# Nomadic Communications

# 802.11e – Service Differentiation

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## Quality-of-Service Provisioning: Some Terminology

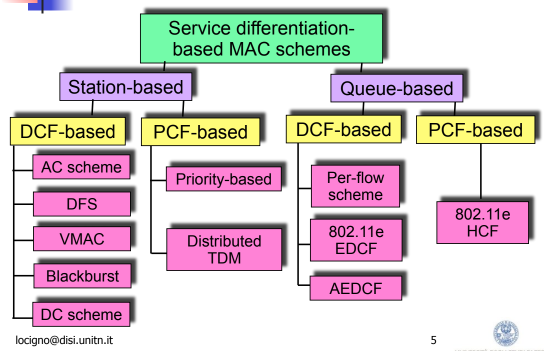
- Definition: A **flow** is a packet stream from a source to a destination, belonging to the same application
- Definition: **QoS** is a set of service requirements to be met by the network while transporting a flow
- Typical QoS metrics include: available bandwidth, packet loss rate, estimated delay, packet jitter, hop count and path reliability

## QoS in Wireless Networks

- QoS schemes in wired networks are NOT suitable for wireless networks
  - e.g., current wired-QoS routing algorithms require accurate link state and topology information
  - time-varying capacity of wireless links, limited resources and node mobility make maintaining accurate information difficult
- Supporting QoS in wireless networks is an even more difficult challenge



## Service Differentiation MAC Schemes ...






## A QoS Standard for WLANs: IEEE 802.11e

- The IEEE 802.11 TG E was formed in 1999
- The Project Authorization Request (PAR) was approved in March 2000
- **Scopes of the IEEE 802.11 Task Group E**
  - Enhance the current 802.11 MAC to improve and manage QoS
  - Consider efficiency enhancements in the areas of DCF and PCF
  - Provide different classes of service (4 TCs)

## 802.11e Standard

- Released 2007
- PHY unchanged (use a/b/g)
- MAC Enhanced: Goals
  - Traffic Differentiation and Guarantee
  - TSPEC and CAC
  - Interoperation with legacy 802.11
- It's also the base for 802.11n MAC



## 802.11e: QSTA, QAP, QBSS, HCF

- A station using 802.11e is called *QoS Enhanced Station* (QSTA)
- An AP using 802.11e is called *QoS Access Point* (QAP)
- QSTA e QAP works within a *QoS Basic Service Set* (QBSS)
- The two coordination functions DCF e PCF are substituted by a single *Hybrid Coordination Function (HCF)*



## TXOPs

- TXOP: Transmission Opportunity
  - Time interval during which a QSTA has the right to transmit
  - It is characterized by a starting time and a maximum duration (TXOP_Limit)
  - Used in both CP and CFP

## 802.11e Coordination Function

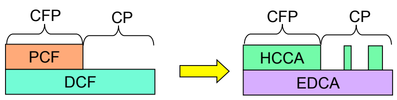
- Hybrid Coordination Function, alternates:
  - EDCA (Enhanced Distributed Channel Access), contention based, conceived to support legacy stations and provide some *stochastic* level of differentiation
  - HCCA (HCF Coordinated Channel Access), polling based, provides collision free periods with guaranteed assignment and *deterministic* differentiation



## 802.11e QoS Mechanisms

802.11e proposes a new access scheme: Hybrid Coordination Function (HCF), composed of two coordination functions

- Enhanced Distributed Channel Access (EDCA)
  - A basis layer of 802.11e; operates in CP
- HCF Controlled Channel Access (HCCA)
  - HCCA operates in CFP






## 802.11e QoS Mechanisms

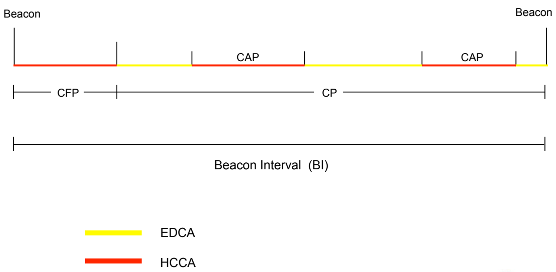
- MAC-level FEC (Hybrid I and II)
- **Ad hoc features:**
  - Direct Communication / Side Traffic
  - WARP: Wireless Address Resolution Protocol
  - AP mobility

## 802.11e: Hybrid Coordinator

- Within a QBSS a centralized controller is needed to coordinated all QSTAs. This is the *Hybrid Coordinator* (HC), normally implemented within a QAP
- An HC has the role of splitting the transmission superframe in two phases continuously altrernating:
  - *Contention Period* (CP), where QSTAs content for the channel using EDCA
  - *Contention-Free Period* (CFP), where HC defines who is going to use the channel and for what time with a collision free polling protocol



## MAC 802.11e: HCCA






## 802.11e: EDCF

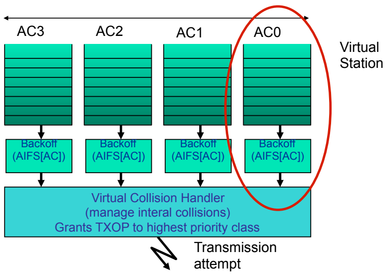
- The *Enhanced Distributed Coordination Function* (EDCF) define a differentiated access scheme based on an improved (yet complex) contention scheme
- It is an evolution of CSMA/CA DCF, with the add-on of traffic classes to support QoS and differentiate traffic
- EDCF is designed to support frames with the same 8 priority levels of 802.1d, but mapping them on only 4 access categories
- Every frame passed to the MAC layer from above, must have a priority identifier (from 0 to 7), called *Traffic Category Identification* (TCId)

## 802.11e: EDCF

- TCId is written in one header field of the MAC frame
- Each 802.11e QSTA & QAP MUST have four separated AC queues
- Each AC queue is FIFO and behaves independently from the others as far as the CSMA/CA MAC protocol is concerned



## 802.11e: EDCF






## 802.11e: EDCF

- ACs are differentiated based on their CSMA parameters:
  - **IFS**
  - **CWmin**
  - **CWmax**
  - **Backoff exponent**

## 802.11e: EDCF

- Higher priority ACs are assigned parameters that result in shorter CWs so that a statistical advantage is gained in accessing the channel
- Protocol parameters become vectors
  - CWmin[AC]
  - CWmax[AC]
  - AIFS[AC]
  - bck[AC]
  - CW[AC,t] is derived with the usual CSMA/CA rules

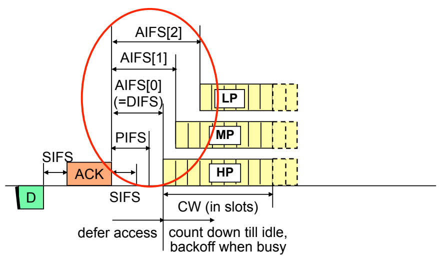


## 802.11e: EDCF

- Arbitration InterFrame Space (AIFS) substitute the common DIFS
- Each AIFS is at least DIFS long
- Befor entering the backoff procedure each *Virtual Station* will have to wait AIFS[AC], instead of DIFS



## Arbitraration IFS (AIFS)




802.11a: slot=9 μs, SIFS=6 μs, PIFS=15 μs, DIFS=24 μs, AIFS ≥34 μs

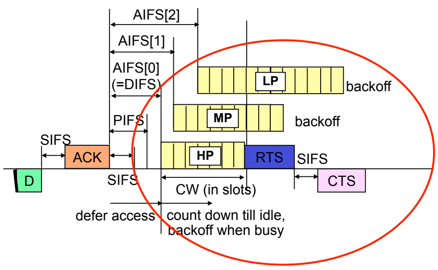
## Contention Window

- $CW_{min}[AC]$ and $CW_{max}[AC]$
- Contention Window update:

$$CW_{new}[AC] = (CW_{old}[AC] + 1) \cdot bck - 1$$



## Backoff




802.11a: slot=9 μs, SIFS=16 μs, PIFS=25 μs, DIFS=34 μs, AIFS ≥34 μs



## Virtual Stations

- Each AC queue behaves like a different virtual station (independent sensing and backoff)
- If the backoff counters of two or more parallel ACs in the same QSTA reach 0 at the same time, a scheduler inside the QSTA avoids l collision by granting the TXOP to the AC with the highest UP
- **The lowest priority colliding behaves as if there were an external collision**

## 802.11e: EDCF – Beacon Frames

- Values of AIFS[AC], CWmin[AC] e CWmax[AC] are determined by the QAP and transmitted within beacon frames (normally every 100 msec)
- QSTAs must abide to the received parameters
- QSTAs may use these parameters to chose the QAP the prefer to connect to (estimate of the expected performance)



## 802.11e: TXOP

- TXOP is the time interval in which a STA may use the channel
- It's an initial time plus a duration, indeed the contention is no more for a PDU, but can be for many aggregated PDUs
- CW[AC] is managed with usual rules of increment (after collisions/failures) and decrement (during idle cahnnel):

  NewCW[AC] = ((OldCW[AC] + 1) * 2) - 1



## 802.11e: EDCF

- Sample allocation of TCId to ACs:

| TCID | CA | Traffic description |
|---|---|---|
| 0 | 0 | Best Effort |
| 1 | 0 | Best Effort |
| 2 | 0 | Best Effort |
| 3 | 1 | Video Probe |
| 4 | 2 | Video |
| 5 | 2 | Video |
| 6 | 3 | Voice |
| 7 | 3 | Voice |

## EDCA Bursting

- Once the station has gained access to the medium, it can be allowed to send more than one frame without contending again
- The station cannot transmit longer than TXOP_Limit
- ACK frame by frame or Burst ACK
- SIFS is used between frames within the same TXOP to maintain the channel control when assigned



## EDCA Bursting: Pros / Cons

- **Pros**
  - Reduces network overhead
  - Increases throughput (SIFS and burst ACKs)
  - Better fairness among the same priority queues: independently of the frame size, a QSTA gets a TXOP every time it wins a contention
    - E.g., STA A uses 500 B frame; STA B uses 1K B frame. Thus B would get higher throughput in 802.11, while in 802.11e both can get approximately same throughput



## EDCA Bursting: Pros / Cons

- **Cons**
  - Possible increasing of delay jitter
  - TXOP_Limit should be longer than the time required for transmitting the largest data frame at the minimum speed
- In any case EDCA does not solve the downlink/uplink unfairness problem

## 802.11e: HCF

- HC may allocate TXOPs to himself (QAP) or to other QSTAs
- Self allocation is done to transmit MSDUs, allocation of resources may solve the uplink/downlink unfairness
- Allocation to AP can be done after a Point coordination InterFrame Space (PIFS) con PIFS < DIFS
- HC (QAP) has priority over other stations and may interrupt a CP to start a CFP transmitting a Poll frame

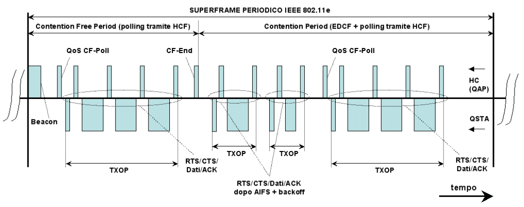


## 802.11e: HCF

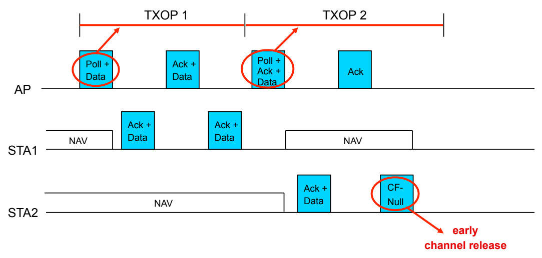
- Time is diveded between contention free periods (CFP) and contention periods (CP), that are alternated roughly cyclically
- A sequence CFP + CP defines a Periodic Superfame of 802.11e
- The CP can be interrpted by other contention free periods called CAPs



## 802.11e: HCF



## MAC 802.11e: HCCA






## 802.11e: HCF – QoS CFPoll Frame

- Within a CP, TXOP is determined either:
  - Through EDCF rules (free channel + AIFS + BO + TXtime)
  - Through a poll frame, called QoS CFPoll, sent by HC to a station
- QoS CFPoll is sent after PIFS, so with priority wrt any other traffic
- Indeed there is not a big difference between a CFP and CAPs
- During CFP, TXOPs are again determined by HC and QoS CFPoll can be piggybacked with data and ACKs if needed
- Stations not polled set NAV and cannot access the channel



## 802.11e: HCF – QoS CFPoll Frame

- The CFP must terminate within a time specified in beacons and it is terminated by the CF-End frame sent by HC
- QoS CF-Poll frame was introduced with the 802.11e amendment, for backward compatibility it contains a NAV field the legacy stations can use to avoid interfering
- NAV specify the whole TXOP duration
- Legacy stations in HCF can only use the CP period

## HCCA

- HCCA effectively provides policing and deterministic channel access by controlling the channel through the HC
- It is backward compatible with basic DCF/PCF
- Based on polling of QSTAs by the HC

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## HCCA

**Crucial features of HCCA**

- HCCA operates in CP and CFP
- Uses TXOPs which are granted through HC (in HCCA!)
  - HC allocates TXOPs by using QoS CF-Poll frames
  - In CPs, the time interval during which TXOPs are polled by HC is called CAP (Controlled Access Period)
  - 4 Traffic Categories (TCs)

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## HC Behavior in HCCA

- According to HCCA:
  - HC may allocate TXOPs to itself to transmit MSDUs whenever it wants, however only after having sensed the channel idle for PIFS
  - In CP, the HC can send the CF-Poll frame after a PIFS idle period, thus starting a CAP
  - In CFP, only the HC can grant TXOPs to QSTAs by sending the CF-Poll frame
  - The CFP ends after the time announced by HC in the beacon frame or by the CF-End frame from HC

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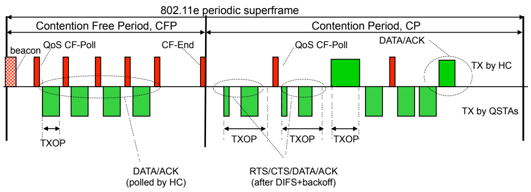
## QSTA Behavior in HCCA

- A QSTA behaves as follows
  - In CP QSTAs can gain a TXOP thanks to a CF-Poll frame issued by HC during CAPs, otherwise they can use EDCA
  - In CFP, QSTAs do not attempt accessing the channel on their own but wait for a CF-Poll frame from the HC
- The HC indicates the TXOP duration to be used in the CF-Poll frame (QoS-control field)
  - Legacy stations kept silent by NAV whenever they detect a CF-Poll frame



## 802.11e Superframe




During the CP, a TXOP may begin because:

- The medium is determined to be available under EDCA rules (EDCA-TXOP)
- The STA receives a special polling frame from HC (polled-TXOP)

## Polling in HCCA

- Polling list is a crucial key in HCCA
  - Traffic scheduling (i.e., how QSTAs are polled) is not specified
  - QSTAs can send updates to the HC on their queue size as well as on the desired TXOP, (through the QoS control field in data frames)
  - QSTAs can send ADDTS requests to initiate a new traffic stream

## Traffic Signaling

- Two types of signaling traffic are supported:
  - Connectionless queue state indicator
    - E.g., Arrival rate measurement: notification and not negotiation between peer entities is used
  - TSPEC (Traffic Specification) between HC and QSTAs
    - E.g., service negotiation and resource reservation



## Traffic Signaling

- TSPEC are the base for CAC
- QoS without CAC is impossible
- QoS is granted to flows not to packets
- Flows are persistent (normally)
- Flows can be predicted (sometimes)



## Resource Scheduling

- Not essential to backward compatibility
  - The standard has just a reference impl. (SS)
- HCF is implemented in the AP
  - HCCA scheduling is a function of HCF
- Requirements of traffic flows are contained in the *Traffic Specifications* (TSPEC):
  - Maximum, minimum and mean datarate
  - Maximum and nominal size of the MSDUs
  - Maximum Service Interval and ***Delay Bound***
  - Inactivity Interval
  - …

# EDCA Differentiation
# HCCF Scheduling

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## Thanks & Disclaimer

- These slides and results are based on the following paper
  - "Performance Evaluation of Differentiated Access Mechanisms Effectiveness in 802.11 Networks", IleniaTinnirello , Giuseppe Bianchi , Luca Scalia, IEEE Globecomm 2004.
- As such they must be considered examples of the possible performances and tradeoffs
- Thanks to Bianchi and all the other authors for providing copy of the papers graphics and slides

## EDCA or HCCA?

- How does EDCA support differentiation?
- Is this enough for standard purposes?
- Are parameters easy to tune and universal?

- How can HCCA polling-based scheduling be implemented?
- Do we need to use the feedback from the STA?
- How can the traffic be described?



## Performance Evaluation of Differentiated Access Mechanisms Effectiveness in 802.11 Networks

G. Bianchi, I. Tinnirello, L. Scalia

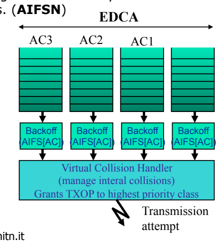
**presented @ Globecom 2004**

## QoS Support issues in legacy 802.11

- DCF is long term fair
  - Equal channel access probability among the stations
  - Averagely, the same channel holding time (for homogeneous packet sizes)
    - Solution: differentiate packet sizes?
    - Solution: differentiate channel holding times?
- NO WAY! QoS is not a matter of how long I hold the channel
  - It means more…
    - Need to manage access delay problems for real-time apps!!!
    - Need to modify 802.11 channel access fairness!!!

## QoS @ IEEE 802.11 MAC

- 802.11e defines different traffic classes onto map data flows
- Each traffic class behaves as an independent MAC entity
- Differentiated access priority is provided by:
  - Giving probabilistically lower backoff counters (**CWmin**, **CWmax**, **PF**)
  - Giving deterministically lower inter-frame spaces and backoff de-freezing times. (**AIFSN**)




Different MAC Access Parameters @ each class to differentiate cha nnel access probability

Backoff based parameters: **CWmin, CWmax, PF**
Channel monitoring based parameters: **AIFS**



## EDCA Performance Evaluation

- Performance Evaluation: answers we try to give…
  - Homogeneous sources
    - Performance effectiveness of each differentiation MAC parameter, individually taken
    - How each differentiation parameter reacts to different load conditions?
  - Hetrogenous sources
    - What are the most effective settings to manage high-priority delay requirements?

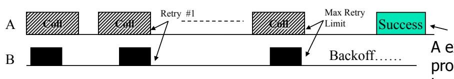


## EDCA Performance Evaluation

- Simulations
  - Same number of HP and LP stations
  - Same packet size (1024 bytes)
- Homogeneous sources scenario
  - Saturation conditions for HP and LP stations
    - Queues never empty
    - Data rate = Phy rate = 1 Mbps
- Heterogeneous sources scenario
  - 3 pkts/sec. for HP traffic
  - Saturation conditions for LP traffic
    - Data rate = Phy rate = 1 Mbps

## CWmax Differentiation (1)

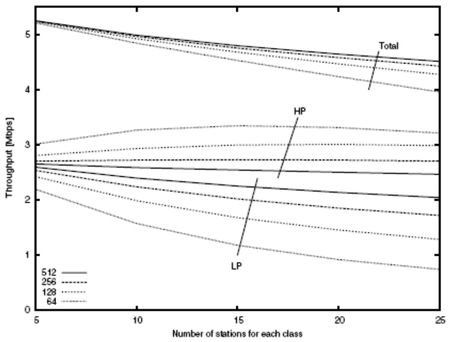
- CWmax(A)<CWmax(B)
  - Once reached CWmax (repetead collisions), A gets access priority over B




A extracts probablistically a lower backoff value due to its lower CWmax

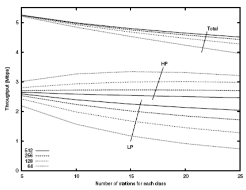


## CWmax Differentiation (2)





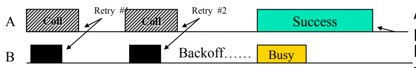

## CWmax Differentiation (3)



- Low throughput differentiation
  - Only with CWmax=64 effective
  - @ low loads poor performance
    - Few collisions
- Inefficient channel usage
  - Consecutive Collisions are needed for the differentiation effect
  - Overall throughput suffers @ high loads

## PF Differentiation (1)

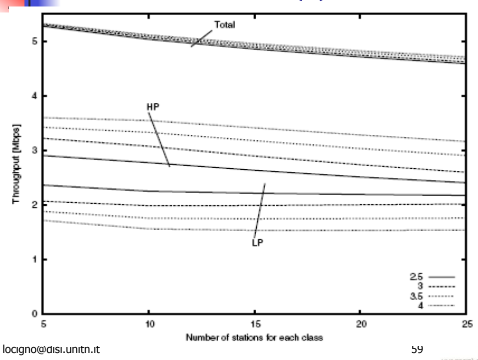
- PF(A)<PF(B)
  - once a collision occurs, station A has probabilistically an higher chance to extract a lower backoff value, thus it may retransmits first.




A extracts probablistically a lower backoff value due to its lower CW

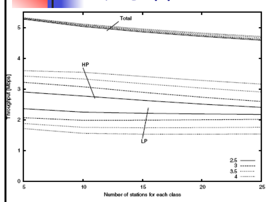


## PF Differentiation (2)





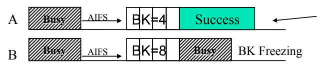

## PF Differentiation (3)



- PF is greater than 2 for LP stations.
- CW_new = PF * CW_old
- It is sufficient a single collision to begin the differentiation process.
- Impossible to force LP traffic to zero!
  - After a packet successful transmission, the PF effect is no more present

## CWmin Differentiation (1)

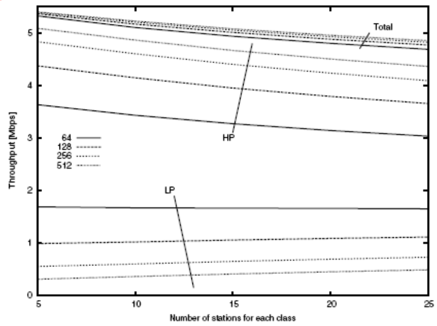
- CWmin(A)<CWmin(B)
  - In average, station A has a lower backoff than B




Thanks to its lower CWmin, A extracts probablistically a lower backoff value

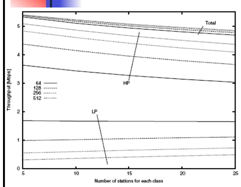


## CWmin Differentiation (2)





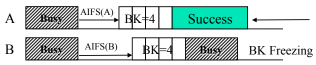

## CWmin Differentiation (3)



- Very good differentiation performance
- @ low loads peformance is good
  - Collision effects among HPs not significant
- @ high loads collisions mainly involve HP stations (because of their small CW)
  - Degradations regard HP traffic -> bad!
  - LP traffic not affected
    - Collision effects un-altered

## AIFS Differentiation (1)

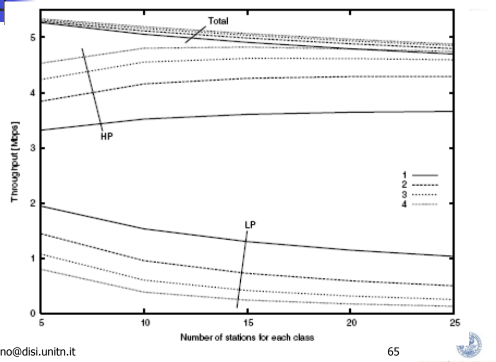
- AIFS(A)<AIFS(B)
  - station A decrements its backoff timer before than station B




Thanks to its lower AIFS, A starts decrementing its backoff value before than B either after busy channel or idle channel conditions

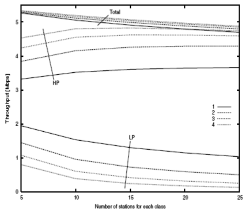


## AIFS Differentiation (2)





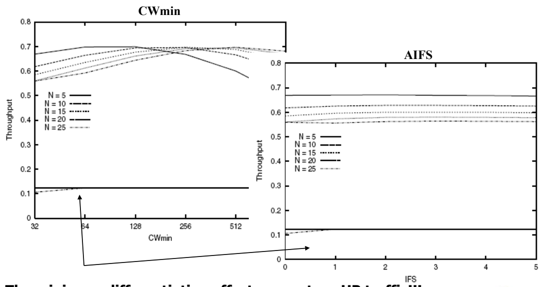

## AIFS Differentiation (3)




- Very High differentiation performance
  - Complementary to CWmin case
- @ low loads differentiation performance suffers
  - Collision are few ->
- @ high loads collisions mainly involve LP stations, since HP stations access first
  - Degradations regard LP traffic -> good!
  - HP traffic not affected

## Heterogeneous Sources: Throughput

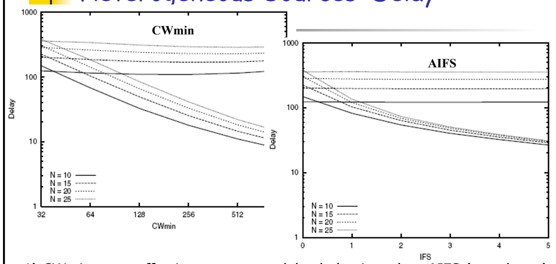
Focus on AIFS and CWmin differentiation, seen to be most effective




**The minimum differentiation effect guarantees HP traffic!!!**



## Heterogeneous Sources: Delay




1) CWmin more effective to manage delay behaviour than AIFS (see slopes)

2) AIFS differentiation slightly sensitive to load in terms of delay

3) Joint use: delay requirements satisfied with AIFS, throughput managed via CWmin (because of the maxima)



## Conclusions

- Cwmin and AIFS differentiation perform better than PF and CWmax differentiation
  - PF and CWmax differentiation operations allowed only by collisions
- CWmin and AIFS show a complementary behaviour
  - CWmin performance degrades @ high loads
  - AIFS performance degrades @ low loads
- Joint use of CWmin and AIFS
  - AIFS to meet delay requirements
  - CWmin to manage thoughput performance
- Complex parameter setting
- Behavior hardly predictable

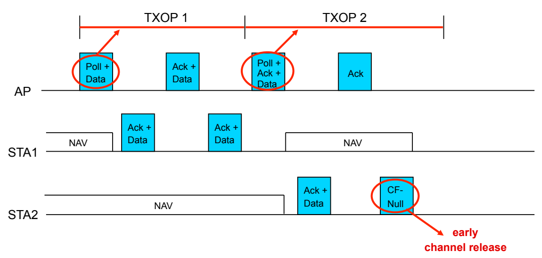
## Scheduling in HCCA: Sample Open and Close-Loop Schedulers

## Outline

- Scheduling: The Rules of The Game
- Sample (on the standard) Scheduler
- Equivalent Bandwidth Approach
- Closed Loop Scheduling: A Control Theoretic Approach



## MAC 802.11e: HCCA



## Resource Scheduling (2)

- KEY notions are
  - Service Interval - SI(j): The maximum amount of time between successive polling to a station j
  - Transmission Opportunities - TXOP(j): The amount of resources (time) assigned to station j in a single polling
- Goals of scheduling:
  - Find suitable values of SIs and TXOPs
  - Fully exploit resources
  - Guarantee quality and differentiation of the TSPECs



## Reference Implementation (SS)

Service Interval — $m = \min_i(MaximumServiceInterval_i)$

$SI = \max(x)$ t.c. $x<m$ e $BI \bmod x = 0$

TXOP — $N_i = \left\lceil \frac{SI \times \rho_i}{L_i} \right\rceil$ $\quad T_i = \max\left(\frac{N_i \times L_i}{R} + O,\ \frac{M_i}{R} + O\right)$

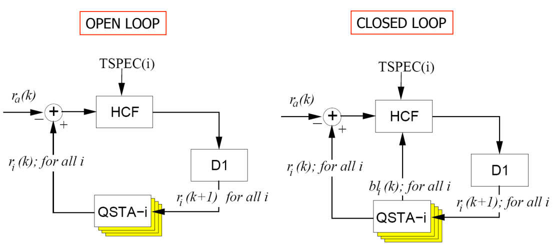
$\rho_i$ Mean datarate
$L_i$ Nominal MSDU size
$M_i$ Maximum MSDU size
$R$ TX rate
$O$ Overhead (Ack, SIFS,…)



## Feedback Information ... or not?

- SS Schedules is open-loop:
  - Uses only TSPEC info
  - Assigns the mean rate: not suited for VBR ...
  - ... but you can assign a rate based on an **Equivalent Bandwidth** approach
- 802.11e has a field to feedback information about backlog (bytes or frames in queue)
  - Use this info for prediction or
  - Use this info for **closed-loop control**?

## Open/Closed Loop Scheduling






## Equivalent Bandwidth

- Well known approach
  - Conceptually simple, just assign resources such that

$$P\left[\frac{\rho}{SI} > \frac{EB(p)}{SI}\right] = p$$

  - EB(p) is the assignment that guarantees p frame loss probability
  - ρ is the actual (time-depended) offered traffic
  - **But** ... requires full stochastic knowledge of the traffic ☹



## Closed-loop Scheduling: Basics

- Discrete time modeling
  - Just throw away time (creates a lot of problems)
  - The system evolves in cycles of SIs: 1,2,3...,k
- Goal: equalize (to zero) all queues
- Max/Min fair approach
  - Only resources above the minimum guarantee are "controlled"
- Assumption: There is a CAC function ensuring long-term stability
  - Can use large loop gains without oscillation risks

## Closed-loop Scheduling: Formulae

$$\frac{1}{K}\sum_{k=1}^{K} r_a(k) > \sum_{i=1}^{N_{QS}} \bar{r}_i$$

CAC based long term stability: the average available resources over a finite time K are larger than the average assigned resources

$$r_j(k) = r_j^{\min}(k) + r_j^{+}(k)$$

$$r_j^{+}(k+1) = \frac{B_j(k)}{\sum_{j=1}^{N_{TS}} B_j(k)}\left[r_a(k+1) - \sum_{j=1}^{N_{TS}} r_j^{\min}(k+1)\right]$$

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## Closed-loop Scheduling: Formulae

$$\frac{1}{K}\sum_{k=1}^{K} r_a(k) > \sum_{i=1}^{N_{QS}} \bar{r}_i$$

Max/Min Fairness
**$r^{min}$** are guaranteed and not subject to control
**$r^{+}$** is strictly non negative

$$r_j(k) = r_j^{\min}(k) + r_j^{+}(k)$$

$$r_j^{+}(k+1) = \frac{B_j(k)}{\sum_{j=1}^{N_{TS}} B_j(k)}\left[r_a(k+1) - \sum_{j=1}^{N_{TS}} r_j^{\min}(k+1)\right]$$

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## Closed-loop Scheduling: Formulae

$$\frac{1}{K}\sum_{k=1}^{K} r_a(k) > \sum_{i=1}^{N_{QS}} \bar{r}_i$$

Simple proportional controller splitting excess resources among all the flows that are backlogged

$$r_j(k) = r_j^{\min}(k) + r_j^{+}(k)$$

$$r_j^{+}(k+1) = \frac{B_j(k)}{\sum_{j=1}^{N_{TS}} B_j(k)}\left[r_a(k+1) - \sum_{j=1}^{N_{TS}} r_j^{\min}(k+1)\right]$$

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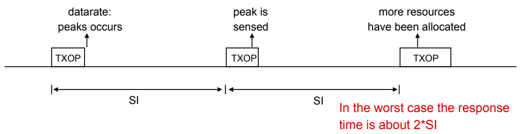
## Details … the real doom!

- Highly quantized resource assignment
  - A minimum assignment of one maximum size segment is mandatory … what if the station transmits at low rate?
  - "Fragments" of frames might lead to waste resources
- Reaction of the controller can be slugghish



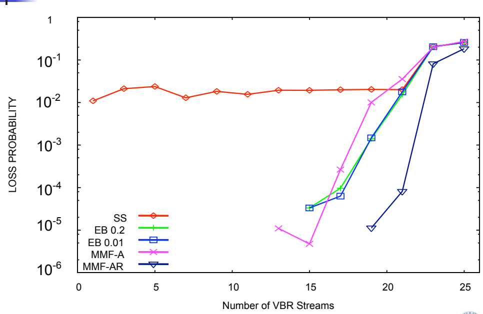



## Closed-loop Schedulers

- MMF-A
  - Implements the formulae above
  - Have quantization and response problems
- MMF-AR
  - Dynamically changes the SI 'on-demand' ☺
  - Reassign spare resources at the end of the CFP
  - Violates proportional assignment to avoid quantization problems

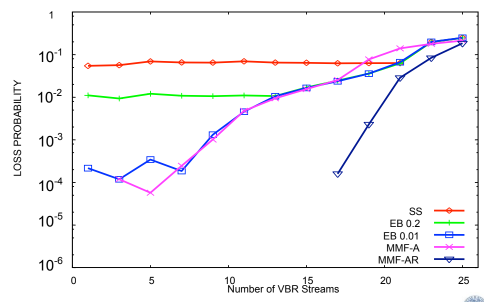


Traffic VBR-3: both packet size and interarrival time change
Delay Bound = ∞ Buffer Size = 50 pck Service Interval = 50 *ms*




## Results

Traffic VBR-3: both packet size and interarrival time change
Delay Bound = 100ms Buffer Size = 50 pck Service Interval = 50 *ms*

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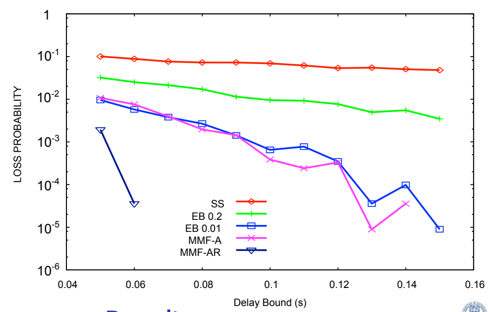
## Results



Sorgenti VBR-3: both packet size and interarrival time change
Buff. = 50pck #stream = 8 Service Interval = 50 *ms*

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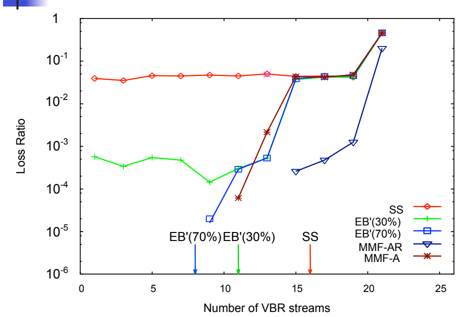
## Results



Real Video Traces: h.263 codec → **EB???**
Delay bound = 150ms Service Interval = 100 *ms*

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## Results

## Conclusions

- Different HCCA scheduling explored
- HCCA complexity is manageable, performances are better than EDCA, configuration is easier
- Closed-loop scheduling:
  - Viable alternative to open-loop or predictive scheduling
  - Complexity much simpler and effective than Equivalent Bandwidth approaches
- The BIG problem are details
  - Quantization, Normalization, Spare Resource Collection, ...