Stateful Detection in High Throughput Distributed Systems

Gunjan Khanna, Ignacio Laguna, Fahad A. Arshad, Saurabh Bagchi

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

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Outline

- Motivation
- Monitor Based Error Detection
- Sampling Approach
- Experiments and Results.
- Related Work
- Conclusions and take-away lessons

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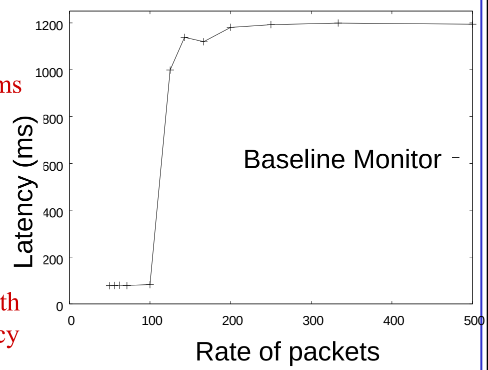
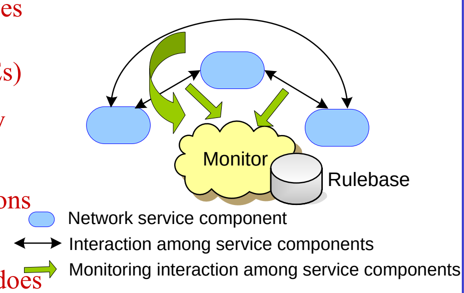
Motivation

- Ever increasing bandwidth has led to proliferation of distributed applications with high throughput streams
- Error detection framework must therefore handle high throughput streams
- Our previous detection mechanism breaks beyond a particular incoming packet rate
- The goal is to push the knee to right with graceful degradation of detection latency and accuracy



Monitor Approach to Detection

- The approach follows an observer-observed model
- The observer (the Monitor) only observes external message interactions between components called protocol entities (PEs)
- The Monitor maintains a set of anomaly based rules to verify the PEs
- The Monitor estimates the state transitions of the PEs
- On an incoming message, the Monitor does the appropriate state transition and matches the state specific rules in the rule base
- A violation of the rule would flag an error leading to a detection of failure



Design Goals

- Online mechanism enforcing low latency and high accuracy
  - Graceful degradation of latency and accuracy
- Treat protocol entities as Black-box
  - Non-intrusive approach
  - Operate asynchronously with respect to application
- Monitor should be executable on off-the-shelf hardware
  - Should not have large memory footprint
  - The computation should scale slowly with the number of PEs
- Stateful approach should be followed
  - Natural errors in systems are stateful
  - Example: Failures in Windows NT
  - Example: Failure prediction in cycle-sharing systems

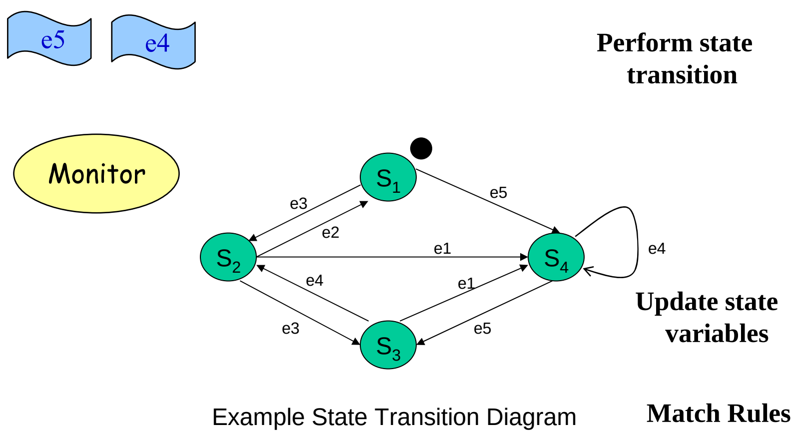
Detection Framework

Step1: On observing a message, perform state transition and if required, update variables corresponding to PE`s STD

Step2: Perform rule matching for the rules associated with the particular state and message combination

Step3: Monitor flags an error if rules don`t match

Detection Framework



Example State Transition Diagram (STD)

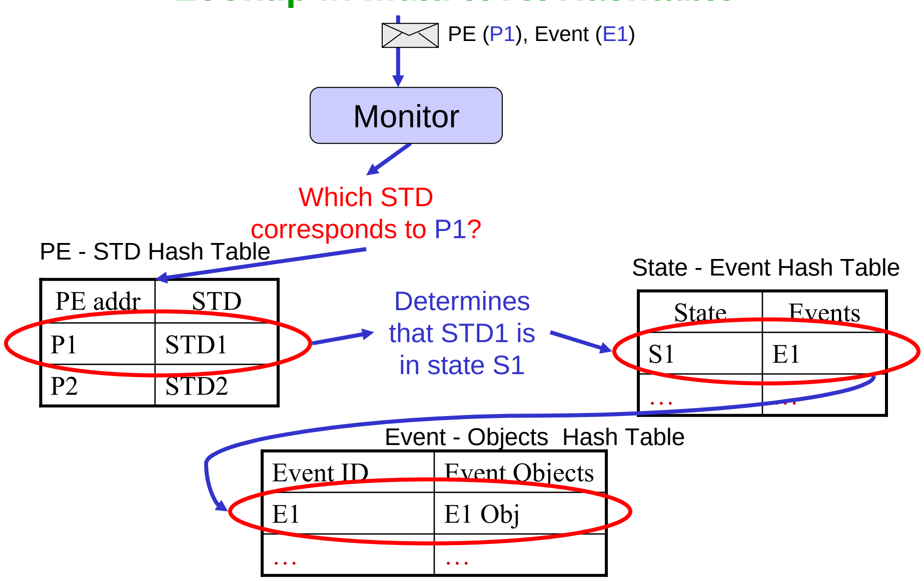
Rule Matching

- **Monitor-Baseline** has linear structures that it needs to traverse for rule matching
- Rules are defined based on protocol specifications and QoS requirements.
- Rules are anomaly based.
  - Define the correct behavior of the protocol
- Five generic temporal rule categories
  - Example:
    - The data message count should be between 10 and 30 for the next 5000 msec. (*QoS*)
    - Sender should receive an Ack after sending 32 Data packets (*protocol specification*)

Solution: Improve Per Message Processing (Monitor-HT)

- Rationale: Make processing of each incoming message more efficient
- Solution Approach:
  - Provide efficient look-up using hashtables
  - Eliminate duplicate copies of the state variables
- State Transition Diagram is organized in a multi-level hashtable
  - Monitor-H has a constant order look-up while Monitor-Baseline was linear in the number of PEs being verified and number of events in each state

Lookup in multi-level Hashtable



Efficient Rule Matching – *Monitor-HT*

Data

Rule 1	[illegible]
Rule 2	[illegible]
Rule 3	[illegible]

Previous Approach

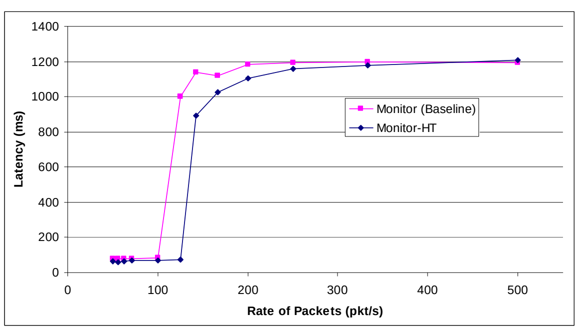
Data

State Var	[illegible]
Rule 1	1
Rule 2	0
Rule 3	1

New Approach

- Multiple rules are matching the same message type
  - Local variables contain snapshots of the global count at instantiation and at matching instant
  - *PE* $\times$ *Event ID* tuple is only incremented once
  - Single copy update of state variables.

Monitor-HT versus Monitor-Baseline



- We compare the latency of detection of Monitor-Baseline and Monitor-HT. Latency is measured from instantiation of rule to the end of rule matching
- Monitor-HT achieves a 25% higher breaking point in terms of rate of incoming packets

Solution: Sample Messages for Detection

- Rationale:
  - Monitor-HT still has to perform a minimum constant amount of work for every incoming message.
  - It gets overwhelmed when the message rate is too high
- Solution Approach
  - Modify Monitor-HT to reduce the incoming workload
  - Sample incoming messages to perform matching on a subset
- Instead of processing every message, sample the incoming messages **(Monitor-S)**
  1. When do we do sampling ?
  2. How do we sample?
  3. How do we handle state non-determinism?

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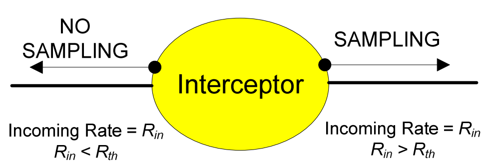
When do we Sample?

- Assume Monitor-Baseline achieves a desired latency and accuracy uptil a rate of incoming messages R_{bp}.
  - Choose a threshold R_{th} such that $R_{th} < R_{bp}$
- When the incoming rate R_{in} is such that $R_{in} > R_{th}$, Monitor-S switches to sampling mode of operation
- Design tradeoff:
  - R_{th} is far below R_{bp}: Inefficient use of Monior resources
  - R_{th} is very close to R_{bp}: Small spike can make the system unstable



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How do we Sample?

- We choose uniform random sampling: rate of sampling is dependent on the rate of incoming messages
  - Uniform random method is oblivious to the incoming message type
  - Any sampling approach based on the information of the incoming message will require some processing of the message before sampling
- Drop message at the rate of 1 in every $R_{in} /(R_{in} - R_{th})$ messages
  - Incoming rate is recalculated after a window of 30 seconds
- Scale the constants in the rules by a factor of R_{th} / R_{in}
  - Original rule — "Receive 10 Acks in 100 sec"
  - Rule modified due to sampling — "Receive 10.(R_{th} / R_{in}) Acks in 100 sec"

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How do we handle Non-Determinism ?

- Dropping a message can cause Monitor-S to lose track of the current state of the PE
- Instead of keeping a single current state for each PE being verified, keep a vector of possible states the PE may be in
  - $\hat{S} = \{S_1, S_2 \ldots S_K\}$
- If r consecutive messages are dropped starting from state S_{start} then the state vector $\hat{S}$ consists of the union of states reachable in r steps from S_{start}
- Computing the state vector at runtime is expensive. So Monitor-S pre-computes state vectors offline

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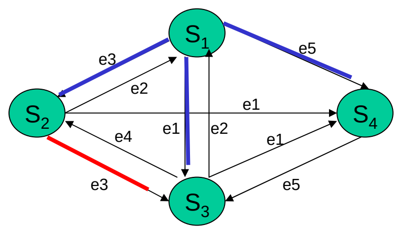
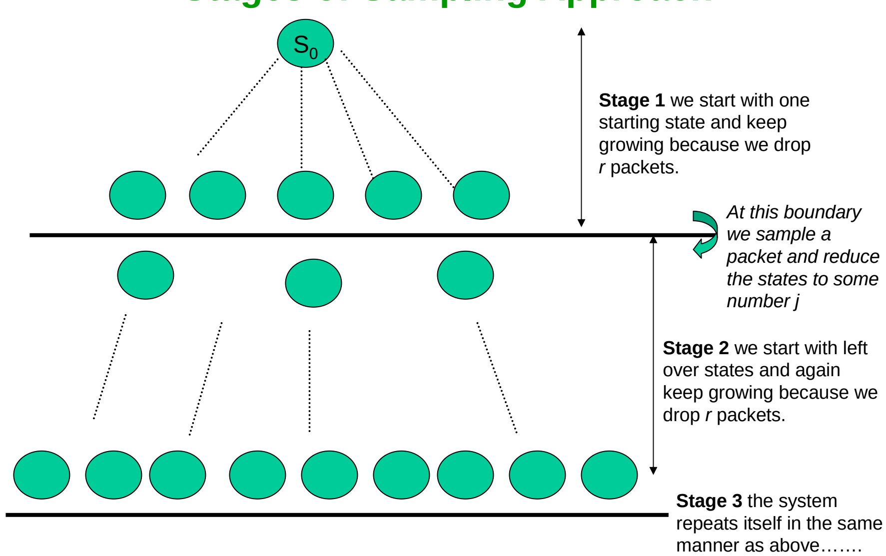
How do we handle Non-Determinism ?

- Size of the state vector does not keep growing
  - Bounded by the total number of states
  - Sampling of a message causes state vector size to reduce since message is only possible in a few of the states of the state vector
- Example: Consider the STD below
  - At start: $\hat{S} = \{S_1\}$
  - Drop a message: $\hat{S} = \{S_2, S_3, S_4\}$
  - Sample a message (say e3): $\hat{S} = \{S_2\}$



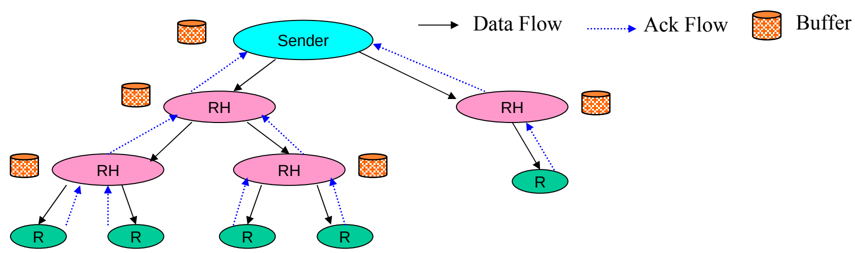
Example State Transition Diagram (STD)

Stages of Sampling Approach



Demonstration: TRAM

- We demonstrate the use of the Monitor on TRAM, *a tree-based reliable multicast protocol.*
- TRAM consists of a single sender, multiple repair heads (RH), and receivers. It ensures reliability of message transfer in case of node or link failures and message errors.
- We emulate TRAM protocol, where sender and receiver are the PEs being verified by the Monitor in all experiments.

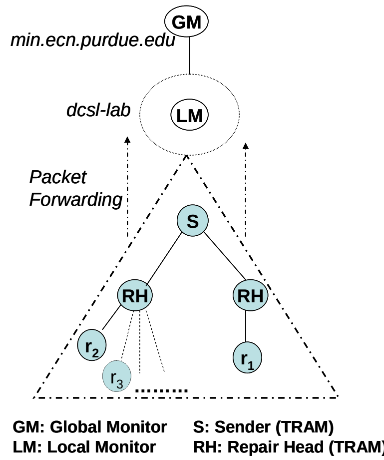


Failure Injection

- We perform *random fault injection* in the header of the emulated TRAM messages to induce failures
- We randomly choose a header field and change it to a randomly selected value, emulating protocol errors
  - Say, too many NACK messages are sent by the receiver
- To mimic faults close to reality, a burst length is chosen since TRAM is robust to isolated faults
  - A PE to inject is chosen (sender, RH or receiver) and faults are injected for a burst length of 500ms after every 5 minutes.

Topology and Metrics for Experiments

- *Accuracy* = (1- % of missed detections)
- Fault injections undetected by the Monitor are called *missed detections*
- *False detections* are errors flagged by Monitor but which do not affect TRAM entities
- *Latency* is measured as the time from the instantiation of a rule to the time when the rule matching is completed



Physical Topology of the TRAM emulator and the Monitor

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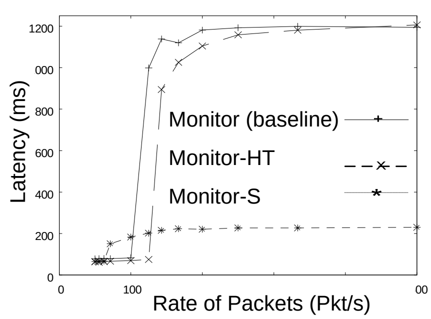
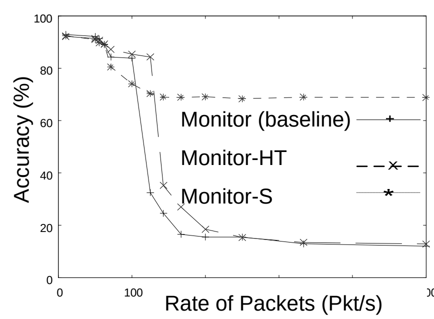
Results: Latency and Accuracy with packet rate (R_{in})





- Montior-Baseline and Monitor-HT break causing a knee. Monitor-HT`s knee is beyond Monitor-Basline`s knee
- Monitor-S shows a relatively smooth degradation in both accuracy and latency results
  - It is able to adjust the workload based on the rate
- Montior-S gives a low latency at the cost of small reduction in accuracy at high input rates
  - Accuracy suffers a little because of non determinism

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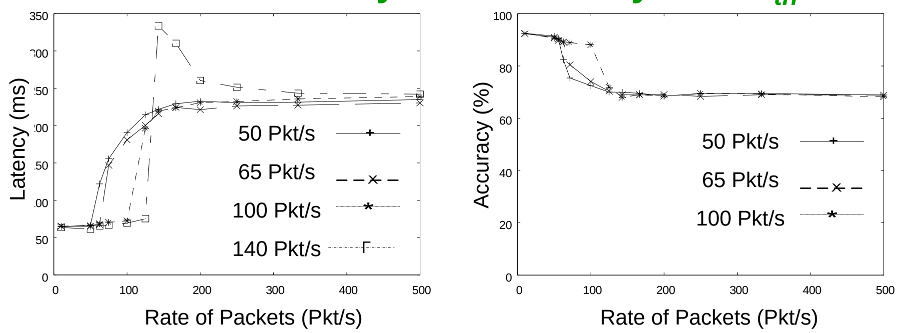
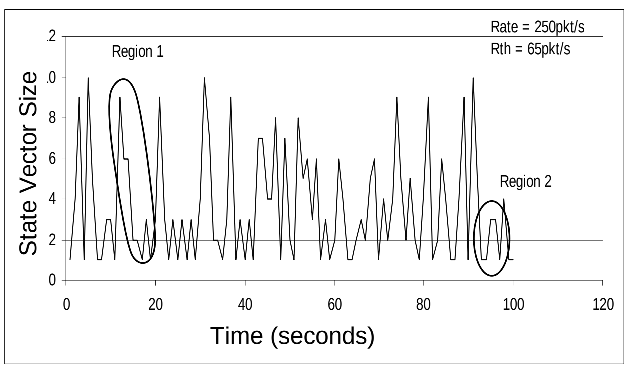
Results: Latency and Accuracy with R_{th}



- For $R_{th} < R_{bp}$ (R_{bp}=125 pkt/s), latency increases slowly before smoothing to a constant value
- For the curve of R_{th} = 140 pkt/s, the jump in latency is because the incoming rate is greater than R_{bp} and Monitor switches from sampling to non-sampling modes after the breakpoint
- The jump in latency translates to a sharp drop in accuracy in the accuracy plot
- A low R_{th} (50 pkt/s, 60 pkt/s) kicks in sampling early reducing accuracy. For R_{th} =100pkts/s the accuracy is high for a larger incoming rate

Results: Variation of State Vector Size



- In Region 1, $|\hat{S}|$ drops in steps from 9 to 6 and finally to 1. The drop in $|\hat{S}|$ is because of the unique possibility of the sampled event in only some of the states
- In Region 2, $|\hat{S}|$ increases from 1 to 3 because of a message drop

Related Research

- Change Detection in Networking
  - Sketch based approaches: Deltoids, Infocom'05, Infocom'06
  - Develop statistical models to describe the stream behavior.
  - In Monitor state of the application is closely examined and it accounts for spikes as well. Provides flexibility to switch to sampling or no-sampling
- Stateful Detection
  - Particular attention from the security community in building Intrusion Detection Systems,
  - Snort uses aggregated information from TCP packets to make decisions
  - SciDive provides stateful detection engine for VoIP, DSN`04
  - Restricted to the domain and focused on accuracy
- Detection in Distributed Systems
  - Heartbeats, watchdogs DSN `00
  - Detection of Failures using event graphs

Conclusions

- We developed a stateful detection mechanism that can scale to a high data rate of the application protocol
- We extend an existing detection approach (Monitor-Baseline) by identifying in-efficiencies in the rule matching process to reduce per packet processing overhead at the Monitor
- We use a sampling approach to reduce the number of packets being processed
- Take-Aways
  - Detection mechanism should do minimal per-packet processing
  - Sampling should be done only when needed (R_{in} close to R_{th})
  - Low sampling rate could lead to state space explosion