MORP4:
A Dynamic Network Telescope

I. Xygkou, *J. K. Sojan, D. Rauthan, F. Zhu,*
T. Holterbach, S. Alcock, B. Flanagan, A. Saeed, A. Dainotti

NSDI 2026, Renton, U.S.A.

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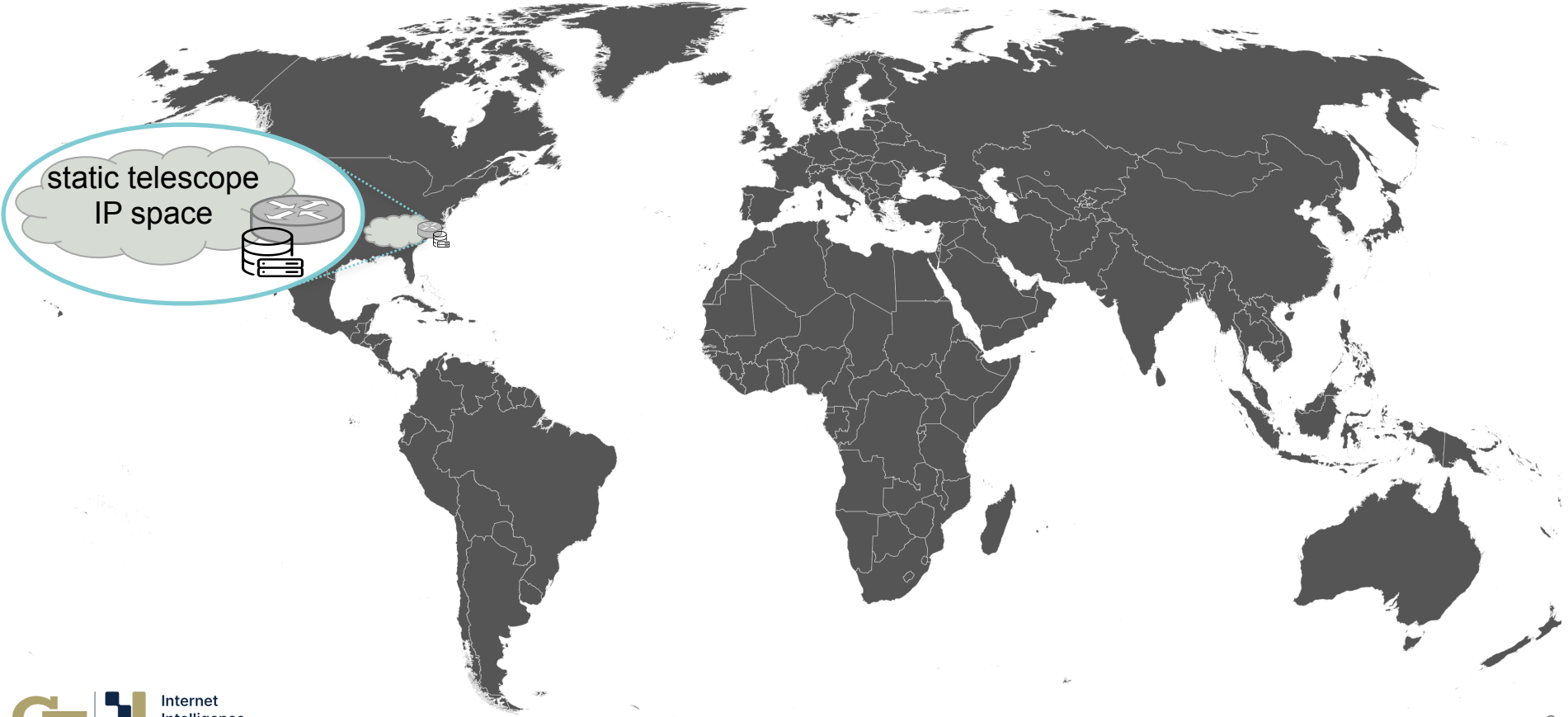
What is a Network Telescope?



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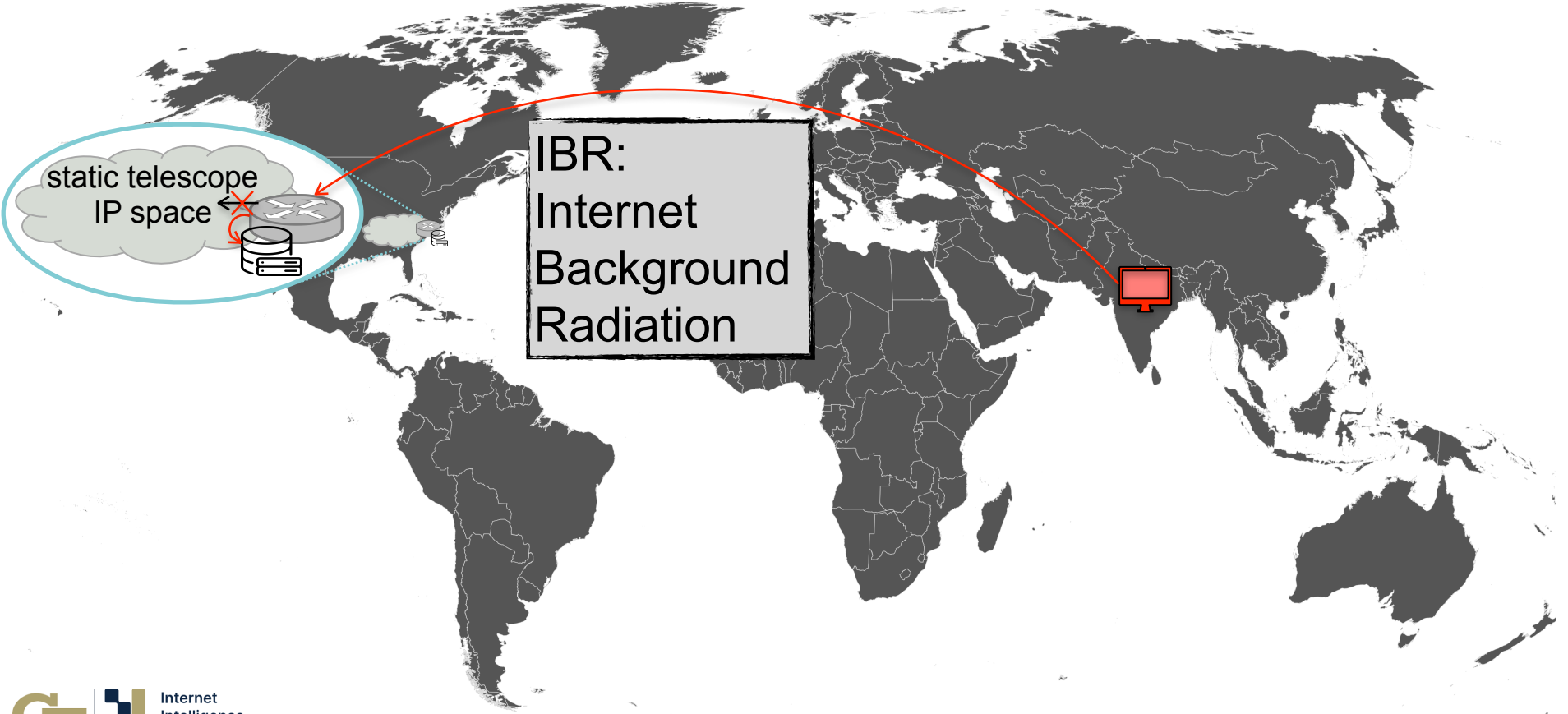
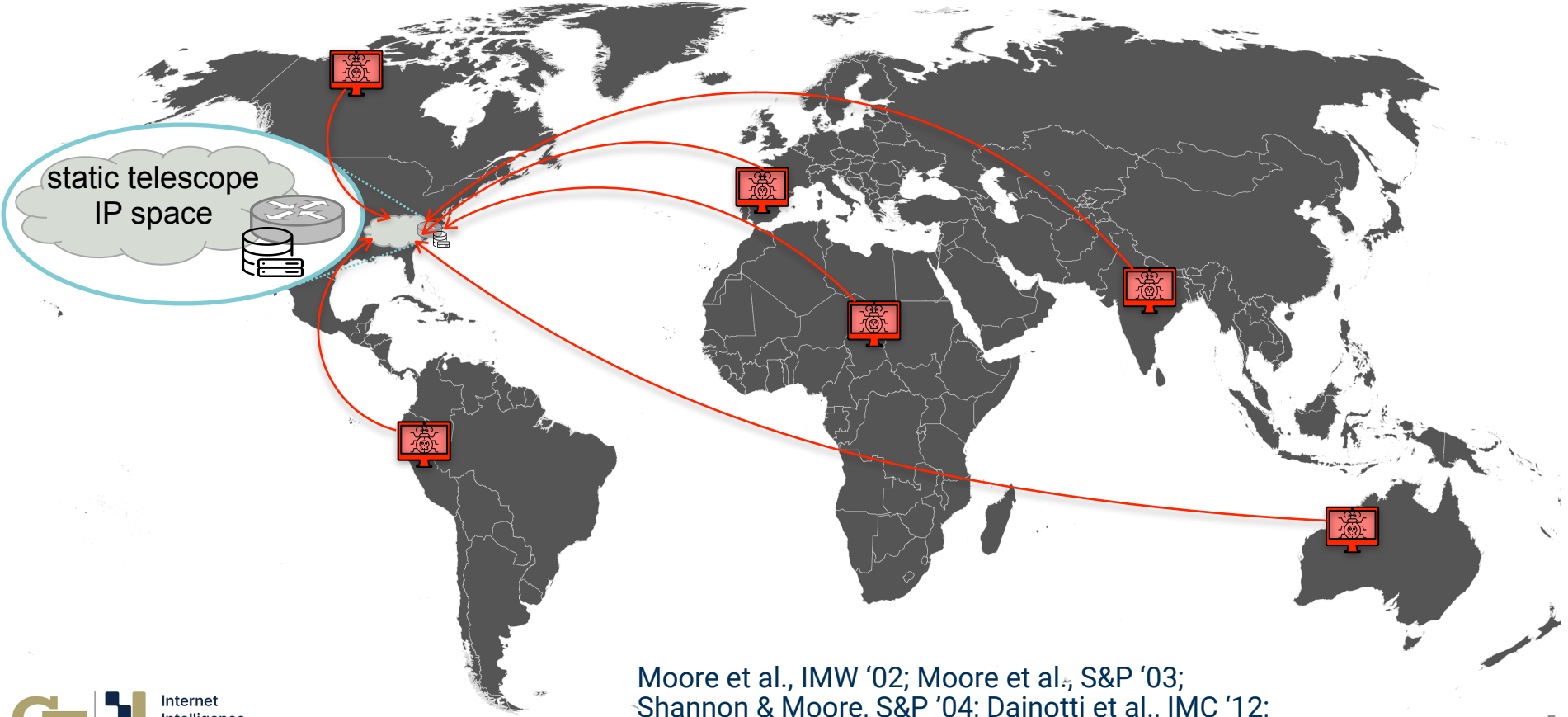


Detecting/Studying Malware & Botnets



Moore et al., IMW ‘02; Moore et al., S&P ‘03;
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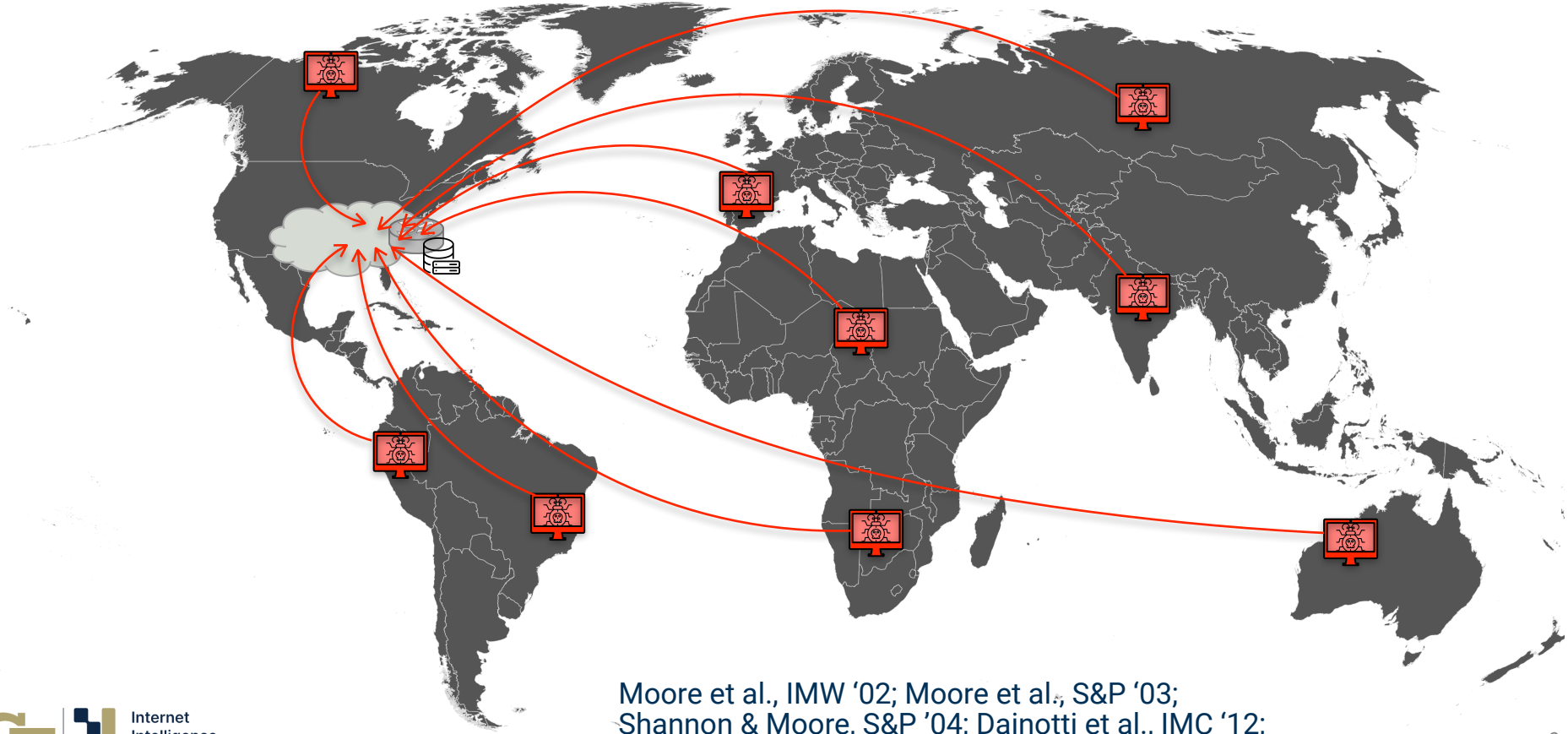

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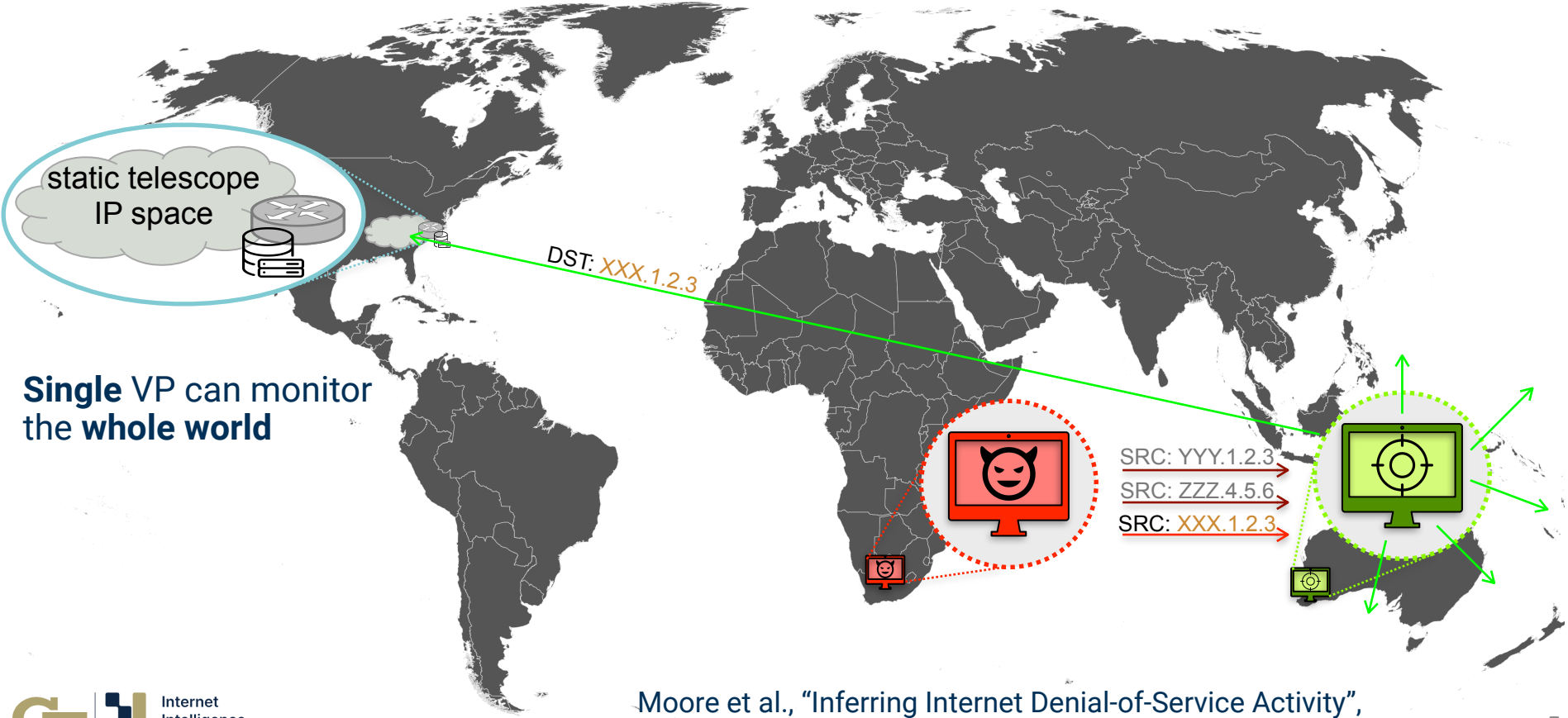
Detecting Spoofed DoS attacks Worldwide



Single VP can monitor the **whole world**

Moore et al., "Inferring Internet Denial-of-Service Activity", USENIX Sec '01 — *USENIX Sec '17 Test of Time Award*

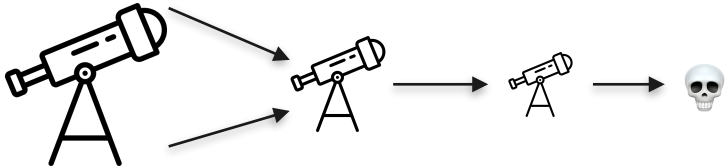
More applications of network telescopes

- Bugs & misconfigurations
  - Benson et al., *IMC ‘15*
- Scanners
  - Durumeric et al., *USENIX Security ’14*
  - Richter et al., *IMC ’19*
  - Hiesgen et al., *USENIX Security ’22*
  - Pauley et al., *USENIX Security '23*
- Large-scale disconnections & shutdowns
  - Dainotti et al., *IMC ’11*
  - Bischof et al., *SIGCOMM ’23*
- …

Limitations of traditional telescopes

LIM.1

Shrinking / Disappearing



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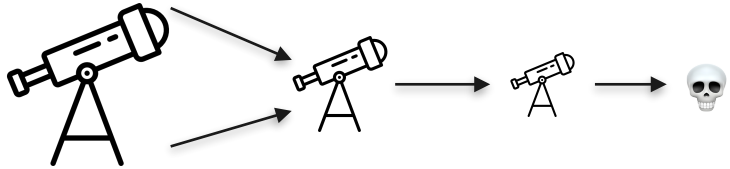
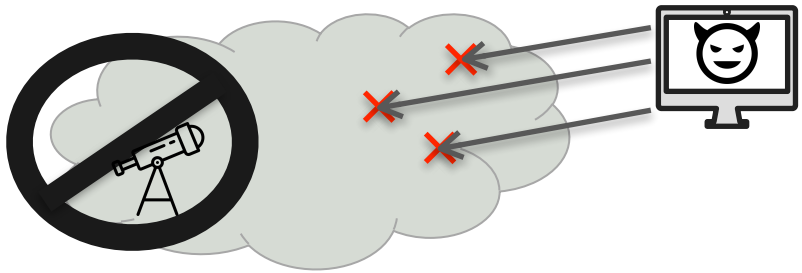


LIM.2 Blacklisting

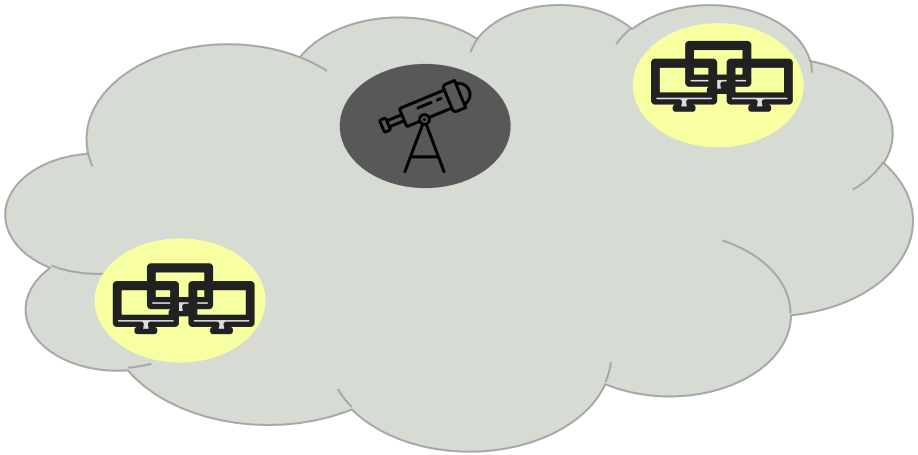


*Manos Antonakakis et al.
“**Understanding the Mirai Botnet**”. USENIX Security ‘17.

Limitations of traditional telescopes

LIM.3

IPv6 IBR is hard to capture



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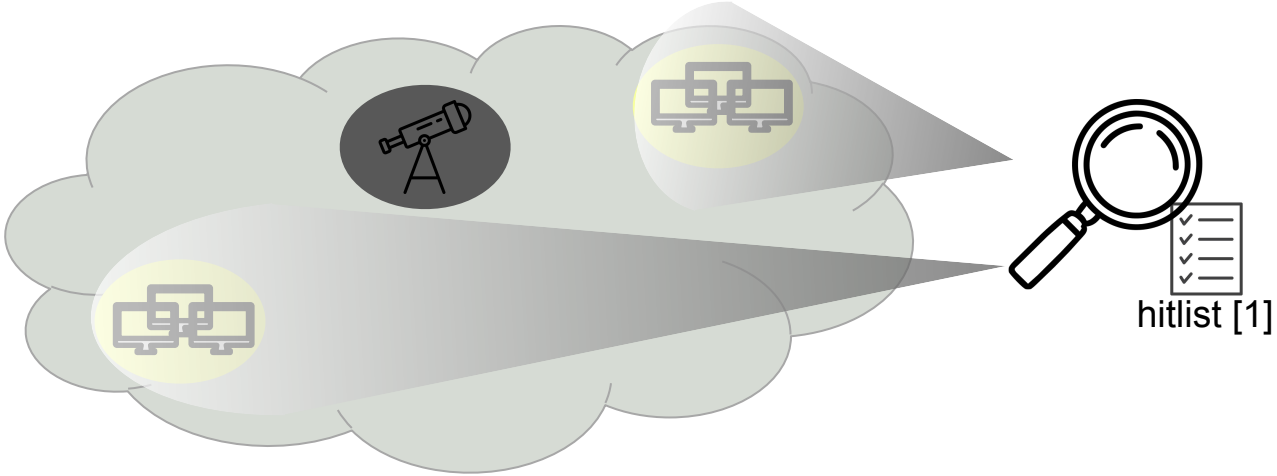

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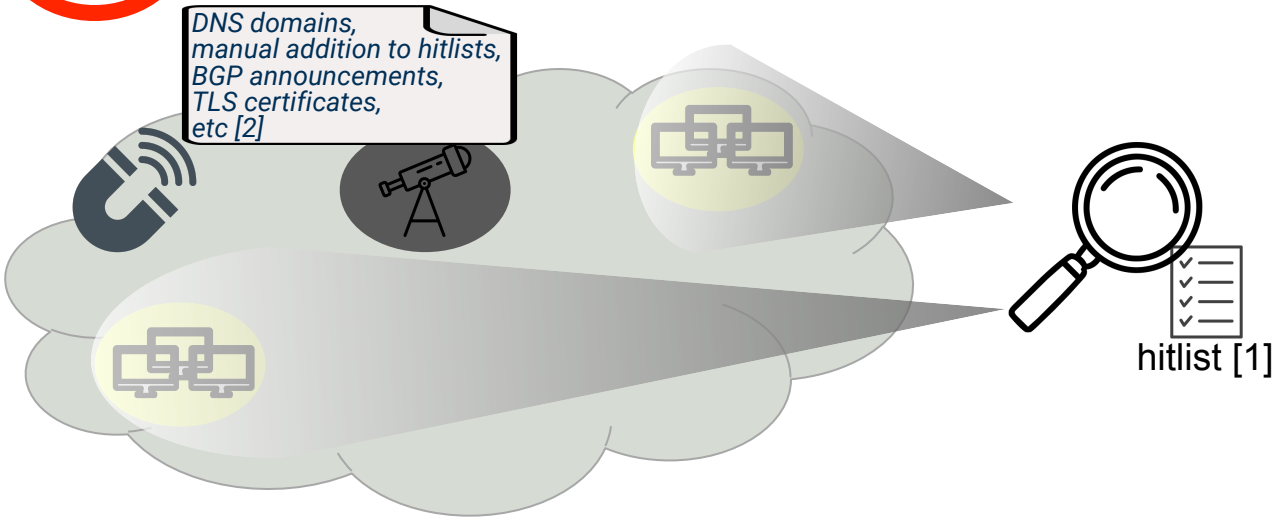

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[2] Tanveer et al., USENIX ‘23; Zhao et al., PAM ‘24; Zhao et al., IEICE Trans. Comm. ‘25; Xin et al. SIGCOMM ‘25 (poster); Egloff et al., CoNEXT ‘25; Tanveer et al., CoNEXT ‘25

Limitations of traditional telescopes

LIM.1 Shrinking

LIM.2 Blacklisting

LIM.3 IPv6 IBR locality

Dynamic Telescope

What is a *dynamic* telescope?

Detect in real time which portions of a network are/become **unutilized** in order to maximize capture of IBR.

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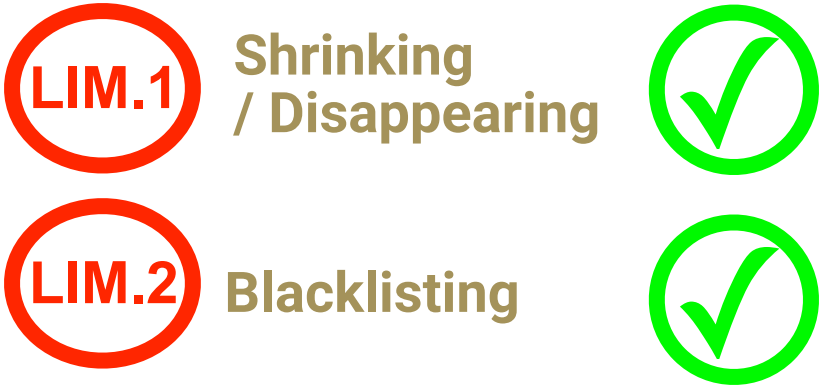

What is a *dynamic* telescope?

Detect in real time which portions of a network are/become **unutilized** in order to maximize capture of IBR.

How do we implement a dynamic telescope?

Requirements

- Non-intrusive
  → No address reservation
- Accurate
  → Detect all (and only) utilized IPs
- Line-rate

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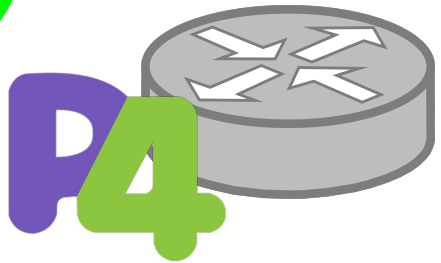
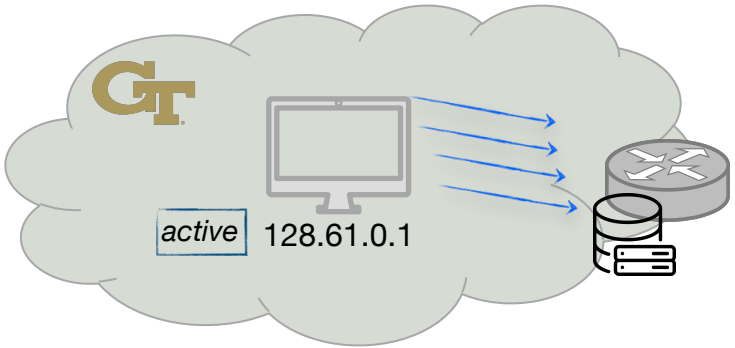
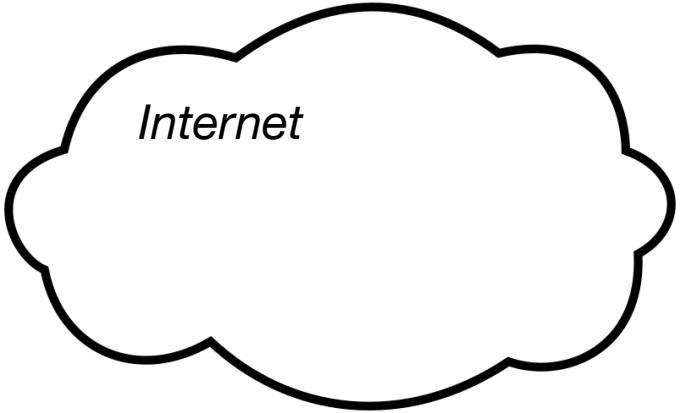
MORP4



Detecting inactive IPs





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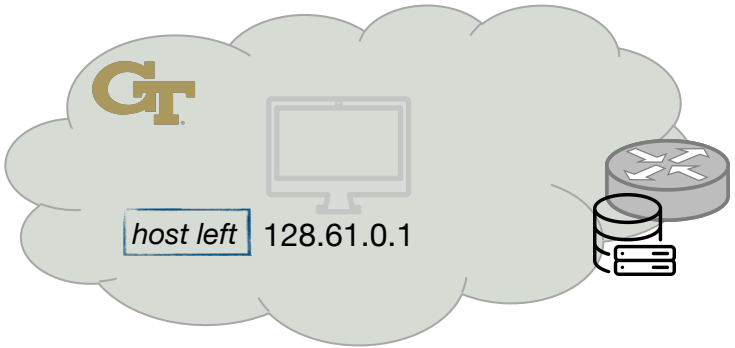
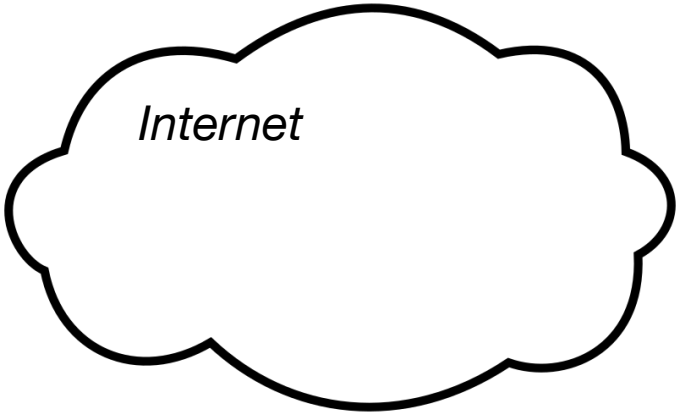
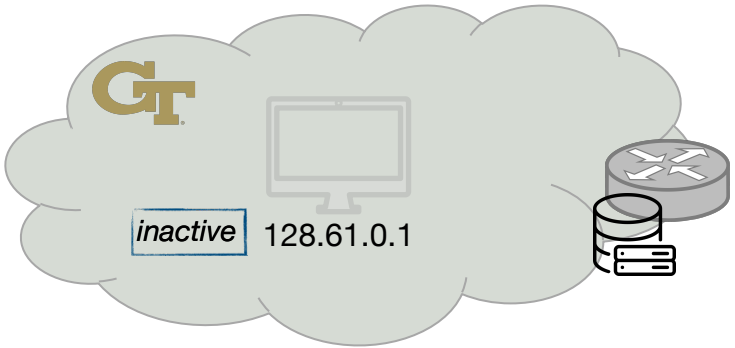
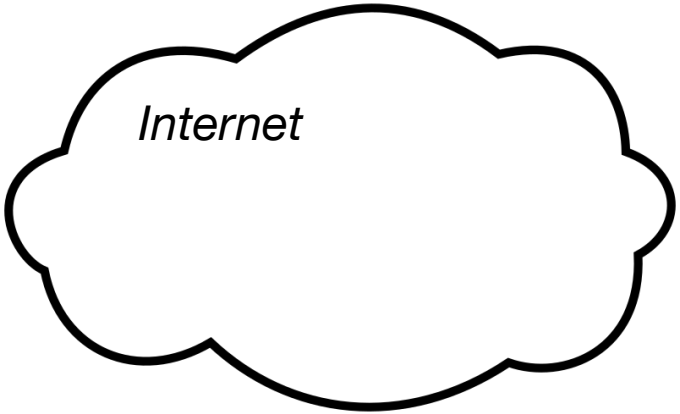




Detecting inactive IPs

After a *timeout…*





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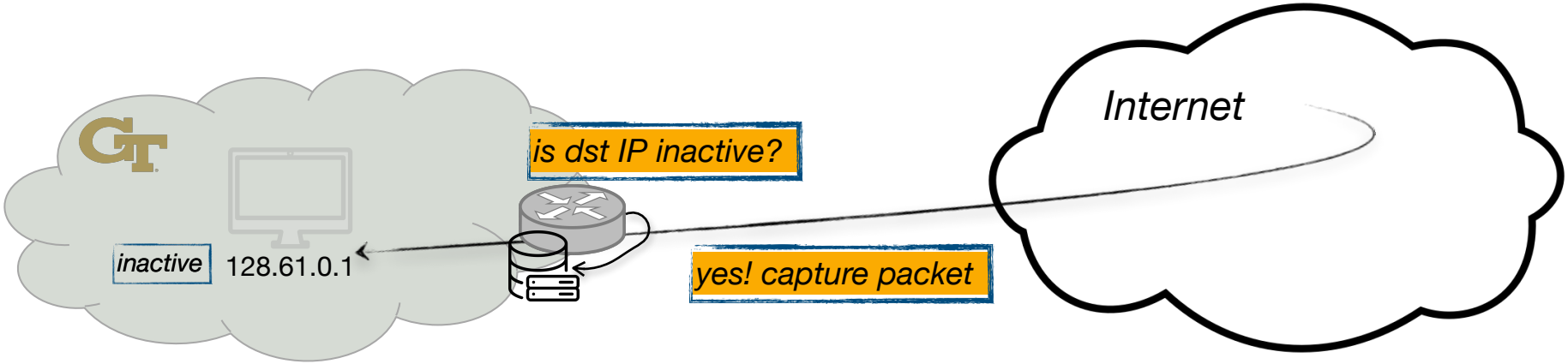

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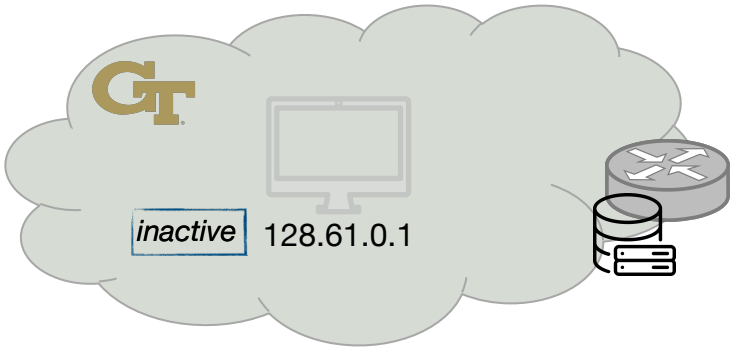

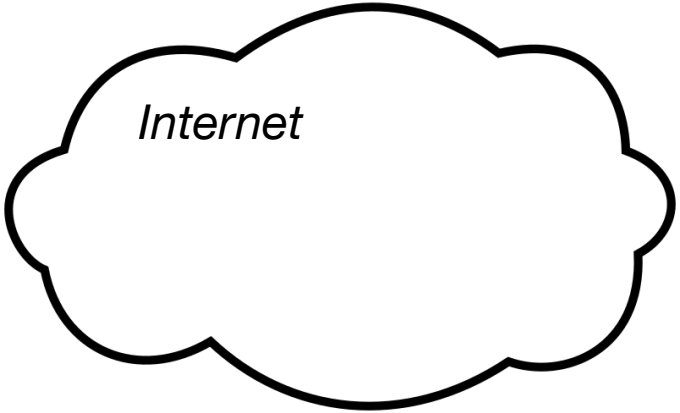

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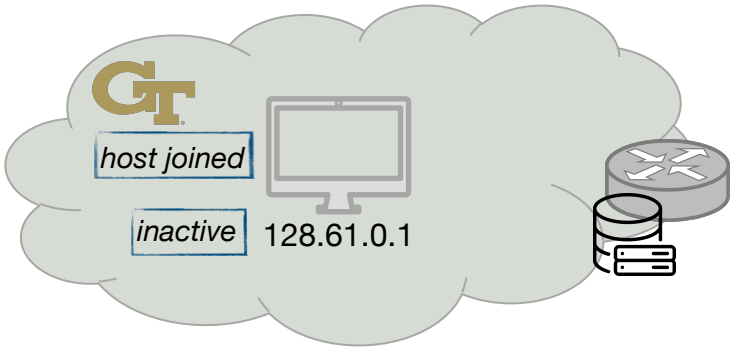

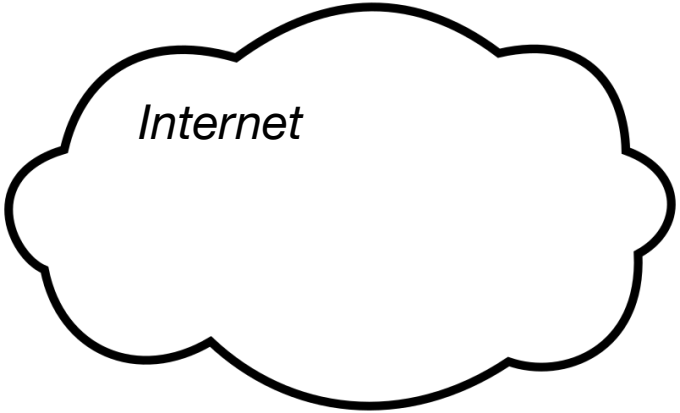

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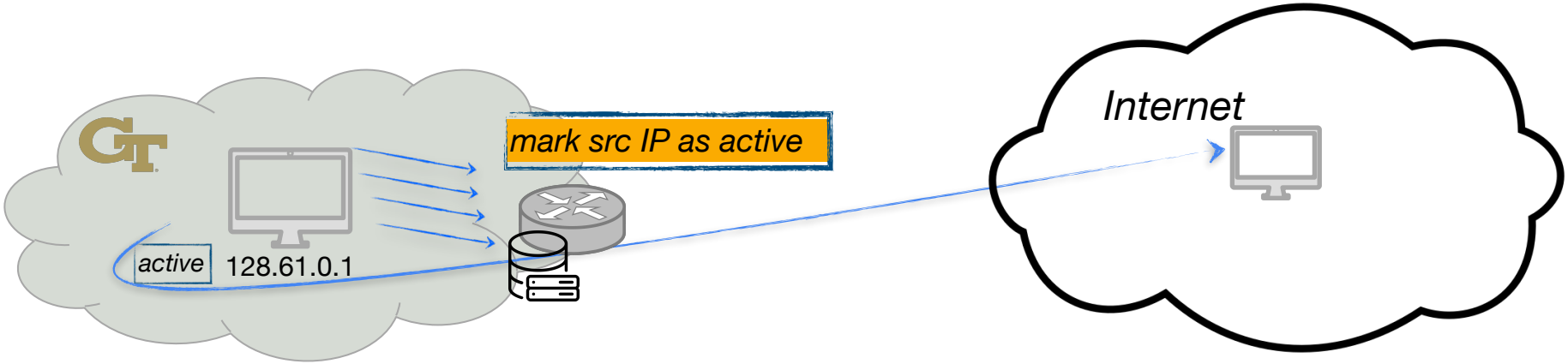

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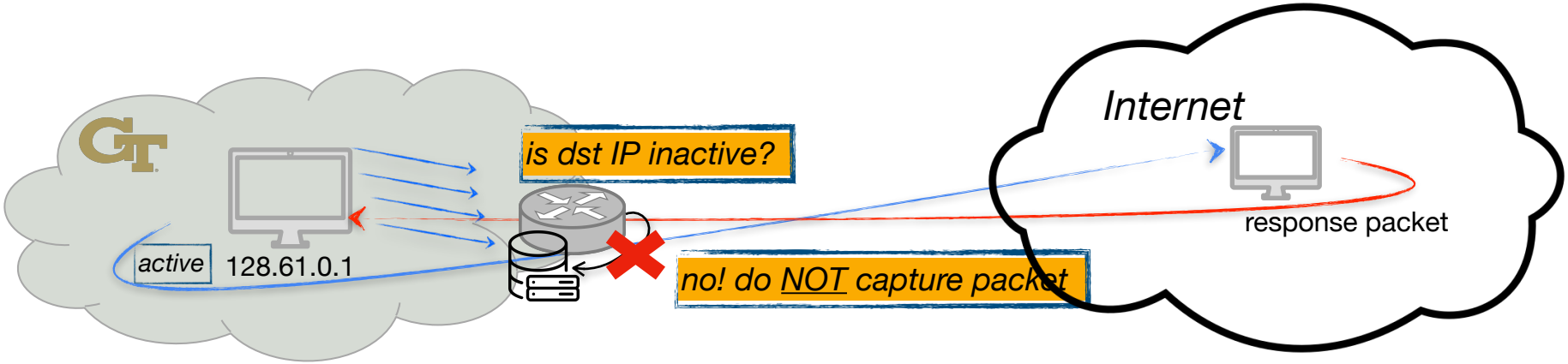
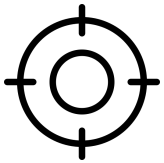


Objectives & Challenges



Obj. 1: State consistency

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CH.1 At line-rate

Two operations:

- Mark an IP as active (write)
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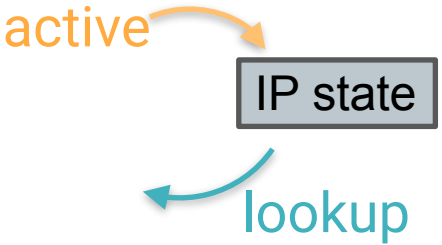

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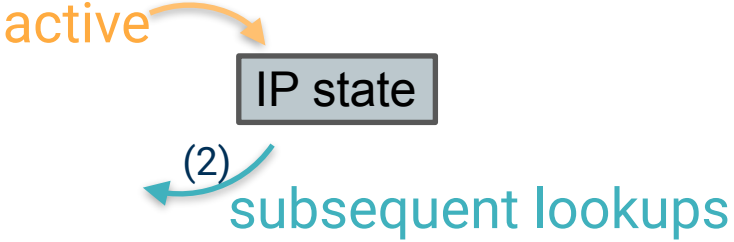

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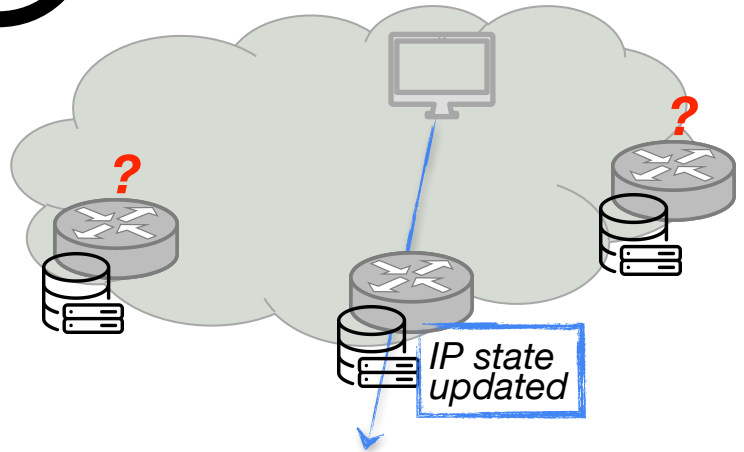
CH.2 Across multiple points



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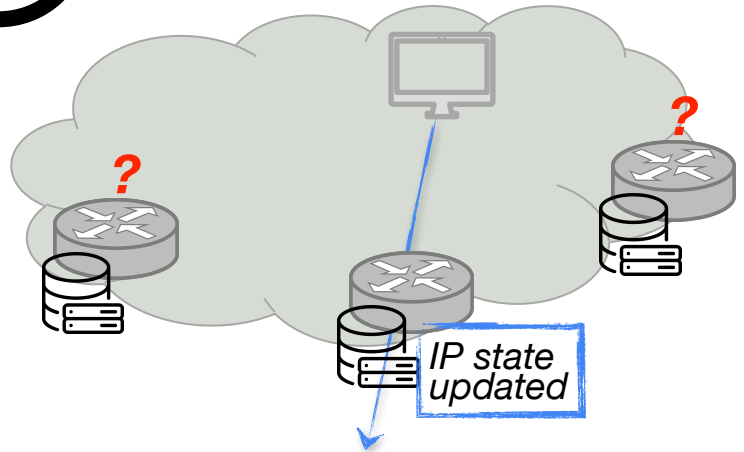
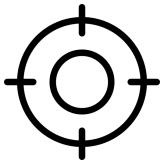


CH.3 Limited resources



Obj. 2: Configurability

Different networks have different characteristics.

Network operators can configure parameters:

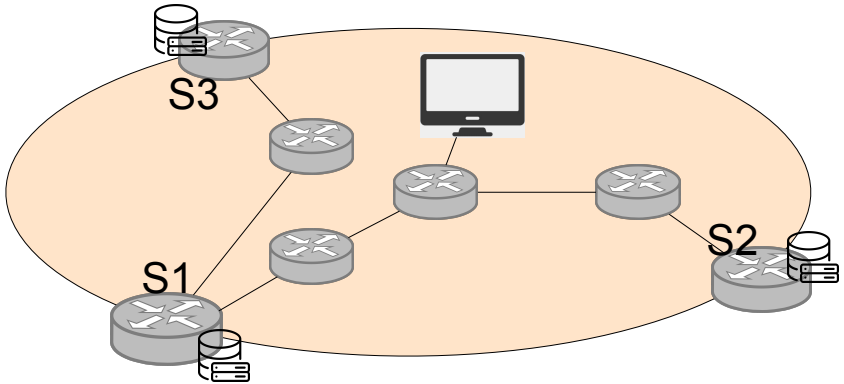
- Monitored subnets
- Monitoring granularity, e.g., in IPv4: /24 or /32
- Timeout, e.g., 6 hrs, or 1 day, or 7 days

State consistency

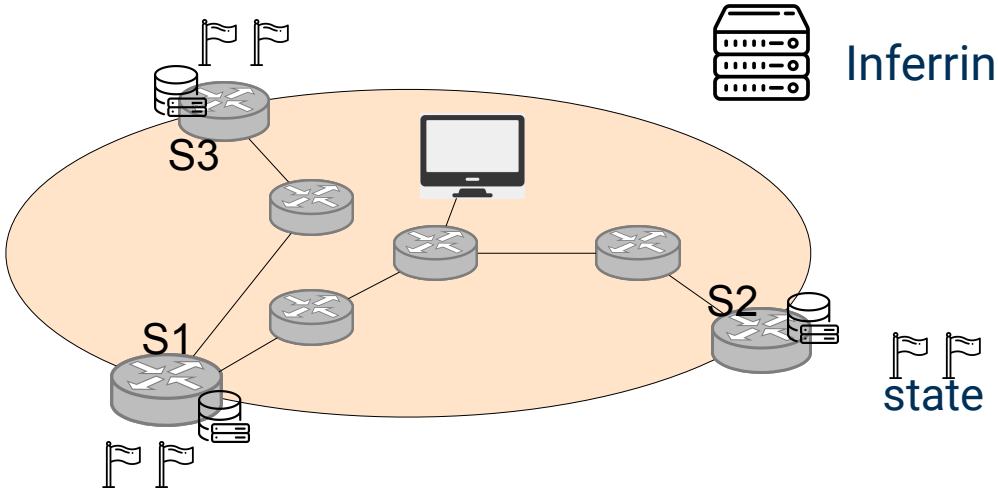
Configurability

MORP4 implements
a *dynamic telescope* in
~430 P4 & ~1,100 C++ lines

Achieving state consistency

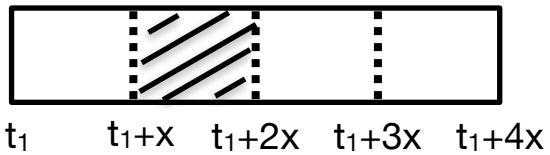


Achieving state consistency through controller



Inferring an IP as inactive is non-time-sensitive

state



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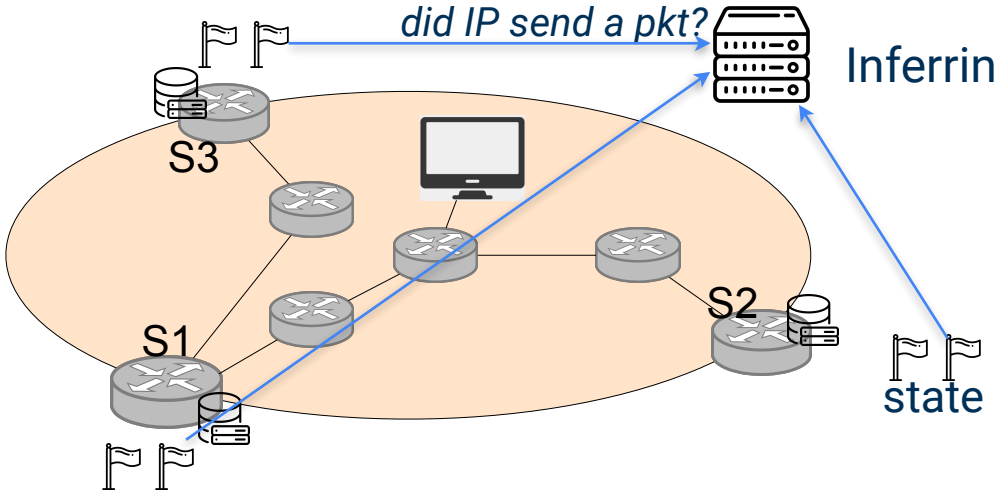

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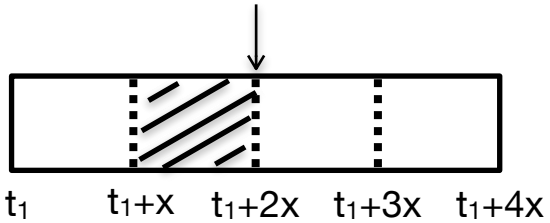

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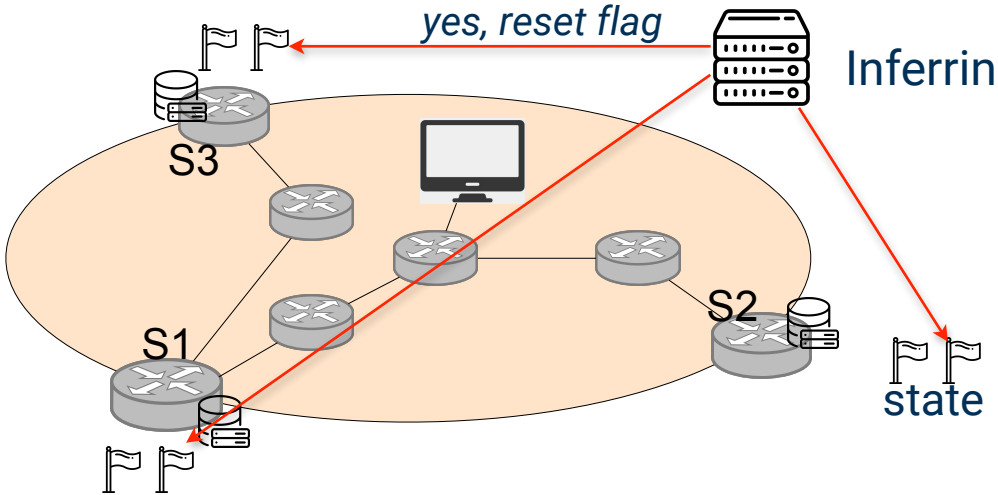

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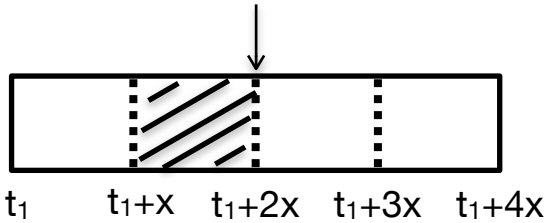

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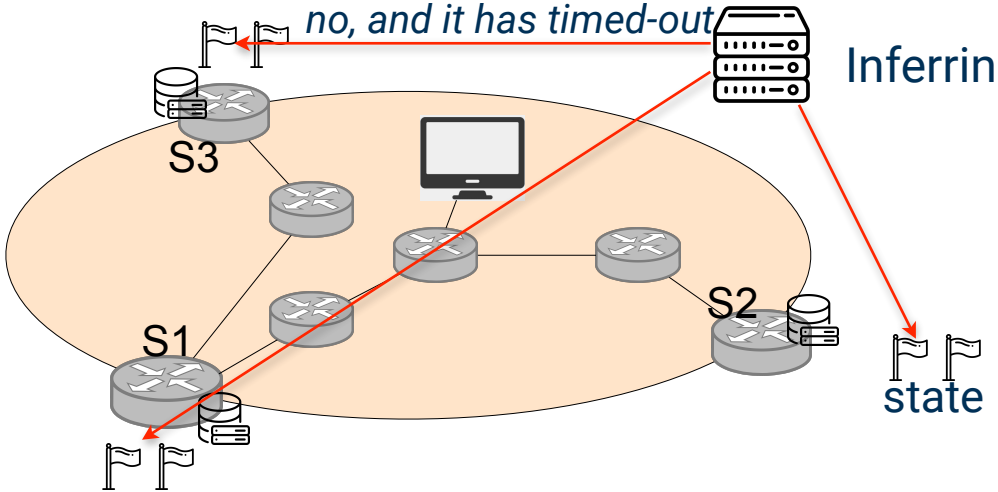

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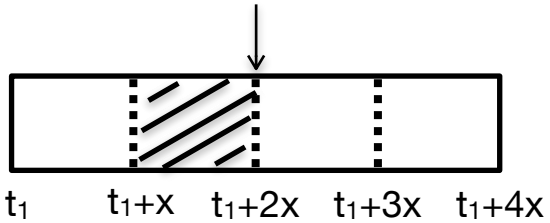
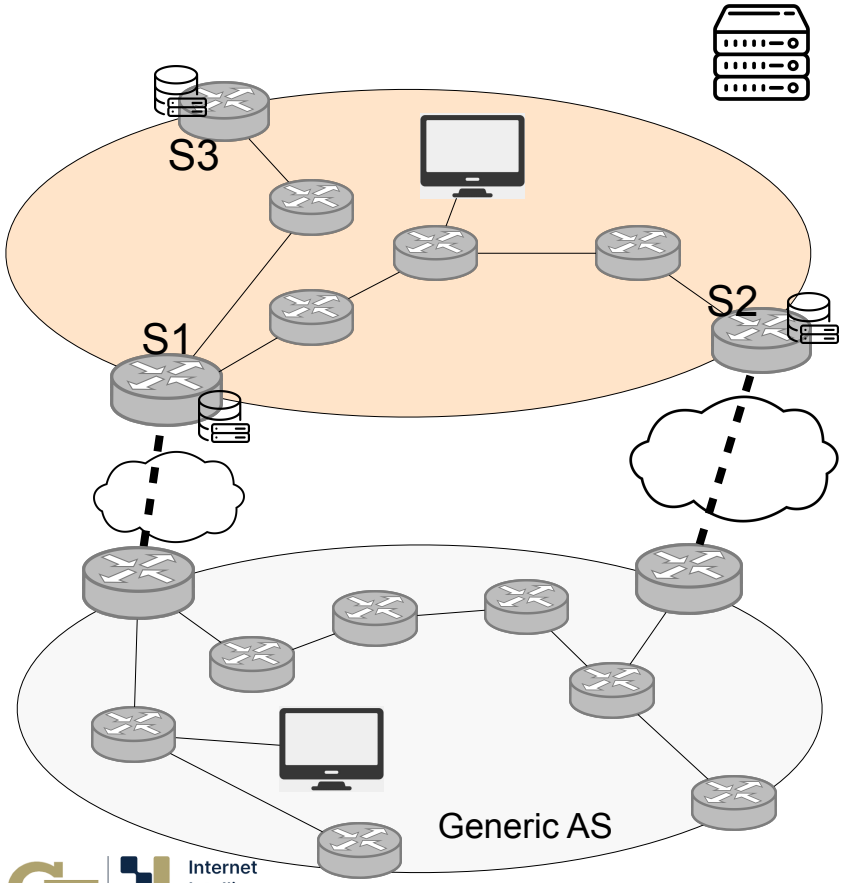
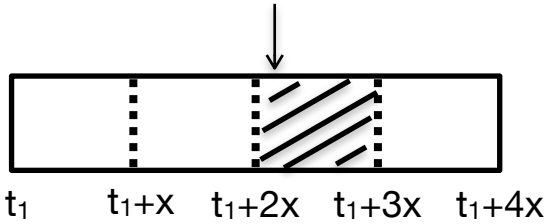


Achieving state consistency through control packets





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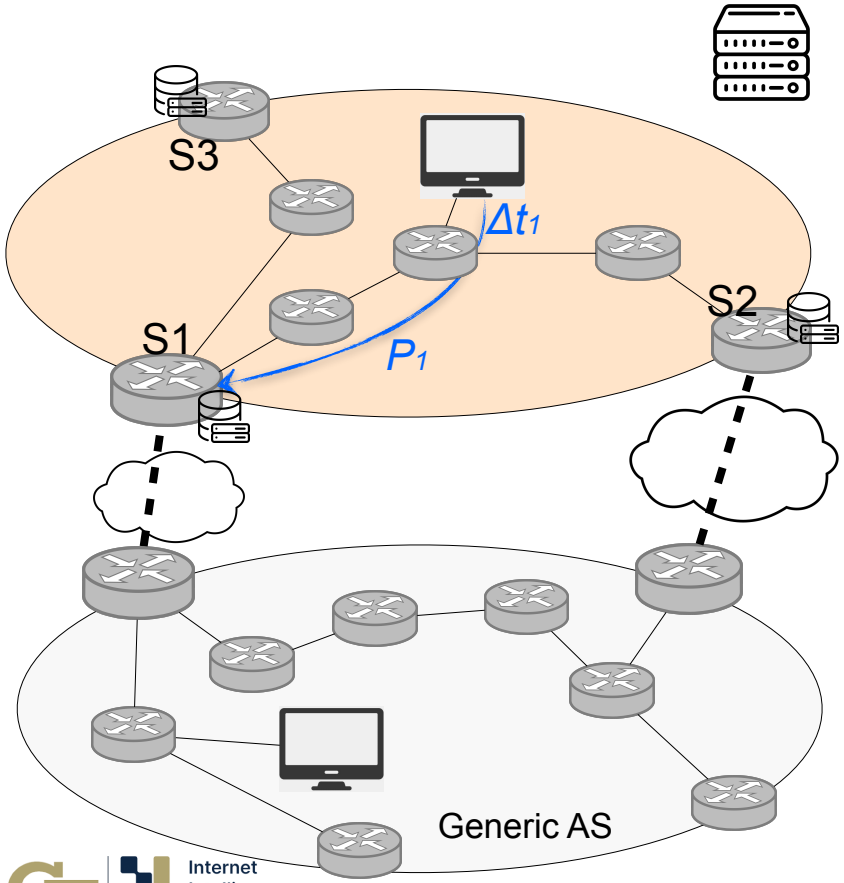

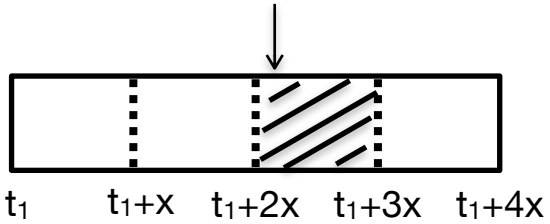

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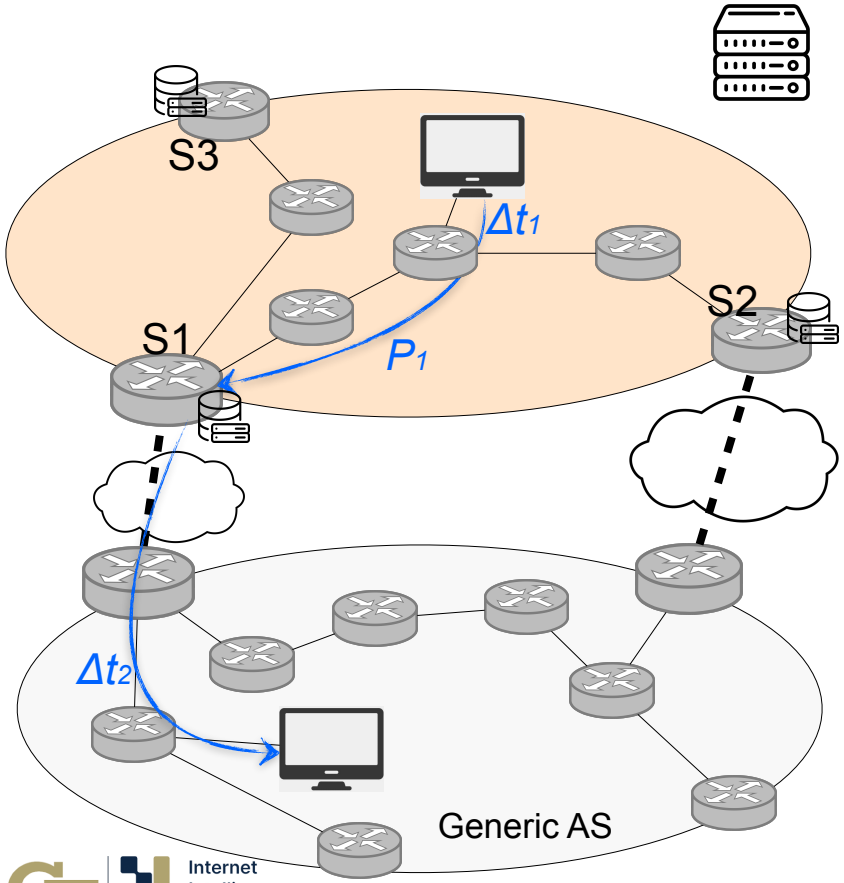

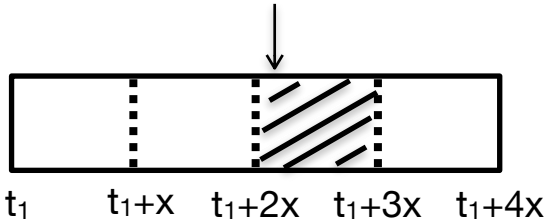

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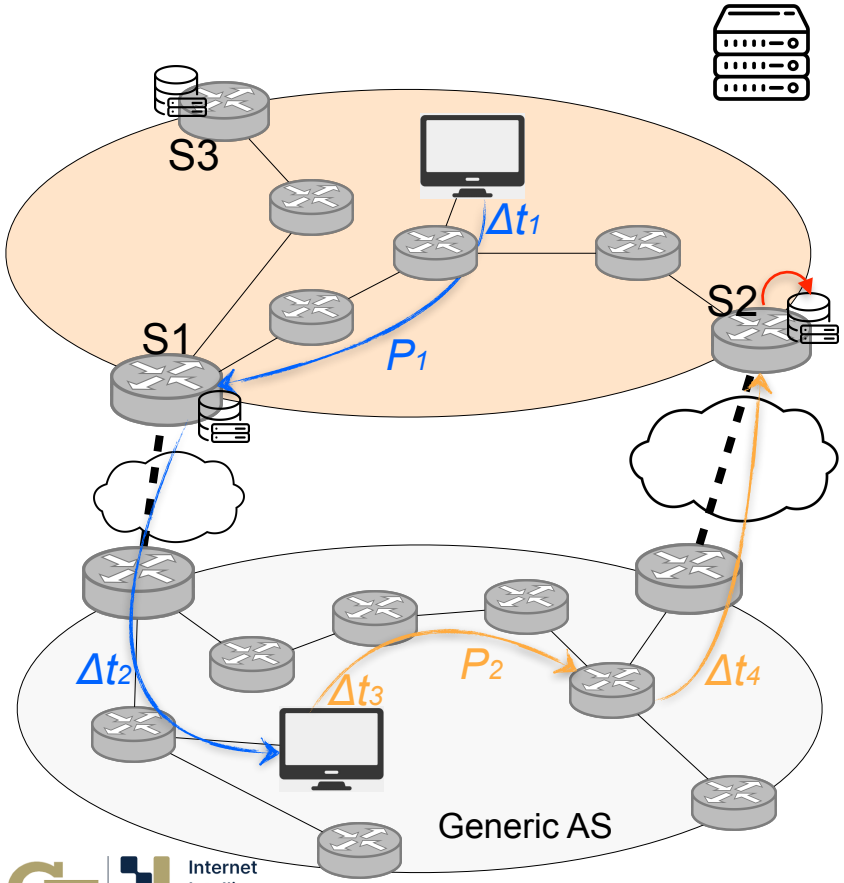

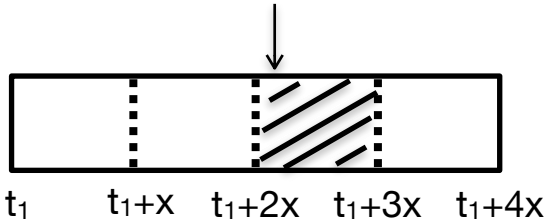

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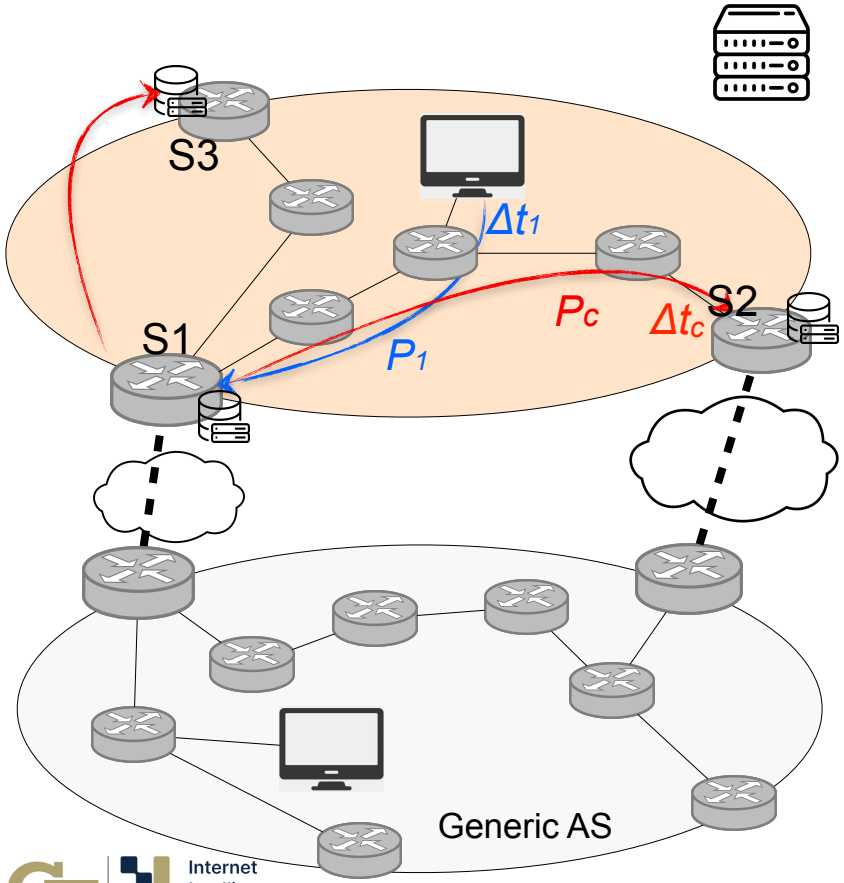
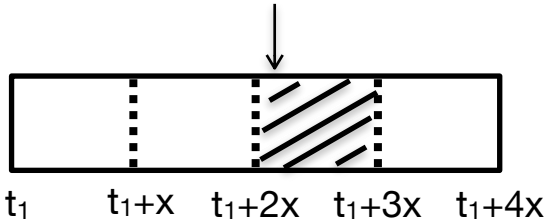
Achieving state consistency through control packets



Switch sends control packet to
all other switches to notify of state change



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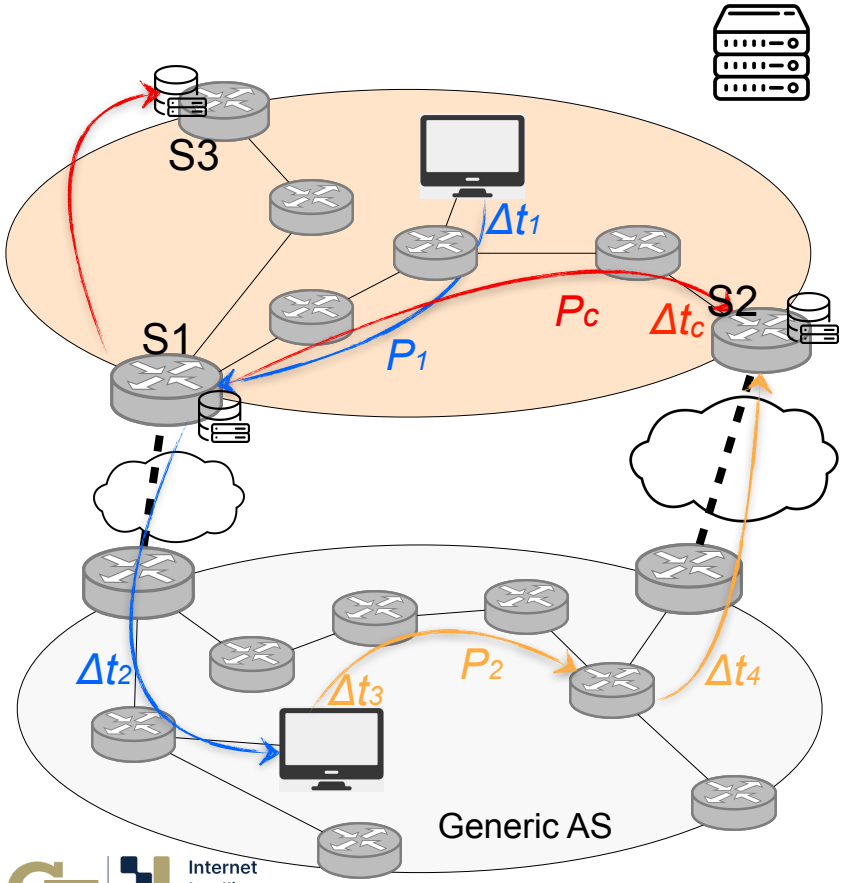

Switch sends control packet to
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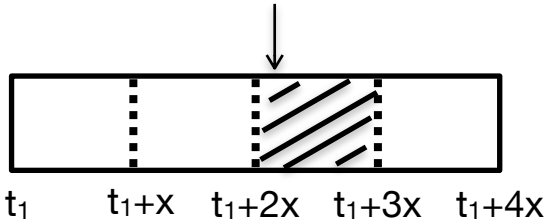
$$\Delta t_c < \Delta t_2 + \Delta t_3 + \Delta t_4$$



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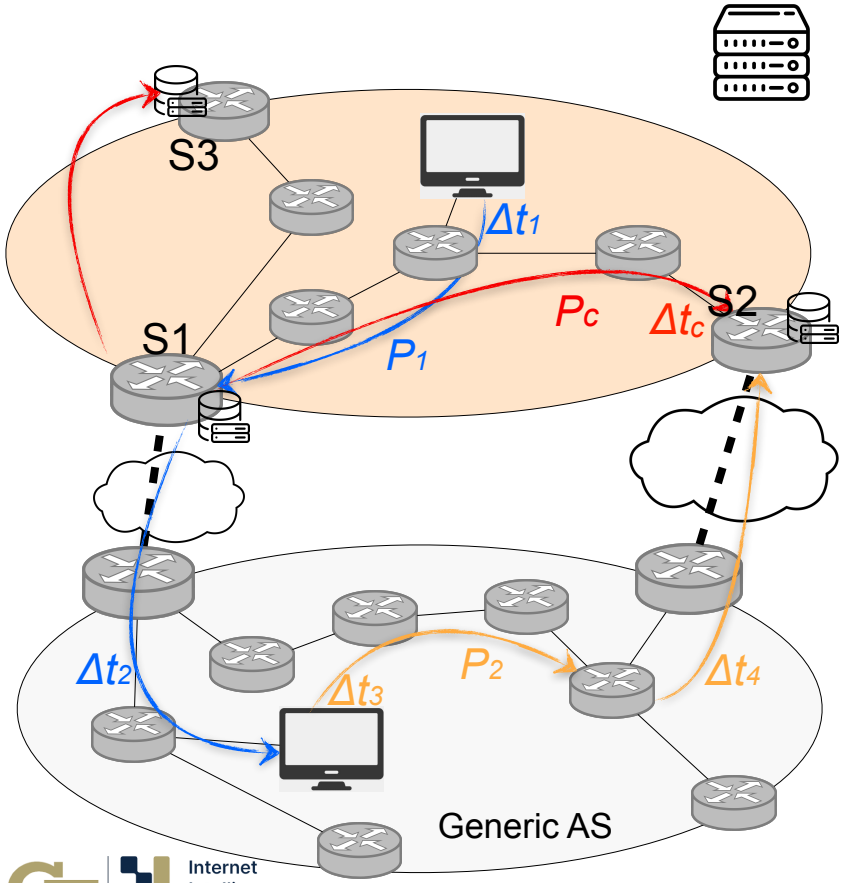

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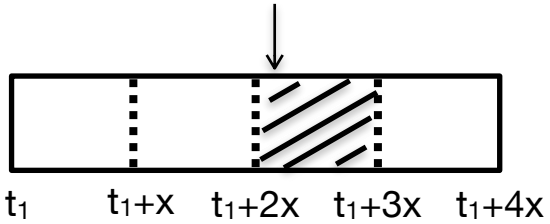

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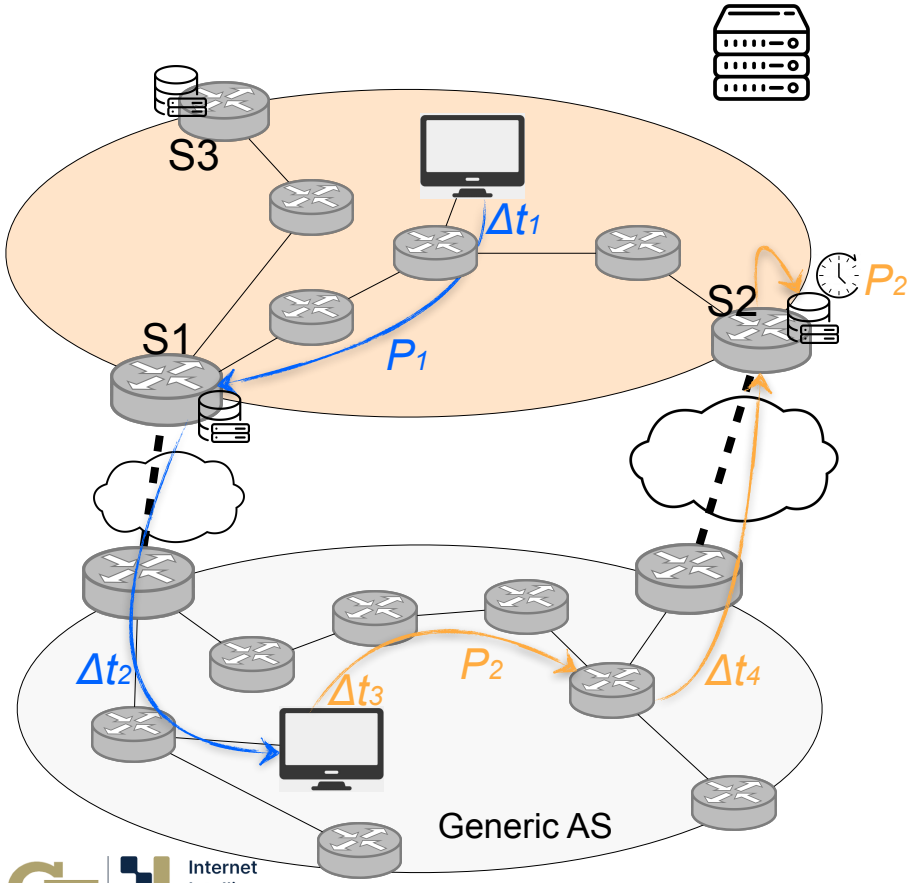

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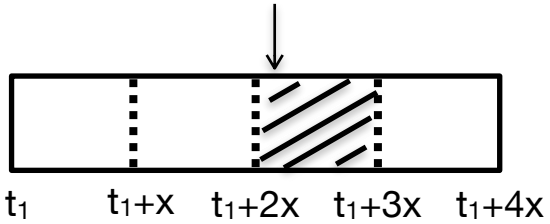
Delay: buffer IBR in capture host for 1sec

$$\Delta t_2 + \Delta t_3 + \Delta t_4 < \Delta t_c < 1s$$



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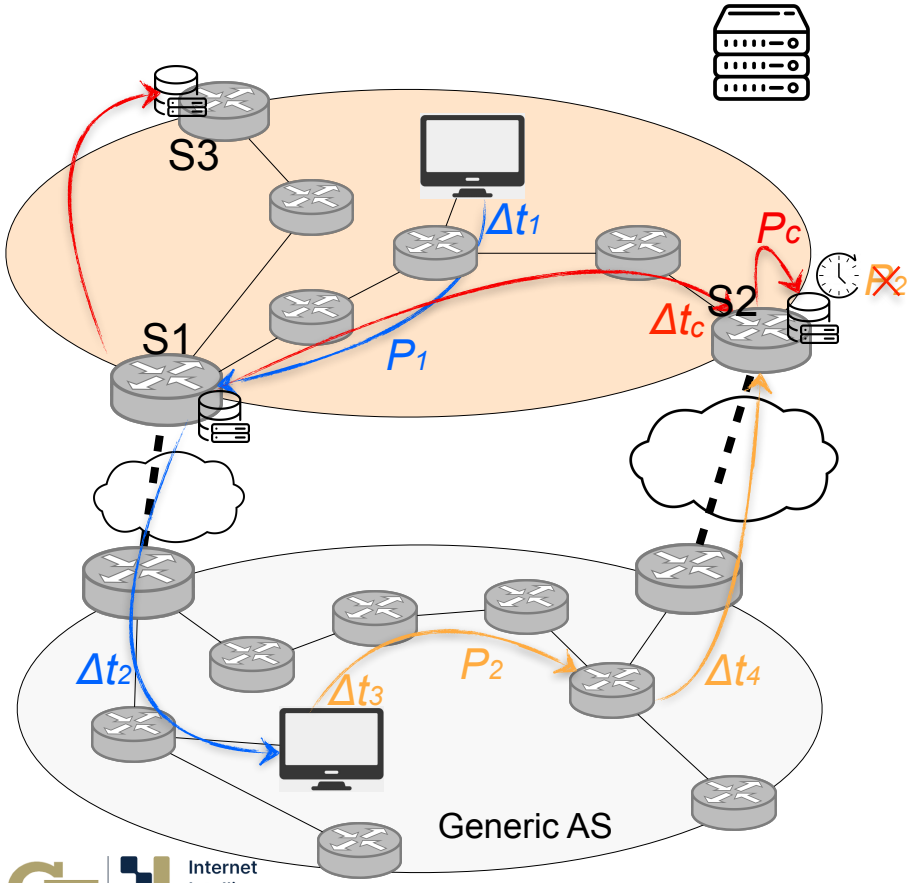

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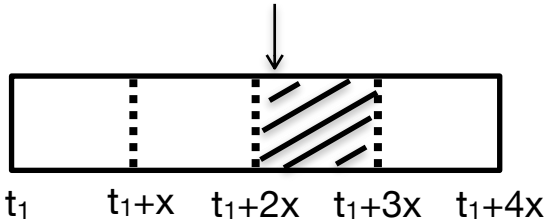


Internet Intelligence Lab

Evaluating MORP4

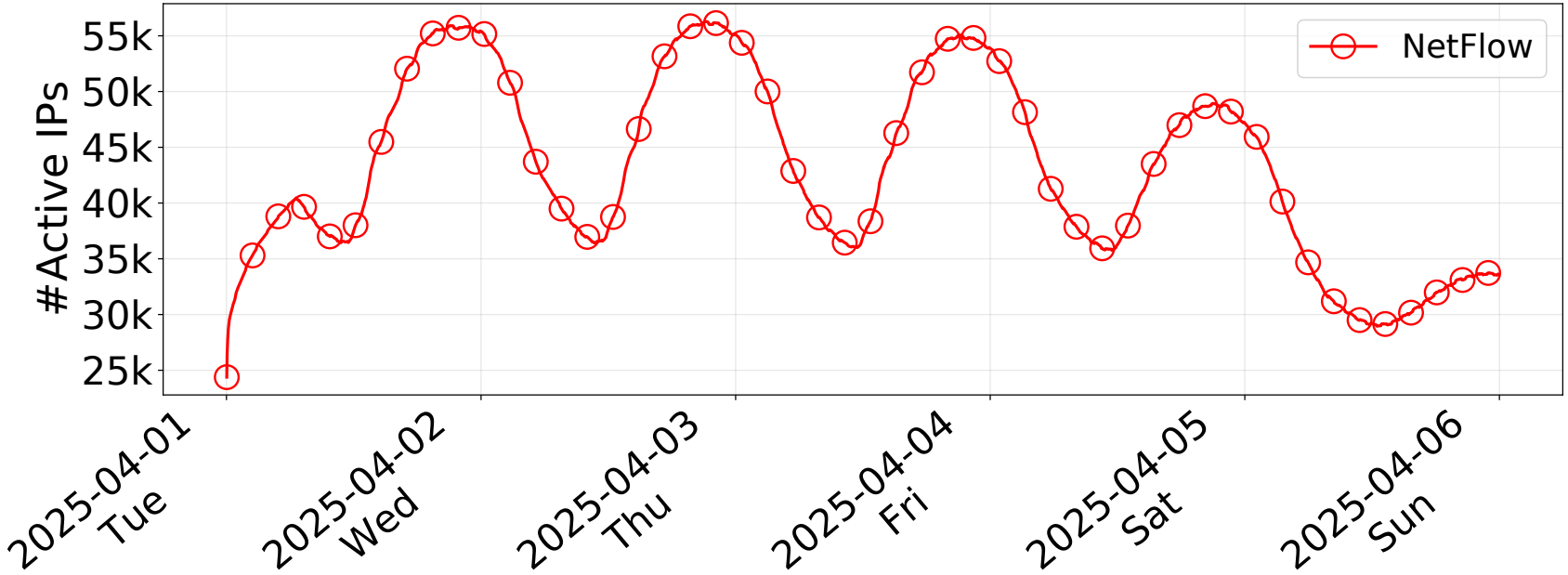
- Does MORP4 accurately detect active IPs?
- Does MORP4 increase our visibility into IBR?

Real-world Deployment

- Real-world deployment on a campus network
  - Monitor
    - 166k IPv4 addresses at /32 granularity
    - 1 /32 IPv6 network at /53 granularity on the same switch
  - 6 hours timeout to consider an IP/subnet inactive

Does MORP4 accurately detect active IPs?

- Ground truth: unsampled NetFlow data



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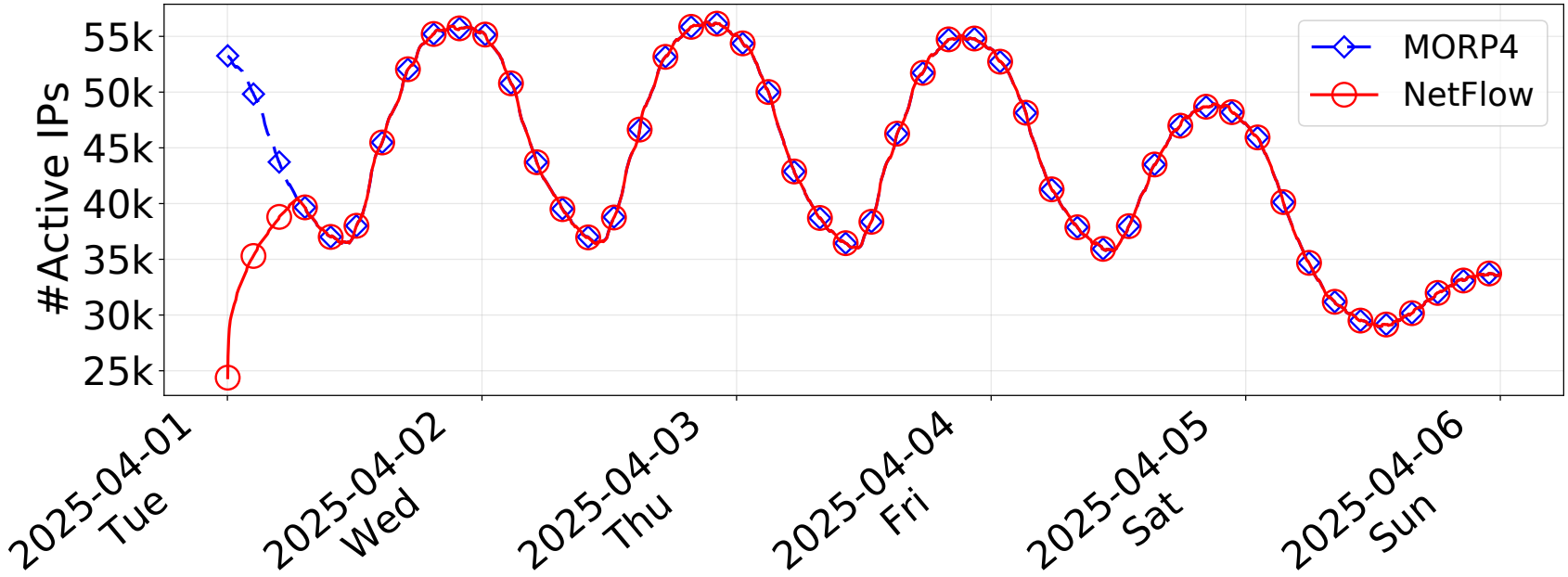
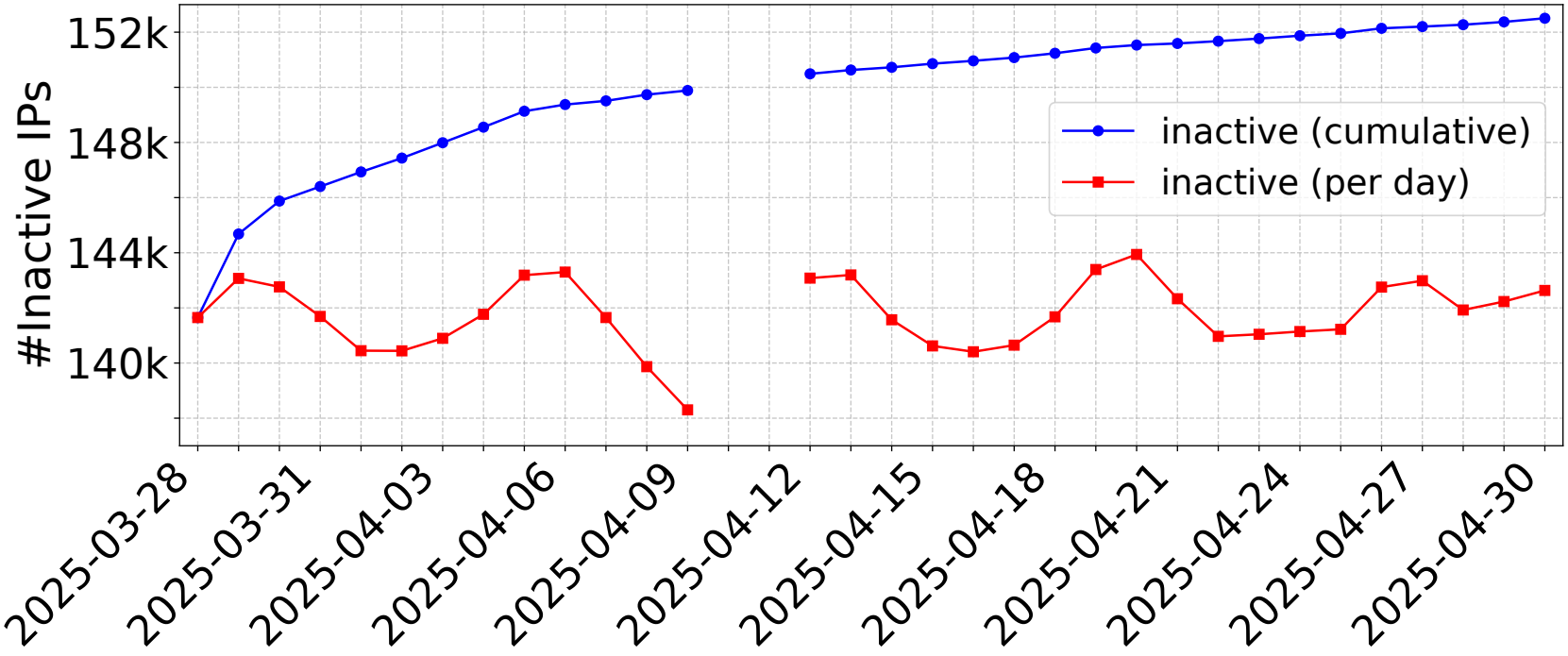


✓ MORP4 == NetFlow simulation

MORP4 recovers unutilized space



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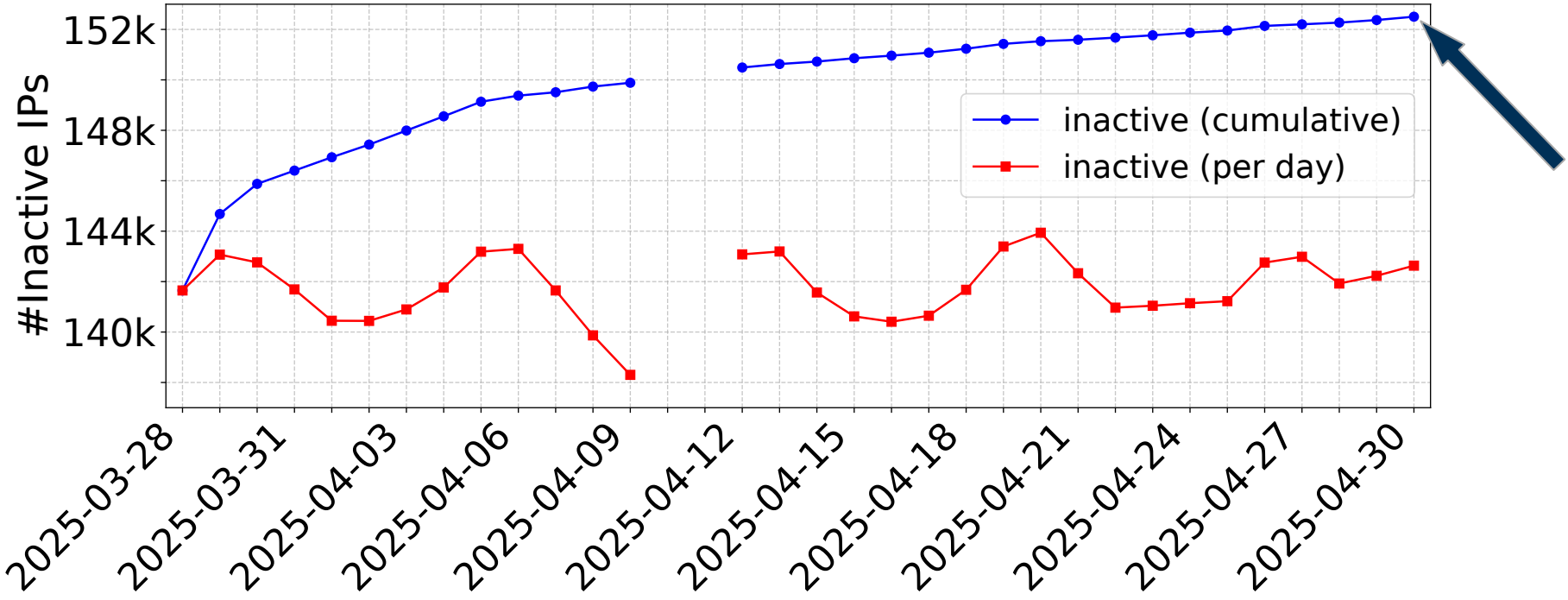
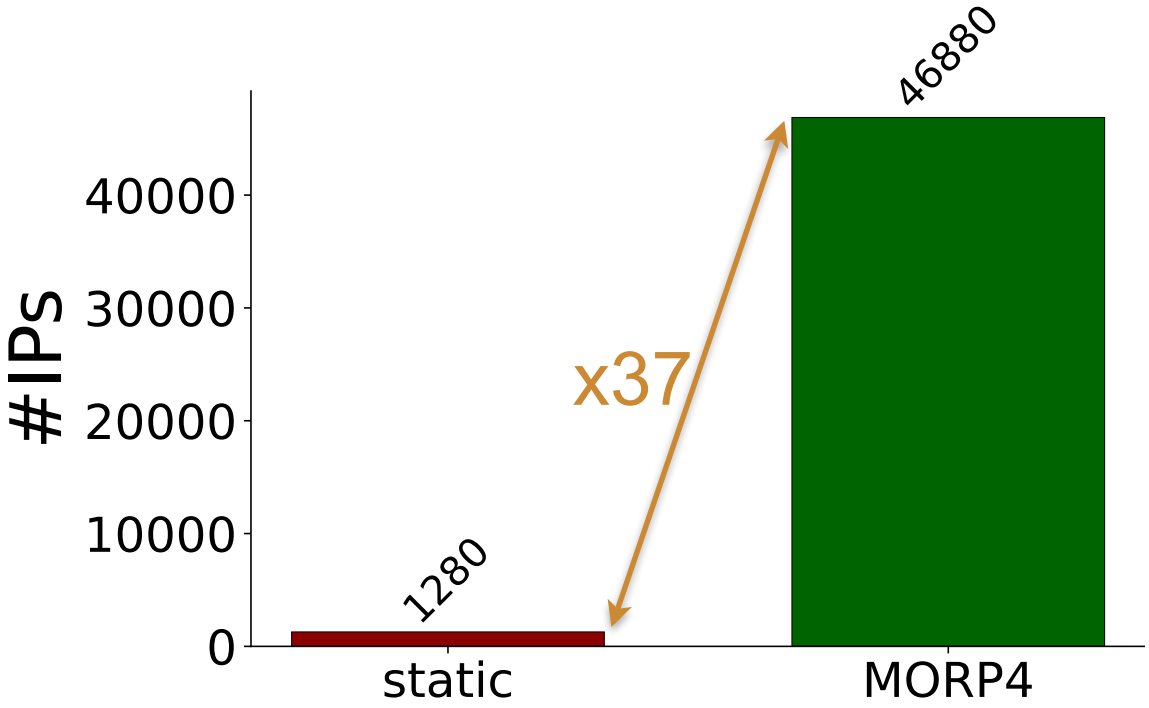


Found 152k out of 166k (~92%) IPs being inactive at some point

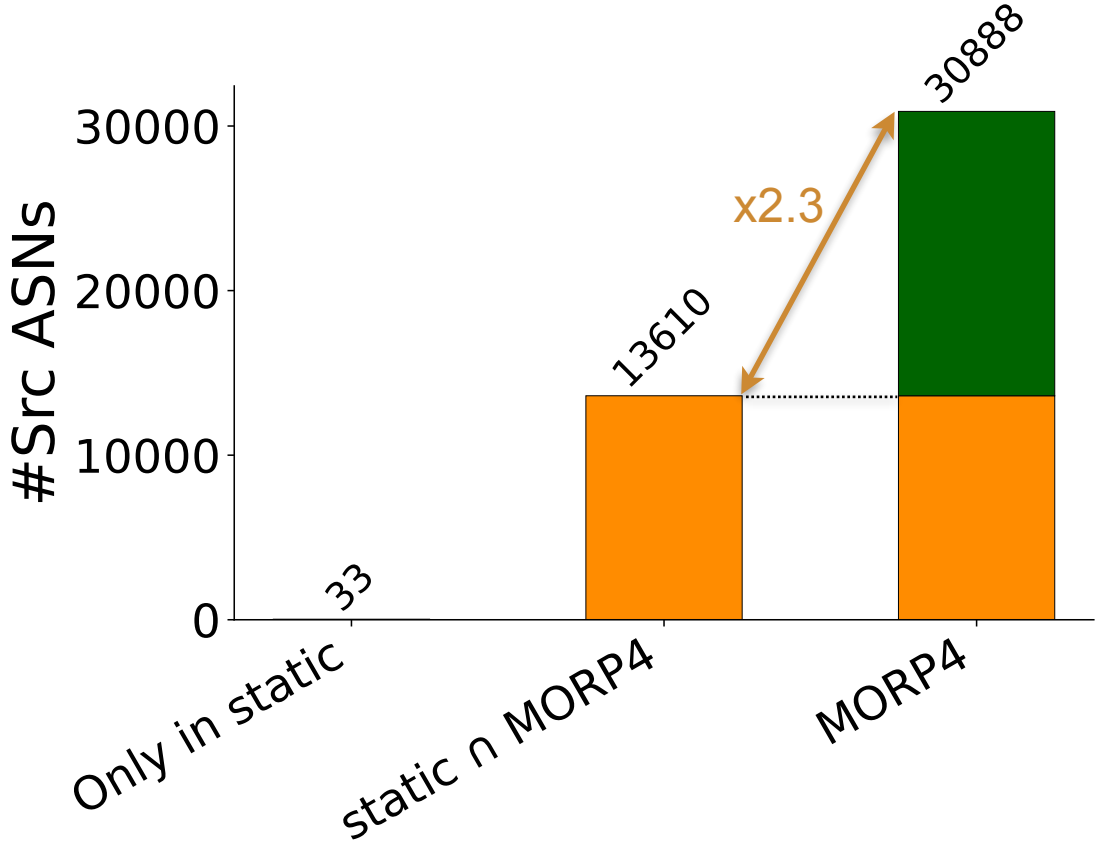
MORP4 expands the telescope size

Our network engineers have dedicated 5 /24s to static telescope



during ~34 days

MORP4 increases visibility into IBR sources

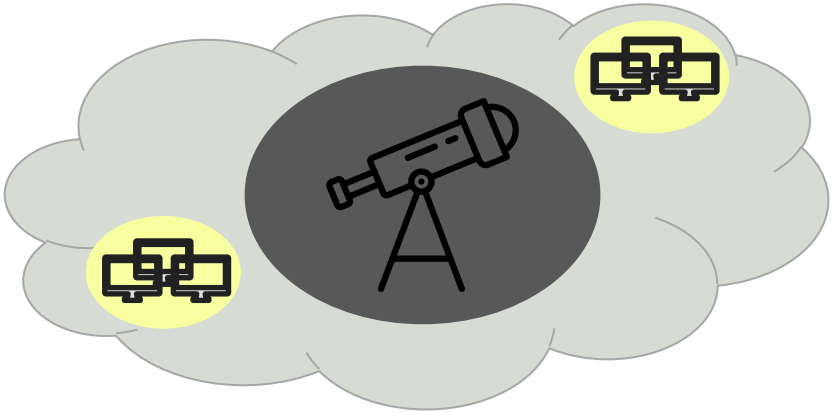


during ~34 days

MORP4 automatically infers candidate useful IPv6 telescope space

Static telescope

TotallyDark subnets



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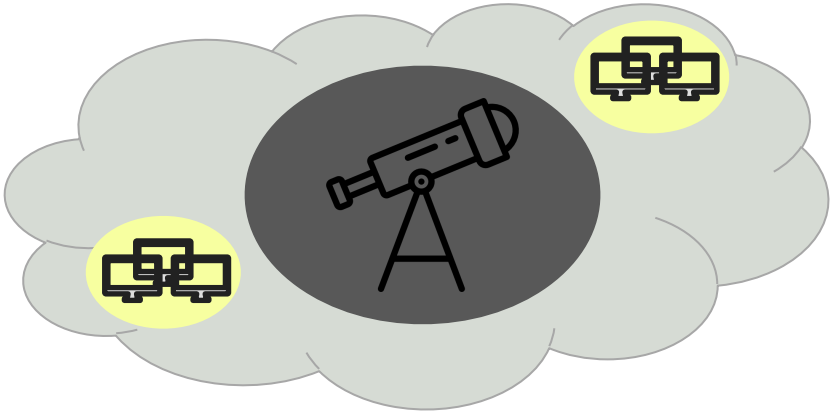

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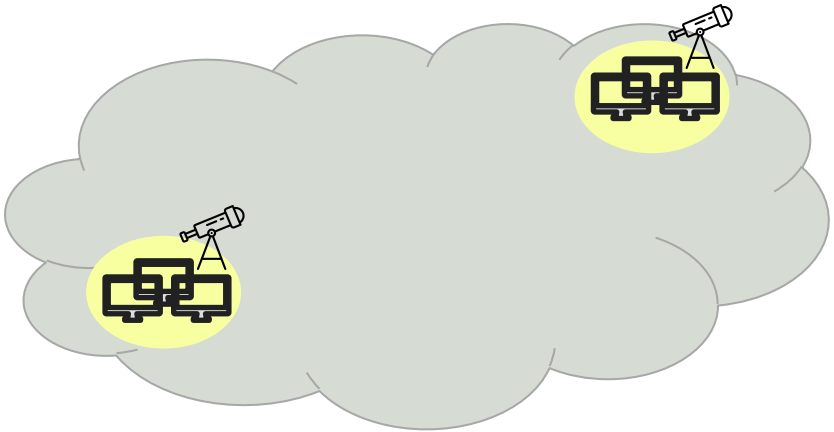
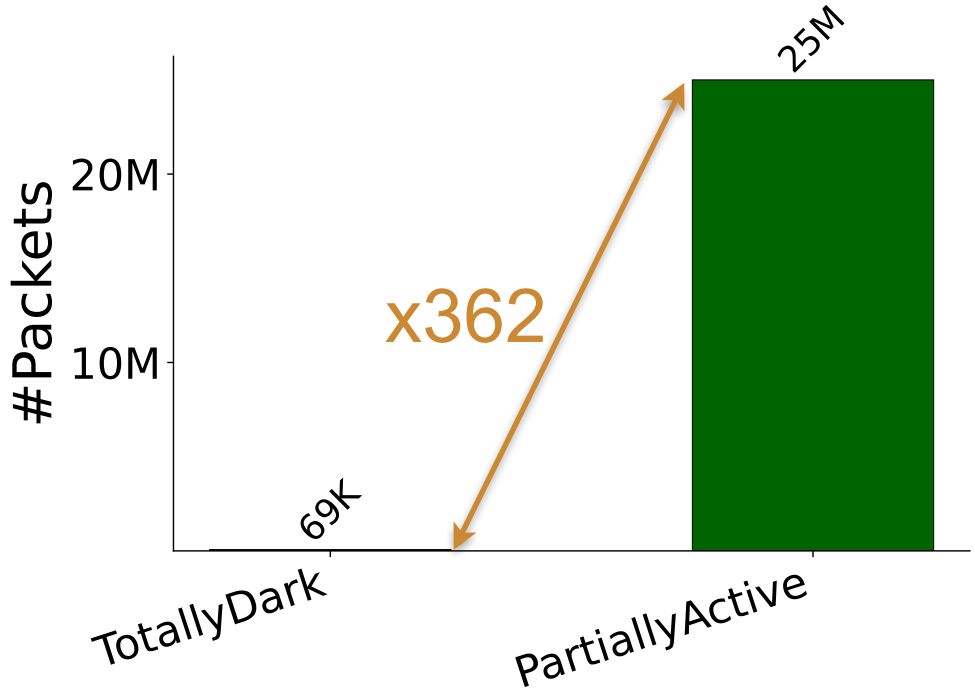


MORP4 collects more IPv6 IBR close to real operational subnets



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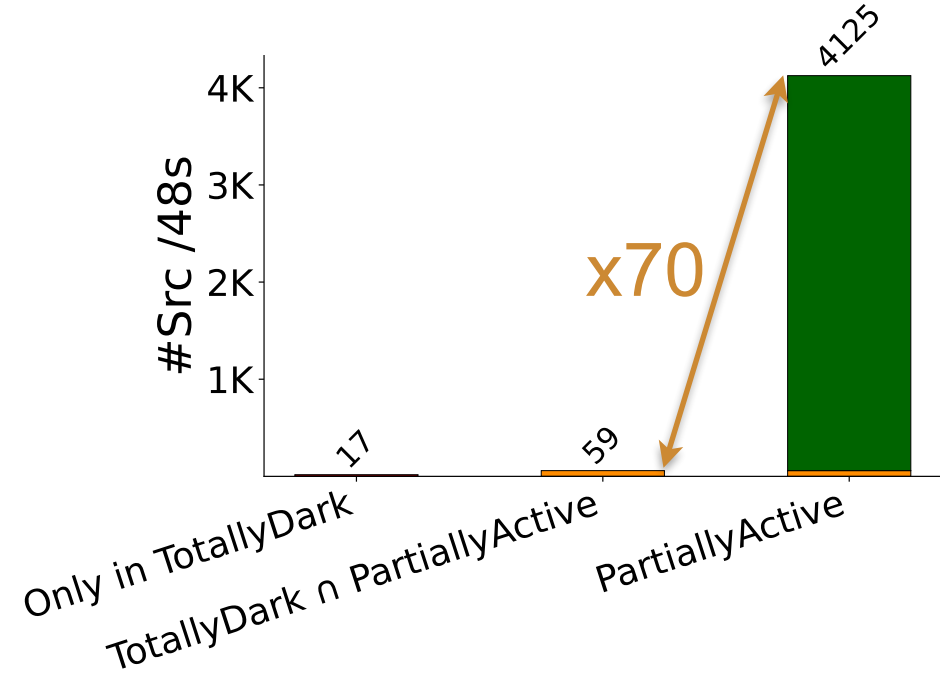
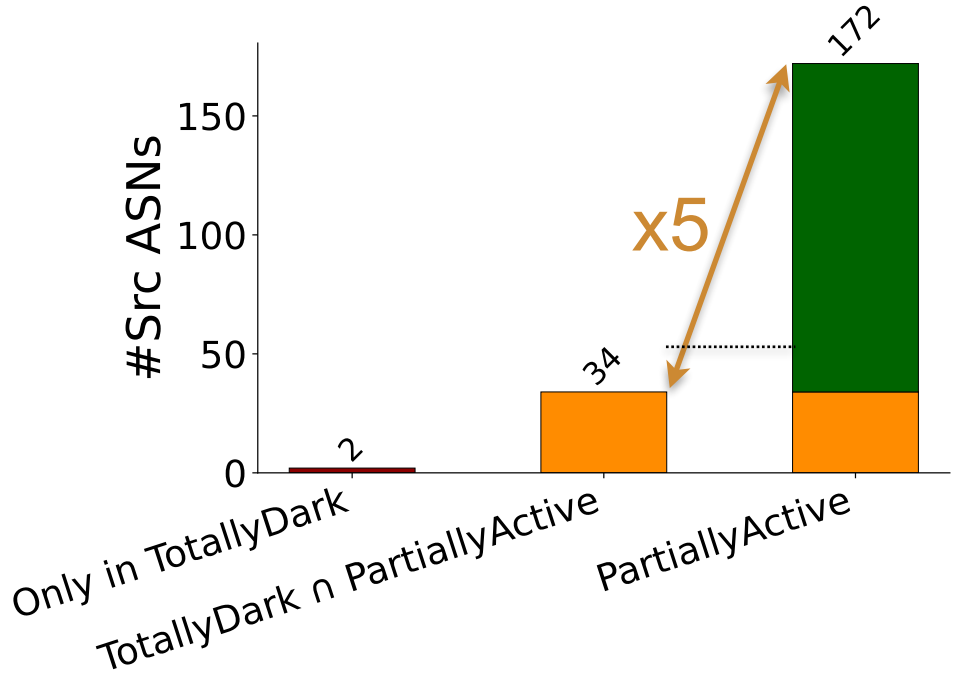
MORP4 collects more diverse IPv6 IBR close to real operational subnets





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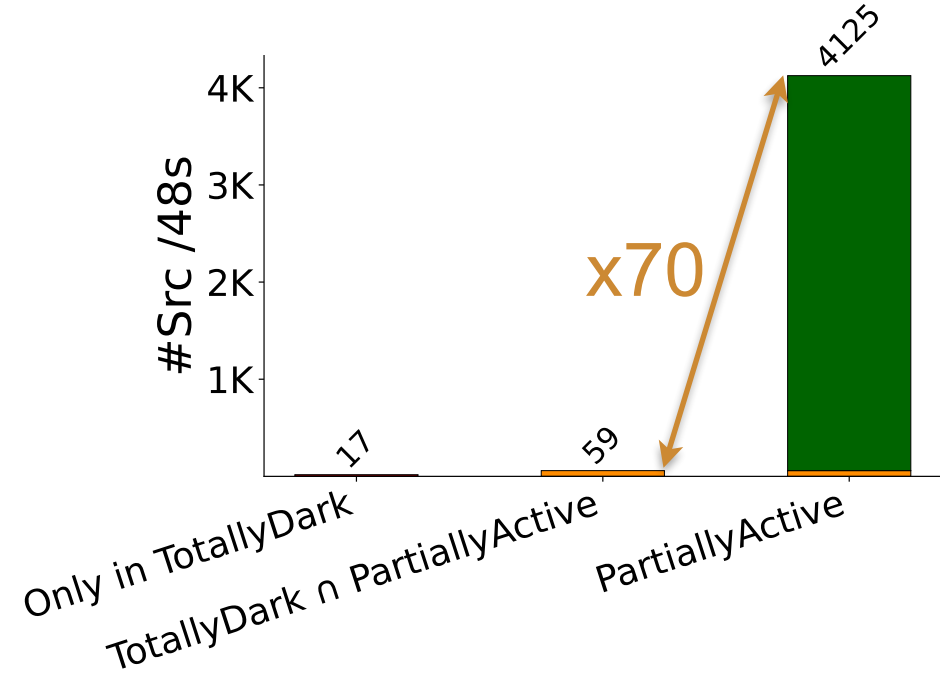

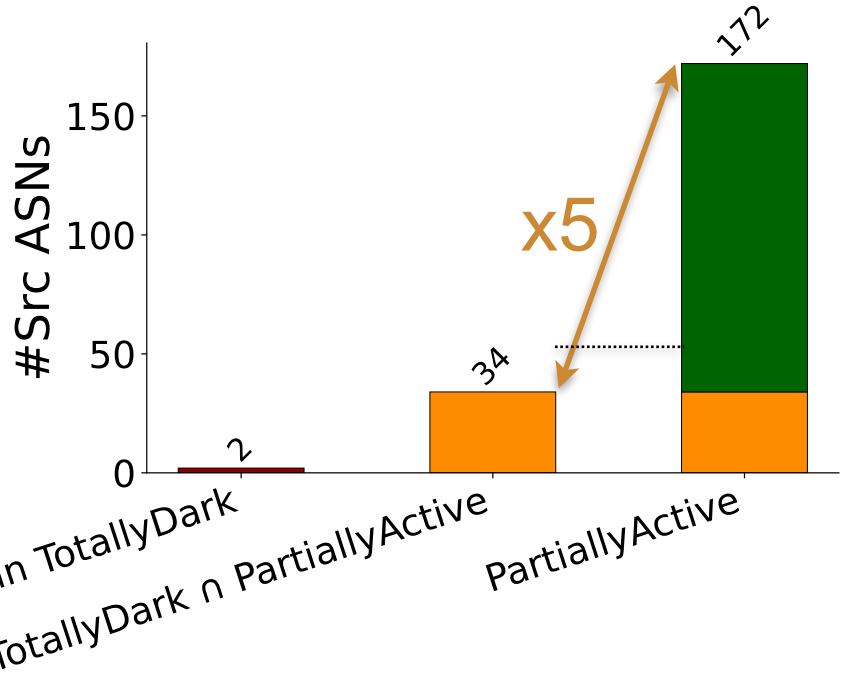

Realistic IBR without artificially attracting scanners

during ~34 days

Conclusions

With MORP4:

✓ Large IPv4 network telescope

✓ Effective IPv6 network telescope

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Ongoing work

- Deployment at another major Research and Educational network
- Comparison of IBR between major static telescope vs MORP4
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Thank you!