End-to-End Transport of Real-Time Traffic Using Adaptive Forward Error Correction

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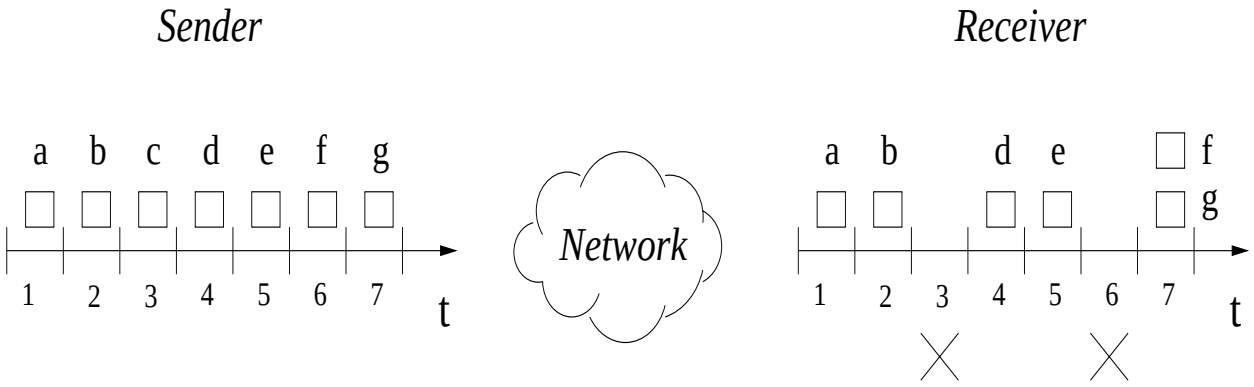
Overall Goal

Facilitate transport of real-time traffic—e.g., video, audio, voice, interactive applications—such that

- QoS-sensitive
- end-to-end
- efficient
- adaptive

Problem

Hard real-time application:



- packet drop
- queueing delay

Thus

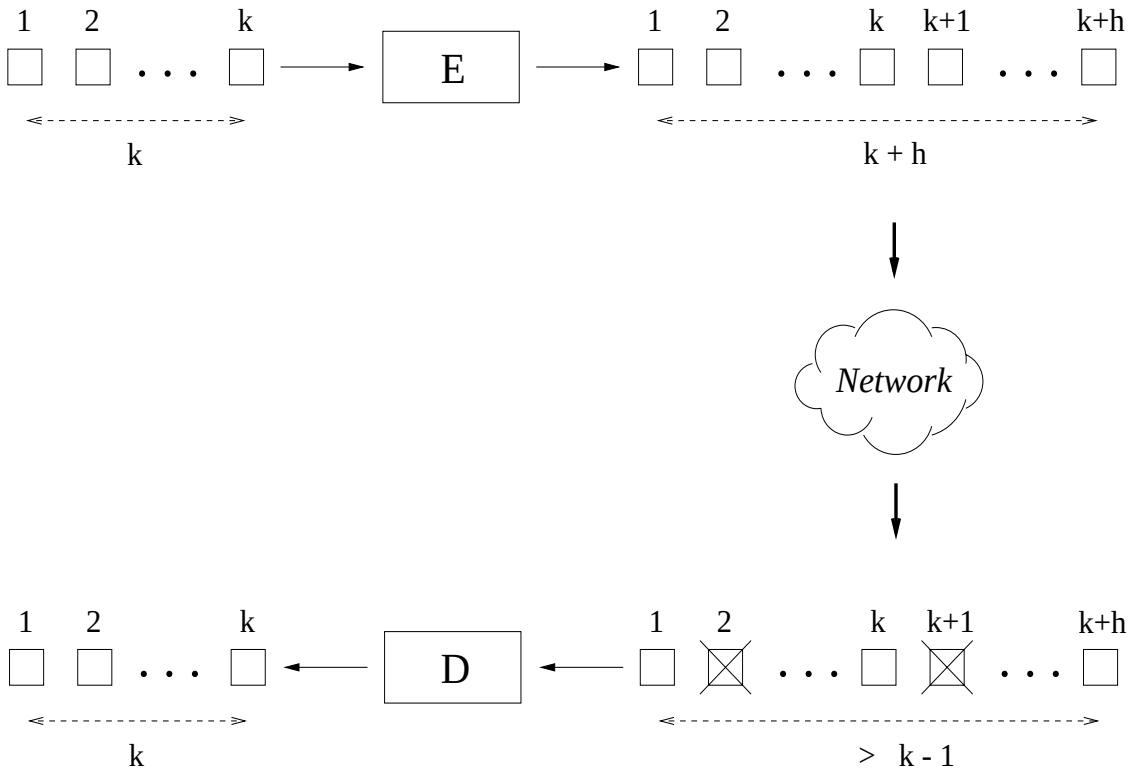
- RTT can exceed time constraint
- retransmission (ARQ) infeasible

Solutions:

- resource reservation & admission control
  - overprovisioning
  - inefficient due to self-similar burstiness
- forward error correction (FEC)

  $\longrightarrow$ proactive

Forward Error Correction



- k data packets encoded as $n = k + h$ code packets
- transmit n code packets
- receipt of *any* k packets allows for recovery

Features:

- packet-level FEC
- E, D with "k-out-of-n" property exist

  $\longrightarrow$ e.g., Reed-Solomon, IDA

Difference with traditional FEC:

- packet-level vs. bit-level
- independent vs. correlated information loss
- queueing-induced correlation
- self-similar burstiness

Effective QoS-control using FEC requires:

- tolerance to burstiness
- adaptability to network state
  - if network is "good," inject low redundancy
  - if network is "bad," inject high redundancy

  $\longrightarrow$ adaptive FEC

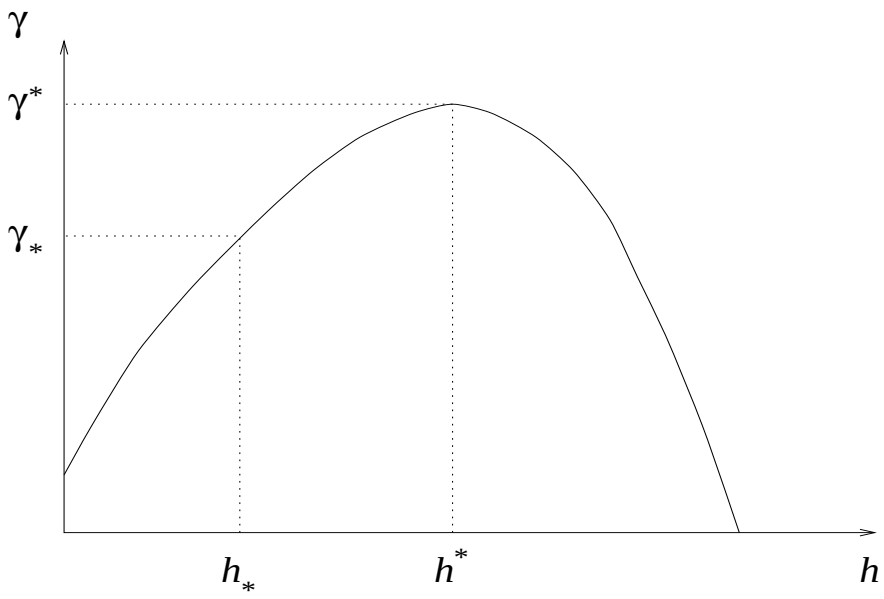
  $\longrightarrow$ maintain invariant target QoS

Caveat: Injecting "too much" redundancy can be counterproductive

$\longrightarrow$ i.e., eventually can decrease QoS

Unimodal redundancy-recovery relation:

- redundancy h
- sender transmits block of $n = k + h$ packets
- γ $(0 \leq \gamma \leq n)$ packets arrive timely at receiver



Features:

- γ is related to perceived QoS
- maximum recovery γ^*
- target recovery γ_*

Optimal control problem:

- given γ_* (user specified)
- adjust h such that $\gamma = \gamma_*$

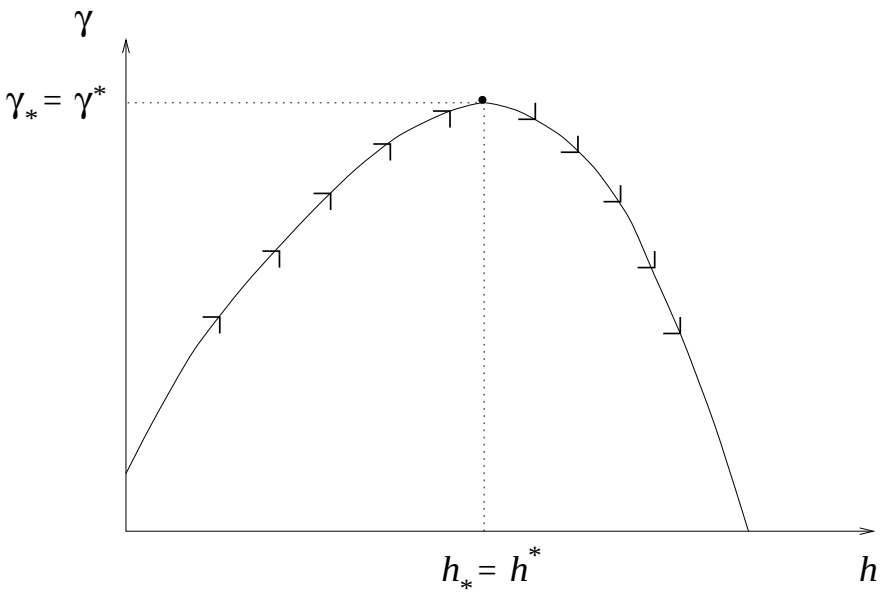
Control law:

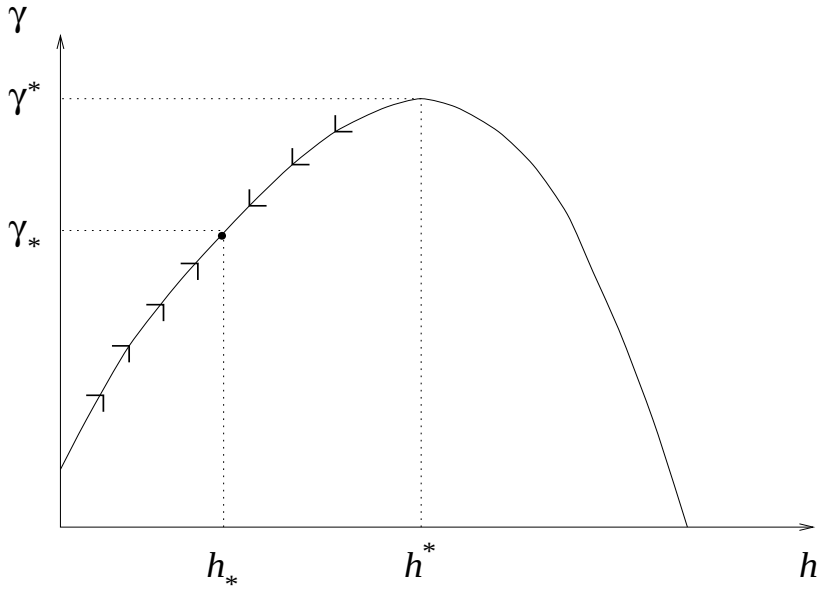
$$\frac{dh}{dt} = f(\text{desired QoS}, \text{network state})$$

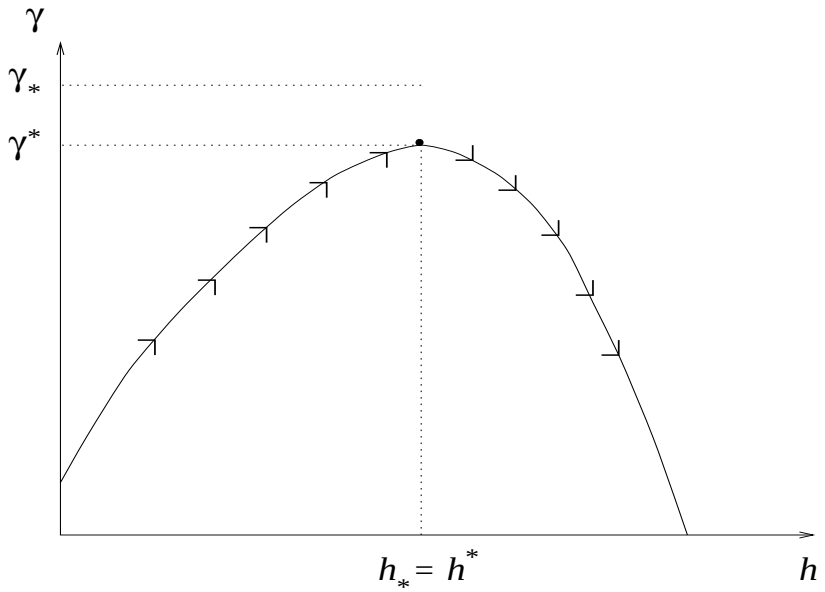
Stability Analysis

Control laws of the form:

- if $\gamma < \gamma_*$, increase h
- if $\gamma > \gamma_*$, decrease h




γ
γ*
γ*
h*
h*
h


γ
γ*
γ*
h* = h*
h

AFEC Protocol

Core protocol:

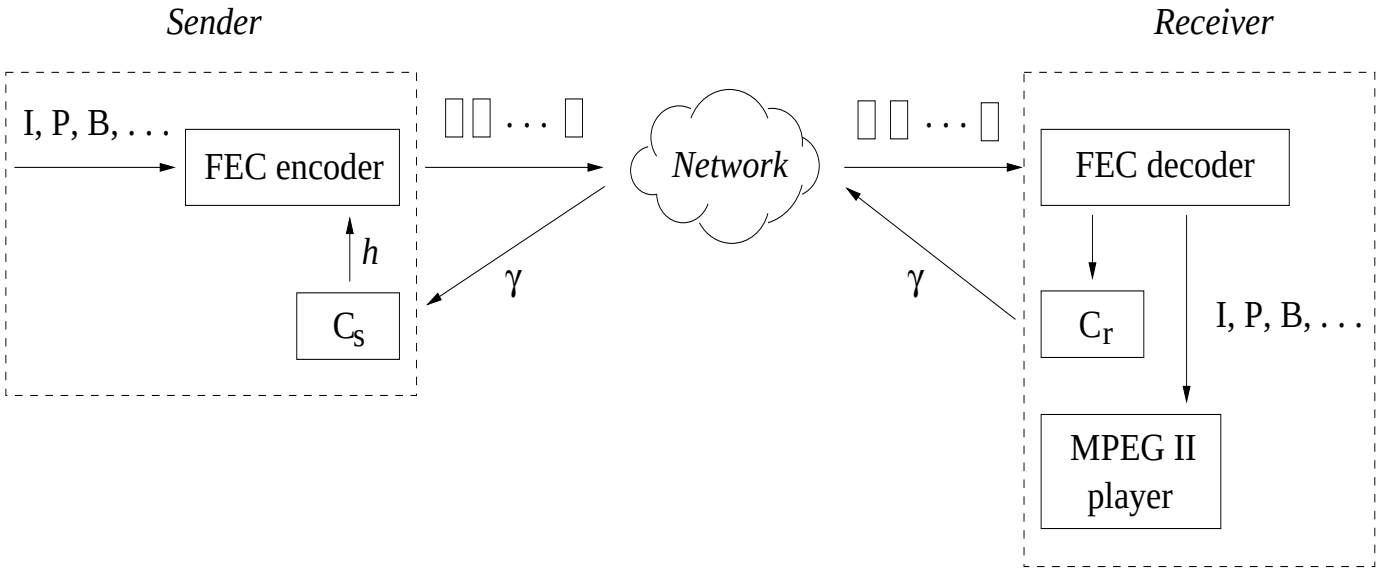
$$\frac{dh}{dt} = \begin{cases} \epsilon(\gamma_* - \gamma), & \text{if } d\gamma/dh \geq 0, \\ -ah, & \text{otherwise.} \end{cases}$$

Main feature:

- inside stable regime: symmetric control
- inside unstable regime: exponential backoff

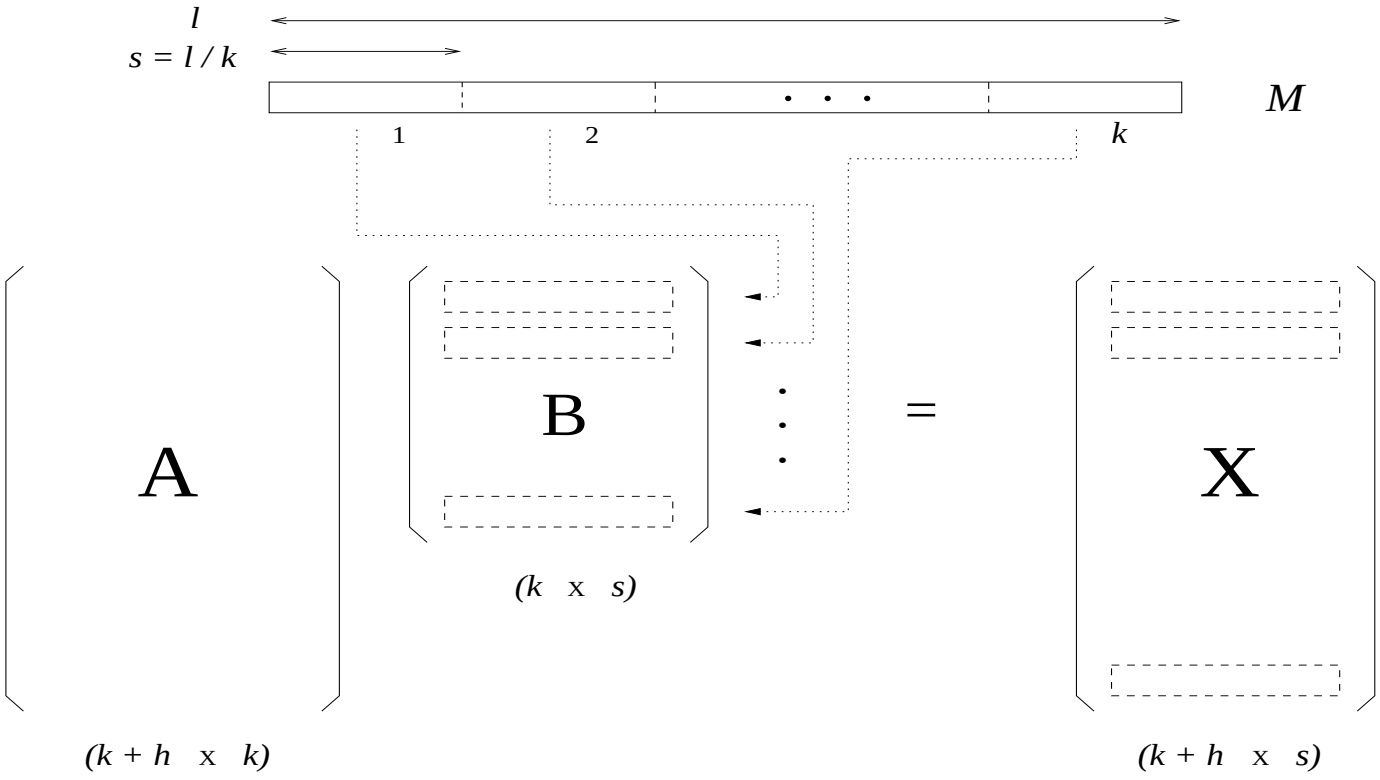
Real-Time MPEG Video Transport

- teleconferencing application
- AFEC customization to MPEG video payload
- end-to-end
- QoS-sensitive transport
- implemented entirely in software



Forward error correction using IDA

Encoding:



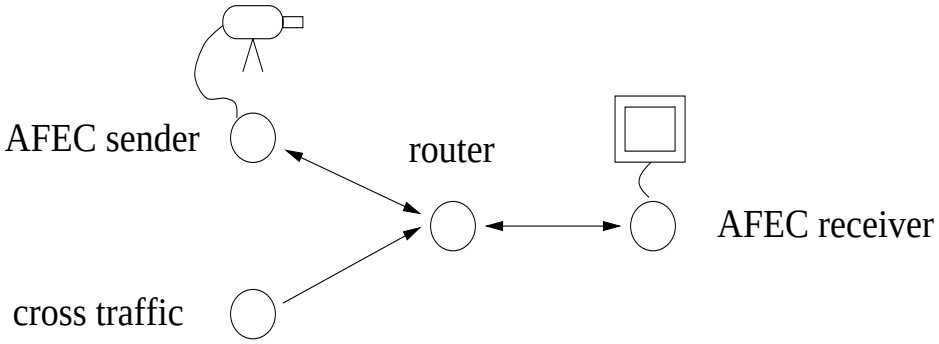
Decoding:

- encoding $\mathbf{X} = \mathbf{A}\,\mathbf{B}$
- decoding $\mathbf{A}_k^{-1}\,\mathbf{X}_k = \mathbf{B}$

Special features of MAFEC:

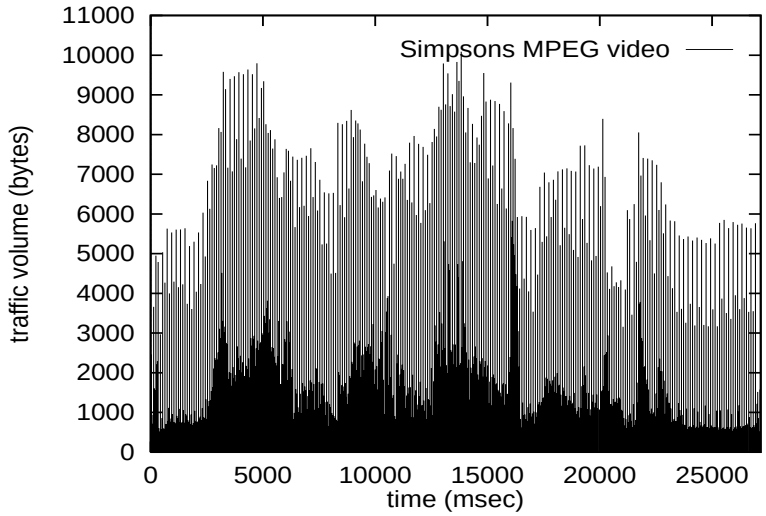
- receiver-oriented QoS control
- Stringency control
- differentiated weighting

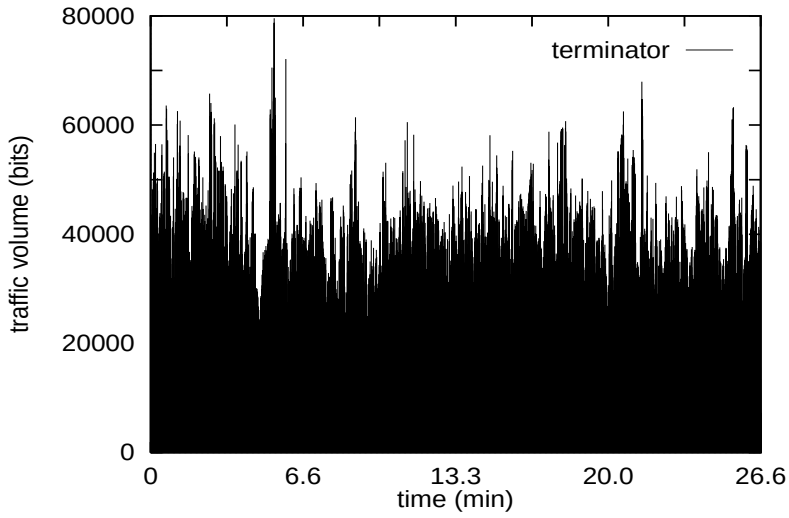
Experimental Set-Up



- MAFEC application (sender/receiver)
- cross traffic source
- configurable router
- UltraSparc 1 workstations
- FastEthernet (100Mbps)

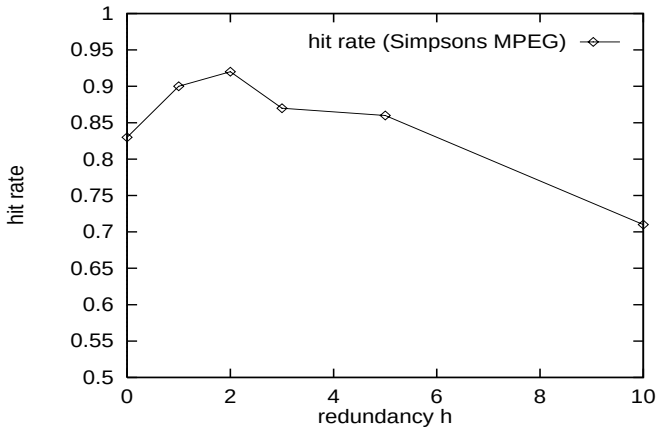
Sample MPEG-I video traces:

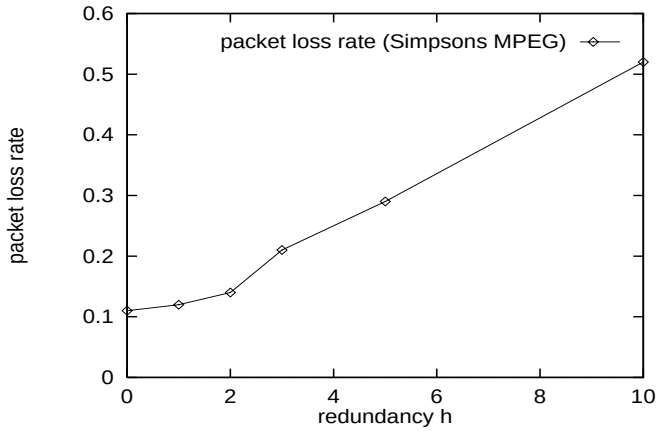


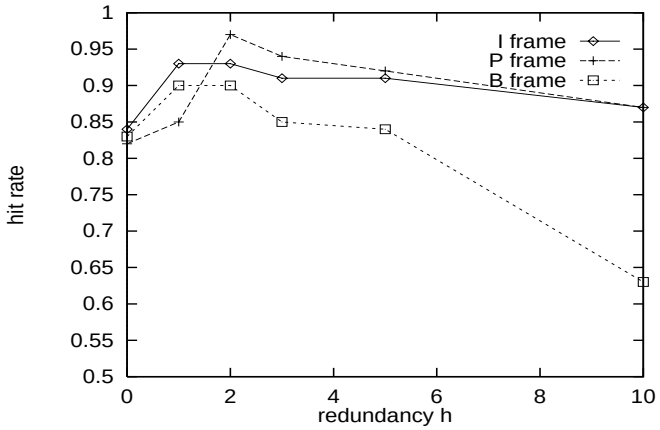


Performance Measurements

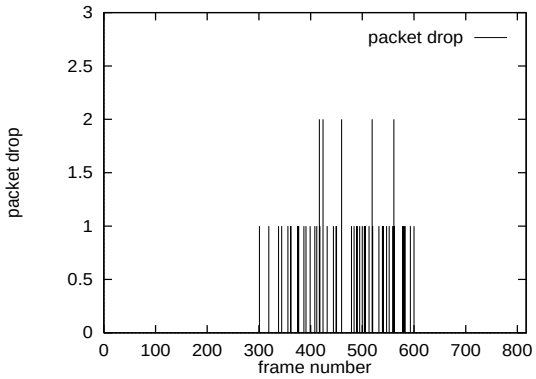
Redundancy and QoS:

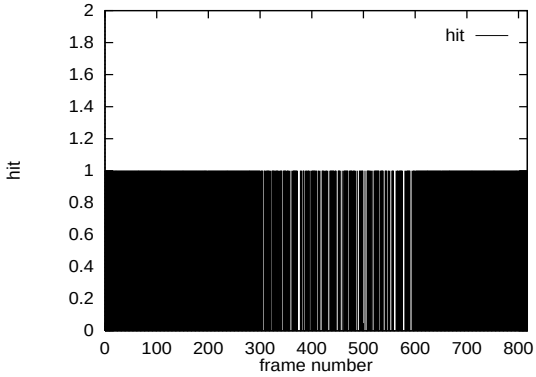


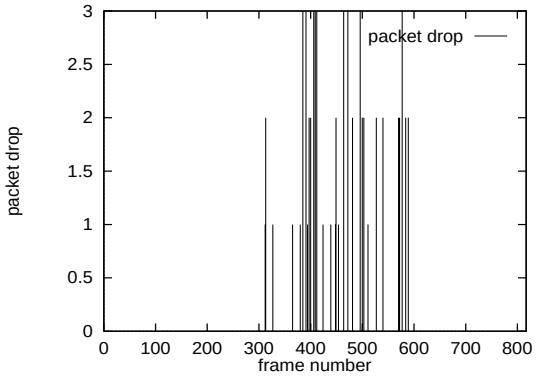


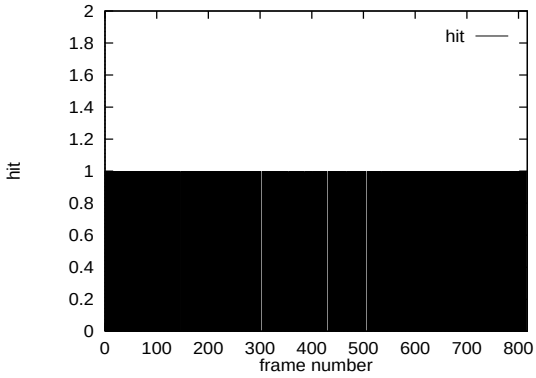

hit rate
redundancy h
I frame
P frame
B frame
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0
2
4
6
8
10

Static FEC vs. AFEC:

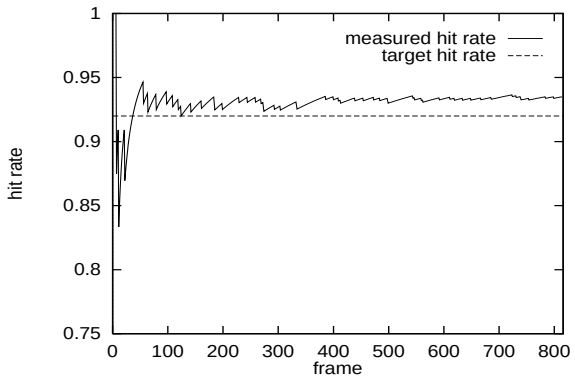


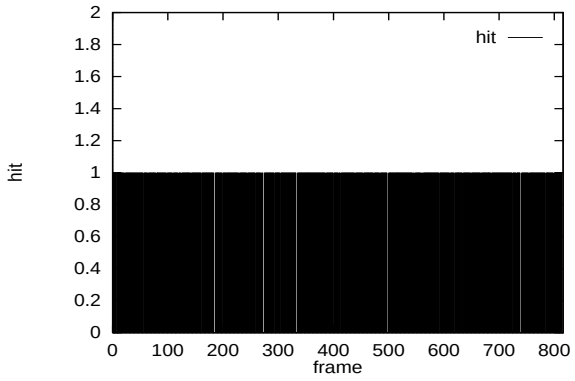


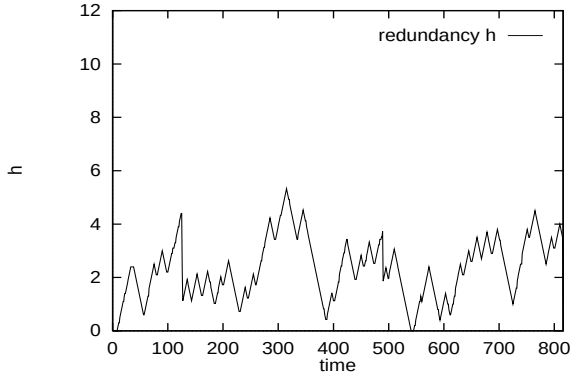


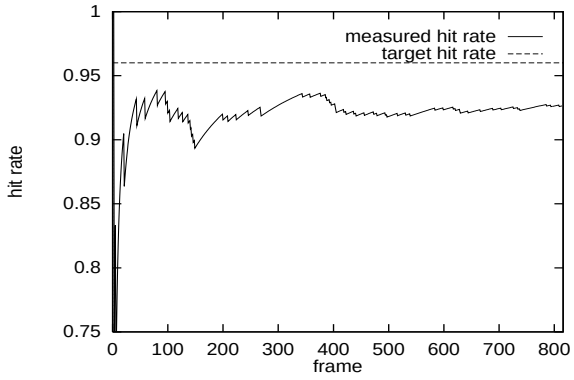


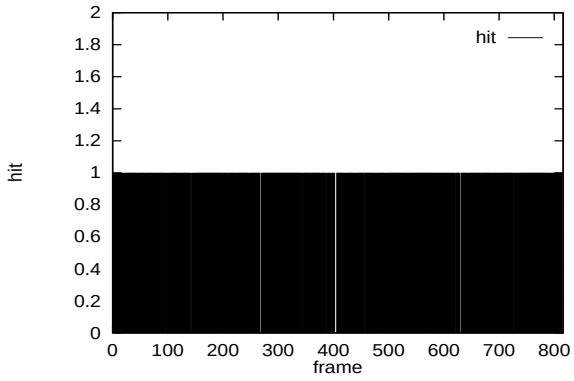
AFEC dynamics:

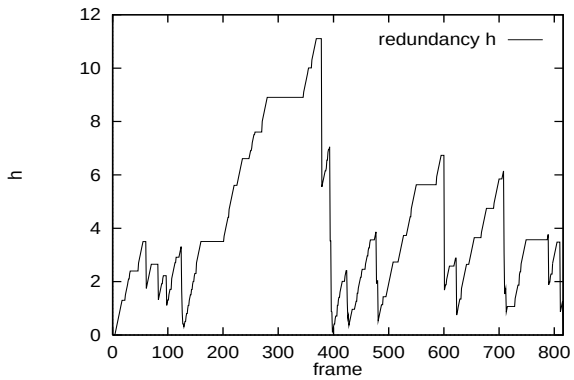




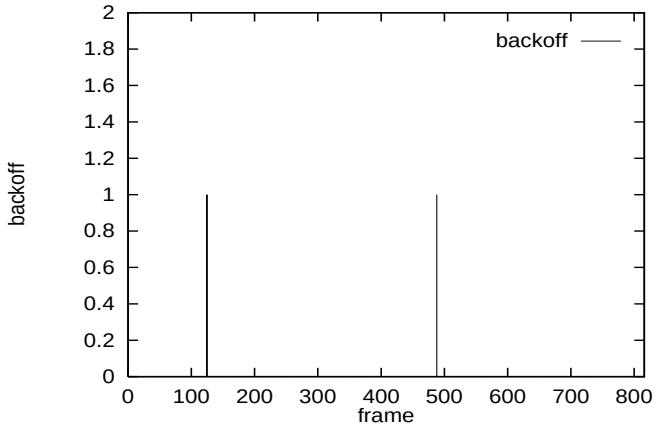


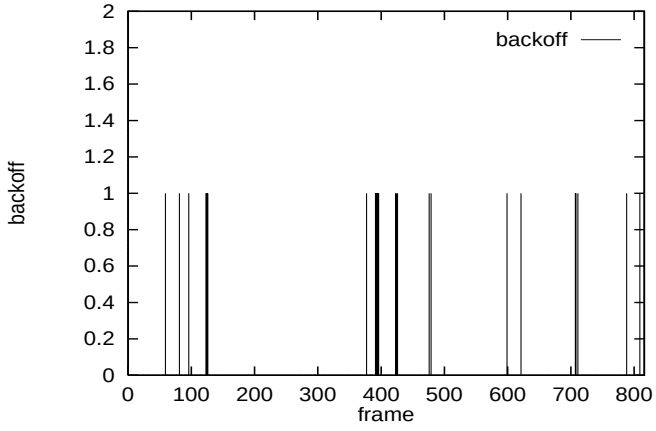

measured hit rate
target hit rate
hit rate
frame
1
0.95
0.9
0.85
0.8
0.75
0
100
200
300
400
500
600
700
800


hit
hit
frame
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
800

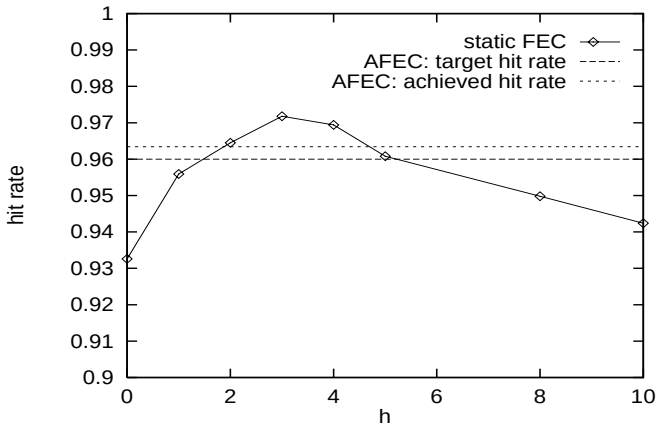

redundancy h
h
frame
12
10
8
6
4
2
0
0
100
200
300
400
500
600
700
800

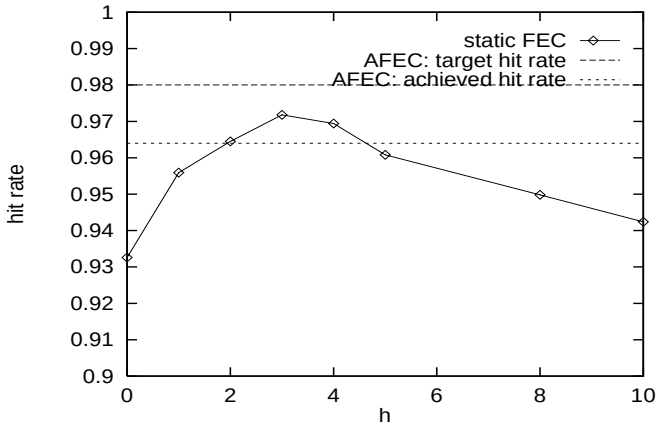
Backoff instances:



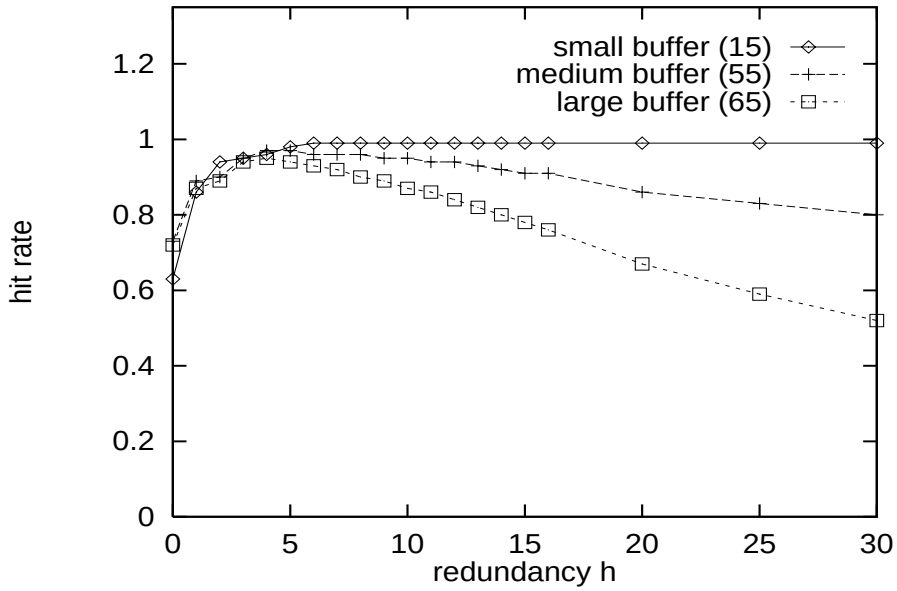


Operating point dynamics:



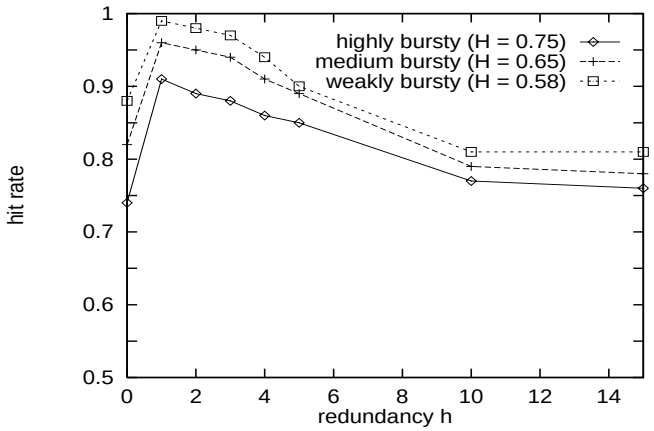


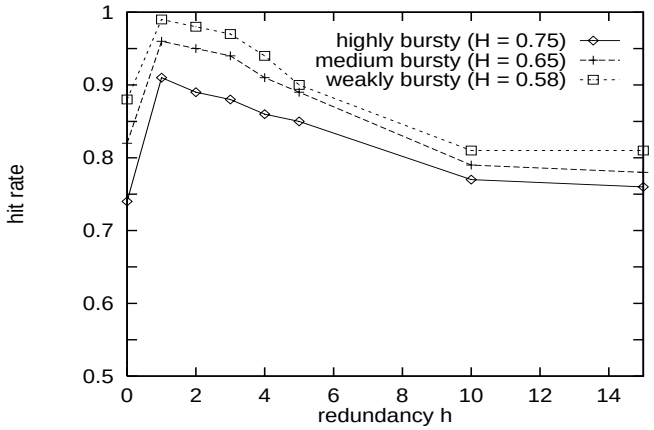
Impact of buffer capacity:

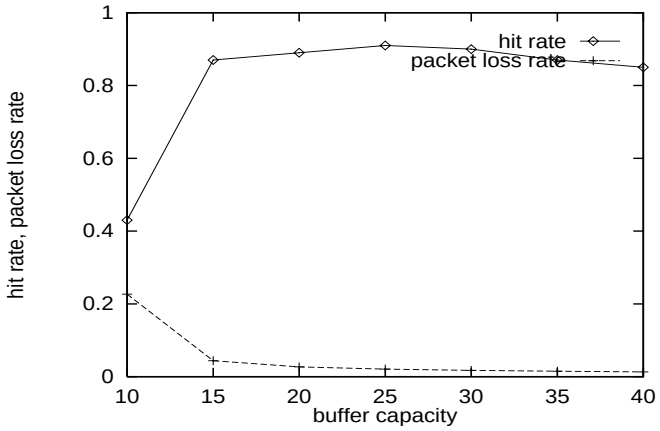


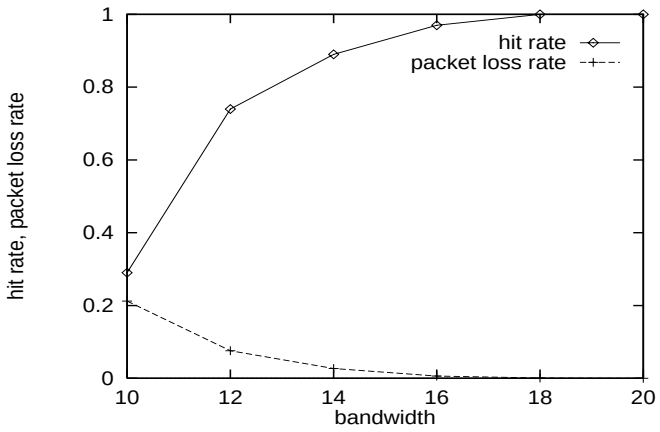
$\longrightarrow$ packet loss vs. delay domination

Impact of self-similar burstiness:






hit rate
packet loss rate
hit rate, packet loss rate
buffer capacity
0
0.2
0.4
0.6
0.8
1
10
15
20
25
30
35
40


hit rate
packet loss rate
hit rate, packet loss rate
bandwidth
0
0.2
0.4
0.6
0.8
1
10
12
14
16
18
20

Conclusion

- QoS-sensitive transport of real-time traffic using FEC
- adaptive FEC
- end-to-end
- optimal control problem
- implementation for real-time MPEG video transport
- software implementation
- desirable performance characteristics

$\longrightarrow$ real-time MPEG audio for Internet telephony