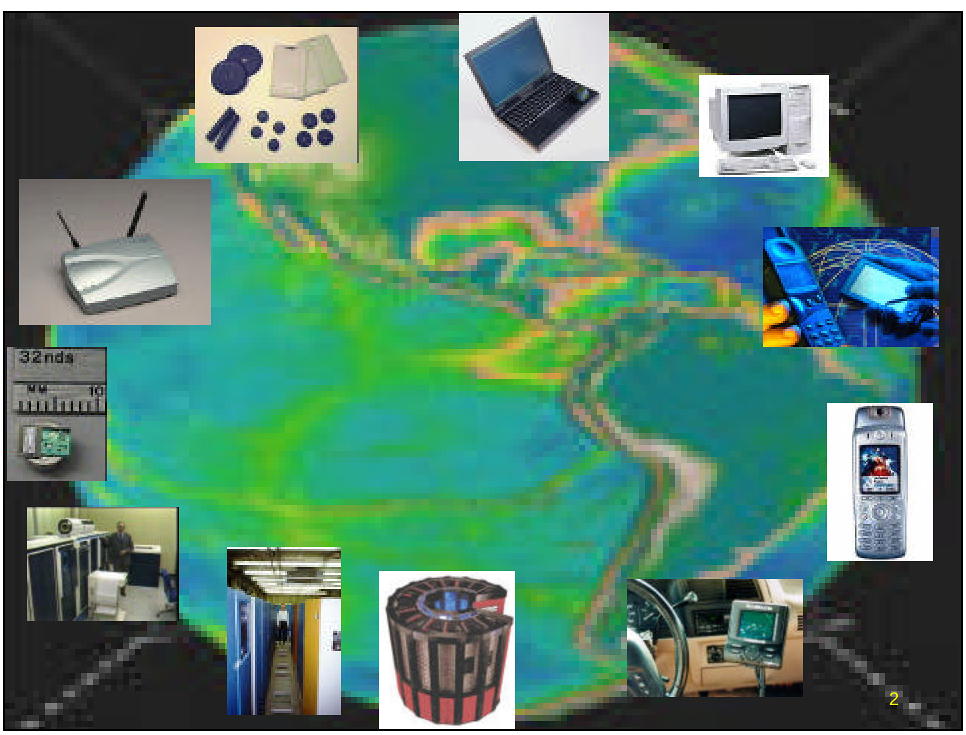
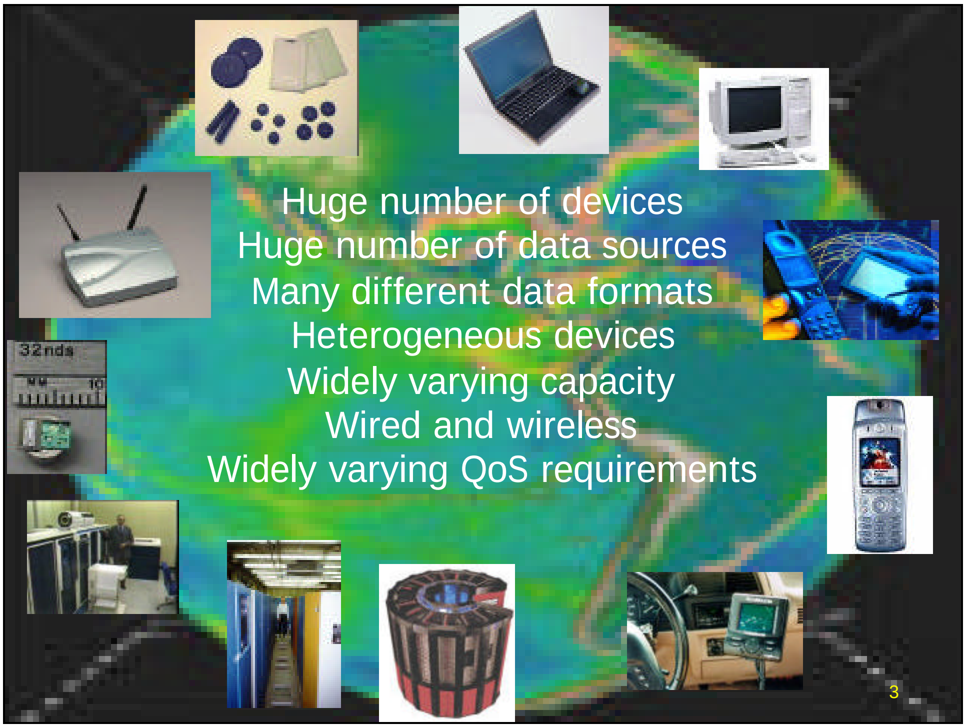
Using Performance Models to Design Self-Configuring and Self-Otimizing Computer Systems

Prof. Daniel Menascé
Department of Computer Science
E-Center for E-Business
George Mason University
Fairfax, VA, USA
Menasce@cs.gmu.edu
www.cs.gmu.edu/faculty/menasce.html




Huge number of devices
Huge number of data sources
Many different data formats
Heterogeneous devices
Widely varying capacity
Wired and wireless
Widely varying QoS requirements
3


Node failures
Connectivity failures
Security attacks
Limited battery power
4

Characteristics of the new generation of distributed software systems

- ❑ Highly distributed
- ❑ Component-based (for reusability)
- ❑ Service-oriented architectures (SOA)
- ❑ Unattended operation
- ❑ Hostile environments
- ❑ Composed of a large number of "replaceable" components discovered at run-time
- ❑ Run on a multitude of (unknown and heterogeneous) hardware and network platforms

Requirements of Next Generation of Large Distributed Systems

- ❑ Adaptable and self-configurable to changes in workload intensity:
  - ➢ QoS requirements at the application and component level must be met.
- ❑ Adaptable and self-configurable to withstand attacks and failures:
  - ➢ Availability and security requirements must be met.

➡ self-configurable, self-optimizing, self-healing, and self-protecting

Important Technologies

- ❑ Web Services:
  - SOAP, UDDI, WSDL
- ❑ Grid Computing
- ❑ Peer to Peer Networks
- ❑ Wireless Networking
- ❑ Sensor and ad-hoc networks

Challenges

- ❑ Dynamically changing application structure.
- ❑ Hard to characterize the workload.
  - ➢ unpredictable
  - ➢ dynamically changing services
  - ➢ application adaptation
- ❑ Difficult to build performance models.
  - ➢ moving target
- ❑ Multitude of QoS metrics at various levels of a distributed architecture
  - ➢ response time, jitter, throughput, availability, survivability, recovery time after attack/failure, call drop rate, access failure rate, packet delay, packet drop rate.
- ❑ Tradeoffs between QoS metrics (response time vs. availability, response time vs. security)

Challenges (cont'd)

- Need to perform transient, critical time (e.g., terrorism attack or catastrophic failures) analysis of QoS compliance. Steady-state analysis is not enough.
- Mapping of global SLAs to local SLAs
  - Cost and pricing issues.
- QoS monitoring, negotiation, and enforcement.
- Platform-neutral representation of QoS goals and contracts.
- Resource management: resource reservation, resource allocation, admission control.
  - non-dedicated resources

What we need …

- Design self-regulating (autonomic systems)
- Embed within each system component:
  - Monitoring capabilities
  - Negotiation capabilities (requires predictive modeling power)
  - Self-protection and recovery capabilities (for attacks, failures, and overloads)
- Push more of the desired system features to individual components
- Design QoS-aware middleware
  - QoS negotiation protocols
  - Mapping of global to local SLAs
  - QoS monitoring

Rest of this talk …

- Novel uses for performance models
- Two examples of self-regulating systems:
  - A three-tiered e-commerce system
  - QoS-aware software components
- Concluding Remarks

Rest of this talk …

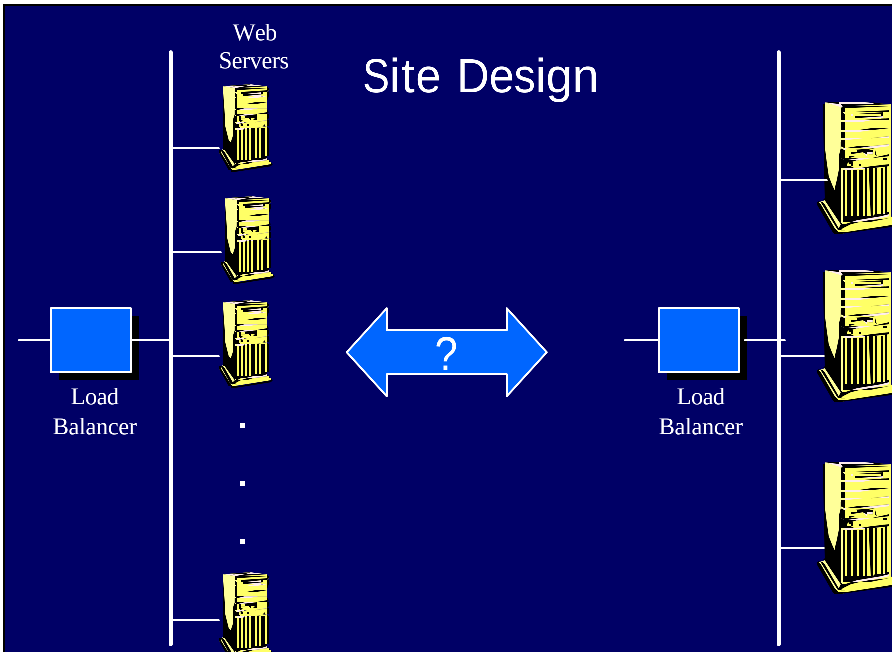
- $\boxed{\text{Novel uses for performance models}}$
- Two examples of self-regulating systems:
  - A three-tiered e-commerce system
  - QoS-aware software components
- Concluding Remarks

What are performance models good for?

- At the design stage:
  - Compare competing design alternatives.
    - A large number of low capacity servers vs. a small number of large capacity servers?

13

Site Design

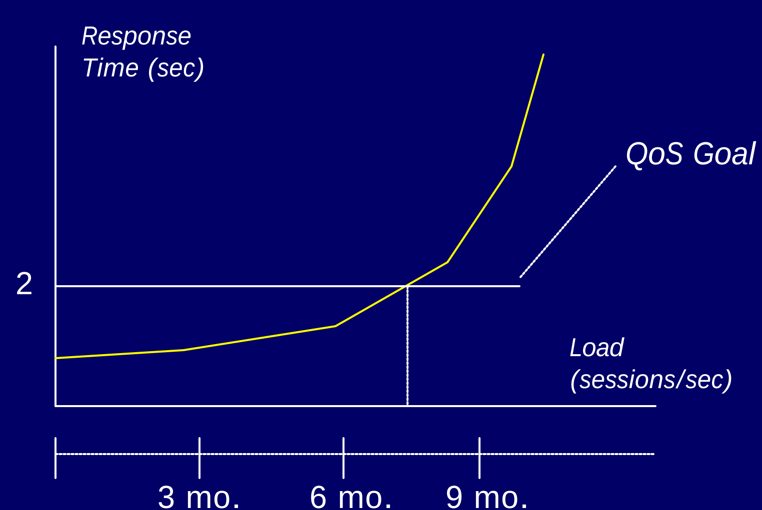


14

What are performance models good for?

- At the design stage:
  - Compare competing design alternatives.
    - A large number of low capacity servers vs. a small number of large capacity servers?
- During production:
  - Medium and long-term (weeks and months):
    - Capacity planning.

Capacity Planning



What are performance models good for?

- At the design stage:
  - Compare competing design alternatives.
    - A large number of low capacity servers vs. a small number of large capacity servers?
- During production:
  - Medium and long-term (weeks and months):
    - Capacity planning.
  - Short-term (minutes):
    - Dynamic reconfiguration.

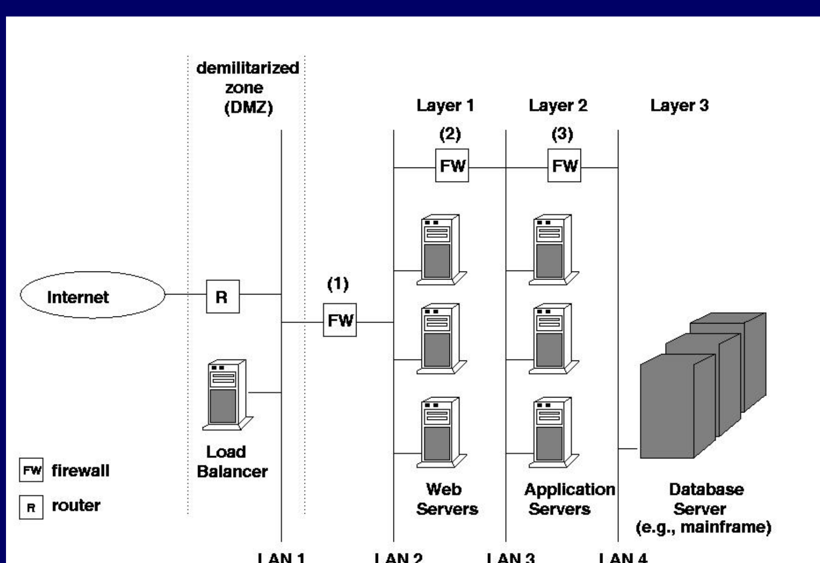
Rest of this talk …

- Novel uses for performance models
- Two examples of self-regulating systems:
  - A three-tiered e-commerce system
  - QoS-aware software components

Automatic QoS Control: Motivation

- ❑ Modern computer systems are complex and composed of multiple tiers.

Multi-tier Architecture



Automatic QoS Control: Motivation

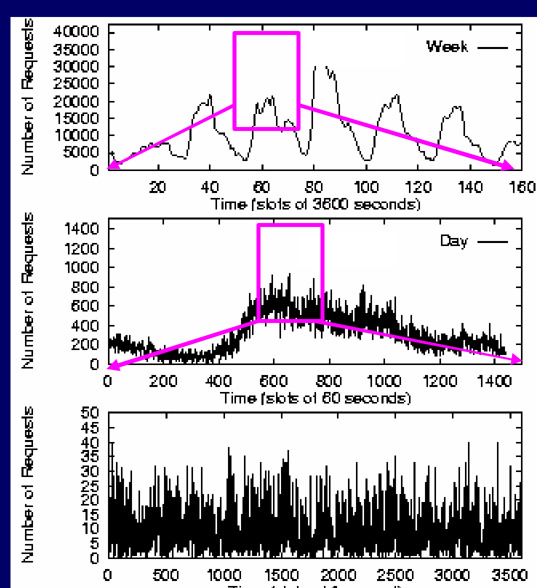
- Modern computer systems are complex and composed of multiple tiers.
- The workload presents short-term variations with high peak-to-average ratios.

Multi-scale time workload variation

3600 sec

60 sec

1 sec

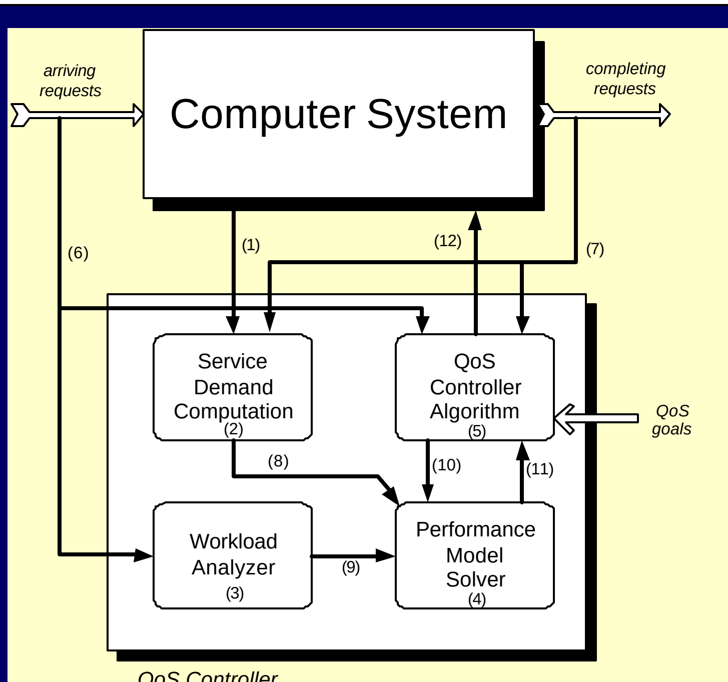


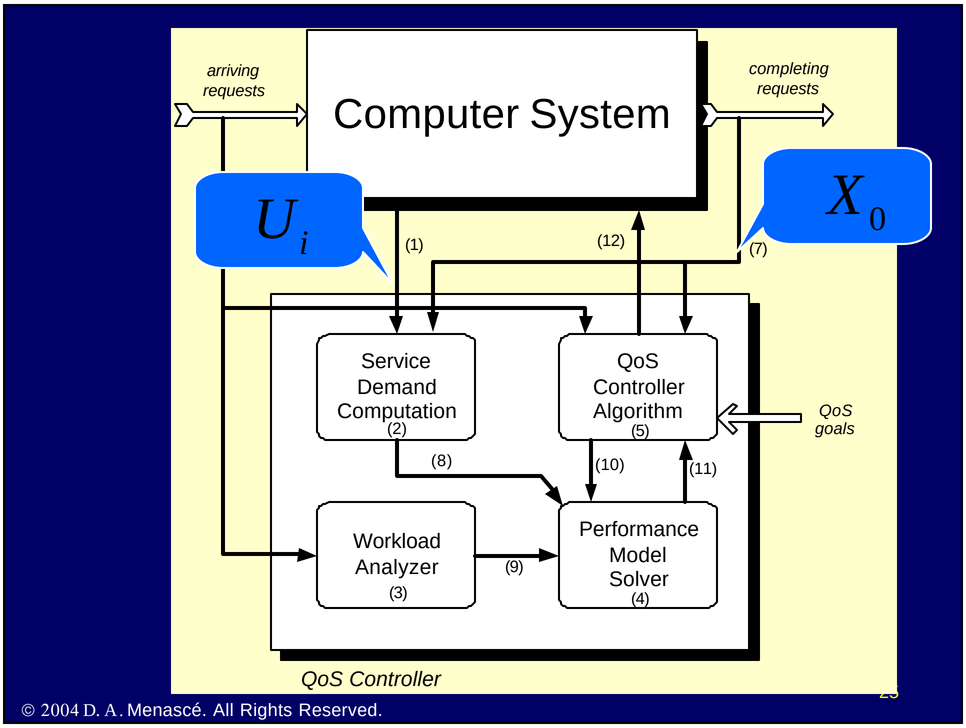
Automatic QoS Control: Motivation

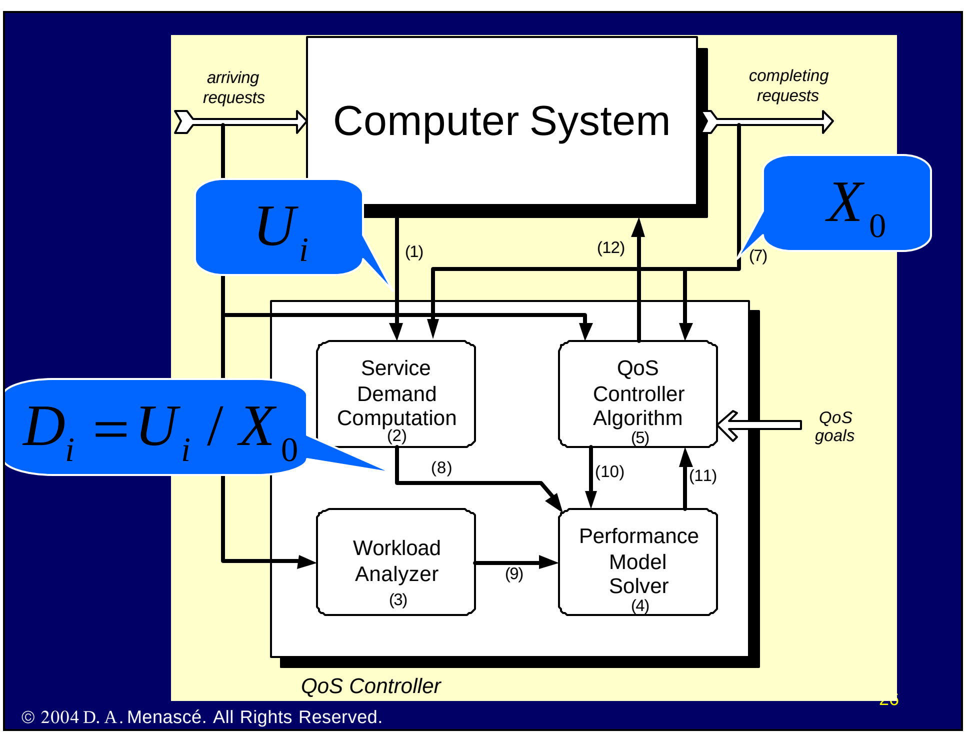
- Modern computer systems are complex and composed of multiple tiers.
- The workload presents short-term variations with high peak-to-average ratios.
- Many software and hardware parameters influence the performance of e-commerce sites.

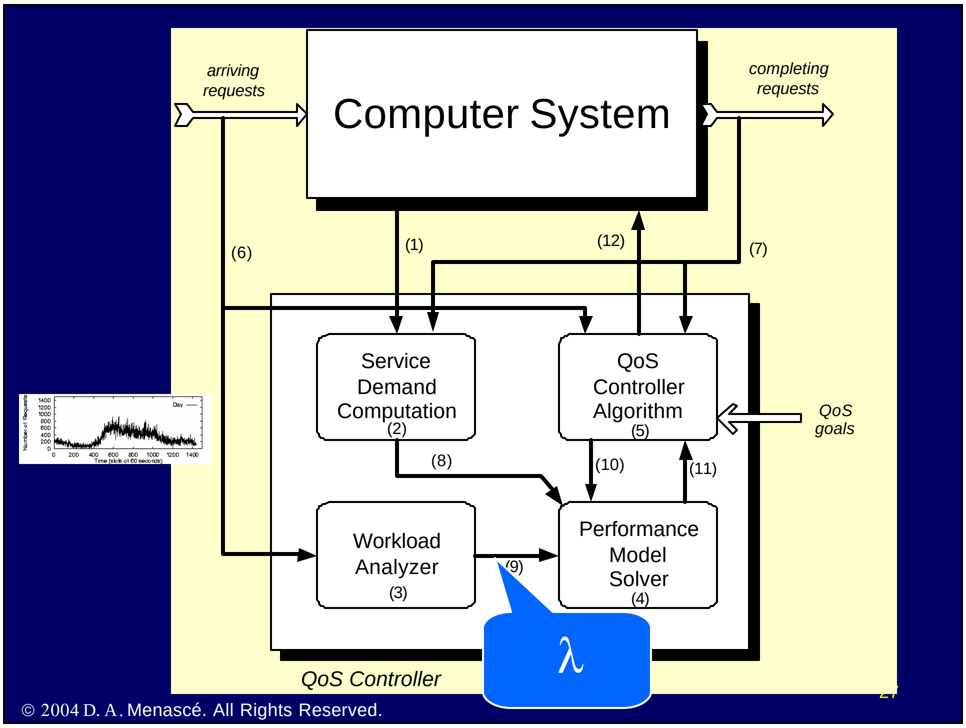
→ Manual reconfiguration is not an option!

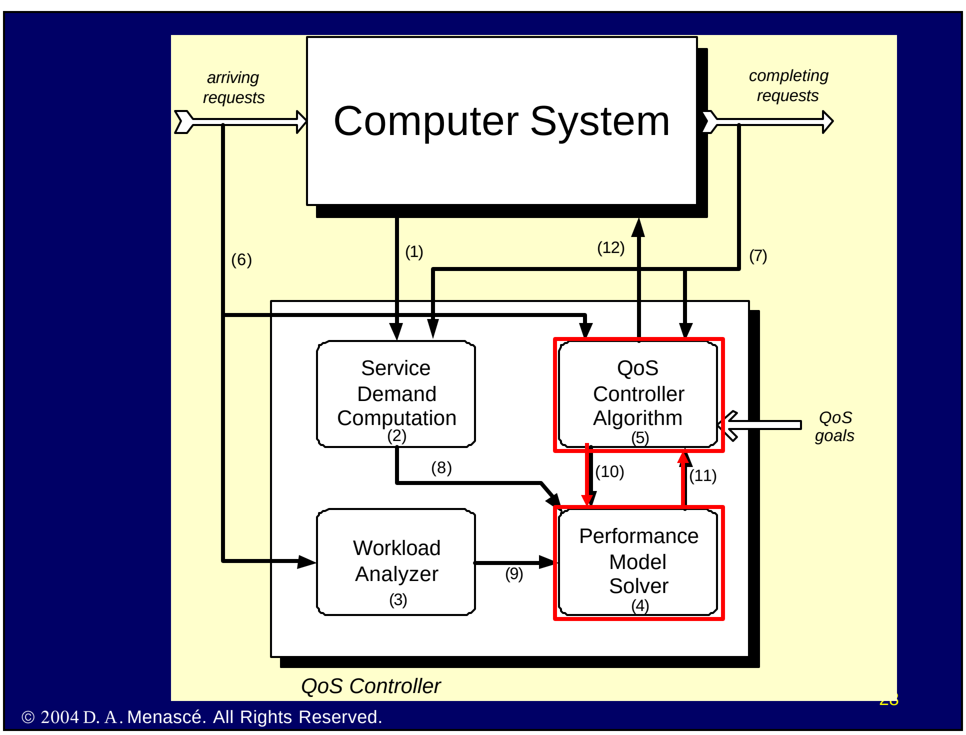
Need self-managing systems.



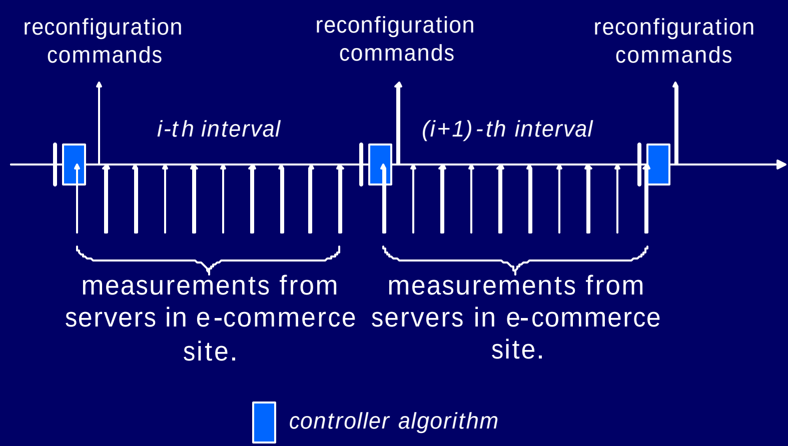

arriving requests
Computer System
completing requests
U_i
X_0
(1)
(12)
(7)
Service Demand Computation (2)
QoS Controller Algorithm (5)
QoS goals
(8)
(10)
(11)
Workload Analyzer (3)
(9)
Performance Model Solver (4)
QoS Controller
© 2004 D. A. Menascé. All Rights Reserved.


arriving requests
Computer System
completing requests
U_i
X_0
(1)
(12)
(7)
Service Demand Computation (2)
QoS Controller Algorithm (5)
QoS goals
$D_i = U_i / X_0$
(8)
(10)
(11)
Workload Analyzer (3)
(9)
Performance Model Solver (4)
QoS Controller
© 2004 D. A. Menascé. All Rights Reserved.


arriving requests
Computer System
completing requests
(1)
(12)
(7)
(6)
Service Demand Computation (2)
QoS Controller Algorithm (5)
QoS goals
(8)
(10)
(11)
Workload Analyzer (3)
(9)
Performance Model Solver (4)
λ
QoS Controller
© 2004 D. A. Menascé. All Rights Reserved.


arriving requests
Computer System
completing requests
(1)
(12)
(7)
(6)
Service Demand Computation (2)
QoS Controller Algorithm (5)
QoS goals
(8)
(10)
(11)
Workload Analyzer (3)
(9)
Performance Model Solver (4)
QoS Controller
© 2004 D. A. Menascé. All Rights Reserved.

Controller Interval



Combined QoS Metric

$$QoS = w_R \times \Delta QoS_R + w_P \times \Delta QoS_P + w_X \times \Delta QoS_X$$

w_R, w_P, and w_X are relative weights that indicate the relative importance of response time, throughput, and probability of rejection.

QoS Metric

$$QoS = w_R \times \Delta QoS_R + w_P \times \Delta QoS_P + w_X \times \Delta QoS_X$$

w_R, w_P, and w_X are relative weights that indicate the relative importance of response time, throughput, and probability of rejection.

- ΔQoS_R, ΔQoS_P, and ΔQoS_X are relative deviations of the response time, throughput, and probability of rejection metrics with respect to their desired levels.

31

QoS Metric

$$QoS = w_R \times \Delta QoS_R + w_P \times \Delta QoS_P + w_X \times \Delta QoS_X$$

w_R, w_P, and w_X are relative weights that indicate the relative importance of response time, throughput, and probability of rejection.

ΔQoS_R, ΔQoS_P, and ΔQoS_X are relative deviations of the response time, throughput, and probability of rejection metrics with respect to their desired levels.

- The QoS metric is a dimensionless number in the interval [-1, 1].

32

QoS Metric

$$QoS = w_R \times \Delta QoS_R + w_P \times \Delta QoS_P + w_X \times \Delta QoS_X$$

w_R w_P, and w_X are relative weights that indicate the relative importance of response time, throughput, and probability of rejection.

ΔQoS_R, ΔQoS_P, and ΔQoS_X are relative deviations of the response time, throughput, and probability of rejection metrics with respect to their desired levels.

The QoS metric is a dimensionless number in the interval [-1, 1].

If all metrics meet or exceed their QoS targets, QoS = 0.

Response Time Deviation

$$\Delta QoS_R = \frac{R_{\max} - R_{measured}}{\max(R_{\max}, R_{measured})}$$

- = 0 if the response time meets its target.
- > 0 if the response time exceeds its target.
- < 0 if the response time does not meet its target.

- $\Delta QoS_R \leq 1 - (\sum_{i=1}^{K} D_i) / R_{\max} < 1$
- $-1 < -(1 - R_{\max} / R_{measured}) \leq \Delta QoS_R$

Probability of Rejection Deviation

$$\Delta QoS_P = \frac{P_{\max} - P_{measured}}{\max(P_{\max}, P_{measured})}$$

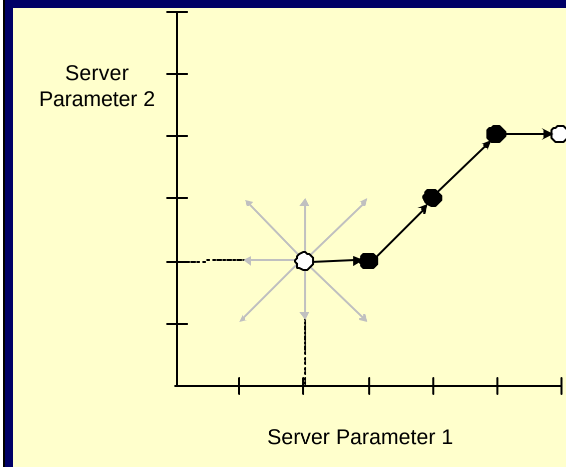
- = 0 if the probability of rejection meets its target.
- > 0 and = 1 if the probability of rejection exceeds its target.
- < 0 and = -1 if the probability of rejection does not meet its target.

Throughput Deviation

$$\Delta QoS_X = \frac{X_{measured} - X^*_{\min}}{\max(X_{measured}, X^*_{\min})}$$

- $X^*_{\min} = \min(l, X_{\min})$
- = 0 if the throughput meets its target.
- > 0 and < 1 if the throughput exceeds its target.
- < 0 and > -1 if the throughput does not meet its target.

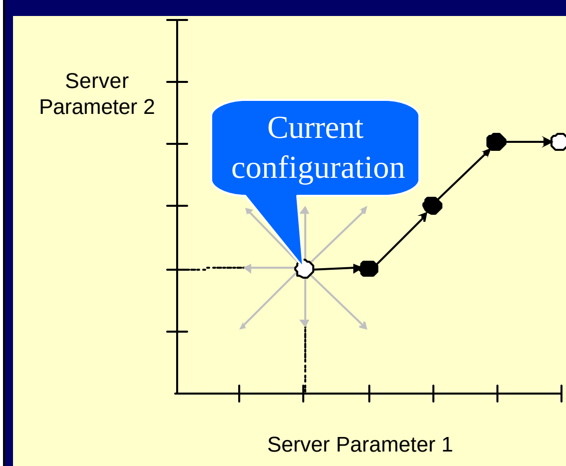
Heuristic Optimization Approach



- The space of configuration points is searched using a combinatorial search technique.
- Each point has a QoS value computed through an analytic performance model.

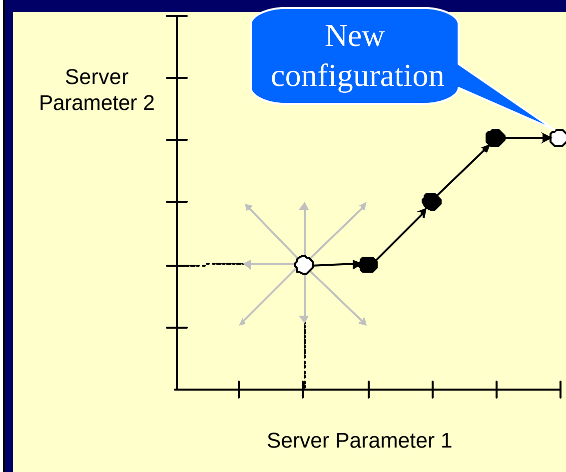
$$QoS = f(\vec{W}, c_1, c_2, \ldots, c_m)$$

Heuristic Optimization Approach



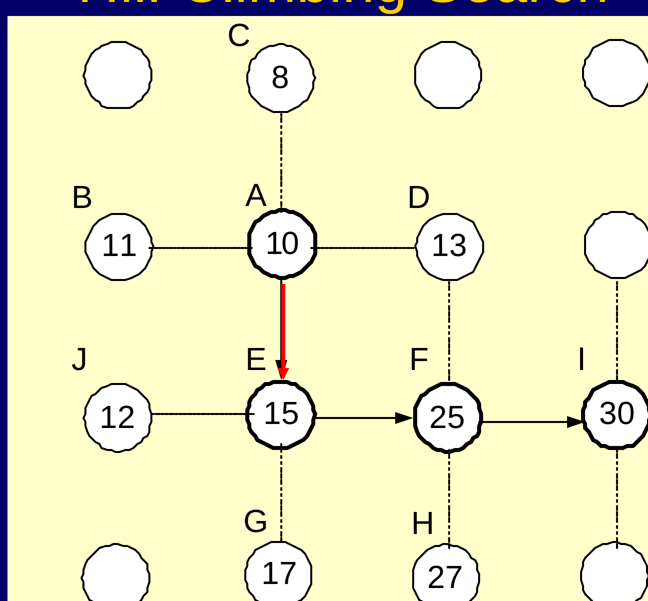
- The space of configuration points is searched using combinatorial search techniques.
- Each point has a QoS value computed through an analytic performance model.

Heuristic Optimization Approach

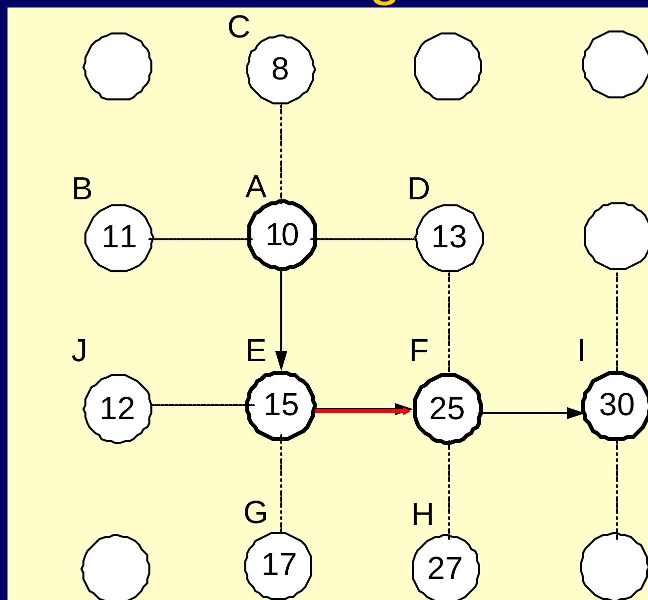


- The space of configuration points is searched using combinatorial search techniques.
- Each point has a QoS value computed through an analytic performance model.

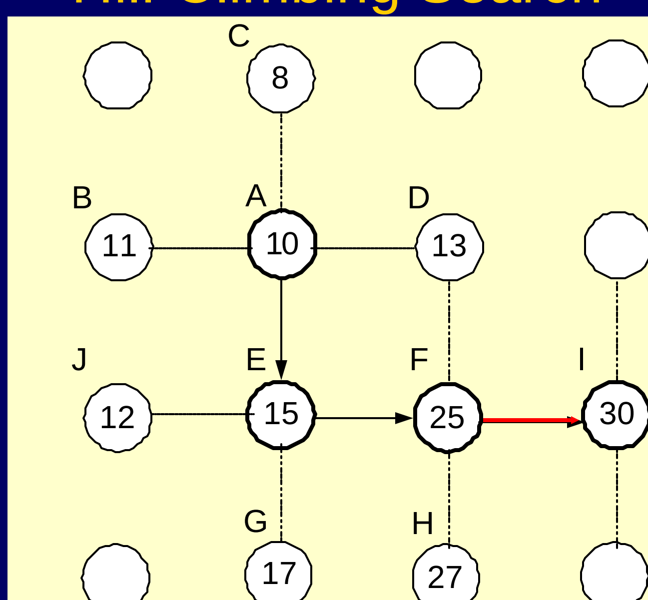
Hill-Climbing Search



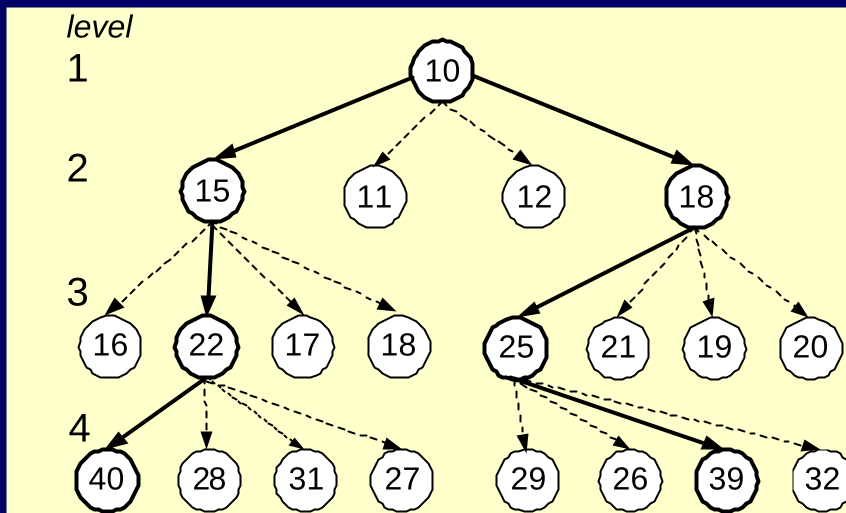
Hill-Climbing Search



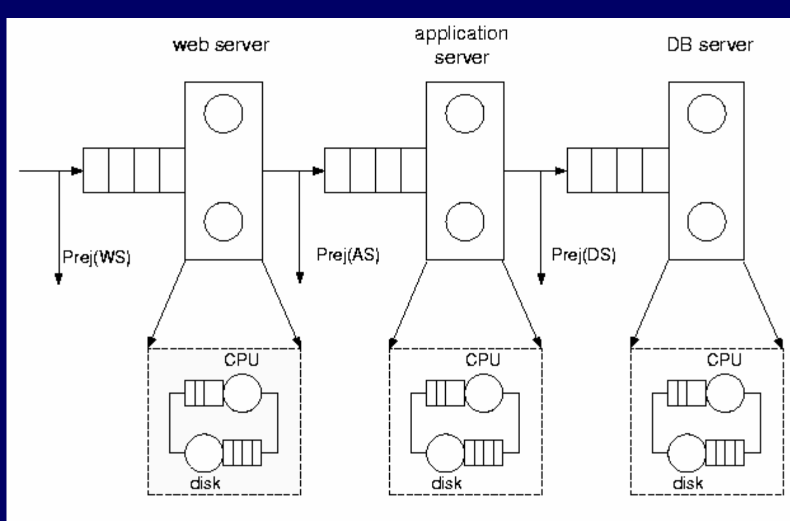
Hill-Climbing Search



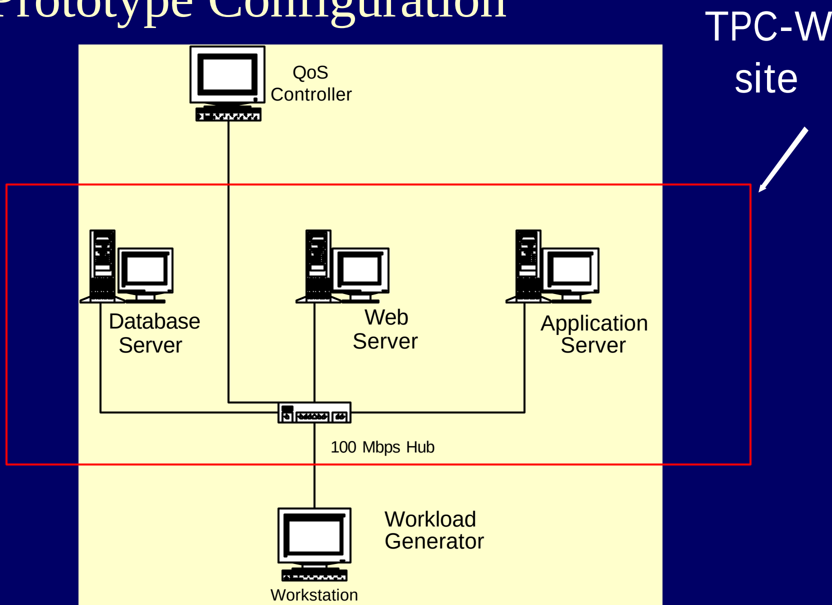
Beam Search



A Queuing Model is Used to Compute QoS Values

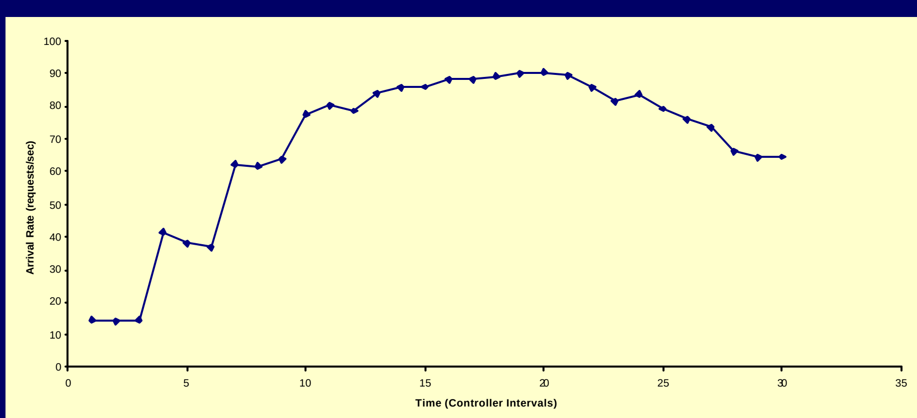


Prototype Configuration

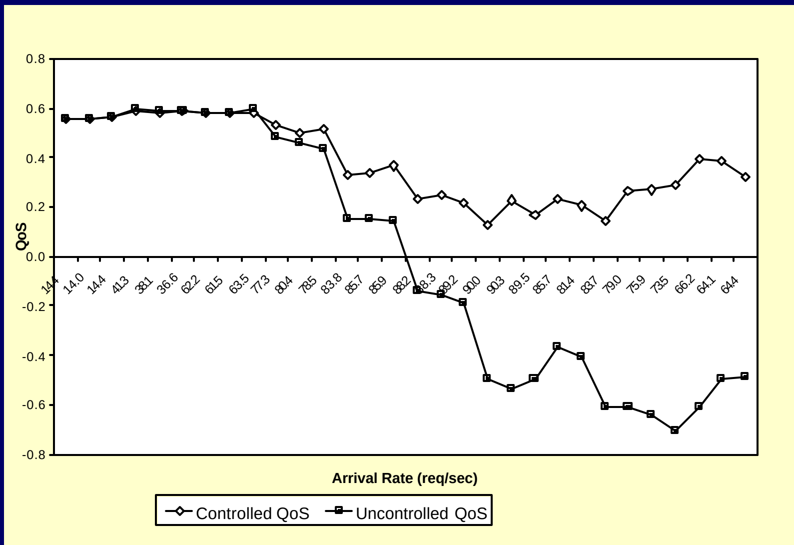


Experiment Results

Arrival rate

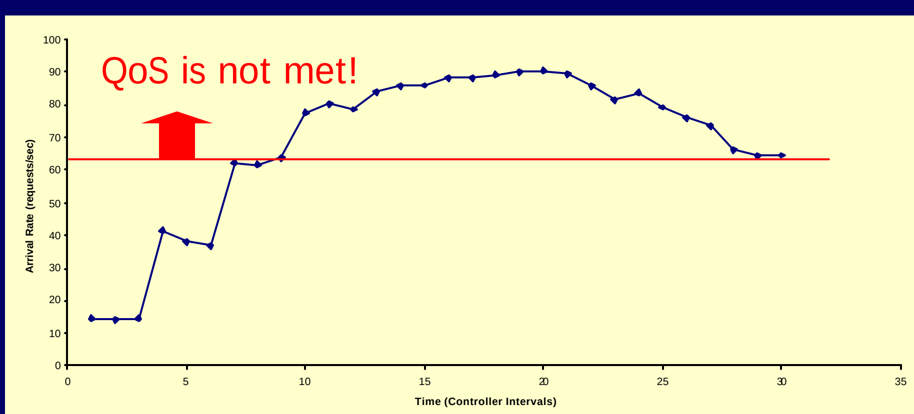


Results of QoS Controller



Experiment Results

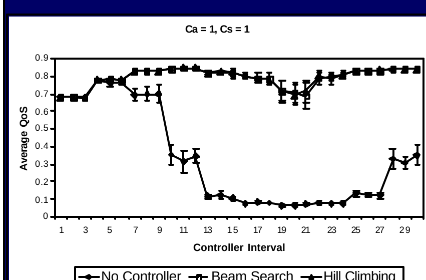
Arrival rate



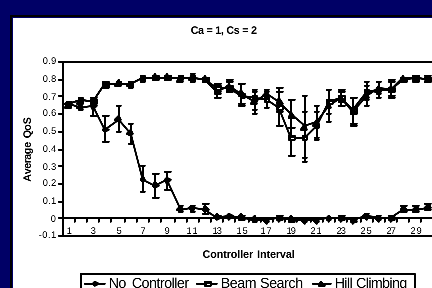
Variable inter-arrival and service times of requests

- ❑Real workloads exhibit high variability in:
  - ➢Traffic intensity
  - ➢Service demands at various system resources
- ❑Need to investigate the efficiency of the proposed self-managing technique under these conditions
- ❑Consider variability in requests inter-arrival time and requests service times at physical resources (e.g., CPU, disk)

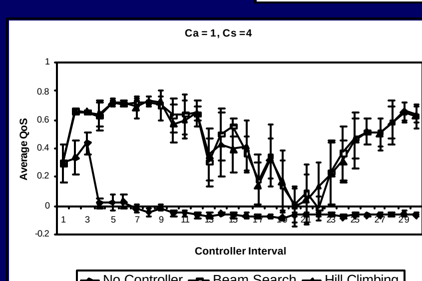
Effect of Varying the COV of the Service Time (Ca = 1)



Cs = 1

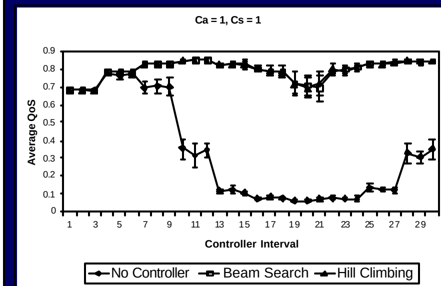


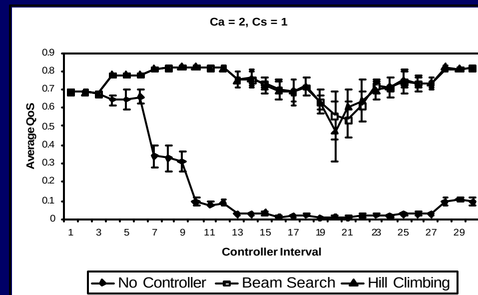
Cs = 2



Cs = 4

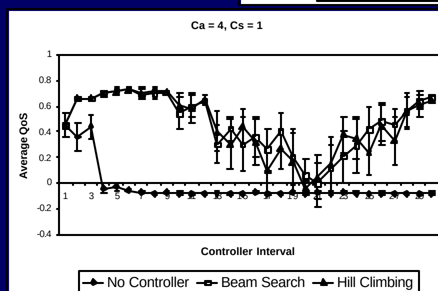
Effect of Varying the COV of the Interarrival Time (Cs = 1)





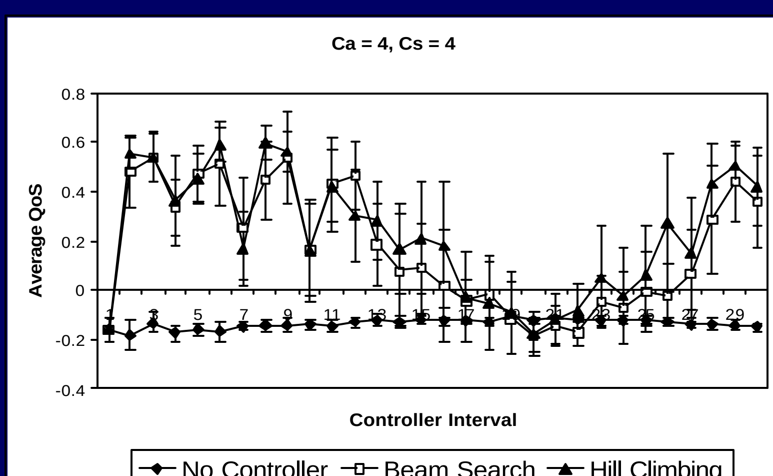
Ca = 1

Ca = 2

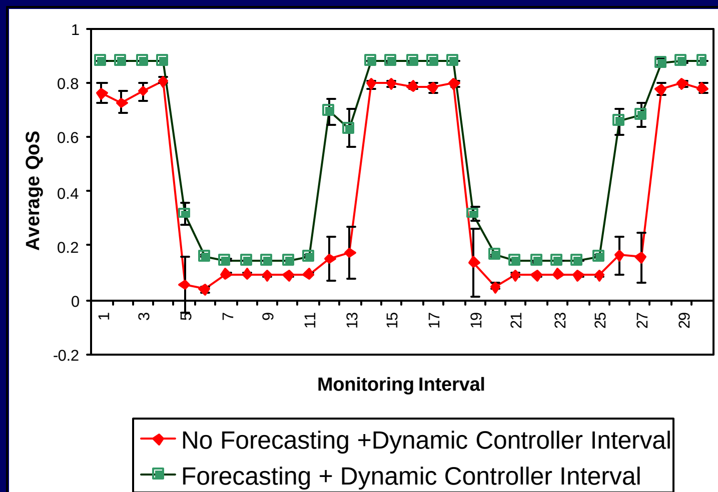


Ca = 4

Extreme values for Ca and Cs



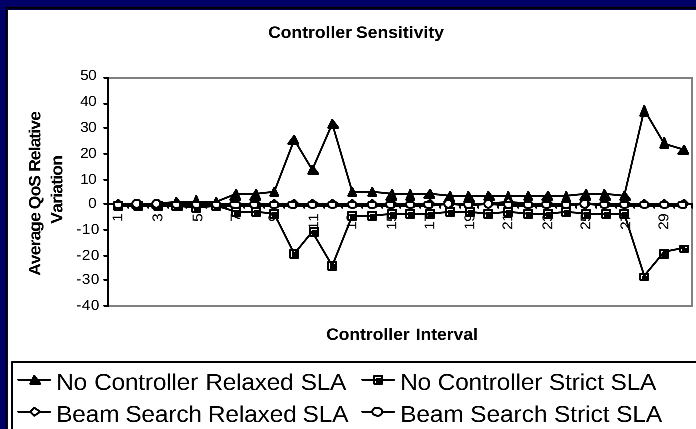
Dynamic Controller Interval and Workload Forecasting



Sensitivity of Controller to SLAs

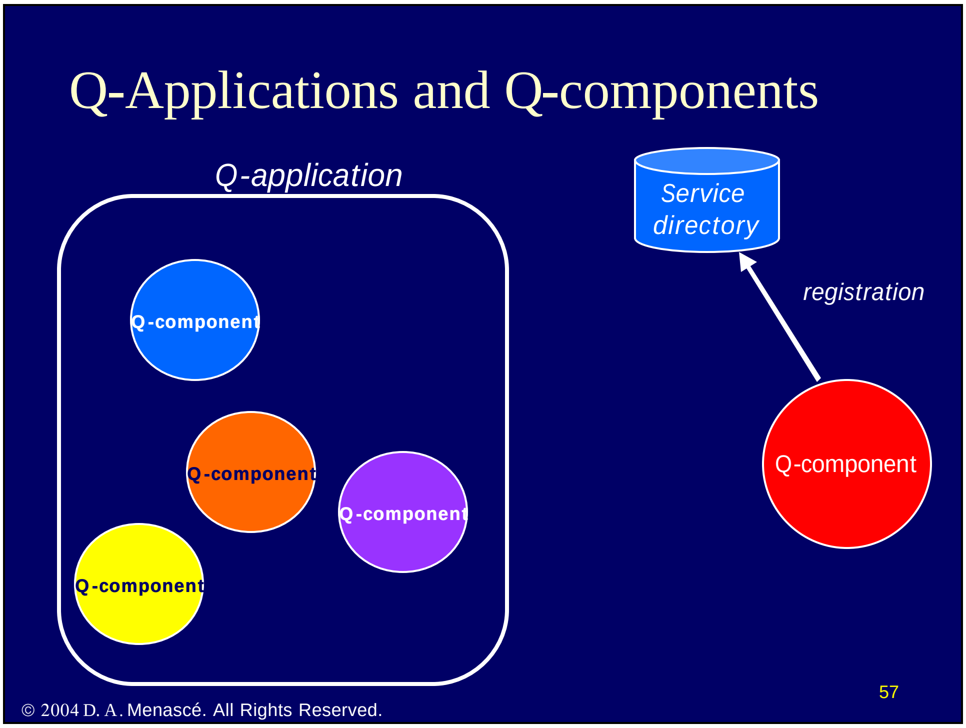
- ❑Need to investigate the controller behavior in the case of a variation in the SLAs
- ❑We ran experiments for stricter and more relaxed SLAs
  - ➢Base: Rmax = 1.2 sec, Xmin = 5 req/sec, Pmax = 0.05
  - ➢Strict: Rmax = 1.0 sec, Xmin = 7 req/sec, Pmax = 0.03
  - ➢Relaxed: Rmax = 1.5 sec, Xmin = 4 req/sec, Pmax = 0.10
- ❑Used Ca = Cs = 2

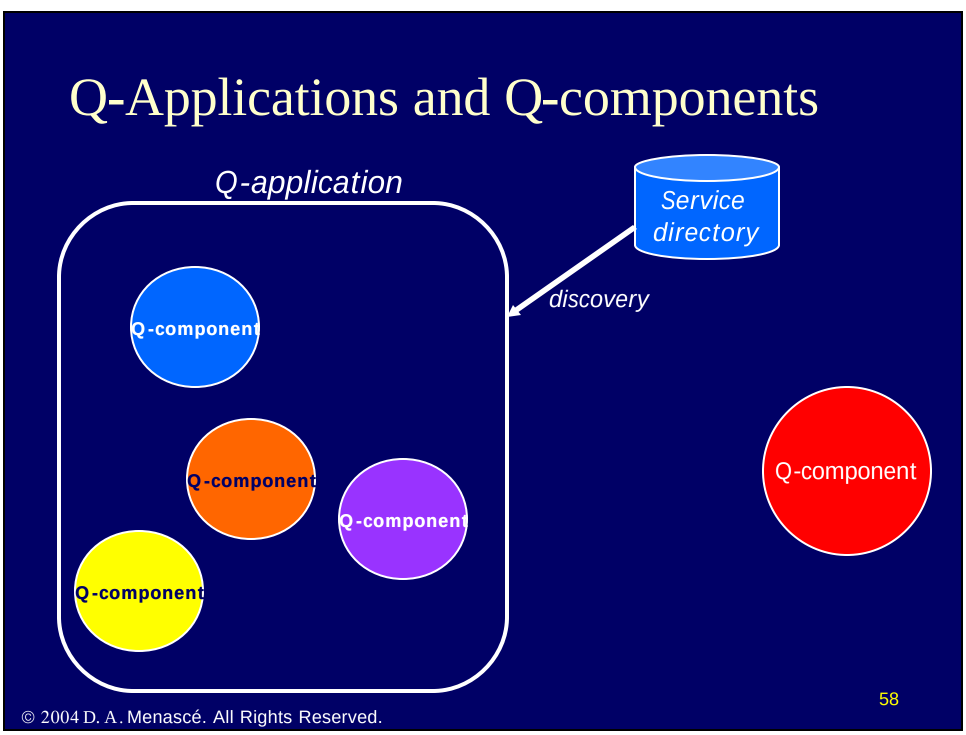
Sensitivity of Controller to SLAs



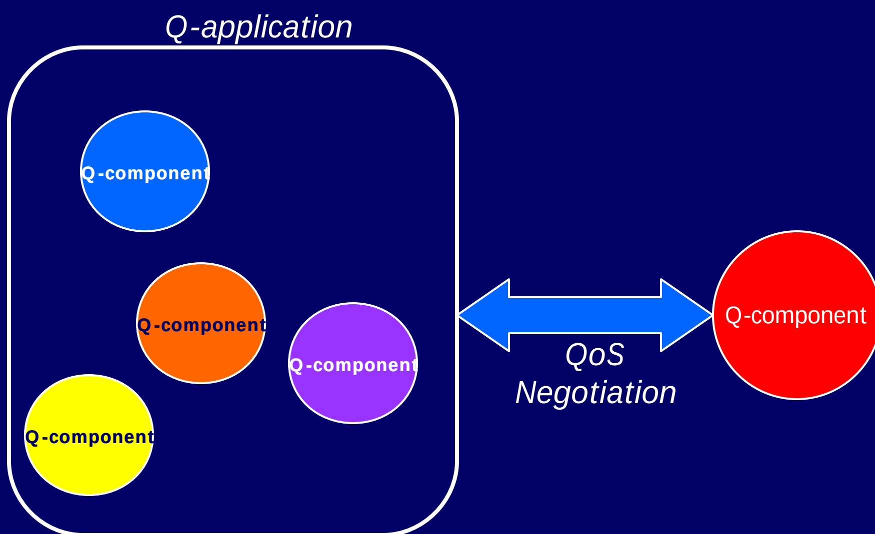
Rest of this talk …

- ❑ Novel uses for performance models
- ❑ Two examples of self-regulating systems:
  - ➢ A three-tiered e-commerce system
  - ➢ QoS-aware software components
- ❑ Concluding Remarks


Q-Applications and Q-components
Q-application
Service directory
registration
Q-component
Q-component
Q-component
Q-component
Q-component
57
© 2004 D. A. Menascé. All Rights Reserved.

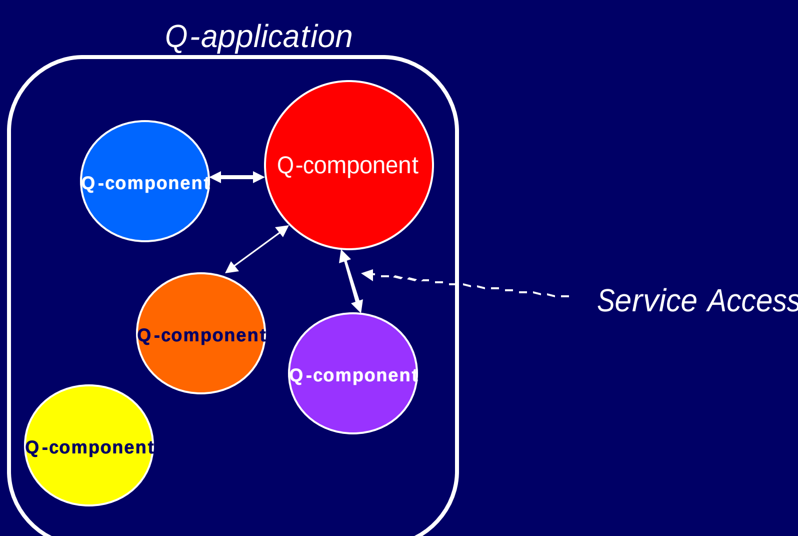

Q-Applications and Q-components
Q-application
Service directory
discovery
Q-component
Q-component
Q-component
Q-component
Q-component
58
© 2004 D. A. Menascé. All Rights Reserved.

Q-Applications and Q-components



59

Q-Applications and Q-components

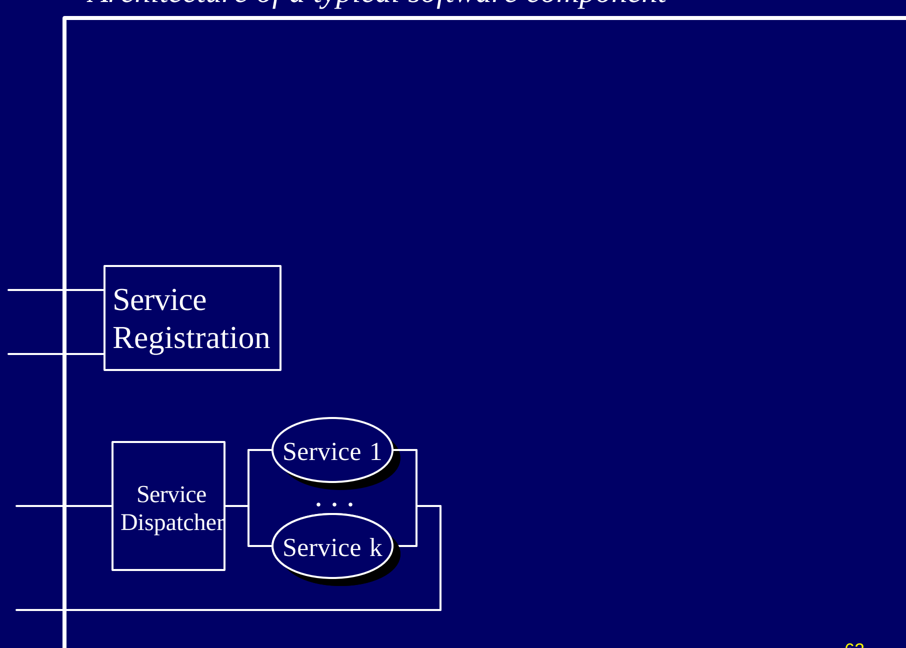


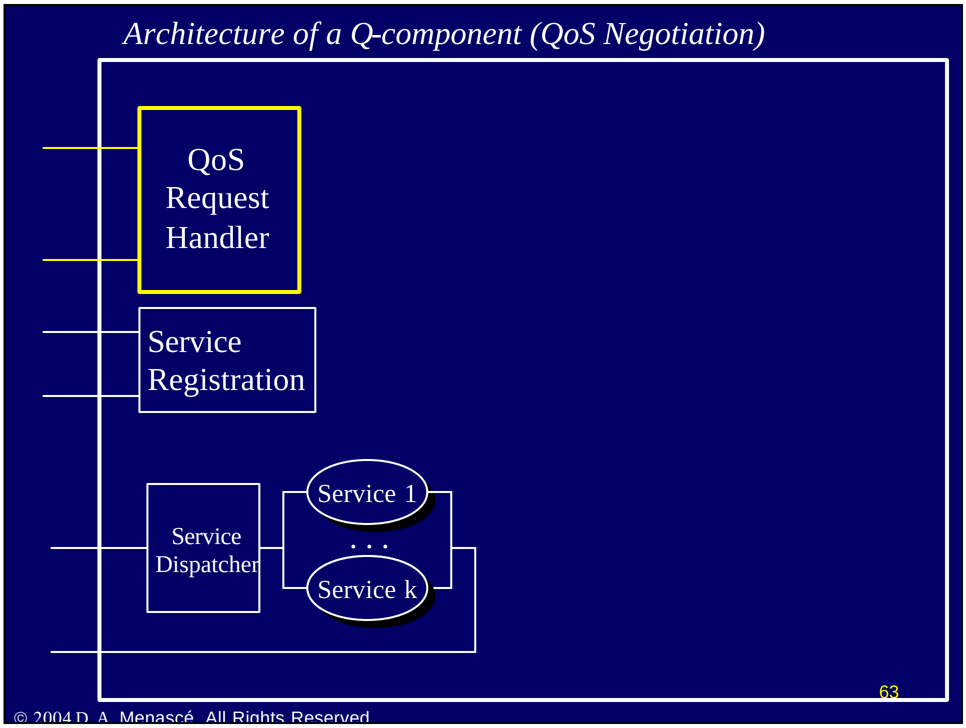
60

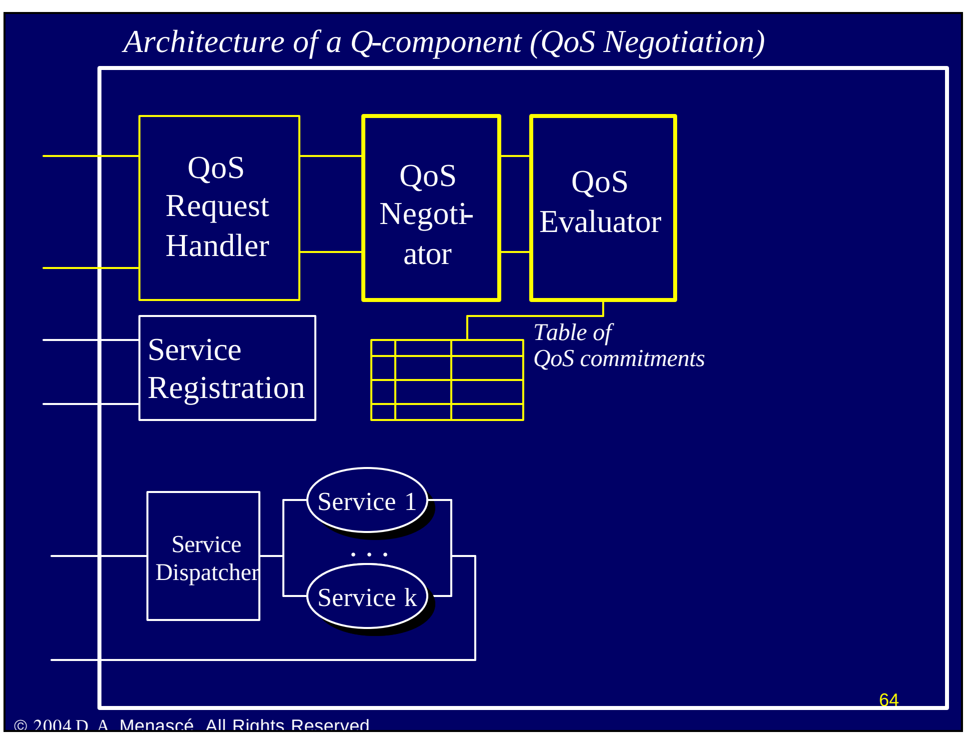
QoS-Aware Software Components: Q-Components

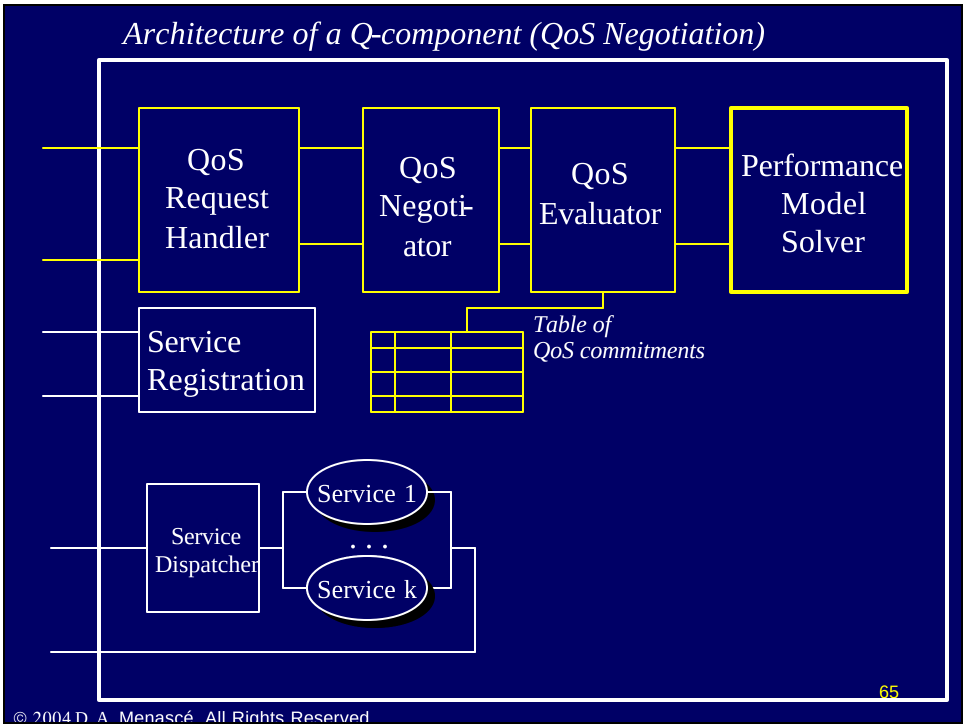
- Engage in QoS Negotiations (accept, reject, counter-offer)
- Provide QoS guarantees for multiple concurrent services
- Maintain a table of QoS commitments
- Service dispatching based on accepted QoS commitments
- Q-components are the building blocks of QoS-aware applications

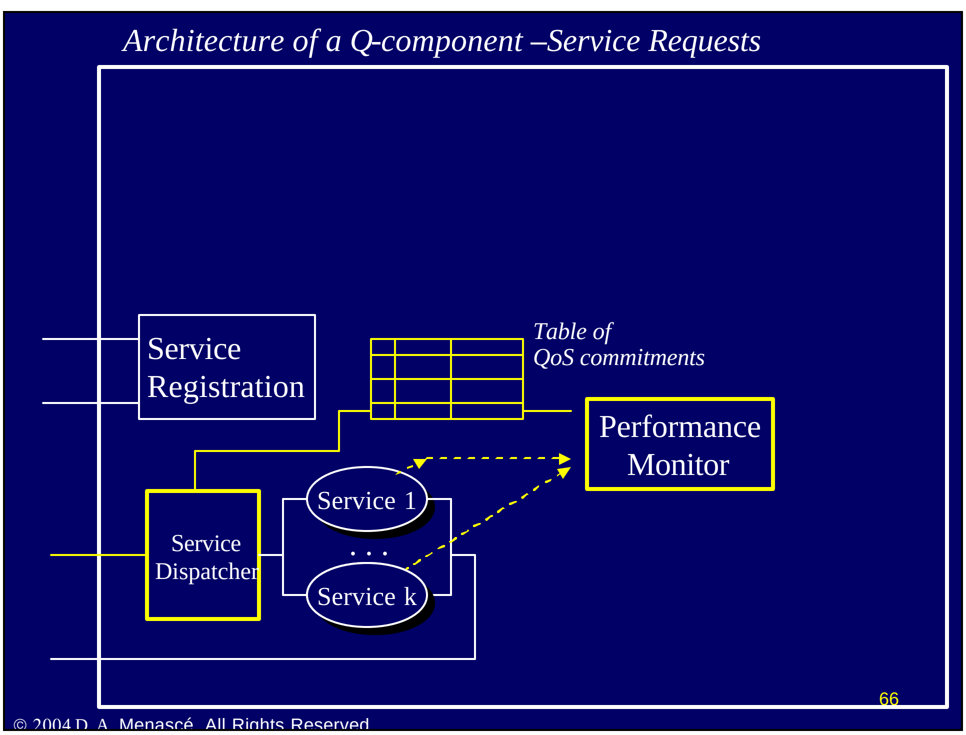
Architecture of a typical software component

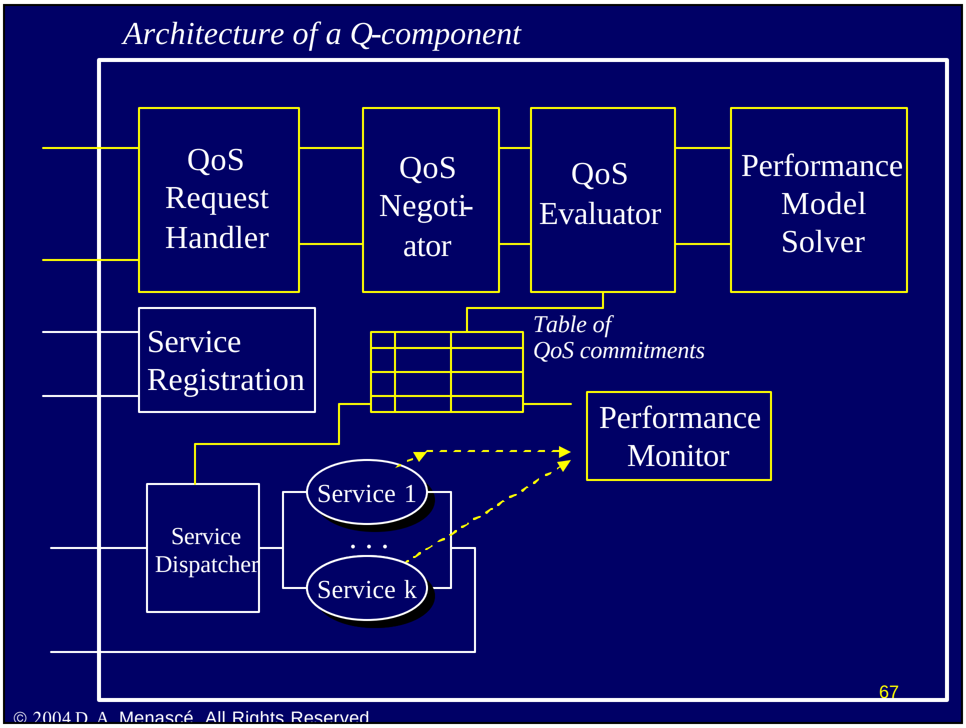



Architecture of a Q-component (QoS Negotiation)
QoS Request Handler
Service Registration
Service Dispatcher
Service 1
. . .
Service k
63
© 2004 D. A. Menascé. All Rights Reserved.

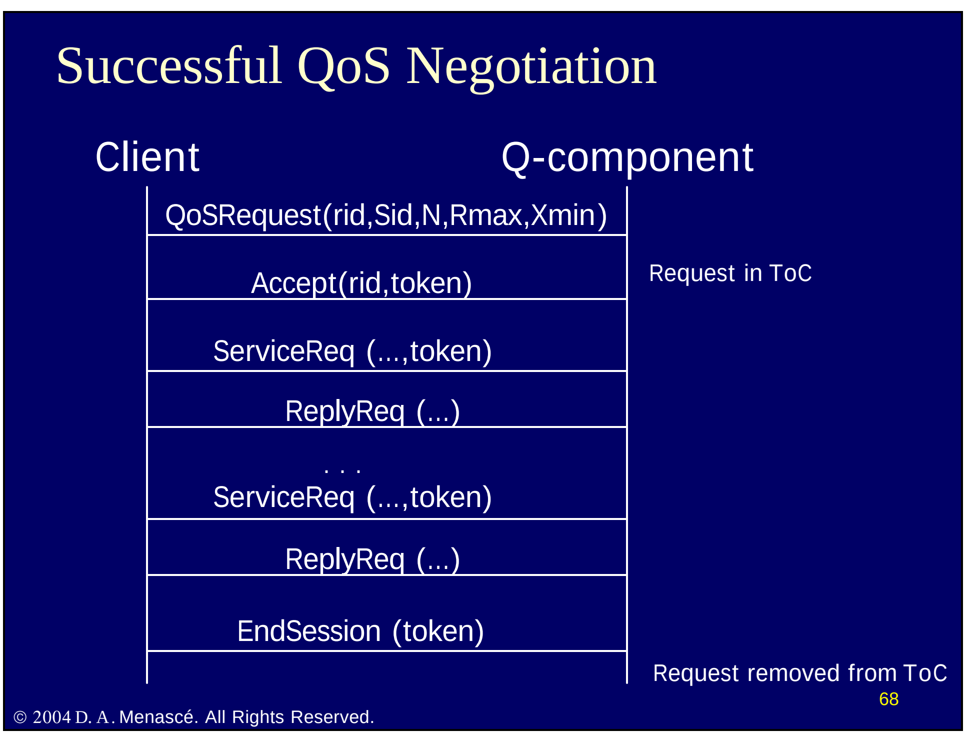

Architecture of a Q-component (QoS Negotiation)
QoS Request Handler
QoS Negoti-ator
QoS Evaluator
Table of QoS commitments
Service Registration
Service Dispatcher
Service 1
. . .
Service k
64
© 2004 D. A. Menascé. All Rights Reserved.


Architecture of a Q-component (QoS Negotiation)
QoS Request Handler
QoS Negoti-ator
QoS Evaluator
Performance Model Solver
Service Registration
Table of QoS commitments
Service Dispatcher
Service 1
. . .
Service k
65
© 2004 D. A. Menascé. All Rights Reserved.

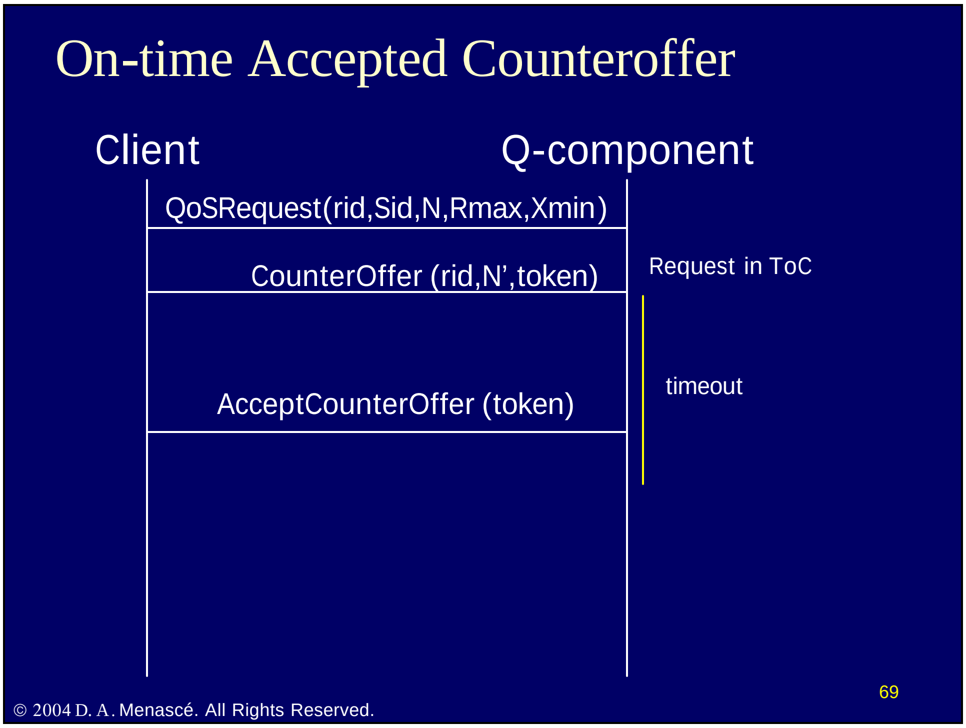

Architecture of a Q-component –Service Requests
Service Registration
Table of QoS commitments
Performance Monitor
Service Dispatcher
Service 1
. . .
Service k
66
© 2004 D. A. Menascé. All Rights Reserved.

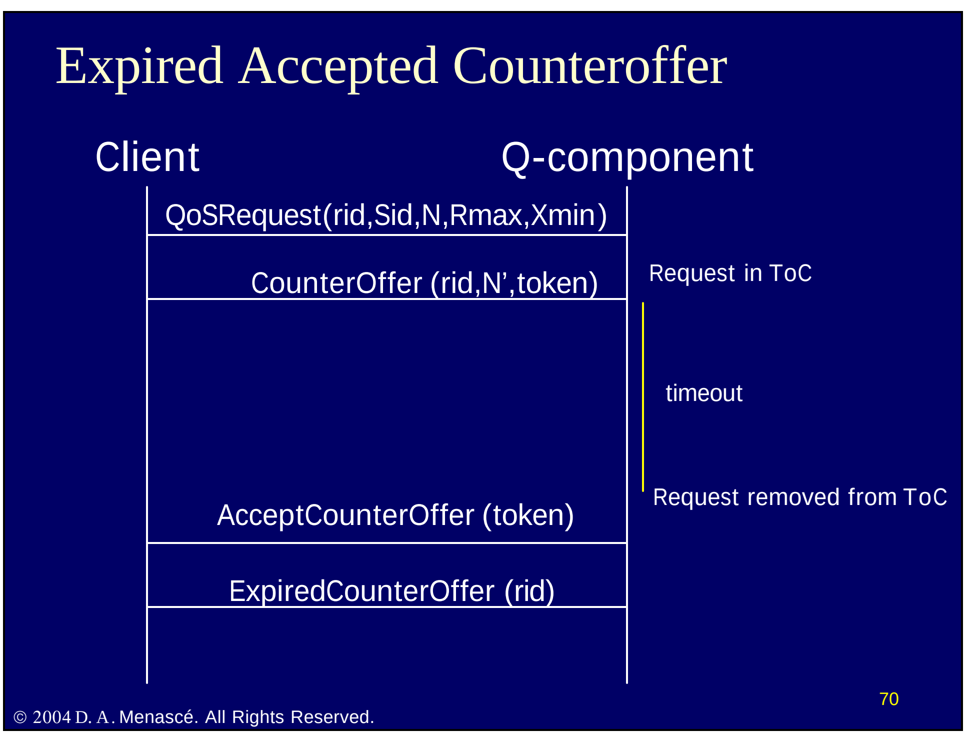


Architecture of a Q-component
QoS Request Handler
QoS Negoti-ator
QoS Evaluator
Performance Model Solver
Service Registration
Table of QoS commitments
Performance Monitor
Service 1
. . .
Service k
Service Dispatcher
67
© 2004 D. A. Menascé. All Rights Reserved.

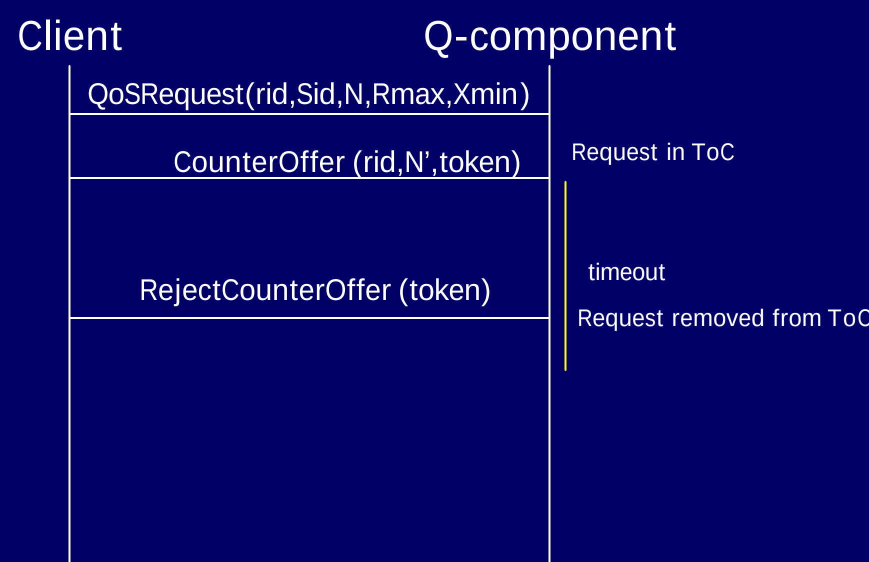


Successful QoS Negotiation
Client
Q-component
QoSRequest(rid,Sid,N,Rmax,Xmin)
Request in ToC
Accept(rid,token)
ServiceReq (...,token)
ReplyReq (...)
. . .
ServiceReq (...,token)
ReplyReq (...)
EndSession (token)
Request removed from ToC
68
© 2004 D. A. Menascé. All Rights Reserved.

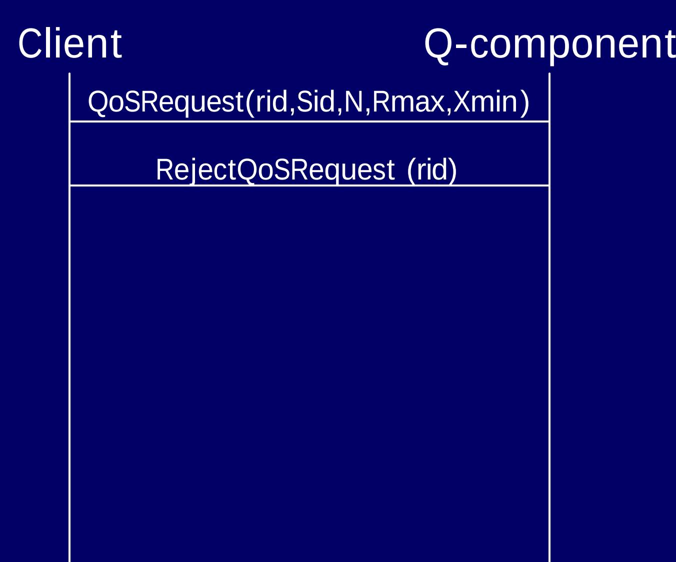

On-time Accepted Counteroffer
Client
Q-component
QoSRequest(rid,Sid,N,Rmax,Xmin)
CounterOffer (rid,N’,token)
Request in ToC
timeout
AcceptCounterOffer (token)
69
© 2004 D. A. Menascé. All Rights Reserved.


Expired Accepted Counteroffer
Client
Q-component
QoSRequest(rid,Sid,N,Rmax,Xmin)
CounterOffer (rid,N’,token)
Request in ToC
timeout
Request removed from ToC
AcceptCounterOffer (token)
ExpiredCounterOffer (rid)
70
© 2004 D. A. Menascé. All Rights Reserved.

Rejected Counteroffer

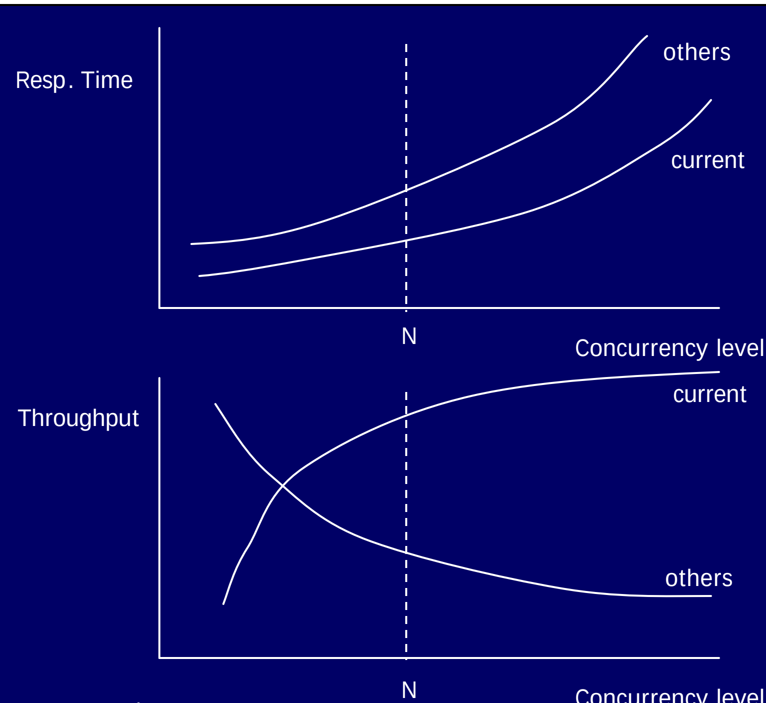


Rejected QoS Negotiation



Decision Table for QoS Negotiation

1. Current and other requests are satisfied				Accept
2. Only Current is Violated				
Reason	Remedy	Current	Others	Decision
Only MAXR is violated	Decrease N	OK	OK	Counter Offer
		Not OK: MINX is violated or N=0	OK	Reject
Only MINX is violated	Increase N	OK	OK	Counter Offer
		OK	Not OK	Reject
		Not OK & MAXR is violated	OK	Reject
		Not OK & MAXR is violated	Not OK	Reject
MINX & MAXR are violated	Decreasing N reduces X and increasing N increases R. So, there is no solution.			Reject
3. Current Request and Others are Violated				
Reason	Remedy	Current	Others	Decision
Only MAXR is violated	Decrease N	OK	OK	Counter Offer
		OK	Not OK	Reject
		Not OK: MINX is violated or N=0	OK or not OK	Reject
Only MINX is violated	X could be increased by increasing N. But this would further violate the QoS of other classes.			Reject
MINX & MAXR are violated	Decreasing N reduces X and increasing N increases R. So, there is no solution.			Reject
4. Only Other Requests are Violated				
Reason	Remedy	Current	Others	Decision
Any	Decrease N	OK	OK	Counter Offer
		OK	Not OK: N=1 but others still violated	Reject
		Not OK: MINX violated or N=0	OK or not OK	Reject



Building a Performance Model

New Request: Sid = 3, N = 12

Base Matrix of Service Demands (in msec):

	Service		
	1	2	3
CPU	25	34	20
Disk 1	30	50	24
Disk 2	28	42	31

Table of Commitments (ToC):

Commitment ID	Service ID	N	…
1	2	10	…
2	3	15	…
3	1	8	…
4	1	20	…
5	2	13	…

Matrix of Service Demands (in msec)

	Class					
	1	2	3	4	5	6
CPU	34	20	25	25	34	20
Disk 1	50	24	30	30	50	24
Disk 2	42	31	28	28	42	31

Vector N:	10	15	8	20	13	12

Building a Performance Model

New Request: Sid = 3, N = 12

Base Matrix of Service Demands (in msec):

	Service		
	1	2	3
CPU	25	34	20
Disk 1	30	50	24
Disk 2	28	42	31

Table of Commitments (ToC):

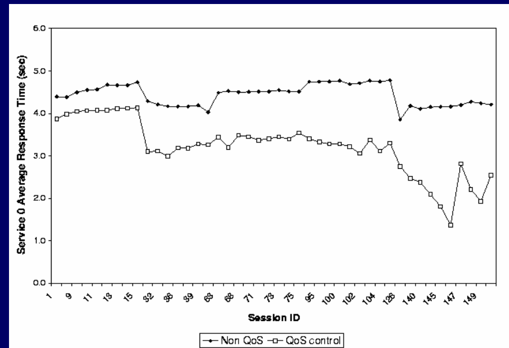
Commitment ID	Service ID	N	…
1	2	10	…
2	3	15	…
3	1	8	…
4	1	20	…
5	2	13	…

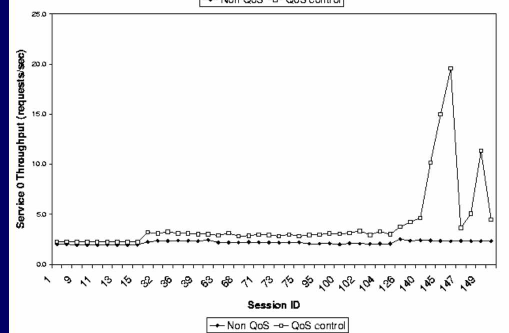
Matrix of Service Demands (in msec)

	Class					
	1	2	3	4	5	6
CPU	34	20	25	25	34	20
Disk 1	50	24	30	30	50	24
Disk 2	42	31	28	28	42	31

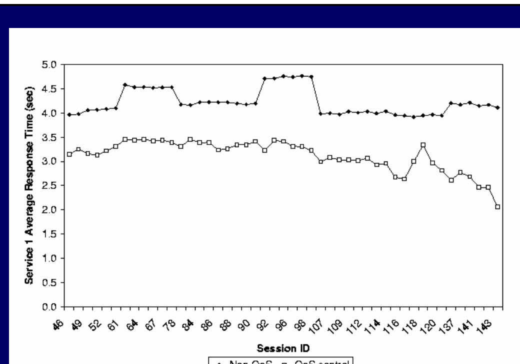
Vector N:	10	15	8	20	13	12

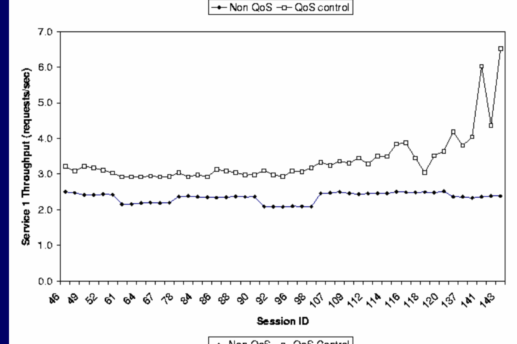
Service 0 Results:



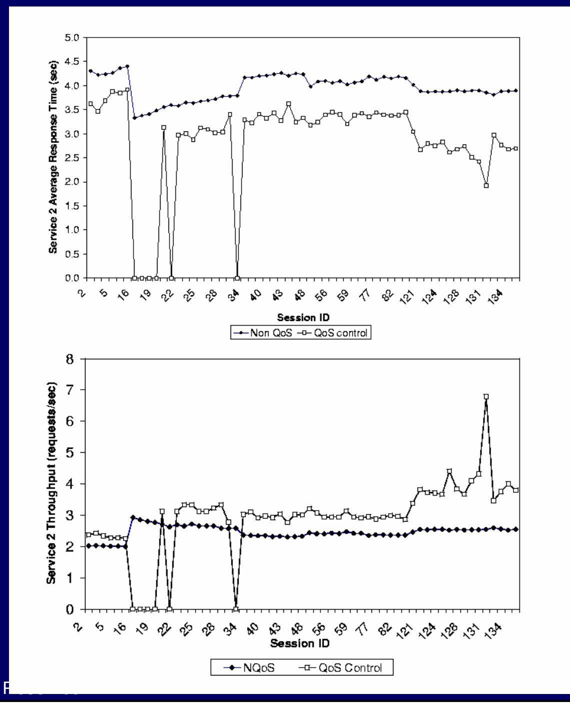


Service 1 Results:



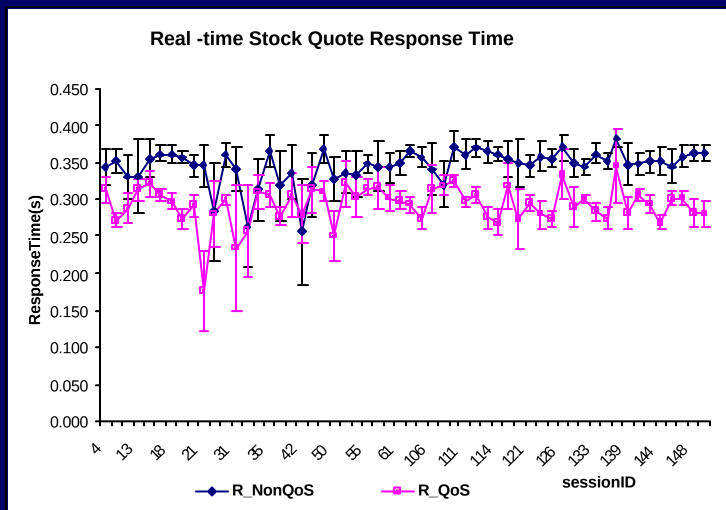


Service 2 Results:

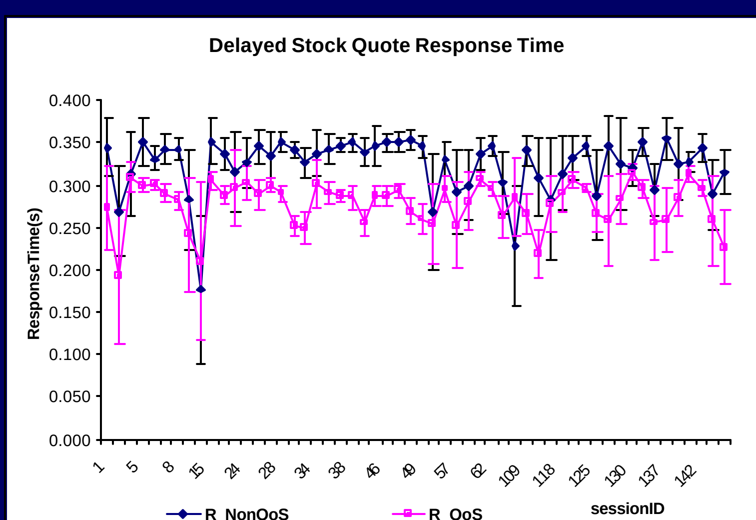


f = 0.0				
Svc No.	No. Dropped Sessions	No. of Sessions	% Drop	% Resp. Time Reduction
0	24	440	5	11
1	19	470	4	9
2	59	590	10	7
Total	102	1500	7	9
f = 0.10				
Svc No.	No. Dropped Sessions	No. of Sessions	% Drop	% Resp. Time Reduction
0	52	440	12	21
1	66	470	14	16
2	148	590	25	12
Total	266	1500	18	16
f = 0.25				
Svc No.	No. Dropped Sessions	No. of Sessions	% Drop	% Resp. Time Reduction
0	92	440	21	28
1	140	470	30	26
2	263	590	45	20
Total	102	1500	33	24

Stock Quote Service



Stock Quote Service



Concluding Remarks

- Performance models can be used to build QoS controllers for complex multi-tiered systems:
  - Controlled system provides better QoS values even in case of high variability in request’s inter-arrival and service times
  - Short term workload forecasting improves the QoS, especially when the workload intensity gets close to system saturation level
  - Dynamic adjustment of the controller interval length improves the QoS further
  - Even when basic model assumptions are violated, the models are robust enough to track the evolution of the performance metrics as the workload and configuration parameters change.

83

Concluding Remarks (Cont’d)

- Performance models can be used by software components to make admission control decisions.
  - QoS components should be able to negotiate QoS requests and perform admission control
  - QoS negotiation overhead is small (it did not exceed 10% of the CPU service demand in our experiments).

84

Bibliography

- "On the Use of Online Analytic Performance Models in Self-Managing and Self-Organizing Computer Systems," D.A. Menascé, M. Bennanni and H. Ruan, in the book Self-Star Properties in Complex Information Systems, O. Babaoglu, M. Jelasity, A. Montresor, C. Fetzer , S. Leonardi, A. van Moorsel, and M. van Steen, eds., Lecture Notes in Computer Science, Vol. 3460, Springer Verlag, 2005.
- "Assessing the Robustness of Self-Managing Computer Systems under Highly Variable Workloads," M. Bennani and D. Menascé, *Proc. International Conf. Autonomic Computing (ICAC-04),* New York, NY, May 17-18, 2004.
- "A Framework for QoS-Aware Software Components," D. Menascé, H. Ruan ,and H. Gomaa, *Proc. 2004 ACM Workshop on Software and Performance (WOSP'04),* San Francisco, CA, January 14, 2004.
- "On the Use of Performance Models to Design Self-Managing Systems," D. Menascé and M. Bennani, Proc. 2003 Computer Measurement Group Conference, Dallas, TX, Dec. 71-2, 2003.
- "Automatic QoS Control," *IEEE Internet Computing*, January/February 2003, Vol. 7, No. 1.
- "Preserving QoS of E-commerce Sites Through Self-Tuning: A Performance Model Approach," D. A. Menascé, R. Dodge and D. Barbara, *Proc. 2001 ACM Conference on E-commerce*, Tampa, FL, October 14-17, 2001.