The Costs and Limits of Availability for Replicated Services

Haifeng Yu , Amin Vahdat
[SOSP 2001]

Presented by: Fahad Arshad, Ignacio Laguna

Dependable Computing Systems Lab
School of Electrical and Computer Engineering
Purdue University

INTRODUCTION

- Explores benefits of dynamically trading consistency for availability using a *continuous consistency model*.
- Continuous Consistency Model
  - Applications specify a max deviation from strong consistency on a per-replica basis.
  - Optimistic consistency models leave this deviation unbounded.
  - Continuous consistency model exposes a tradeoff between consistency and availability that can be dynamically varied based on changing network and service characteristics.

INTRODUCTION

- Goal
  - Enable services to tune their system availability as their workload changes and as network reliability changes
- Main contributions
  - Evaluate availability as a function of consistency level, consistency protocol, and failure characteristic.
  - Maximizing availability requires as strong a consistency level as possible during times of full connectivity. This is required to build up a large "cushion" for the times when failures prevent communication.
  - Demonstrate that simple optimizations to existing consistency protocols result in significant availability improvements.
  - Provide tight upper bounds on the availability of services.

BACKGROUND

- Motivation
  - 0.1% availability improvement gives 8 more hours of uptime corresponding to approximately $1 million in additional revenue for every $1 billion in annual revenue conducted online.
- Study TACT consistency model [Yu, Vahdat OSDI 2000]
  - TACT gradually reduces the amount of required synchronous communication among replicas in moving from strong to optimistic consistency.
  - The model allows replicas to locally buffer a max number of writes before requiring remote communication.
  - At any replica , updates can be in either TENTATIVE or COMMITED state.

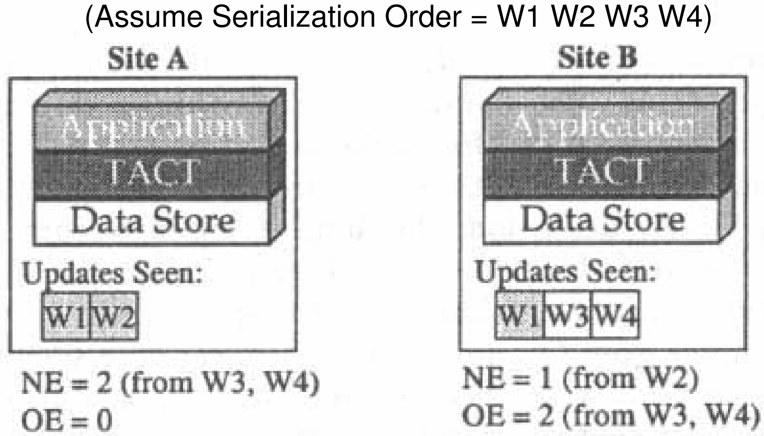
Consistency Metrics

- Three per replica consistency metrics
  - *Numerical error* (NE) is the max weight of writes not seen by a replica.
  - *Order error* (OE) is the max weight of writes that have not established their commit order at the local replica.
  - *Staleness* (STL) is the max amount of time before a replica is guaranteed to observe a write accepted by a remote replica.
- Strong consistency is defined as NE=0, OE=0, STL=0
- Optimistic consistency is defined as NE=∞, OE= ∞, STL= ∞
- Consider a TACT application as a replicated airline reservation system.

TACT application Example

- NE corresponds to the maximum number of system-wide reservations that have not been propagated to the local replica.
- OE corresponds to the maximum number of tentative reservations in a replica's local view i.e. have n`t established the final COMMIT.
- NE bounds the max rate of conflicting reservations, OE bounds the rate of false negatives, staleness guarantees the max elapsed time before a reservation is seen system-wide.

(Assume Serialization Order = W1 W2 W3 W4)



Assumptions and Methodology

- Replica failures are modeled as singleton network partitions.
- Failures are symmetric. (Approximation to protocols like TCP)
- They do not assume reachability among hosts to be transitive.
- CPU processing time and network delay is negligible compared to the duration of time where network connectivity does not change.
- TACT supports the notion of application-specific consistency units (or conits) that determine the granularity over which consistency is enforced.

Definitions

- Availability is defined over *submitted accesses* from the client to the network service.
  - A *failed access* if the request cannot reach any replica because of network failures.
  - A *rejected access* if it is received by some replica but its acceptance would violate some consistency requirement.
  - An *accepted access* otherwise.
- $Avail_{client}$ = *accepted accesses / submitted accesses*.
- $Avail_{network}$ = the % of accesses that can reach a replica
- $Avail_{service}$ = the % of accesses reaching replicas that are actually accepted.
- $Avail_{client} = Avail_{network} \times Avail_{service}$

Workload & Faultload Approach

- Investigate $Avail_{service}$ using a workload & faultload approach.
- A workload is a trace of time stamped accesses.
- A faultload is a trace of timestamped fault events.
- A fault event is either a failure that divides an existing network component into two components or a recovery that merges two existing components.

Deriving Approach to Availability Upper Bounds

- At a higher level, any consistency maintenance protocol must answer a number of questions to achieve a target level of consistency among replicas.
  - The protocol must determine which writes to accept/reject from clients
  - The protocol must determine when and where to propagate writes.
  - The protocol must decide the serialization order i.e. which writes to commit and in what order.
- Divide these questions into two disjoint sets:
  - $Q_{offiline}$ is the set of questions with optimal answers that can be pre-determined offline.
  - Q_{online} contains all remaining questions whose optimal answers depend on consistency level, workload, and faultload.
- For proving upper bounds on $Avail_{service}$, it is necessary to search for the optimal answers to these questions.
- Problem: the set of possible answers is exponential.

Deriving Approach to Availability Upper Bounds

- A key challenge is to make the search of the set of possible answers tractable by proving that certain types of answers will always result in better availability than others.

- Using the pre-determined optimal answers to $Q_{offline}$, an abstract *dominating algorithm* is constructed.

- By def *dominating algo* makes strictly better decisions then other protocols for $Q_{offline}$.

Deriving Approach to Availability Upper Bounds

- *Dominating algorithm* does not specify the answer of any question from Q_{online}, rather it takes some inputs that specify these answers.

- For a given workload and faultload, we say that a consistency protocol P_1 *dominates* protocol P_2, if i) P_1 achieves the same or higher level of availability as P_2 and ii) P_1 maintains the same or higher level of consistency as P_2.
- The upper bound is the availability achieved by the protocol *P* that dominates all protocols.

Availability Upper Bound as a Function of Order Error

- Order error bounding protocol needs to answer three kinds of questions:
  - questions regarding write propagation
  - questions regarding write acceptance
  - questions regarding write commitment.
- To commit a write, a replica must see all preceding writes in the *serialization order*
- *Serialization order* is the global total write order that an OE bounding protocol tries to maintain across all replicas
- Consider a system with two replicas that are partitioned from each other
  - Suppose $replica_1$ receives W_1 then W_2, while $replica_2$ receives W_3 then W_4. A serialization order here can be any permutation of the four writes.
  - If the serialization order is $S = W_1W_2W_3W_4$, then a replica can only commit W_3 after it sees and commits W_1 and W_2.

Availability Upper Bound as a Function of Order Error

- If $replica_2$ propagates W_3 to $replica_1$ before $replica_1$ accepts W_2, then $replica_1$ cannot commit W_3 and its order error is increased.
  - Therefore aggressive write propagation always reduces NE, Staleness
  - In certain cases it can actually increase the OE.
- Optimizing approach for aggressive write propagation.
  - Remote writes seen by a replica are not immediately applied to data store and thus do not count towards OE.
  - Apply them only when they can be committed. (Increases NE)
  - Local writes are always applied to the data store immediately.

Availability Upper Bound as a Function of Order Error

- To optimize search on serialization orders, a small set of serialization orders that are strictly "better" than all other serialization orders is found.

- *S* dominates *S′* if *S* allows the commitment of any write that could be committed using *S ′*. From previous example
  - *Serialization order S = W1W2W3W4 dominates S′ = W2W1W3W4*
  - *This is because whenever W_2 can be committed using S′, the replica must have already seen W_1 (which is accepted before W_2), and thus can also commit W_2 in S.*

Availability Upper Bound as a Function of Order Error

- Using this definition of "domination", the prove that *S* dominates *S'* outlined .
  - *ALL* All possible serialization orders.
  - *CAUSAL* Serialization orders compatible with causal order.
  - *CLUSTER* Serialization orders where writes accepted by the same partition during a particular interval cluster together.
- From previous example of 2 replicas
  - ALL contains all possible permutations of the four writes
  - CAUSAL contains the six orderings where W1 precedes W2 and W3 precedes W4.
  - CLUSTER only contains W1W2W3W4 and W3W4W1W2
- They prove that CAUSAL dominates ALL and CLUSTER dominates CAUSAL, so the upper bound becomes tractable by restricting our search scope to CLUSTER.

Availability Upper Bound as a Function of Order Error

- To prove CAUSAL dominates ALL, only need to show that if write W1 causally precedes write W2, then it is always "better" to place W1 before W2 in the serialization order.

- The proof of CLUSTER dominating CAUSAL is intricate .

- For each serialization order enumerated, they derive the upper bound by solving a linear programming problem.

IMPLEMENTATION

- Sample Faultloads
  - Collect a sample of Internet connectivity with average measurement intervals of 3 seconds on each path. (previous intervals 10 min)
  - Measure interconnectivity among 8 sites.
  - Total duration of the trace is 6 days with over 12 million samples.
  - Faultload has an average failure time on all paths of 0.046%.
  - Focus on the first day of this trace (SAMPLED1). Failure rate=0.17%
  - Use a simple event-driven simulator (Internet topology generator) to obtain diverse faultloads based on a sample Internet-like topology.
  - 24 backbone routers in the sample topology (vary replica 1 to 24)
  - Use exponential distributions for both failure duration and failure inter-arrival time. Vary parameters of distributions to have simulated faultloads

IMPLEMENTATION

- WAN Prototype Details
  - Prototype is written in Java based on RMI.
  - Run availability experiments using the bulletin board service.
  - To bound NE, each replica ensures that the error bound on other replicas is not violated. [Yu, Vahdat *VLDB* 2000]
  - To bound OE, the work implements 3 such protocols
    - Primary copy [Petersen *SOSP* 97]
    - Golding's algorithm [Golding *Computing Systems* 92]
    - Voting [Gifford *SOSP* 79]
  - Primary copy protocol
    - A write is committed when it reaches the primary replica.
    - Serialization order is the write order seen by the primary replica.
    - Replica that needs to reduce order error commits writes by first pushing its tentative writes to the primary and then pulling any other unseen updates from the primary.

IMPLEMENTATION

- Golding's algorithm
  - Each write is assigned a logical timestamp that determines the serialization order
  - Each replica maintains a version vector to determine whether or not it has seen all writes with logical time less than t.
  - To reduce OE, a replica pulls writes from other replicas to advance its version vector
- Voting
  - Voting protocol conducts a series of elections to determine a serialization order
  - During a round, each replica casts a vote for the first uncommitted write.
  - The write with the most votes wins and is committed next (in serialization order) across all replicas.
  - To reduce OE with voting, a replica first pushes writes to remote sites.
  - These sites then cast their votes and the results are pulled in subsequent sessions to allow write commitment.

IMPLEMENTATION

- Emulation Environment and Verification
  - Major evaluation done using a local area emulation environment.
  - Emulation accuracy is verified through live wide-area deployment.
  - To validate emulation results, the prototype system running the replicated bulletin board service is deployed on the 7 sites they use.
  - Run two separate 24 hour experiments at two different target consistency levels using Golding's algorithm to bound order error.
  - In the first experiment, NE = 6 (recall that there are 7 replicas total) and leave OE unbounded,

IMPLEMENTATION

  - In the second experiment, NE is unbounded and OE = 1.
  - The system logs all writes with timestamps.
  - The 2 runs produce two sample faultloads that are played back to emulation environment, with writes injected at the same rate as the wide-area deployment based on timestamp logs.
- Table 2 summarizes the accuracy of the emulation

Consistency	# Writes (WAN)	# Rejected (WAN)	Avail. (WAN)	# Writes (emulation)	# Rejected (emulation)	Avail. (emulation)	Accuracy
NE=6, OE=∞	120,703	1,699	98.6%	120,703	1,762	98.5%	96.3%
NE=∞, OE=1	60,439	293	99.5%	60,439	298	99.5%	98.3%

Table 2: Wide-area deployment and emulation verification results.

Results

- Data points are from repeated runs of the TACT software while varying:
  - NE, OE, Cosistency protocols & Fault Loads.
  - Workload is a uniform update rate of one write per 10 seconds on each replica, resulting in 0.8 writes per second system-wide for the eight emulated replicas.
- For initial set of results, $Avail_{service}$ is used as the availability metric
  - Assume that replicas accept all reads and reject the writes that would violate global consistency requirements.
  - Service availability is re-defined to be the percentage of writes that are accepted by the replicas.

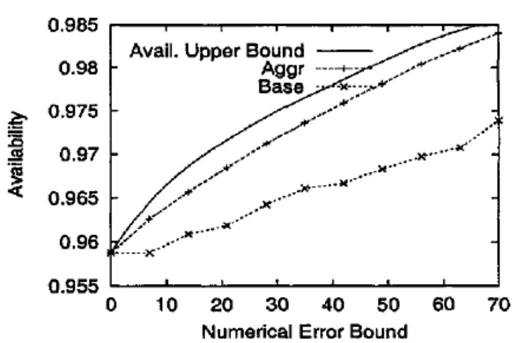


Figure 2: Availability as function of numerical error (SIM1_00).

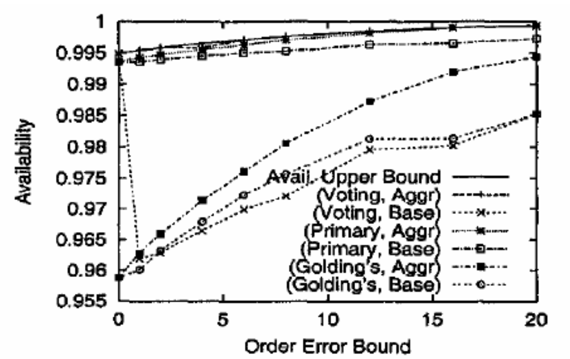


Figure 3: Availability as function of order error

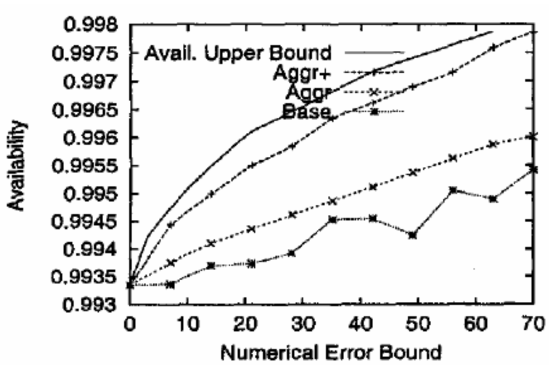


Figure 4: Availability as function of numerical error (SAMPLED1).

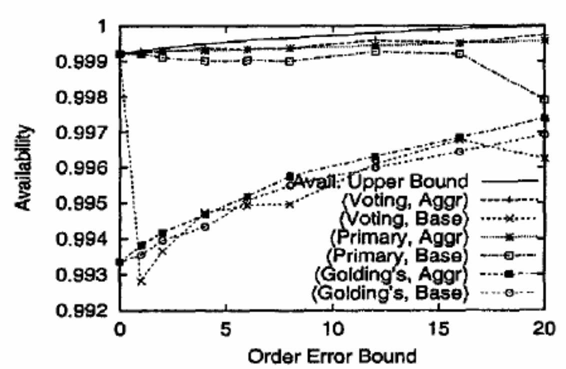


Figure 5: Availability as function of order error (SAM PLED1).

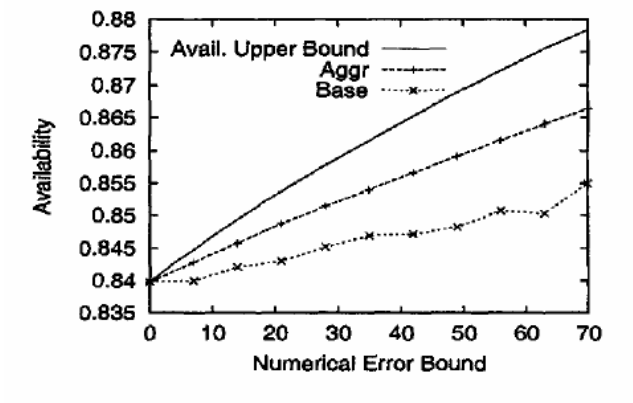


Figure 6: Availability as function of numerical error (SIM5_00).

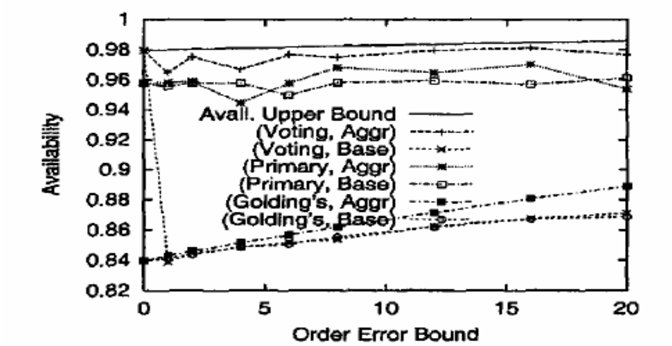


Figure 7: Availability as function of order error (SIM5_00).

Availability/Communication Tradeoffs

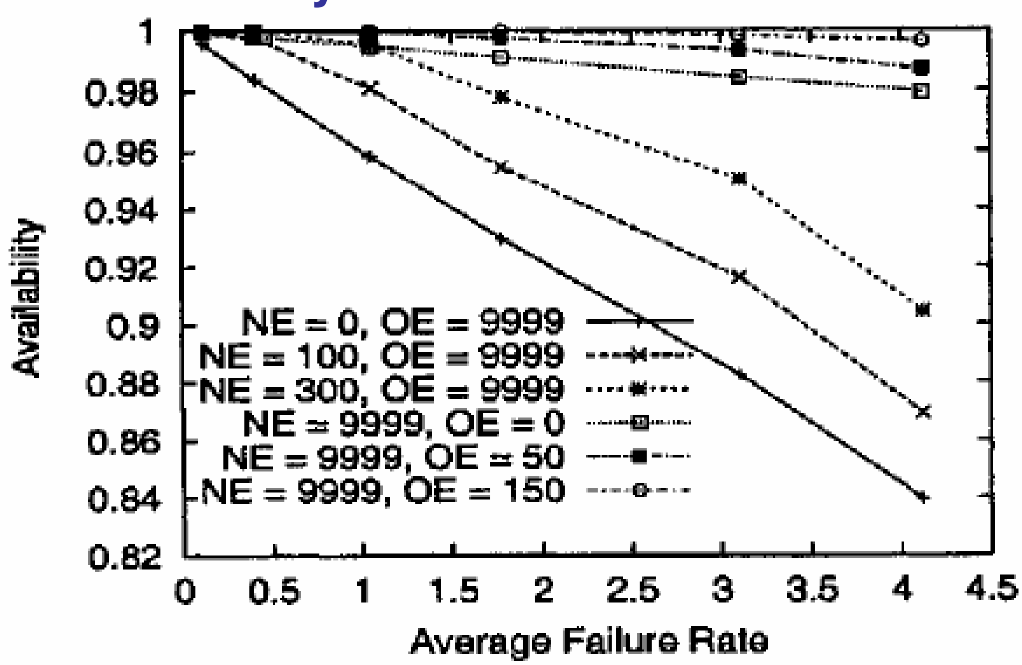


Figure 8: Availability with different average failure rate.

Availability/Communication Tradeoffs

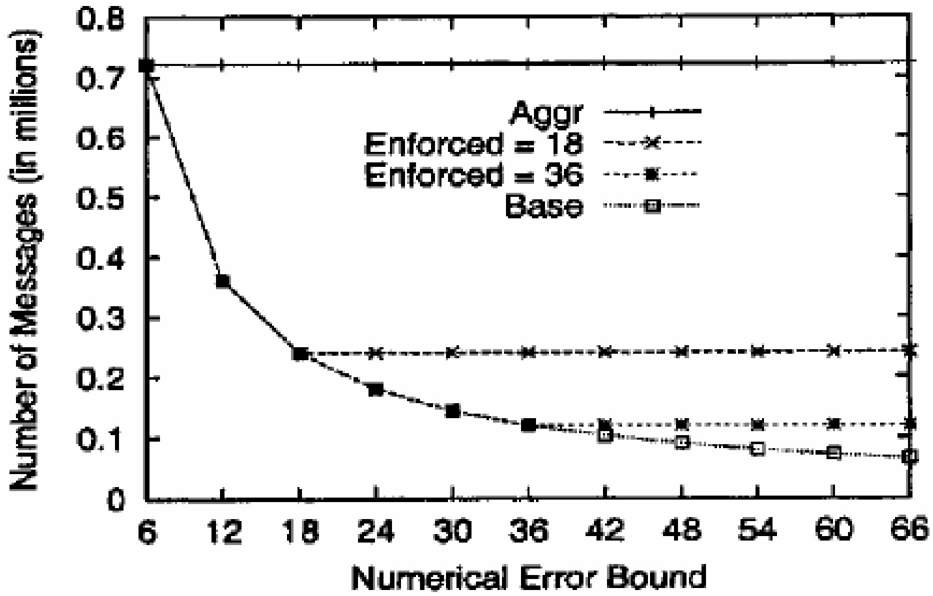


Figure 9: Number of messages to maintain numerical error. 7

Availability/Communication Tradeoffs

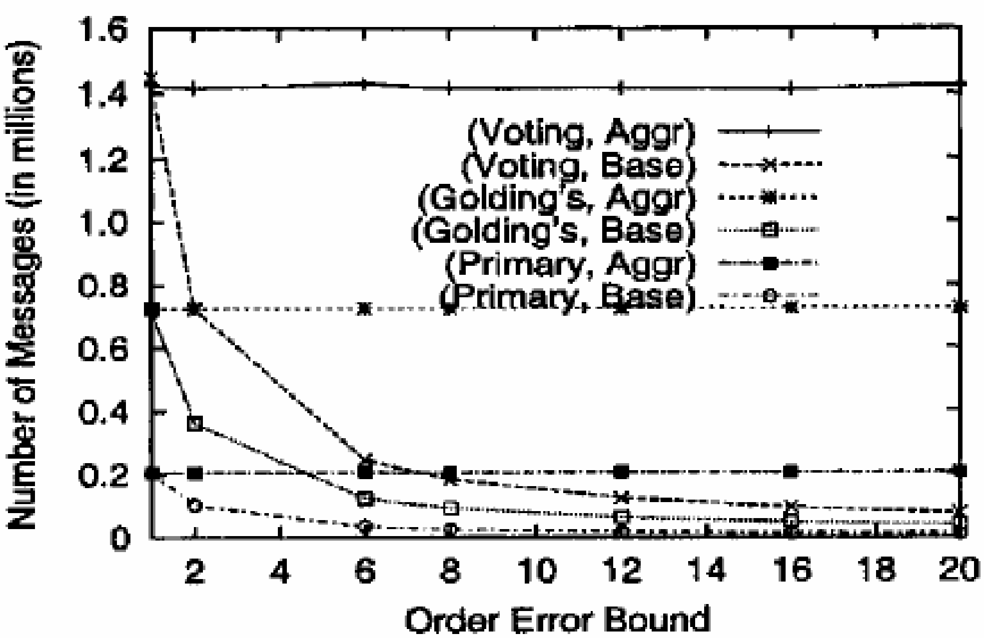


Figure 10: Number of messages to maintain order error.

Availability/Communication Tradeoffs

- An interesting result is that achieving maximum $Avail_{service}$ with a relaxed consistency model can entail increased communication overhead.
- The communication costs of maintaining consistency can be reduced by waiting as long as possible to propagate writes.
- Results show that maximizing availability requires aggressive write propagation.

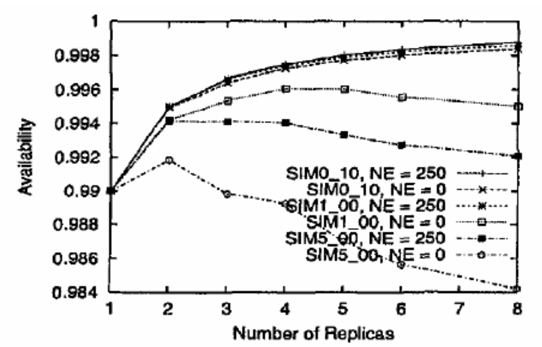


Figure 11: $Avail_{client}$ as function of replication scale with $Avail_{network} = 1 - 1\%/n$.

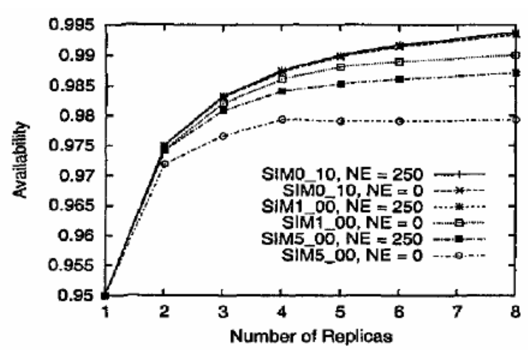


Figure 12: $Avail_{client}$ as function of replication scale with $Avail_{network} = 1 - 5\%/n$.

SUMMARY

- Evaluation shows that simple optimizations to existing consistency protocols can greatly improve the availability of replicated services.
- Staying as close to strong consistency as possible during times of good connectivity allows services to approach the tight upper bounds on availability derived.
- Voting and primary copy generally achieve the best availability
- Additional replicas will not always improve service availability and can in fact reduce it.

» THANK YOU