Automated Attack Discovery in TCP Congestion Control Using a Model-Guided Approach

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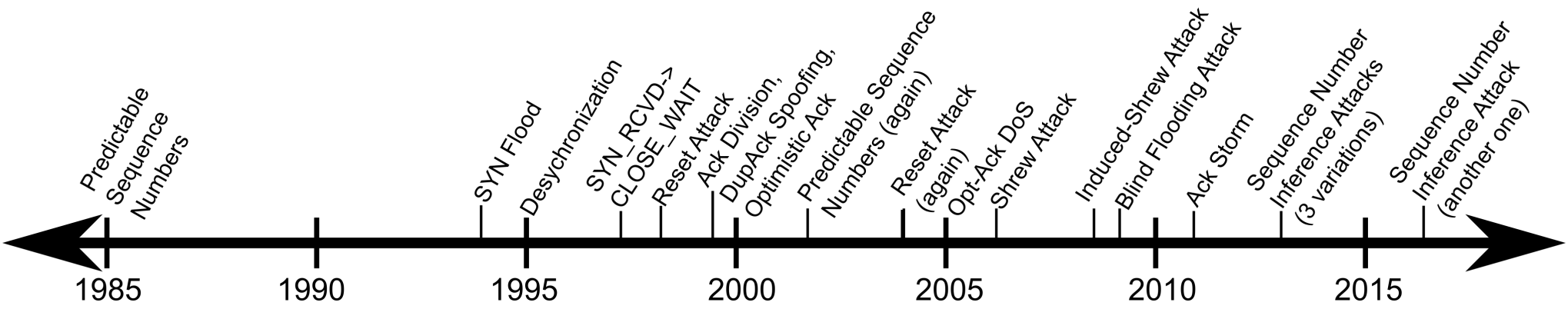
TCP

- Transport protocol used by vast majority of Internet traffic
  - Including traffic encrypted with TLS
  - Including network infrastructure protocols like BGP
- Thousands of implementations
  - Over 5,000 implementation variants detectable by nmap
- Provides:
  - Reliability
  - In-order delivery
  - Flow control
  - Congestion control

TCP attacked for 30 years!



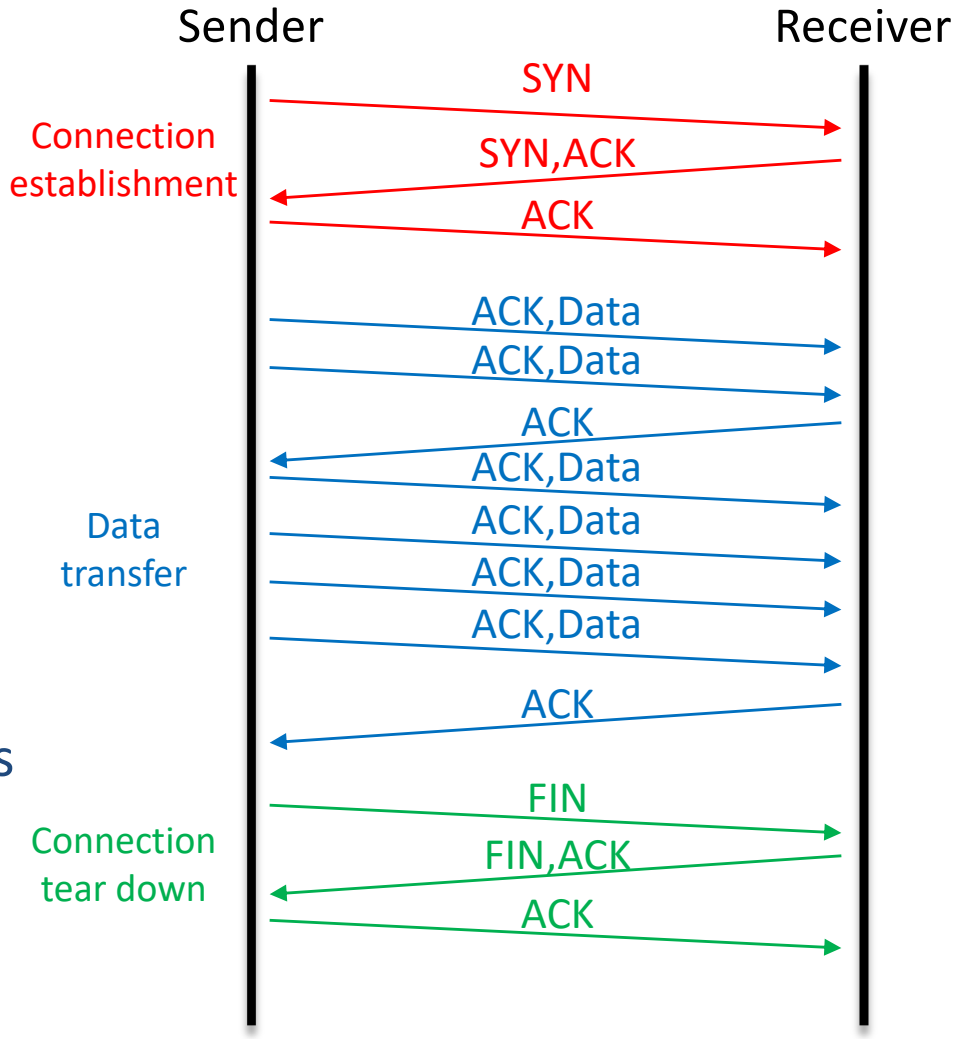
Why so many attacks?

- Complex goals
  - Reliability, in-order delivery, congestion control
- Many designs and implementations
  - Different designs for congestion control: Tahoe, Reno, New Reno, SACK, Vegas, BIC, CUBIC
  - Hundreds of implementations
- Written in low level languages
  - Highly efficient, but error-prone
- Heavily optimized
  - Prefers performance to ease of understanding and maintenance

Over 20 RFCs

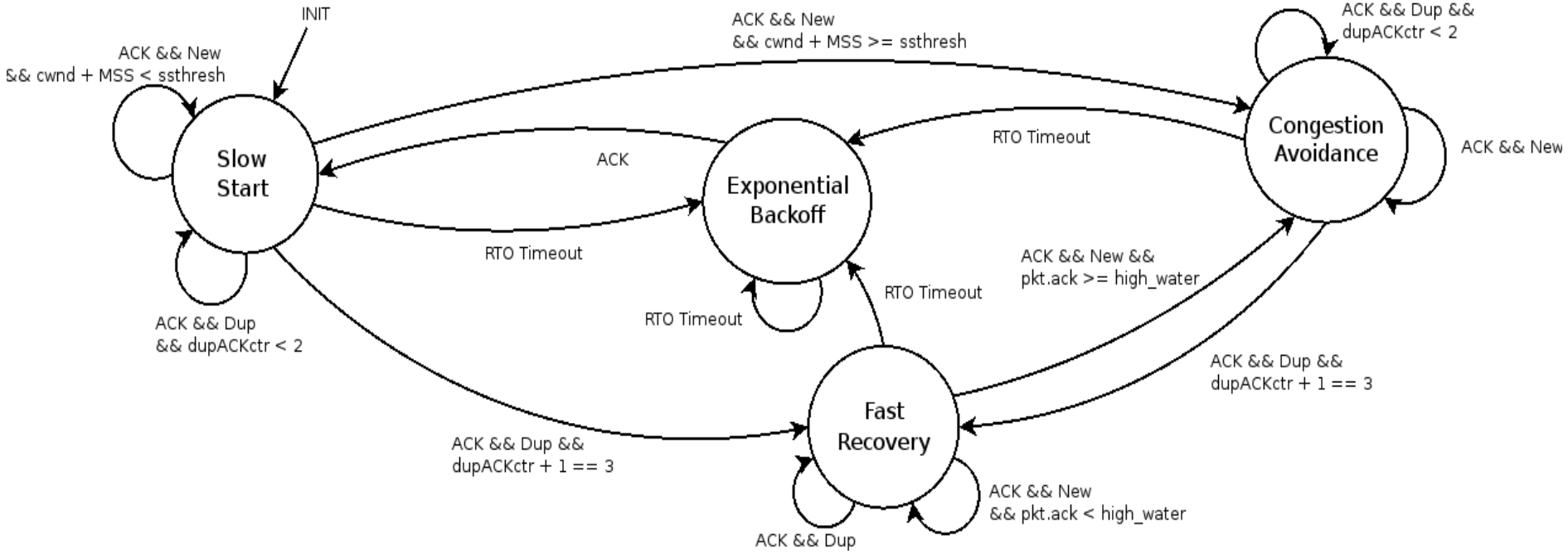
TCP connection set up and tear down

- Connection establishment
  - Check the other end exists
  - Set communication parameters on both directions
- Data sending
  - Bytes are numbered
  - Receiver periodically sends cumulative ACKS to sender
- Connection teardown
  - Graceful - each end releases its side of the connection
  - Abrupt - prevent attacks, lack on resources



TCP congestion control

- Protects against congestion collapse, provides fairness
- Many designs and implementations
  - Multiple Variations: Reno, New Reno, SACK, Vegas, BBR
  - Multiple Optimizations: PRR, TLP, DSACK, FRTO, RACK
  - Hundreds of implementations



This talk

Can we automatically find attacks in TCP implementations?
(without instrumenting the code)

- Connection establishment: SNAKE
  - State-machine based attack injection
- Congestion control: TCPwn (loss), aBBRate (model)
  - Model-based testing approach

Current methods

- Developer test suites
  - Tests used by developer to make sure implementation is cor
  - Packetdrill [USENIX 13]
- Fuzzi
  - KiF
  - Fin uts
- MAX [SIGCOMM 11]
  - Au
    exe

Ad-hoc, focused on benign scenarios

Difficulty reaching deep states, focus on crashes

Requires the user to select vulnerable lines of code

Attack model

Availability Attacks

- Keep resources allocated -- Denial of Service (DoS)
- Make a network service unavailable to all users
- Targeting a single connection using very focused actions

Performance Attacks

- Decrease the throughput of a target connection
- Stall a connection
- Increasing the throughout of a connection (basically making TCP behave as UDP – denial of service)

Our approach

- Test unmodified binaries in their native environment for close to deployment environment
- Testing for performance and availabilty issues, we need ts
- No code instrumentation
- Minimal input from user

1.Virtualization

2.Network emulation

5. AUTOMATED

3.Messages interception

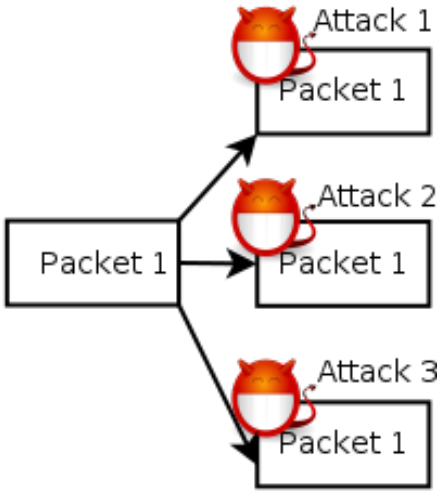
4.Message format, metric, topology, malicious nodes

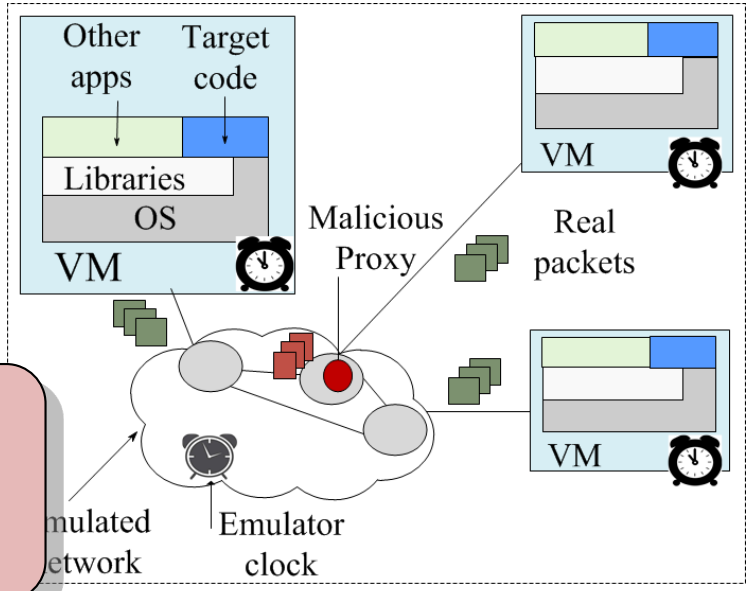
Design questions

- What attacks to create:
  - Disrupt message delivery: Delay, Divert, Duplicate, Drop:
  - Corrupt message content: lie field by field (based on field type range and on original value): Min and max, Zero, Scaling, Spanning, Random
- How to decide that the result was an attack:
  - Throughput, latency
- How to find attacks:
  - Brute force, greedy search algorithm, weighted greedy
- **When to inject an attack:**
  - Packet send-based, time-based, state machine-based

Attack injection: Packet send-based

- How
  - For each packet, inject each attack at packet send call
- Pros.
  - Simple
  - Systematic
- Cons.
  - Does not support injecting new packets

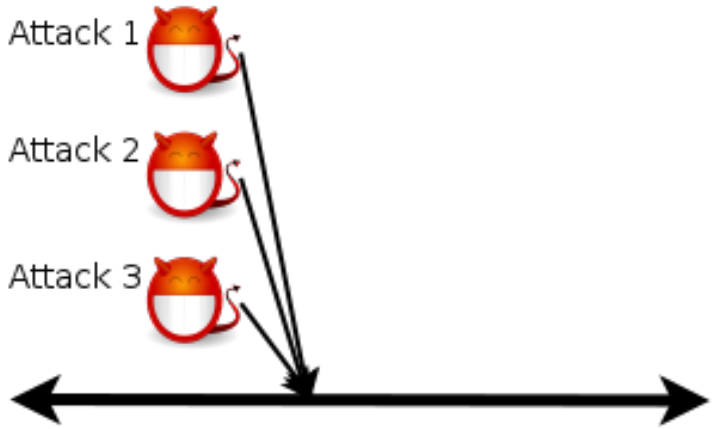




Not a good fit for finding attacks in TCP handshake

Attack injection: Time-based

- How
  - Every n seconds, inject a message attack and observe the result
  - Supports injecting new packets



Cannot achieve scalability and coverage!

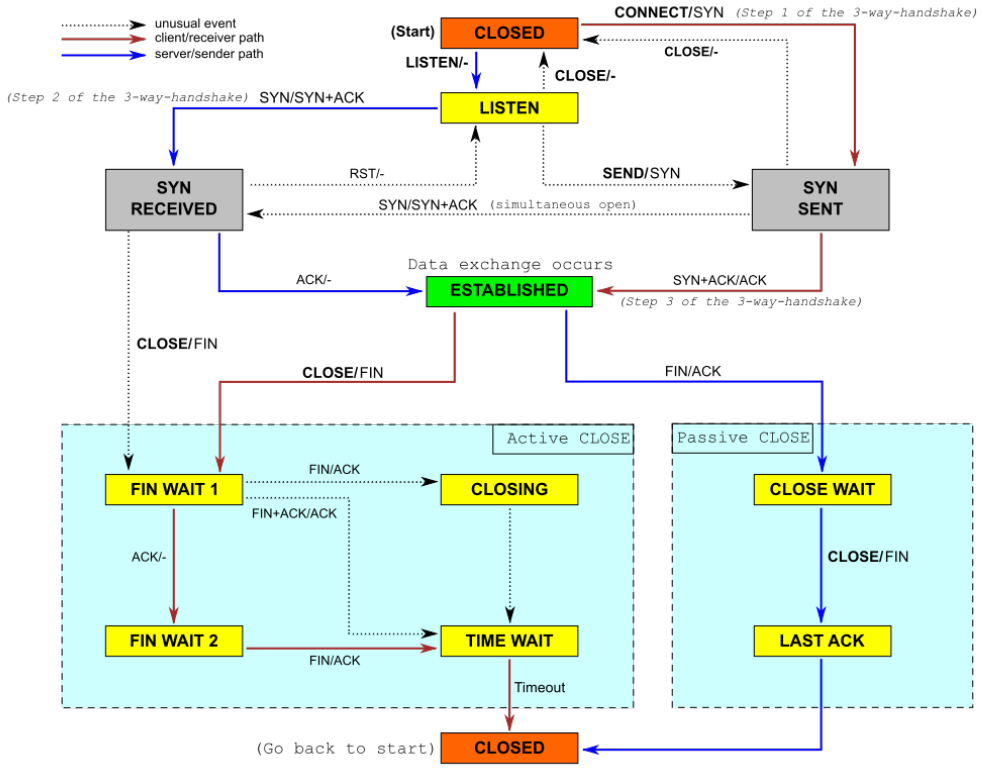
Scales with n*connection_length*attacks

- A minimum sized TCP packet takes 5 microseconds to transmit at 100Mbits/sec

12 million pkts*60 attacks*2min = 24 million hours

Our approach: Leverage state machine

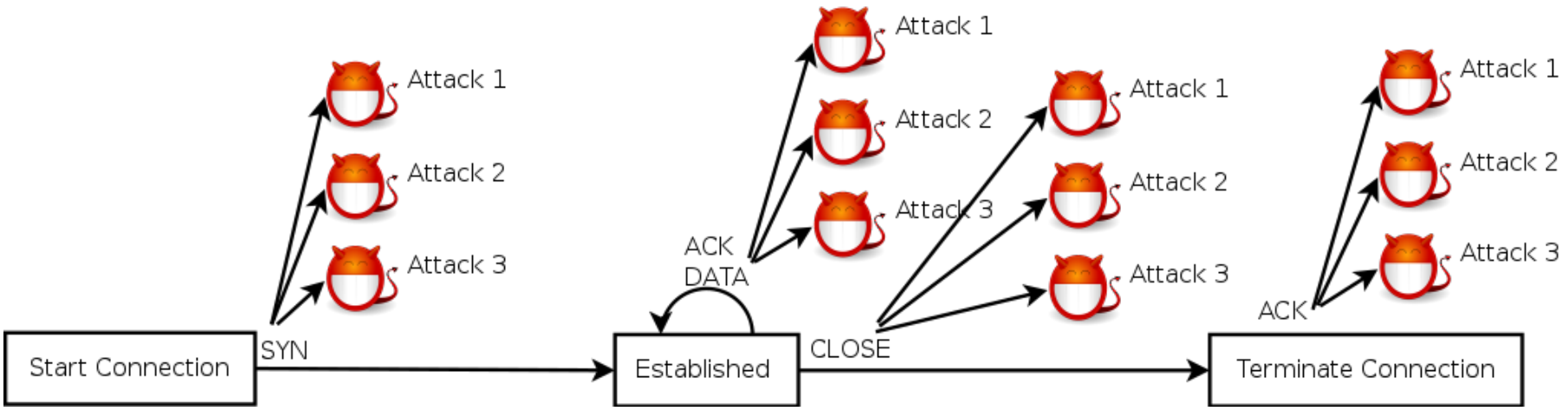
- Improved scalability and coverage
- State machine identifies key protocol areas
- Similar packet types received in the same state often perform similar actions
- Combine protocol state and packet type for attack injection



TCP Connection State Machine

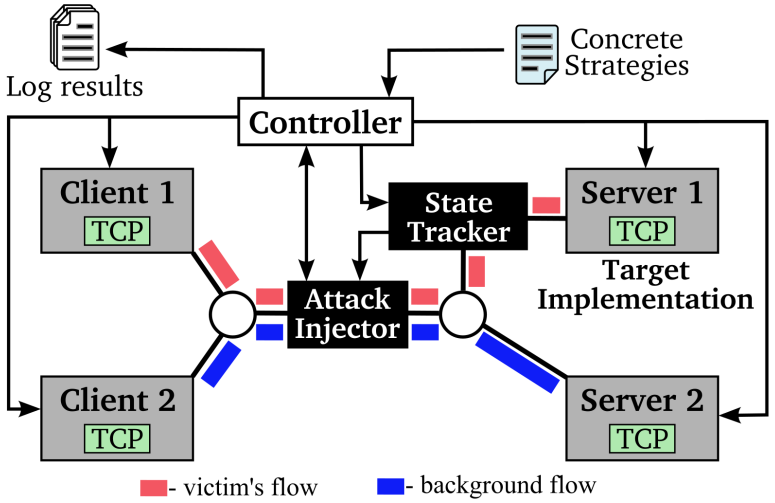
Attack injection: State machine-based

- How
  - Consider the protocol state, packet type pairs and apply each message attack to each pair
- Pros.
  - Scalable
  - Can apply attacks to more than a single packet
- Cons.
  - Assumes state machine is available
  - Assumes state machine is implemented correctly

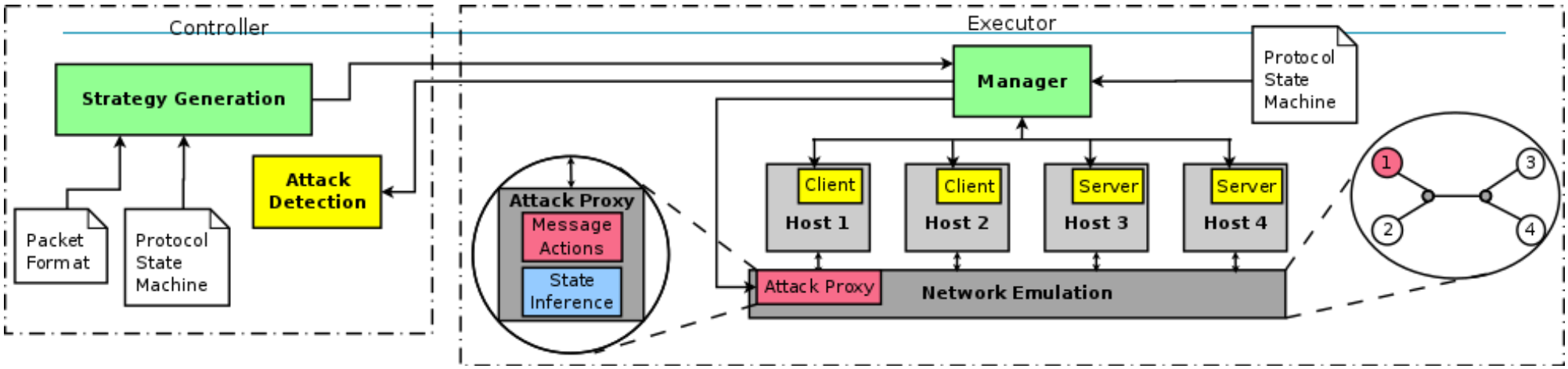


Decide if it was an attack or not

- During testing, performance and resource usage information collected to identify attacks
- Attack declared if:
  - Throughput of a flow is different that of the competing flow's by more than a factor of 2
  - Server resources are not released at the end of the test



SNAKE



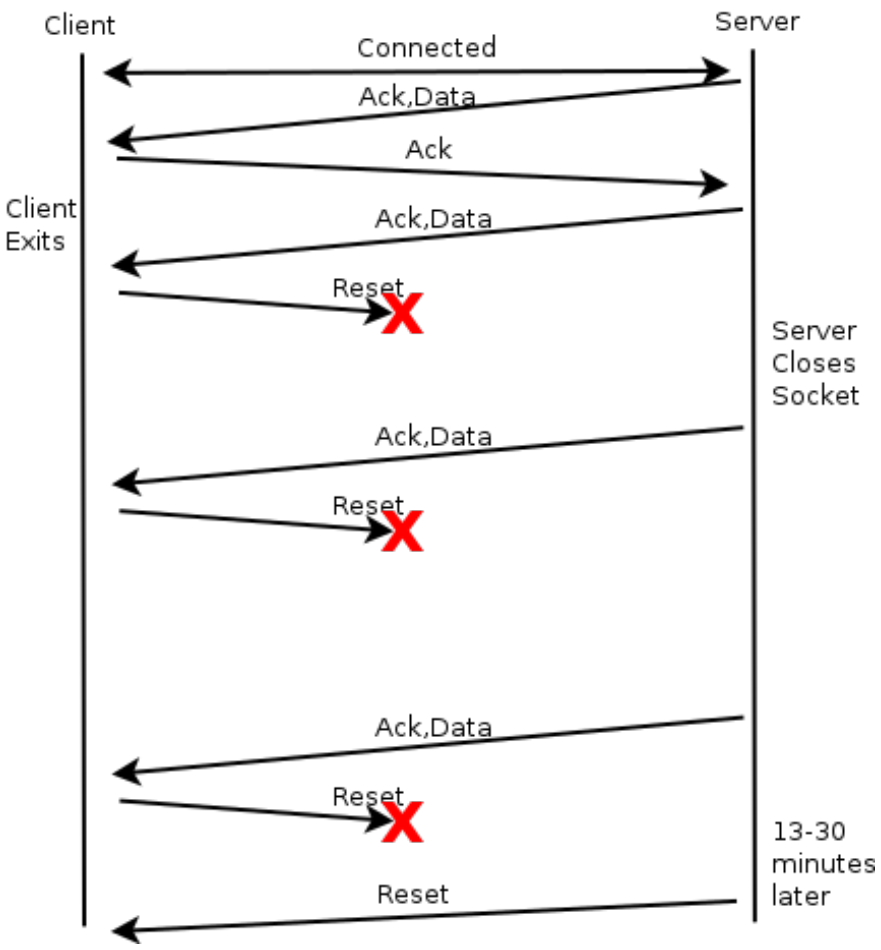
- Supported attacks: Drop, Duplicate, Delay, Batch, Reflect, Lie about packet fields, Inject, and HitSeqWindow
- Current protocol state tracked by monitoring packets

Leveraging State Information for Automated Attack Discovery in Transport Protocol Implementations
Samuel Jero, Hyojeong Lee, and Cristina Nita-Rotaru. DSN 2015. Best Paper Award.

TCP CLOSE_WAIT resource exhaustion attack

Client can force the server to keep socket state around for 13-30 minutes

- Client application exits
- Client responds to all future data with Resets
- Resets are dropped
- Server must receive ACKs for all data before it can close connection



TCP and DCCP

Protocol	Attack	Impact	OS	Known
TCP	CLOSE_WAIT Resource Exhaustion	Server DoS	Linux 3.0/3.13	Partially
TCP	Packets with Invalid Flags	Fingerprinting	Linux 3.0 / Win 8.1	No
TCP	Duplicate Ack Spoofing	Poor Fairness	Win 95	Yes
TCP	Reset Attack	Client DoS	All	Yes
TCP	SYN-Reset Attack	Client DoS	All	Yes
TCP	Duplicate Ack Rate Limiting	Degraded Throughput	Win 8.1	No
DCCP	Ack Mung Resource Exhaustion	Server DoS	Linux 3.13	No
DCCP	In-window Ack Sequence Number Modification	Degraded Throughput	Linux 3.13	No
DCCP	REQUEST Connection Termination	Client DoS	Linux 3.13	No

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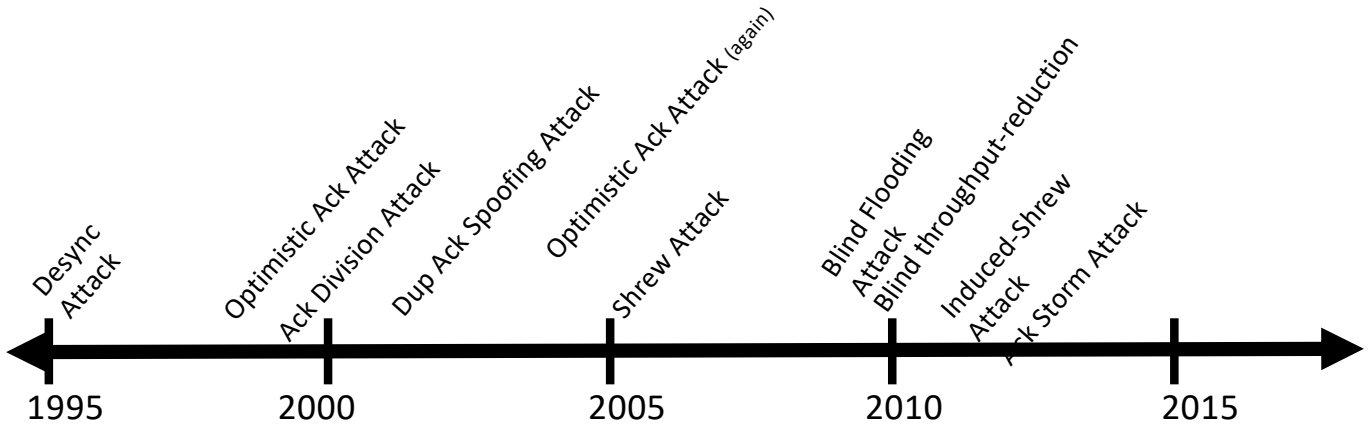
Congestion control-related attacks



Attacks may result in:

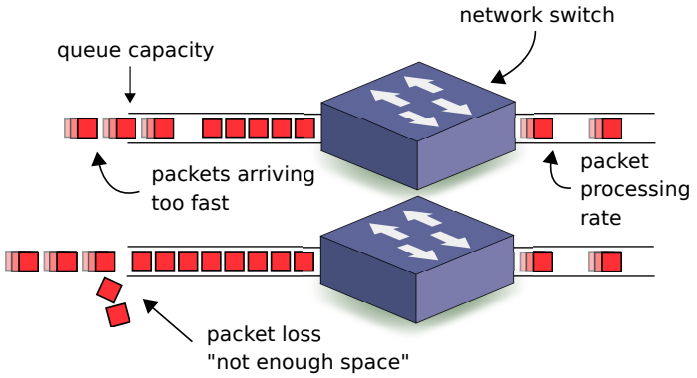
- **Decreased** throughput
- **Increased** throughput that starves competing flows
- **Stalled** data transfer

SNAKE could not find these attacks

Congestion control

- Goals
  - Avoid overwhelming the network
  - Divide bandwidth to flows sharing network
- How
  - Use signals from network to detect congestion
- TCP Congestion Control
  - Leverages acknowledgments (ACKs) to detect packet loss

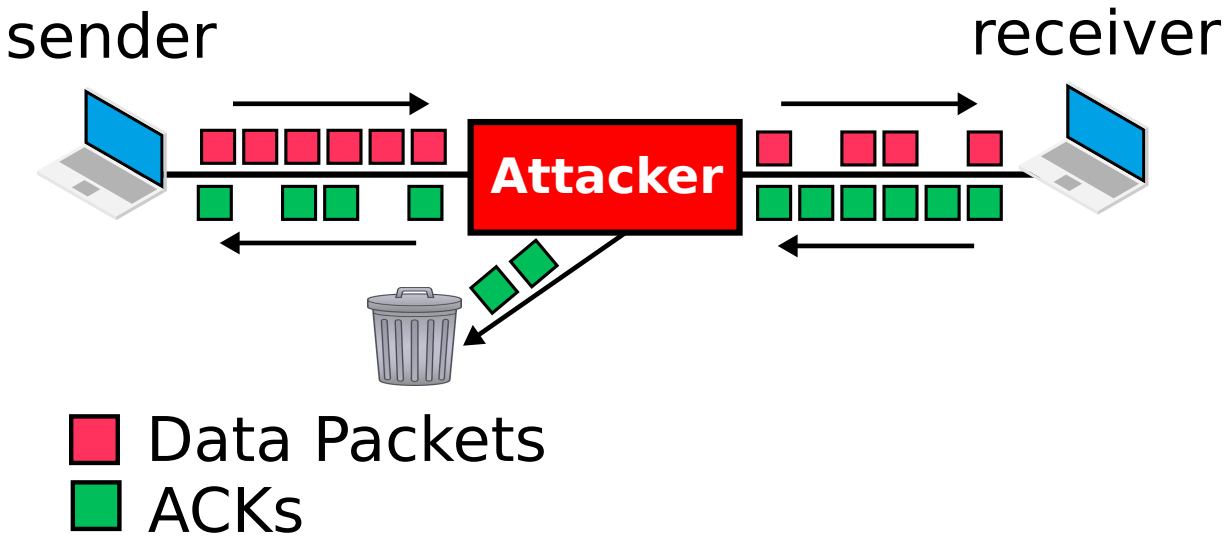
Packet loss as congestion signal



How it works: Some queue along path overflowed due to congestion

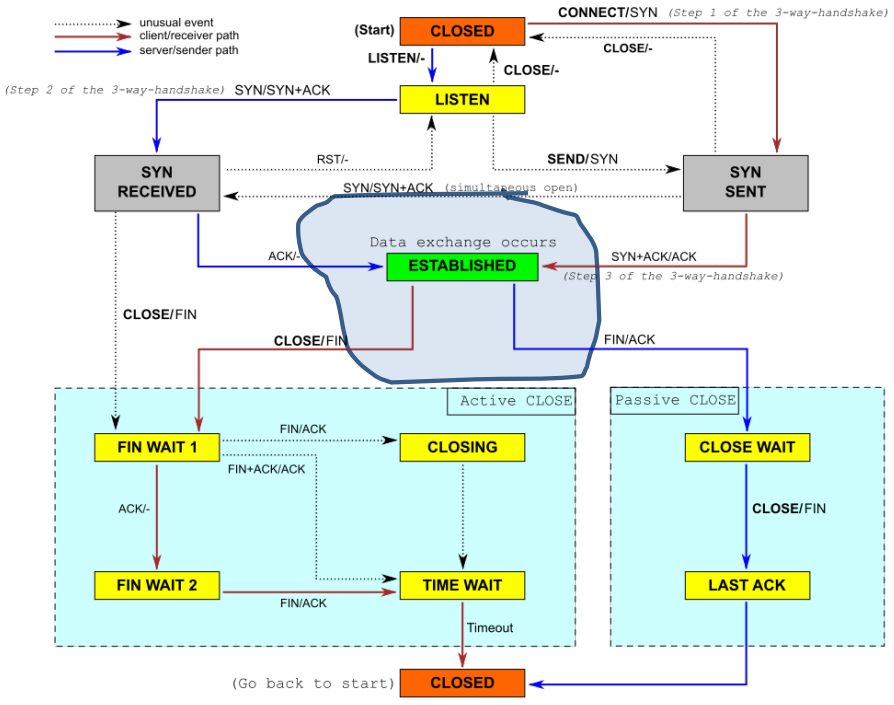
ACK manipulation attacks

- Manipulate ACKs to fool sender about actual congestion
- Attacker needs to observe (on-path) or predict (off-path) a sequence to be able to inject packets
- Cause sender to **send too fast, too slow or stall**



Why SNAKE could not find those attacks?

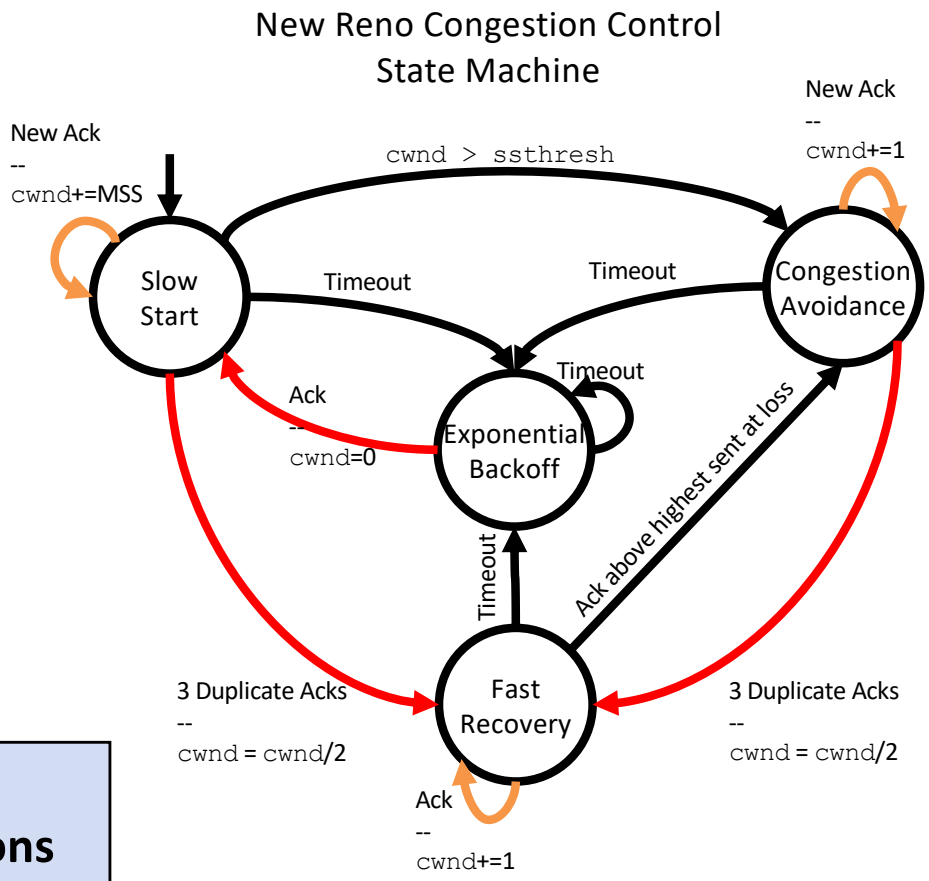
- State machine we modeled perceived congestion control as a black-box, we modeled only connection establishment, steady state was modeled as one state
  - No visibility into ACKs and their relation to the different stages of congestion control



Optimistic Ack Attack

How does it work: Increase sending rate by acknowledging data that has not been received yet

- Acknowledging new data causes yellow transitions to be taken
- Increases `cwnd` and thus throughput with each loop
- Avoids red transitions which reduce `cwnd` and thus throughput

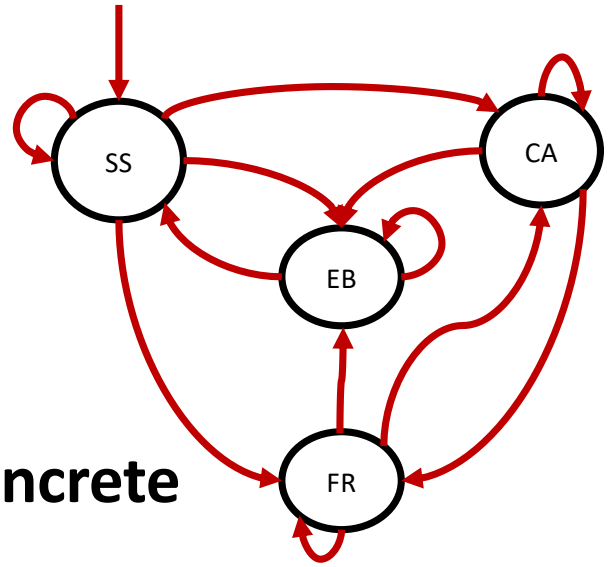


Key Takeaways:

- **Attacks attempt to cause desirable transitions**
- **Attacks must repeatedly execute transition to have noticeable impact**

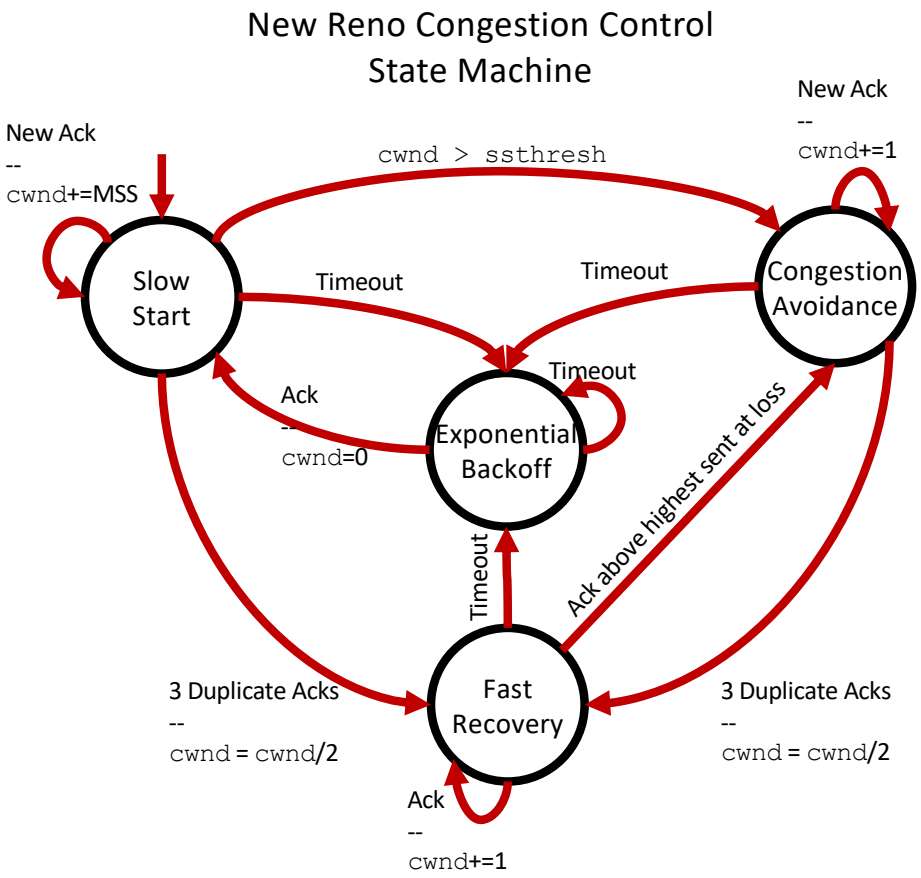
Our approach for congestion control: TCPwn

- Use **model-based testing** to identify all possible attacks in a *scalable* manner
  - Use an abstract model to generate abstract strategies
  - Map abstract strategies to concrete strategies
  - Execute concrete strategies on implementations to find attacks causing:
    - Decreased throughput
    - Increased throughput
    - Connection stall
- **1. How to select the abstract model**
- **2. How to find abstract strategies**
- **3. How to map abstract strategies to concrete strategies**



Our model: New Reno

- State machine
  - Input: Acks and Timers
  - Output: Congestion Window (`cwnd`) = sending rate
- Four states:
  - *Slow Start*—Quickly find available bandwidth
  - *Congestion Avoidance*—Steady state sending with occasional probe for more bandwidth
  - *Fast Recovery*—React to loss by slowing down
  - *Exponential Backoff*—Timeout, slow down



Why New Reno

- General-enough state machine
- It is the starting based for _most_ TCP congestion control algorithms
- Does not capture optimizations, but our results show that was good enough in practice
- (As we will show later we need to also be able to infer the state at ran time so simpler is better)
- We trade-off precision for generality

Model-based attack generation

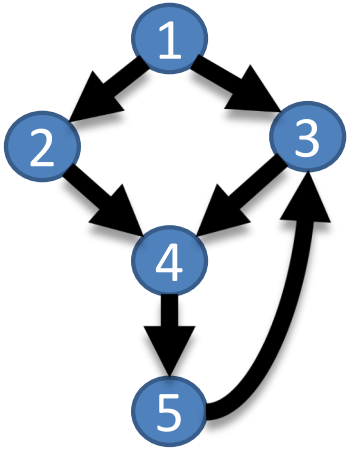
Generate all cycles with the following pattern:

- **`cwnd` increases/decreases along cycle**
- **A set of actions exist that force TCP to follow this cycle**

1. Consider state machine model of congestion control
2. Identify cycles containing desirable transitions
   - Abstract strategy generation
3. Force TCP to follow each cycle
   - Concrete strategy generation

Abstract strategy generation

- Enumerate all paths
  - No standard graph algorithm
  - We adapt *depth first search* to this problem
- Check that path contains cycle
- Check that cycle contains desirable transitions
  - Any change to `cwnd`
- Add path and transition conditions to abstract strategies



✓ **Cycle**

✓ **Desirable Transition**

Abstract strategies are merely desirable cycles; they may not be realizable in practice!

From abstract to concrete strategies

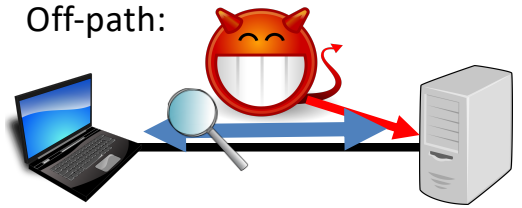
We want to test implementations

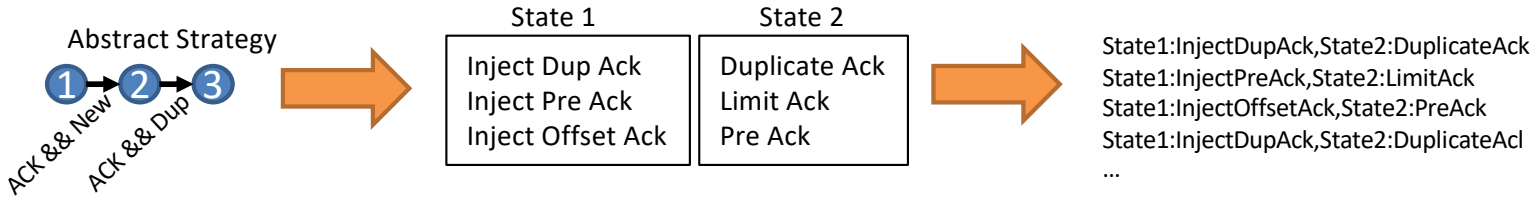
- Limited to packet manipulation and injection to cause abstract strategies
- Consider each abstract strategy separately
- Map each transition to a set of basic malicious actions
  - Actions chosen to cause transition
  - Based on attacker capabilities

Attacker Types:

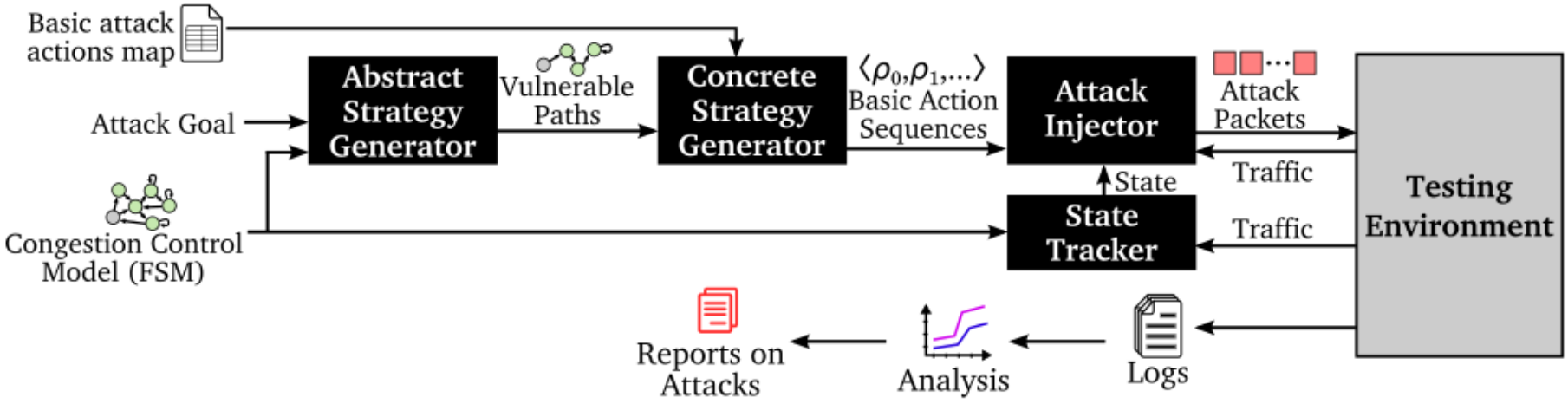
On-path:

Off-path:

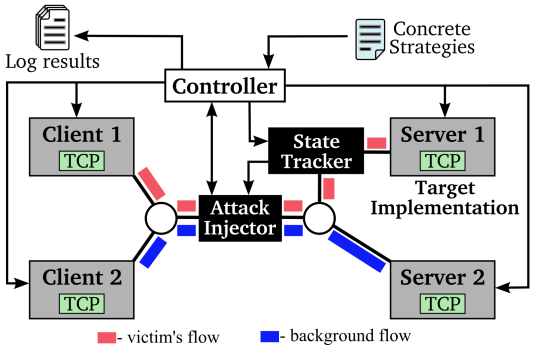




TCPwn design



- Test strategies created using model-based testing and our abstract and concrete strategy generators
- Attack injector applies malicious actions
- Performance of target TCP connection identifies attacks



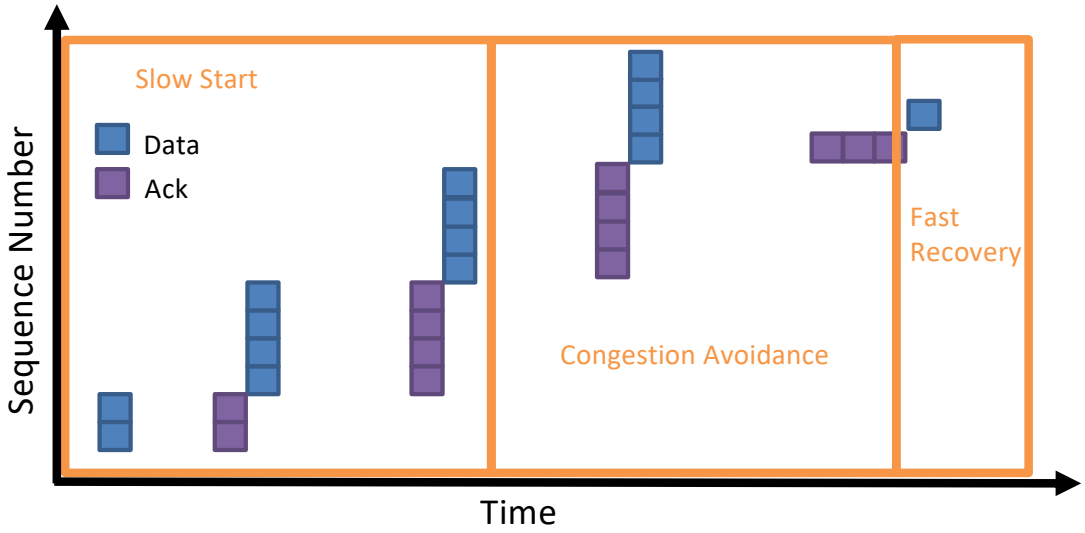
Automated Attack Discovery in TCP Congestion Control Using a Model-guided Approach. S. Jero, E. Hoque, D. Choffnes, A. Mislove, C. Nita-Rotaru. NDSS 2018, CISCO Network Security Distinguished Paper Award

Inferring congestion control state

To apply concrete strategies to an implementation, we need to know the sender's congestion control state

- Approximate congestion control state and assume normal application behavior
- Take a small timeslice and observe the bytes sent and acknowledged by the implementation

Bytes Sent*2 ≈ Bytes Acked
State: Slow Start
Bytes Sent ≈ Bytes Acked
State: Congestion Avoidance
Retransmitted packets or ACK pkts > Data pkts
State: Fast Recovery
ACK pkts == 0 and Data pkts > 0
State: Exponential Backoff



Evaluation

We tested five TCP implementations:

Implementation	Date	Congestion Control
Ubuntu 16.10 (Linux 4.8)	2016	CUBIC+SACK+FRTO+ER+PRR+TLP
Ubuntu 14.04 (Linux 3.13)	2014	CUBIC+SACK+FRTO+ER+PRR+TLP
Ubuntu 11.10 (Linux 3.0)	2011	CUBIC+SACK+FRTO
Debian 2 (Linux 2.0)	1998	New Reno
Windows 8.1	2014	Compound TCP + SACK

Found 11 classes of attacks, 8 of them unknown

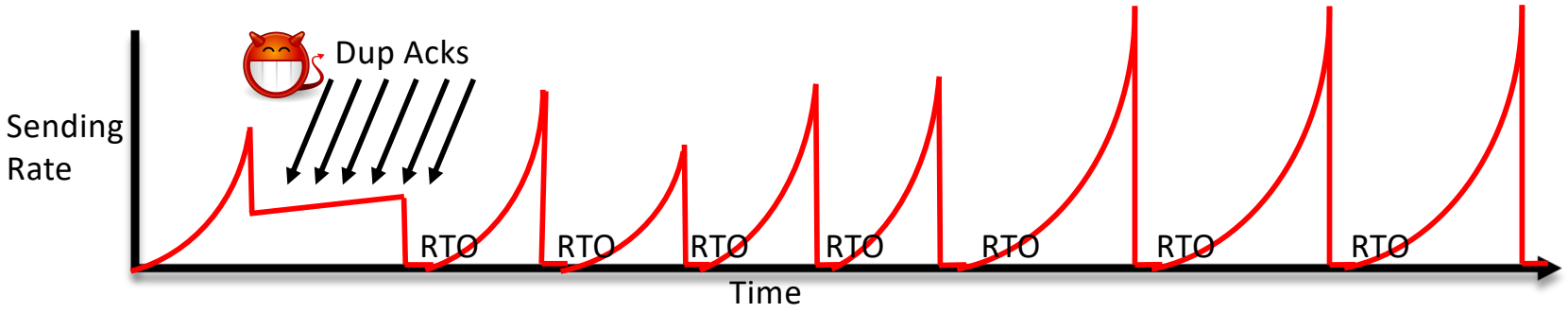
Results summary

Attack Class	Attacker	Impact	OS	New?
Optimistic Ack	On-path	Increased Throughput	ALL	No
On-path Repeated Slow Start	On-path	Increased Throughput	Ubuntu 11.10, Ubuntu 16.10	Yes
Amplified Bursts	On-path	Increased Throughput	Ubuntu 11.10	Yes
Desync Attack	Off-path	Connection Stall	ALL	No
Ack Storm Attack	Off-path	Connection Stall	Debian 2, Windows 8.1	No
Ack Lost Data	Off-path	Connection Stall	ALL	Yes
Slow Injected Acks	Off-path	Decreased Throughput	Ubuntu 11.10	Yes
Sawtooth Ack	Off-path	Decreased Throughput	Ubuntu 11.10, Ubuntu 14.04, Ubuntu 16.10, Windows 8.1	Yes
Dup Ack Injection	Off-path	Decreased Throughput	Debian 2, Windows 8.1	Yes
Ack Amplification	Off-path	Increased Throughput	Ubuntu 11.10, Ubuntu 14.04, Ubuntu 16.10, Windows 8.1	Yes
Off-path Repeated Slow Start	Off-path	Increased Throughput	Ubuntu 11.10	Yes

Off-path repeated slow start attack

- Linux includes adjustable dup ack threshold
  - Based on observed duplicate and reordered packets
- Attacker injects many duplicate acks
  - Increasing dup ack threshold
- Timeout occurs before dup ack loss detection
- Enter Exponential Backoff and then Slow Start
  - Instead of Fast Recovery
- Short 200ms timeout causes throughput to be >= normal
- Competing connections also suffer badly due to repeated losses

Off-path attacker can increase throughput for Linux senders



Discussion

- Use of New Reno as model
  - Model limited by ability to infer sender's state from network traffic
  - More precise inference or instrumentation would enable more precise modeling
  - We trade off precision for ease of application to a wide range of implementations
- What about CUBIC, SACK, etc?
  - Most algorithms/optimizations are similar to New Reno (includes: SACK, CUBIC, TLP, PRR)
  - We actually tested implementations of these and found attacks
- What about algorithms not similar to New Reno?
  - For example: BBR, TFRC, Vegas
  - Model-based testing still readily generates abstract strategies
  - Need a method to infer sender's congestion control state

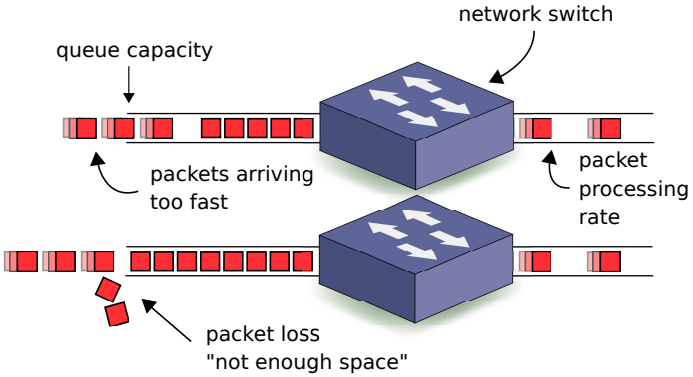
This talk

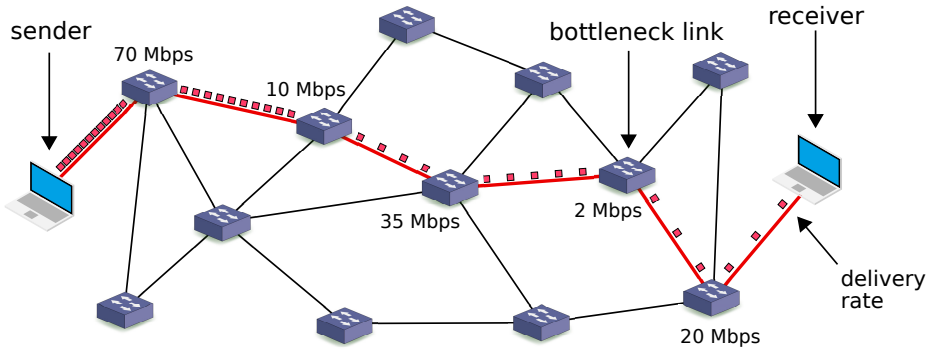
Can we automatically find attacks in TCP implementations?
(without instrumenting the code)

- Connection establishment: SNAKE
  - State-machine based attack injection
- Congestion control: TCPwn (loss), aBBRate (model)
  - Despite using a different congestion control approach, is BBR prone to acknowledgment-based manipulation attacks?
  - Are there any known attacks that BBR is immune to?

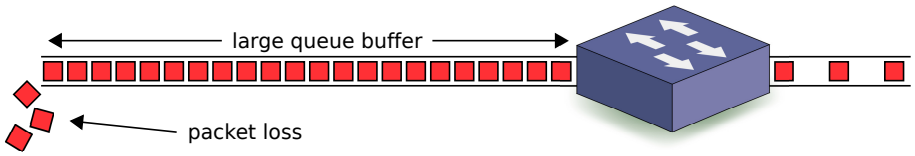
BBR: Motivation

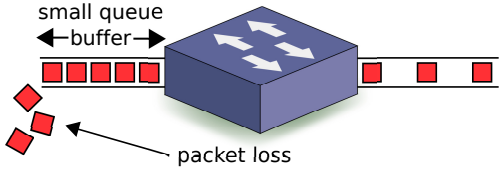
Packet loss as congestion signal





How it works: Some queue along path overflowed due to congestion





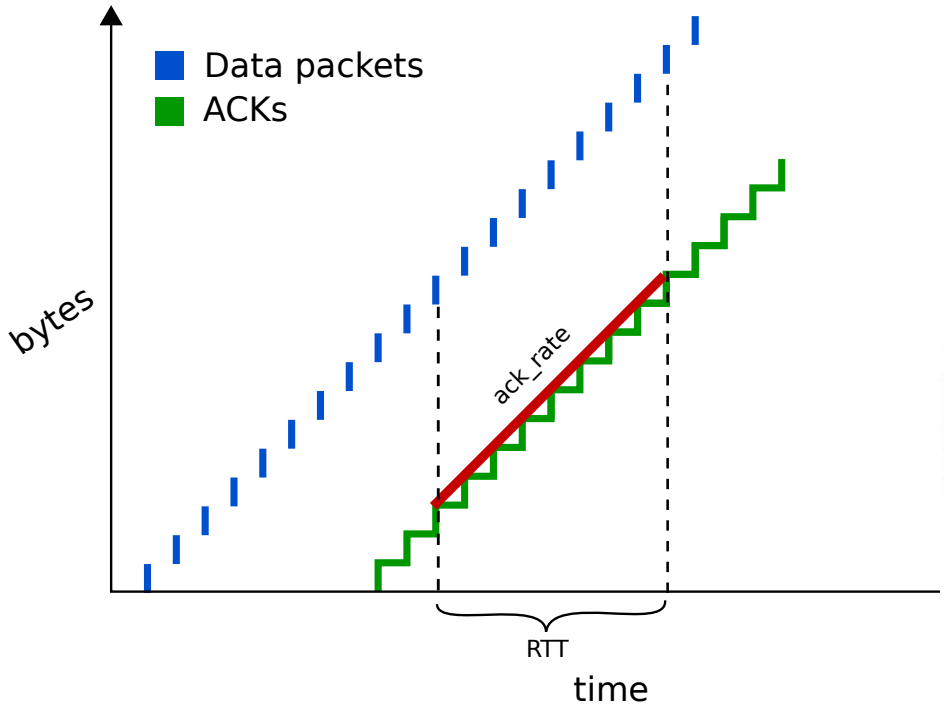
What is actually needed is to estimate the bottleneck link and not send faster than that

In modern networks: less effective

BRR: Congestion Control

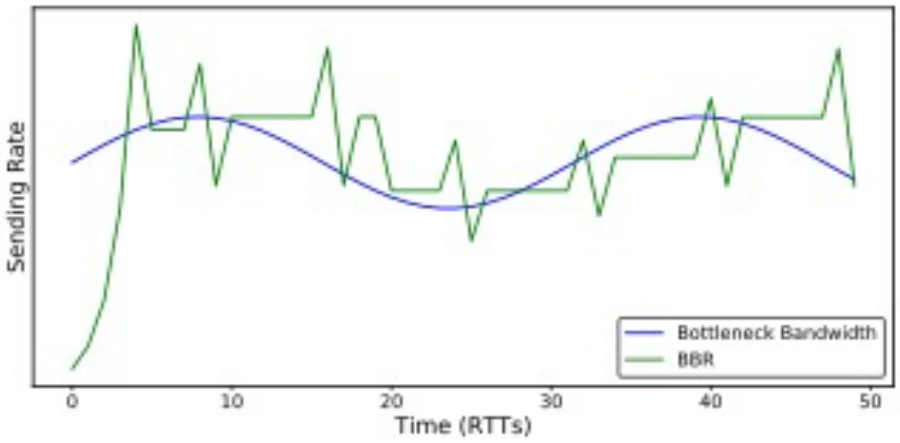
Detecting congestion

- Estimates the Bottleneck Bandwidth
- By measuring fine-grained ACK rate across RTT intervals



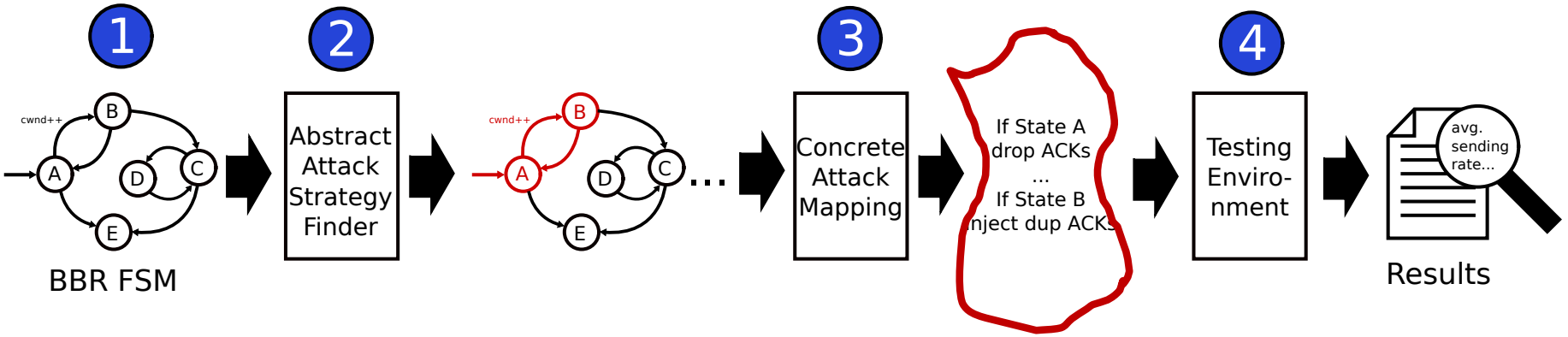
Reacting to congestion:

- Retain max delivery rate sample for 10 RTTs, and send proportionally
- Send 25% faster 1/8 RTTs to approach network limit
- Backs off from network when old max delivery rate sample expires



Adapting TCPwn for BBR

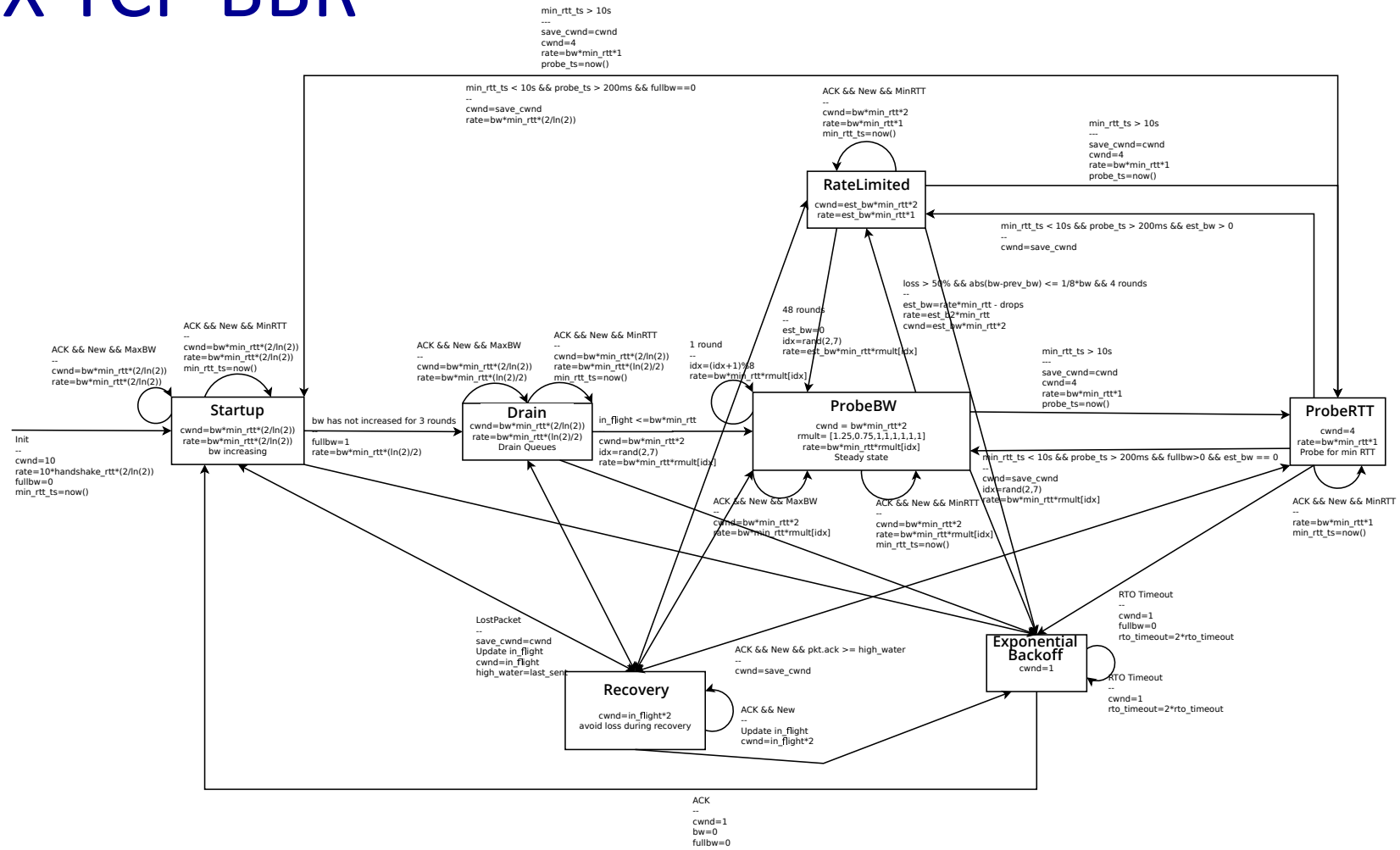
- TCPwn use the congestion control finite-state machine (FSM) encoding
- Searches for all paths in FSM that manipulate its sending rate
- Map paths to actual attacks
- Execute attack while measuring sending rate



On-path concrete attacks supported

- ACK duplication: send same ACK several times
- ACK stepping: several ACKs are dropped and then several let through in a cycle
- ACK bursting: ACKss are sent in bursts
- Optimistic ACK: acknowledge highest byte, dropping duplicates
- Delayed ACK: delay ACKs for a fixed amount of time
- Limited ACK: prevent ACK numbers from increasing
- Stretch ACK: forward only every n^{th} ACK
- Off-path: ACK duplication, offset acknowledgments, and incrementing ACKS

LINUX TCP BBR



- We extracted BBR FSM from code (not available anywhere)

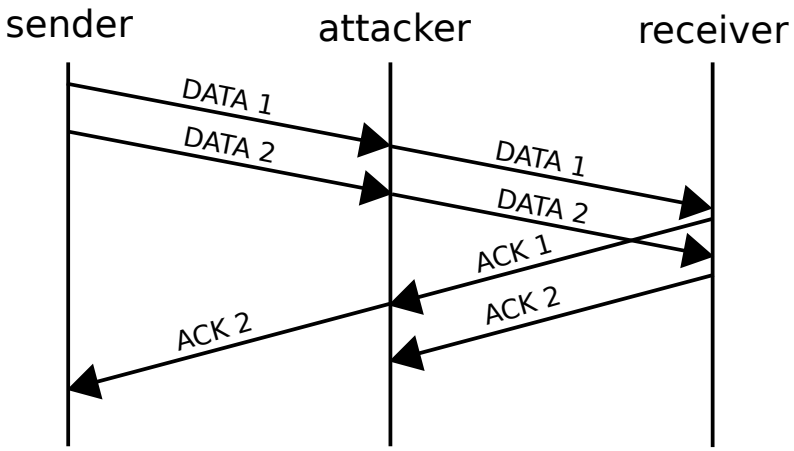
aBBRate: Automating BBR Attack Exploration Using a Model-Based Approach A. Peterson, S. Jero, E. Hoque, D. Choffnes, C. Nita-Rotaru. RAID 2020

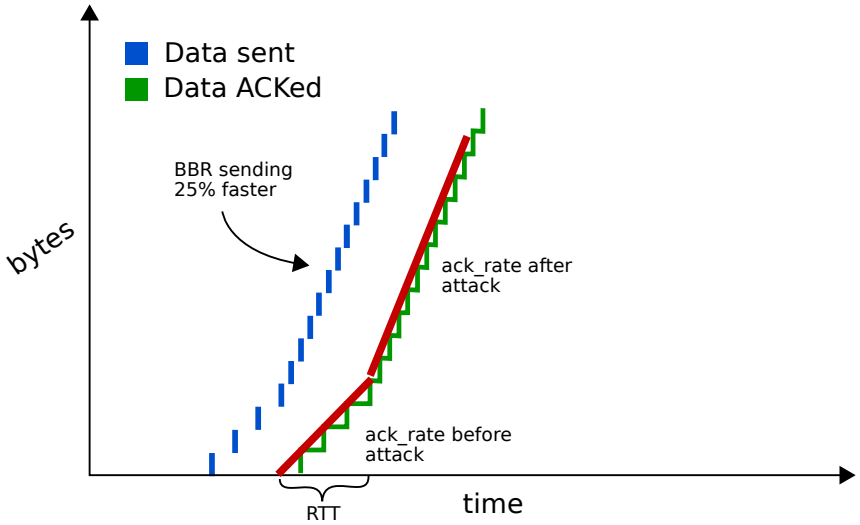
Evaluation

- Generated 30,297 attack strategies
- 8,859 caused faster, slower or stalled connections
- 14 – Faster
  4,025 – Slower
  4,820 – Stalled (transmission halts)
- 5 classes of attacks

Attack class	Impact
Optimistic acknowledgments	Faster
Delayed acknowledgments	Slower
Repeated Re-transmission timeout	Slower
Re-transmission timeout stall	Stalled
Sequence number de-sync stall	Stalled

Optimistic ACK

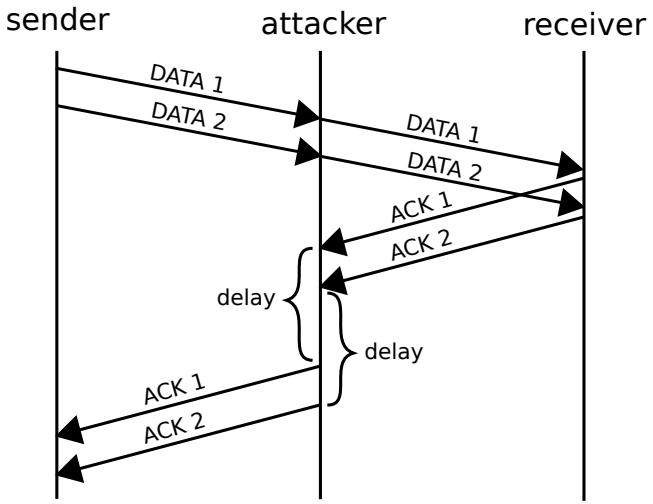


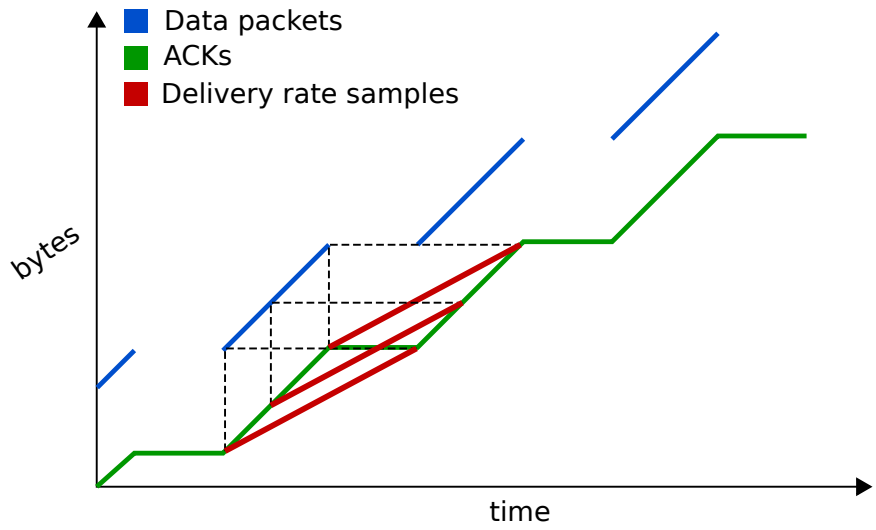


ACK highest observed data sequence, makes the sender send faster

- When BBR probes for bandwidth, it sends 25% faster for 1 RTT
- ACK rate follows the increased sending rate
- BBR believes the network can sustain the increased rate

Delayed ACK

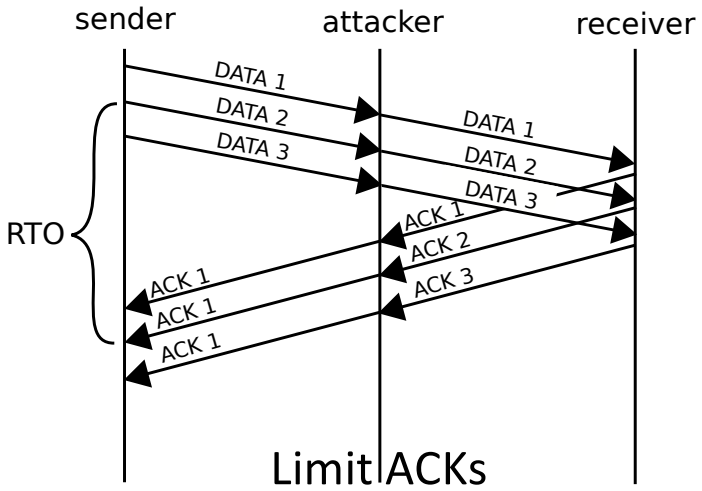


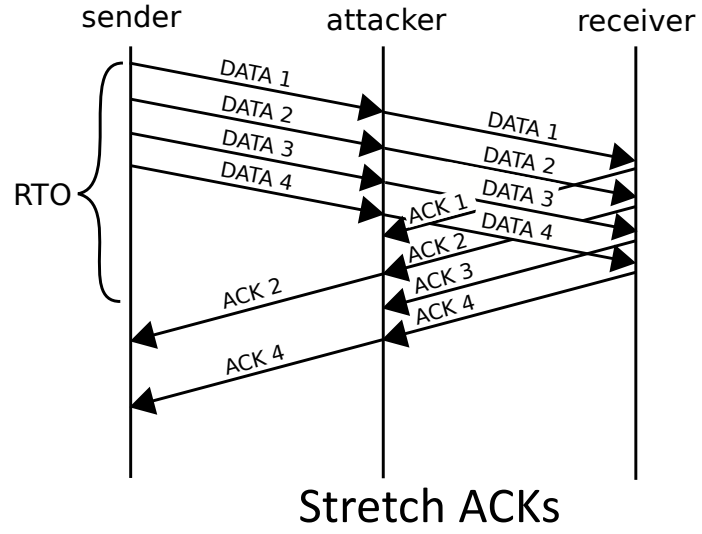


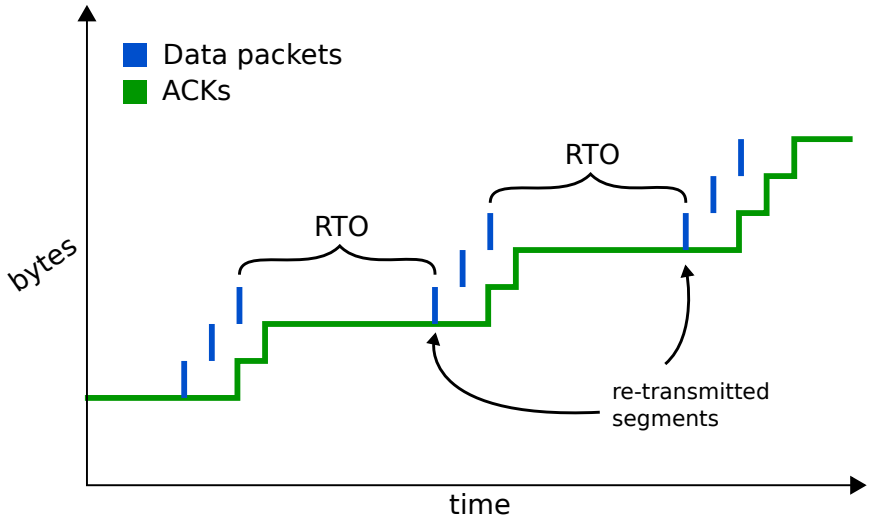
Delay ACKs for a constant amount of time

- Initial delay in ACKs at sender
- Sender stops sending data because no data is ACKed
- BBR believes the bottleneck bandwidth is smaller than reality
- Takes effect after 10 RTTs, due to bottleneck bandwidth filter

Repeated retranssmission timeout

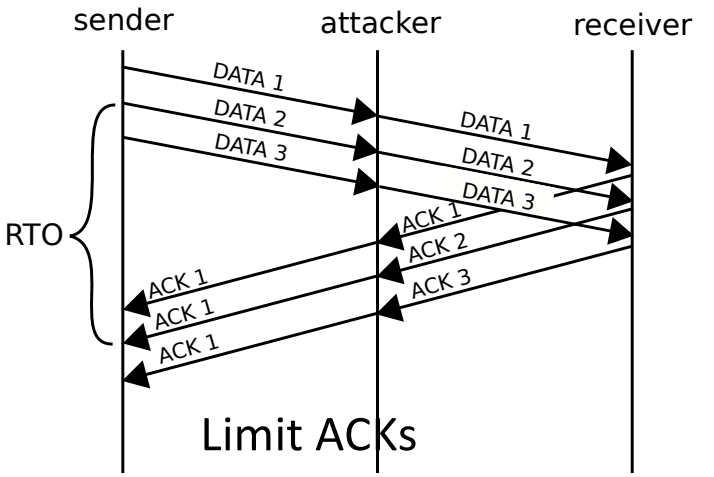


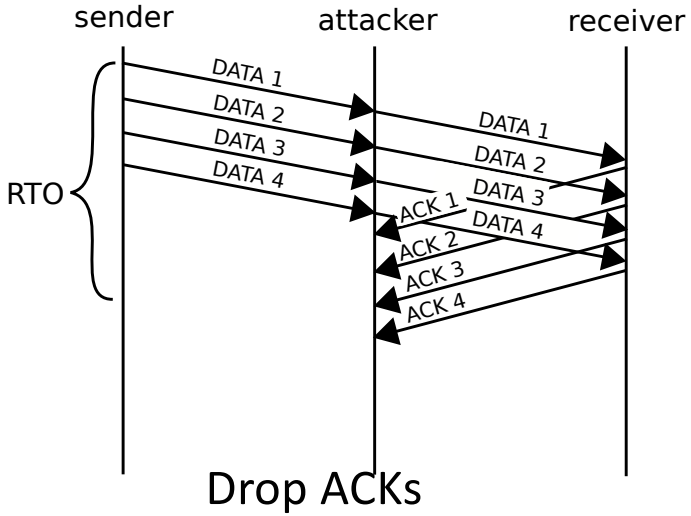


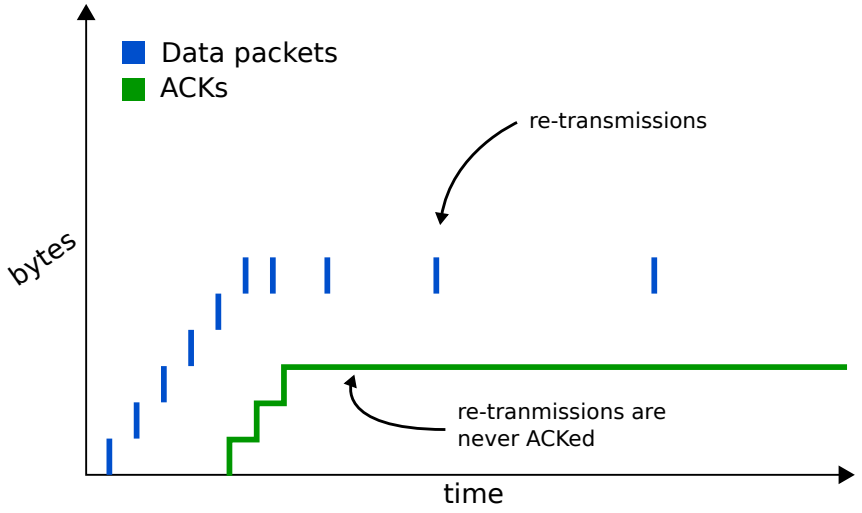


- Until RTO occurs, sender waits and does not send data
- A lot of time is wasted idling
- Data is sent in small bursts between RTOs

Re-transmission timeout Stall



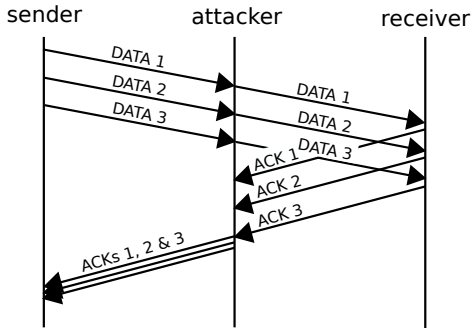




- If no new data is ACKed, no new data will be sent

Attacks ineffective against TCP BBR

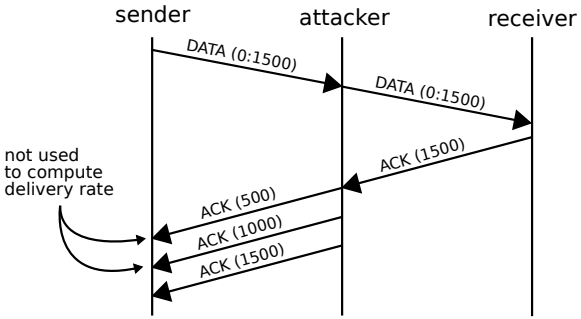
ACKs Bursts



Attacker accumulates n ACKs and sends in a burst

BBR immune because it sends data proportional to average ACK rate over RTT intervals

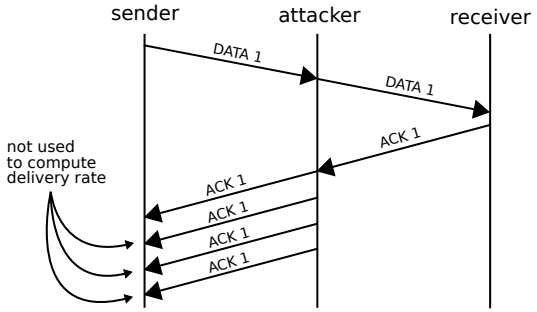
Divided ACKs



Attacker divides single ACK into n smaller ACKs

BBR immune because it only computes delivery rate samples for segments that the ACK specifically acknowledges

Duplicate ACKs



Duplicate single ACK n times

BBR immune because it does not use packet loss to signal congestion, duplicate ACKs are not used to compute delivery rate samples

Summary

- Show how to find automatically attacks in TCP implementations without instrumenting the code
  - Connection establishment
  - Congestion control

Check out the code!
https://github.com/samueljero/snake
https://github.com/samueljero/TCPwn

ISEC Building

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Relevant publications

- **Leveraging State Information for Automated Attack Discovery in Transport Protocol Implementations** Samuel Jero, Hyojeong Lee, and Cristina Nita-Rotaru. 45th IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Jun. 2015. Best Paper Award.
- **Automated Attack Discovery in TCP Congestion Control Using a Model-guided Approach.** Samuel Jero, Endadul Hoque, David Choffnes, Alan Mislove, Cristina Nita-Rotaru. NDSS 2018, Feb. 2018. CISCO Network Security Distinguished Paper Award
- **aBBRate: Automating BBR Attack Exploration Using a Model-Based Approach** Anthony Peterson, Samuel Jero, Endadul Hoque, Dave Choffnes, Cristina Nita-Rotaru. RAID 2020