Performance Analysis of 802.11 Wireless LAN Networks

Giuseppe Bianchi

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Giuseppe.bianchi@uniroma2.it

Outline

- ➔ **Introduction & review of the 802.11 DCF**
- ➔ **DCF Overhead**
- ➔ **Throughput Bounds**
- ➔ **Saturation Throughput: Markov Chain Approach**
- ➔ **Throughut & delay computation**
- ➔ **Revisiting the analysis: elementary probability approach**
- ➔ **Error-prone channels**

- ➔ **Very briefly:**
  - ⇨ Non Saturation conditions: issues and modeling alternatives
  - ⇨ Models for multihop networks: issues and references to modern models

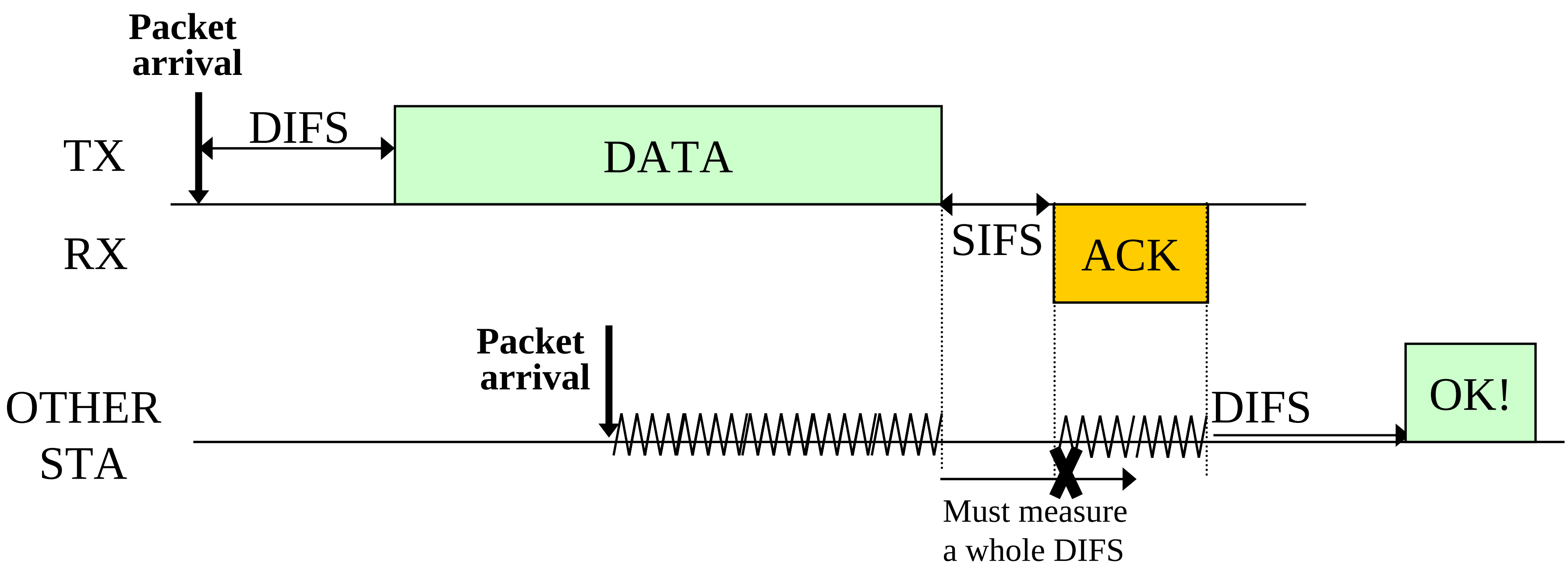
Motivation

- **Technical**
  - Understand how to model the 802.11 MAC layer
- **Methodological**
  - Understand how a properly chosen time-scale may be effective
  - Highlight the effectiveness of fixed-point analyses
  - Show how models that appear complex at a first insight, can be indeed lead to much simpler formulation with some additional research effort

802.11 Distributed Coordination Function

Carrier Sense Multiple Access

- **Station may transmit ONLY IF senses channel IDLE for a DIFS time**
  - DIFS = Distributed Inter Frame Space
- **Key idea: ACK replied after a SIFS < DIFS**
  - SIFS = Short Inter Frame Space
- **Other stations will NOT be able to access the channel during the handshake**
  - Provides an atomic DATA-ACK transaction



DATA/ACK frame format

DATA frame: 28 (or 34) bytes + payload

Frame Control	Duration / ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	Frame check sequence
2	2	6	6	6	2	6	0-2312	4

0 0	1 0	0 0 0 0	x	x	x	x	x	x	x	x
Protocol version	Type	Sub Type	To DS	From DS	More Frag	Retry	Pwr MNG	More Data	WEP	Order
2	2	4	1	1	1	1	1	1	1	1

Type = Data (10)
SubType = Data (0000)

ACK frame: 14 bytes – No need for TA address (the station receiving the ACK knows who's this from)!!

Frame Control	Duration / ID	Address (RA)	Frame check sequence
2	2	6	4

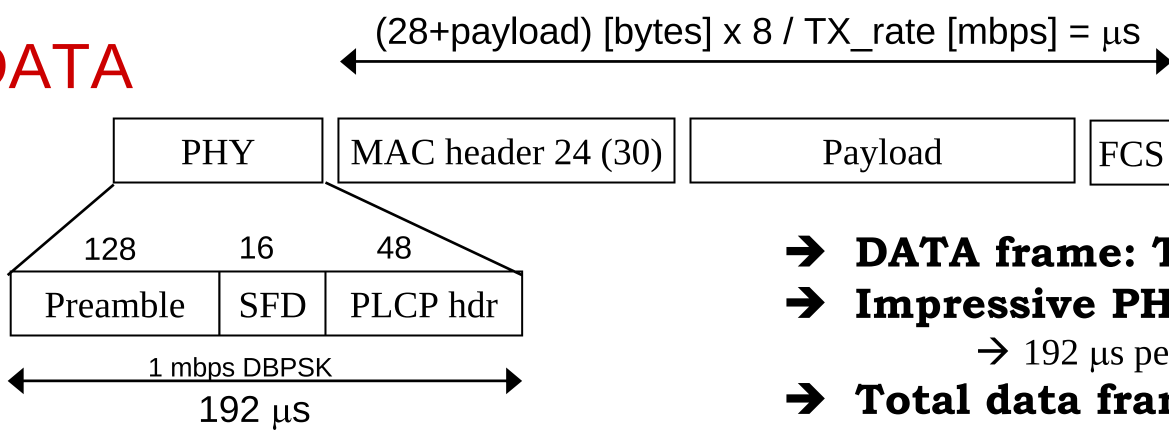
0 0	0 1	1 1 0 1	0	0	0	0	x	0	0	0
Protocol version	Type	Sub Type	To DS	From DS	More Frag	Retry	Pwr MNG	More Data	WEP	Order
2	2	4	1	1	1	1	1	1	1	1

Type = Control (01)
SubType = ACK (1101)

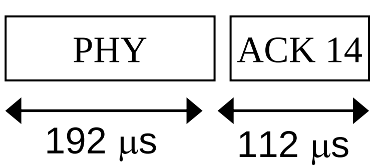
Grasping wi-fi (802.11b) numbers

- **DIFS = 50 µs**
  - Rationale: 1 SIFS + 2 slot-times
    - **Slot time = 20 µs**
      - » To account for RX_TX + Busy_Detect
- **SIFS = 10 µs**
  - Rationale: RX_TX turnaround time
    - The shortest possible!

DATA



ACK



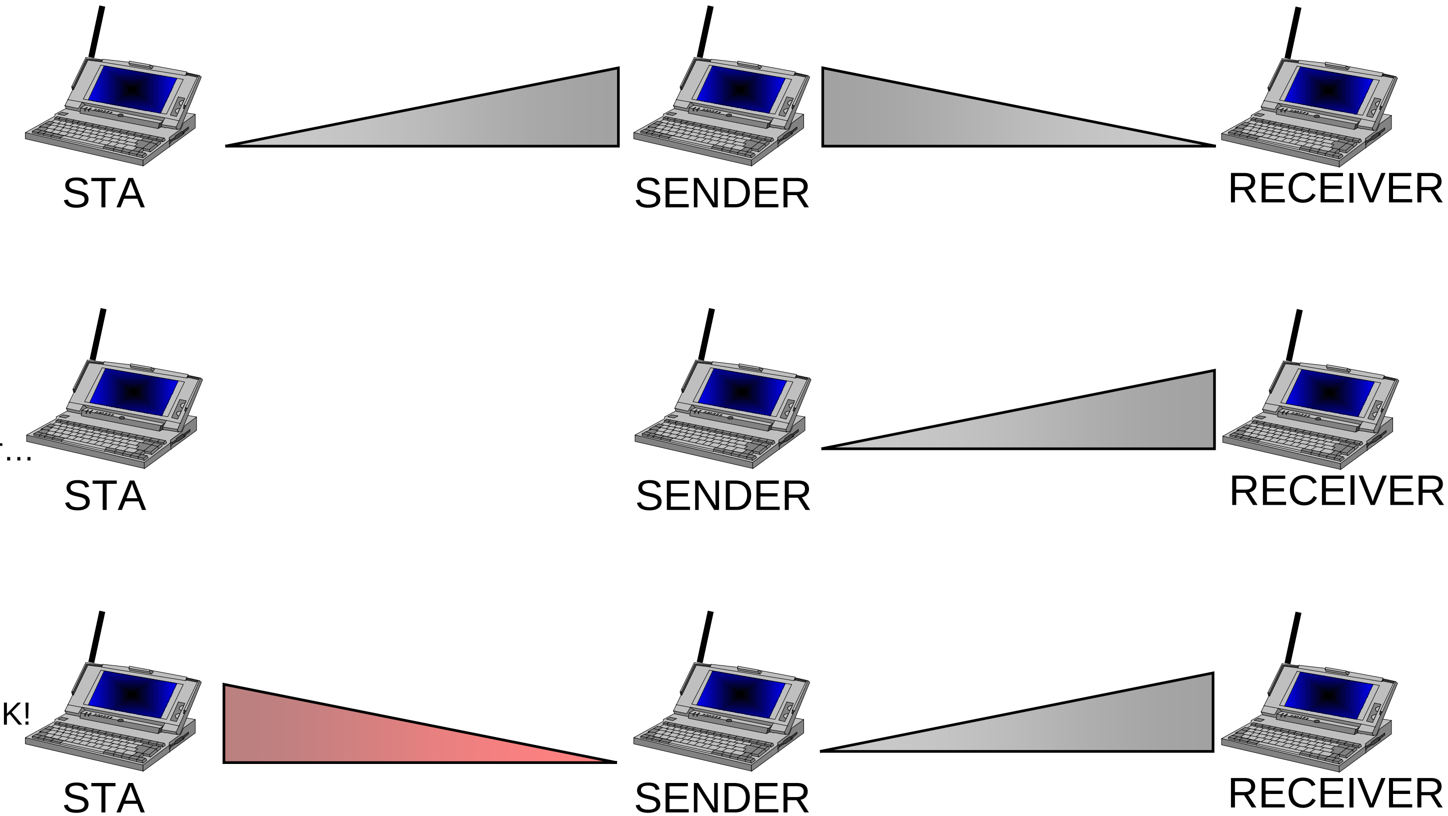
- **DATA frame: TX time = f(rate)**
- **Impressive PHY overhead!**
  - 192 µs per every single frame
- **Total data frame time (1500 bytes)**
  - @1 Mbps: 192+12224= 12416 µs
    - » PHY+MAC overhead = 3.3%
  - @11 Mbps: 192+ 1111.3 = 1303.3 µs
    - » PHY+MAC overhead = 16.%
  - Overhead increases for small frames!
- **ACK frame: TX at basic rate**
  - Typically 1 mbps but 2 mbps possible…
  - ACK frame duration (1mbps): 304 µs

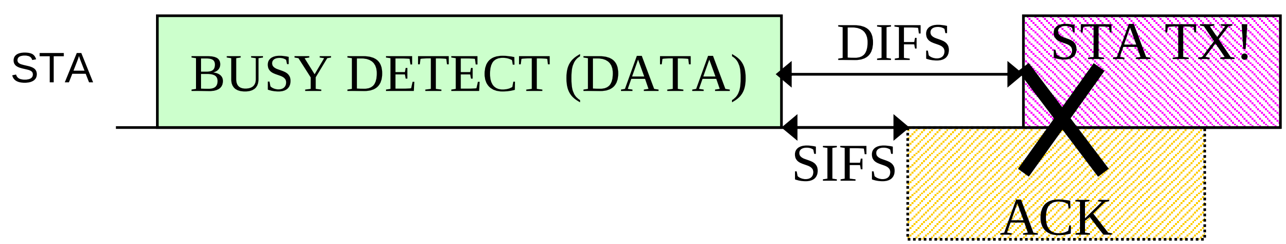
And when an ACK is "hidden"?

1) Sender TX
Receiver RX
STA defers

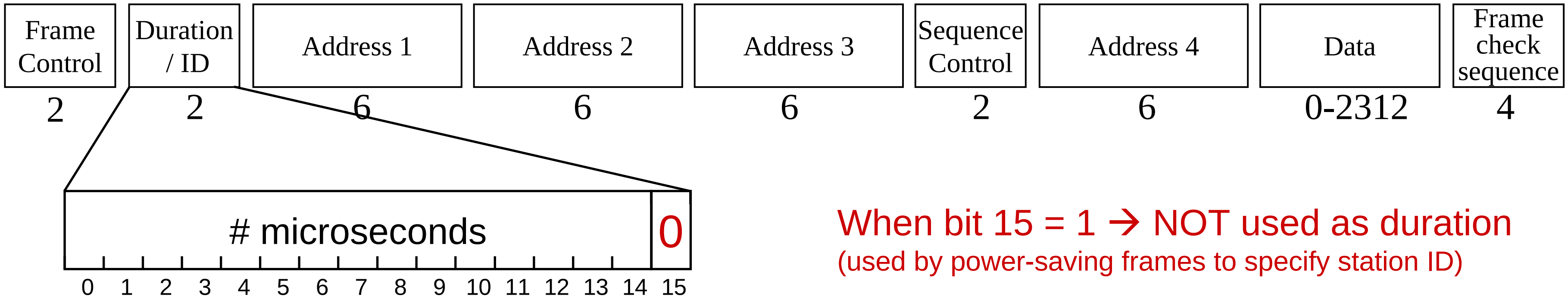
2) Receiver ACKs
(after SIFS)
STA cannot hear…

3) STA tranmits
And destroys ACK!





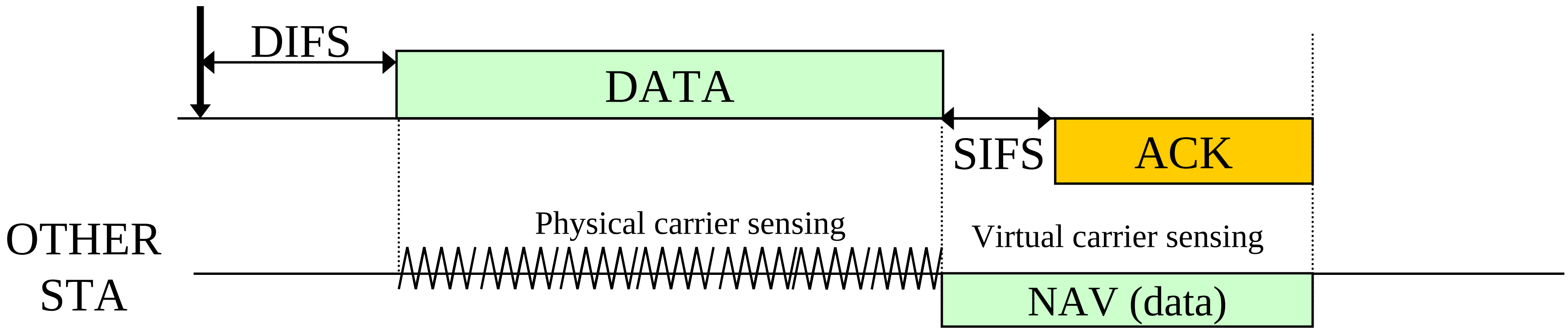
The Duration Field



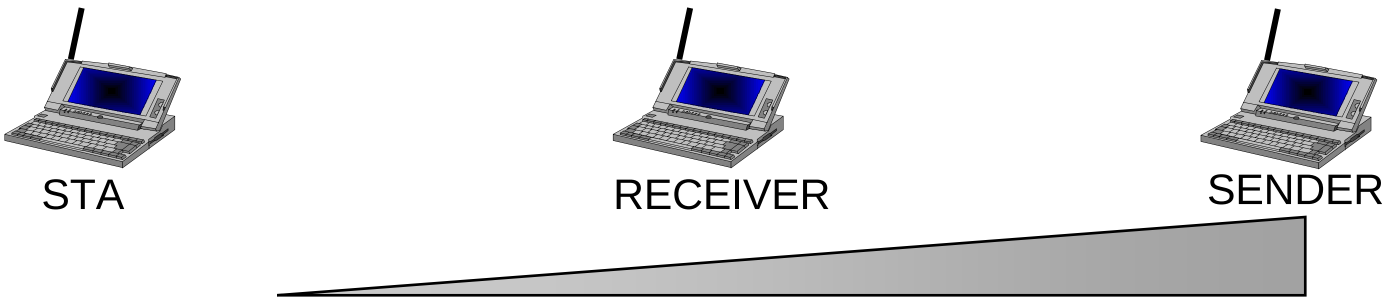
When bit 15 = 1 → NOT used as duration
(used by power-saving frames to specify station ID)

→ Allows "Virtual Carrier Sensing"

- ⇨ Other than physically sensing the channel, each station keeps a Network Allocation Vector (NAV)
- ⇨ Continuously updates the NAV according to information read in the duration field of other frames



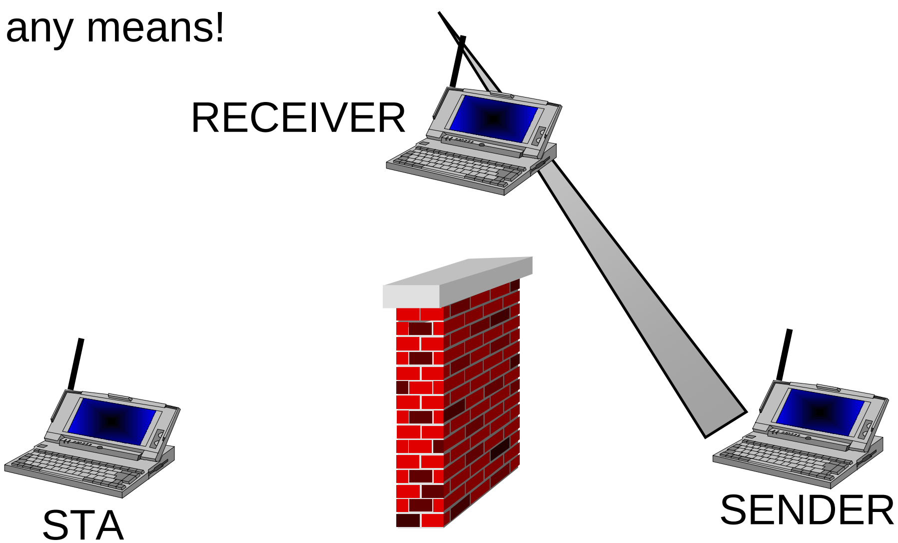
And when a terminal is "hidden"?



… this can be "solved" by increasing the sensitiveness of the Carrier Sense…

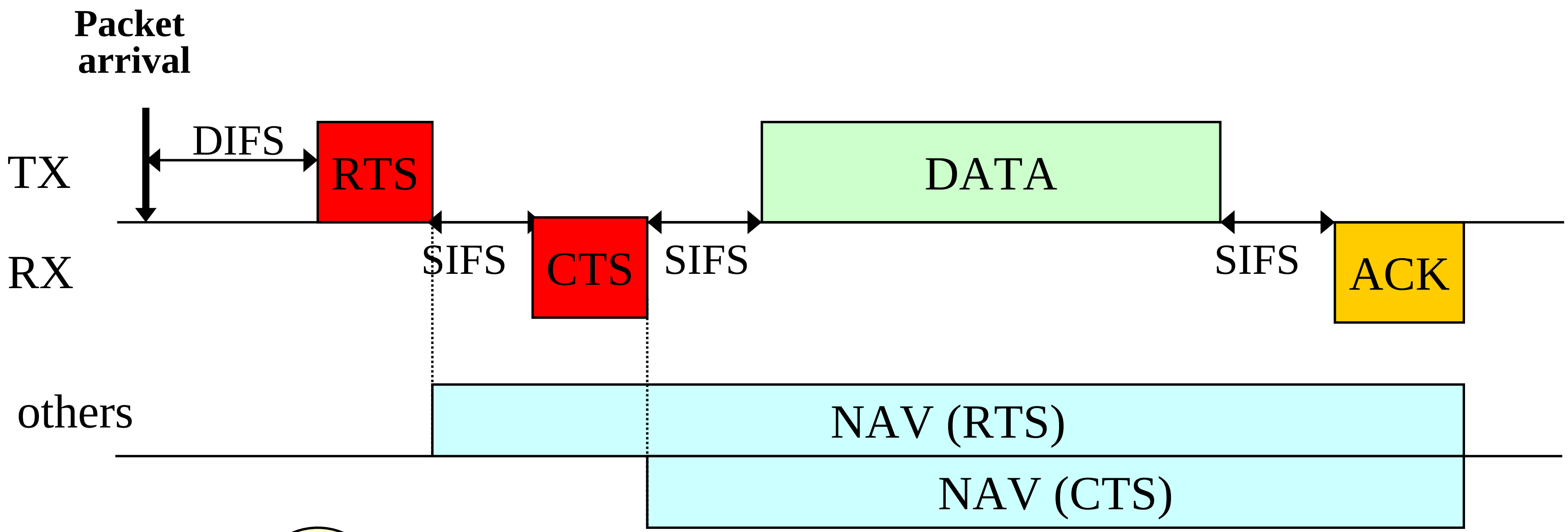
Quite stupid, though (LOTS of side effects – out of the goals of this lecture)

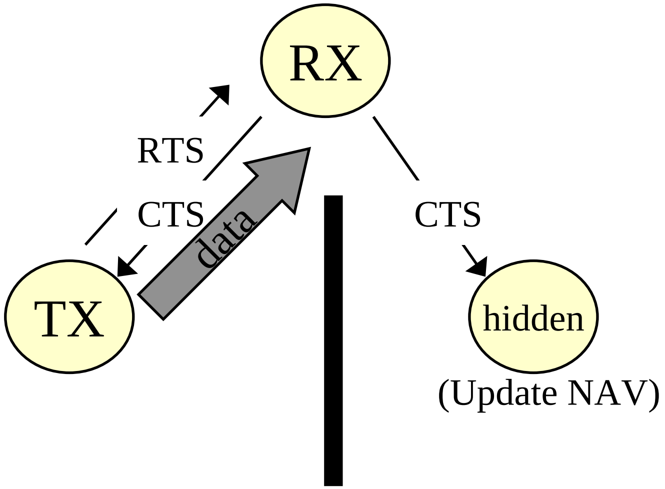
… this can's be "solved" by any means!



- **The Hidden Terminal Problem**
  - SENDER and STA cannot hear each other
  - SENDER transmits to RECEIVER
  - STA wants to send a frame
    - Not necessarily to RECEIVER…
  - STA senses the channel IDLE
    - Carrier Sense failure
  - Collision occurs at RECEIVER
- **Destroys a possibly very long TX!!**

The RTS/CTS solution





RTS/CTS: carry the amount of time the channel will be BUSY. Other stations may update a Network Allocation Vector, and defer TX even if they sense the channel idle
(Virtual Carrier Sensing)

RTS/CTS frames

RTS frame: 20 bytes

Frame Control	Duration / ID	Address 1 (RA)	Address 2 (TA)	Frame check sequence
2	2	6	6	4

Protocol version	Type	Sub Type	To DS	From DS	More Frag	Retry	Pwr MNG	More Data	WEP	Order
0 0	0 1	1 0 1 1	0	0	0	0	x	0	0	0
2	2	4	1	1	1	1	1	1	1	1

Type = Control (01)
SubType = RTS (1011)

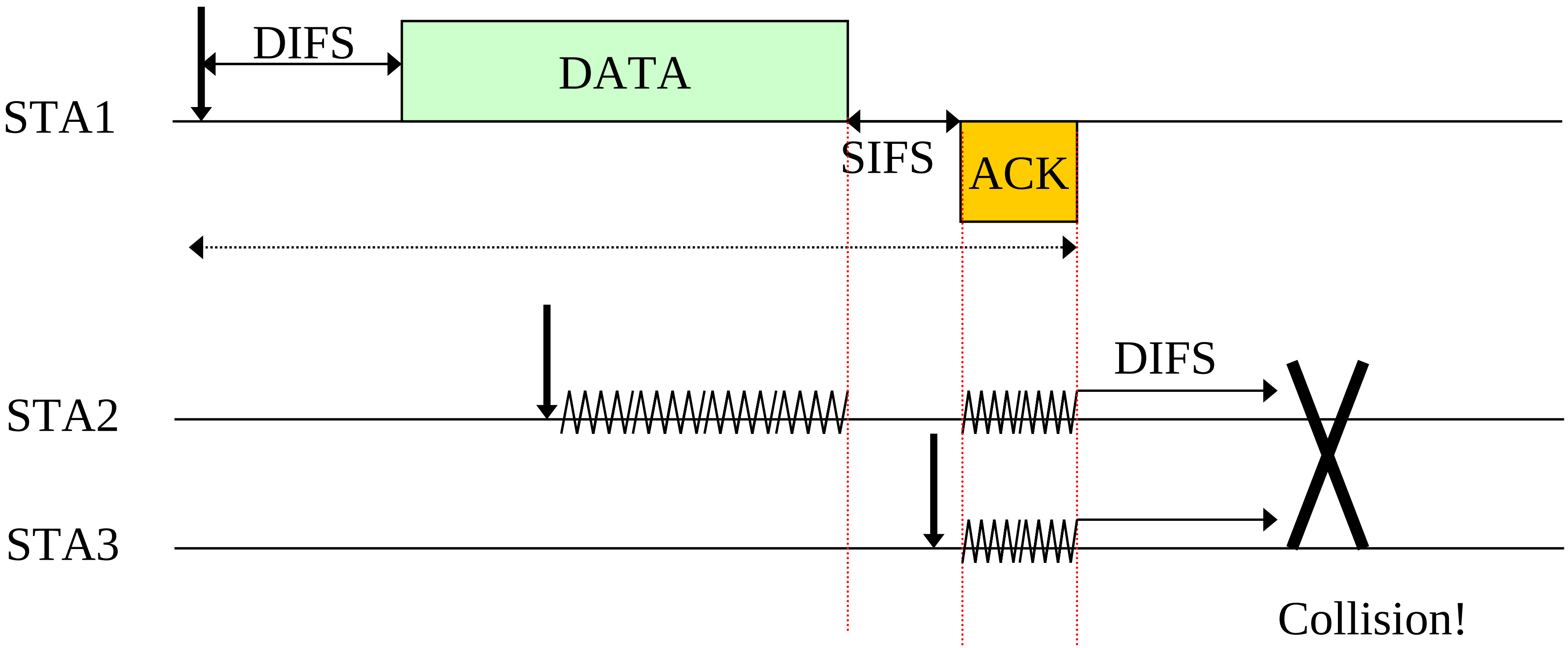
CTS frame: 14 bytes (same as ACK)

Frame Control	Duration / ID	Address (RA)	Frame check sequence
2	2	6	4

Protocol version	Type	Sub Type	To DS	From DS	More Frag	Retry	Pwr MNG	More Data	WEP	Order
0 0	0 1	1 1 0 0	0	0	0	0	x	0	0	0
2	2	4	1	1	1	1	1	1	1	1

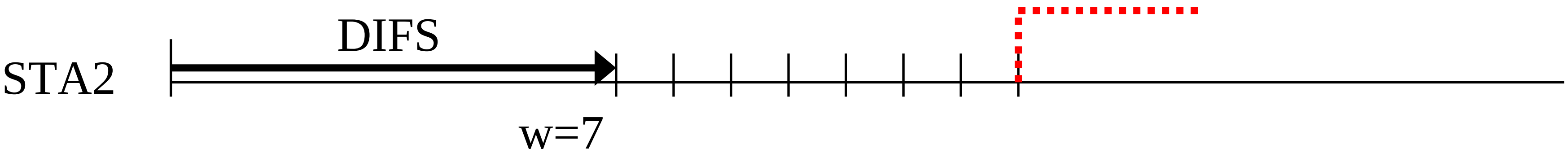
Type = Control (01)
SubType = CTS (1100)

Why backoff?

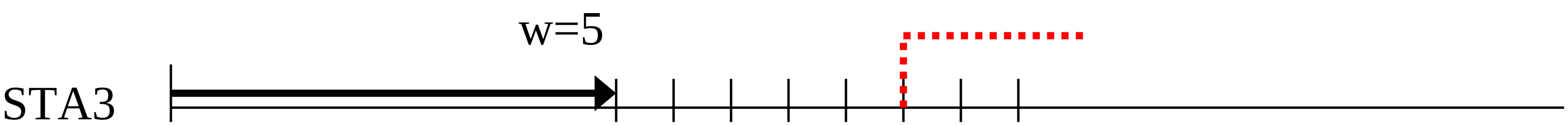


RULE: *when the channel is initially sensed BUSY, station defers transmission; THEN,when channel sensed IDLE again for a DIFS, defer transmission of a further random time (Collision Avoidance)*

Slotted Backoff



Extract random number
in range (0, W-1)
Decrement every slot-time σ



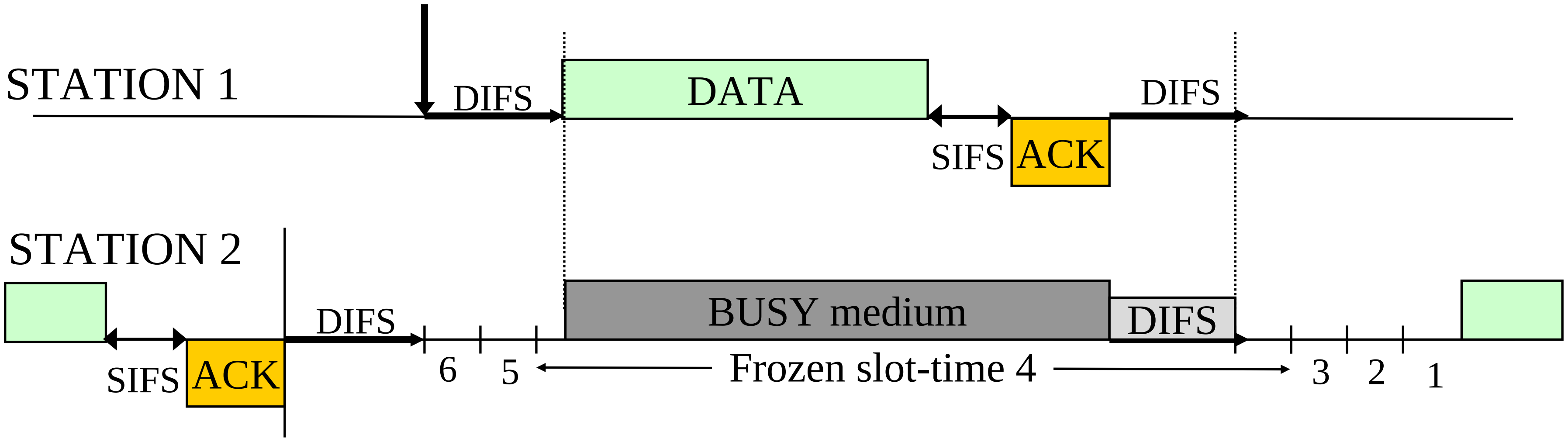
Note: slot times <u>are not physically delimited</u> on the channel!
Rather, they are logically identified by every STA

Slot-time values: 20μs for DSSS (wi-fi)

Accounts for: 1) RX_TX turnaround time
2) busy detect time
3) propagation delay

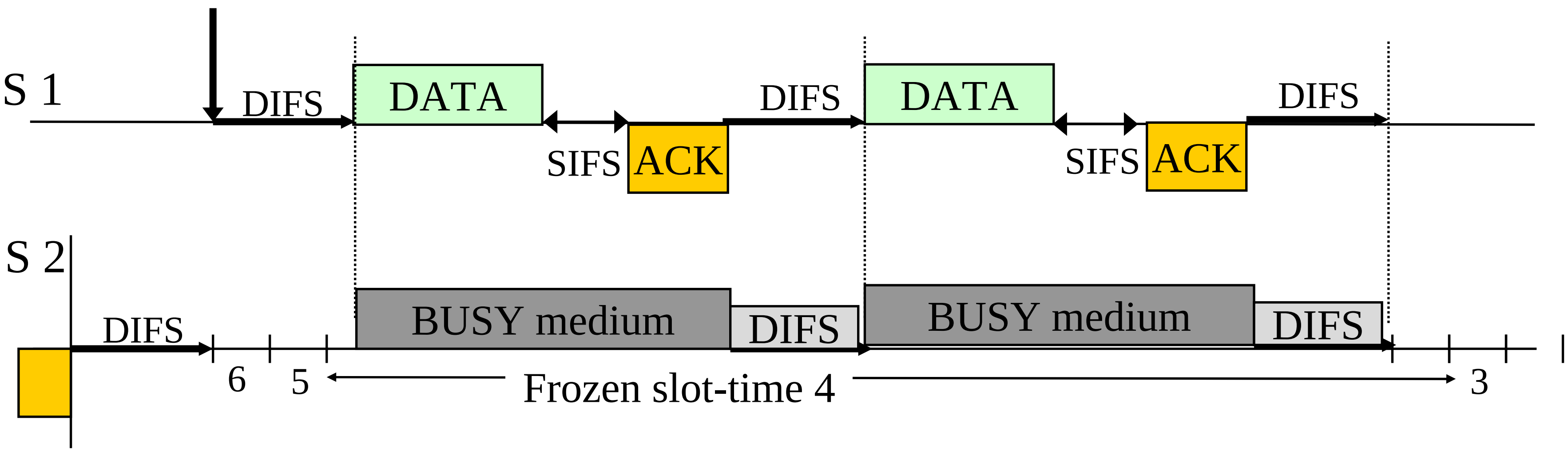
Backoff freezing

- **When STA is in backoff stage:**
  - It freezes the backoff counter as long as the channel is sensed BUSY
  - It restarts decrementing the backoff as the channel is sensed IDLE for a DIFS period



Why backoff between consecutive tx?

- ➔ **To avoid Channel Capture**
  - ⇨ Made worse by the “wrong” backoff counter decrement legacy specification – corrected in 802.11e
  - ⇨ A listening station would never find a slot-time after the DIFS (necessary to decrement the backoff counter)
  - ⇨ Thus, it would remain stuck to the current backoff counter value forever!!



Backoff rules

- **First backoff value:**
  - Extract a uniform random number in range $(0, CW_{min})$
- **If unsuccessful TX:**
  - Extract a uniform random number in range $(0, 2\times(CW_{min}+1)-1)$
- **If unsuccessful TX:**
  - Extract a uniform random number in range $(0, 2^2\times(CW_{min}+1)-1)$
- **Etc up to $2^m\times(CW_{min}+1)-1$**

Exponential Backoff!
For 802.11b:
CWmin = 31
CWmax = 1023 (m=5)

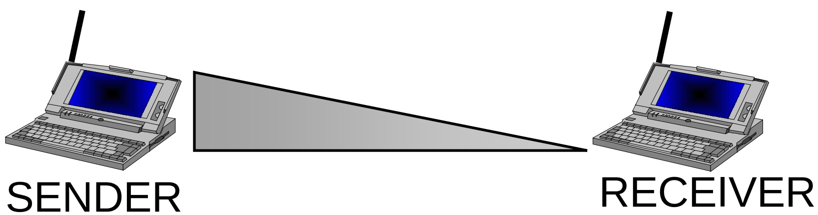
Further backoff rules

- **Truncated exponential backoff**
  - After a number of attempts, transmission fails and frame is dropped
  - Backoff process for new frame restarts from CWmin
  - Protects against cannel capture
    - unlikely when stations are in visibility, but may occur in the case of hidden stations
- **Two retry limits suggested:**
  - Short retry limit (4), apply to frames below a given threshold
  - Long retry limit (7), apply to frames above given threshold
  - (loose) rationale: short frames are most likely generated bu realk time stations
    - Of course not true in general; e.g. what about 40 bytes TCP ACKs?

DCF Overhead

Question

- ➔ **1 TX, 1 RX**
  - ⇨ No competing stations
  - ⇨ No transmission errors
- ➔ **What is the maximum transmission rate achievable?**



DCF overhead

$$S_{station} = \frac{E[payload]}{E[T_{Frame\_Tx}] + DIFS + CW_{\min}/2}$$

$$T_{Frame\_Tx} = T_{MPDU} + SIFS + T_{ACK}$$

$$T_{Frame\_Tx} = T_{RTS} + SIFS + T_{CTS} + SIFS + T_{MPDU} + SIFS + T_{ACK}$$

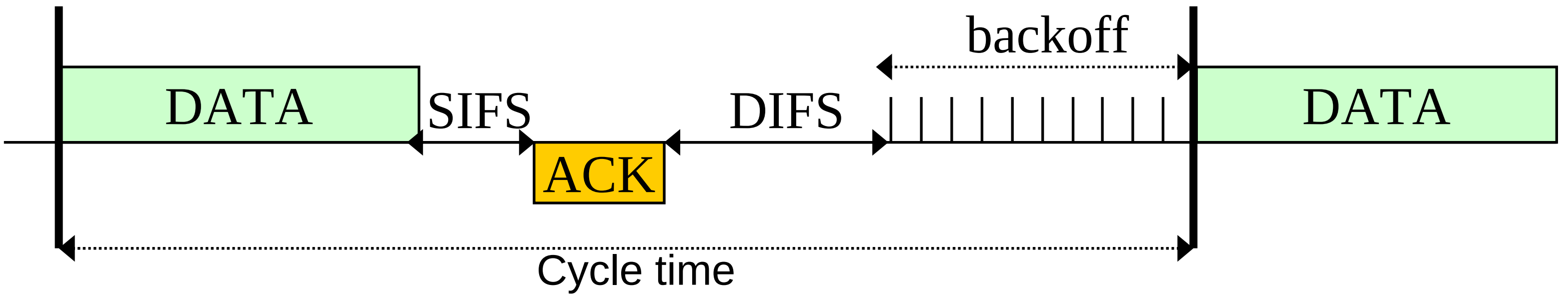
$$T_{MPDU} = T_{PLCP} + 8 \cdot (28 + L) / R_{MPDU\_Tx}$$

$$T_{ACK} = T_{PLCP} + 8 \cdot 14 / R_{ACK\_Tx}$$

$$T_{RTS} = T_{PLCP} + 8 \cdot 20 / R_{RTS\_Tx}$$

$$T_{CTS} = T_{PLCP} + 8 \cdot 14 / R_{CTS\_Tx}$$

Example: maximum achievable throughput for 802.11b



- ➔ **Data Rate = 11 mbps; ACK rate = 1 mbps**
- ➔ **Payload = 1500 bytes**

$$T_{MPDU} = 192 + 8 \cdot (28 + 1500)/11 \approx 1303$$

$$T_{ACK} = 192 + 8 \cdot 14/1 = 304$$

$$SIFS = 10; \quad DIFS = 50$$

$$E[Backoff] = \frac{31}{2} \times 20 = 310$$

$$Thr = \frac{1500 \times 8}{1303 + 10 + 304 + 50 + 310} = 6.07 Mbps$$

- ➔ **Data Rate = 11 mbps; ACK rate = 1 mbps**
- ➔ **Payload = 576 bytes**

$$T_{MPDU} = 192 + 8 \cdot (28 + 576)/11 \approx 631$$

$$T_{ACK} = 192 + 8 \cdot 14/1 = 304$$

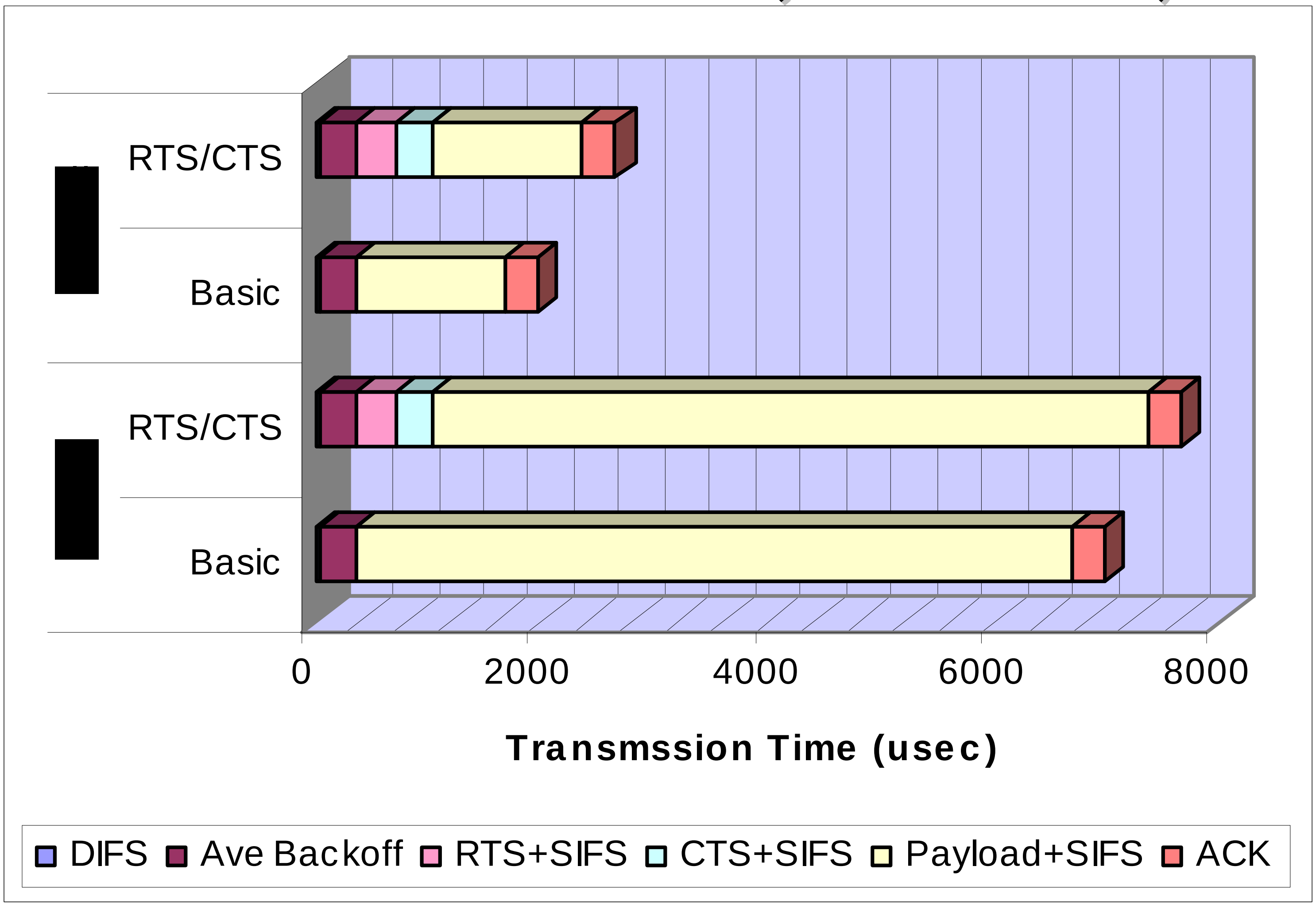
$$SIFS = 10; \quad DIFS = 50$$

$$E[Backoff] = \frac{31}{2} \times 20 = 310$$

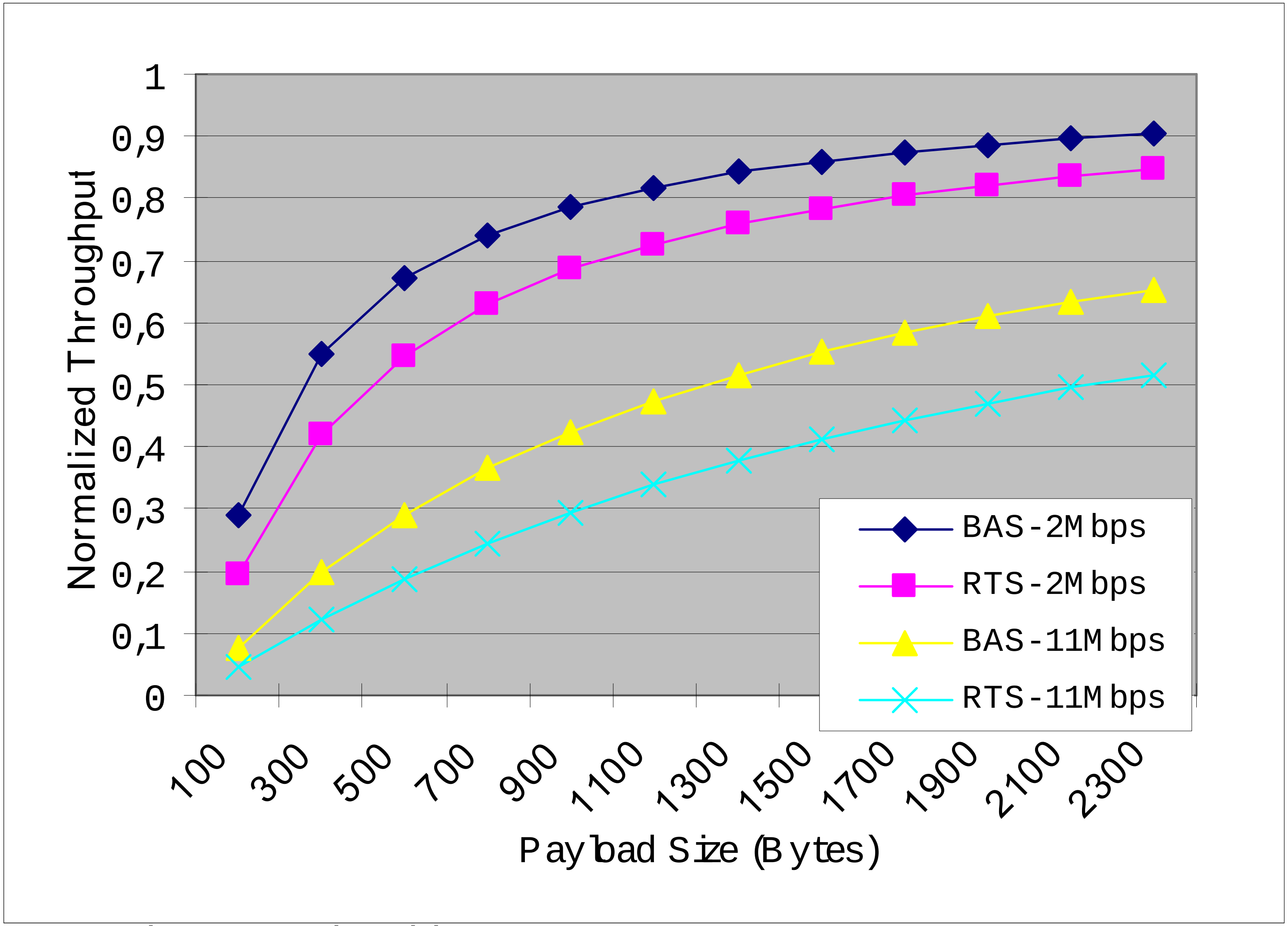
$$Thr = \frac{576 \times 8}{631 + 10 + 304 + 50 + 310} = 3.53 Mbps$$

REPEAT RESULTS FOR RTS/CTS → Not viable (way too much overhead) at high rates!

DCF overhead (802.11b)



DCF overhead (802.11b)



Multi-rate operation

- **Rate selection: proprietary mechanism!**
  - Result: different chipsets operate widely different
- **Two basic approaches**
  - Adjust rate according to measured link quality (SNR estimate)
    - How link quality is computed is again proprietary!
  - Adjust rate according to frame loss
    - How many retries? Step used for rate reduction? Proprietary!
    - Problem: large amount of collisions (interpreted as frame loss) forces rate adaptation

Performance Anomaly

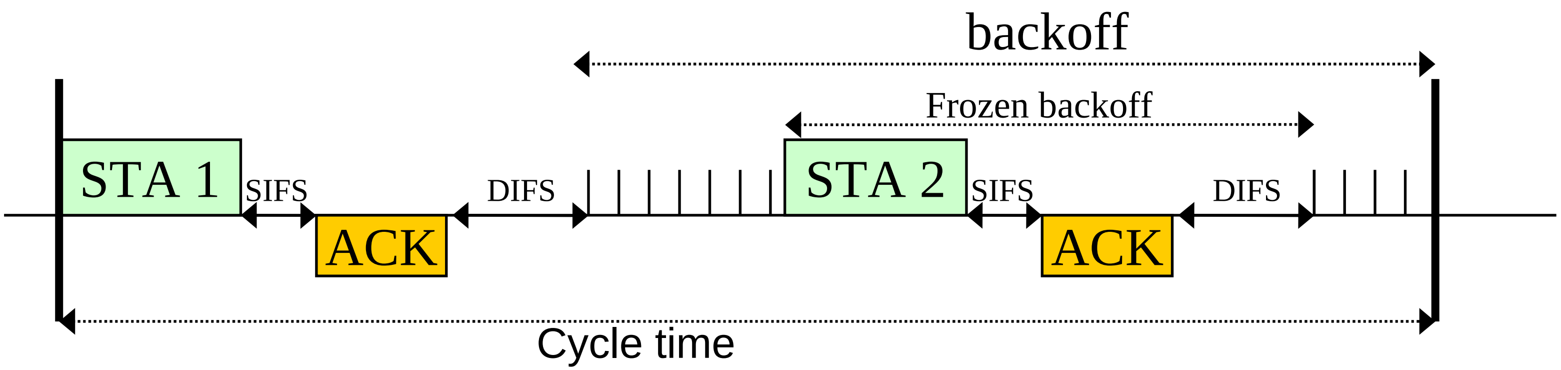
- **Question 1:**
  - Assume that throughput measured for a single 11 mbps greedy station is approx 6 mbps. What is per-STA throughput when two 11 mbps greedy stations compete?
- **Answer 1:**
  - Approx 3 mbps (easy ☺)

- **Question 2:**
  - Assume that throughput measured for a single 2 mbps greedy station is approx 1.7 mbps. What is per-STA throughput when two 2 mbps greedy stations compete?
- **Answer 2:**
  - Approx 0.85 mbps (easy ☺)

- **Question 3:**
  - What is per-STA throughput when one 11 mbps greedy station compete with one 2 mbps greedy station?
- **Answer 3:**
  - ...

Understanding Answers 1&2

(neclect collision – indeed rare – just slightly reduce computed value)



$$Thr[1] = Thr[2] = \frac{E[payload]}{E[cycle\ time]} = \frac{1500 \times 8}{T_{MPDU}[1] + SIFS + ACK + DIFS + T_{MPDU}[2] + SIFS + ACK + DIFS + E[backoff]}$$

- ➔ **Data Rate = 11 mbps; ACK rate = 1 mbps**
- ➔ **Payload = 1500 bytes**

$$T_{MPDU} = 192 + 8 \cdot (28 + 1500)/11 \approx 1303$$

$$T_{ACK} = 192 + 8 \cdot 14/1 = 304$$

$$SIFS = 10; \quad DIFS = 50$$

$$E[Backoff] = \frac{31}{2} \times 20 = 310$$

$$Thr = \frac{1500 \times 8}{2 \times (1303 + 10 + 304 + 50) + 310} = 3.3 Mbps$$

- ➔ **Data Rate = 2 mbps; ACK rate = 1 mbps**
- ➔ **Payload = 1500 bytes**

$$T_{MPDU} = 192 + 8 \cdot (28 + 1500)/2 \approx 6304$$

$$T_{ACK} = 192 + 8 \cdot 14/1 = 304$$

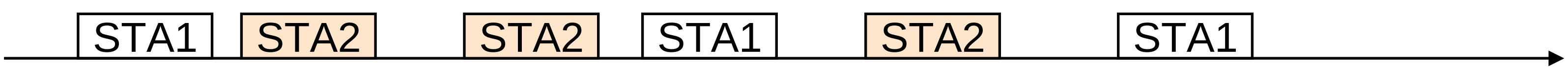
$$SIFS = 10; \quad DIFS = 50$$

$$E[Backoff] = \frac{31}{2} \times 20 = 310$$

$$Thr = \frac{1500 \times 8}{2 \times (6304 + 10 + 304 + 50) + 310} = 0.88 Mbps$$

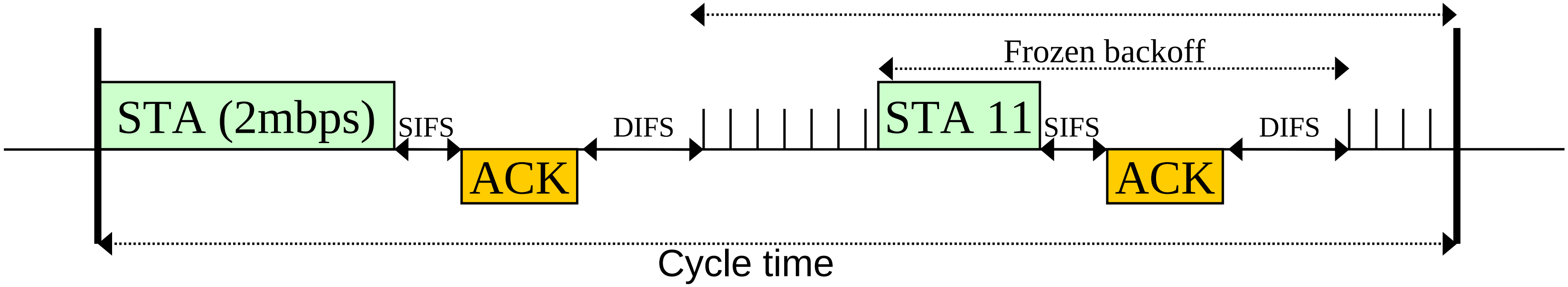
Emerging "problem": long-term fairness!

- If you have understood the previous example, you easily realize that
- **802.11 provides FAIR access to stations**
- **in terms of EQUAL NUMBER of transmission opportunities in the long term!**



- **But this is INDEPENDENT OF transmission speed!**

Computing answer 3



RESULT: SAME THROUGHPUT (in the long term)!!

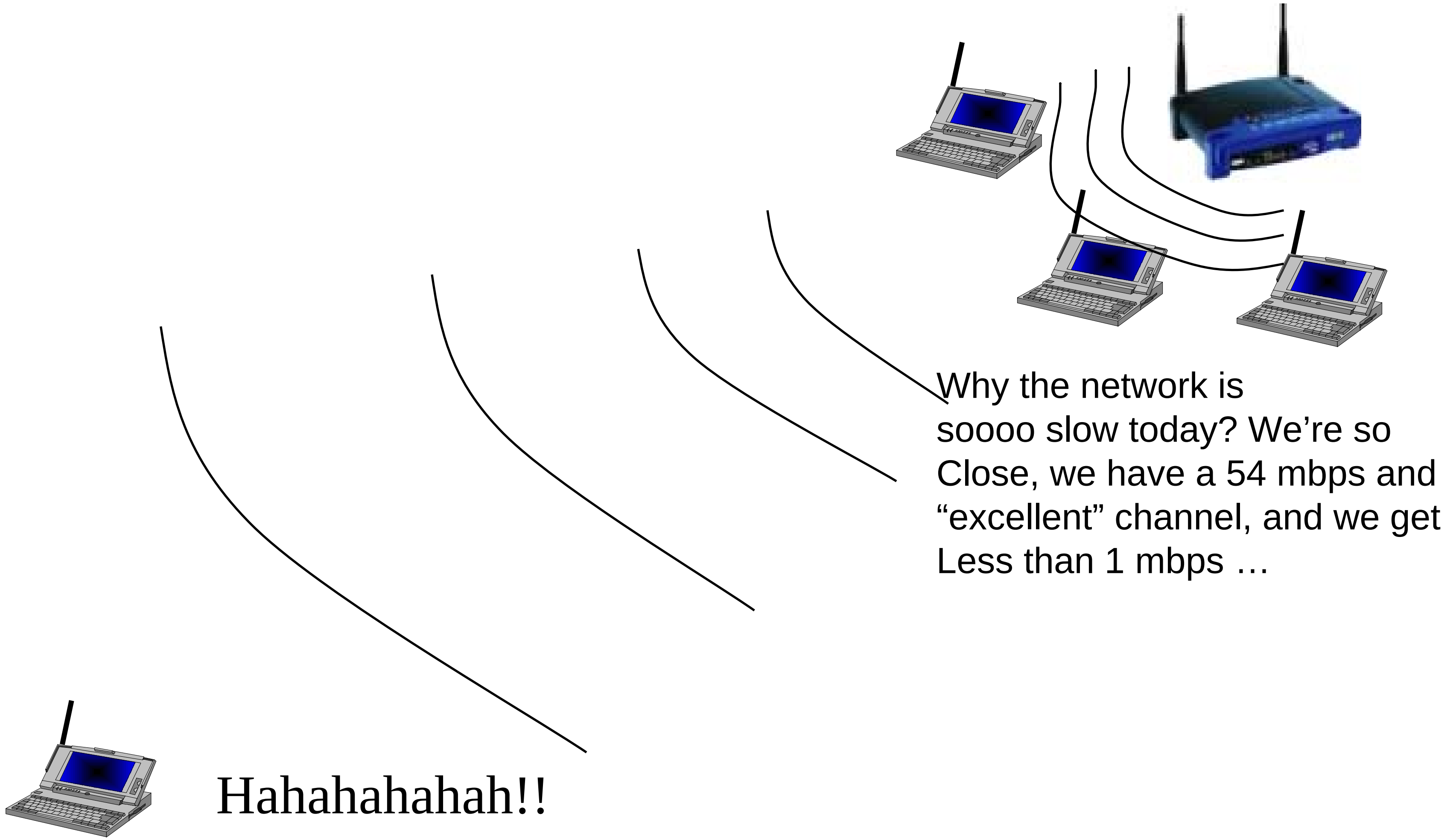
$$Thr[1] = Thr[2] = \frac{E[payload]}{E[cycle\ time]} =$$

$$= \frac{1500 \times 8}{T_{MPDU}[1] + SIFS + ACK + DIFS + T_{MPDU}[2] + SIFS + ACK + DIFS + E[backoff]} =$$

$$= \frac{1500 \times 8}{6304 + 1303 + 2(10 + 304 + 50) + 310} = 1.39\ Mbps!!!!!!$$

DRAMATIC CONSEQUENCE: throughput is limited by STA with slowest rate (lower that the maximum throughput achievable by the slow station)!!

Performance anomaly into action

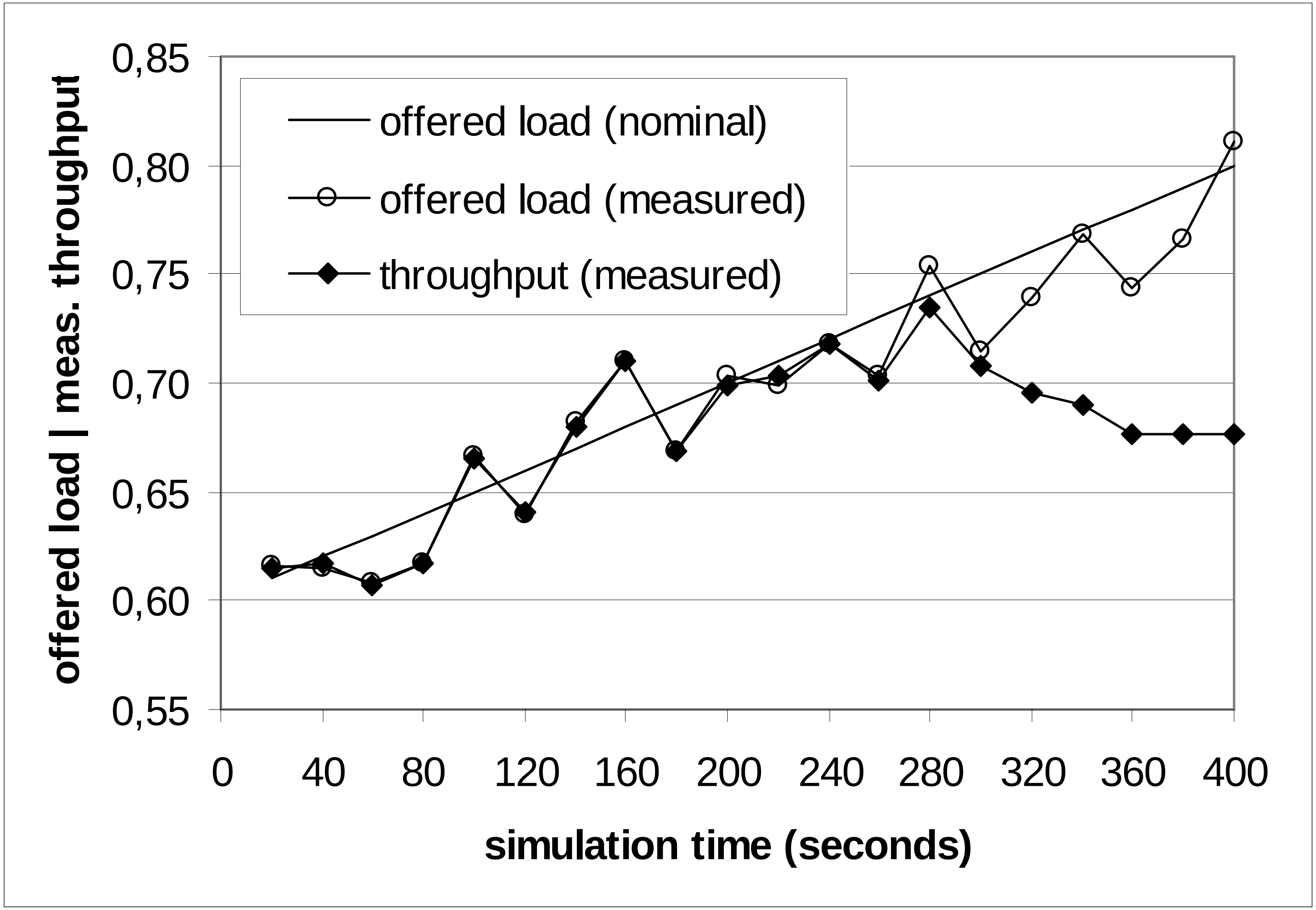


Poor channel, Rate-fallbacked @ 1mbps ☺

Throughput Bounds

question: what is the maximum achievable throughput when N stations compete, assuming we can optimally tune their access parameters?

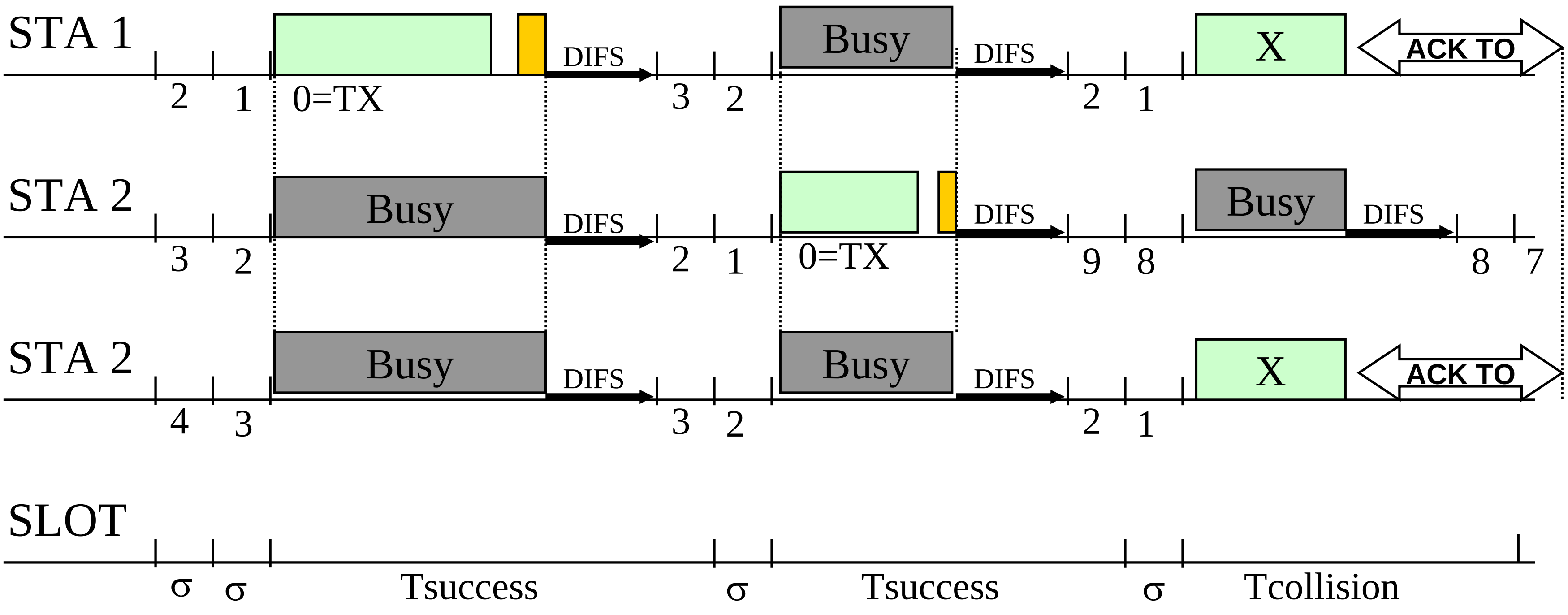
Concept of saturation throughput



Modeling framework

➔ **An external observer may see a slotted time scale!!**

⇨ Understood this, all the rest is straightforward



Minor approximations

- Colliding stations might not be perfectly sync (depends on ACK-TO)
- Not a real issue when N gets large (2 colliding stations, N-2 listening)

Key probabilities

➔ **Assume that each station independently transmits in a slot with same probability τ. Then**

$$P_{idle} = (1-\tau)^n \longrightarrow \sigma$$

$$P_{success} = n\tau(1-\tau)^{n-1} \longrightarrow \text{Tsuccess}$$

$$P_{coll} = 1 - P_{idle} - P_{success} \longrightarrow \text{Tcollision}$$

Maximum Saturation Throughput

$$S = \frac{P_{success} E[P]}{E[slot]} = \frac{P_{success} E[P]}{P_{idle}\sigma + P_{success} T_s + \left(1 - P_{idle} - P_{success}\right) T_c} =$$

$$= \frac{E[P]}{T_s + \sigma \frac{P_{idle} + T_c^* \left(1 - P_{idle} - P_{success}\right)}{P_{success}}} =$$

For τ value that maximizes the above expression

$$\left(1 - \tau_{\max}\right)^N - T_c^* \left\{ N\tau_{\max} - \left(1 - \left(1 - \tau_{\max}\right)^N\right) \right\} = 0$$

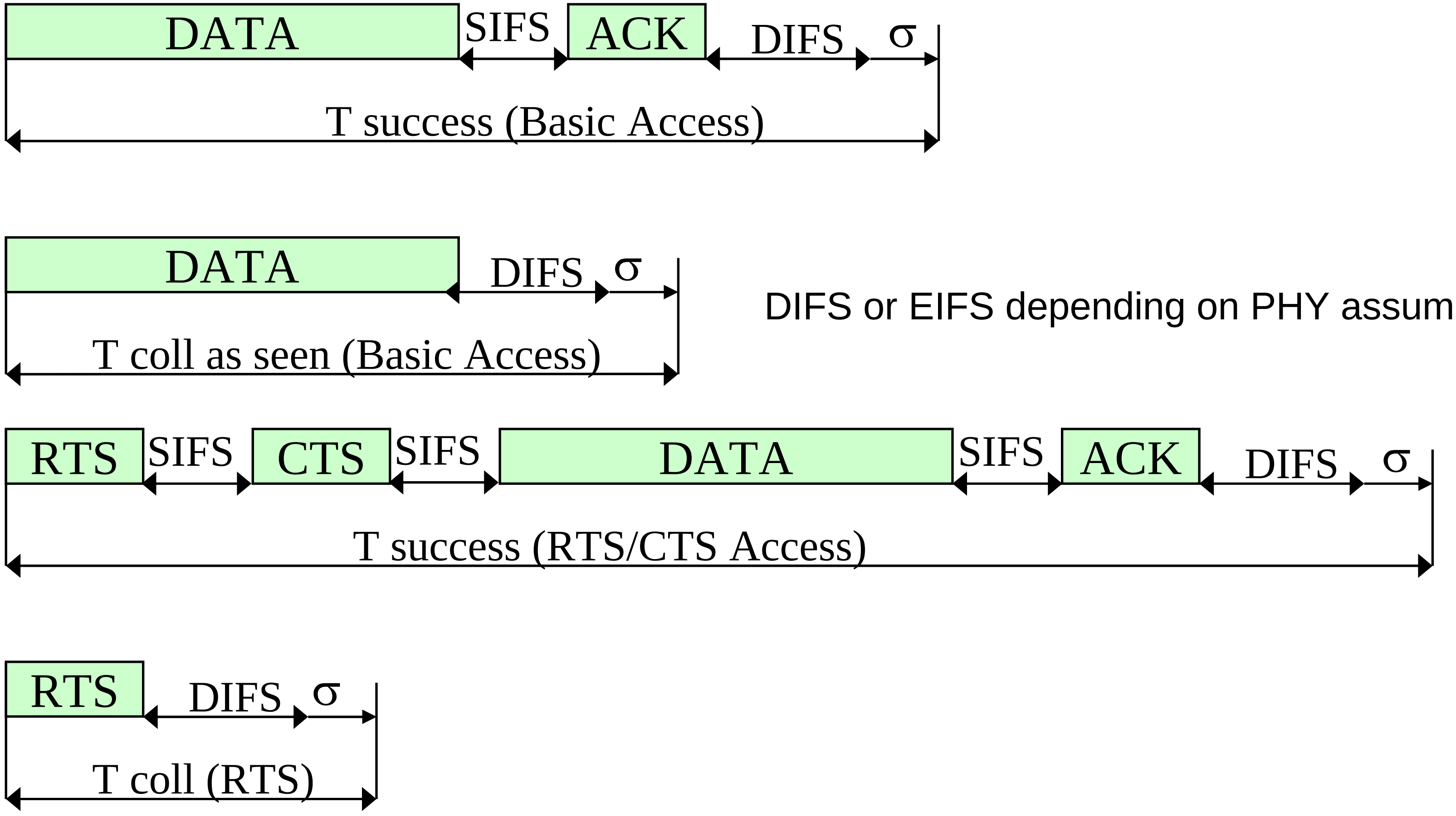
Optimal τ (approx)

$$\tau_{\max} = \frac{\sqrt{1 + 2\left(T_c^* - 1\right)\frac{(N-1)}{N}} - 1}{(N-1)\left(T_c^* - 1\right)} \approx \frac{1}{N\sqrt{T_c^* / 2}}$$

$$\tau_{\max} = \frac{1}{1 + CW_{opt} / 2}$$

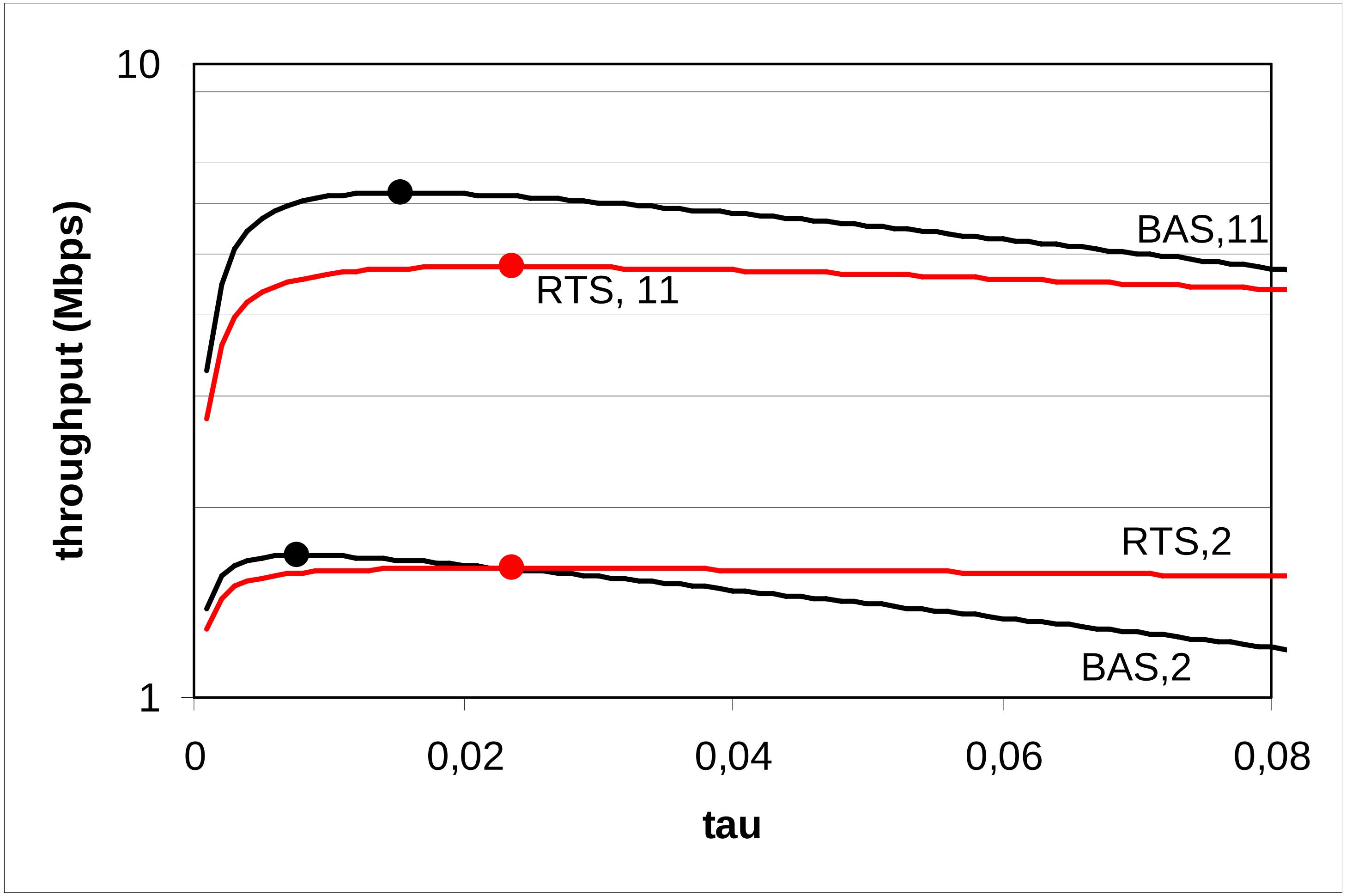
$$CW_{opt} \approx 2N\sqrt{T_c^* / 2} - 2 \approx N\sqrt{2T_c^*}$$

Ts, Tc



DIFS or EIFS depending on PHY assumptions

802.11b max performance
(N=10)



Max sustainable performance marginally depends on N

$$K = \sqrt{T_c^* / 2}$$

$$\lim_{N\to\infty} S_{\max} = \lim_{N\to\infty} \frac{E[P]}{T_s + \sigma \dfrac{P_{idle} + T_c^*\left(1 - P_{idle} - P_{success}\right)}{P_{success}}} =$$

$$= \lim_{N\to\infty} \frac{E[P]}{T_s + \sigma \dfrac{(1-\tau_{\max})}{N\tau_{\max}} - T_c + T_c \dfrac{\left(1-(1-\tau_{\max})^N\right)}{N\tau_{\max}(1-\tau_{\max})^{N-1}}} =$$

$$= \frac{E[P]}{T_s + \sigma K - T_c(1 + K - Ke^{1/K})}$$

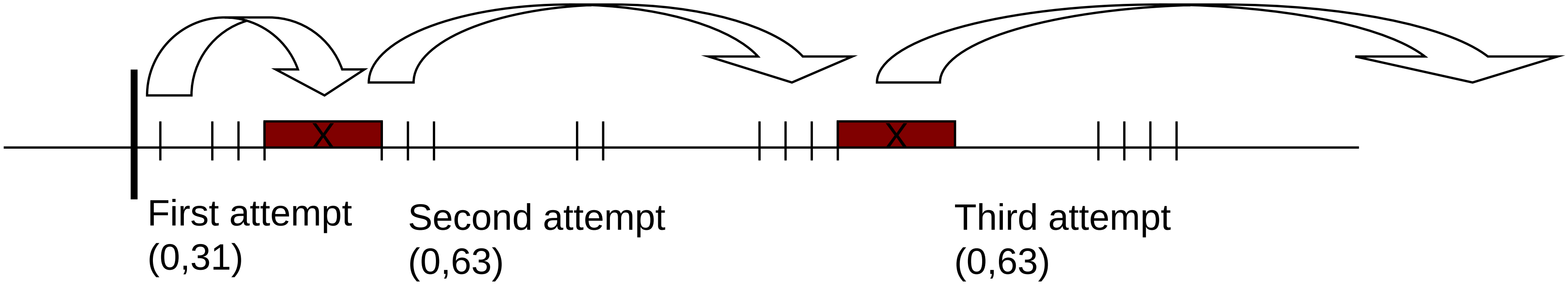
2 Mbps case: BAS=1.669 RTS/CTS=1.596 Mbps
11 Mbps case: BAS=6.210 RTS/CTS=4.763

Saturation Throughput Analysis

question: what is the maximum achievable throughput when N stations compete <u>using the standard parameters and exponential backoff?</u>

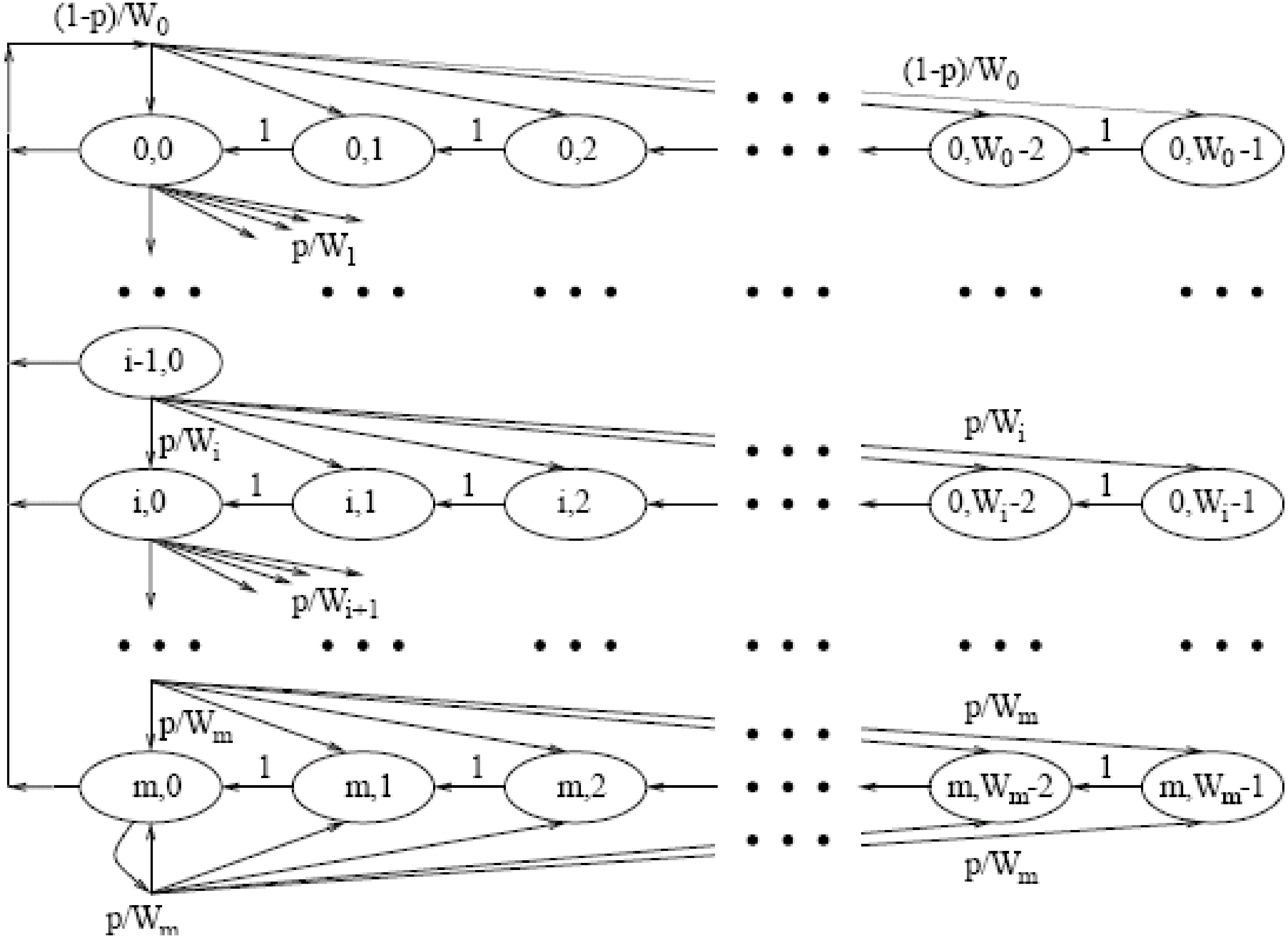
Key idea: decouple

focus on a single “tagged” stations

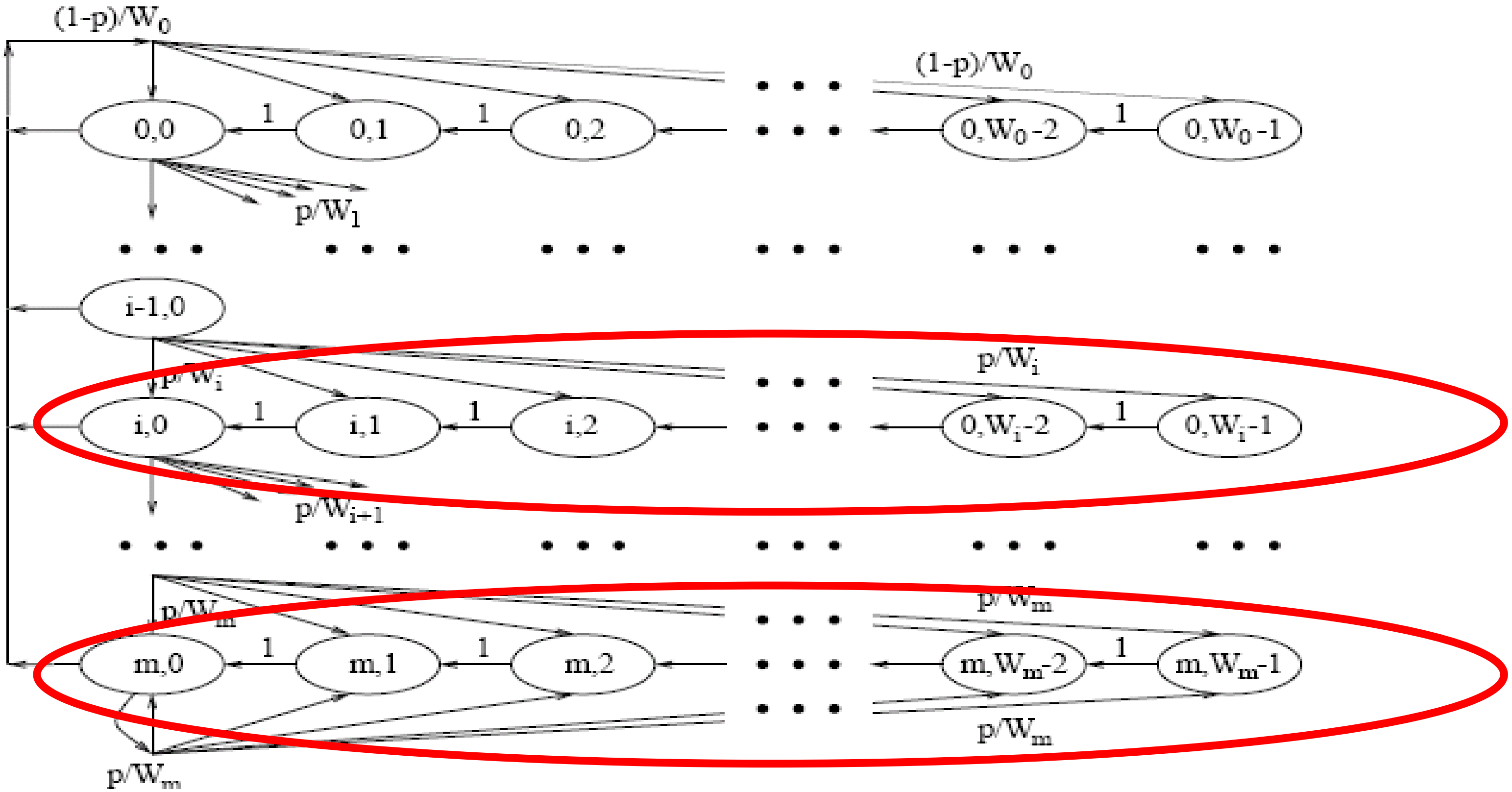


Key assumption:
assume that the conditional collision probability is the same, p (unknown), regardless of the Number of previous attempts

Bidimensional Markov Chain
(unlimited retries case)



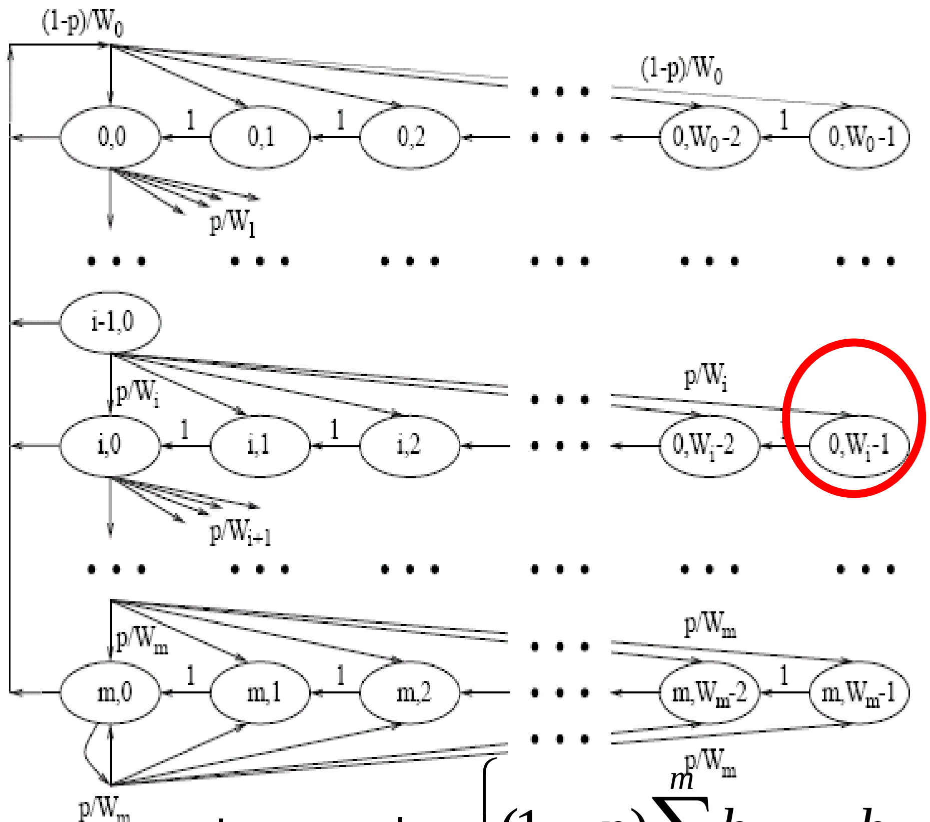
Markov Chain Solution / 1



$$b_{i-1,0}\,p = b_{i,0}\,(p + (1-p)) = b_{i,0} \quad \rightarrow \quad b_{i,0} = p^i b_{0,0}$$

$$b_{m-1,0}\,p = b_{m,0}(1-p) \quad \rightarrow \quad b_{m,0} = \frac{p^m}{1-p} b_{0,0}$$

Markov Chain Solution / 2



$$b_{i,W_i-1} = p\frac{1}{W_i}b_{i-1,0} = p\frac{W_i-(W_i-1)}{W_i}b_{i-1,0}$$

$$b_{i,W_i-2} = p\frac{2}{W_i}b_{i-1,0} = p\frac{W_i-(W_i-2)}{W_i}b_{i-1,0}$$

$$b_{i,k} = p\frac{k}{W_i}b_{i-1,0} = p\frac{W_i-k}{W_i}b_{i-1,0}$$

In general:

$$b_{i,k} = \frac{W_i-k}{W_i}\cdot\begin{cases}(1-p)\sum_{j=0}^{m} b_{j,0} = b_{0,0} & i=0\\ pb_{i-1,0} = b_{i,0} & 0<i<m\\ pb_{m-1,0}+pb_{m,0} = b_{m,0} & i=m\end{cases} \quad \Rightarrow b_{i,k} = \frac{W_i-k}{W_i}b_{i,0}$$

Markov Chain Solution / 3

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} = \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2} =$$

$$= \frac{b_{0,0}}{2} \left[W \left(\sum_{i=0}^{m-1} (2p)^i + \frac{(2p)^m}{1-p} \right) + \frac{1}{1-p} \right]$$

from which:

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

Transmission probability

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

➔**Result:**

⇨ We have expressed the transmission probability τ versus the conditional collision probability p

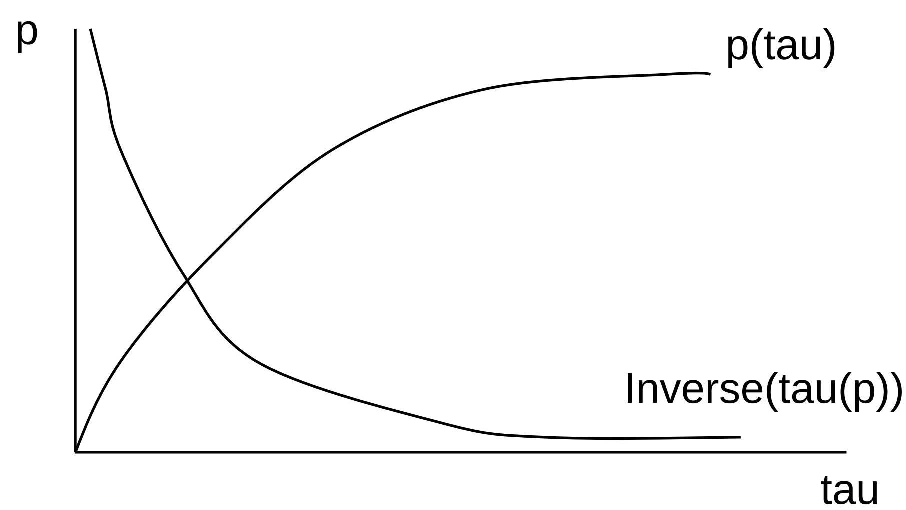
⇨ To solve the problem we need to find an explicit value for p

Conditional collision probability & final solution

- ➔ **Easy!**
  - ⇨ p = probability that another of the n-1 stations transmit in my same selected slot → p(τ)

$$p = 1 - (1 - \tau)^{n-1}$$

- ➔ **2 non linear equations in 2 unknown**
  - ⇨ Unique solution
    - → Thanks to the monotonicity of the involved functions



Throughput analysis

» Same as throughput bound, but with actually computed τ value

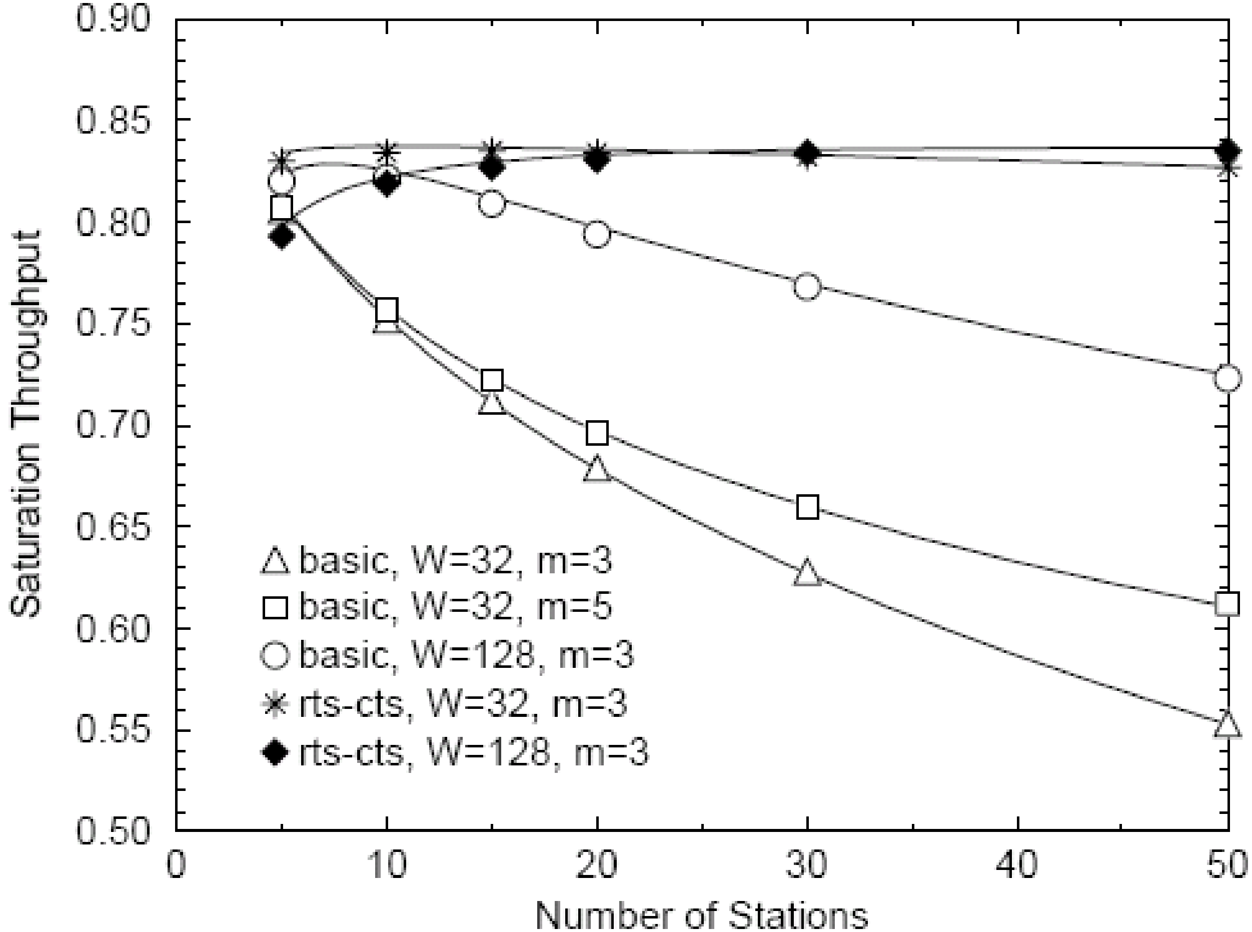
$$P_{idle} = (1-\tau)^n \longrightarrow \sigma$$

$$P_{success} = n\tau(1-\tau)^{n-1} \longrightarrow \text{Tsuccess}$$

$$P_{coll} = 1 - P_{idle} - P_{success} \longrightarrow \text{Tcollision}$$

$$S = \frac{P_{success}E[P]}{E[slot]} = \frac{P_{success}E[P]}{P_{idle}\sigma + P_{success}T_s + (1 - P_{idle} - P_{success})T_c}$$

Analysis vs simulation



Average Delay

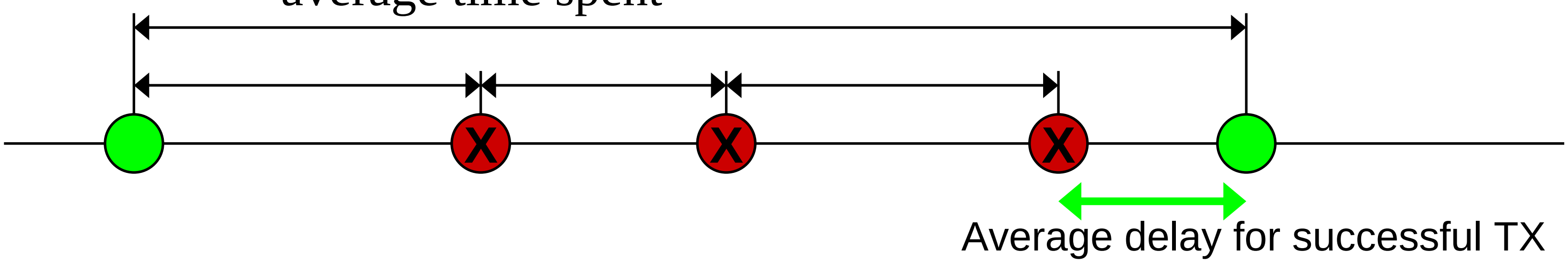
- **Trivial to determine in the case of unlimited retries**
  - By Little's formula: $$D = \frac{N}{S/E[P]}$$

- **More elaborated derivation when retry limit R**
  - But still, intuitive final result:

$$D = \frac{N}{S/E[P]} - E[slot]\frac{p^{R+1}}{1-p^{R+1}}\sum_{i=0}^{R}\left(1+E[b_i]\right)$$

→First term = Little's Result = average inter-departure time between two <u>**successfully delivered**</u> frames.

→Second term = average number of dropped frames multiplied by average time spent



Saturation Throughput Analysis: Alternative formulation

Much simpler, more general

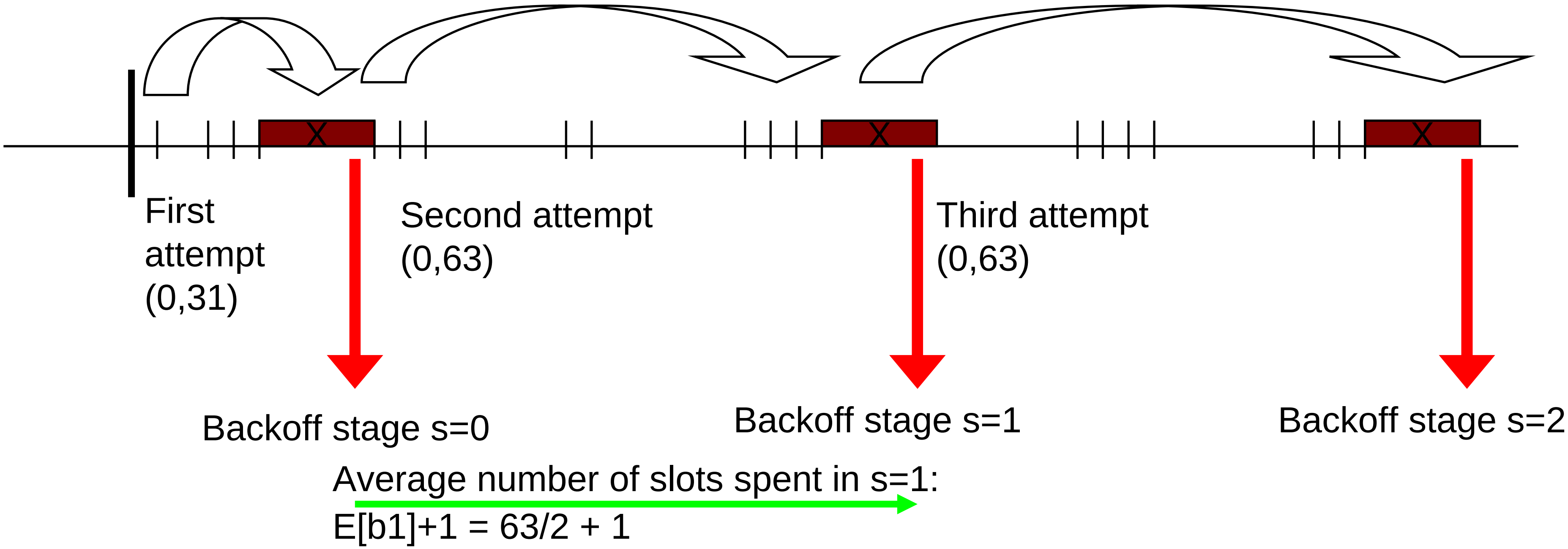
Motivation

- **A simple solution, but a complex markov chain formulation**
  - Experience shows that in most cases (but not all ☺) simple results have simple demonstration
- **The Markov chain rows and columns are solved in a decoupled manner**
  - There must be some underlying physical reason

- **Question: is there an alternative approach to derive the same equations?**

Backoff stage model

- **Condition to the instants of transmission**
  - Two distinct components:
    - Backoff stage
    - No. slots spent in a given stage

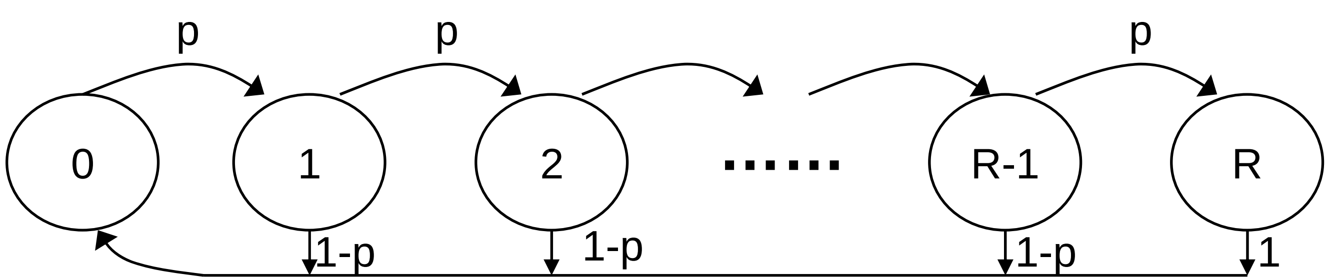


Backoff stage probability

- **Trivially described by an elementary geometric distribution!**
  - Eventually truncated if a max retry limit R is considered (as in the 802.11 standard)

$$P\{s = i \mid TX\} = \frac{1-p}{1-p^{R+1}} p^i$$

- **Trivial generalization to different backoff process models**
  - Just replace "geometric" markov chain with more elaborated one



Putting all together / 1

- Transmission probability looked for: $\tau = P\{TX\}$

- Bayes' Theorem: $P\{TX\} = \dfrac{P\{TX \mid Event\}}{P\{Event \mid TX\}} P\{Event\}$

- Event = prob. being in stage i $P\{TX\} \dfrac{P\{s=i \mid TX\}}{P\{TX \mid s=i\}} = P\{s=i\}$

- Sum for all stages $P\{TX\} \sum_{i=0}^{R} \dfrac{P\{s=i \mid TX\}}{P\{TX \mid s=i\}} = \sum_{i=0}^{R} P\{s=i\} = 1$

$$\Rightarrow \quad P\{TX\} = \frac{1}{\sum_{i=0}^{R} \dfrac{P\{s=i \mid TX\}}{P\{TX \mid s=i\}}}$$

Putting all together / 2

$$P\{s=i \mid TX\} = \frac{1-p}{1-p^{R+1}} p^i$$

$$P\{TX \mid s=i\} = \frac{1}{1+E[b_i]}$$

$$\tau = \frac{1}{\sum_{i=0}^{R} \frac{1-p}{1-p^{R+1}} p^i \left(1+E[b_i]\right)}$$

This is the same as before…

- **R=infinity**
- **Backoff windows:**
  - W=CWmin+1
    - $E[b_0]=(W-1)/2$
    - $E[b_1]=(2W-1)/2$
      - …
    - $E[b_i]=(2^iW-1)/2$
      - …
    - $E[b_m]=(2^mW-1)/2$
    - $E[b_{m+1}]=(2^mW-1)/2$
      - …

$$\tau = \frac{1}{\sum_{i=0}^{R} \frac{1-p}{1-p^{R+1}} p^i \left(1+E[b_i]\right)} =$$

$$= \frac{1}{(1-p)\left[\sum_{i=0}^{m} p^i \frac{2^i W+1}{2} + \sum_{i=m+1}^{\infty} p^i \frac{2^m W+1}{2}\right]} =$$

$$= \frac{2(1-2p)}{1-2p+W-Wp-2^m p^{m+1} W} =$$

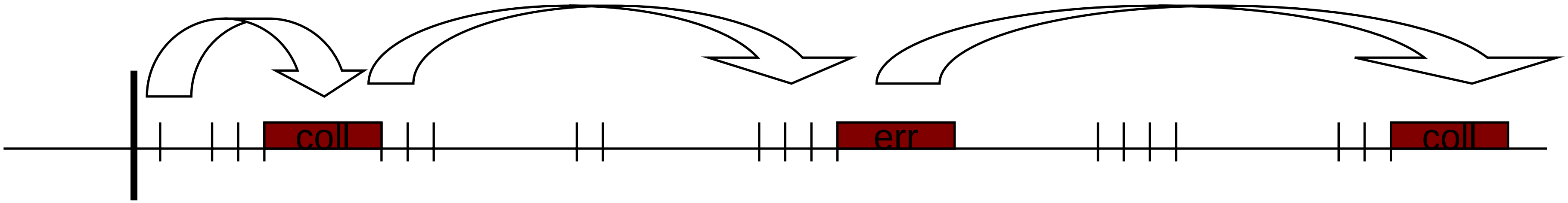
$$= \frac{2(1-2p)}{(1+W)(1-2p)+Wp(1-(2p)^m)}$$

…but cleaner and easy to extend

- ➔ **Plug your backoff stage model**
  - ⇨ If different than a geometric one
- ➔ **Plug your average backoff window values**
  - ⇨ Note the insensitivity with respect to the backoff distribution!
- ➔ **And get the tau(p) equation needed to compute the throughput**

Error-prone channel

- ➔ **802.11 does NOT distinguish collision from wireless error**
  - ⇨ No ACK → Retransmit



- ➔ **Trivial extension if we assume:**
  - ⇨ Uncorrelated losses
  - ⇨ Constant PER value ζ
  - ⇨ Neglect RTS/CTS/ACK errors
    - →Or include all them in ζ

Error prone channel - eqs

Tau(p) expression remains the same:

$$\tau = \frac{1}{\sum_{i=0}^{R} \frac{1-p}{1-p^{R+1}} p^i \left(1+E\left[b_i\right]\right)}$$

However p now shall include channel errors:

$$p = 1-\left(1-\zeta\right)\left(1-\tau\right)^{n-1}$$

And the throughput computation will also account for channel errors

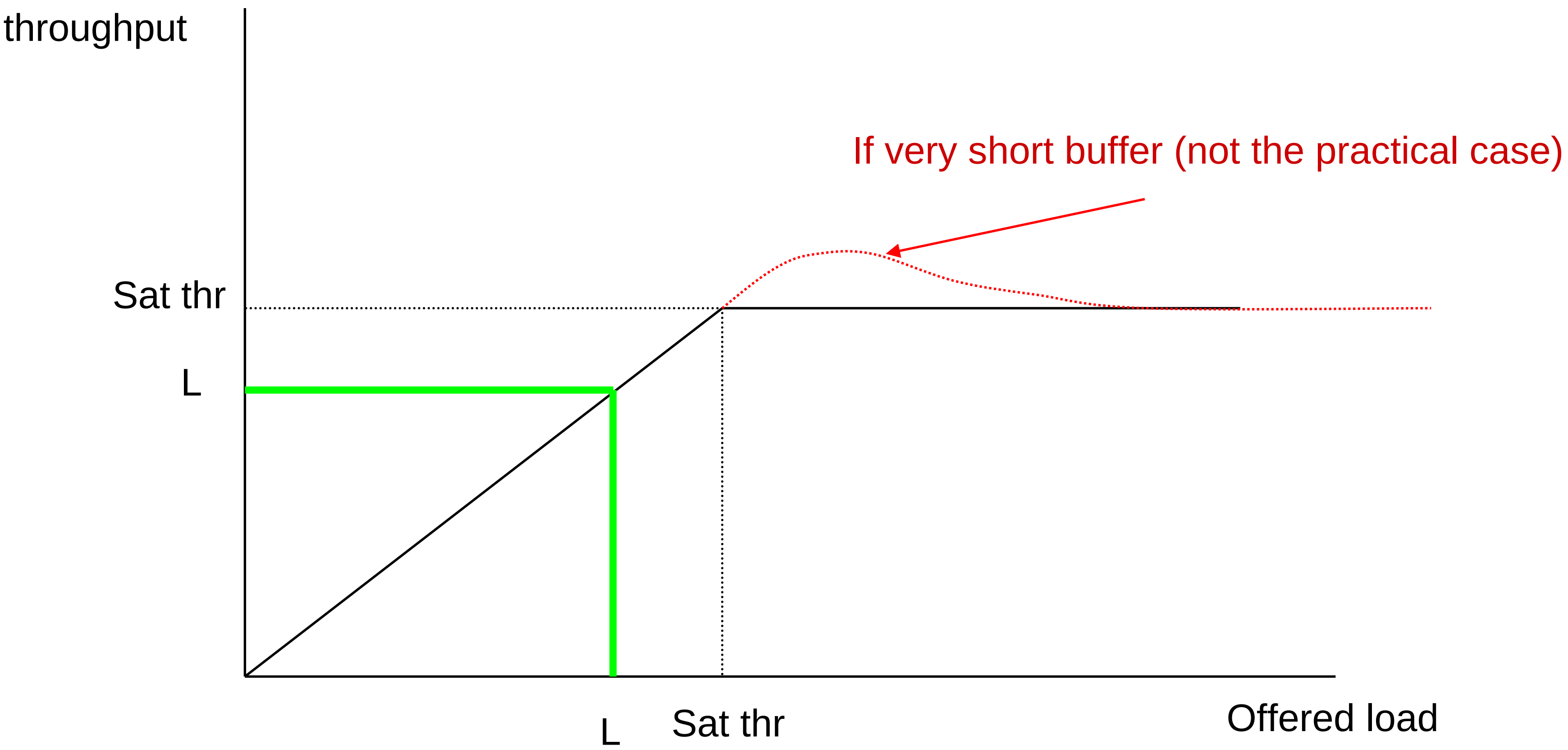
$$S = \frac{\left(1-\zeta\right)P_{success}E[P]}{P_{idle}\sigma + \left(1-\zeta\right)P_{success}T_s + \zeta P_{success}T_e + \left(1-P_{idle}-P_{success}\right)T_c}$$

Extras

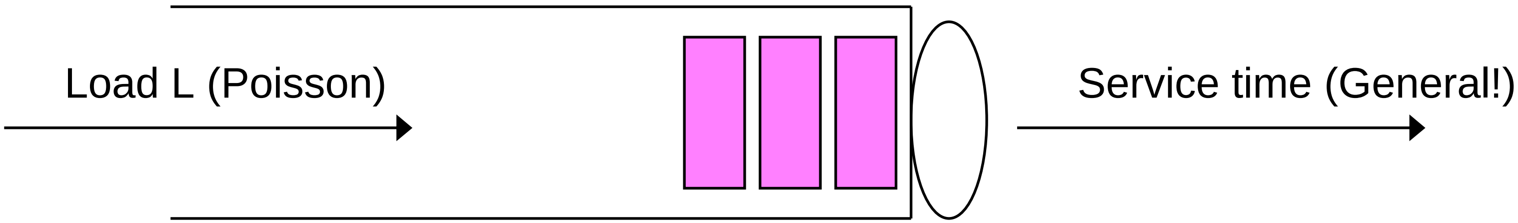
very short (no details)

Non saturation conditions

no need to compute throughput



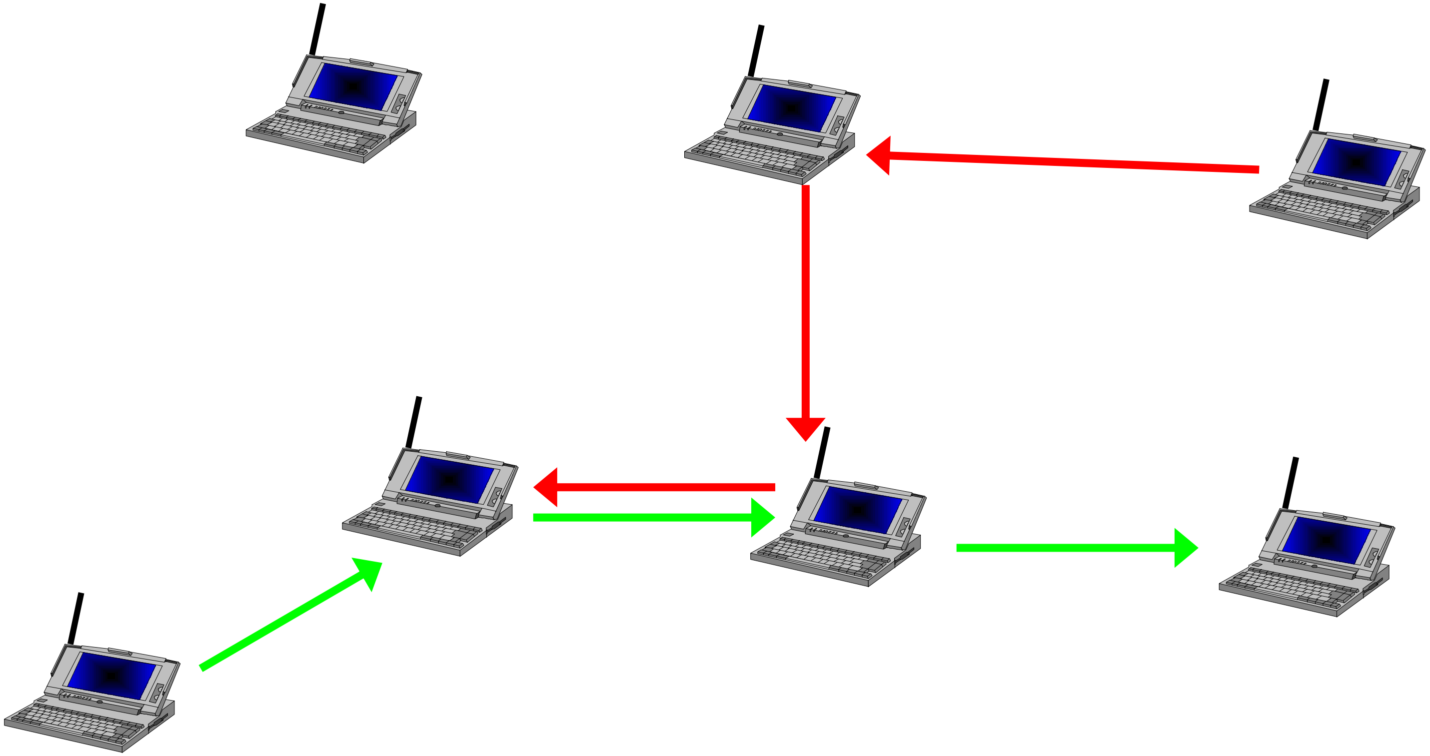
Non saturation conditions delay analysis via M/G/1



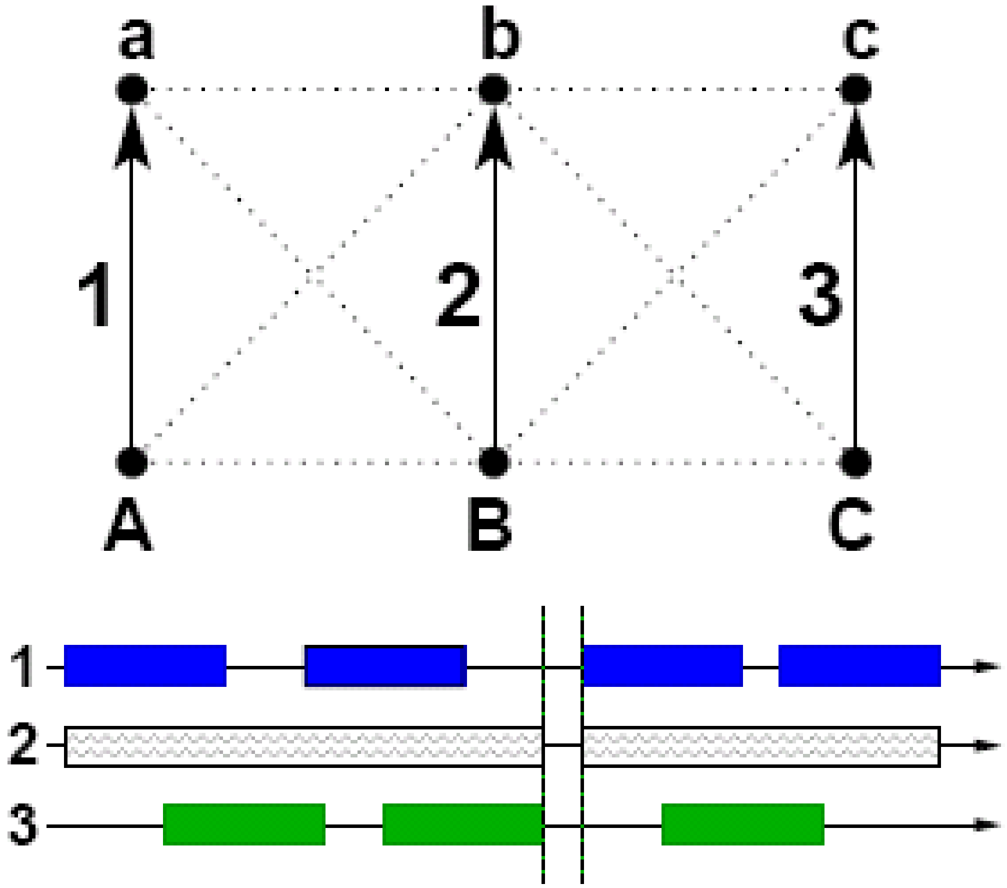
- **Idea:**
  - Compute average and variance of the service time
    - i.e. time needed to transmit the HOL frame
    - Lengthy derivation, but conceptually simple
  - Then use Pollaczek-Khinchin formula to derive average queueing delay
  - Details omissed (refer to literature)

Multihop

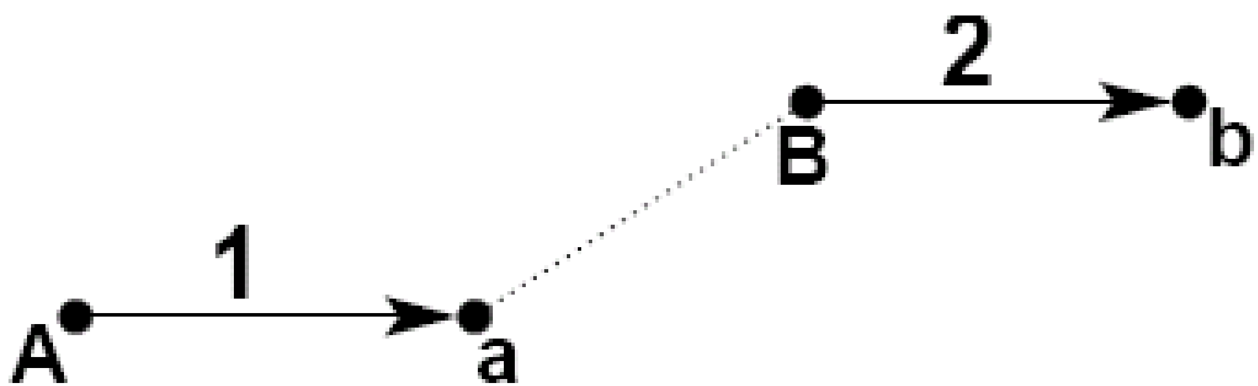
- ➔Ad Hoc networks
- ➔Mesh Networks

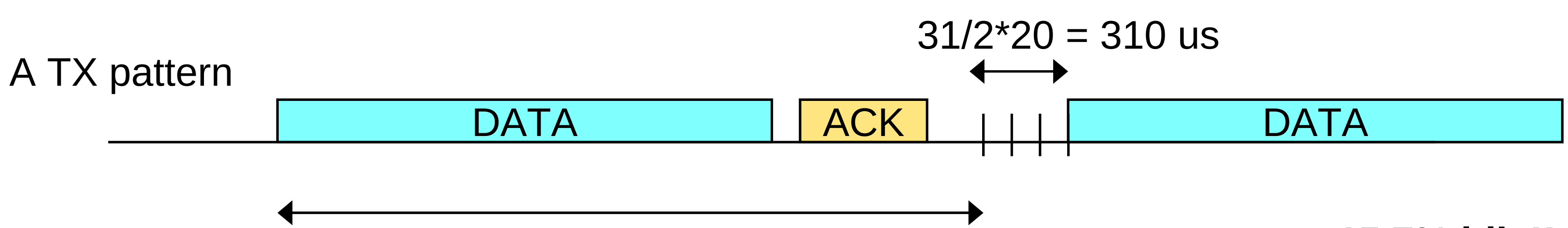


CSMA Pathological behavior of multi-hop scenarios / 1



CSMA Pathological behavior of multi-hop scenarios / 2

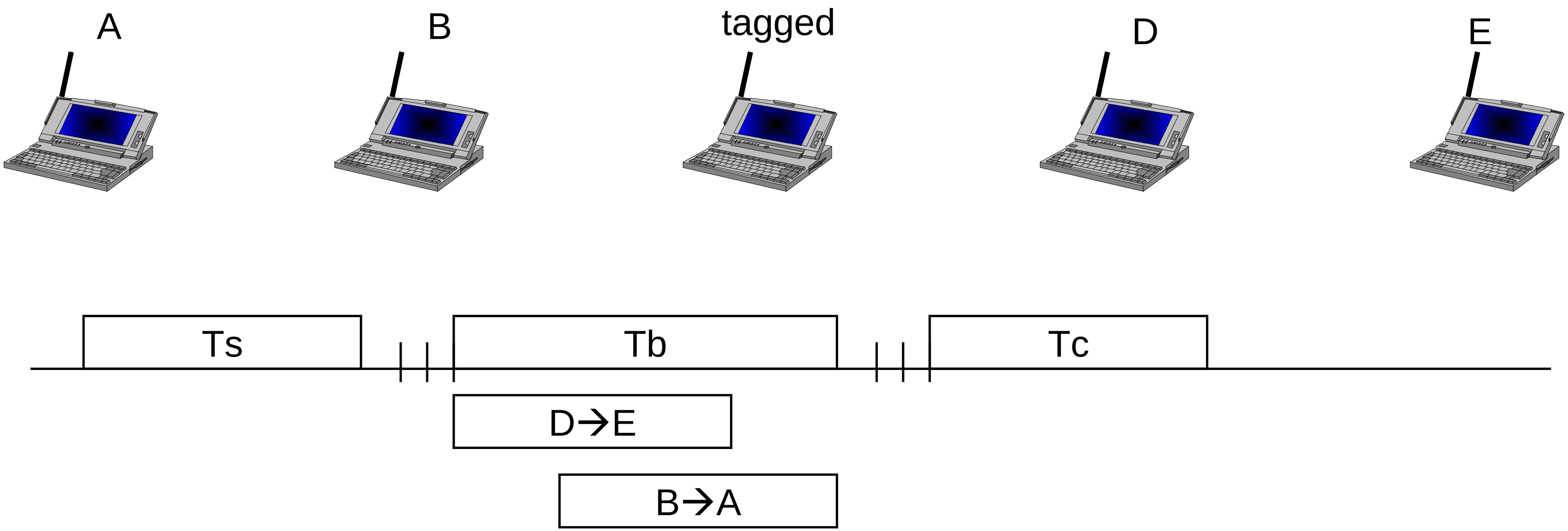




192 + [1500*8+(24+4)*8]/11 + 10 + 192 + 14*8/1 + 50 = 1667.3 us

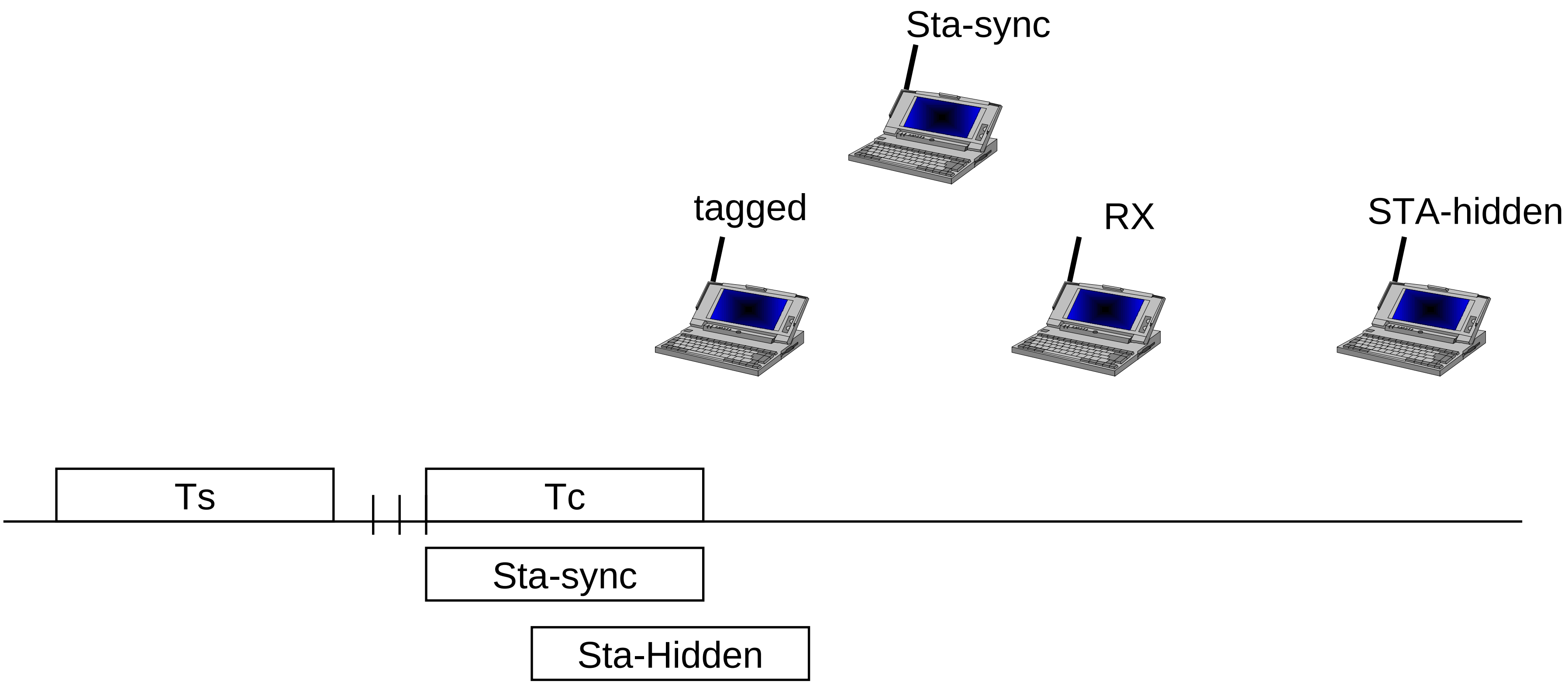
15.7% idle!!

Analysis – key ideas / 1



Tbusy = superposition of mutually hidden stations

Analysis – key ideas / 2



Collision: massive contribution of hidden stations!!

Approaches

- ⇨ Garetto, Salonidis, Knightly, Infocom 06
- ⇨ Medepalli, Tobagi, Infocom 06

➔ **Same decoupling approach**

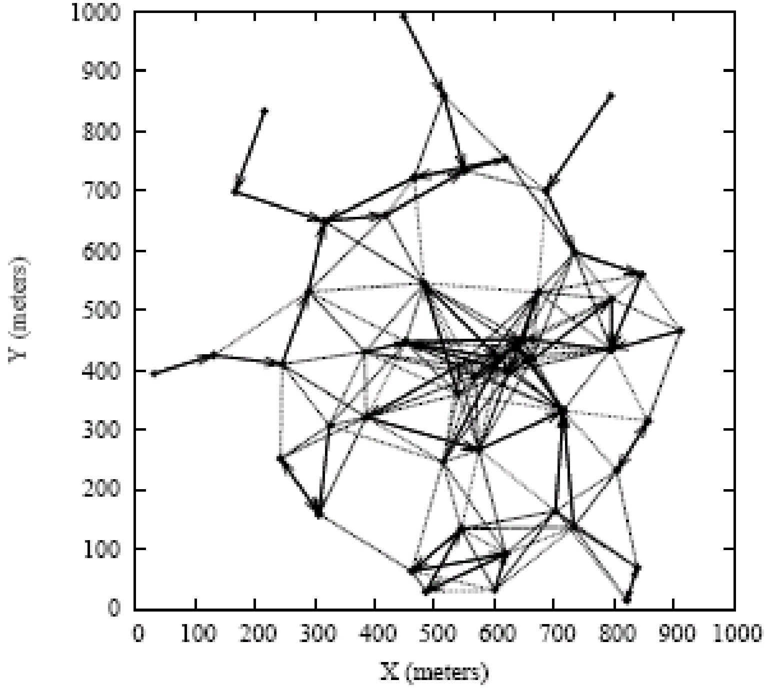
- ⇨ Study the behaviour of a single tagged station
- ⇨ Hence derive a tau(p) equation in a very similar manner of single-hop analysis

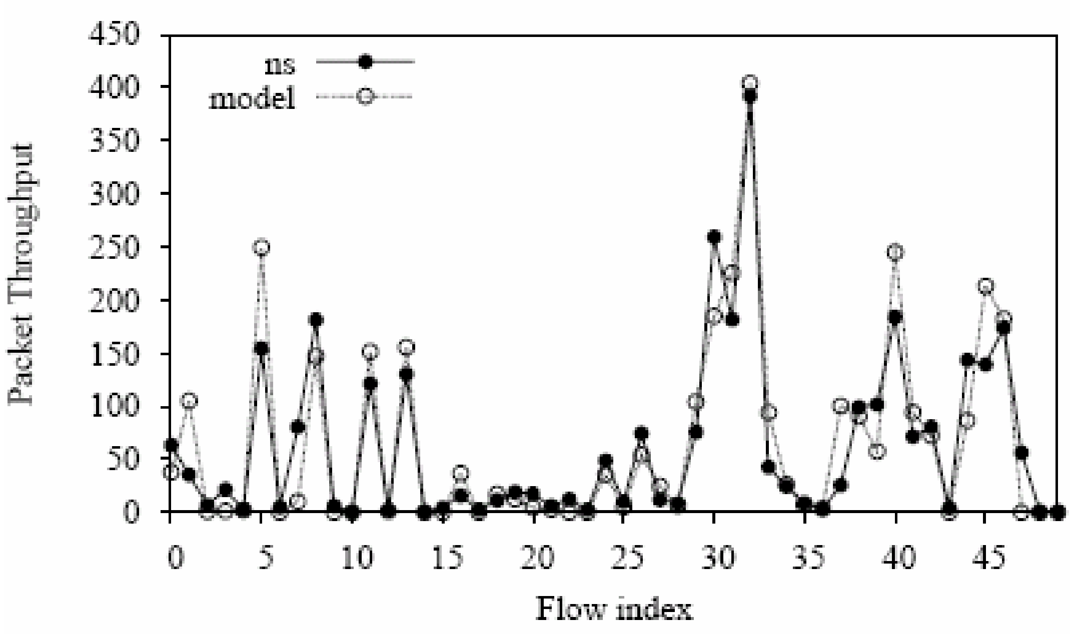
➔ **But formally much more complex**

- ⇨ Collision due to hidden terminals must be modeled through a continuous time analysis
- ⇨ Hidden stations depend on WHO is transmitting/receiving
- ⇨ Parameters (tau_i, p_i) differ for each single station in the networks, depending on topology!
- ⇨ The p(tau) equation and the throughput formulation dramatically changes!
  - → No more "just" a function of tau, but a function of many other probabilities
  - → Must also duly characterize Tbusy: supplementary non linear equations

Results

- **Key insight: throughput results in arbitrary topology networks**
  - Show that CSMA leads to massive intrinsic unfairness





Source: [Garetto-06]