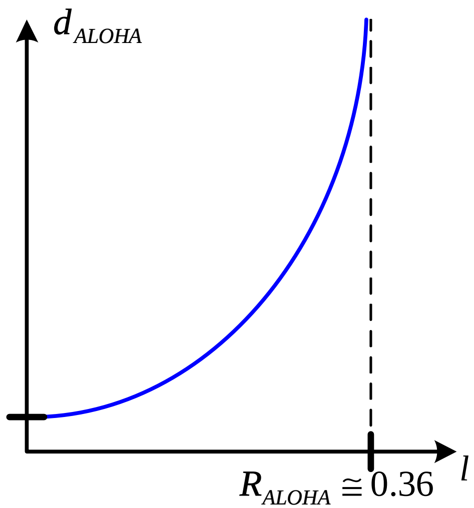
- Finite population, Bernoulli source: $\boxed{M < \infty}$



Tx with independent probability p in each slot after **C**

Assume saturation conditions:





Stability requirement: $E[\sum_{j=1}^{M} X_j^{(t)}] < E[Y^{(t)}]$

$$M \cdot z = l < \Pr\{Success\_in\_slot\_t\} = \binom{M}{1} \cdot p \cdot (1-p)^{M-1} = f(p, M)$$

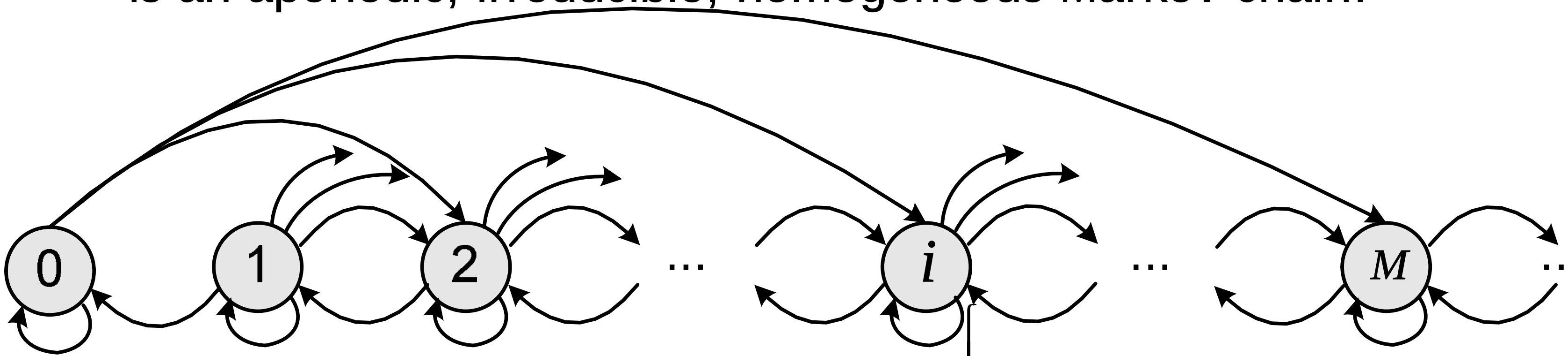
$$\max_p f(p, M) = (1 - \frac{1}{M})^{M-1} \cong \frac{1}{e} \quad \text{for} \quad p = \frac{1}{M}$$

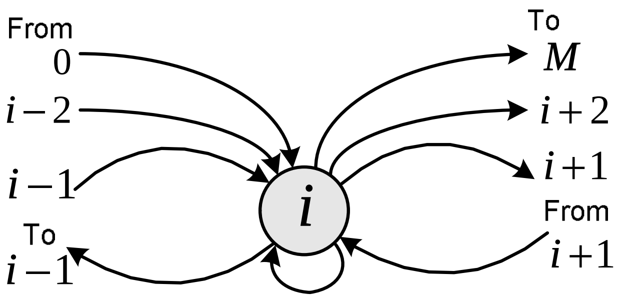
Infinite Population Slotted ALOHA

- Infinite population, Poisson source: $M = \infty$

$N^{(t)}$ is the number of backlogged users in **t**-th time slot,

$N^{(t)}$ is an aperiodic, irreducible, homogeneous Markov chain:





$$p_{ij} = \Pr\{N^{(t+1)} = j \mid N^{(t)} = i\} = \begin{cases} 0, \; j \le i-2 \\ i \cdot p \cdot (1-p)^{i-1} \cdot e^{-l}, \; j = i-1 \\ (1-p)^{i} \cdot l \cdot e^{-l} + [1 - i \cdot p \cdot (1-p)^{i-1}] \cdot e^{-l}, \; j = i \\ l \cdot e^{-l} \cdot [1 - (1-p)^{i}], \; j = i+1 \\ \dfrac{l^{\,j-i}}{(j-i)!} \cdot e^{-l}, \; j \ge i+2 \end{cases}$$

Slotted ALOHA Instability

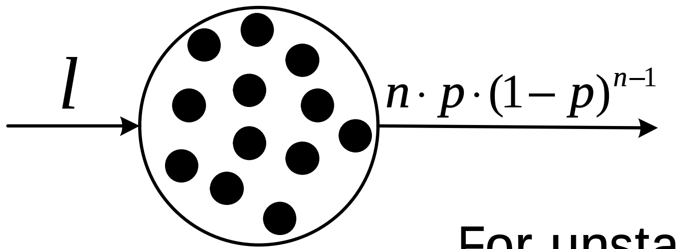
- Infinite population, Poisson source: $\boxed{M=\infty}$ (contd.)

$\forall \lambda > 0:$ Markov chain $N^{(t)}$ is **not** stable

Sufficient to show that $\exists d > 0, N > 0 : \forall n > N$

$$E[(N^{(t+1)} - n) \mid N^{(t)} = n] > d$$

$$\lambda - \Pr\{(Success\_in\_slot\_t) \mid N^{(t)} = n\} = \lambda - n \cdot p \cdot (1-p)^{n-1}$$



Backlogged (active) users

For $n \to \infty$ $\quad n \cdot p \cdot (1-p)^{n-1} \to 0$

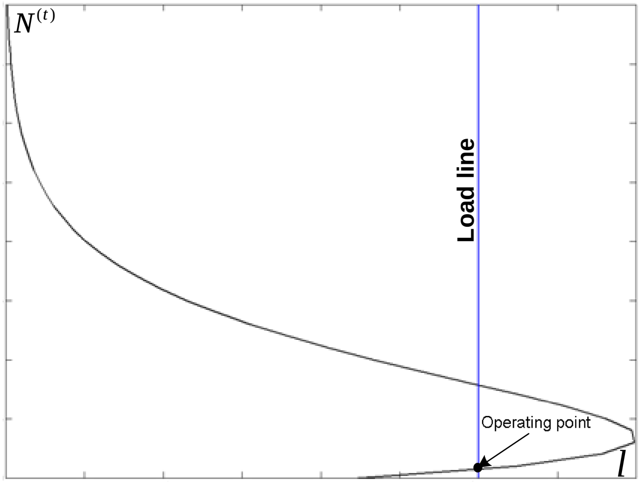
System is 'jammed' with collisions for any $\lambda > 0$

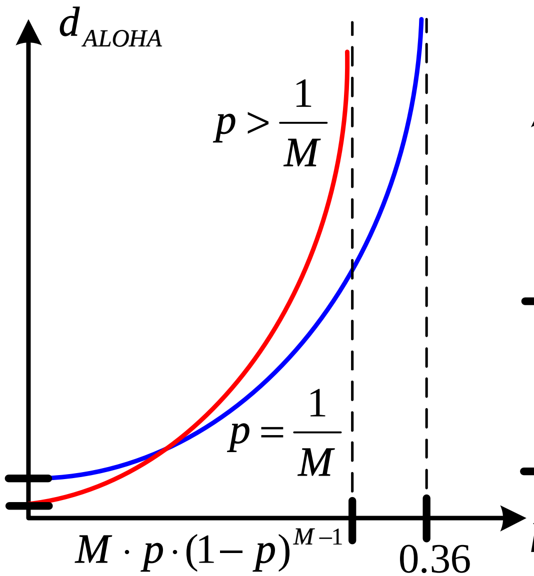
For unstable system packet **delay is unbounded!**

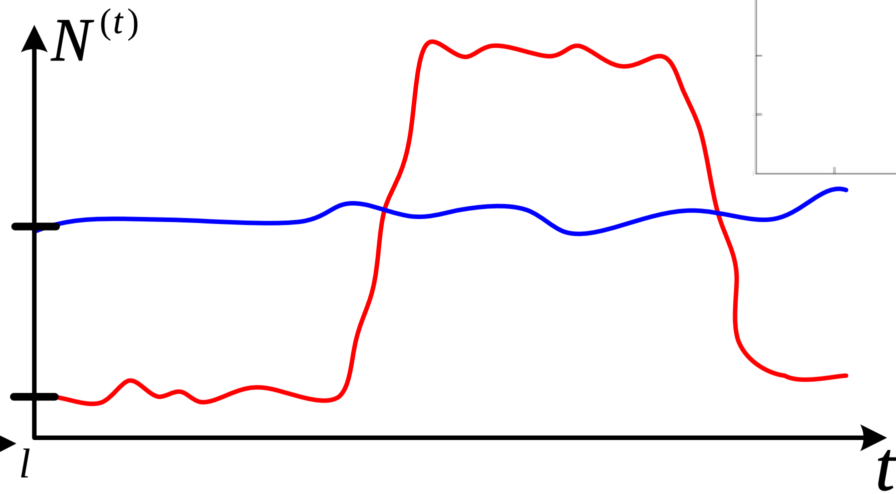
$R_{ALOHA} = 0$

Slotted ALOHA Summary

- For $\boxed{M = \infty}$ ALOHA is unstable $\longrightarrow$ $R_{ALOHA} = 0$
- For $\boxed{M < \infty}$ ALOHA is stable $\longrightarrow$ $R_{ALOHA} \cong 0.36$
- For large M ALOHA is bistable:





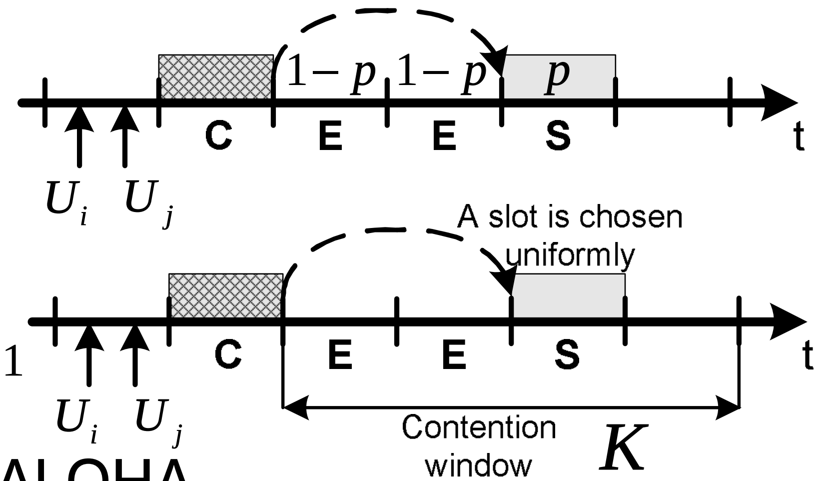


Binary Exponential Backoff Algorithm

- Binary Exponential Backoff (BEB) Algorithm is a retransmission control procedure to stabilize ALOHA system
- It ‘accounts’ for channel condition
- Consider 2 variations of slotted ALOHA
  - Geometrical randomization

    Tx with independent probability p in each slot after **C**
  - Uniform randomization

    Use contention window of size $K = \frac{2}{p} - 1$



- BEB is adaptive uniform slotted ALOHA

  Initialization and after each **S**uccess $K_0 = K_{\min}$

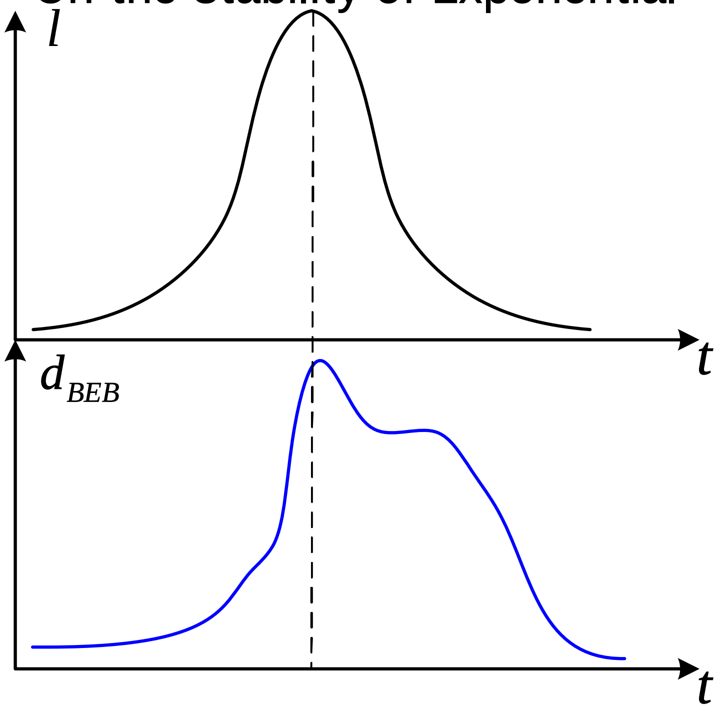
  After $\boldsymbol{i}$-th packet **C**ollision $K_i = \min(2^i \cdot K_0, K_{\max})$

BEB Instability

- For $\boxed{M = \infty}$ BEB is unstable $\rightarrow$ $R_{BEB} = 0$

  Shown by D. Aldous: “Ultimate Instability of Exponential Back-Off Protocol ...”, 1987
- For $\boxed{M < \infty}$ BEB is stable $\rightarrow$ $R_{BEB} = \frac{1}{2} \cdot \ln 2 \cong 0.346$

  Shown by N.-O. Song, B.-J. Kwak, L. Miller: “On the Stability of Exponential Backoff”, 2003
- For large M BEB is stable but very ‘slow’ to cope with arrival intensity l peaks



Research targets

- Achieve $R_a > R_{ALOHA} > R_{BEB}$
- Combat instability effect
- Ensure fast d_a reaction

Tree RMA **algorithms** as a possible solution for the instability problem

Contention Tree (CT) Algorithm

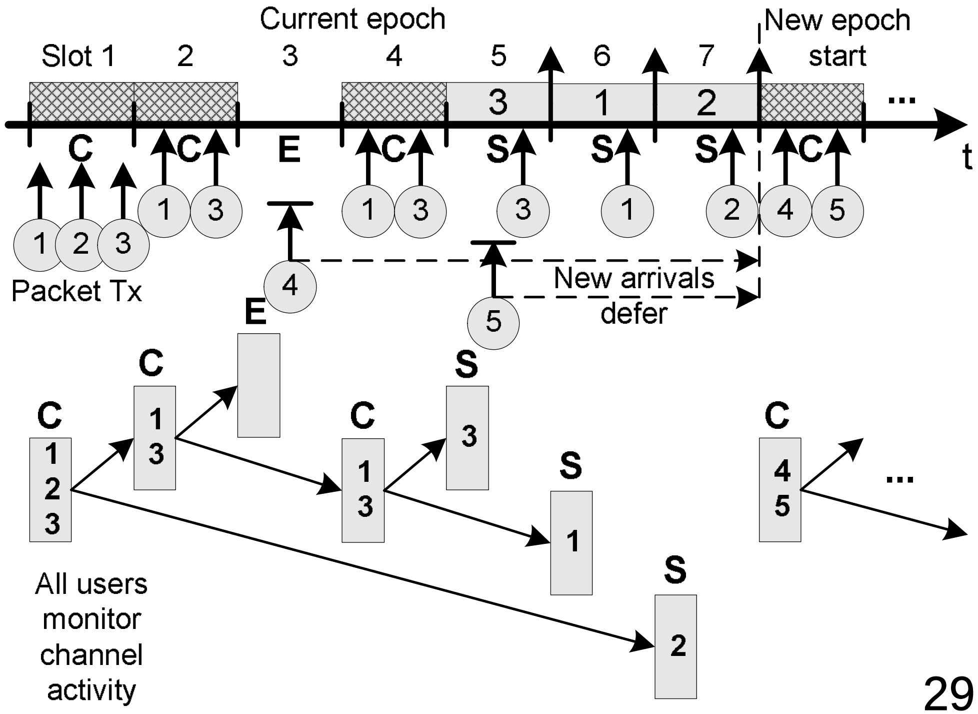
Introduced by

B. Tsybakov, V. Mikhailov: “Slotted multiaccess packet-broadcasting feedback channel”, 1978
J. Capetanakis: “Tree algorithms for packet broadcast channels”, 1979

Main features

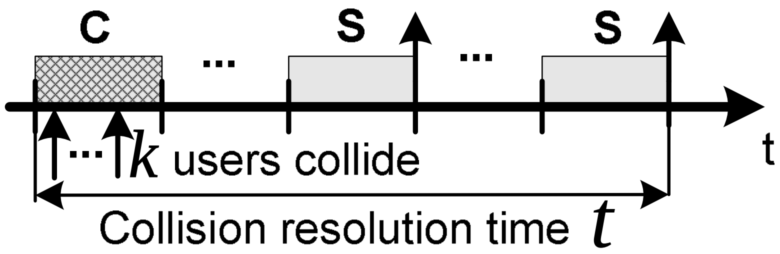
- Random retransmission attempts for conflicting users
- Newly backlogged users defer Tx until current epoch is finished

(blocked channel access)



CT Stability Analysis

- Infinite population, Poisson source: $\boxed{M = \infty}$
- Define average conflict resolution time:



$$T_k = E[t \mid (k\_collided\_users)]$$

Stability requirement: $\lambda \cdot E[t] < k \rightarrow \lambda < \dfrac{k}{T_k}$

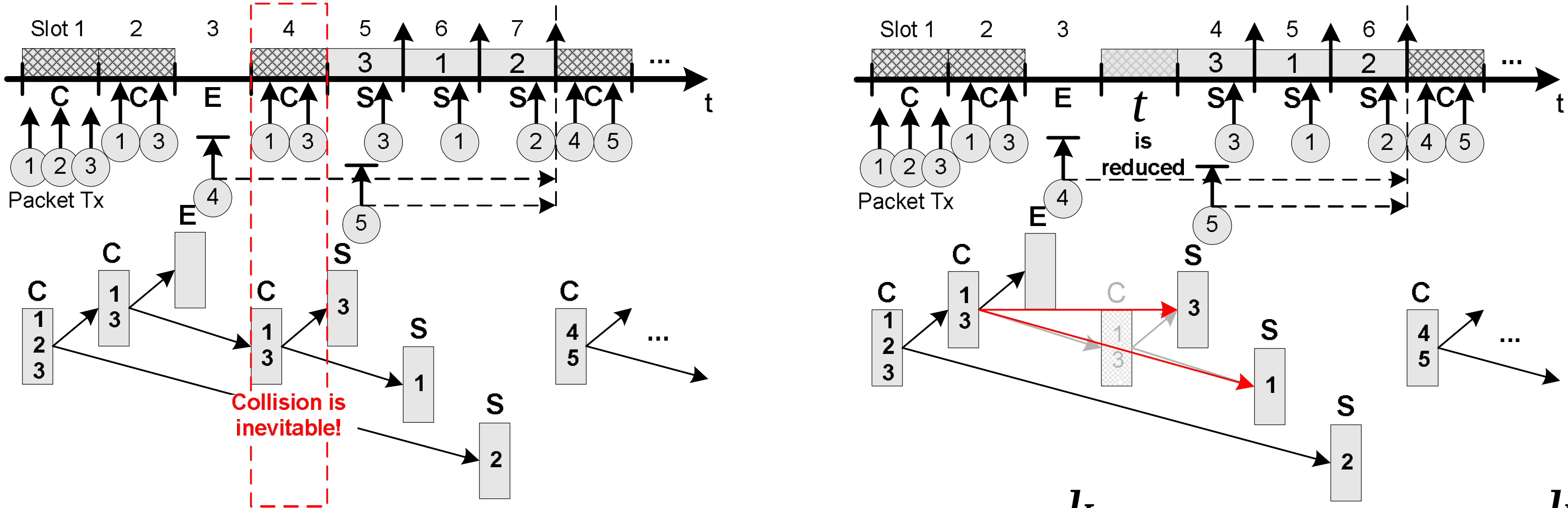
Last known bounds according to L. Györfi, S. Győri, J. Massey "Principles of Stability Analysis for Random Accessing with Feedback", 2007 are

$$\liminf_{k\to\infty} \frac{k}{T_k} < R_{CT} < \limsup_{k\to\infty} \frac{k}{T_k}$$

$$0.34657320 < R_{CT} < 0.34657397$$

Shown that $R_{CT} \cong \frac{1}{2} \cdot \ln 2 \cong 0.346$ which equals to $R_{BEB} \cong 0.346$ for $\boxed{M < \infty}$

Frugal Contention Tree (FCT) Algorithm



Analogously, algorithm rate is bounded by $\liminf_{k\to\infty} \frac{k}{T_k} < R_{FCT} < \limsup_{k\to\infty} \frac{k}{T_k}$

$$R_{FCT} \cong \left(\frac{3}{2\cdot\ln 2}+\frac{1}{2}\right)^{-1} \cong 0.375$$

Last known bounds according to
L. Györfi, S. Győri, J. Massey
"Principles of Stability Analysis for
Random Accessing with Feedback", 2007 are

$$0.3753690 < R_{FCT} < 0.3753698$$

Blocked and Free Channel Access

- CT and FCT operation may be interpreted as packet PUSH/POP in a **virtual stack** (only 2 variables are used)

  Let $L^{(t)}$ be the number of packets in the stack

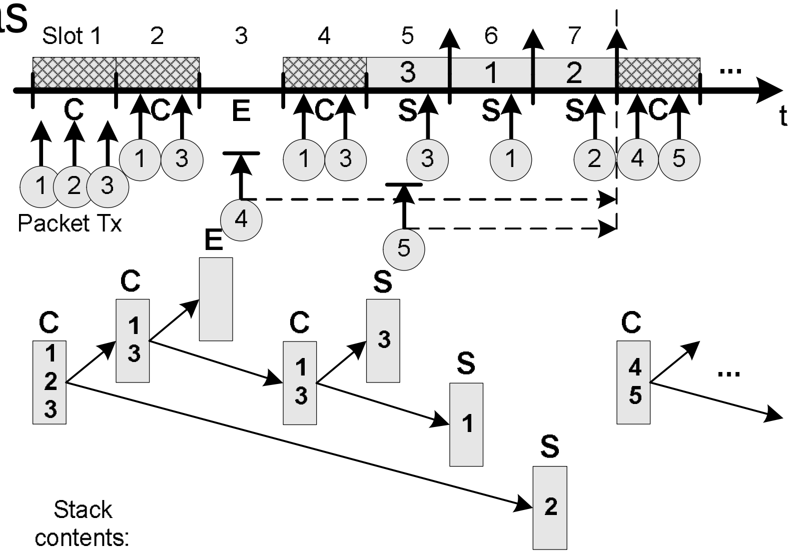
  $L^{(t)} = 1$ in the first epoch slot and

  $$L^{(t+1)} = \begin{cases} L^{(t)} + 1 & \text{in case of a Collision} \\ L^{(t)} - 1 & \text{otherwise} \end{cases}$$

  User should also keep track of its packet number in the stack

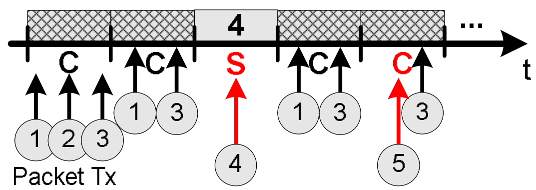
- Blocked access rule **complicates implementation** → use free access instead

  1 variable is enough to implement the **free channel access algorithm**



Stack contents:

0	1 2 3	1 3		1 3	3	1	1
1		2	1 3	2	1	2	
2			2		2		
	...	...	...	...	...	...	...



CT vs. BEB Comparison

- For $\boxed{M = \infty}$ BEB is unstable $\rightarrow$ $R_{BEB} = 0$

  Shown by D. Aldous: "Ultimate Instability of Exponential Back-Off Protocol …", 1987

- For $\boxed{M < \infty}$ BEB is stable $\rightarrow$ $R_{BEB} = \frac{1}{2} \cdot \ln 2 \cong 0.346$

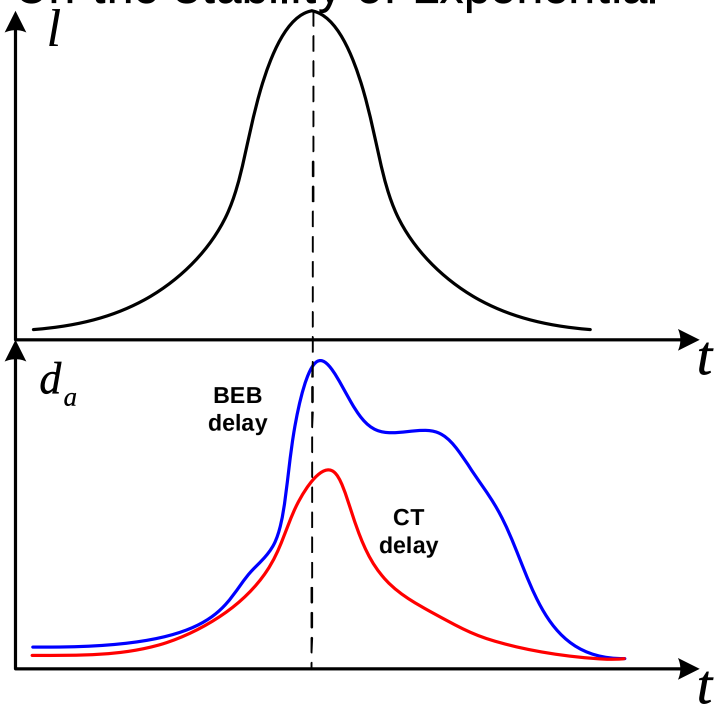
  Shown by N.-O. Song, B.-J. Kwak, L. Miller: "On the Stability of Exponential Backoff", 2003

- All CT modifications

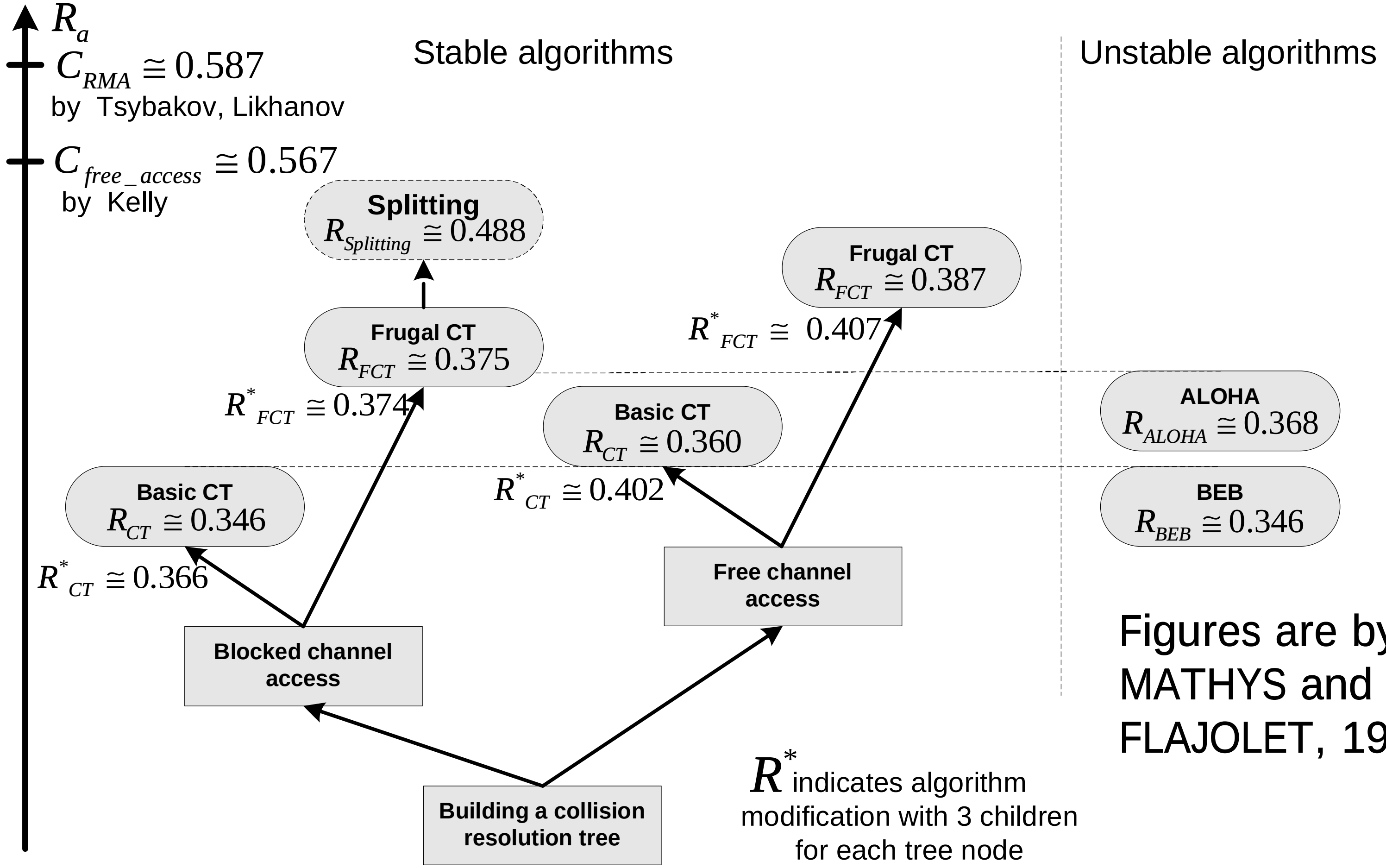
  are stable even for $\boxed{M = \infty}$

$$R_{CT} \cong \frac{1}{2} \cdot \ln 2 \cong 0.346$$

$$R_{FCT} \cong \left(\frac{3}{2 \cdot \ln 2} + \frac{1}{2}\right)^{-1} \cong 0.375$$

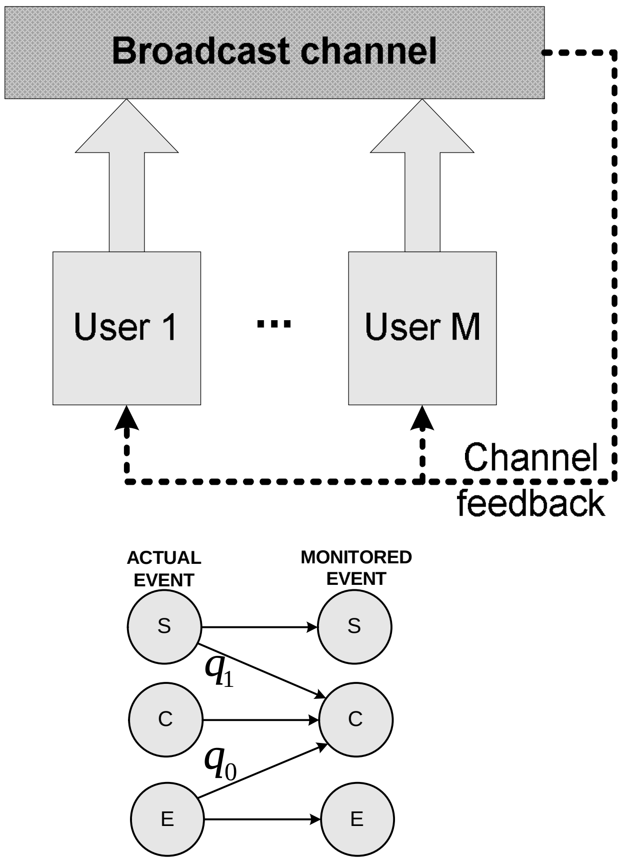


General RMA Algorithms Comparison



Figures are by PETER MATHYS and PHILIPPE FLAJOLET, 1985

A5: Noisy Channel Conditions



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: Ternary channel feedback

A4: Immediate channel feedback

A5: Noisy channel

- A model with '**false conflicts**' by G. Evseev, N. Ermolaev, 1982

A6: Input source probabilistic model

CT for Noisy Channel (CTN) Performance

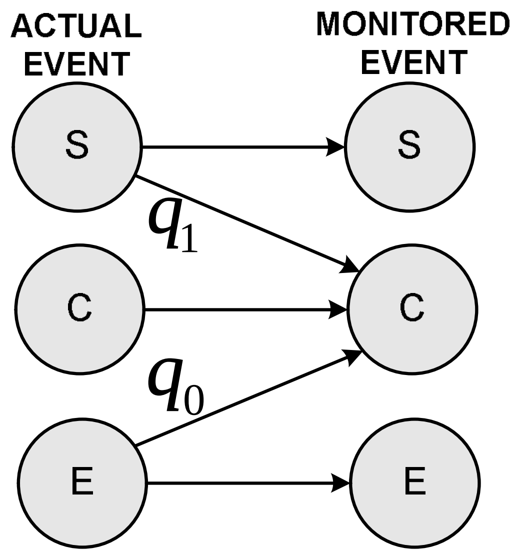
- CT is shown* to be **stable** for

$$\begin{cases} q_0 < 0.5 \\ q_1 < 1 \end{cases}$$

- FCT is shown* to be **unstable** for $q_0 > 0$

$$R_{CTN} \cong \frac{1-2\cdot q_0}{1-q_0}\cdot\left(\frac{2}{\ln 2}+\frac{2\cdot(q_1-q_0)}{(1-q_1)\cdot(1-q_0)}\right)$$

- A modification of CT was introduced**, which is **stable** for $q_0 < 1$



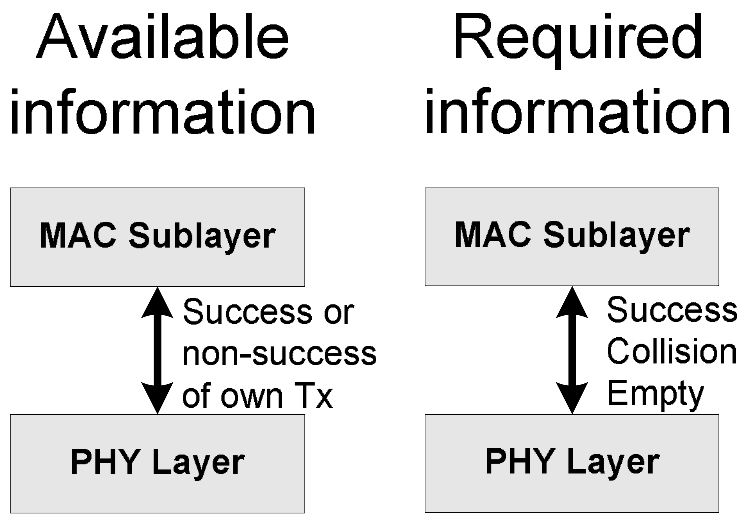
* G. Evseev, N. Ermolaev "Performance Evaluation of the Collision Resolution for a Random-Access Noisy Channel", 1982

** G. Evseev, A. Turlikov "Throughput Analysis for a Noise-Resistant Multiple Access Algorithm", 1986

CT Algorithms Summary

Benefits

- **Higher rate** than that of BEB algorithm
- **Lower** packet **delay** than that of BEB algorithm
- **Stability** for high user population
- **Easy implementation**



Open problems

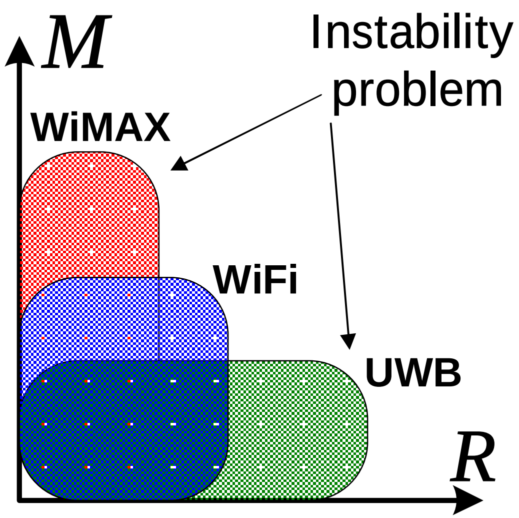
- **Extended** PHY-MAC **interface** is required **or stabilization technique*** for Success Non-Success feedback

* partially resolved in A. Malkov, A. Turlikov "Random-Multiple Access Protocols for communication Systems with "Success – Failure" Feedback", 1995

Tree algorithms **implementation issues** and alternative proposals

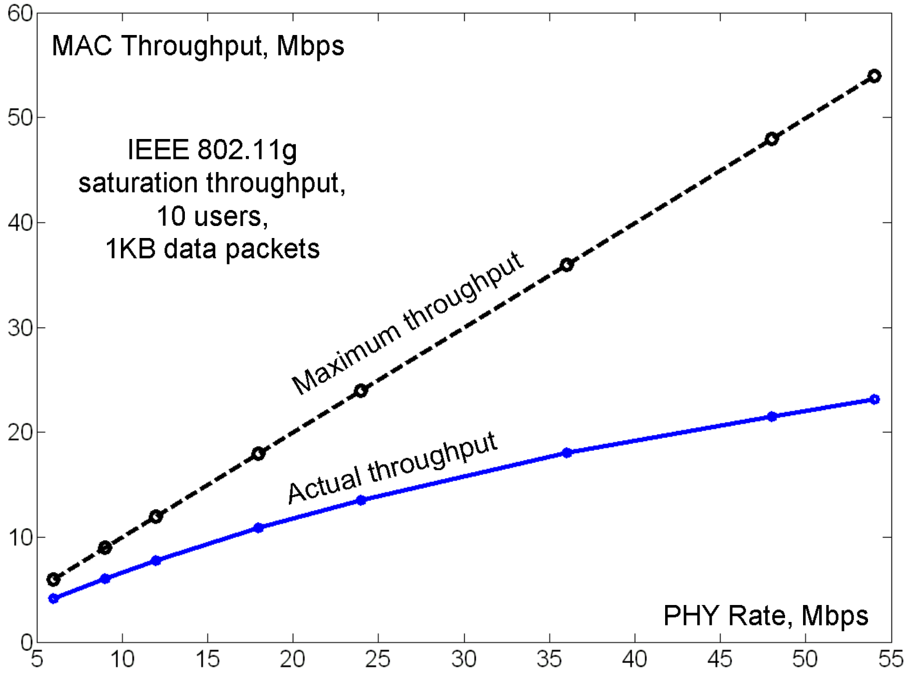
Research Directions

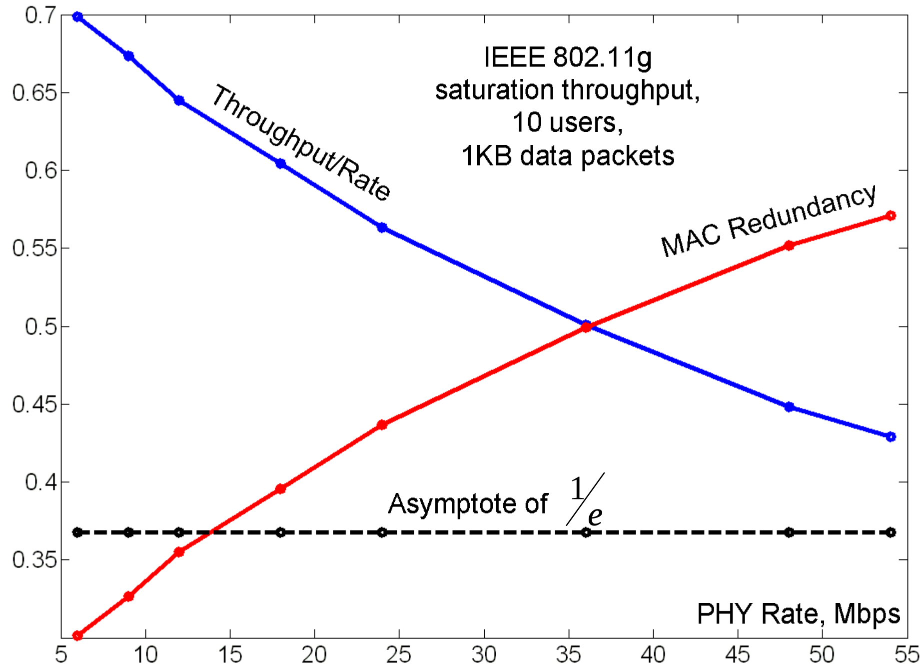
- By intervention level
  - Analysis/optimization of existing systems (□)
  - Novel approaches and algorithms (□)
  - Supportive activity (□)
- By system under consideration
  - PAN: IEEE 802.15.3c, ISO 26907 (UWB)
  - LAN: IEEE 802.11 (WiFi)
  - WAN: IEEE 802.16 (WiMAX)



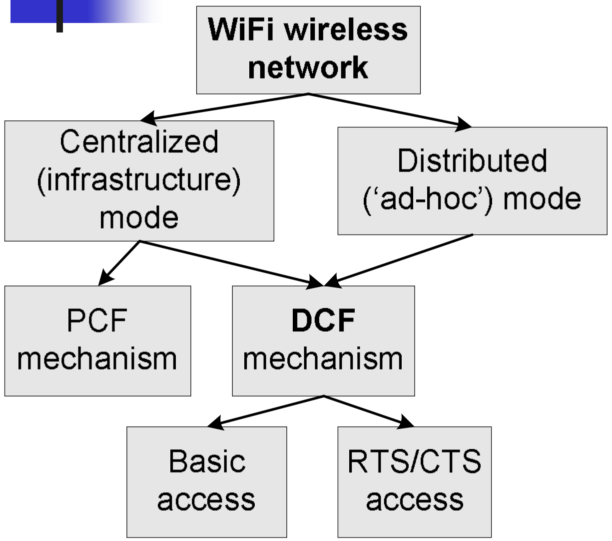
Open Problems: IEEE 802.11 LAN

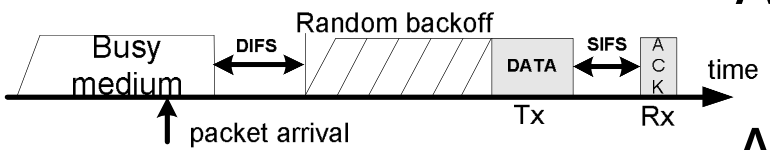
- Follow Bianchi approach to calculate **throughput in saturation conditions**
- **Gap** between PHY rate and MAC SAP throughput **increases** as rate grows
- With user population or data rate increase a system **will show instability**





Reference Model: IEEE 802.11 LAN





Principal assumptions:

A1: **Unequally-slotted** system

- **S**uccess = DATA + SIFS + ACK + DIFS
- **C**onflict = DATA + EIFS
- **E**mpty = aSlotTime

A2: Collision or perfect reception

A3: **Binary** channel feedback

- **Success, Non-success**

A4: Immediate channel feedback

A5: Noise-free or **Noisy** channel

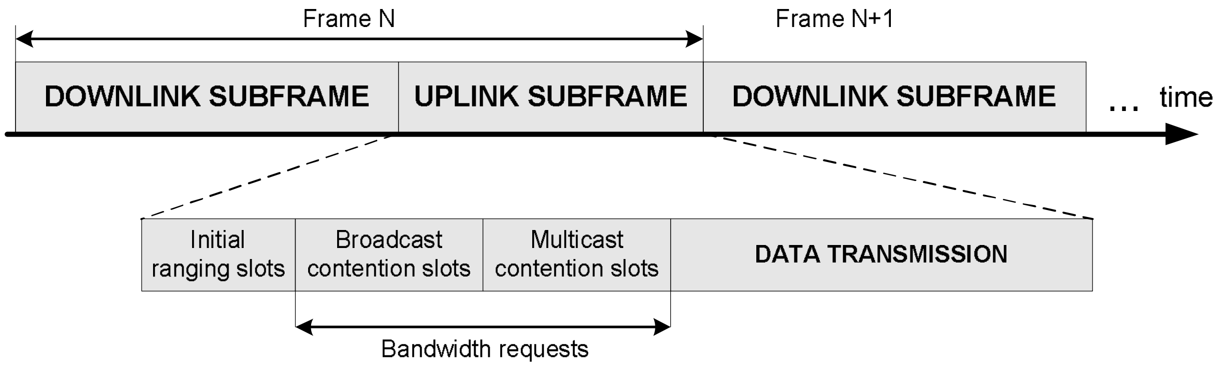
A6: Input source probabilistic model

IEEE 802.11 Research Directions

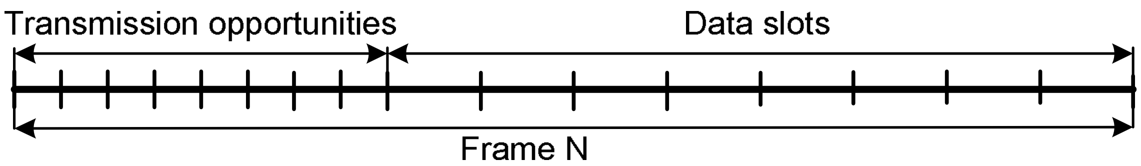
- Analytical model for mean delay analysis
- New standards simulation (.11e and .11n)
- High-precision throughput measurement
- Experimental wireless channel model
- BEB optimization proposal
- Performance enhancement for noisy channel (NACK)
- Tree algorithm consideration

Open Problems: IEEE 802.16 WAN

- Optimal **bandwidth reservation** scheme
  - Broadcast polling
  - Multicast polling and grouping

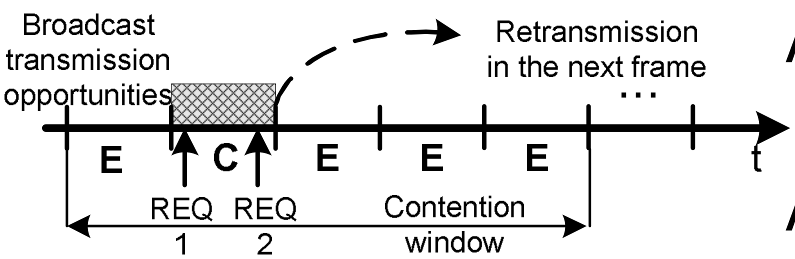


- **Performance optimization** and stability enforcement
  - Optimal Polling slots / Data slots separation



Reference Model: IEEE 802.16 WAN

BEB is used to resolve bandwidth request collisions



Principal assumptions:

A1: Slotted (synchronous) system

A2: Collision or perfect reception

A3: **Binary** channel feedback

- **Success, Non-success**

A4: **Delayed** channel feedback

- Feedback available by the next frame

A5: Noise-free channel

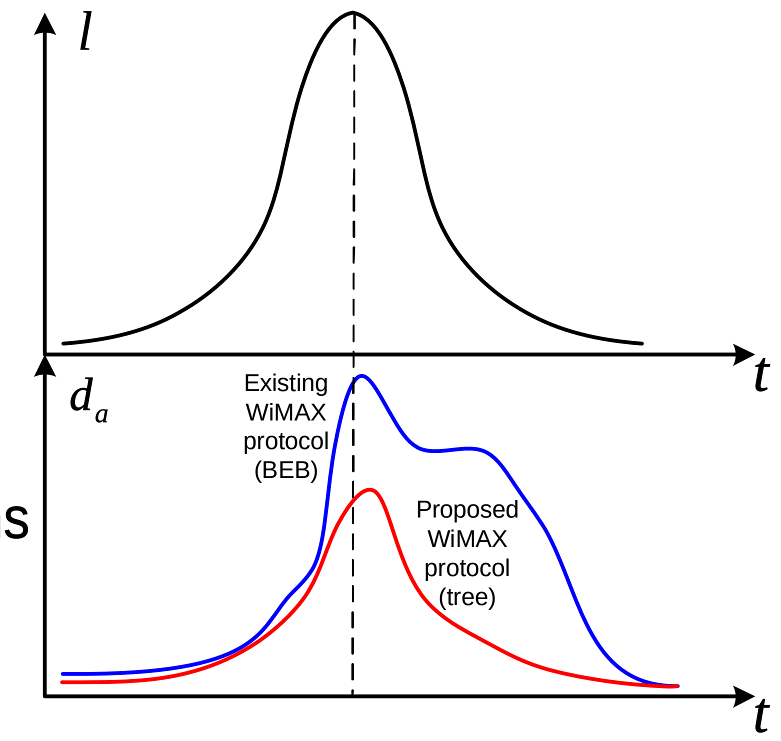
A6: Input source probabilistic model

IEEE 802.16 Research Directions

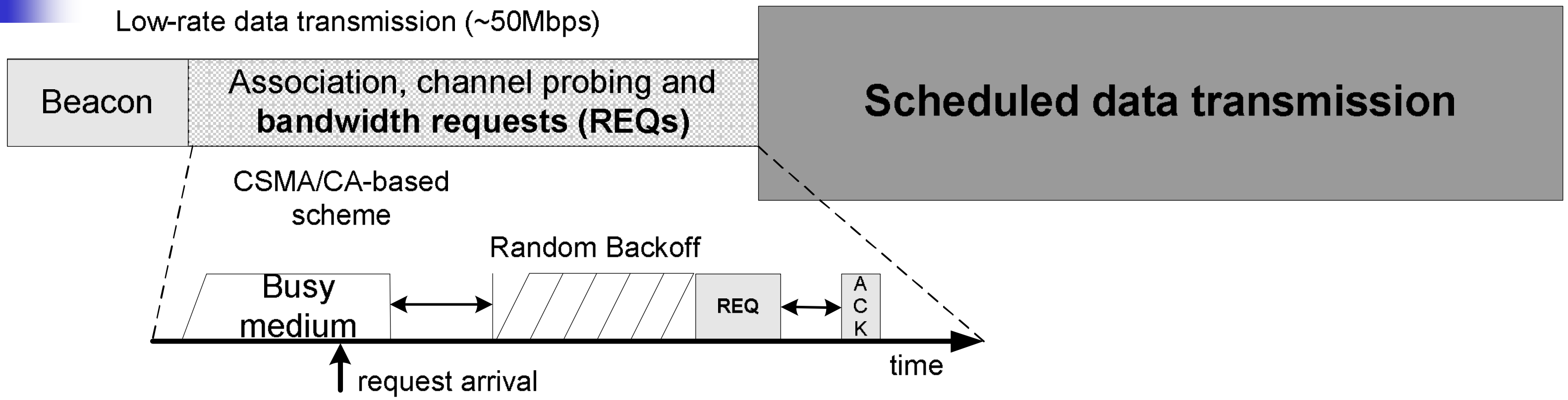
- Broadcast polling mechanism analysis
- Multicast polling mechanism analysis
- User grouping for different QoS criteria
- Performance optimization, optimal Polling slots / Data slots separation

  (A. Turlikov, A. Vinel "Capacity Estimation of Centralized Reservation-Based Random Multiple-Access System", 2007)
- MAC protocol replacement considerations

  (V. Kobliakov, A. Turlikov, A. Vinel "Distributed Queue Random Multiple Access Algorithm for Centralized Data Networks", 2006)
- MAC protocols stability research

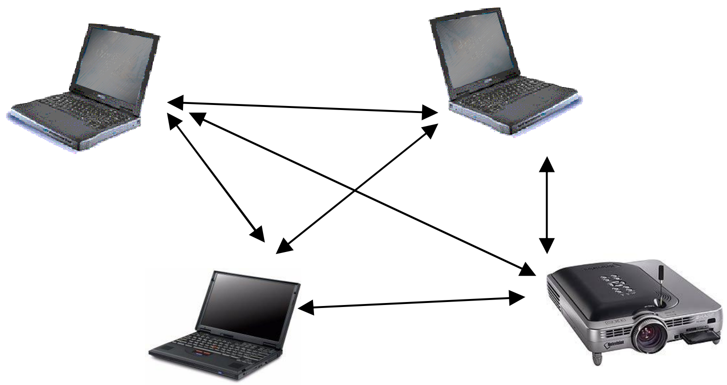


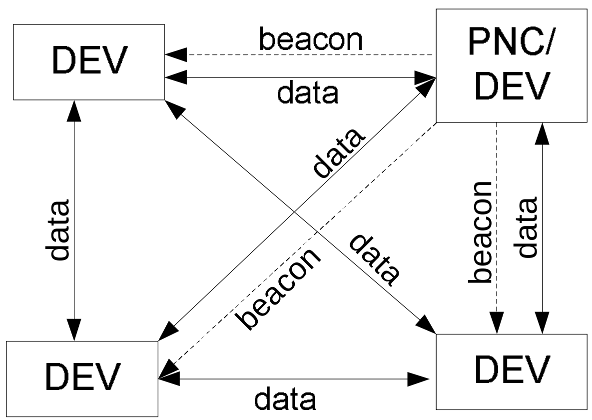
Open Problems: IEEE 802.15.3c PAN



- **Low-rate** data transmission **time** should be **minimized** (protocol overhead)
- **Instability problem** may arise due to saturation conditions
- **Packet delay** for request Tx should be **minimized**

Reference Model: IEEE 802.15.3c PAN





Principal assumptions:

A1: **Unequally-slotted** system

- **S**uccess = *undefined*
- **C**onflict = *undefined*
- **E**mpty = *undefined*

A2: Collision or perfect reception

A3: **Binary** channel feedback

- **Success, Non-success**

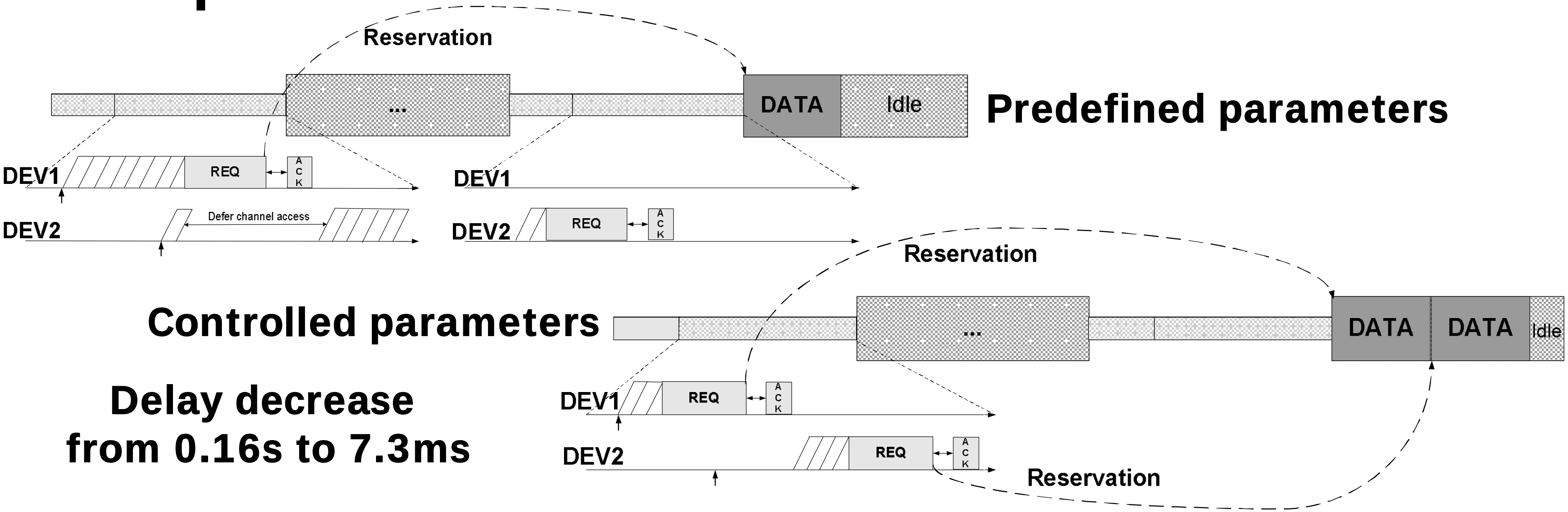
A4: Immediate channel feedback

A5: Noise-free or **Noisy** channel

A6: Input source probabilistic model

IEEE 802.15.3c Research Directions

- Performance enhancement for noisy channel (NACK)*
- **BEB parameters control scheme**



Delay decrease from 0.16s to 7.3ms

- Tree algorithm consideration

* S. Andreev, A. Vinel “Performance Analysis and Enhancement of an Ultra-Wideband WPAN MAC in the Presence of Noise”, 2007

Multiple Access Group Achievements

- Research
  - Analytical models of MAC operation are built (UWB, WiFi, WiMAX)
  - Performance of standard MAC protocols is optimized (UWB, WiMAX)
  - Alternative protocols are considered (WiMAX)
  - 12 scientific publications during 2007
- Education
  - 2 lecture courses on the subject
  - 2 PhD dissertations defended in 2006, 1 in 2007

Discussion