A Network Coding Approach to IP Traceback

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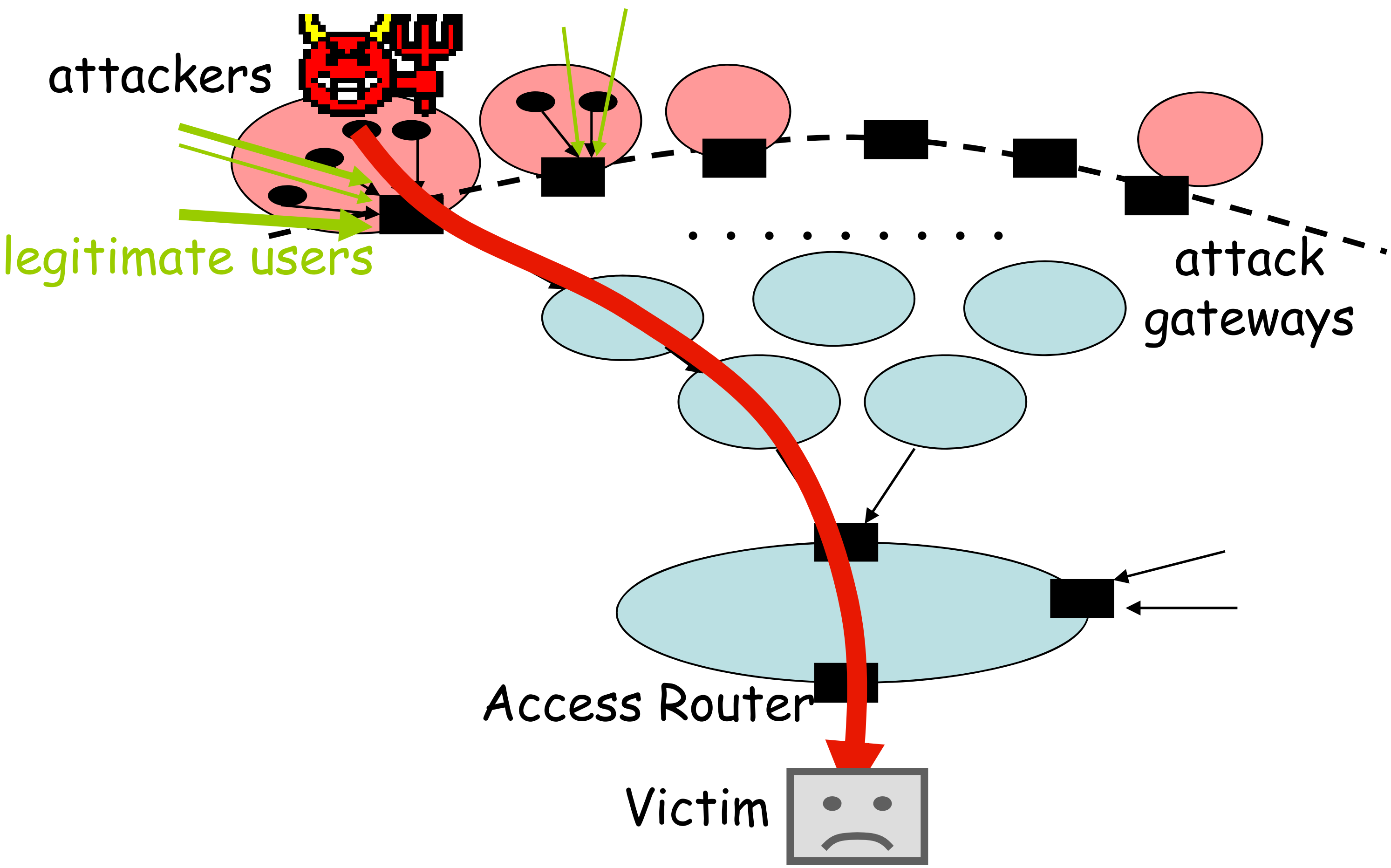
Outline

- Background on Traceback
- Main idea PPM+NC
- Practical PPM+NC
- Simulation Results
- Conclusion and future work

Where is malicious traffic coming from?



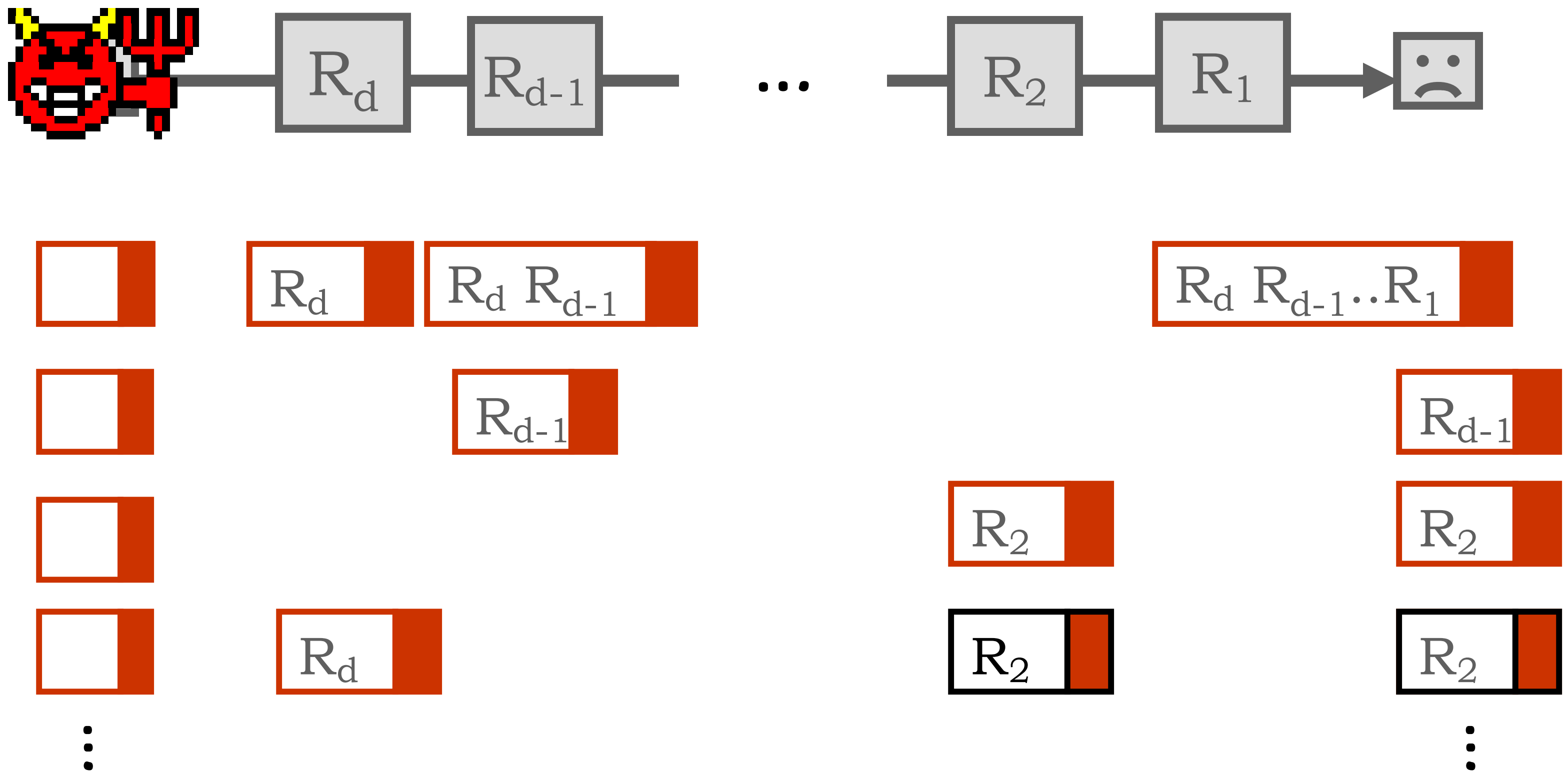
Goal: traceback source and path of attack

Prior Work on Traceback

- Early ideas [Burch and Cheswick 1999]
- Send specialized (ICMP) packets [Bellovin et al. 2001]
- Routers keep logs of all packets [Snoeren et al. 2001] …
- Packet Marking
  - routers mark packets with information about their ID, victim uses the marks of several packets to reconstruct path
  - [Savage et al. 2001]: probabilistically mark fragments of IP addresses
  - Authentication + hashing [Song et al. 2001], [Yaar et al. 05], adjusting marking probability, …
- Algebraic Traceback
  - [Dean et al. 2002]: encodes the information of n routers on the attack path as coefficients of a polynomial of degree n-1.
  - [Das et al. 2010]: tracks changes in a single path, network coding
- Information theoretical [Adler 2002]
  - studied the tradeoff of #bits vs. #packets

Traceback

via Probabilistic Packet Marking (PPM)



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Main Idea

Problem Statement

- Probabilistic Packet Marking (PPM):
  - Routers probabilistically mark packets with (partial) information about their address.
  - The goal of PPM is to enable the victim to recover d router IDs after receiving a sufficient number of packets.
  - PPM+NC tries to achieve the same goal with a smaller #packets, by appropriately choosing the marking scheme at intermediate routers.

Main Idea

PPM+NC

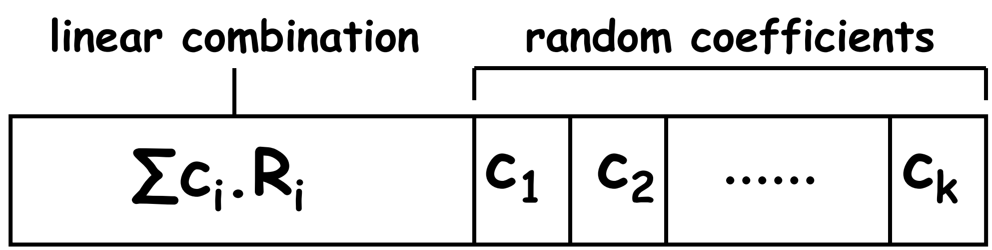
- PPM is essentially a coupon collector's problem
  - Collect all router ids $\{R_d, R_{d-1}, \ldots. R_2, R_1\}$
  - A coupon collector's problem with unequal probabilities:
    - The further a router is from the victim, the less likely that its mark will not be overwritten as the packet moves along the path.

$$E[X_{PPM}] = \int_0^{\infty} (1 - \prod_{i=1}^{d} (1 - e^{-p(1-p)^{i-1}x}))dx$$

- NC helps the coupon collector problem:
  - NC increases the chance of getting an innovative coupon
  - equally likely coupons: E[X] reduces from Θ(dlogd) to Θ(d)

Main Idea

PPM+NC cont'd



- Router i:
  - instead of marking with its own id "R_i", picks a random coefficient "c_i", and adds $c_i \cdot R_i$ to the existing mark.
- Victim:
  - instead of ids themselves, it receives random linear combinations of router ids ($\sum c_i \cdot R_i$):
  - solves a system of equations and find the ids.

Main Idea

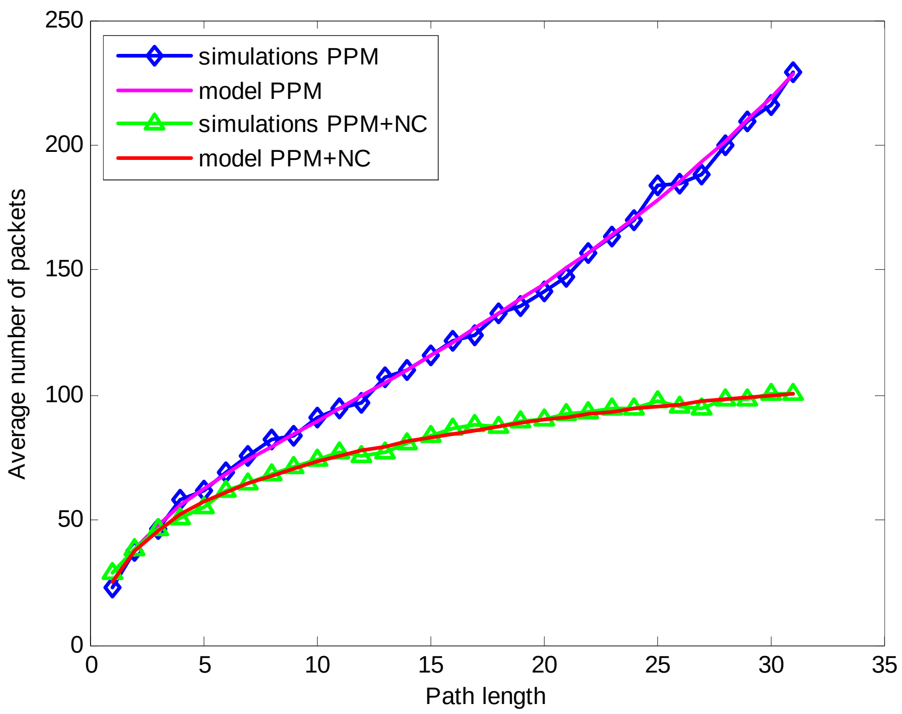
PPM+NC for a single path

Setup:

- path length d=1…31, field F_4, p=1/25, 500 realizations.
- Metric of interest: number of marks X needed to reconstruct the attack path

Observations:

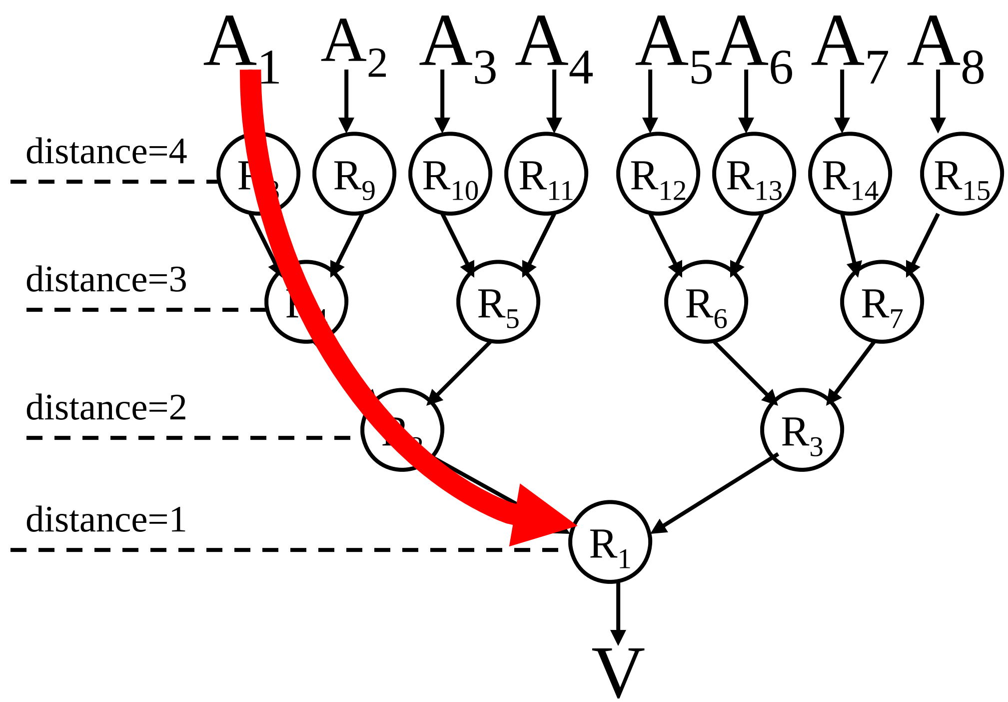
- $E[X_{PPM+NC}]<E[X_{PPM}]$
- Models perfectly agree with simulation



Main Idea

Multiple-path scenario as the union of multiple paths

- Typically DDoS attacks is distributed:



- The attack path from $\{A_i\}$ is the ordered list of routers between $\{A_i\}$ and V that the attack packet has gone through.

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  - Reconstruction procedure
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Practical PPM+NC

Practical Constraints

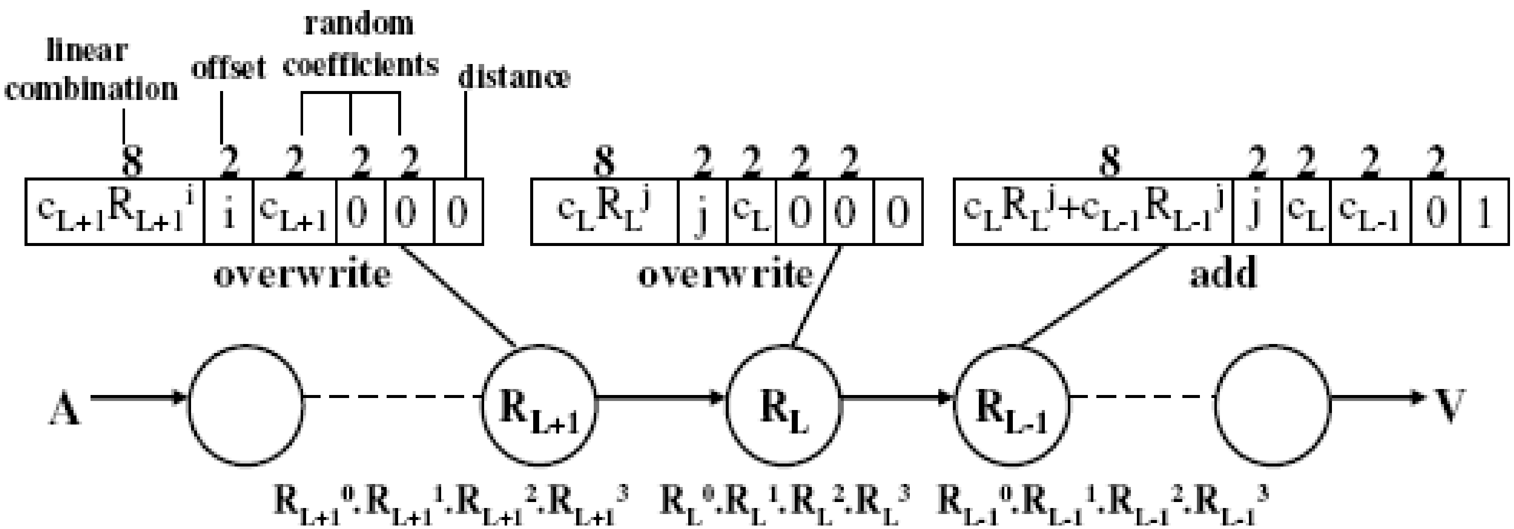
- Limited number of bits (16 ID + 1 flag = 17)
  - Mark with Fragments of IP addresses
  - f=4 fragments (of 8 bits each), 2-bit fragment offset, k=3 coefficients, of b=2 bits each, distance=1 bit. Total: 17 bits.
  - 8 bits used for the linear combination, 2 bits for the coefficients.

$$\lceil \frac{32}{f} \rceil + \lceil log_2 f \rceil + k \cdot b + \texttt{distance} \leq \texttt{bit budget}$$

- Spoofing by the attacker
  - Probabilistically overwrite the previous mark
  - Distance field (approximate traceback)
- Identifying nodes vs. reconstructing the attack graph
  - Distance field
  - Markings from consecutive routers

Practical PPM+NC

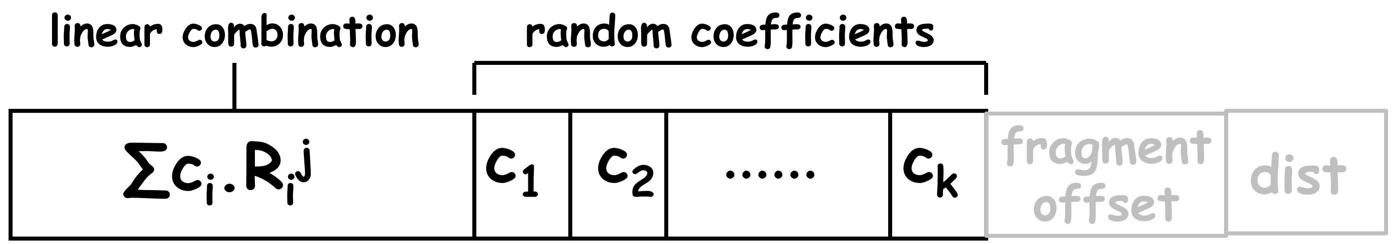
Marking Procedure



- Each router probabilistically decides whether to overwrite or not.
- If overwrite:
  - zero out the field+ mark with a fragment of the router ID.
- If not_overwrite & there is space:
  - add to the combination of the same fragment
  - increase distance field

Practical PPM+NC

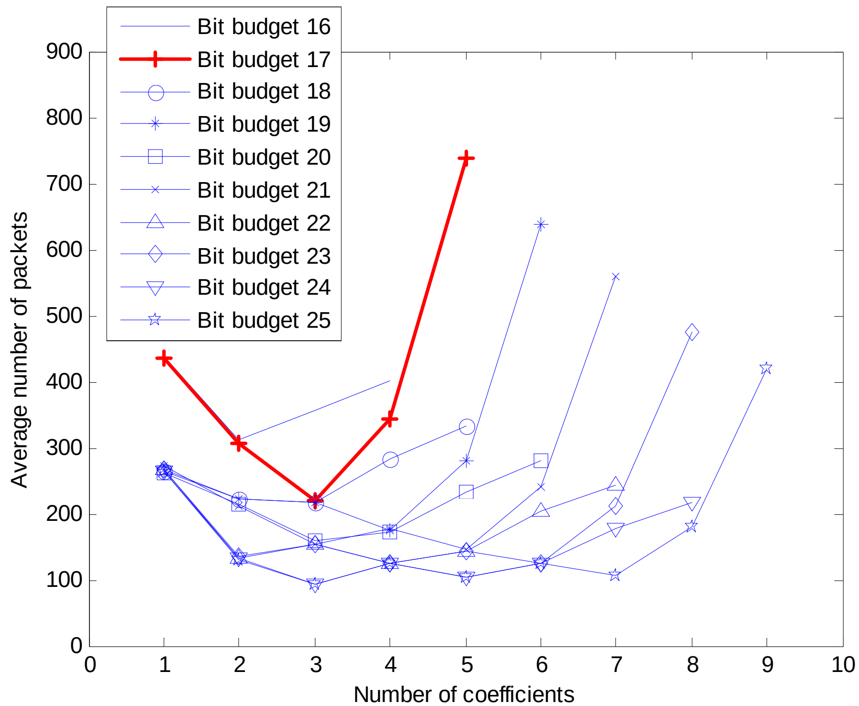
Tradeoff in the packet header



- R_i^j: The j^{th} fragment of R_i.
- We want both parts to be as large as possible:
  - A linear combination of larger fragments.
  - A linear combination of as many fragments of IP addresses as possible (random coefficients).
- Always an optimal k minimizes #packets. For bit budget 17, it is k = 3 (our selection).

Practical PPM+NC

Tradeoff in the packet header, cont'd



- Best choice: 8 bits for fragments (f=4), 2 bits for fragment offset, 3 coefficients (k=3), of 2 bits each (b=2), 1 bit for distance.
- 17 bits in total, within the bit-budget.

Practical PPM+NC

Reconstruction Procedure – Single Path

- Once the victim receives the packet P, it forms:
  $c_L . R_L^j + c_{L-1}.R_{L-1}^j + c_{L-2}.R_{L-2}^j$ = P.linearCombination

- The unknowns are the fragments of the IP addresses: R_i^j , i=1…d, j=1…f

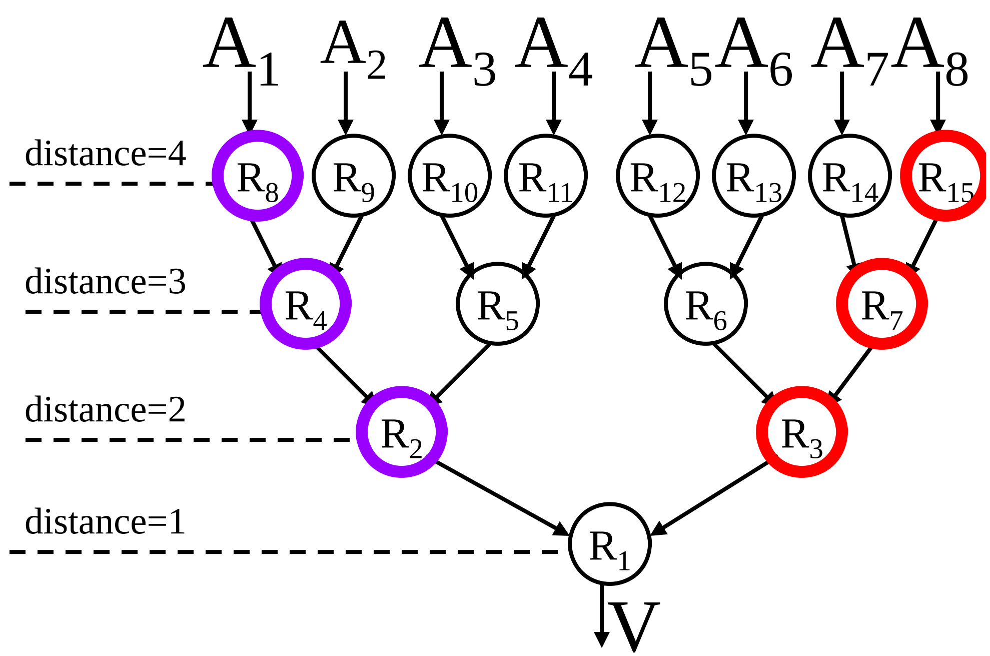
- The victim can solve the system of linear equations after receiving d·f innovative packets

- Use fragment offset to order fragments of same router ID (same distance)
- Path consists of router IDs ordered by distance

Practical PPM+NC
Reconstruction Procedure, cont'd

- Multiple-paths:
  - Multiple routers at the same distance from the victim.
  - Need to distinguish equations coming from different paths.

- E.g., victim receives 2 packets from distance=4
- One from R_8,R_4,R_2, the other from R_{15},R_7,R_3
- Do they belong to the same triplet or not?!



Practical PPM+NC
Reconstruction Procedure, cont'd

- Two solutions:
  1. Use 8 bits (TOS field) to store a checksum that helps identify a triplet of marking routers
     - E.g., each router pre-computes a hash of its IP address
     - The less bits we use, the larger the probability of collision
  2. Assume the victim has knowledge of the map of its upstream routers [Song et al., Yaar et al.].
     - Given the distance value, fragment offset, and random coefficients, the victim tries all possible triplets in the map and picks the one that matches.
     - Does not even solve a system of linear equations

Practical PPM+NC

Cost

- Benefit of the PPM+NC approach
  - Reconstruct the paths after receiving a smaller number of marked packets
- Cost of PM+NC approach:
  - increased computational complexity and processing time.

- Need to generate more random numbers,
  - both for the marking decision and for the random coefficients:
    - only when there is space
    - can be pre-computed and used for all packets
- Routers need to compute linear combinations in F_{256}
  - can be done quickly using a transition (log) table
- Victim needs to solve a system of linear equations or to try addresses against a given linear combination

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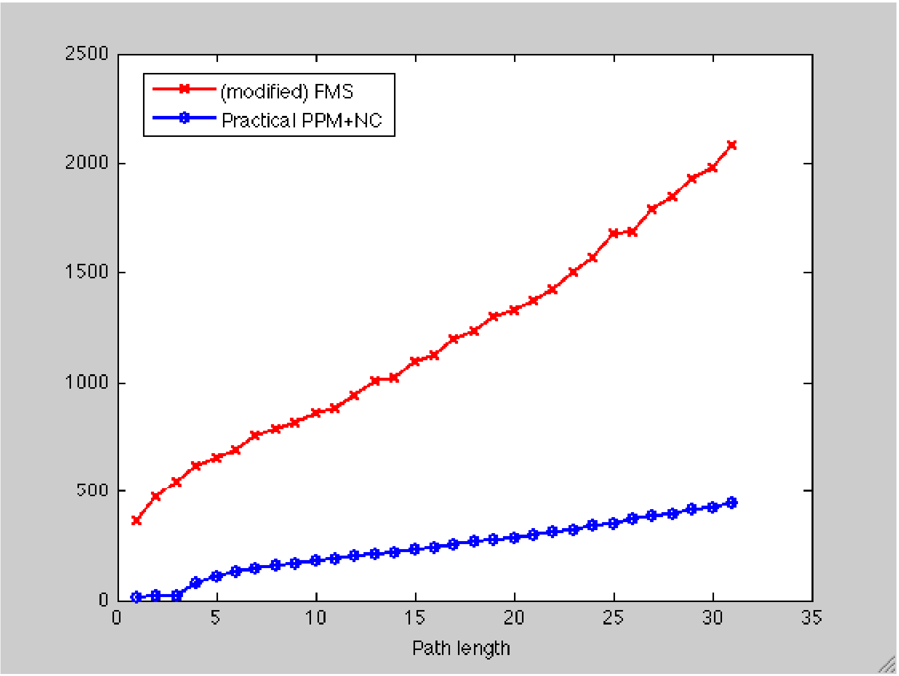
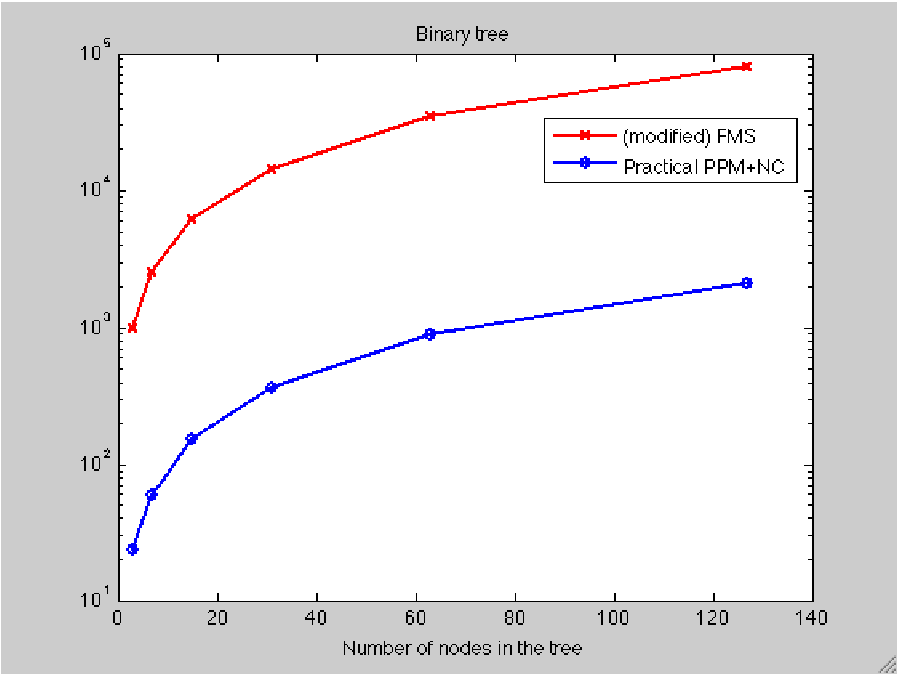
Simulation Results

paths vs. trees



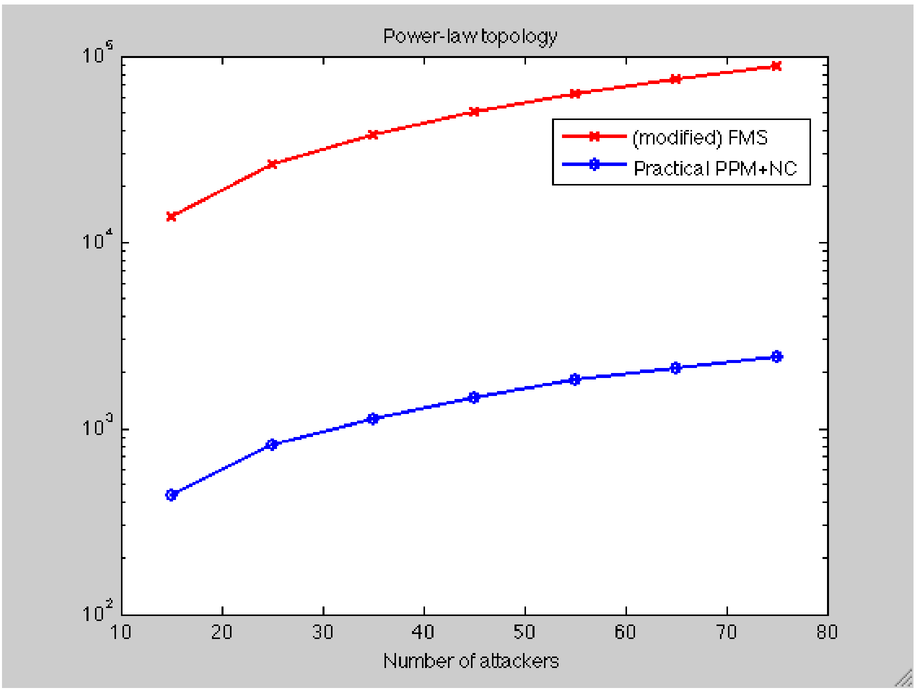
Single path, d=1…31



Binary tree, 3…127 nodes

- Fair comparison against modified FMS [Savage et al. 2001], such that it uses 17bits +TTL-based distance.
- p=1/25, 500 realizations

Simulation Results
power-law graphs



Setup:

- BRITE topology generator
- Router-only mode, GLP model, preferential connectivity, incremental growth, random node placement.
- #links added per new node=2
- generated a 150 node graph, extracted a tree out of it, and tried different #attackers.
- p=1/25, 500 realizations.

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Conclusion

- A network coding-based approach to PPM: marking packets with random linear combinations of router IDs, instead of individual IDs.
- Implemented the idea in practice, taking into account the bit limitations and other constraints.
- Simulated several attack scenarios. Showed it significantly reduces number of required packets.

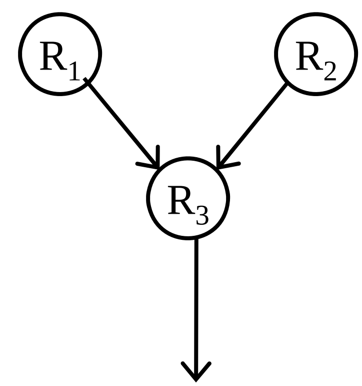
NC + other PPM Schemes

- NC-based marking is orthogonal to and can be combined with:
  - hashing-based PPM
  - authentication schemes
  - adjusted probabilities

Future Work

inter-path coding for multipath traceback

- When network coding is deployed in the network
  - use one mark $f(R_1, R_2, R_3)$
  - instead of two $g(R_1, R_3)$, $h(R_2, R_3)$
- Potential Benefits
  - Can signal coding point
  - Can distinguish among paths
  - Can signal the distance
- Connections with the work on topology inference + network coding



Thank you!

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