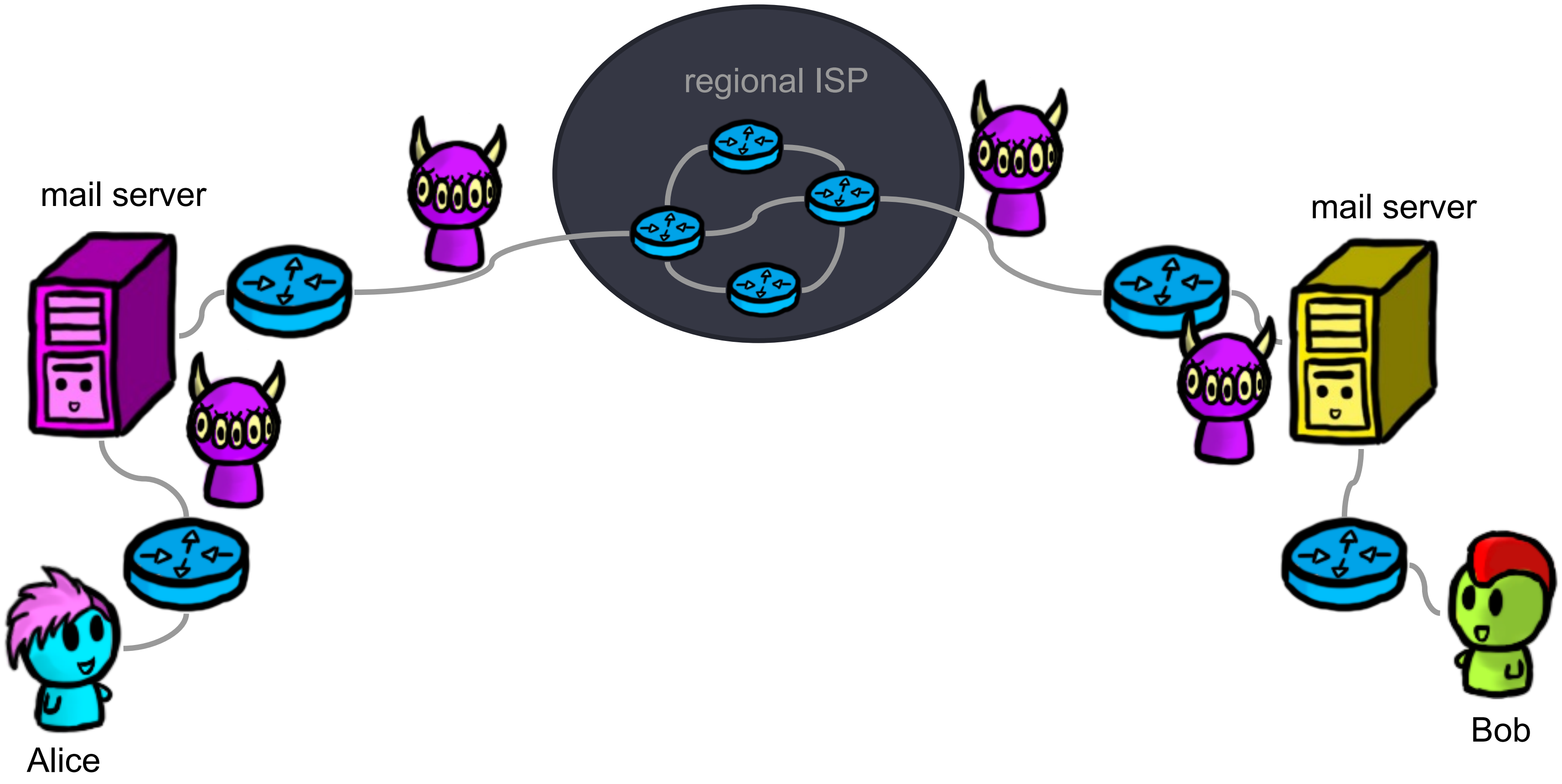
CS489/698 Privacy, Cryptography, Network and Data Security

Encrypted Traffic Analysis

Spring 2024, Monday/Wednesday 11:30am-12:50pm

Traffic Analysis



Easy attack surface:

- Mallory has access to one of the many hops traffic takes on the internet

Communication media (WiFi)

- WiFi
  - Can be easily intercepted by anyone with a
- WiFi-capable (mobile) device
    - Don’t need additional hardware, which would cause suspicion
- Maybe from kilometers away using a directed antenna
- WiFi also raises other security problems
  - Physical barriers (walls) help against random devices being connected to a wired network, but are (nearly) useless in case of wireless network

Communication media

- Copper cable
  - Inductance allows a physically close attacker to eavesdrop without making physical contact
  - Cutting cable and splicing in secondary cable is another option
- Optical fiber
  - No inductance, and signal loss by splicing is likely detectable
- Microwave/satellite communication
  - Signal path at receiver tends to be wide, so attacker close to receiver can eavesdrop
- All these attacks are feasible in practice, but require physical expenses/effort

Traffic Analysis

- TCP/IP has each packet include unique addresses for the packet's sender and receiver end nodes, which makes traffic analysis easy
- The attacker simply needs to sniff packets to determine what is going where and when.
    - Can be sensitive info such as two CEOs talking or a whistle blower.
- tcpdump is a text-based traffic analysis tool

Tcpdump (1 of 3)

```
`14:47:26.566195 IP 192.168.2.2.22 > 192.168.1.1.41916: Flags [P.], seq 196:568, ack 1, win 309,
options [nop,nop,TS val 117964079 ecr 816509256], length 372
```

- 14:47:26.566195 the timestamp of the received packet
- IP is the network layer protocol (IPv4)
- 192.168.2.2.22 is the source IP address and port
- 192.168.1.1 is the destination IP address and port

Tcpdump (2 of 3)

```
`14:47:26.566195 IP 192.168.2.2.22 > 192.168.1.1.41916: Flags [P.], seq 196:568, ack 1, win 309,
options [nop,nop,TS val 117964079 ecr 816509256], length 372
```

- TCP Flag (`Flags [P.]`) fields include:

Value	Flag Type	Description
S	SYN	Start Connection
F	FIN	End (Finish) Connection
P	PUSH	Push data
R	RST	Reset connection
.	ACK	Acknowledgement

Tcpdump (3of 3)

```
`14:47:26.566195 IP 192.168.2.2.22 > 192.168.1.1.41916: Flags [P.], seq 196:568, ack 1, win 309,
options [nop,nop,TS val 117964079 ecr 816509256], length 372
```

- `seq 196:568` is the sequence number of the data contained in the packet (196 bytes to 568 bytes)
- `ack 1 is the ack number, which is` 1 (sender) or the next expected byte (receiver)
- `win 309` is the number of bytes available in the receiving buffer
- `options [nop,nop,TS val 117964079 ecr 816509256],` are the TCP options
- `length 372` is the length, in bytes, of the payload data (the difference between the first and last byte in the sequence number)

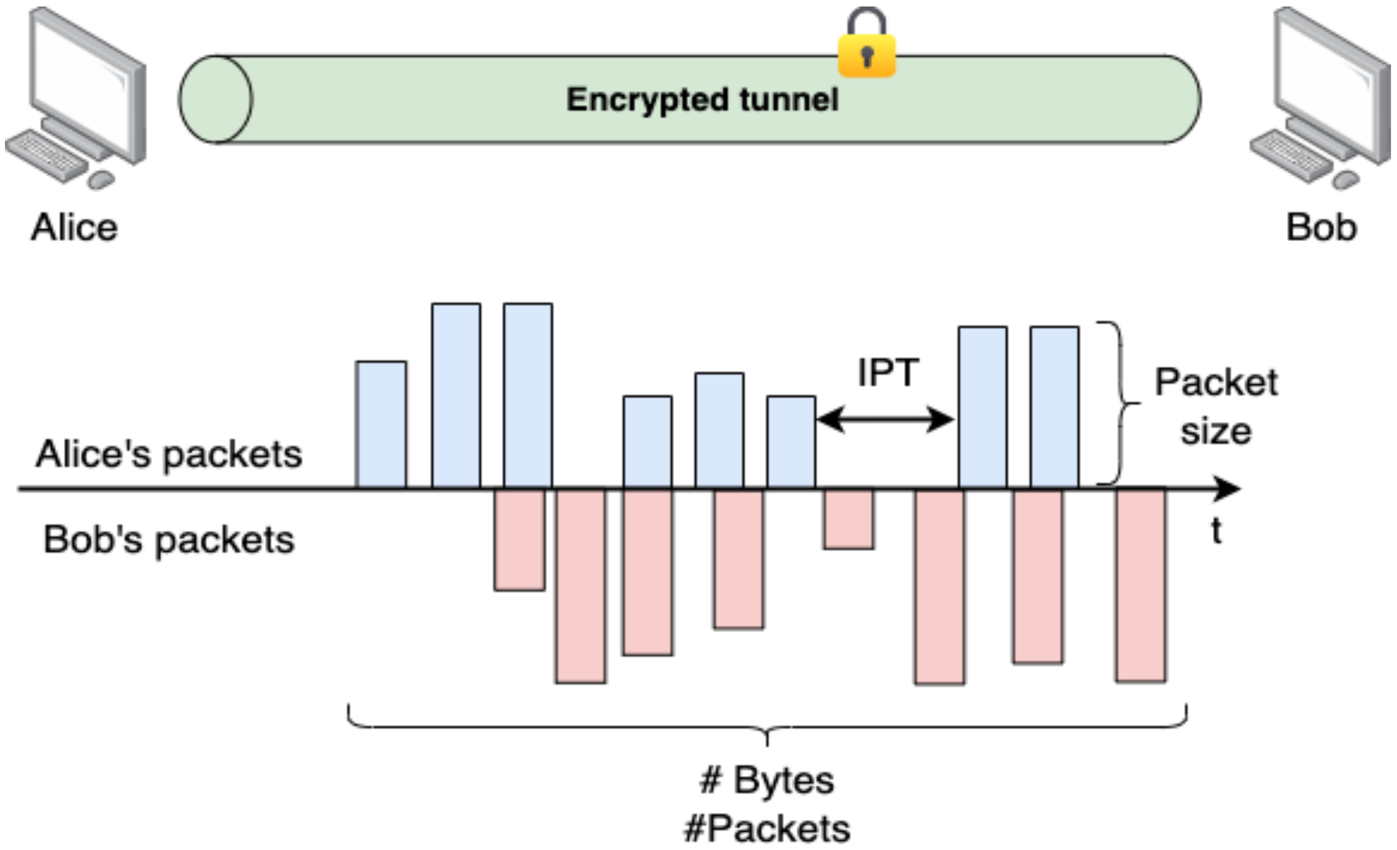
Encrypted Traffic Analysis

Encryption reduces visibility over network traffic

- TLS and other PETs significantly improved security and privacy for Internet users
  - Plaintext is no longer visible
  - Traffic monitoring capabilities are significantly reduced
- But one should not assume that traffic encryption provides absolute protection
  - e.g., against behavioural analysis
- There are strong incentives to “see” beyond encryption
  - Both for network adversaries and network administrators

Encrypted traffic analysis (ETA)

- Let’s look at an encrypted tunnel between Alice and Bob:



Network flows and metadata

- What is a network flow?
  - A flow is typically represented by a five-tuple
  - <Src. IP, Dest. IP, Src. port, Dest. port, Proto>
- One can extract additional metadata tied to a flow:
  - Flow duration
  - Amount of packets exchanged Packet sizes
  - Packet inter-arrival times
  - Payload byte entropy And more...
- What is this good for?

Encrypted traffic analysis (ETA) as a side channel

- Think of ETA as a sort of network side channel!

- ETA can be used to infer information about encrypted traffic

- We'll look at three particular ETA applications for:
  - network analytics
  - network security
  - privacy breaches

- We'll also discuss potential countermeasures

Network Analytics

Network Analytics

- Traffic Engineering
  - Prioritize application traffic (e.g., WhatsApp, Skype)
    - e.g., for non-neutral Internet ISPs
  - Throttle selected protocols (e.g. BitTorrent)
    - e.g., for “traffic management” purposes

- Quality-of-Service
  - Derive quality metrics from encrypted flows
    - e.g. videoconferencing and video streaming QoE
    - e.g. websites’ page load time, speed index

Use case: Identification of mobile applications

- Mobile applications' traffic leaves a fingerprint
  - Network observers can understand which apps you are using
- Build a classifier based on summary statistics from each flow
  - Look at the packet size/timing distributions
  - Minimum, maximum, mean, standard deviation, variance, skew, kurtosis, percentiles, etc.
- May need to separate traffic bursts
  - Network packets occurring together within a threshold of time
  - Traffic bursts may encompass multiple flows

Let's classify some apps!

Feature set

Total Packets	Total Bytes	Max Size	Min Size	Mean Size	Std. Dev Size	Percentile 10th	.....	Percentile 90th	CLASS

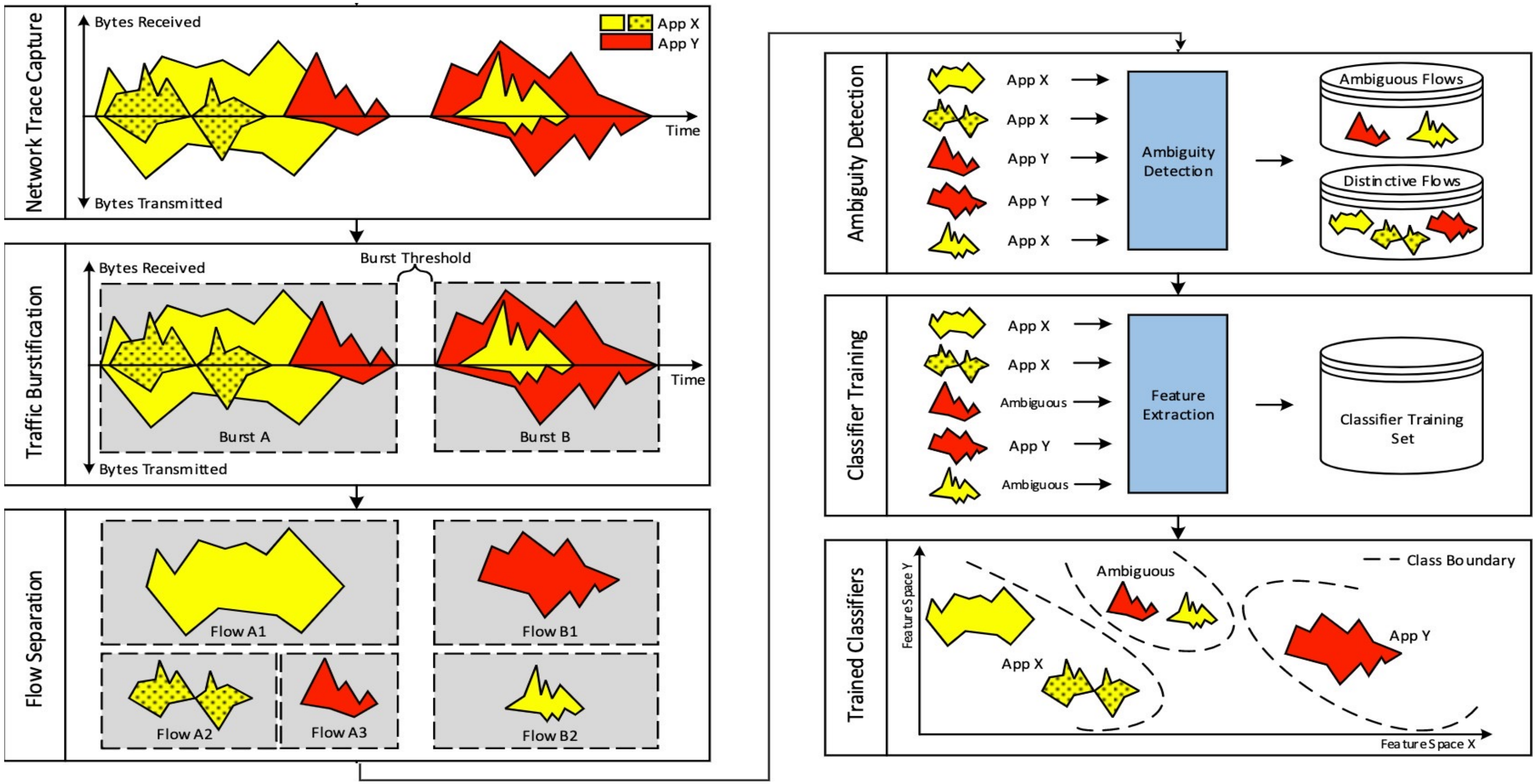
Training data

	Total Packets	Total Bytes	Max Size	Min Size	Mean Size	Std. Dev Size	Percentile 10th	.....	Percentile 90th	CLASS
S_{T1}	1405	123400	980	60	700	43	125	.....	948	Twitter
S_{Tn}	1566	134050	1250	60	842	54	143	.....	1014	Twitter
S_{I1}	2864	236544	1204	60	1024	64	92	.....	1140	Instagram
S_{In}	3264	286458	1280	60	1120	82	104	.....	1220	Instagram

New data sample

Total Packets	Total Bytes	Max Size	Min Size	Mean Size	Std. Dev Size	Percentile 10th	.....	Percentile 90th	CLASS
1479	125382	1240	60	792	56	142	.....	1002	**???**

Use case: Identification of mobile applications



- Taylor et al., IEEE TIFS ’17

Use case: Measuring video QoE

- Majority of video traffic is delivered over adaptive bitrate
  - A video is encoded in multiple resolutions and split into chunks of variable length
  - Clients continuously fill a buffer of chunks, where ensuing chunks are based on network conditions

- DPI solutions can no longer be used to extract meaningful QoE metrics
  - e.g., initial delays, playback stalls frequency, resolution switch

Use case: Measuring video QoE (cont)

- Features extracted from encrypted traffic guide the models to detect quality impairments
  - Able to detect stalls, average quality, and video quality adjustments

Network Features	Ground Truth (URI)
minimum RTT	chunk resolution
average RTT	stall count
maximum RTT	stall duration
Bandwidth-delay product	video session ID
average bytes-in-flight	
maximum bytes-in-flight	
% packet loss	
% packet retransmissions	
chunk size	
chunk time	

- Dimopoulos et al., IMC ’16

Network Security

Malware Detection

- Traditional network-based malware detection relies on unencrypted data
  - Heavy use of deep packet inspection
  - e.g., for signature-based detection over packet payloads
- No longer useful to detect viruses or data exfiltration
- Encrypted traffic analysis helps us to identify:
  - Malware communications towards C&C servers
  - Unusual network traffic patterns in the network

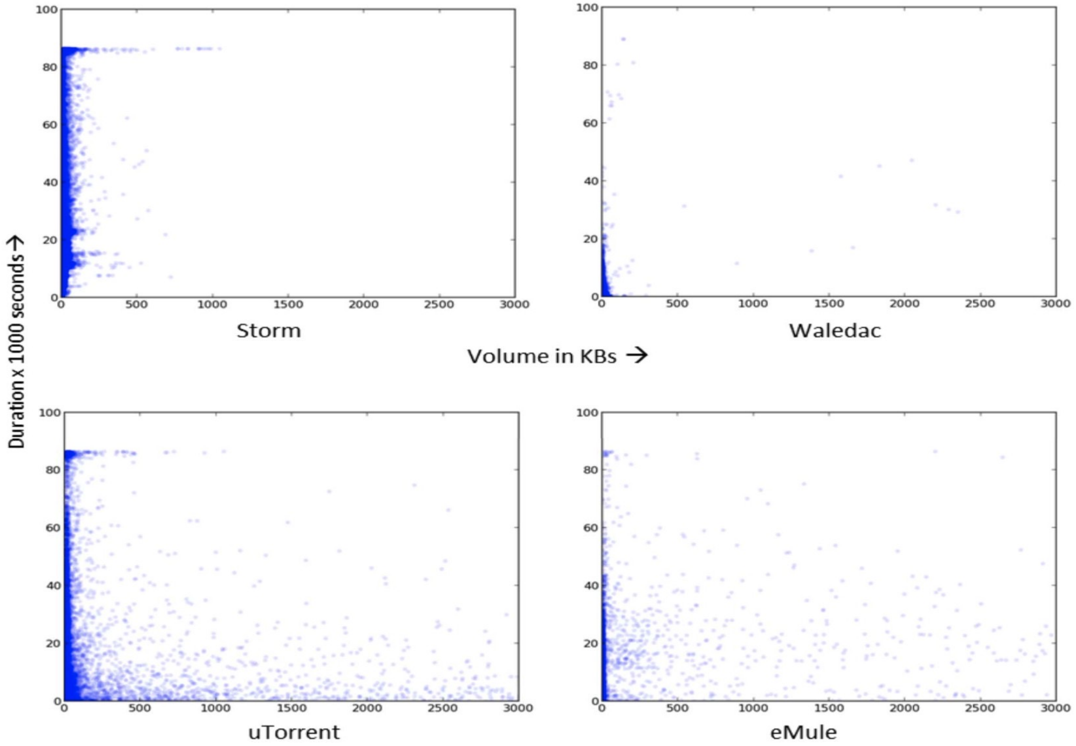
Malware Detection

- Malware classification:
  - Build a model out of legitimate / malicious network activity
  - Leverage “fingerprints” of legitimate / malicious behaviour
  - What if a new malware stream emerges?

- Anomaly detection:
  - Build a model for legitimate traffic and flag strange behavior
  - Via one-class learning or clustering
  - What if legitimate behavior changes over time?

Use case: P2P botnet detection

- Can we pinpoint interactions between bots and C&Cs?
  - Tend to be low-volume and long-standing vs. benign P2P apps



Narang et al., IEEE SPW '14

Use case: P2P botnet detection

- Flows
  - P2P applications (including botnets) randomize port numbers
  - The usual flow definition leads to the generation of multiple flows out of what can be a continued interaction between two peers

- Super-flows
  - Aggregate multiple flows between two IPs into a super-flow
    - What if two IPs have benign and malicious flows between them?

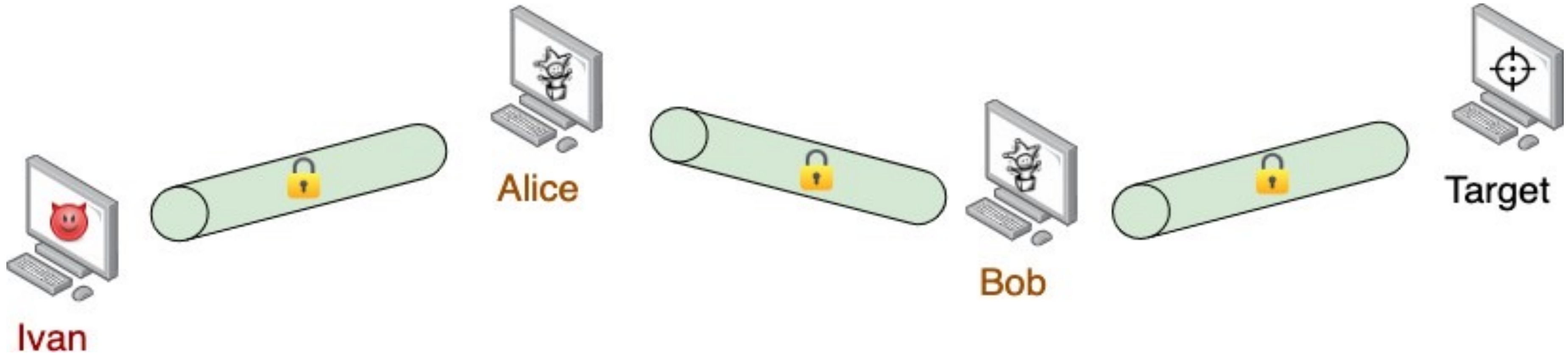
Narang et al., IEEE SPW ’14

Use case: P2P botnet detection

- Conversations
  - Start by clustering flows:
    - Protocol, packets per second, avg. payload size
  - Create conversations from flows placed within the same clusters
  - Finally, classify conversations as malicious or benign based on:
    - Duration of the conversation
    - Number of packets exchanged
    - Volume of data exchanged
    - Median of packet inter-arrival times
- This approach was also shown effective for detecting previously unseen botnets!

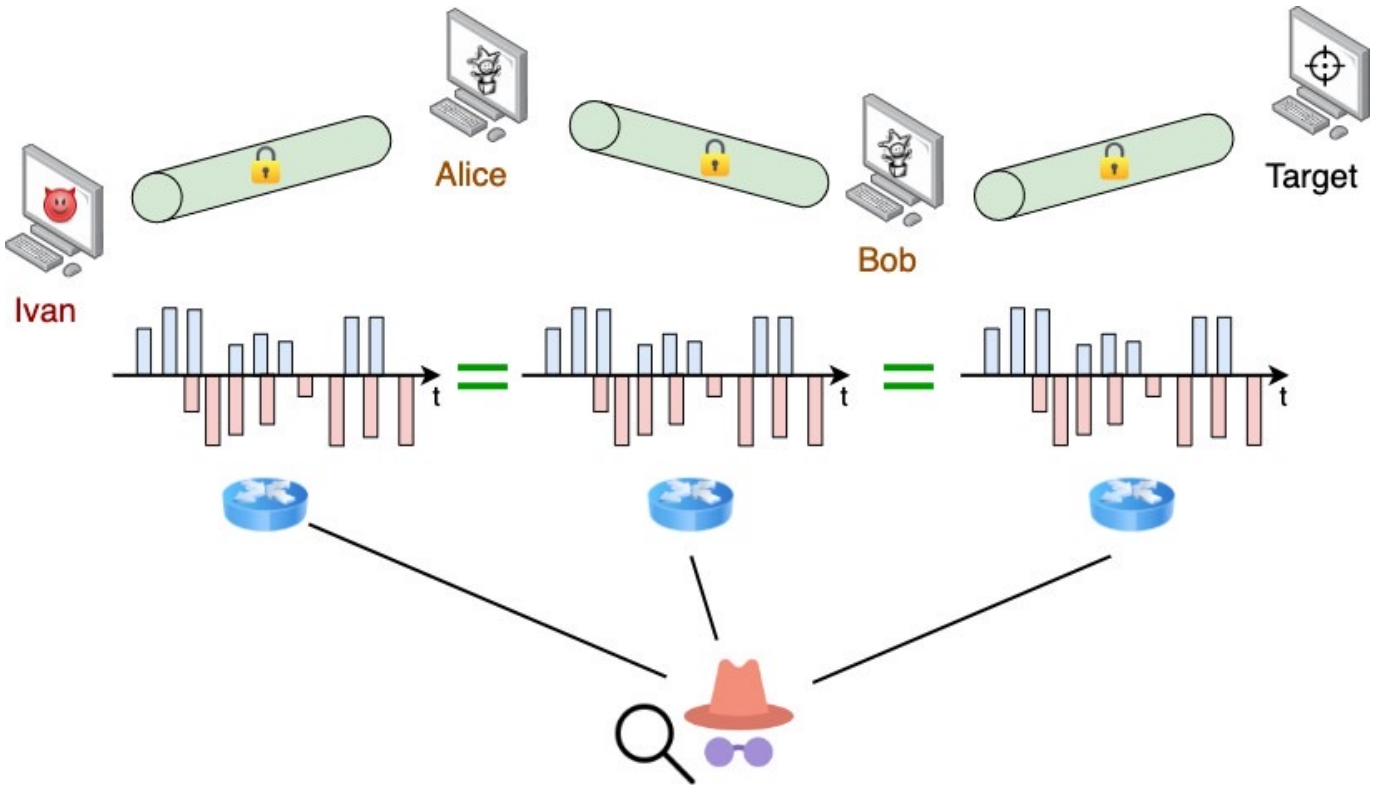
Stepping stones

- An attacker can hide its identity by using other machines as intermediaries (i.e., stepping-stones)
  - e.g., by hopping through compromised machines or by using Tor



Traffic Correlation

- Detection of stepping-stones
  - Attempt to match (roughly) the same sequence of packets at different network vantage points



Difficulties in Performing Traffic Correlation

- In practice, flow observations will not be an exact match
  - Due to network imperfections
    - Packet delays, jitter, loss
- Due to countermeasures
  - Chaff and delay injection at intermediate nodes, padding
- Traffic correlation algorithms must account for small differences between each flow observation

$$\delta_t(C, C') = \log\left(\prod_{k=1}^{K} |T_k(C', t) - T_k(C, t)|\right)$$

Staniford-Chen and Heberlein, IEEE S&P ’95

Privacy Breaches

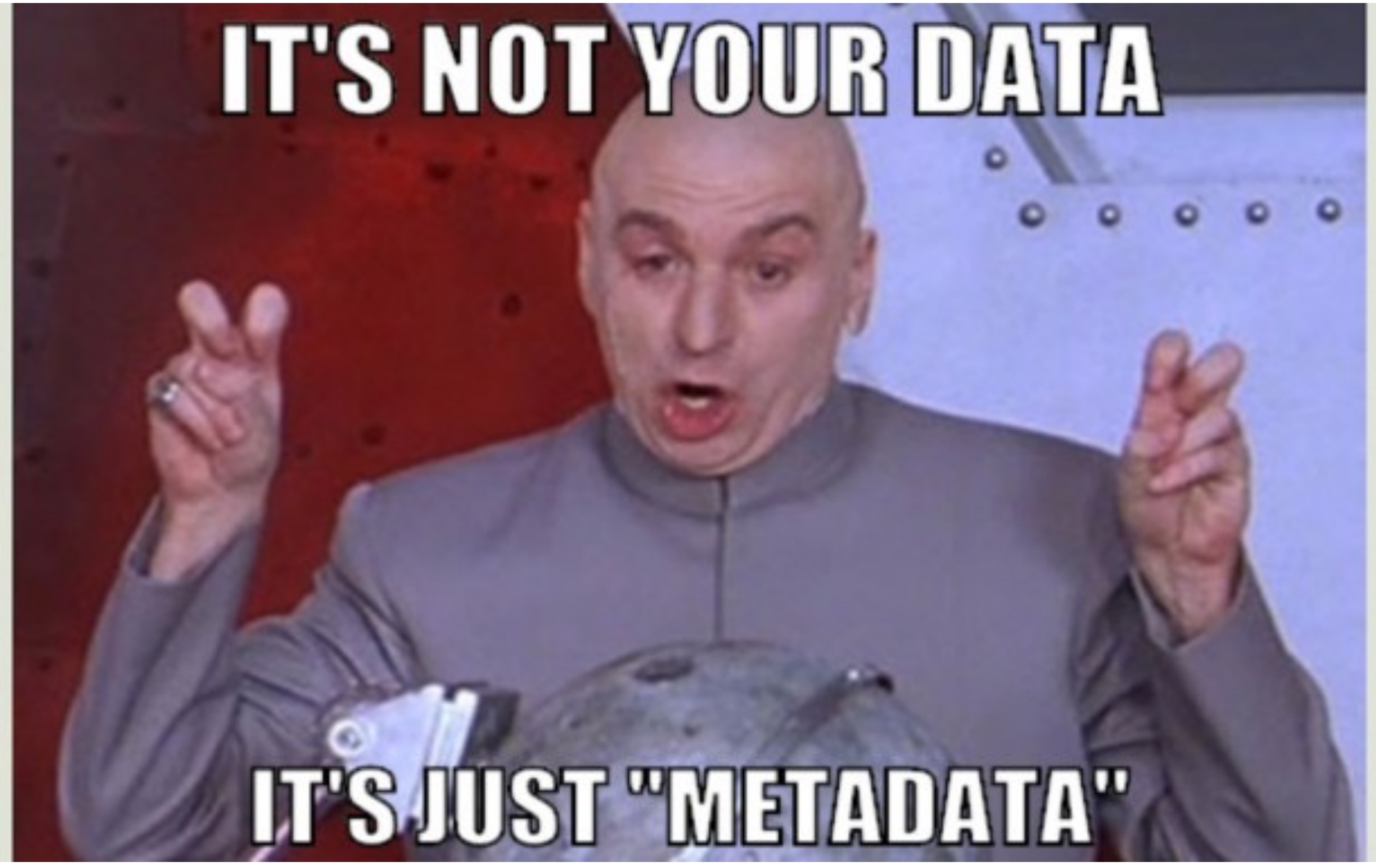
Nefarious uses of encrypted traffic analysis

- One would assume that encryption is all that is needed to securely communicate over the Internet

- Unfortunately, encryption does not hide traffic patterns

- Traffic analysis can be weaponized to breach users' privacy

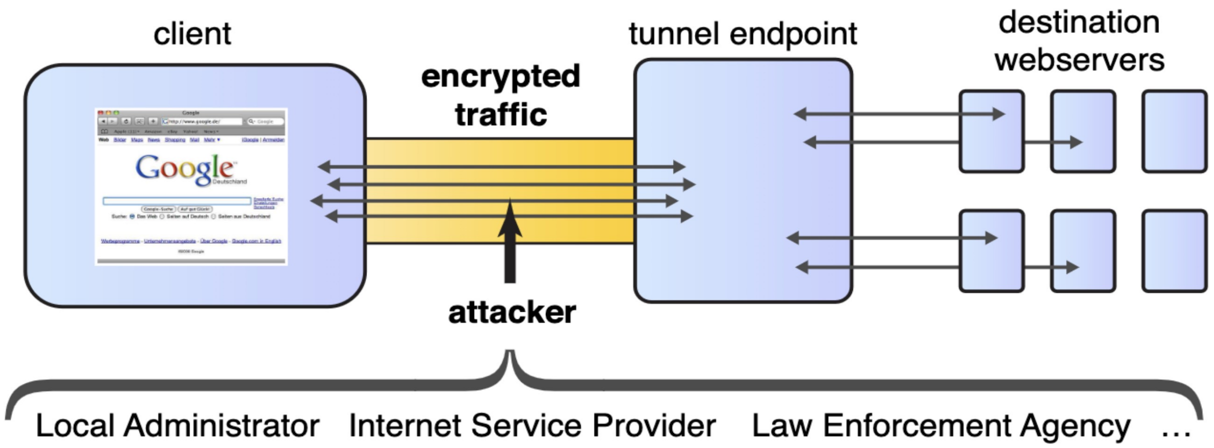
Metadata is not your data. Or is it?



(Dr. Evil making you think metadata is useless)

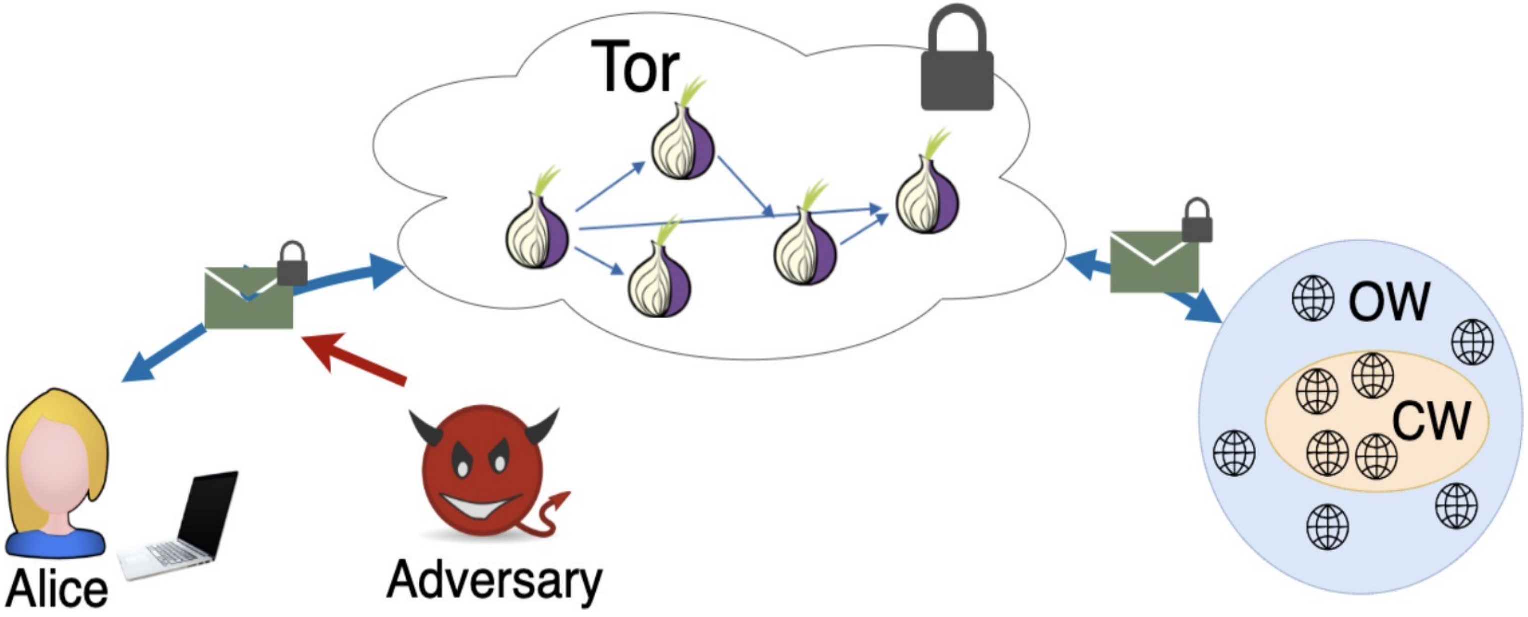
Website fingerprinting over VPNs

- VPNs are advertised as the “holy-grail” of Internet security
  - Passive adversaries can uncover which website is being visited
  - By building traffic fingerprints and using a classifier
- The attack can be launched in two settings:
  - Closed-world Open-world



Website fingerprinting over Tor

- The Tor network can be seen as one “big VPN node”
  - Tor exchanges data in fixed-size cells
  - But packet direction and timing still leaks information



Website fingerprinting over Tor

- Features based on different traffic representations have been used to launch website fingerprinting attacks on Tor
  - Directional representation - Rimmer et al., NDSS ’18
  - Directional + timing representation - Saidur Rahman et al., PoPETs ’20

Rimmer et al. (Directional representation)

+1	-1	+1	+1	-1	-1	-1	+1	+1	yahoo.com
+1	+1	-1	-1	-1	-1	+1	-1	+1	google.com

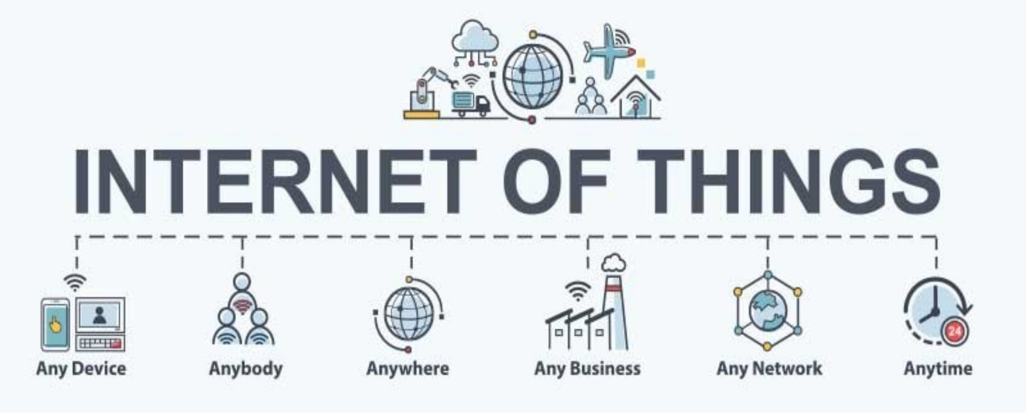
Saidur Rahman et al. (Directional + timing representation)

+0.02	-0.01	+0.03	+0.01	-0.03	-0.04	-0.01	+0.01	+0.02	yahoo.com
+0.01	+0.04	-0.02	-0.01	-0.01	-0.01	+0.02	-0.01	+0.02	google.com

Fixed-size input to neural network

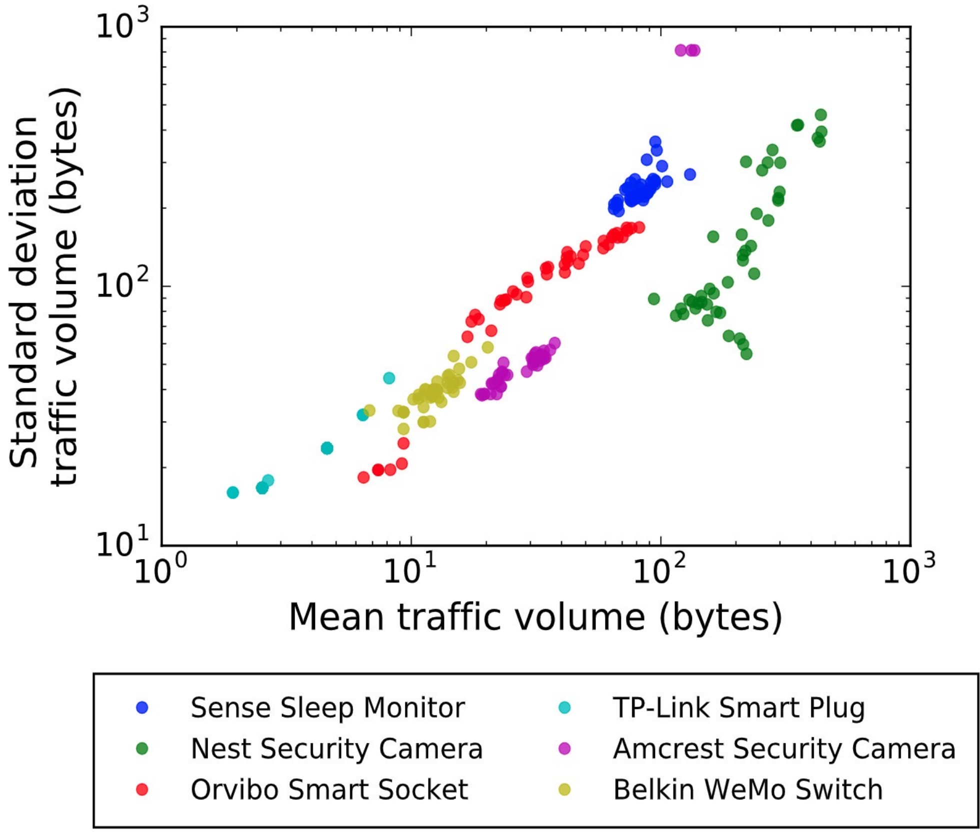
IoT device fingerprinting

- Passive network observers can potentially analyze IoT network traffic to infer sensitive details about users
  - Does this user have a blood monitor? A security camera? A sex toy?
- DNS queries associated with each encrypted flow often contain the device manufacturer name
  - We can even pinpoint the exact device



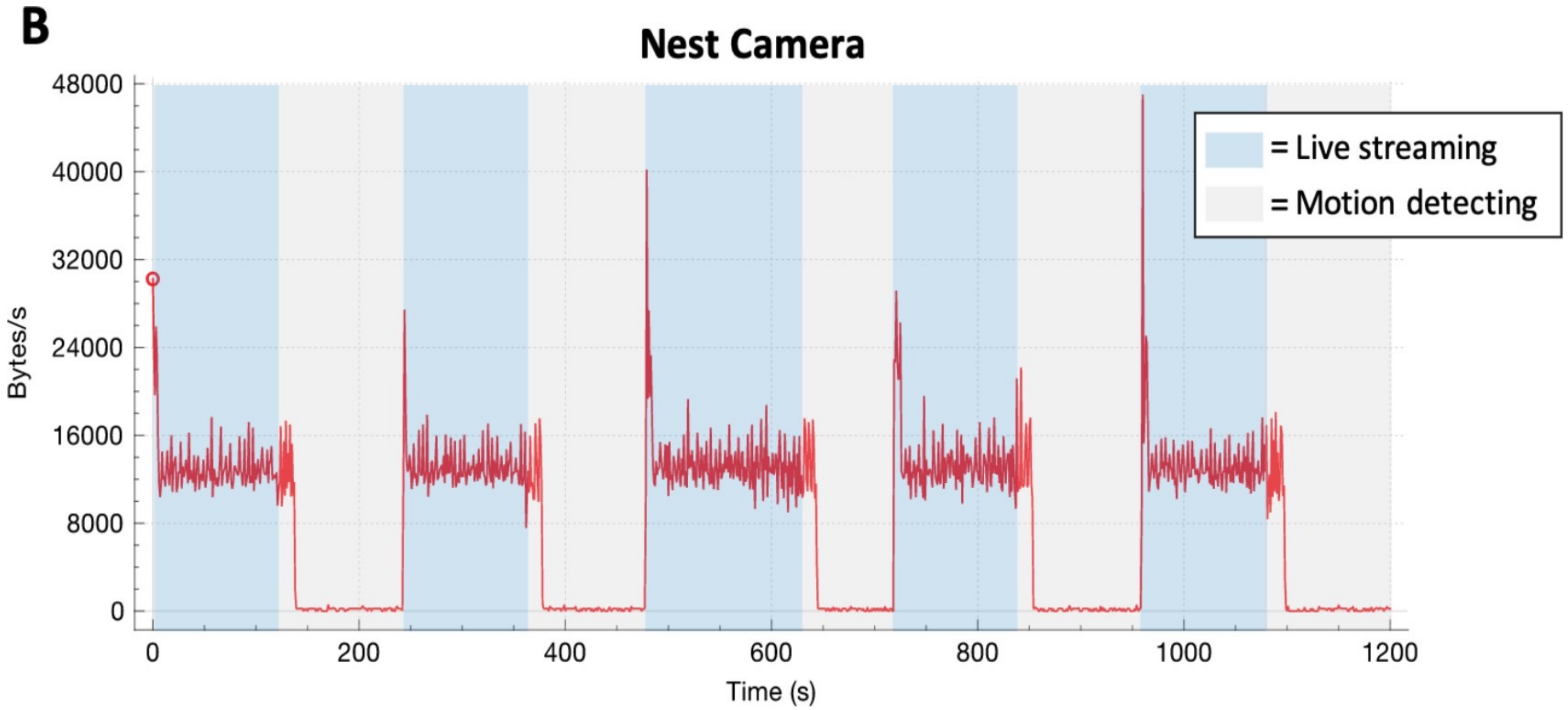
Distinguishing devices through traffic volume

- Rather simple volumetric features allow us to identify IoT devices (Apthorpe et al., ConPro ’17)
  - Once a device is identified, one can also infer its state



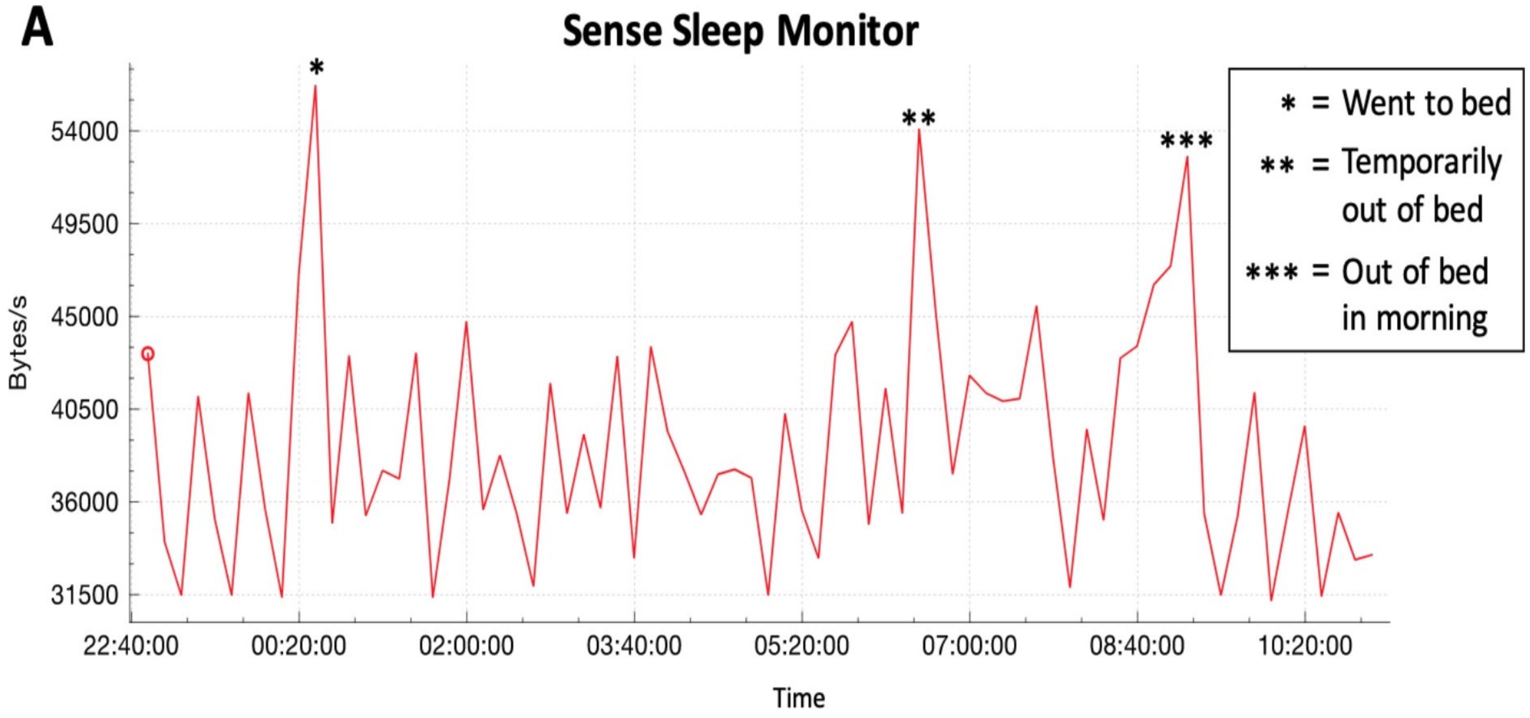
Motion sensor - Nest indor security camera

- Easy to discern when the camera picks up movement
  - Easy to discern when nobody's home?



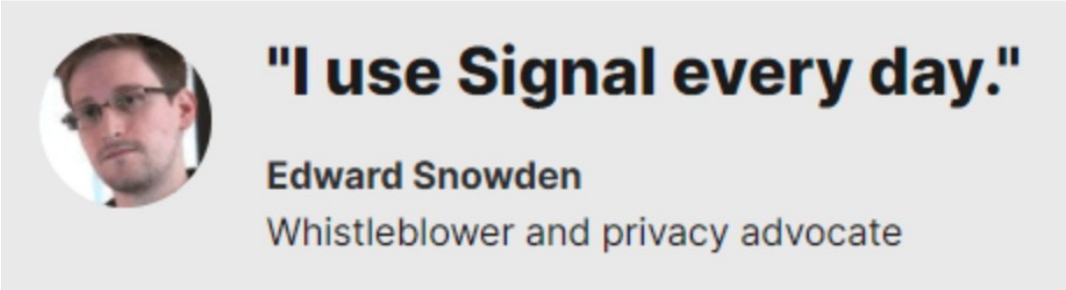
Sleep tracker example - Sense sleep monitor

- Easy to discern when a user goes to bed and wakes-up
  - Easy to discern if a burglar should leave the crime scene?



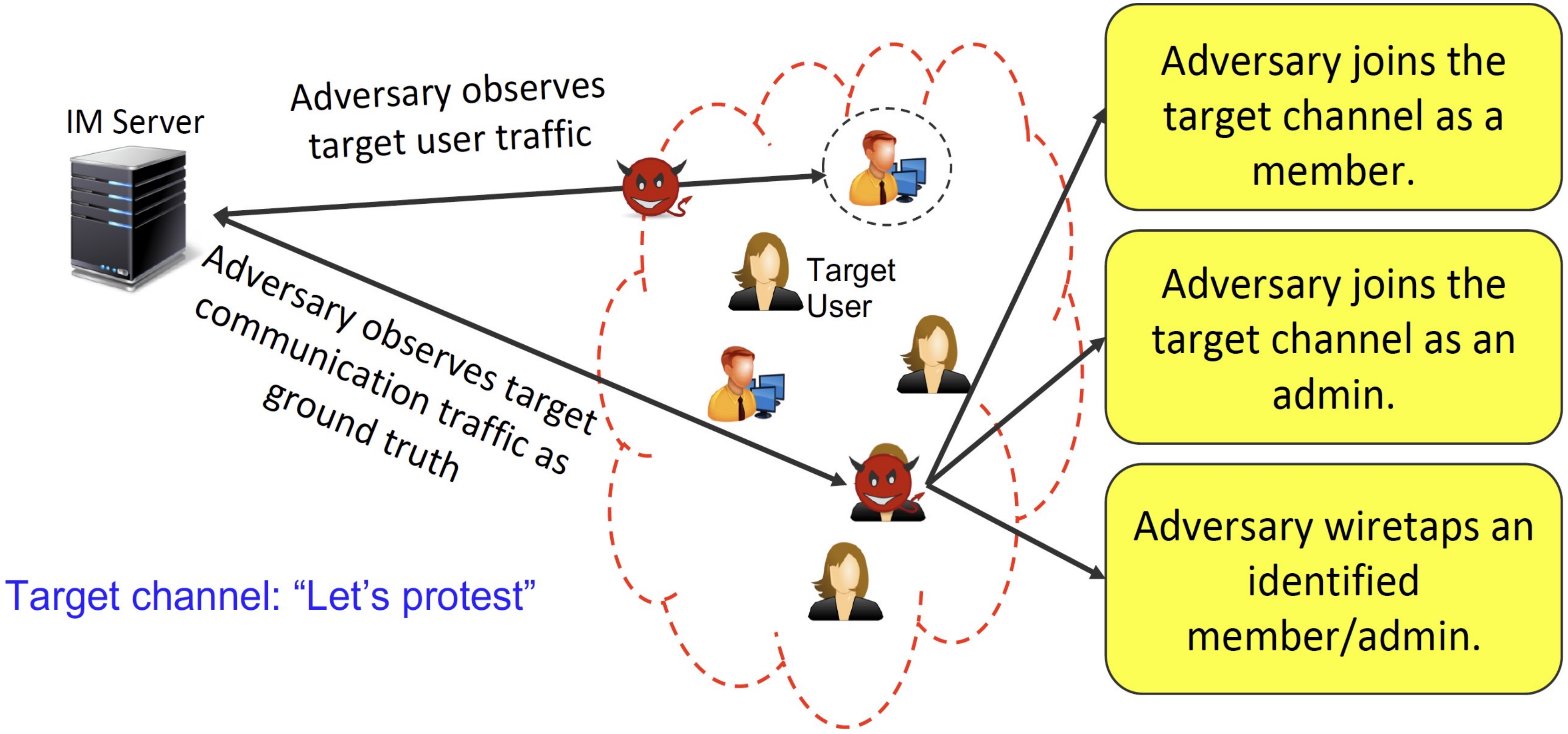
Practical attacks against IM applications

- IM applications are extensively used to exchange potentially sensitive content securely
    - Remember OTR and Signal
    - Oftentimes used to exchange politically and socially sensitive content
    - Governments and corporations may be interested in identifying participants of IM conversations
        - e.g., target whistleblowers or dissidents



Adversary aims to uncover group membership

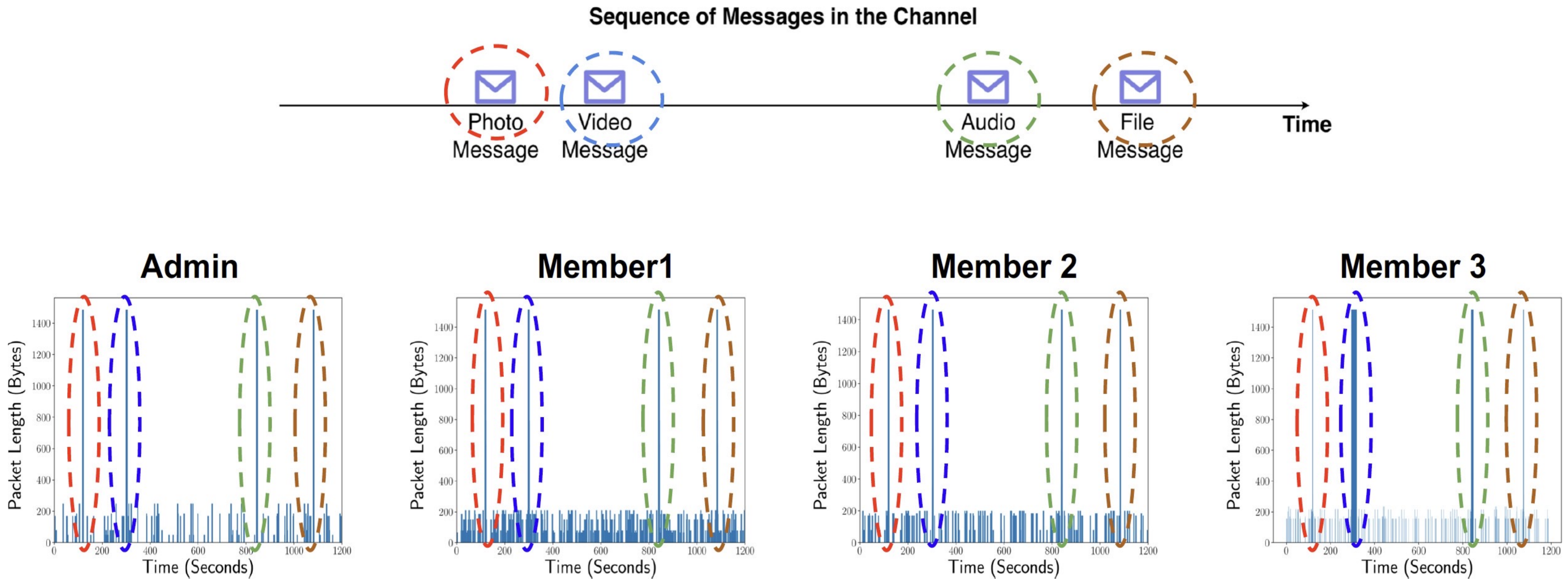
- How can the adversary set up the attack?



Bahramali et al., NDSS ’20

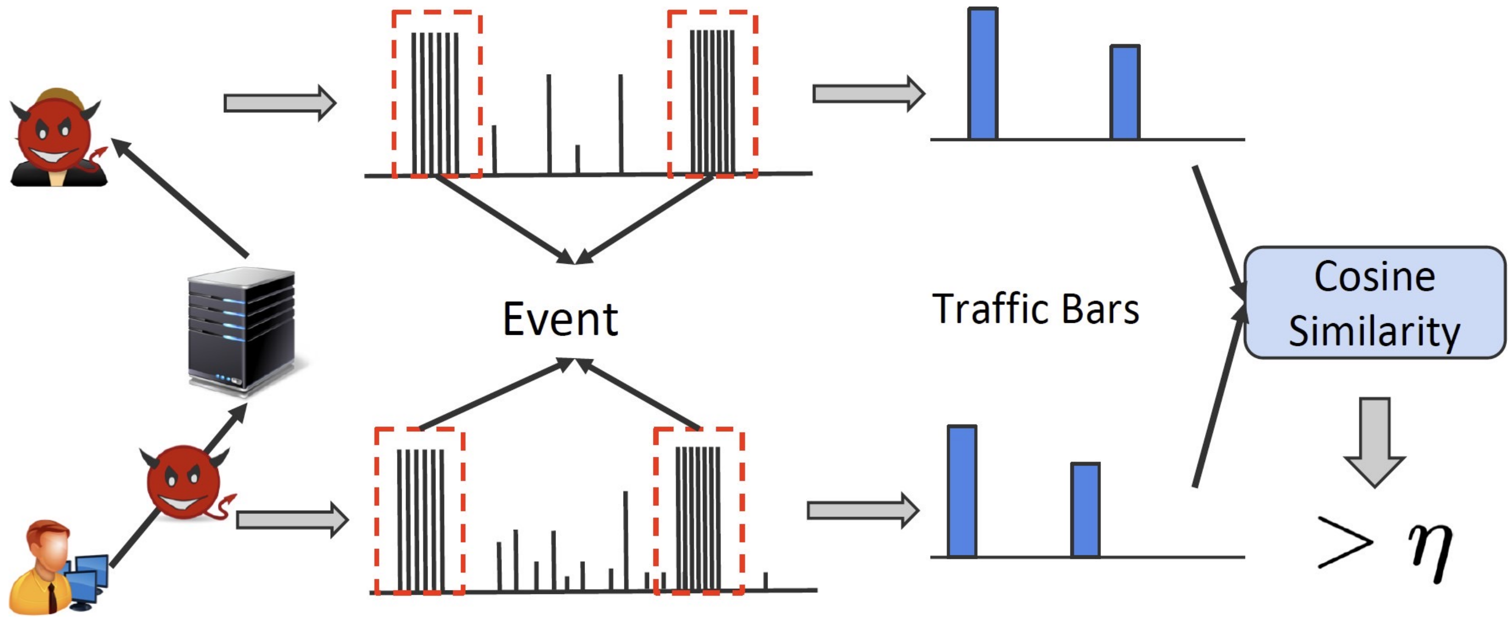
Looking for messaging events

- Messaging events have different fingerprints



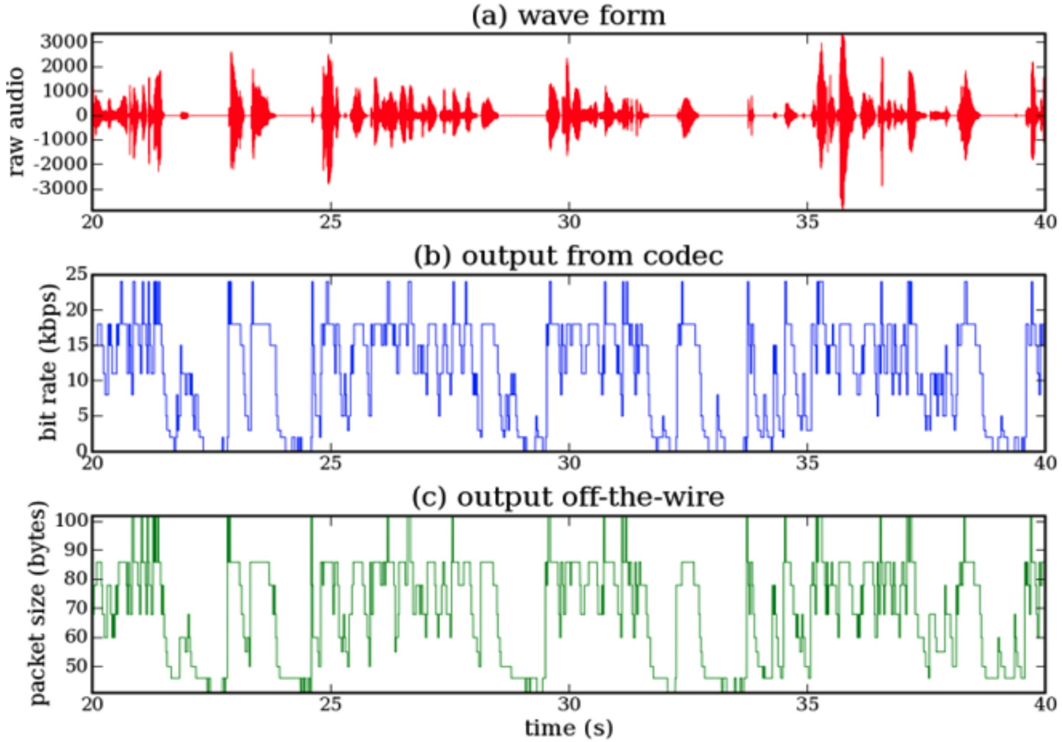
Matching messaging events fingerprints

- Extract meaningful events and compare similarity
- Attack succeeded against Signal, Telegram, and WhatsApp!



VoIP eavesdropping

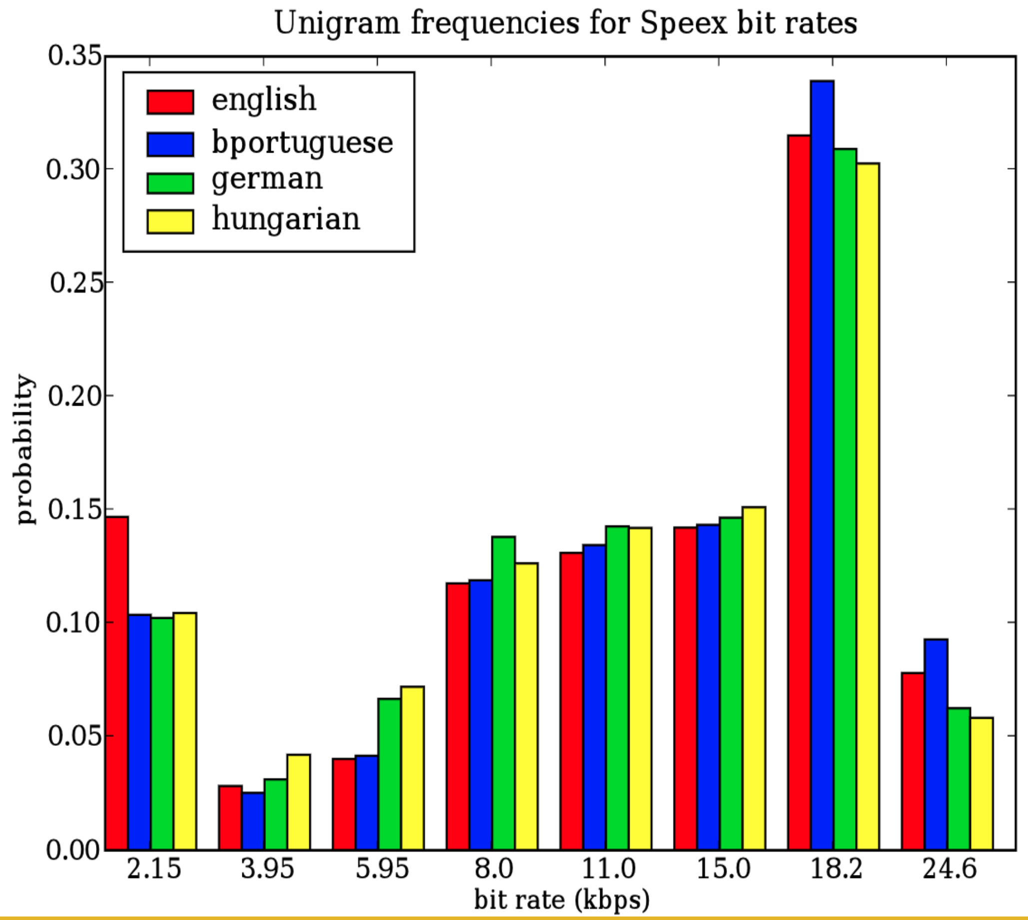
- Encrypted packet patterns resemble VBR codec bitrates
    - Can we infer meaningful semantics from the transmission of encrypted audio frames?



Wright et al., USENIX SEC ’07

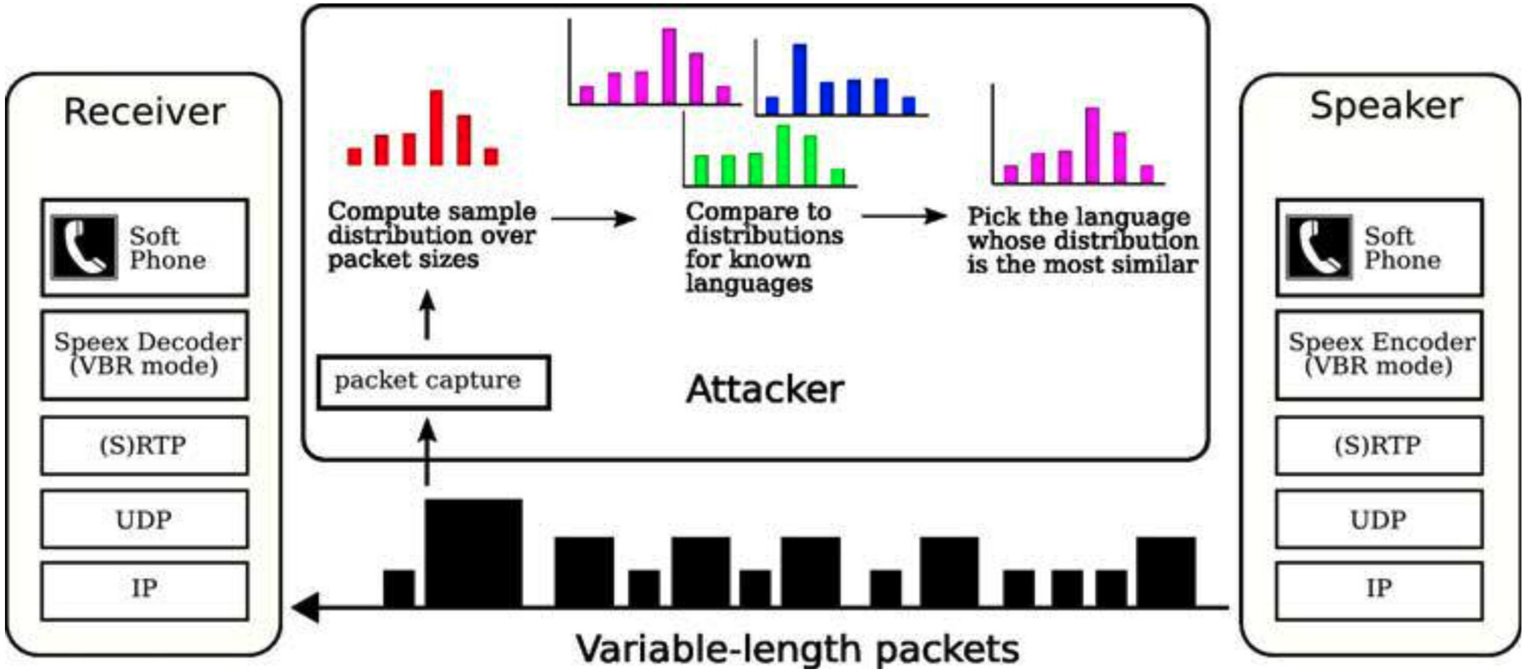
Noticeable (coarse-grained) differences

- Maybe we can identify the language being spoken?
  - Languages have different bitrate frequencies



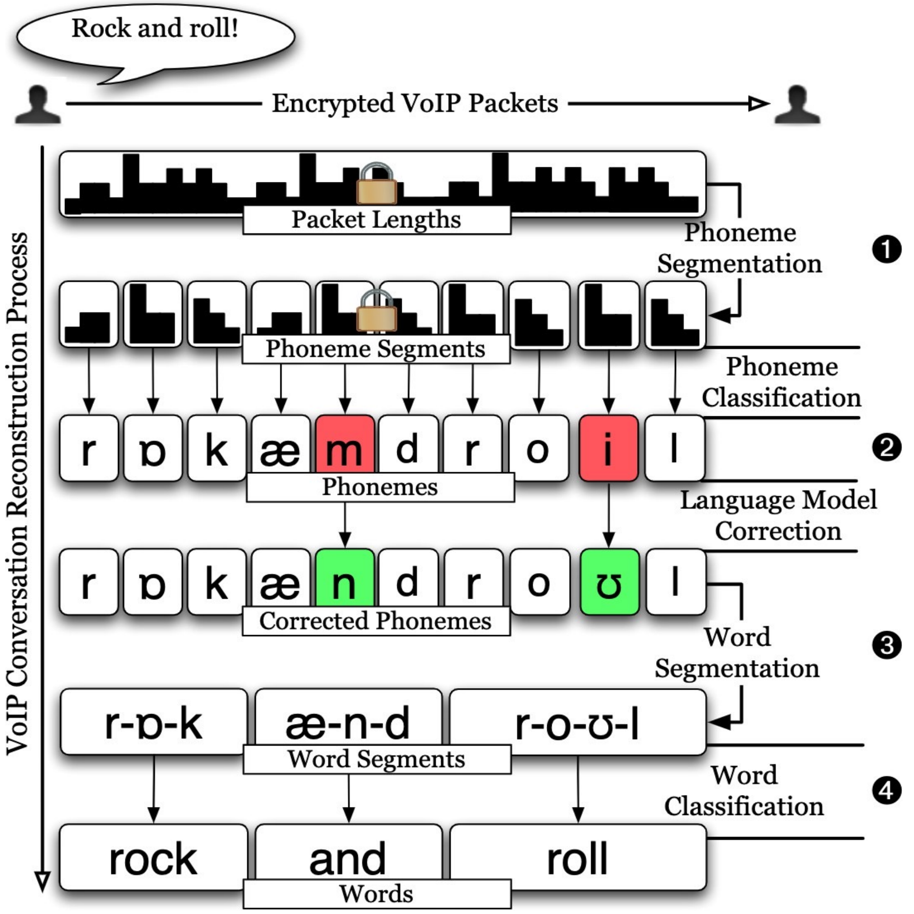
How to distinguish different languages?

- Compute distance between probability distributions
  - Samples from same language have similar distribution
  - Compute packet size n-grams for even better results
    - Given sequence 10, 20, 30, 15 –> {(10, 20), (20, 30), (30, 15)}



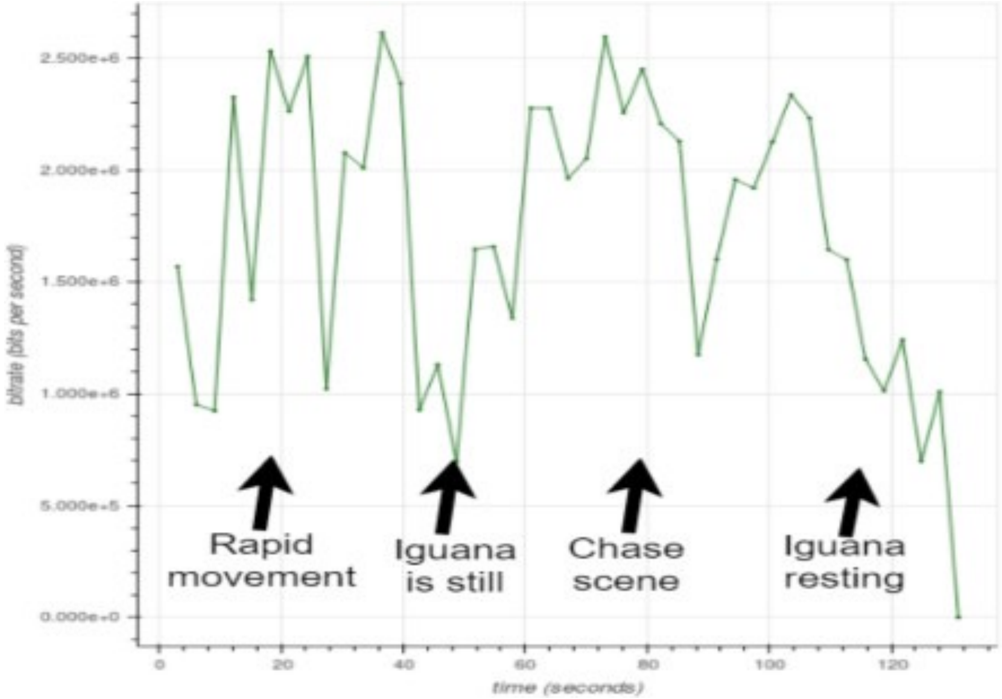
Noticeable (fine-grained) differences

- Can we segment packet size sequences into phonems?
  - If so, we can recover approximated transcripts



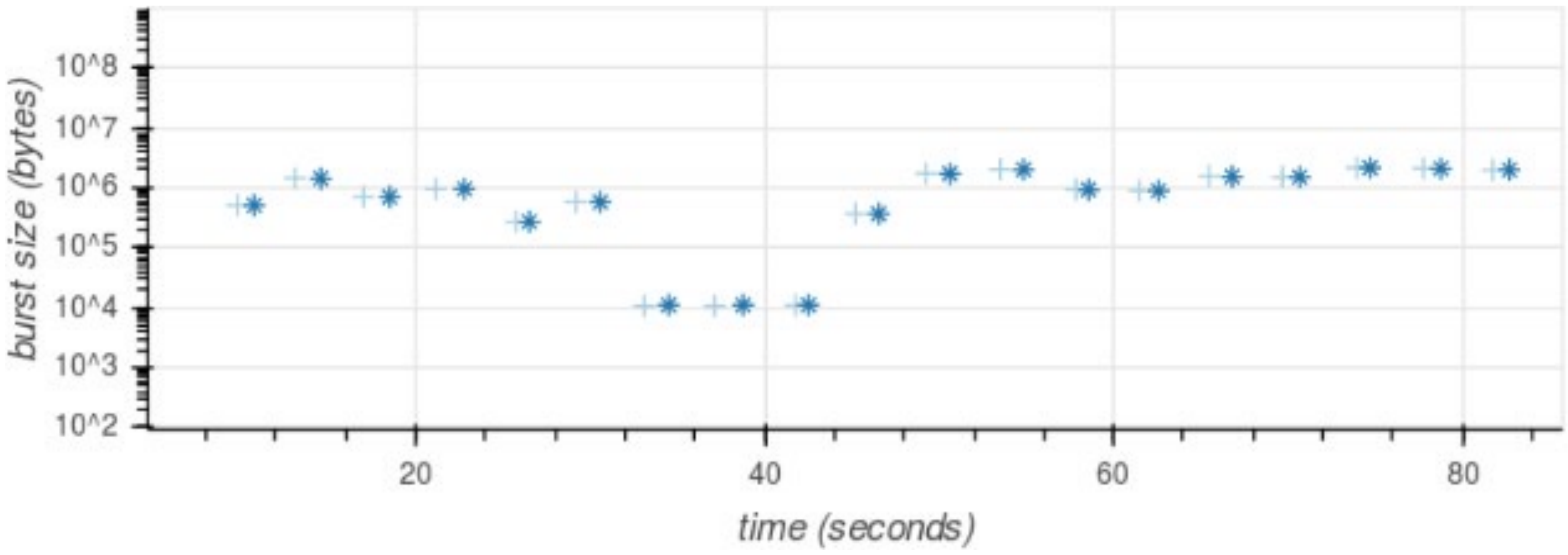
Video re-identification

- At this point, you've probably guessed it, traffic analysis can also be used to uncover which videos you are streaming
    - The bitrate of VBR video sequences also leaks some information



Re-identification of Netflix video streaming

- Burst sizes of a streamed scene of “Reservoir Dogs”
  - Very similar, even when watched over different networks



Schuster et al., USENIX SEC ’17

Countermeasures to traffic analysis

- Introduce padding
- Add chaff traffic
- Shape traffic (look like something)
- Aggregate traffic (e.g, multiplex over single connection)
- Split a single connection across multiple networks

- Main trade-off to consider is overhead
    - Achievable throughput
    - Spent bandwidth

Schuster et al., USENIX SEC ’17