# A Principled Approach to Measuring the IoT Ecosystem


## Deepak Kumar

### Advised By: Michael Bailey

**Committee: Michael Bailey, Nikita Borisov, Adam Bates, Gang Wang, Zakir Durumeric**

# Internet of Things… are here!

## It’s 2020.



# To this point, there is little work on measuring the network capabilities and behaviors of IoT devices deployed in practice

# Challenges to IoT Measurement

## Vantage Points

- Vantage Point – Where you draw the measurement from
  - Home networks: Many IoT devices are behind NATs, requiring a local network to study devices
  - Public IPv4: Public fingerprint of a device is often the only perspective researchers have for security analysis

# Challenges to IoT Measurement

## Techniques

- Techniques – How you conduct the measurement
  - Active: Probe devices (e.g., send TCP SYN) to learn of device capabilities
  - Passive: Observe devices (e.g., network tap, darknet) to learn their behaviors

**Thesis Statement: Network measurements of IoT devices drawn from an external or internal vantage point using only active or passive techniques present a biased view of network services in the IoT ecosystem.**

# Thesis Outline

| | **Active Measurement** | **Passive Measurement** |
|---|---|---|
| **Internal Vantage Point** | All Things Considered | IoT Inspector |
| | IoT Inspector | |
| **External Vantage Point** | Understanding the Mirai Botnet | IoT Inspector |

# Thesis Outline

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# All Things Considered – Recap

- Partnered with Avast antivirus to measure IoT devices inside home networks
- Quantified the devices, vendors, and offered services of devices inside 16M homes containing 83M devices from around the world through active, internal scans
- IoT devices are widespread: more than half of households have at least one IoT devices in three regions, and 66% of homes in North America have at least one IoT devices
- 67.5% of IoT devices supported at least one TCP- or UDP- based service based on active probing
- Regions have unique device type and vendor preferences, highlighting a fractured and heterogeneous ecosystem

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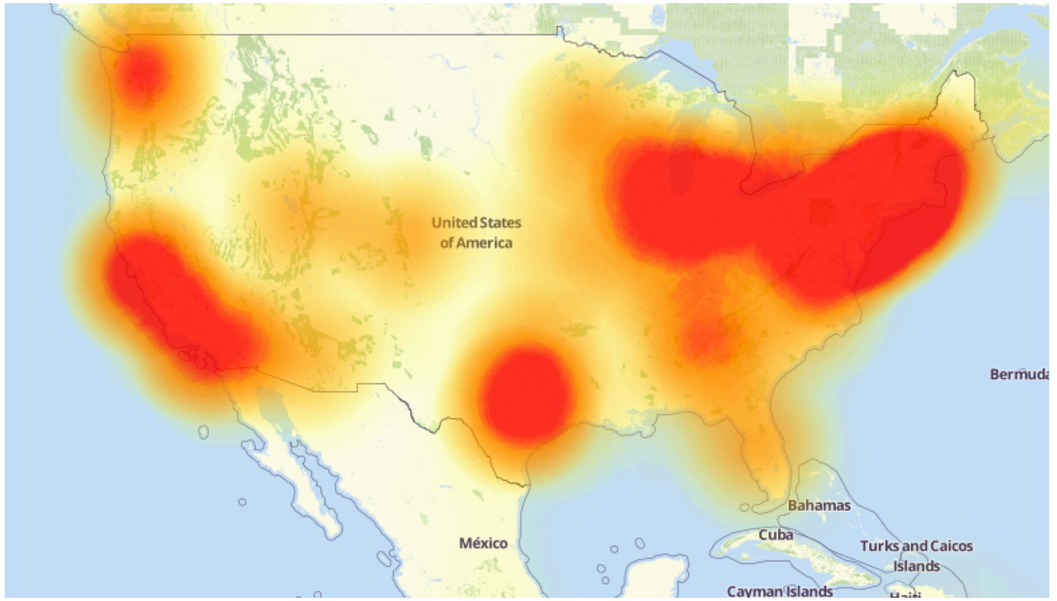
# Cyberattack Knocks Out Access to Websites

Popular sites such as Twitter, Netflix and PayPal were unreachable for part of the day

**Here are the 61 passwords that powered the Mirai IoT botnet**

That time your smart toaster broke the internet

**How 1.5 Million Connected Cameras Were Hijacked to Make an Unprecedented Botnet**



# Studying the Mirai Botnet

| Data Source | Size |
|---|---|
| Network Telescope | 4.7M unused IPs |
| Active Scanning | 136 IPv4 scans |
| Telnet Honeypots | 434 binaries |
| Malware Repository | 594 binaries |
| Active/Passive DNS | 499M Daily RRs |
| C2 Milkers | 64K issued attacks |
| Krebs DDoS Attack | 170K attacker IPs |
| Dyn DDoS Attack | 108K attacker IPs |

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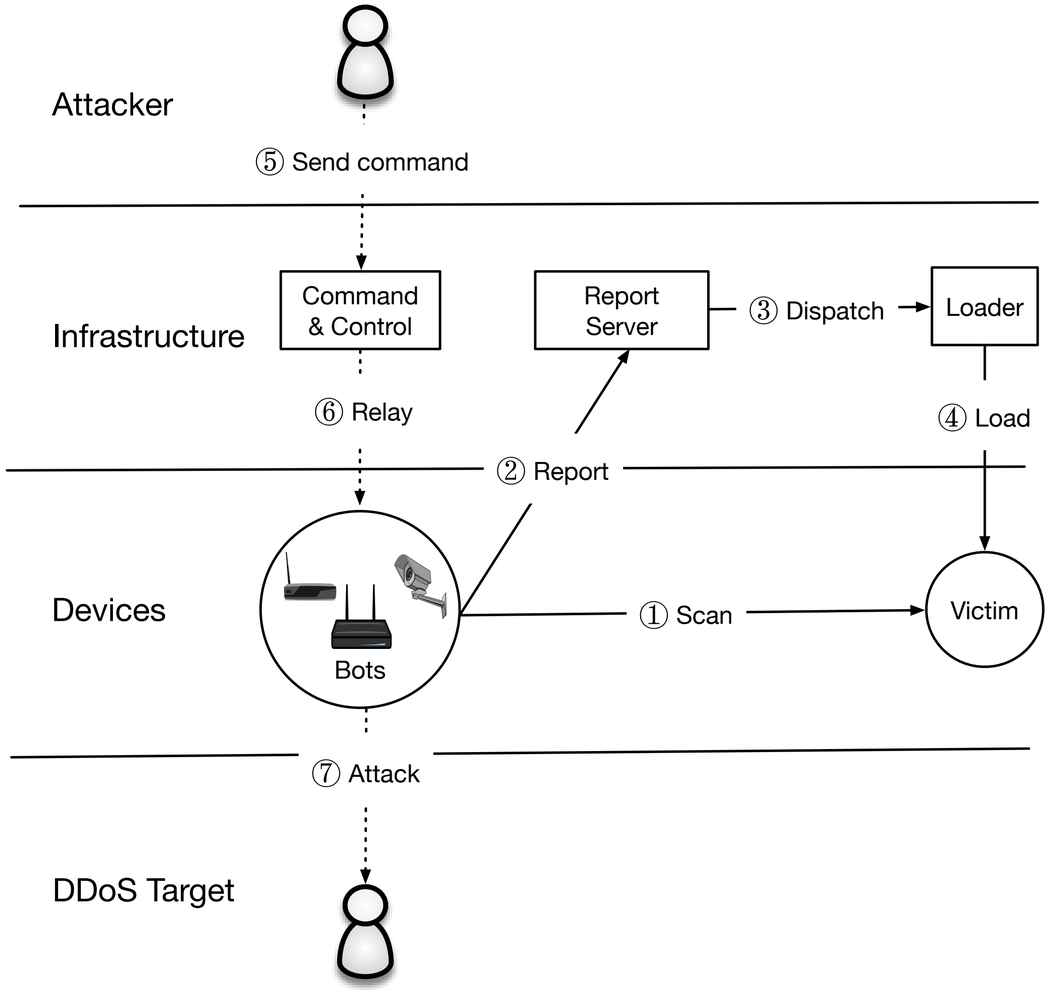
# How Did Mirai Work?



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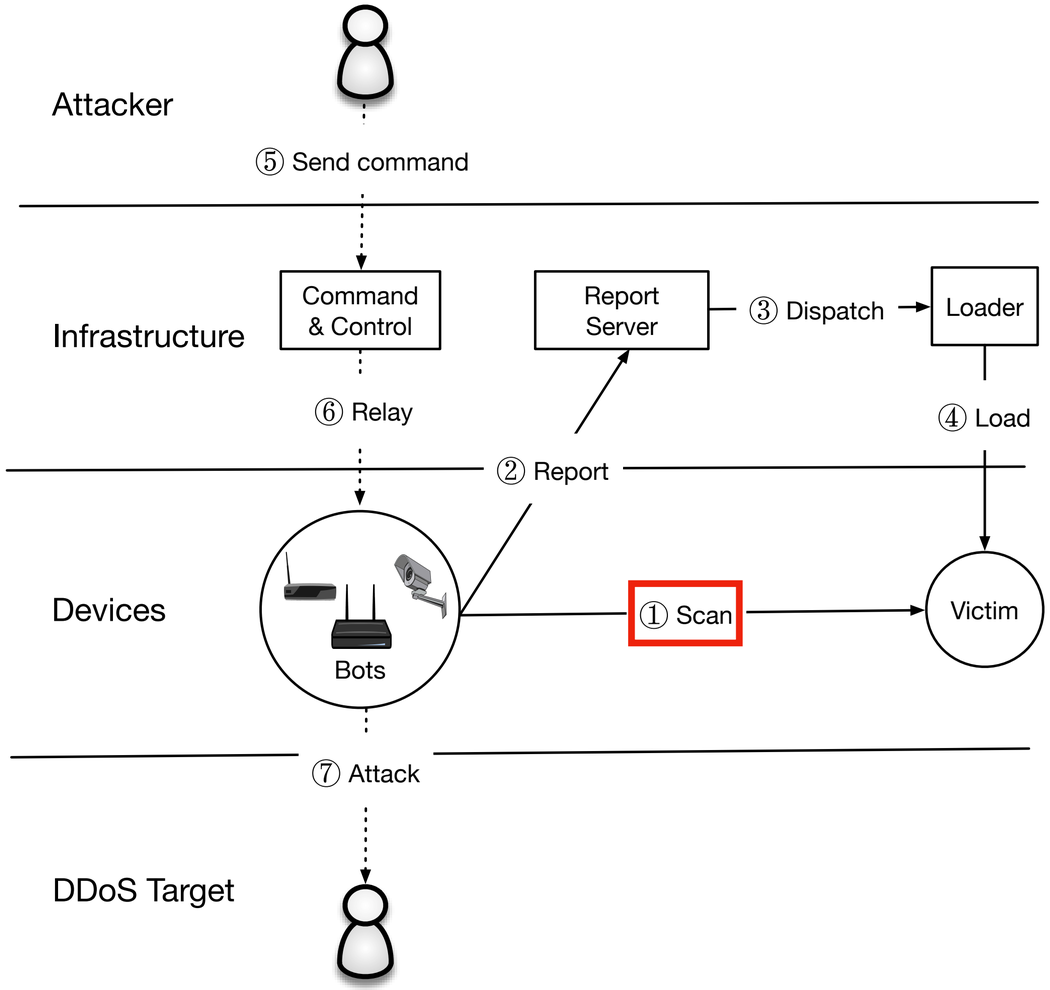

# What Devices did Mirai Infect?

# Active, External Scanning for Device Identification

- We leveraged active, external scans from Censys for five application layer protocols
- Our passive darknet identified 1.2M IP addresses that were scanning with the Mirai signature with 1.8M banners total
- Used regular expressions generated by Nmap project and custom rules for HTTPS, CWMP
- Identified either the device type, model, or vendor for 31.5% of IPs

| Protocol | Banners | Devices Identified |
|---|---|---|
| **HTTPS** | 342K | 271K (79.4%) |
| **FTP** | 320K | 144K (45.1%) |
| **Telnet** | 473K | 104K (22%) |
| **CWMP** | 506K | 35K (7%) |
| **SSH** | 150K | 8K (5.5%) |
| **Total** | 1.8M | 588K (31.5%) |

**Banner Identification per Protocol**

# Identified Devices

| CWMP | Telnet | HTTPS | FTP | SSH |
|---|---|---|---|---|
| Router (4.7%) | Router (17.4%) | Camera/DVR (36.8%) | Router (49.5%) | Router (4%) |
| | Camera/DVR (9.4%) | Router (6.3%) | Storage (1%) | Storage (0.2%) |
| | | Storage (0.2%) | Camera/DVR (0.4%) | |
| | | Other (0.3%) | Media (0.1%) | |
| Unknown (95.3%) | Unknown (73.1%) | Unknown (56.4%) | Unknown (49%) | Unknown (95.6%) |

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# Comparing Active Internal and Active External

- Collected IoT devices from Avast and Censys active scans on a single day, May 2, 2020
- Performed external device type identification using five protocols: HTTPS, CWMP, Telnet, SSH, FTP
- CWMP, Telnet most descriptive (by label), while HTTPS, CWMP offered on most devices
- Labeled 6.1M external IoT devices, 1.8M internal IoT devices

| Protocol | % IPv4 Responded | % IPs Labeled |
|---|---|---|
| **443/HTTPS** | 38.3% | 3.7% |
| **7547/CWMP** | 19.3% | 16.3% |
| **22/SSH** | 16% | 2.4% |
| **21/FTP** | 9.1% | 6.8% |
| **23/Telnet** | 2.4% | 20.6% |

**Labeled IPs per Protocol**

# Comparing Active Internal and Active External

| Service | Protocol | Internal Rank | External Rank |
|---|---|---|---|
| **80** | **HTTP** | 1 (72%) | 3 (15.9%) |
| **53** | **DNS** | 2 (37%) | 8 (3%) |
| **443** | **HTTPS** | 3 (30%) | 2 (27%) |
| **8080** | **HTTP** | 4 (14.5%) | 7 (5.8%) |
| **22** | **SSH** | 5 (12%) | 6 (7%) |
| **631** | **IPP** | 6 (10%) | 12 (0.35%) |

| Service | Protocol | Internal Rank | External Rank |
|---|---|---|---|
| **23** | **Telnet** | 7 (8.3%) | 5 (9.2%) |
| **21** | **FTP** | 8 (7.4%) | 4 (11.6%) |
| **7547** | **CWMP** | 9 (3.9%) | 1 (59%) |
| **8888** | **HTTP** | 10 (2.4%) | 14 (0.3%) |
| **8883** | **MQTT** | 11 (1.6%) | 37 (0%) |

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| Service | Protocol | Avast Rank | Censys Rank |
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| 80 | HTTP | 1 (37%) | 3 (15.9%) |
| 53 | DNS | 2 (37%) | 8 (1%) |
| 443 | HTTPS | 3 (32%) | 2 (17%) |
| 8080 | HTTP | 4 (14.5%) | 7 (5.8%) |
| 445 | SMB | 5 (13%) | 11 (0.4%) |
| 22 | SSH | 6 (12%) | 6 (7%) |
| 631 | IPP | 7 (10%) | 12 (0.35%) |

| Service | Protocol | Avast Rank | Censys Rank |
|---|---|---|---|
| 5000 | [illegible] | [illegible] | 5 (9.2%) |
| 21 | FTP | 9 (7.4%) | 4 (11.6%) |
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| 8888 | HTTP | 11 (2.4%) | 14 (0.3%) |
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**The distribution of services offered by externally available IoT devices differ from those offered by internally available IoT devices**

# Comparing Active Internal and Active External

| Device Type | % Internal Devices | % External Devices |
|---|---|---|
| **Router** | 61.9% | 92.3% |
| **Media** | 20.7% | 1.5% |
| **Work Appliances** | 6.7% | 0.7% |
| **Camera** | 3.4% | 0.6% |
| **Generic IoT** | 1.1% | 0.4% |
| **Storage** | 0.9% | 4.3% |

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| **Storage** | 0.9% | **4.3%** |

# Comparing Active Internal and Active External

## Devices that support SSH

| SSH | |
|---|---|
| **Internal** | **External** |
| Router (88.3%) | Router (97.9%) |
| Storage (4.2%) | Generic IoT (0.2%) |
| Work (3.2%) | |
| Camera (2%) | |
| Media (1.4%) | |

# Comparing Active Internal and Active External

## Devices that support HTTPS

| HTTPS ($r = 0.97$, $p < 0.01$) | |
|---|---|
| **Internal** | **External** |
| Router (73.3%) | Router (63%) |
| Work (19.9%) | Storage (24%) |
| Storage (3.4%) | Media (8%) |
| Media (1.6%) | Camera (2.8%) |
| Camera (1.3%) | Gen. IoT (2.2%) |

# Comparing Active Internal and Active External

## Devices that support HTTPS

| HTTPS (r = 0.97, p < 0.01) | |
|---|---|
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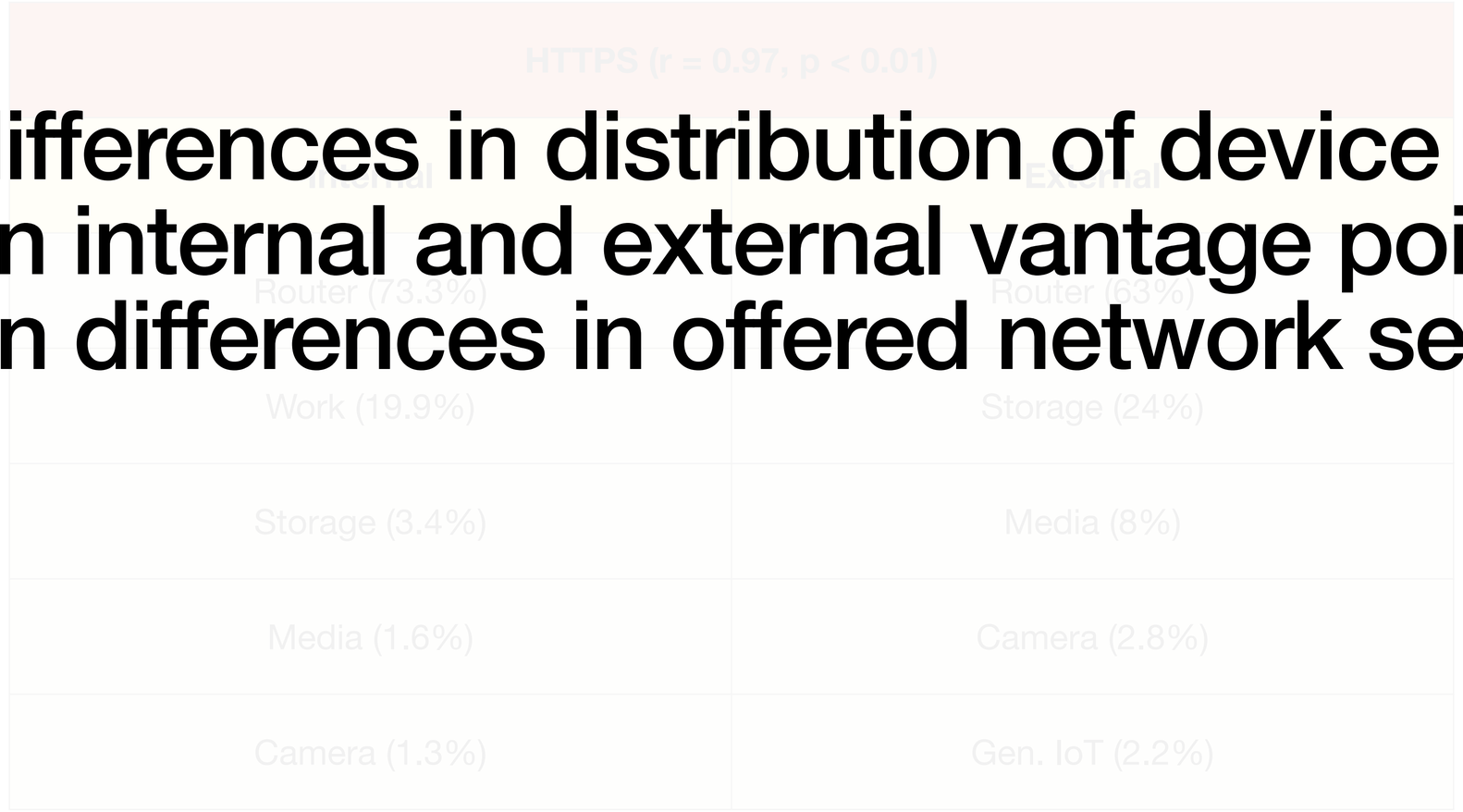
# Comparing Active Internal and Active External

## Devices that support HTTPS




**The differences in distribution of device types between internal and external vantage points can explain differences in offered network services**

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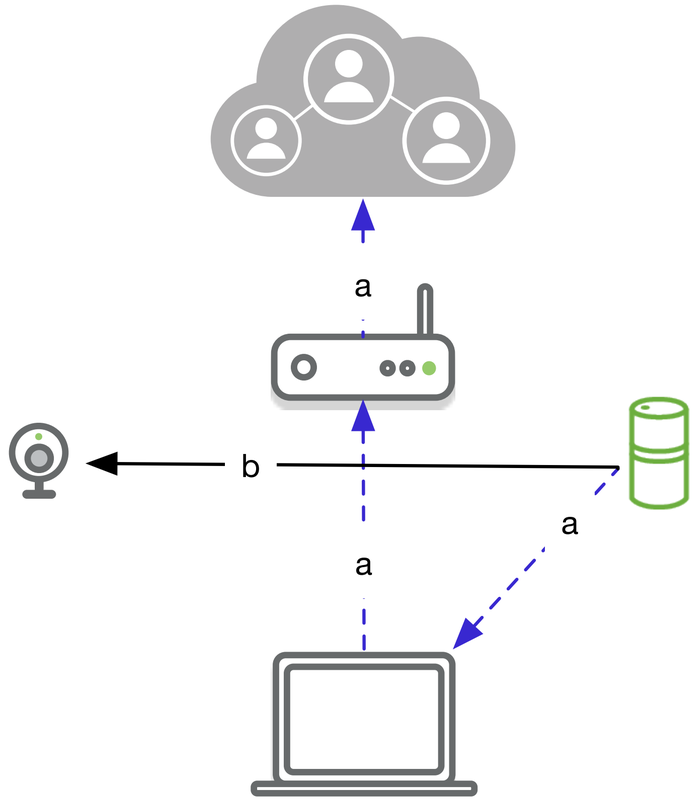
# IoT Inspector

- Princeton IoT Inspector is an open source tool that inspects IoT device communication to outside world to drive security and privacy insight
- Works by setting itself up as a voluntary man-in-the-middle between all devices and the gateway, logs aggregate traffic
- Design and usage approved usage by IRB




**Example inspection**

# Instrumenting IoT Inspector

- Added ability to passively observe traffic between all devices and actively probed devices for services

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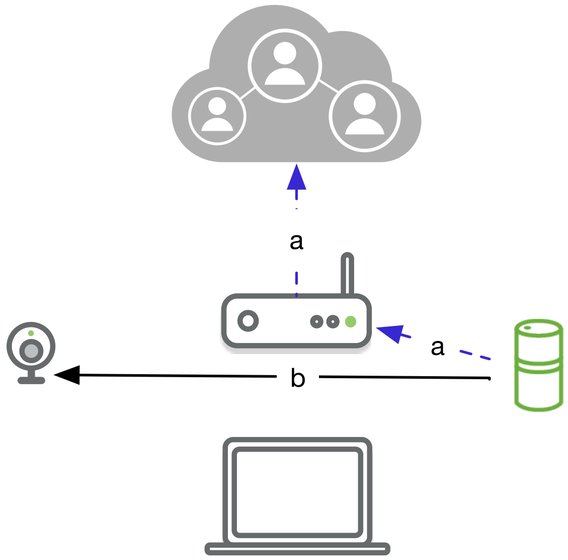


**Inspector Off**

# Instrumenting IoT Inspector

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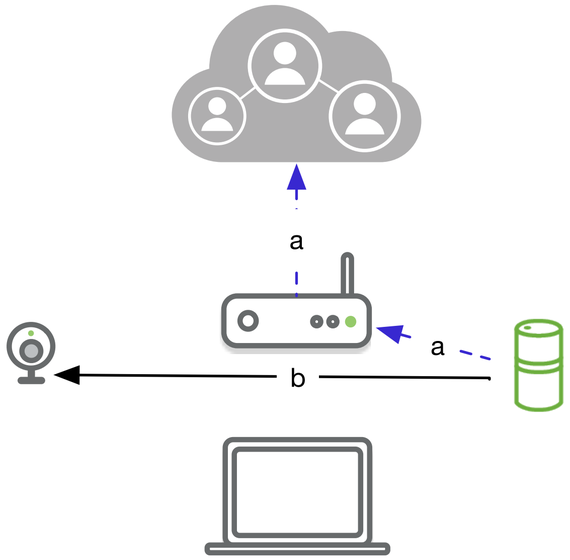


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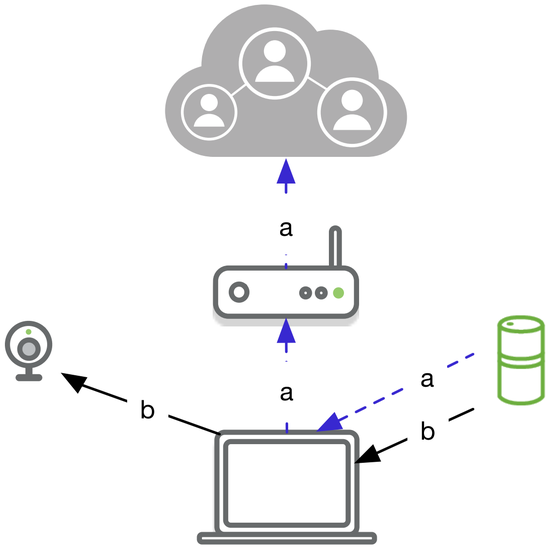


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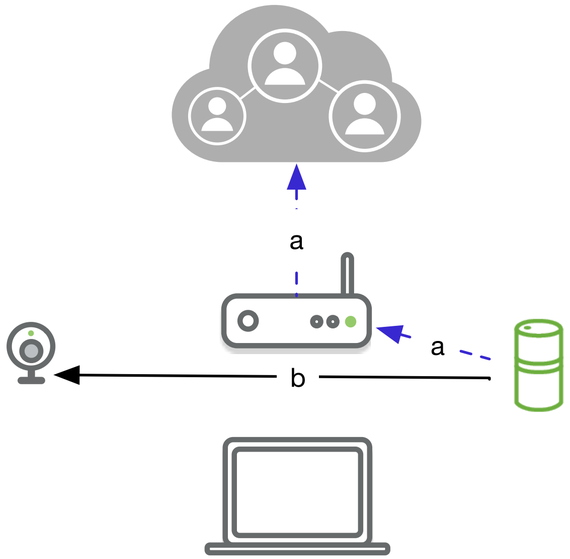


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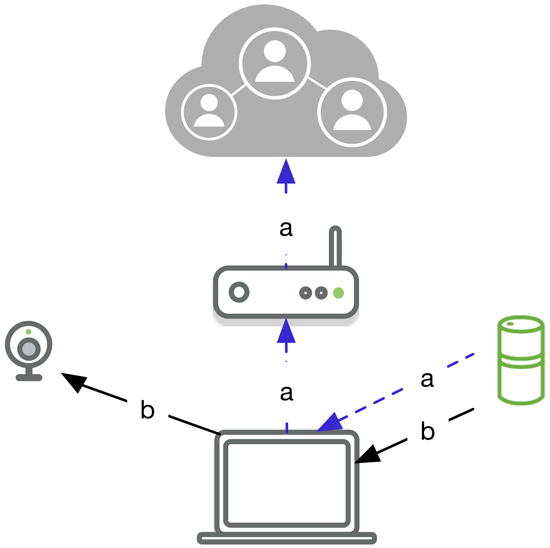


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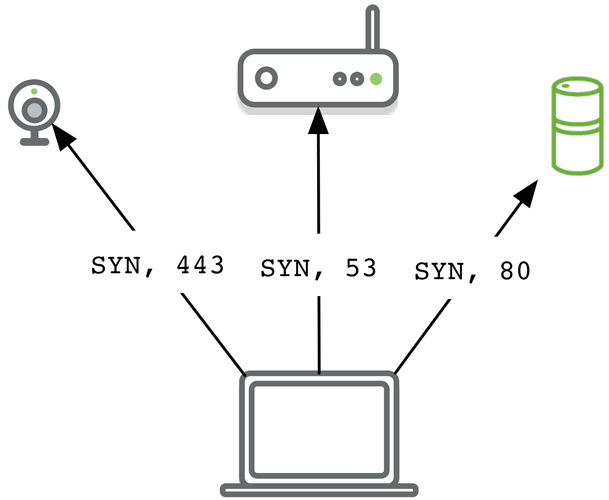
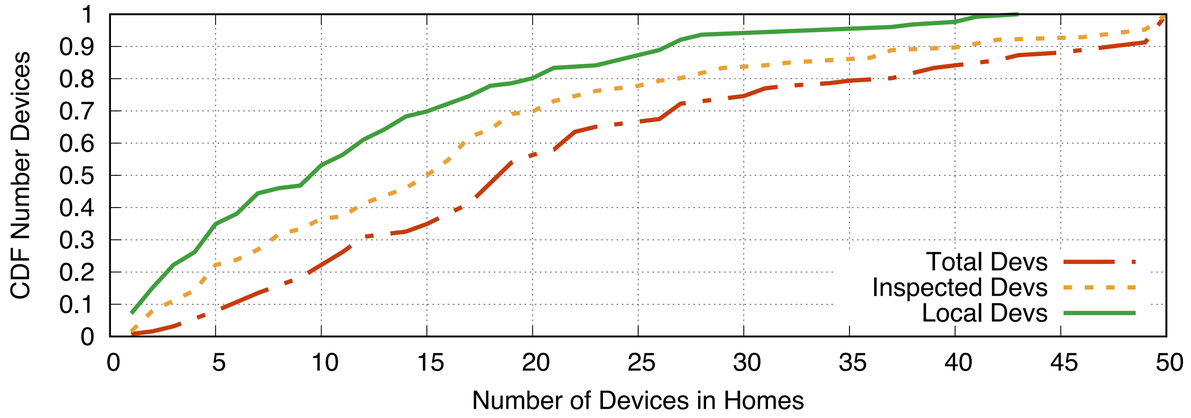



**SYN Scanning**

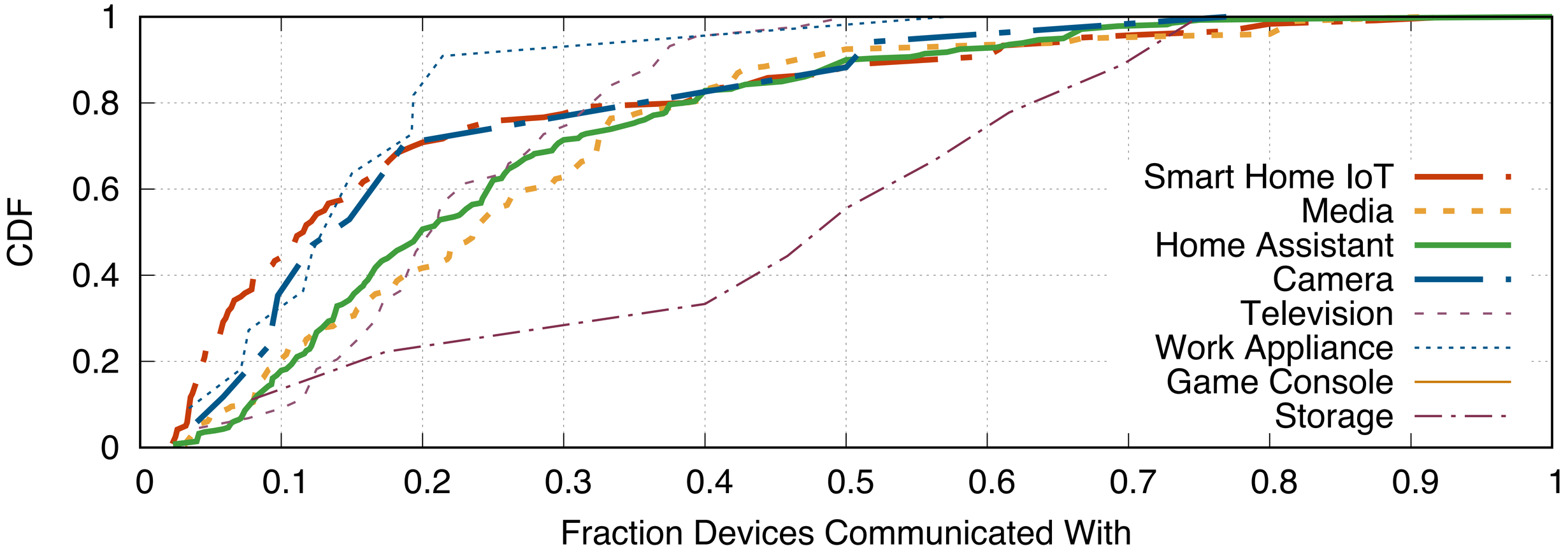
# Passive Dataset

- Recruited 275 participants to run our augmented version of IoT Inspector for a 3-week period, May 8 – May 31st, 2020 in their smart homes
- 3,308 inspected devices, 2365 IoT devices
  - Used fingerbank.org for device identification, which is based on crowdsourced active + passive collected data
- Homes in our dataset contain median 19 devices



# How do devices behave on local networks?

# Fraction of Device Communication



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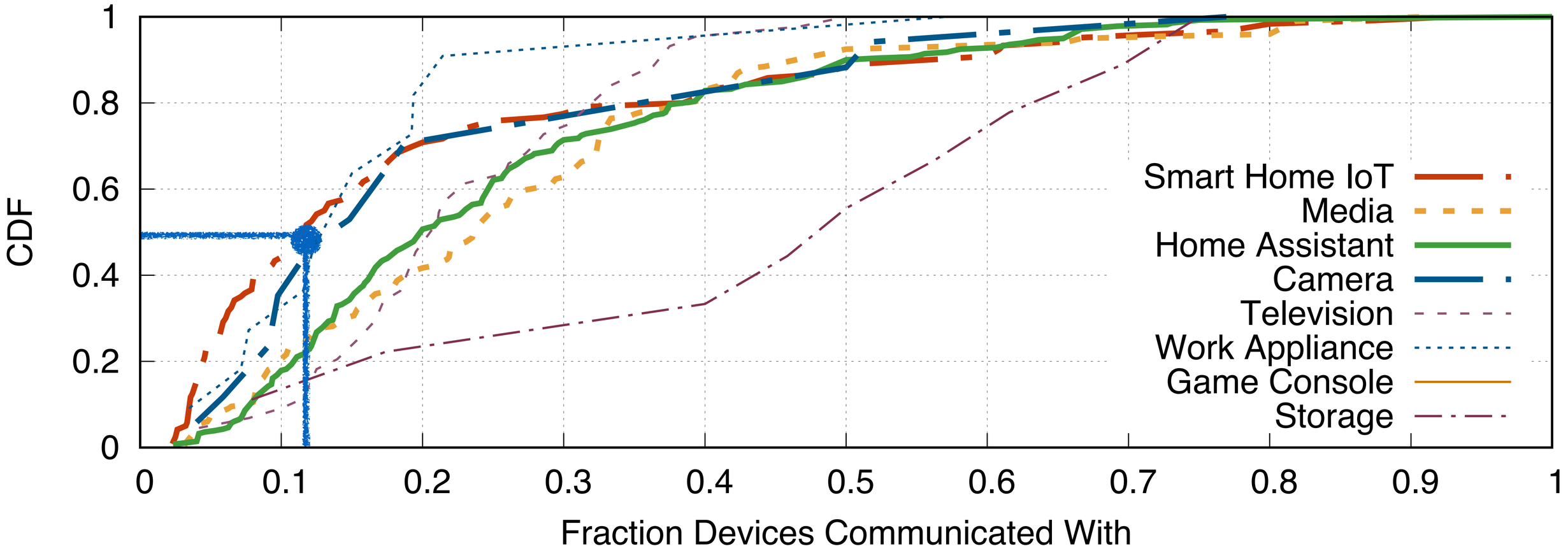

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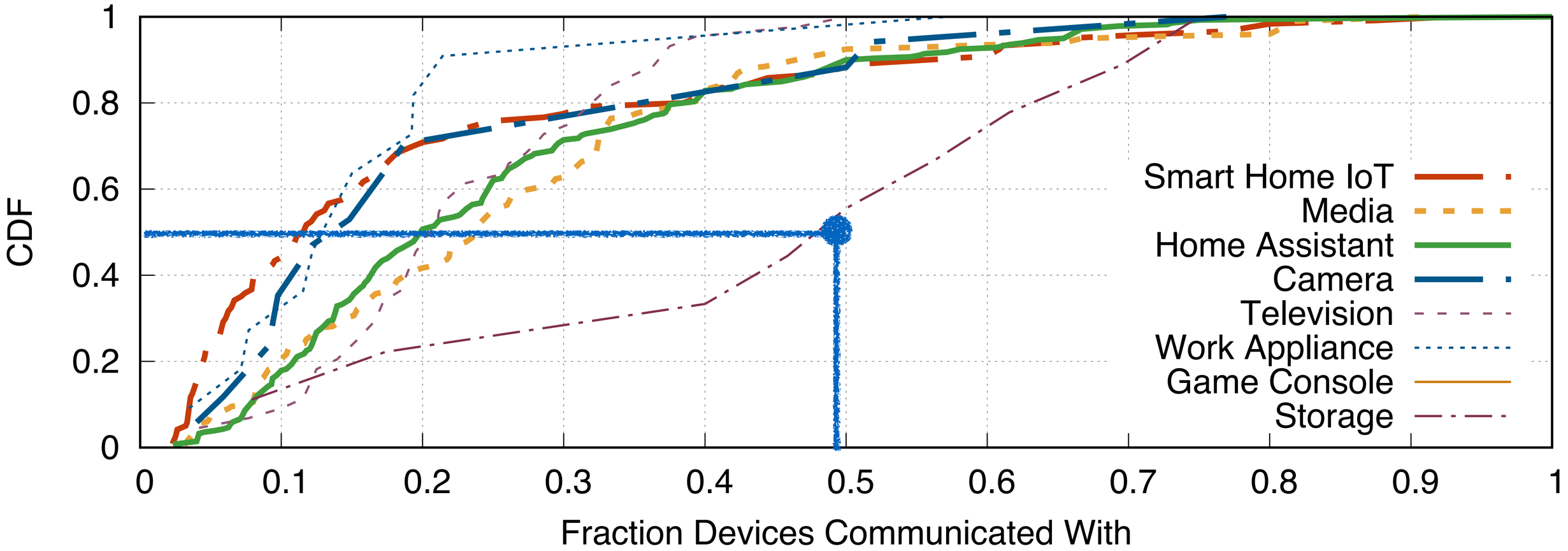
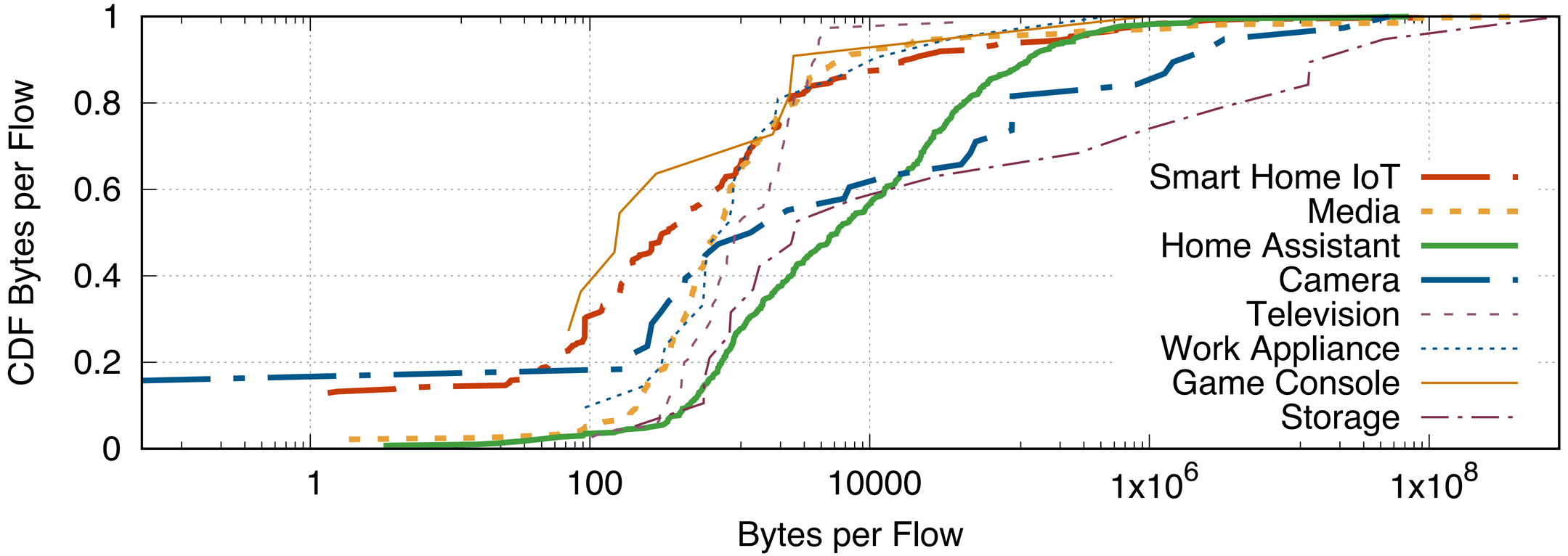


# Bytes sent per flow



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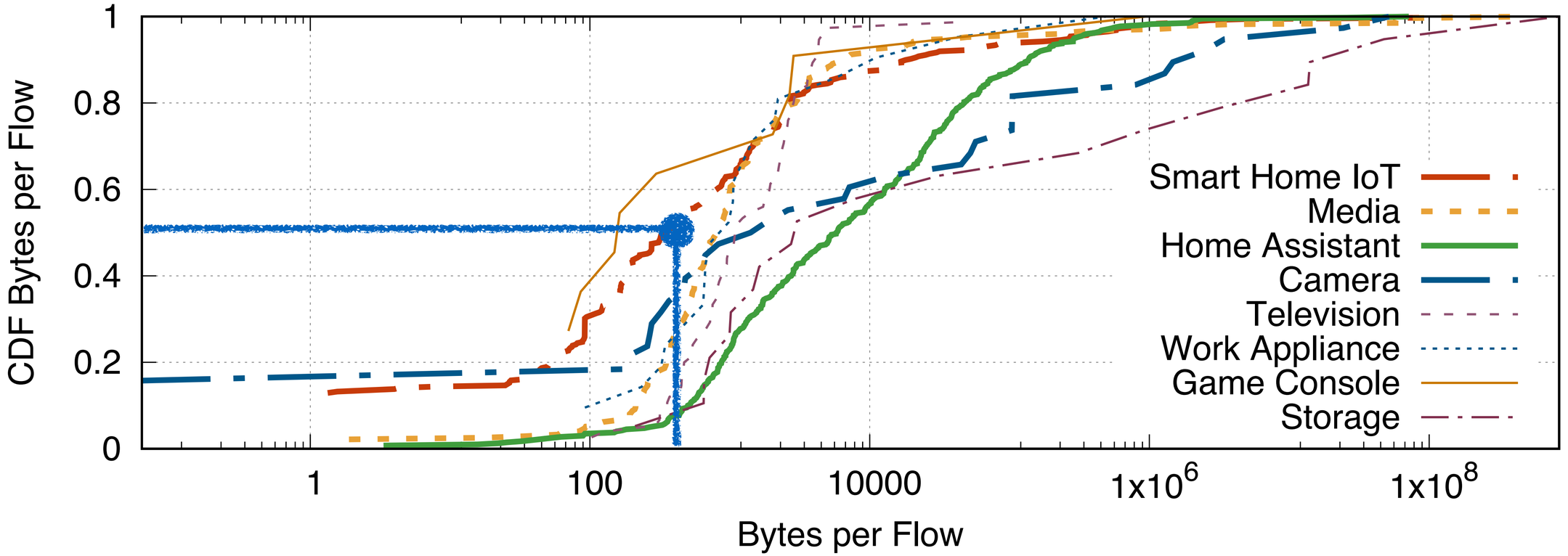

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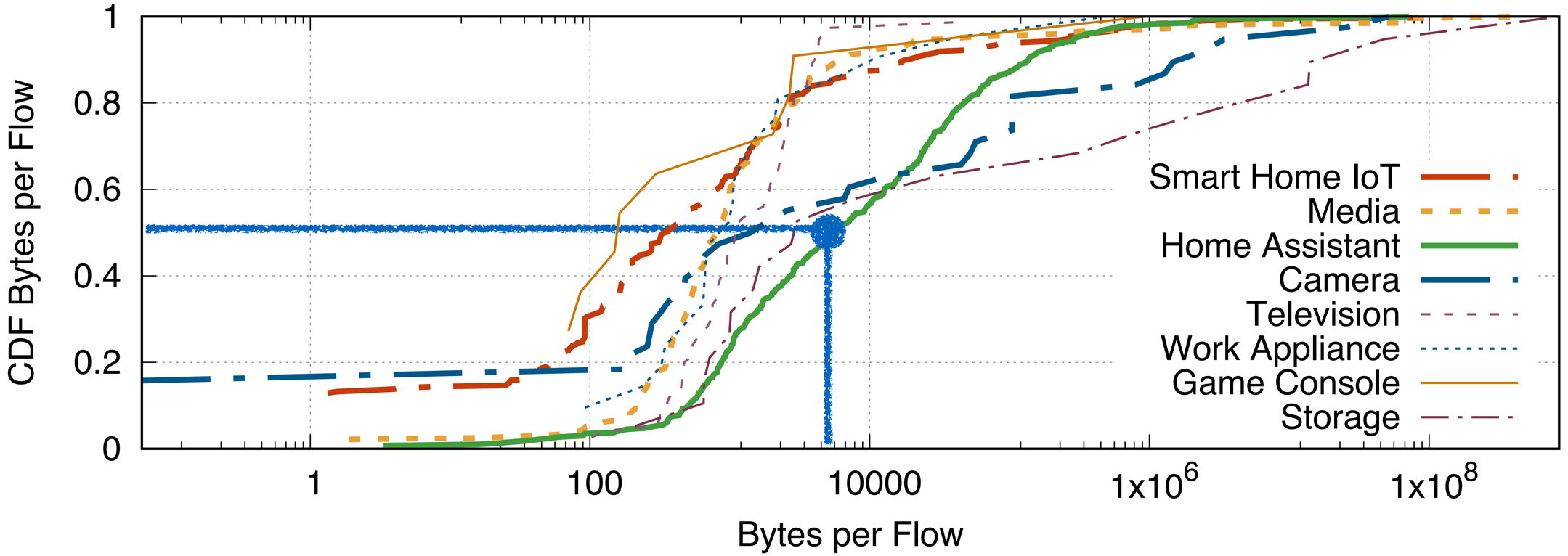

# Port Usage by Fraction of Devices

| Port | Protocol | Service | % Devices |
|---|---|---|---|
| 8009 | TCP | HTTP | 12.5% |
| 80 | TCP | HTTP | 9.9% |
| 1400 | TCP | HTTP | 4.8% |
| 10001 | UDP | — | 4.6% |
| 8008 | TCP | HTTP | 4.4% |
| 9000 | TCP | — | 2.9% |
| 8060 | TCP | HTTP | 2.2% |
| 10001 | TCP | — | 2.0% |
| 55443 | TCP | — | 2.0% |
| 161 | UDP | SNMP | 1.9% |

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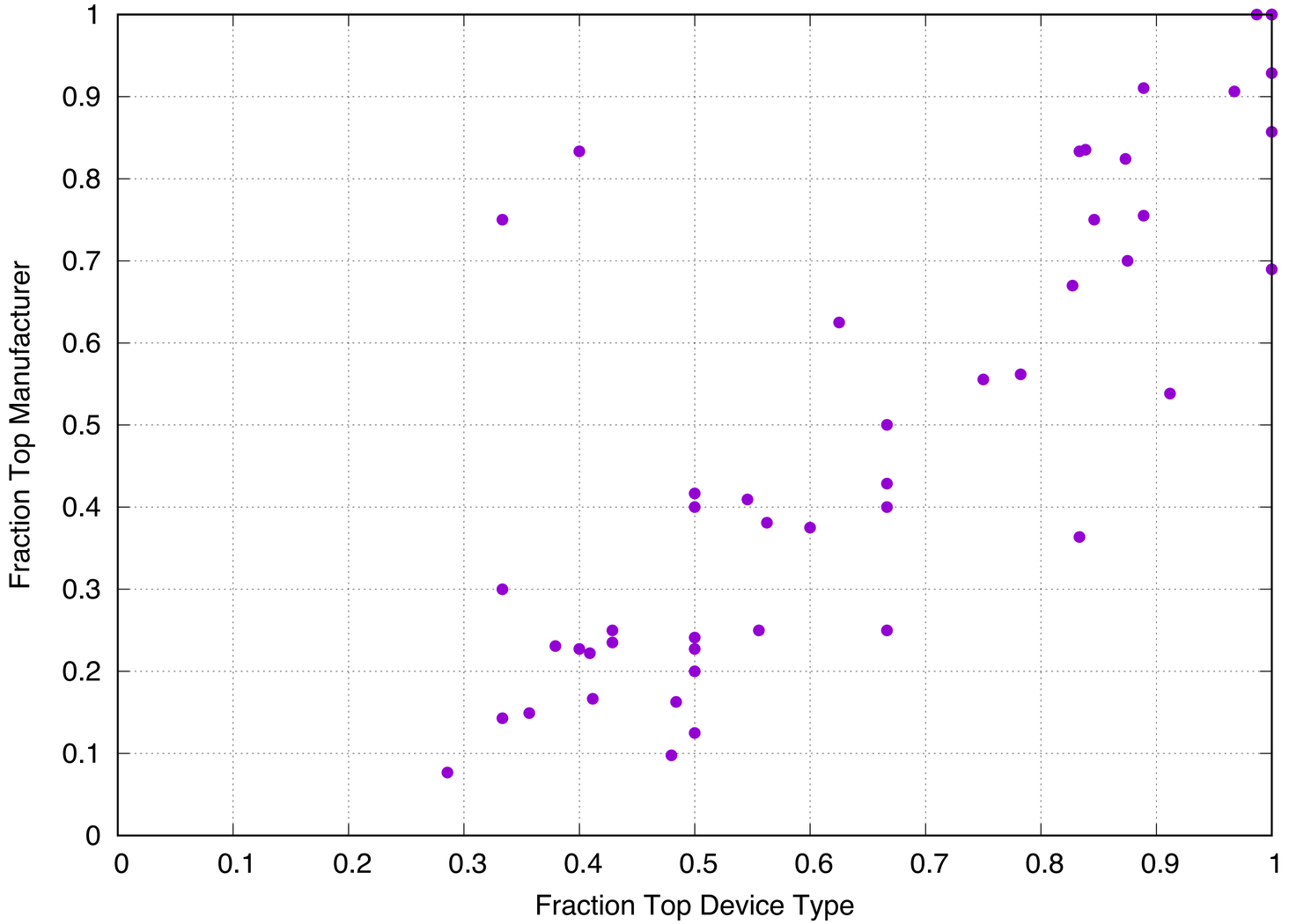

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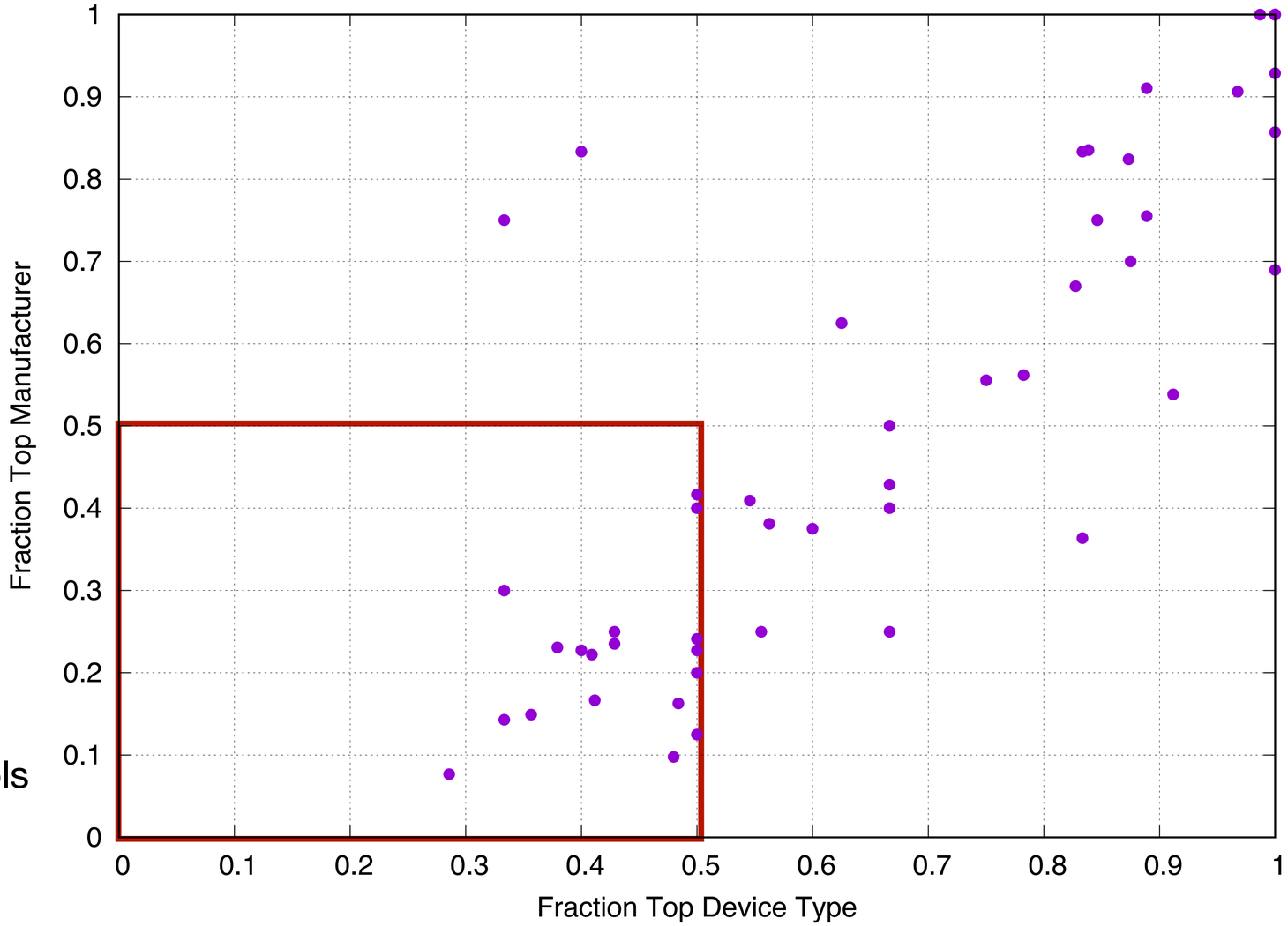
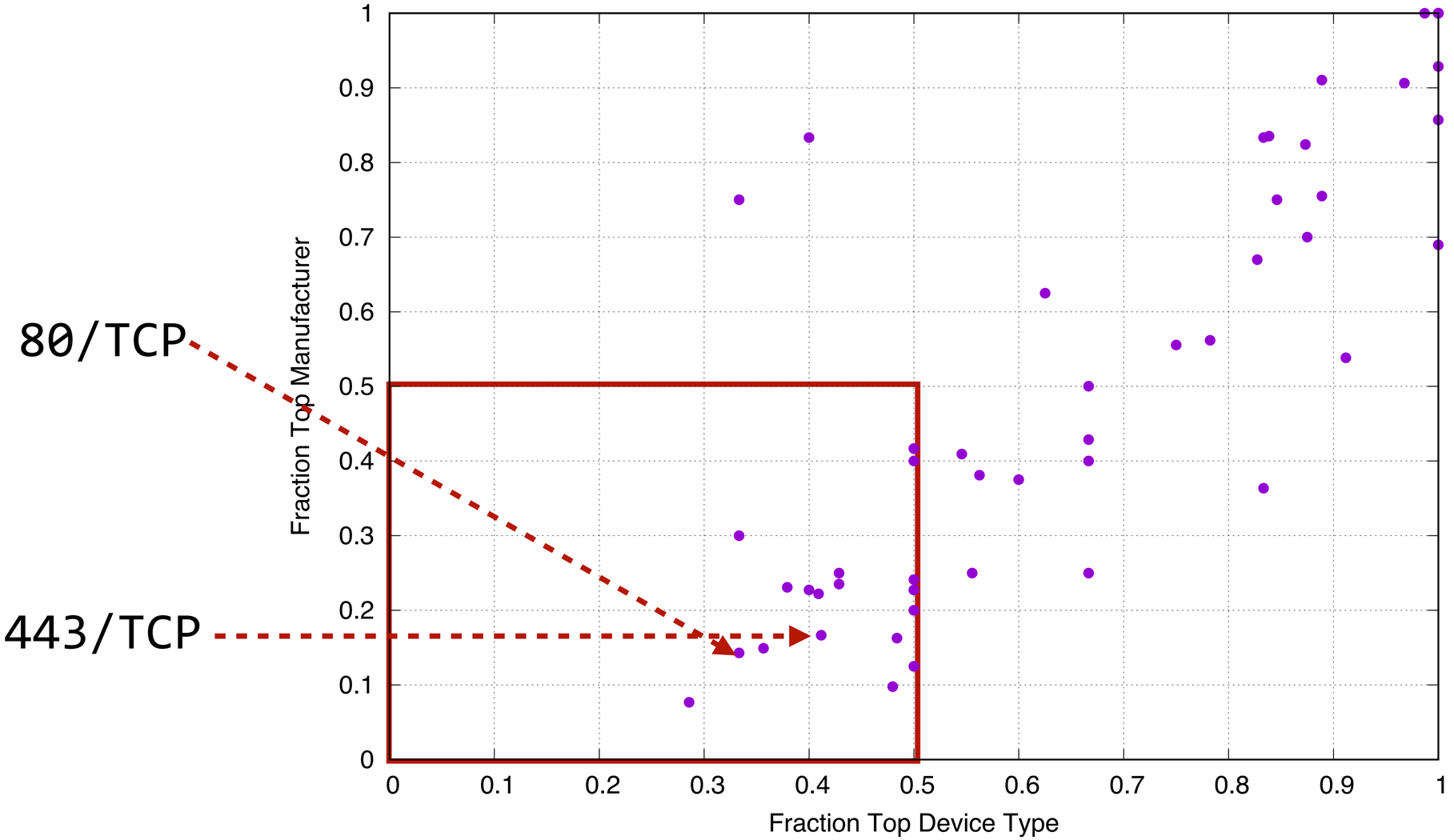



24% ports are shared by many manufacturers and device types – these are standard ports and protocols

# Port Distributions



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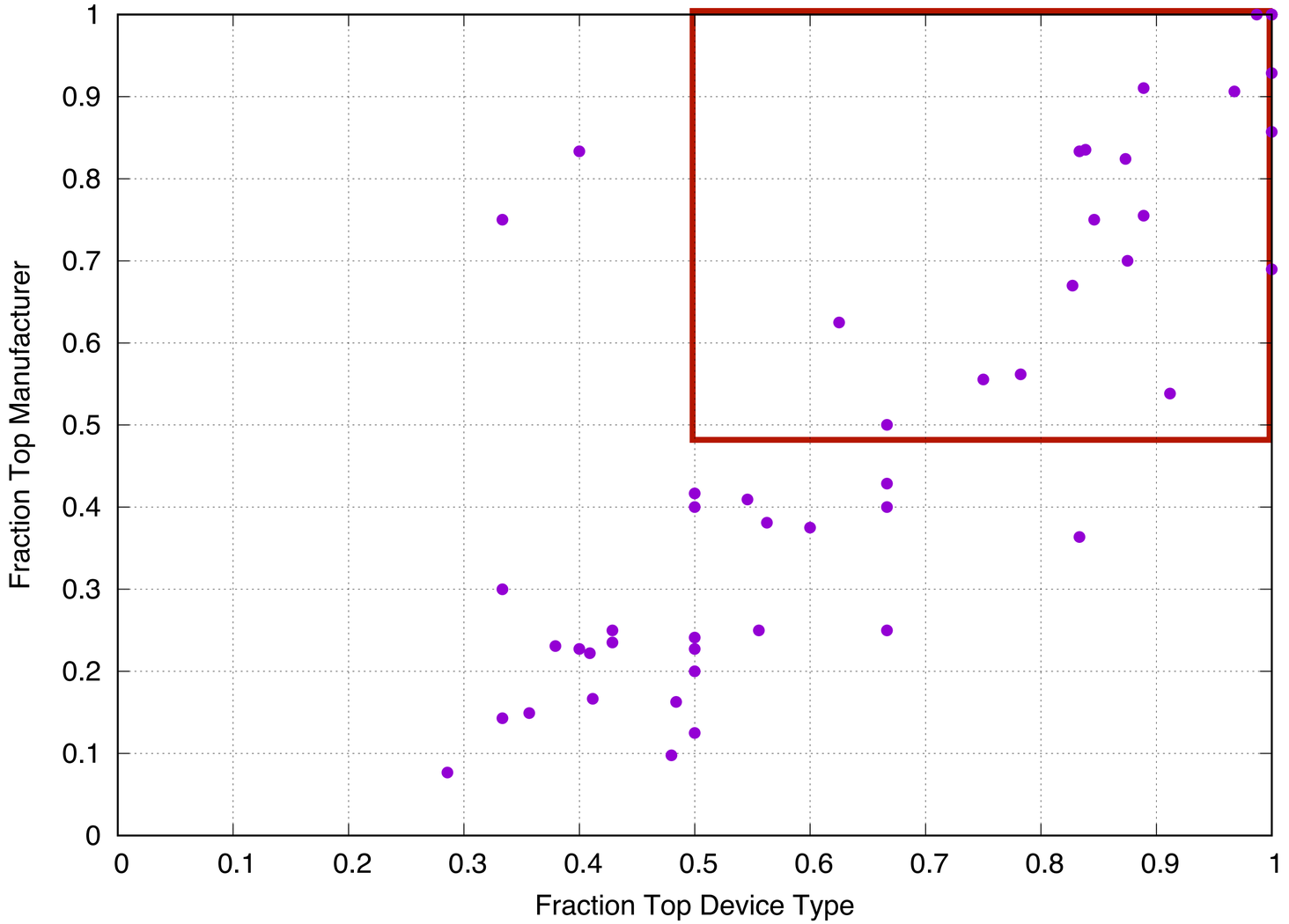
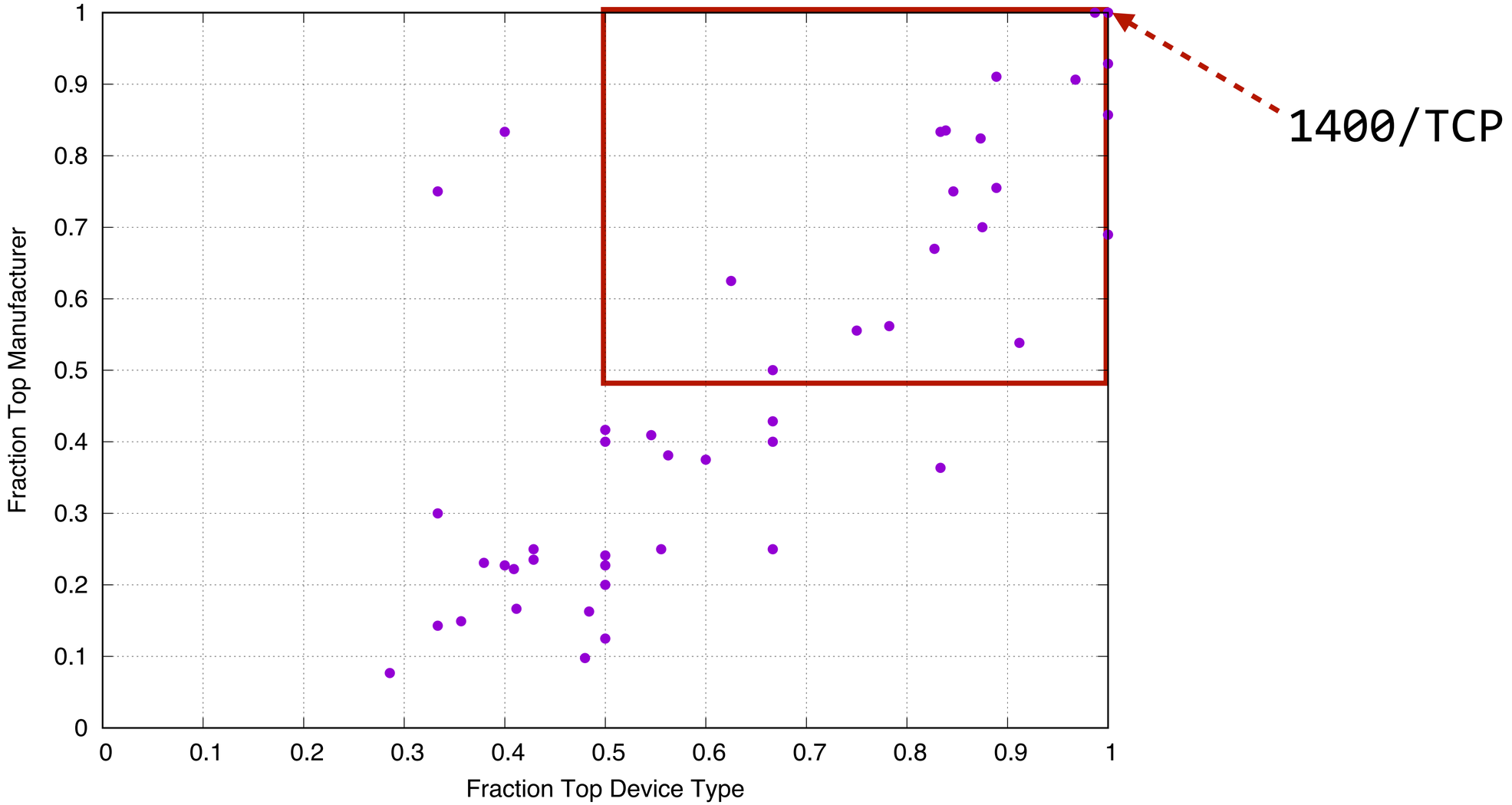



44% of ports were largely specific to a single manufacturer/device type

# Port Distributions



# Thesis Outline

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</table>

# Active Measurements through IoT Inspector

- Sent a SYN probe to a series of IoT specific ports informed by prior work and those used by Internet-scanning systems
- 73% of IoT devices in our network responded to at least one SYN probe
- Devices inside home networks support a host of active services, many popular ones run HTTP servers for remote control

| Protocol | % Devices Support |
|---|---|
| **8008/HTTP** | 36% |
| **8443/HTTPS** | 36% |
| **80/HTTP** | 31% |
| **443/HTTPS** | 17% |
| **8080/HTTP** | 12% |
| **1843/—** | 11% |
| **1443/—** | 11% |
| **22/SSH** | 8% |
| **8060/—** | 6% |

**Active services on IoT devices**

# Comparing Active Internal and Passive Internal

- Compared the protocols that were offered (through SYN scan) to the protocols we observed used by devices
- Devices use an average 19% of services offered during our measurement period
- Full services are identified after median 25% of inspection time

# Comparing Active Internal and Passive Internal

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- Full services are identified after median 25% of inspection time

| Protocol | % Devices Unused |
|---|---|
| 22/SSH | 100% |
| 9100/CUPS | 100% |
| 8081/HTTP | 100% |
| 111/rpcbind | 100% |
| 1080/SOCKS | 100% |
| 8443/HTTPS | 97% |
| 23/Telnet | 96% |
| 631/IPP | 91% |

**Top Unused Services**

# Comparing Active Internal and Passive Internal

| Device Type | Fraction Ports Used |
|---|---|
| Television | 61% |
| Camera | 41.3% |
| Router | 37.5% |
| Gaming Console | 25% |
| Smart Home IoT | 17.1% |
| Media | 16.8% |
| Work Appliance | 13.3% |
| Voice Assistant | 12.2% |
| Storage | 12% |

# Comparing Active Internal and Passive Internal

- Compared the protocols that were offered (through SYN scan) to the protocols we observed used by devices
- Devices use only a median 50% of services they offer during the measurement period
- Many of these services are security critical (e.g., 23/Telnet, 111/rpcbind)

| Protocol | % Devices Used | Can Explain? |
|---|---|---|
| 22/SSH | 100% | ✘ |
| 80/HTTP | 100% | ✘ |
| 4064/HTTP | 100% | ✘ |
| 111/rpcbind | 100% | ✘ |
| 8443/MQTT | 97% | ✔ |
| 23/Telnet | 96% | ✘ |

**Network capabilities through active scanning are often much wider than network behavior through passive observation**

# Thesis Outline

| | Active Measurement | Passive Measurement |
|---|---|---|
| **Internal Vantage Point** | All Things Considered | IoT Inspector |
| | IoT Inspector | |
| **External Vantage Point** | Understanding the Mirai Botnet | IoT Inspector |

# Comparing Passive Internal to Passive External

- IoT Inspector captures traffic to the outside world as well as behavior on the local network
- Devices only use a small fraction of ports when communicating externally
- Primarily features communication over ports 53, 443, 80, all standard protocols to support DNS, HTTPS, and HTTP

| Protocol | % Devices Communicated |
|---|---|
| **53/UDP** | 69% |
| **443/TCP** | 67% |
| **80/TCP** | 43% |
| **123/UDP** | 31% |
| **443/UDP** | 12% |
| **8883/TCP** | 6.4% |

**External Communication**

# Comparing Passive Internal to Passive External

| Port | Protocol | Service | % Devices |
|---|---|---|---|
| 8009 | TCP | HTTP | 12.5% |
| 80 | TCP | HTTP | 9.9% |
| 1400 | TCP | HTTP | 4.8% |
| 10001 | UDP | — | 4.6% |
| 8008 | TCP | HTTP | 4.4% |
| 9000 | TCP | — | 2.9% |
| 8060 | TCP | HTTP | 2.2% |

**Local Communication**

| Protocol | % Devices Communicated |
|---|---|
| **53/UDP** | 69% |
| **443/TCP** | 67% |
| **80/TCP** | 43% |
| **123/UDP** | 31% |
| **443/UDP** | 12% |
| **8883/TCP** | 6.4% |

**External Communication**

# Comparing Passive Internal to Passive External

| Device Type | Fraction Observed Externally |
|---|---|
| Media | 6% |
| Work Appliance | 12.5% |
| Television | 22% |
| Voice Assistant | 27% |
| Smart Home IoT | 35% |
| Storage | 42% |
| Camera | 75% |

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# Comparing Active Internal to Passive External

- We *expect* the behavior of devices to the outside world to be different from the services offered inside networks
- We find no correlation between the services offered from active internal and passive external

| Protocol | % Devices Support |
|---|---|
| **8008/HTTP** | 36% |
| **8443/HTTPS** | 36% |
| **80/HTTP** | 31% |
| **443/HTTPS** | 17% |
| **8080/HTTP** | 12% |
| **1843/—** | 11% |
| **1443/—** | 11% |
| **22/SSH** | 8% |
| **8060/—** | 0% |

**Active services on IoT devices**

# Comparing Passive Internal to Passive External

| Device Type | Fraction Observed Externally |
|---|---|
| Smart Home IoT | 35% |
| Home Automation | 97% |
| Camera | 75% |
| Television | 22% |
| Work Appliance | 12.5% |
| Storage | 42% |

**External device behavior does not match internal device behavior or capabilities**

# Thesis Outline

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# Comparing Active External to Passive Behavior

- Internal and external device behavior cannot be observed from active probing on the outside
  - At best, can attribute behavior to an externally facing router, but unknown if the router is producing the traffic
  - Recent research from Alrawi et. al suggests using a passive external fingerprint collected from homes (e.g., DNS traces) to identify IoT devices on the network, but this too cannot be observed through an active external probe

# Recap

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# Principles for Measuring IoT

- An internal vantage point provides access to finer-grained data about network behaviors and capabilities compared to external vantage points
- IoT Devices often exhibit different behaviors and capabilities, requiring both passive and active measurement to properly quantify

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- IoT Devices often exhibit different behaviors and capabilities, requiring both passive and active measurement to properly quantify

**Measurements drawn from a local network vantage point using passive and active techniques provides a holistic view of network services used by IoT devices**

# Lessons Learned and Future Directions

- Our results challenge current security assumptions about IoT devices and their behavior
- Homesnitch, Hestia, Honeyscope aim to improve local network security guarantees
  - Network behavior in practice is more complex than simple “hub/device” model
- Alrawi et. al, and Huang et. al primarily use external IoT network behavior to make claims about threat models: DNS, HTTP, UPnP, NTP
  - However, local network behavior shows us that there are far more ports, services, and protocols, many of which we could not identify
- Our results can help inform future security systems to match what happens in practice

# Big Thank You!

Nikita Borisov

Adam Bates

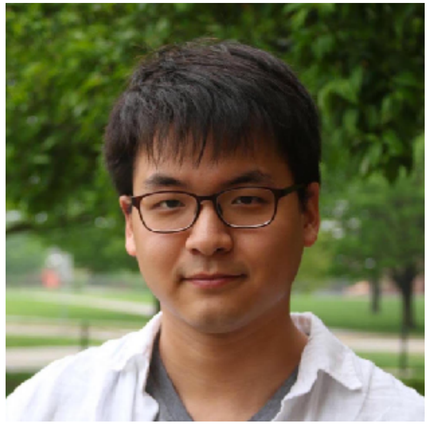
Gang Wang

Zakir Durumeric

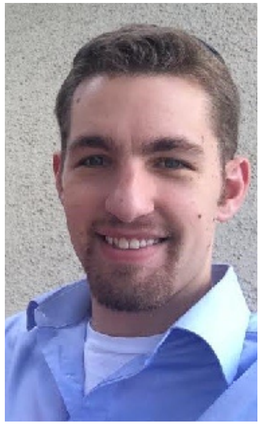
Would not have been possible without your guidance!

# Big Thank You!

Zane Ma



Simon Kim



Paul Murley

Joshua Reynolds

Suyup Kim, Yi Zhou

# Last But Not Least…

Josh Mason

Michael Bailey

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Questions?