

Bottleneck Analysis in IEEE 802.11e Ad Hoc Networks

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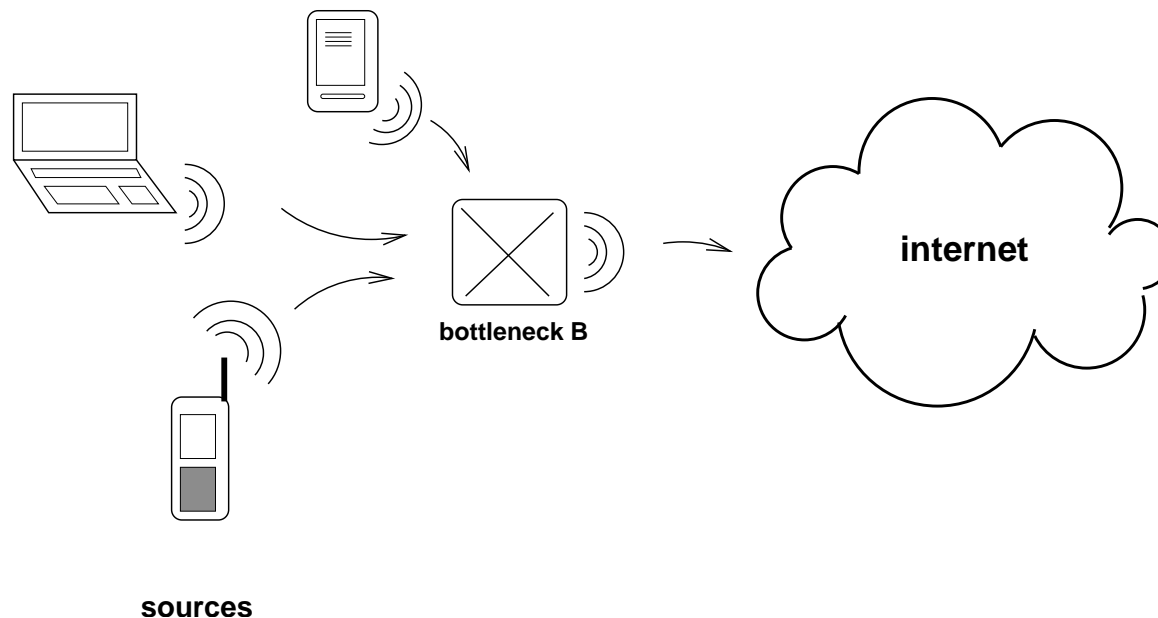
Design and Analysis of Communication Systems

Enschede, the Netherlands

<http://dacs.cs.utwente.nl/>

ad hoc networks

- stations communicate through IEEE 802.11
- all stations contend for the same radio capacity C (pps)
- distributed coordination function (DCF) divides radio capacity
- medium access control based on CSMA/CA

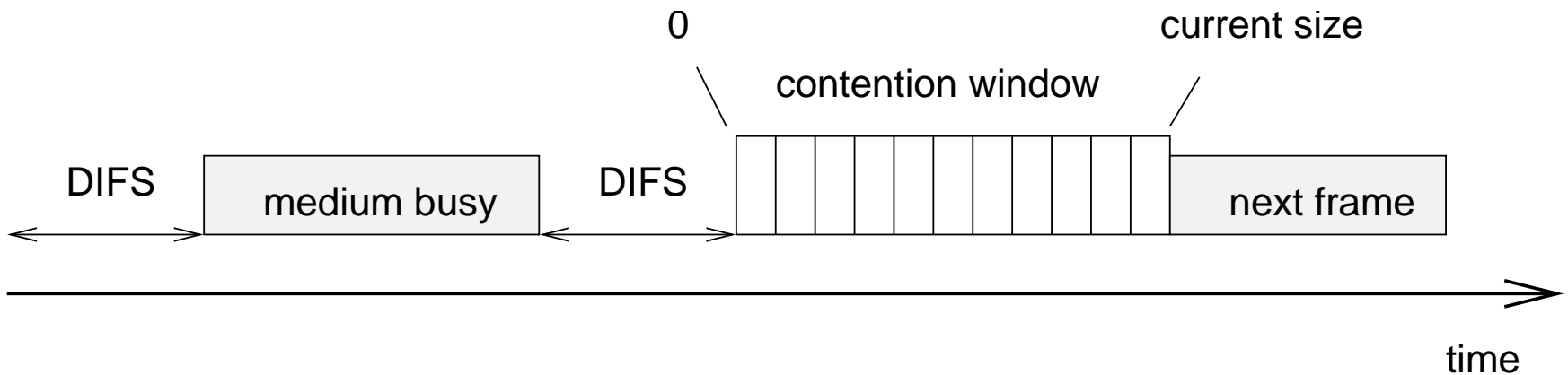


overview

- QoS enhancements in IEEE 802.11e
- bottleneck scenario
- modeling and analysis approach
- bottleneck as iSPN
- introducing a QoS parameter into our model
- results
- conclusions

IEEE 802.11 CSMA/CA

- carrier sense multiple access with collision avoidance
- random access scheme with random backoffs
 - draw random backoff time b within contention window
 - station with the smallest backoff b_{\min} accesses the medium after $\text{DIFS} + b_{\min}$



contention window

- initially: $[0, CW_{\min} - 1]$
- maximum: $[0, CW_{\max} - 1]$
 - $CW_{\max} = 2^{r_{\max}} \cdot CW_{\min}$
- doubles with every collision:

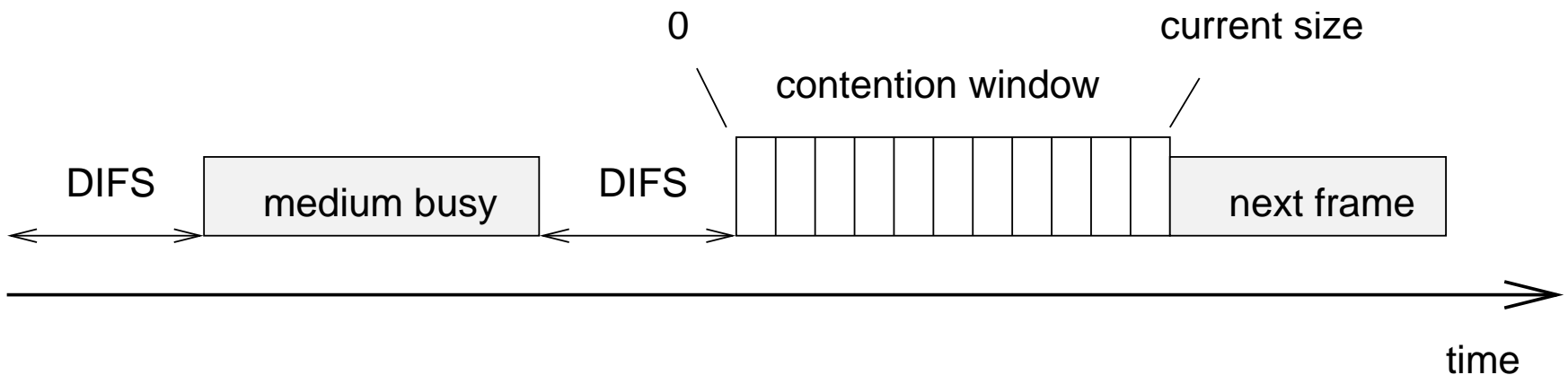
$$CW(i) = \begin{cases} 2^i \cdot CW_{\min}, & i < r_{\max}, \\ 2^{r_{\max}} \cdot CW_{\min}, & i \geq r_{\max}. \end{cases}$$

bottleneck

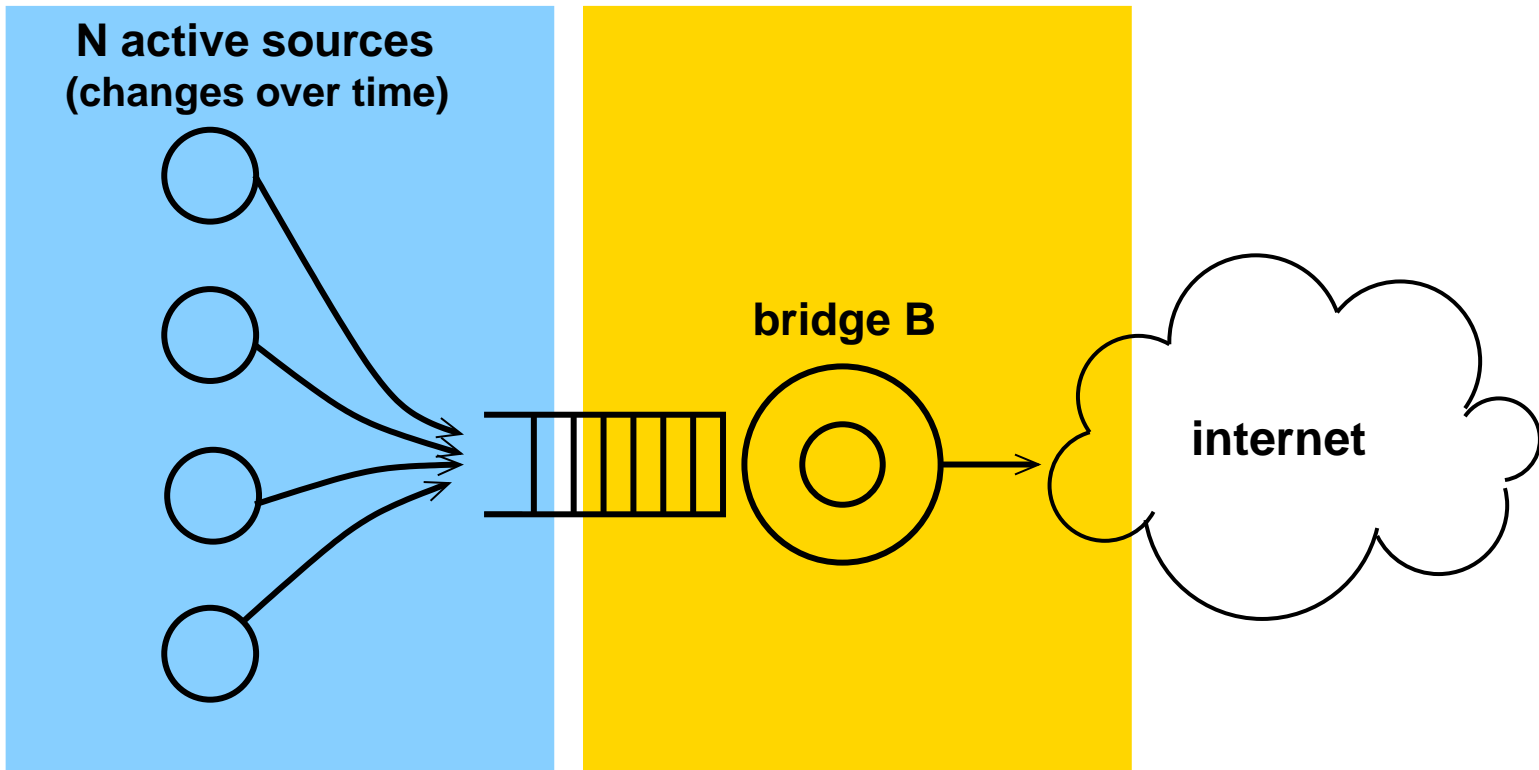
- access mechanism effectively equally shares capacity over active nodes
 - benefits the sources
 - may lead to very high buffer occupancy (in B)
 - bottleneck arises in multi-hop networks
- adaptive capacity sharing strategies
 - divide radio capacity in a smarter way
 - keep buffer content low
 - yield better throughputs in B

QoS enhancement: IEEE 802.11e

- adaptive capacity sharing is made possible with differentiation parameters
 - arbitrary inter frame spacing (AIFS)
 - initial value of contention window (CW_{min})
 - maximum value of contention window (CW_{max})
 - transmission opportunity limit ($TXOP_{limit}$)
- other possibilities for adaptive capacity sharing?
 - ⇒ start access mechanism for each supported flow



bottleneck scenario



overview

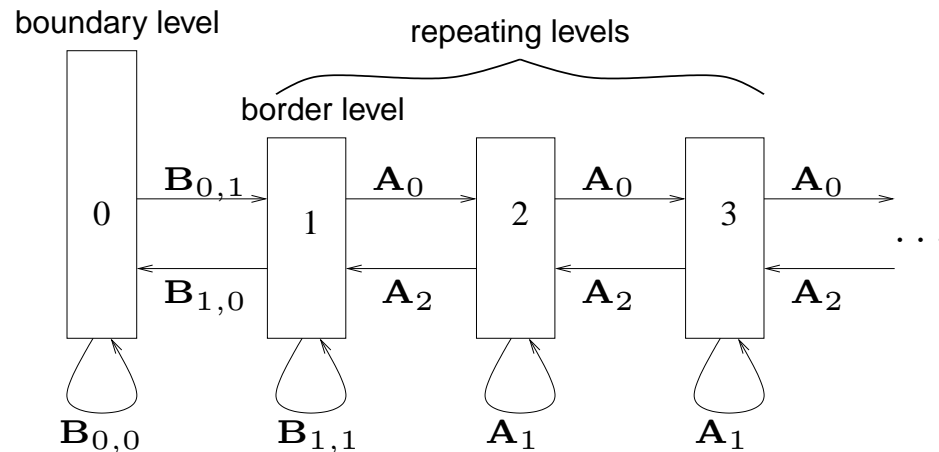
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modeling and analysis approach

- models are infinite state stochastic Petri nets (iSPNs)
 - high level specification with modeling flexibility
 - have underlying QBD structure (automatically derived)
- measures are expressed using CSRL (continuous stochastic reward logic)
- fully automatic evaluation with new model checking algorithms for CSRL on QBDs (not presented here)
- measures of interest
 - expected buffer occupancy
 - expected number of active sources

labeled QBD with rewards

- infinite-state CTMCs, infinite countable set of states S
- generator matrix $Q : S \times S \rightarrow \mathbb{R}$
- labeling function $L : S \rightarrow 2^{AP}$ (atomic propositions)
- reward function $R : S \rightarrow \mathbb{R}^+$
- repeating levels have similar transition structure



measures of interest

- firm specification through logic CSRL
 - specification formalism for performability measures with time and reward bound

$$\Phi ::= tt \mid ap \mid \neg\Phi \mid \Phi \wedge \Phi \mid \mathcal{S}_{\bowtie p}(\Phi) \mid \mathcal{P}_{\bowtie p}(\phi) \mid \mathcal{E}_{\bowtie r}(\Phi)$$

- where ϕ is a path formula constructed by

$$\phi ::= \mathcal{X}_{\leq r}^{\leq t} \Phi \mid \Phi \mathcal{U}_{\leq r}^{\leq t} \Phi$$

- automatic evaluation with model checking algorithms

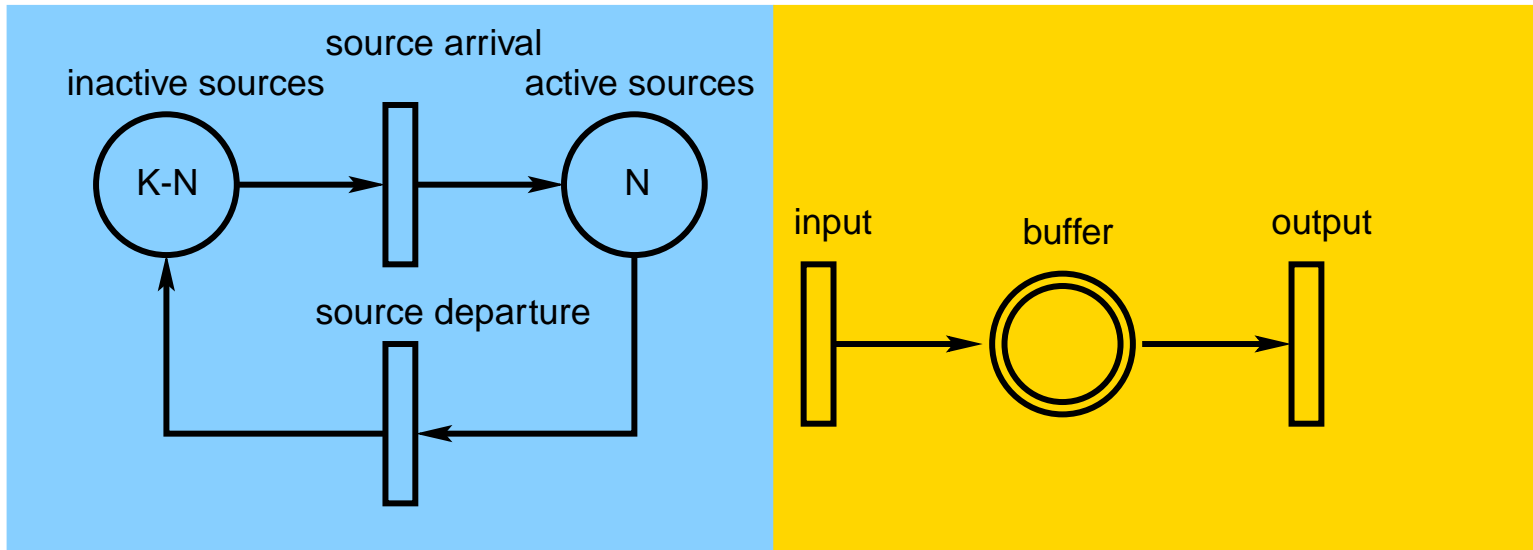
buffer occupancy and active sources

- expressed using the *expected reward operator*
- use $\mathcal{E}_{\Delta r}(\Phi)$, where Φ is *true*
- expected buffer occupancy:
 - reward \leftarrow number of packets currently in the buffer
 - \rightarrow level-dependent reward
- expected number of active sources:
 - reward \leftarrow number of active sources
 - \rightarrow level-independent reward

overview

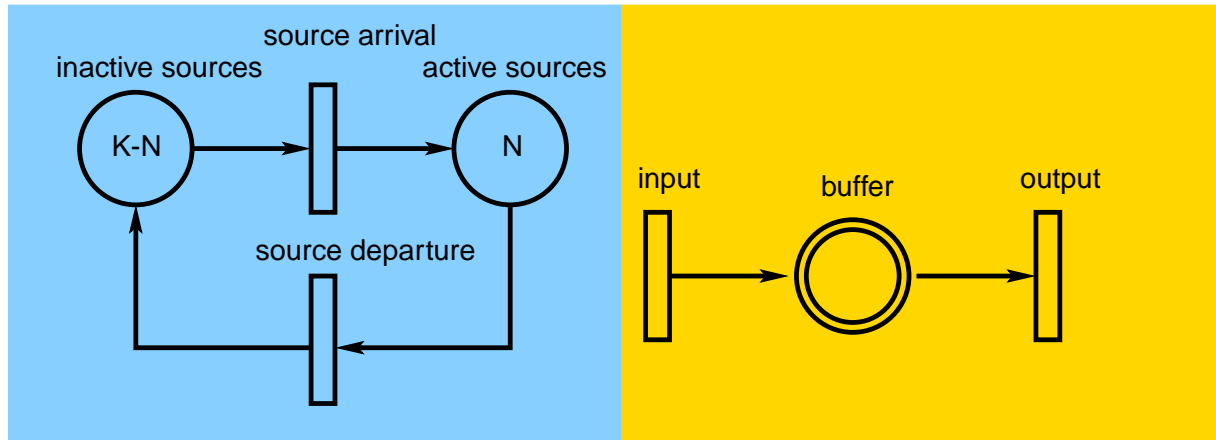
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a generic iSPN for the bottleneck



- maximum number of sources K (res. restriction)
- an inactive source
 - becomes active after Neg. Exp. (λ)
 - immediately instantiates a flow
 - active during *flow time*
 - flow time depends on flow length (packets) and acquired capacity

transitions in the iSPN



input:

```

if  $N = 0$  then
    return 0;
else if  $B = 0$  then
    return  $C$ ;
else
    return  $C \cdot s_i(\cdot)$ ;
end if
    
```

output:

```

if  $B = 0$  then
    return 0;
else if  $N = 0$  then
    return  $C$ ;
else
    return  $C \cdot b_i(\cdot)$ ;
end if
    
```

source departure:

```

if  $B = 0$  then
    return  $C/E[F]$ ;
else
    return  $C \cdot s_i(\cdot)/E[F]$ ;
end if
    
```

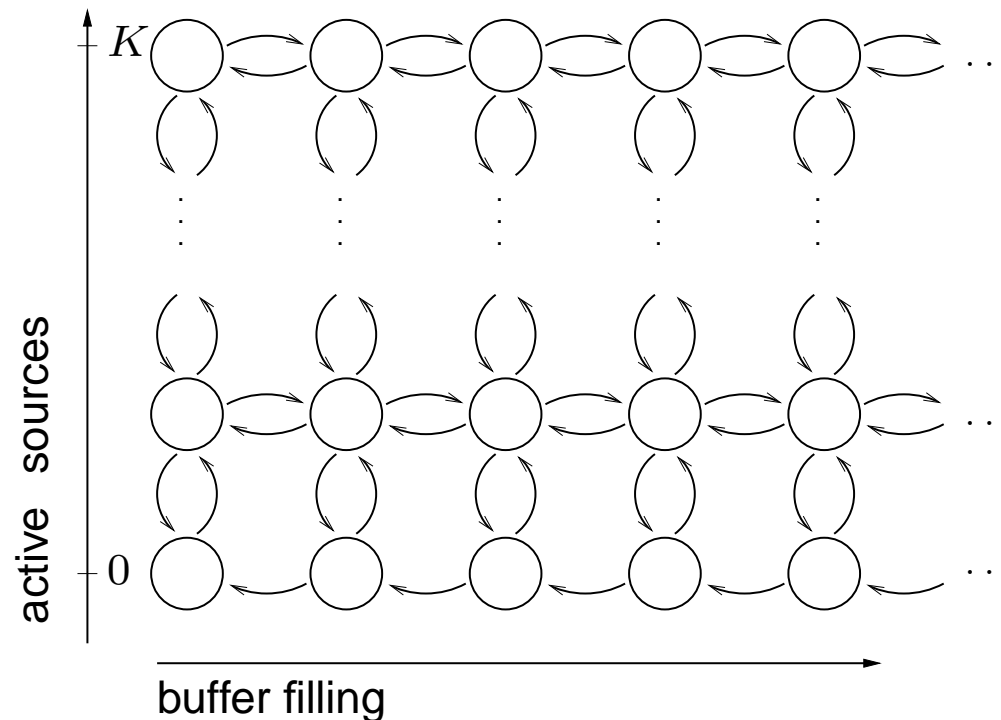
⇒ capacity sharing is introduced via $b_i(\cdot)$ and $s_i(\cdot)$

basic IEEE 802.11

- access mechanism equally shares capacity:

- $b_{\text{basic}}(N) = \frac{1}{(N+1)}$

- $s_{\text{basic}}(N) = \frac{N}{(N+1)}$

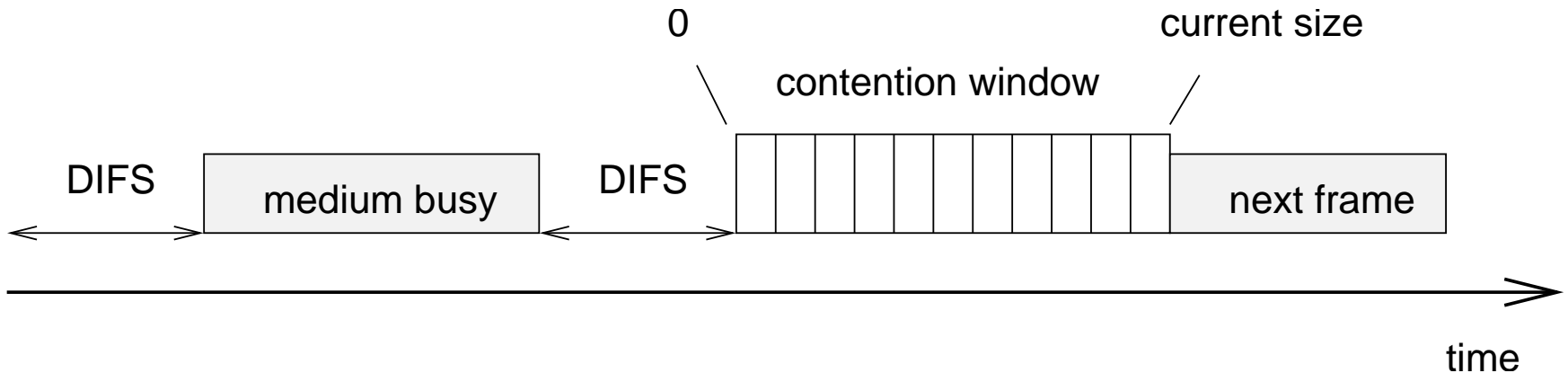


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AIFS

- every station may have its own AIFS
- shorter AIFS leads to faster medium access
- the effect of AIFS depends on the current window size
 - window size depends on the number of collisions



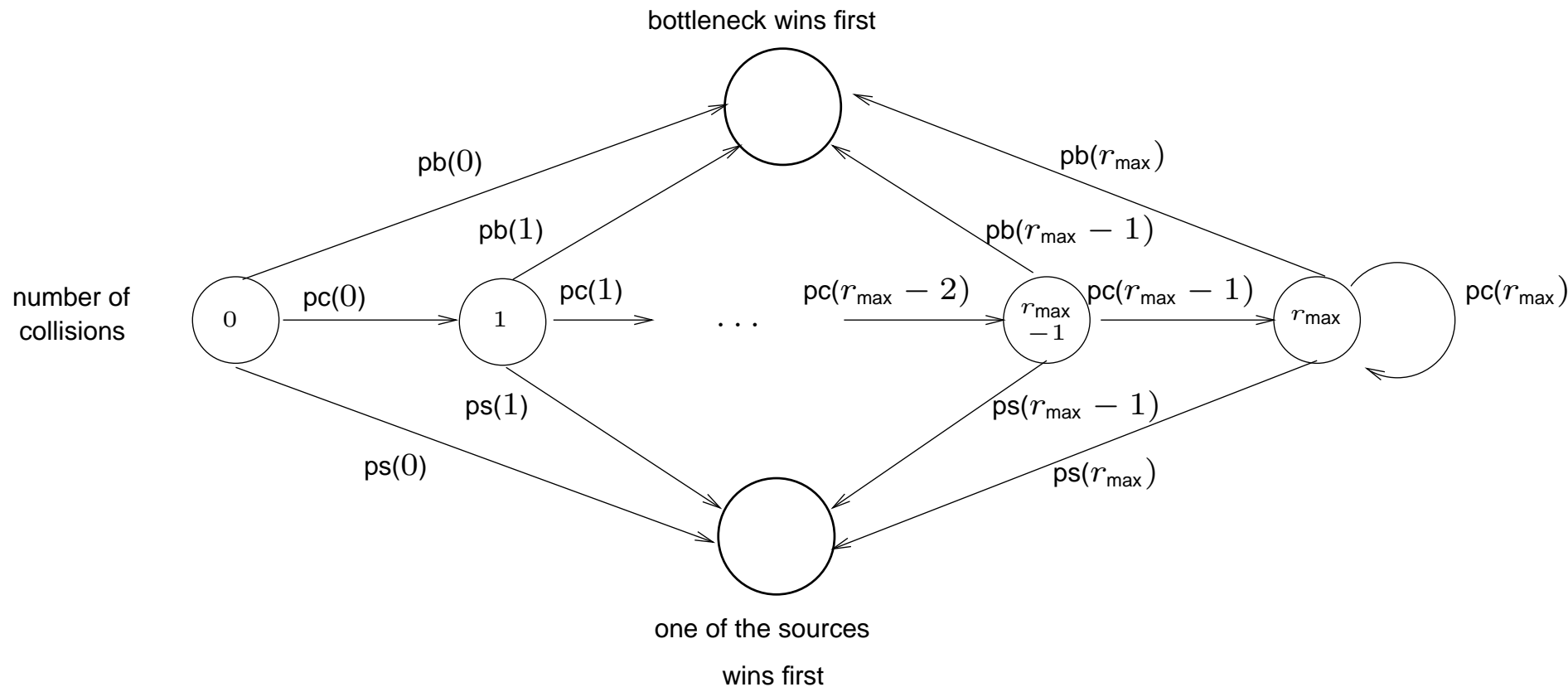
advantage for the bottleneck

- $pb(i) = \Pr\{\text{bottleneck wins contention} \mid i \text{ collisions}\}$
 $= \Pr\{b_b + \text{AIFS}_b < \min(b_1, b_2, \dots, b_N) + \text{AIFS}_s \mid i \text{ collisions}\}$
 $= \sum_{k=0}^{\text{CW}(i)-1} \Pr\{b_b = k\} \cdot \Pr\{\min(b_1, b_2, \dots, b_N) > k - \delta\}$
 $= \dots$
 $= \frac{1}{\text{CW}(i)^{N+1}} \sum_{k=0}^{\text{CW}(i)-1} (\text{CW}(i) - 1 - k - \delta)^N$
- $\delta = \text{AIFS}_s - \text{AIFS}_b$
- same can be done for the probability that one of the sources wins ($ps(i)$)

eliminate the influence of the collisions

- in each contention either
 - the bottleneck wins ($p_b(i)$)
 - one of the sources wins ($p_s(i)$), or
 - a collision occurs ($p_c(i) = 1 - p_b(i) - p_s(i)$)
- eventually either the bottleneck or one of the sources wins

dynamic contention mechanism



- consider all paths that lead from state 0 to the absorbing state *bottleneck success*

share of capacity

- $b_{\text{AIFS}}(N, \delta)$

$$= \Pr\{\text{bottleneck wins contention} \mid N \text{ active sources}\}$$

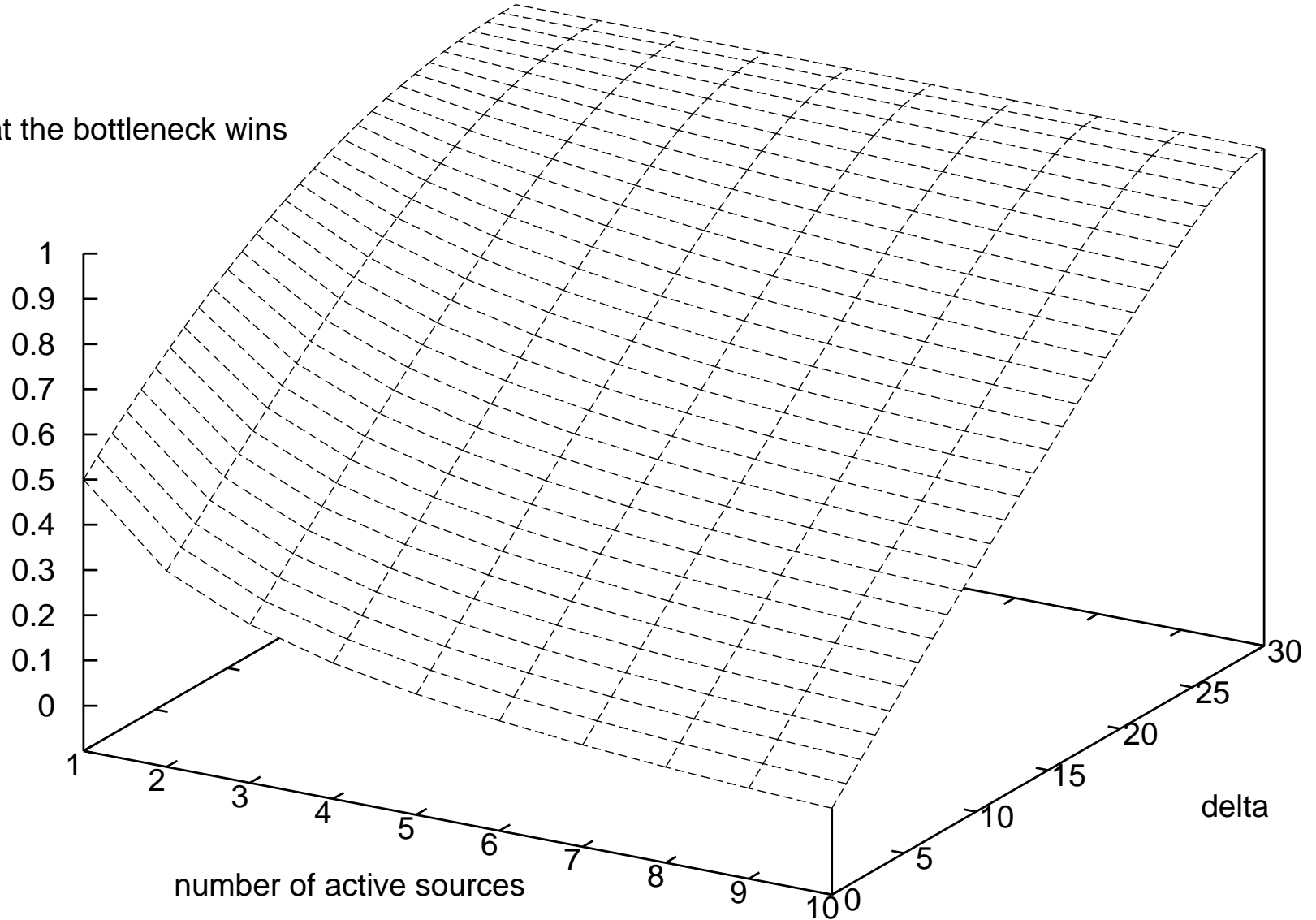
$$= \sum_{i=0}^{r_{\max}-1} \left(\prod_{k=0}^{i-1} \text{pc}(k) \right) \cdot \text{pb}(i)$$

$$+ \left(\prod_{k=0}^{r_{\max}-1} \text{pc}(k) \right) \cdot \frac{1}{1 - \text{pc}(r_{\max})} \cdot \text{pb}(r_{\max})$$

- $s_{\text{AIFS}}(N, \delta) = 1 - b_{\text{AIFS}}(N, \delta)$

success probability according to b_{AIFS}

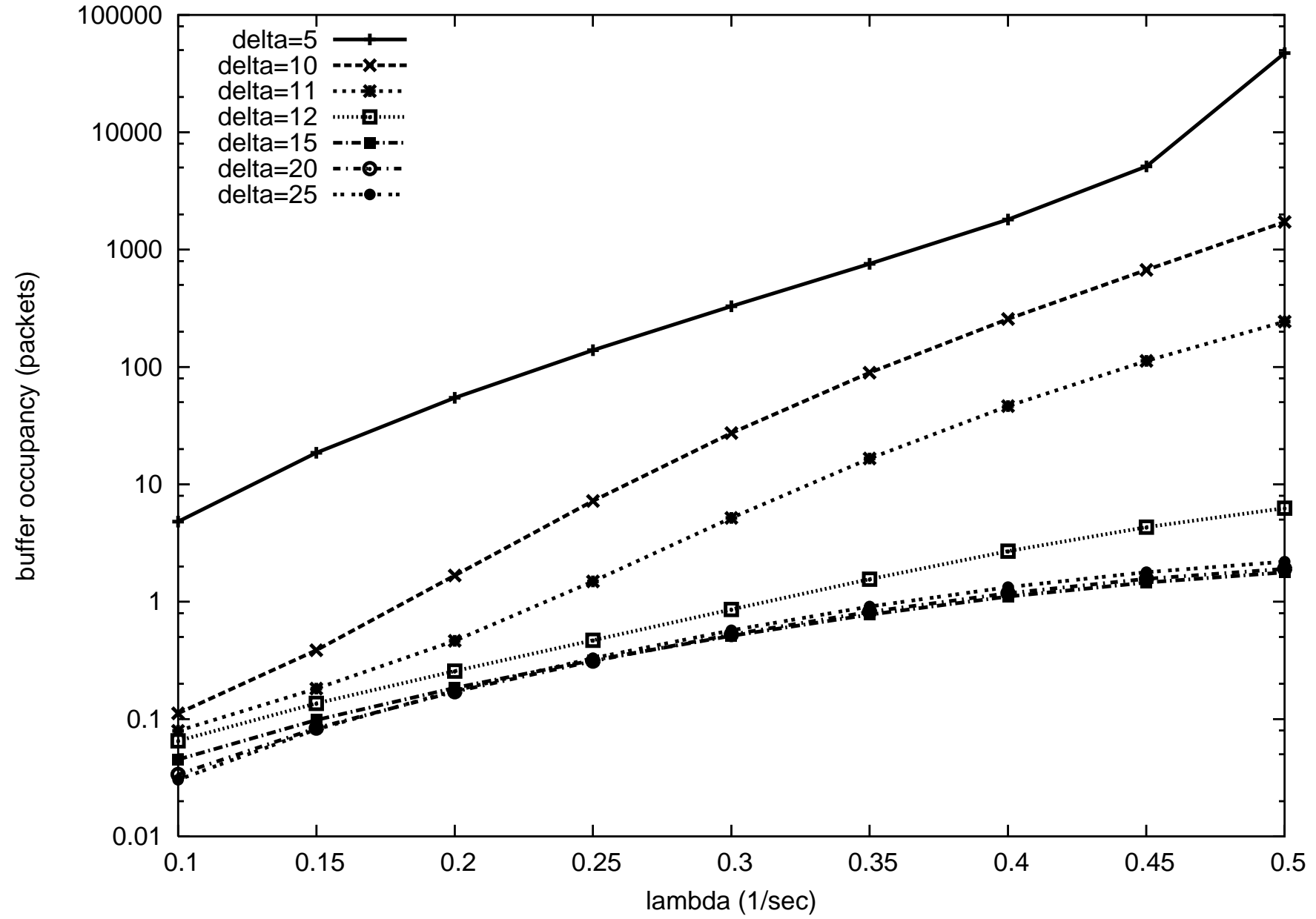
prob. that the bottleneck wins



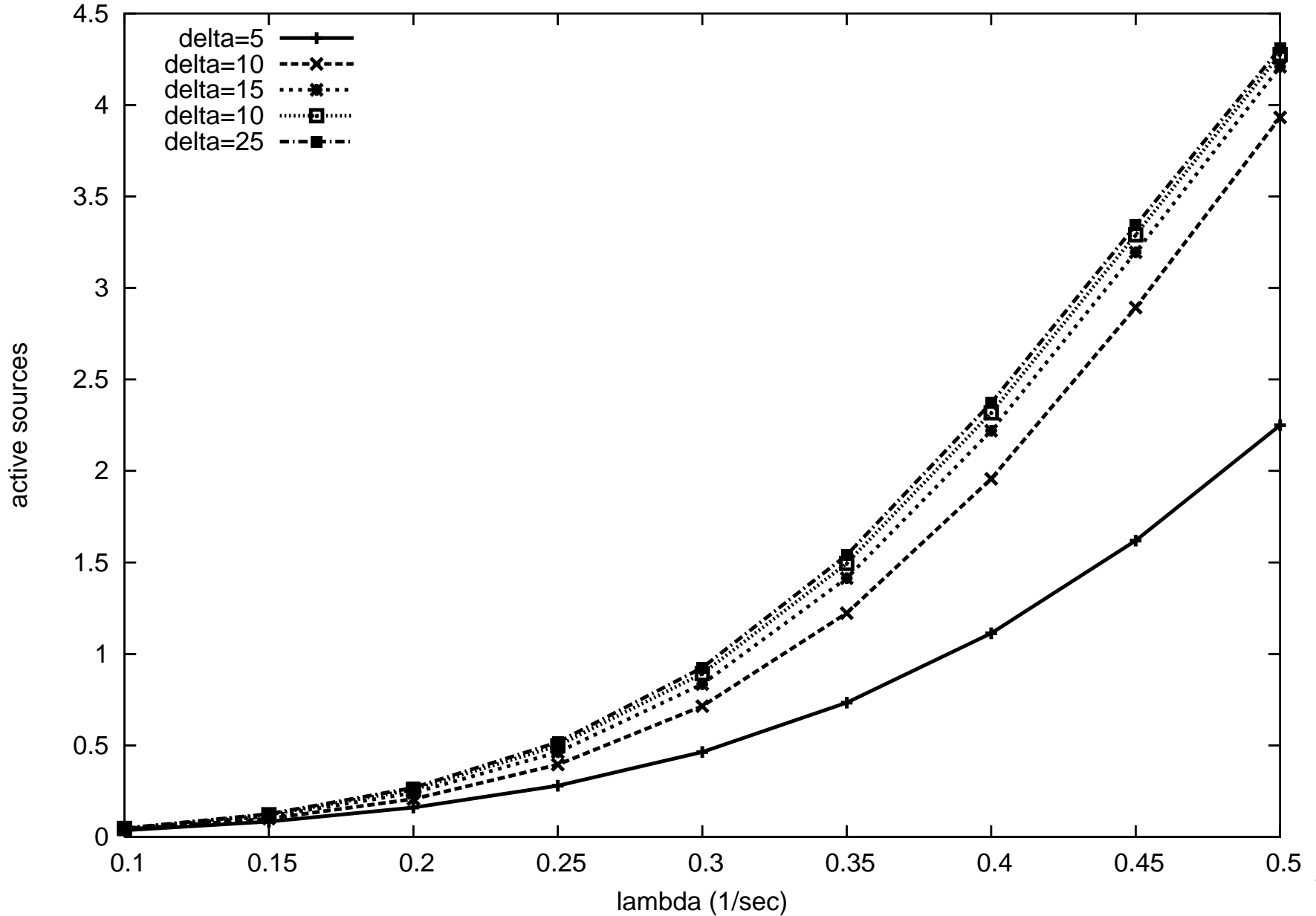
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expected buffer occupancy AIFS



expected number of sources AIFS



other QoS parameters

- recall four QoS parameters plus multiple backoff
- modeling AIFS:
 - uses probability for the smallest unique backoff
 - needs hierarchical modeling
 - introduces two simplifications
- CW_{\min} and CW_{\max} can be modeled along the same lines as AIFS
- $TXOP_{\text{limit}}$ and multiple backoff fit much more natural

conclusions

- we provide
 - a versatile modeling and evaluation approach for capacity sharing
 - new model checking algorithms for CSRL on QBDs
 - wide flexibility for modeling and measure specification
- we study
 - how to use the 802.11e differentiation parameters to achieve smart capacity sharing
 - how well differentiation parameters fit into our model
- future work:
 - build a more elaborate model that captures the complete contention mechanism with collisions and time slots