Tuple Space Explosion:

A Denial-of-Service Attack Against a Software Packet Classifier

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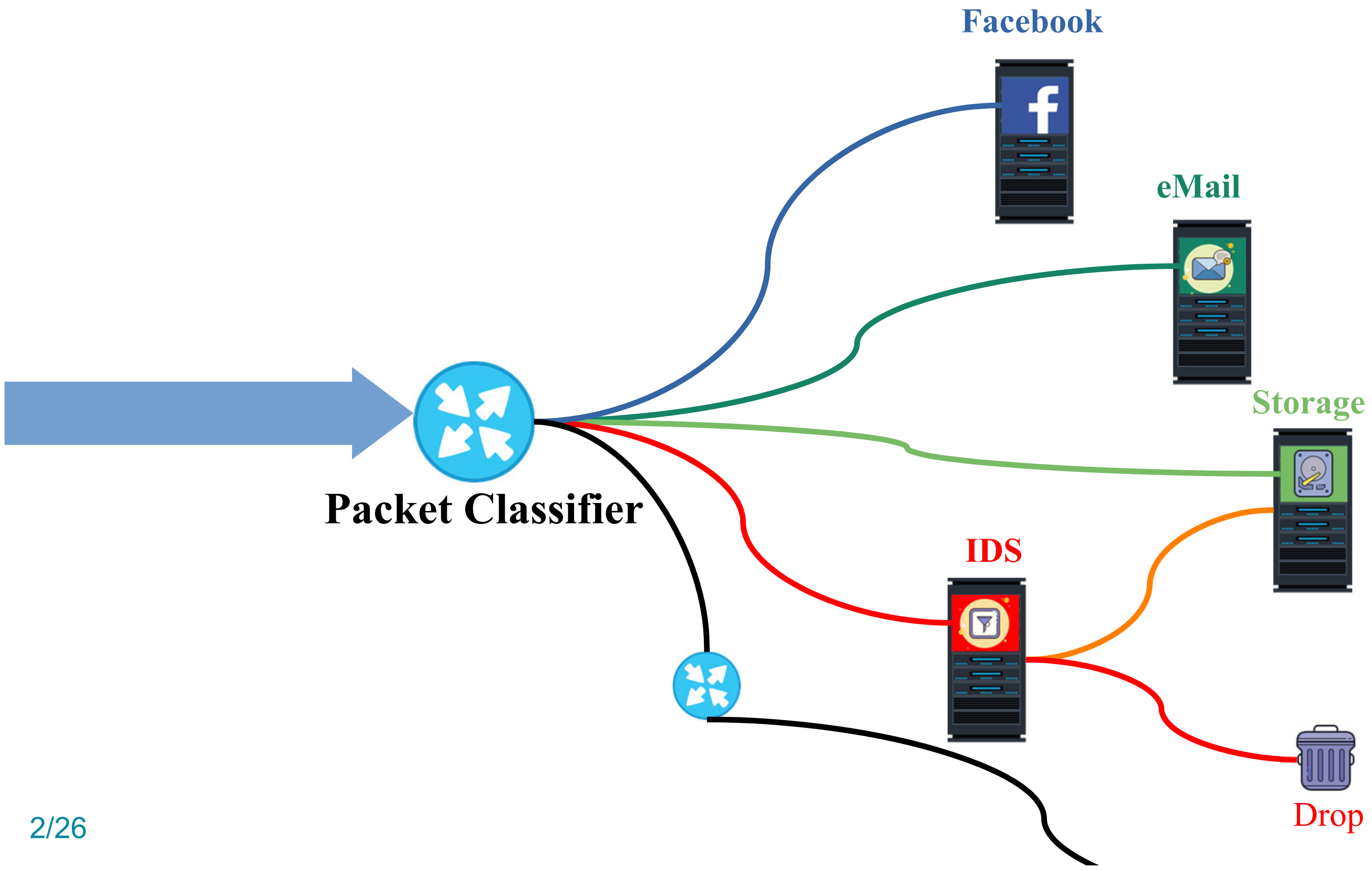
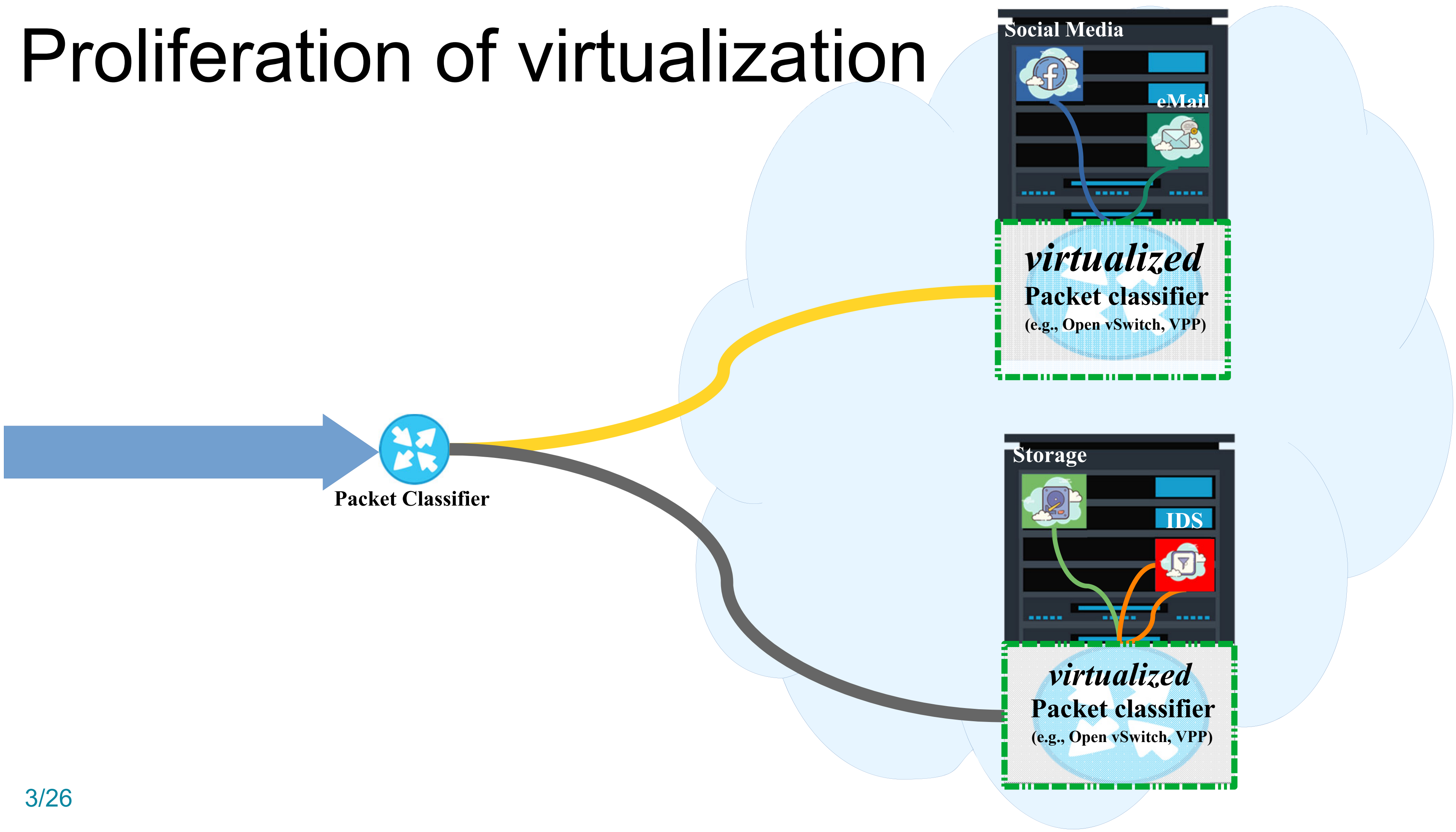
Packet Classification in the Past



Proliferation of virtualization



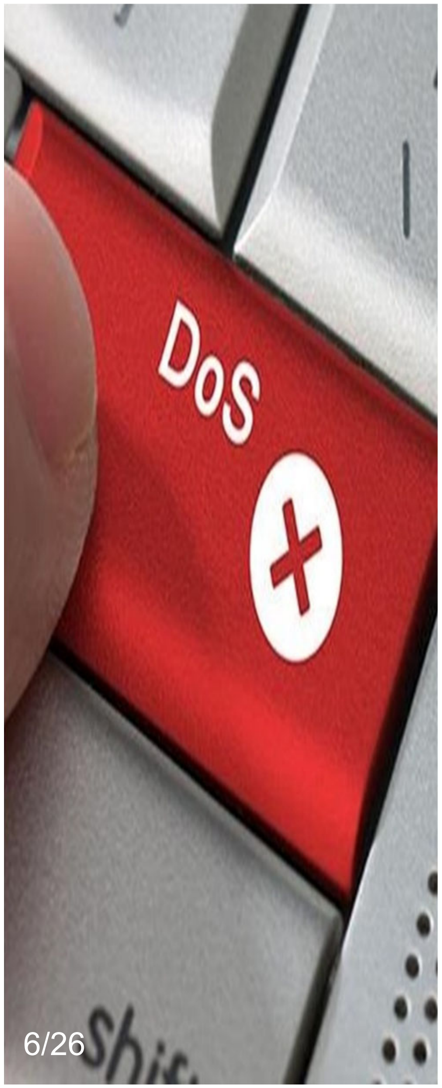
Algorithmic packet classification is expensive on general purpose processors...

Ben Pfaff et al. *"The Design and Implementation of Open vSwitch"*, USENIX NSDI 2015.

In this talk

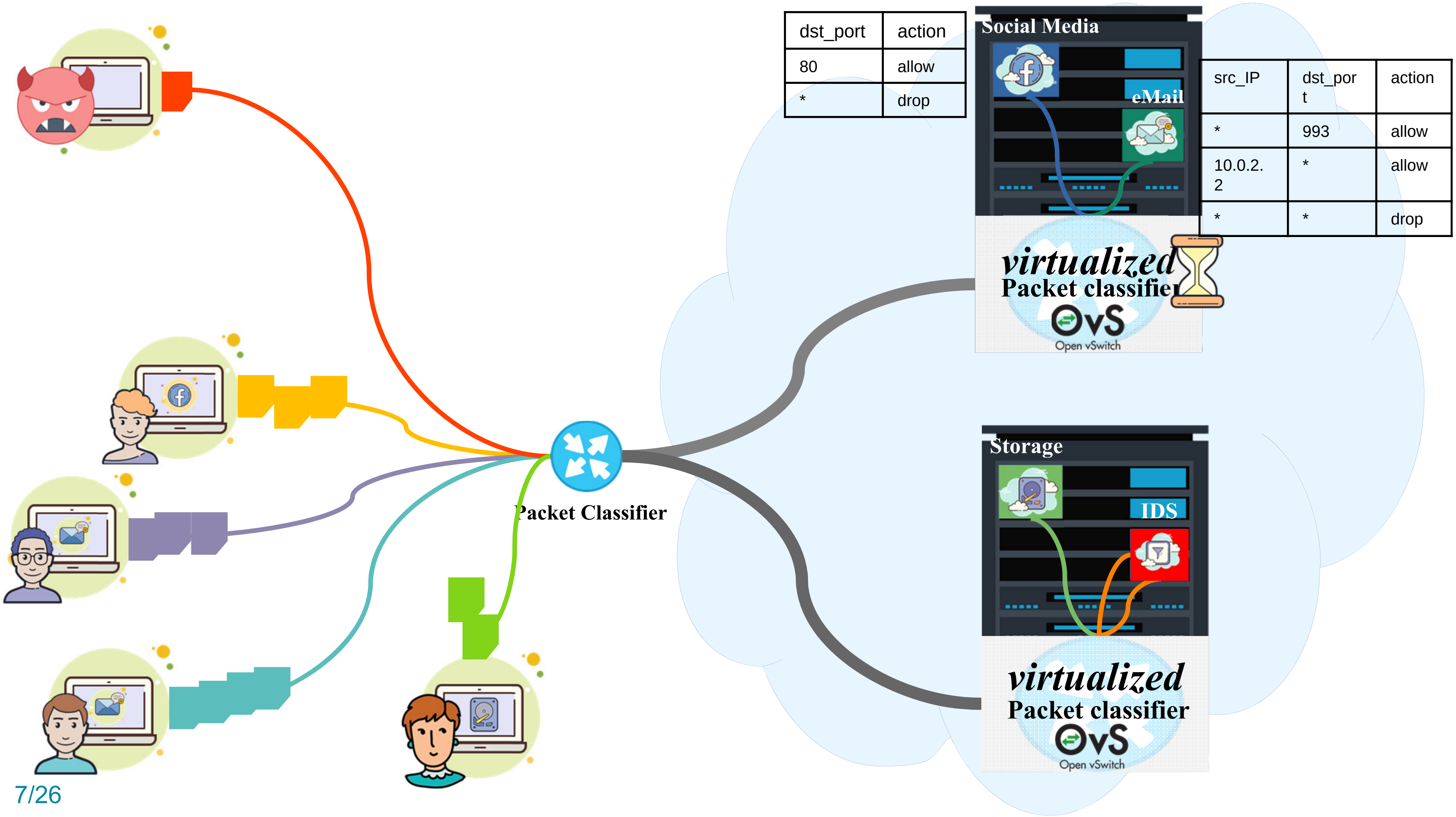
- Tuple Space Explosion (TSE): ***Family of novel Denial-of-Service (DoS) attacks*** against the ***de facto packet classifier*** algorithm (Tuple Space Search scheme) used in Open vSwitch, VPP, GSwitch, etc.
- **Remote adversary** can degrade the performance **to 12% of the baseline** (10 Gbps) with only **672 *kbps (!)* attack traffic**
- **Co-located adversary** can virtually bring down the **performance to 0%**

- Attack traffic is particularly hard to **filter out**:
  - **no attack signature** (packets w/ random headers)
  - **low-rate** (thousands of packets per second)
  - **legitimate packets**
- Countermeasures



Threat model

- **System model:**
  - typical multi-tenant cloud
  - OVS is used for packet processing
  - tenants use the Cloud Management System (CMS) to set up their ACLs to
  - access-control, redirect, log, etc.
- **Attacker's goal**
  - send some packet towards the virtual switch that when subjected to the ACLs will exhaust resources
- **Attacker's capability**
  - craft and send arbitrary packets to a target OVS
  - No privilege of the target (General TSE)
  - Co-locate with the target (Colocated TSE)



dst_port	action
80	allow
*	drop

src_IP	dst_port	action
*	993	allow
10.0.2.2	*	allow
*	*	drop

Explosion in the Tuple Space

- **Problem**: more masks → slower packet classification
- **Tuple Space Explosion phenomenon:**

1) **16-bit** TCP destination port → **16 masks**
2) **32-bit** source IP address → **32 masks**

- And that's only ONE *allow rule* on ONE *header*

- Multiple `allow rules` on multiple header fields result in an exponential growth → cross-product

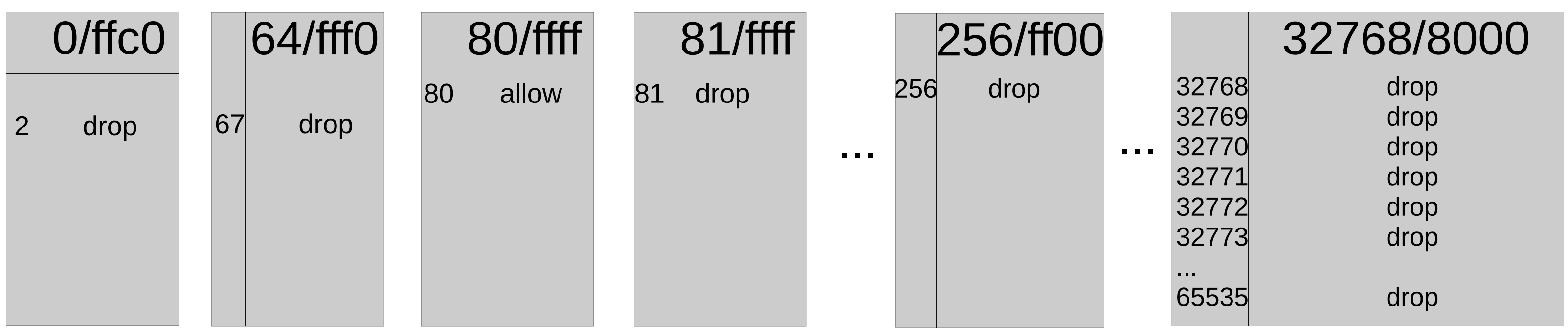
- matching on either **1)** or **2)** → 16*32 = **512 masks**

(TSE)

- **Goal**: blow up the tuple space
  - Spawn as many masks (and hashes) as possible
  - to make classification a costly linear search
  - One packet for each bucket
  - port=[0, 64, 80, 81, …, 32768] (16 packets)

MFC masks in OVS

TCP DST PORT	action
80	output:1
*	drop



(TSE)

- Without the flow table → **Difficult**
  - All possible packets seems fine
  - BUT: 2^k packets for a header of k bits!
    - too much effort
    - easily detectable (like a portscan, easily becomes volumetric)

- Can we just send *random* packets?

TSE w/ random packets

- Q: What are the chances that a random header spawns a new mask (and hash)?

dport=32769

	32768/8000
32768	drop
32769	drop
32770	drop
32771	drop
32772	drop
32773	drop
...	
65535	drop

- key finding is the number of wildcarded bits (k) for header length h

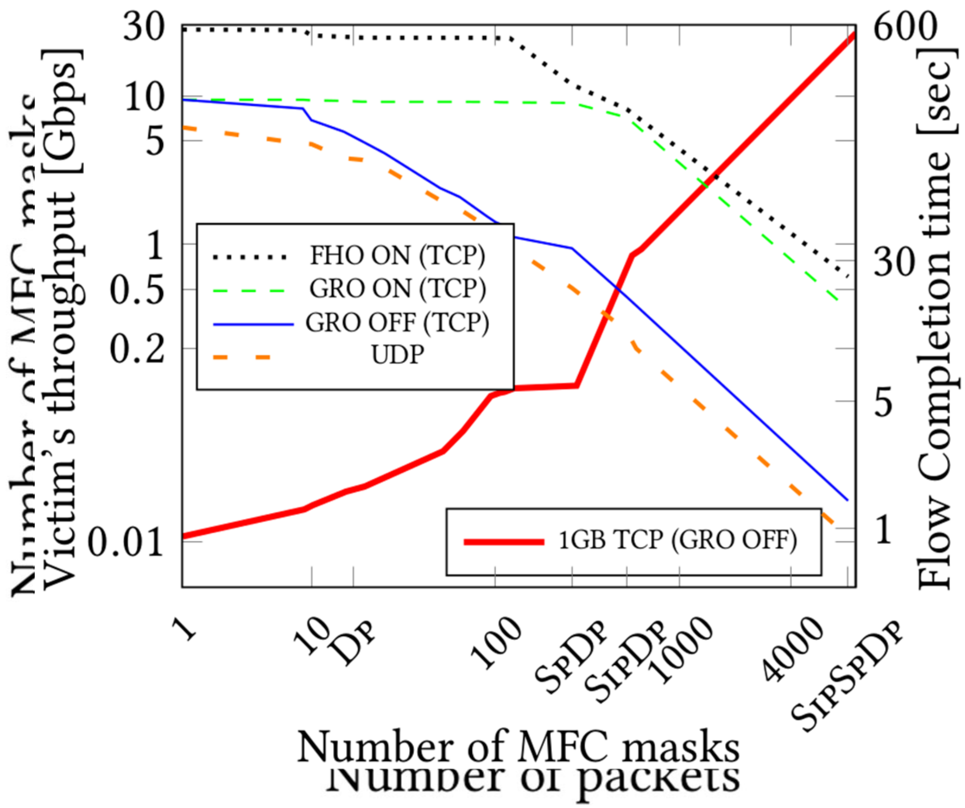
$$p_k(MFC) = \frac{2^k}{2^h}$$

- 1*** **** **** **** (32768) ~ **50%**
- 0000 0000 01** **** (64) ~ **0.1%**

	64/fff0
64	drop
65	drop
66	drop
67	drop
68	drop
69	drop
...	...
79	drop

TSE w/ random packets

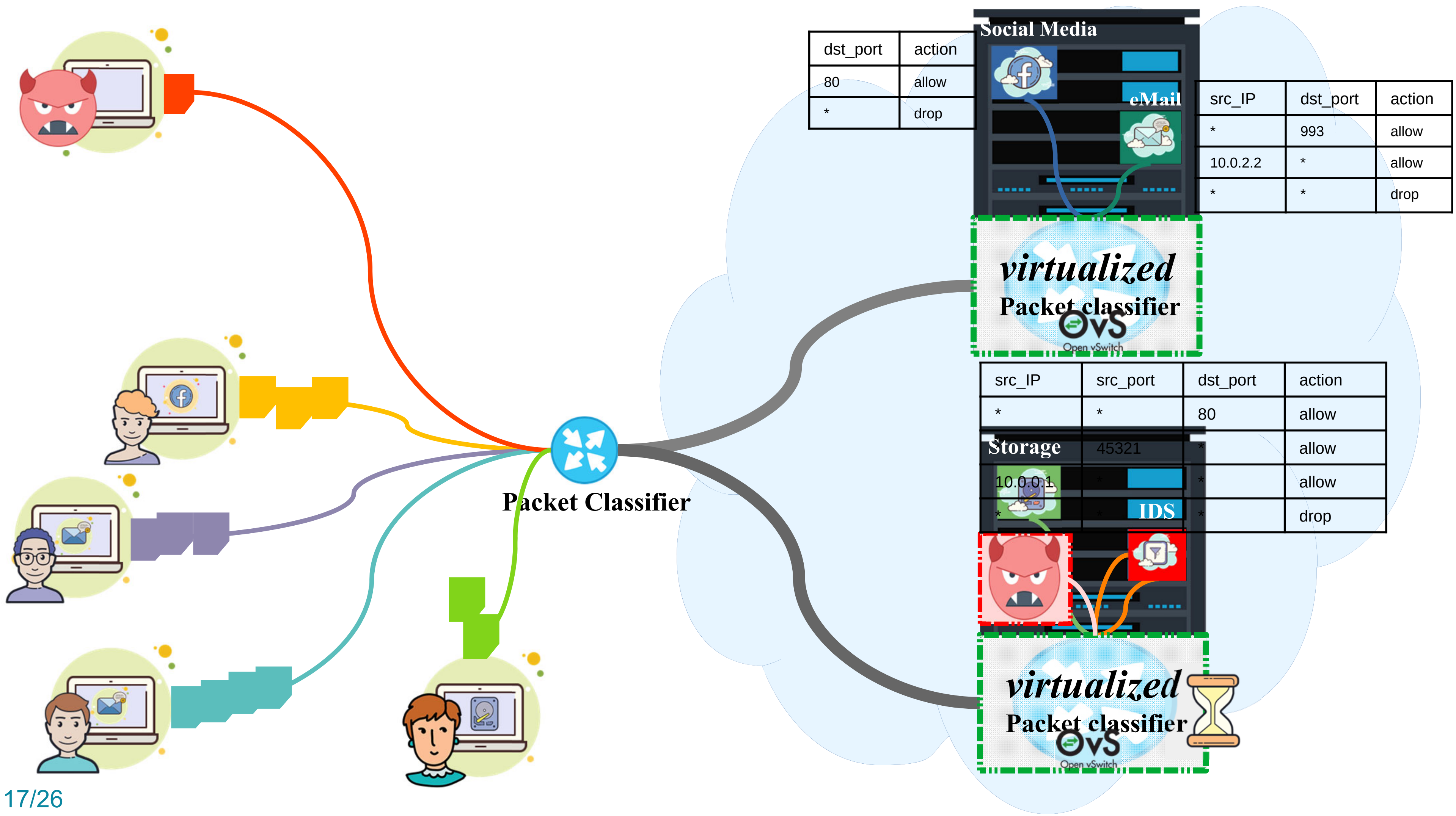
- **(M)**easured and **(E)**xpected numbers for different ACLs assumed to be installed by the victim
  drop to 10%
  - Dp
    - dst_port only
  - SipDp
    - src_IP + dst_port
  - SpDp
    - src_port + dst_port
  - SipSpDp (full-blown)
    - src_IP+ src_port + dst_port



Denial-of-Service

- Success rate of randomly generated packets
  - **672 kbps (!) attack traffic → 88% performance drop**
  - 1,000 pps → reduce from 10 Gbps to 1,2 Gbps

- **What if the adversary has more knowledge/resources?**



dst_port	action
80	allow
*	drop

src_IP	dst_port	action
*	993	allow
10.0.2.2	*	allow
*	*	drop

src_IP	src_port	dst_port	action
*	*	80	allow
[illegible]	45321	*	allow
10.0.0.1	*	*	allow
*	*	*	drop

Co-located TSE attack

- Adversary leases resources in the cloud
- Configures its own ACL
- Sends only the required number of packets
  - one packet for each mask (and hash)

- *More significant service degradation* – much *less packets*
  - **1000 pps → thousands of masks → close to 0% (full DoS)**
- However:
  - Attack is against the infrastructure *not* a specific target
  - **DoS against the co-located services "*only*"**

Effects in a broader scale

- In a cloud, an attacker can easily exploit this!
- Several public cloud deployments are affected
  - Docker/OVN (based on OVS)
  - ✓ **Kubernetes/OVN (based on OVS)**
  - Contiv/VPP Kubernetes (based on VPP)
  - ✓ **OpenStack/Neutron/OVN (based on OVS)**
  - OpenStack/Neutro-VPP (based on VPP)

Countermeasures

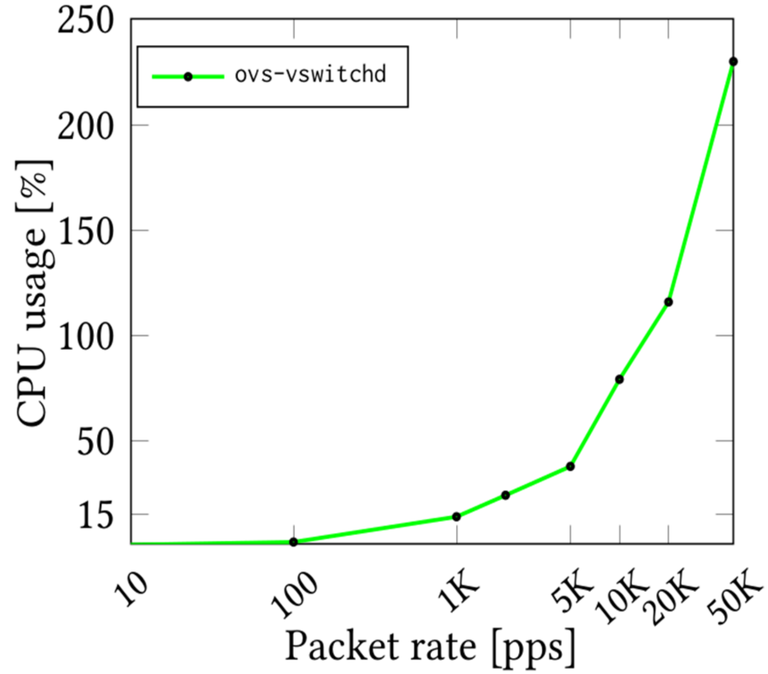
- **Filtering out** the attack traffic is **hard**
  - legitimate traffic
  - no attack signature (random packets w/ random headers)
  - low-attack rate (thousands of packets per second)

- A long term solution
  - Different classifiers:
  - Hierarchical trees, HyperCuts, HaRP, etc.

MFC Guard (MFCg) in action

MFC Guard (MFCg)

- When MFC is cleaned the victim's performance goes back to its baseline
  - attack packets → slow path
- CPU overhead?
  - **1 *kpps* attack rate = 15% CPU usage**
  - **10 *kpps* attack rate = 80% CPU usage**



General TSE

- Random packets
  - Probability that from *n* random packets there will be at least 1 packet that sparks an MFC entry for a given *k* is:

$$p_{(k,n)}(MFC) = (1 - (1 - p_k(MFC))^n) * C_k$$

  - C_k is the number entries for a given *k* (e.g., k=0, C_k = 2
- Expected value can be formalized by:

$$\mathbb{E}_{(k,n)}(MFC) = \sum_{k=0}^{h} p_{(k,n)}(MFC)$$

Countermeasures

- Immediate yet impractical remedies
  - offload ACL implementation to a different switch
    - others might suffer from the same attack
  - high performance gateway appliance
    - cannot help against an attack within the cloud
  - switch MFC completely OFF
    - biggest performance improvement so far

Tuple Space Search

TCP DST PORT	action
80	output:1
*	drop

- entries matching on the same header are collected into a hash
  - masked packet headers can be found fast
- Masks and associated hashes are searched sequentially
- in

Can be a costly linear search in case of lots of mas

- PKT_IN → APPLY_MASK → LookUp → Repeat until found

dport=80

dport=32777

	0/ffc0
1	drop
2	drop
3	drop
4	drop
5	drop
6	drop
...	...
63	drop

	64/fff0
64	drop
65	drop
66	drop
67	drop
68	drop
69	drop
...	...
79	drop

	80/ffff
80	allow

	81/ffff
81	drop

...

	256/ff00
256	drop
257	drop
258	drop
259	drop
260	drop
261	drop
...	...
511	drop

...

	32768/8000
32768	drop
32769	drop
32770	drop
32771	drop
32772	drop
32773	drop
...	
65535	drop