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One Bad Apple Can Spoil Your IPv6 Privacy

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ABSTRACT

IPv6 is being more and more adopted, in part to facilitate the millions of smart devices that have already been installed at home. Unfortunately, we find that the privacy of a substantial fraction of end-users is still at risk, despite the efforts by ISPs and electronic vendors to improve end-user security, e.g., by adopting prefix rotation and IPv6 privacy extensions. By analyzing passive data from a large ISP, we find that around 19% of end-users' privacy can be at risk. When we investigate the root causes, we notice that a single device at home that encodes its MAC address into the IPv6 address can be utilized as a tracking identifier for the entire end-user prefix—even if other devices use IPv6 privacy extensions. Our results show that IoT devices contribute the most to this privacy leakage and, to a lesser extent, personal computers and mobile devices. To our surprise, some of the most popular IoT manufacturers have not yet adopted privacy extensions that could otherwise mitigate this privacy risk. Finally, we show that third-party providers, e.g., hypergiants, can track up to 17% of subscriber lines in our study.

1 INTRODUCTION

The adoption of IPv6 in the Internet is continuously increasing [46]. One of the drivers is the unprecedented demand for smart devices at home, ranging from voice assistants to smart TVs and surveillance cameras, that all have to be assigned addresses to have access to the Internet and the cloud [29]. While the use of Network Address Translation (NAT) and concerns about IPv6 addressing privacy have delayed its adoption, operators, vendors, and the research community have long ago provided privacy solutions to mitigate these risks. ISPs have adopted prefix rotation [37] and network equipment manufacturers and software developers have enabled IPv6 privacy extensions [24, 39].

A recent work [43] shows that if the home network gateway router, also referred to as customer premises equipment (CPE), is using a legacy IPv6 addressing standard employing EUI-64 (Extended Unique Identifier), it is possible to track devices that use IPv6 at home using active measurements. Unfortunately, in this paper, we report that even if the CPE and the ISP apply best common practices, i.e., IPv6 privacy extensions and prefix rotation, it is still possible to track devices that use IPv6 at home. In detail, we show that the existence of only a single device that uses EUI-64 at home can spoil the privacy of potentially all IPv6-enabled devices and eventually end users' privacy across these devices. To estimate the risk in a realistic setting, we rely on passive measurements, namely network flows collected at a large European ISP. However, any third-party provider, such as hypergiants [22], network traffic aggregators (Internet exchange point, upstream providers), or service providers (e.g., NTP, DNS providers), receiving connections from devices at the same home can potentially defeat the privacy of current IPv6 solutions even if only one these devices uses the legacy EUI-64 technique. Unfortunately, the average end-user is not in a position to know which of their devices use EUI-64.

Our contributions can be summarized as follows:

- We perform a study at a large European ISP. Our analysis shows that around 19% of end-user prefixes host at least one device that does not use IPv6 privacy extensions.
- We show that the existence of even a single device without privacy extensions in an end-user prefix can defeat the ISP-deployed prefix rotation and IPv6 privacy extensions adopted by hardware vendors to preserve user privacy.
- Our analysis shows that the majority of devices without privacy extensions, responsible for spoiling users' privacy, are devices of IoT manufacturers. However, computer and mobile manufacturers are also contributing.
- We show that, in most cases, a single device without privacy extensions is responsible for privacy leakage. Unfortunately, these devices have been manufactured by market leaders. Thus, it would have been possible to prevent this privacy leakage if these manufacturers had adopted best common practices, i.e., IPv6 privacy extension.
- We also show that a popular content provider, application, or service contacted by a device that is not using privacy extensions can track the user and other contacting devices across rotating prefixes. Unfortunately, the privacy of up to 17% of subscriber lines can face this risk.

2 BACKGROUND

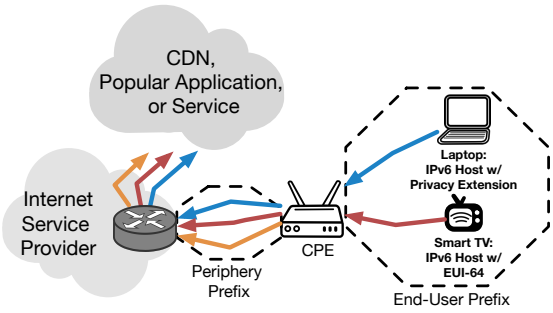
To solve the address shortage in IPv4 among other things, the networking community introduced the IPv6 protocol more than two decades ago [13, 14]. Nevertheless, IPv6 is only recently being deployed on a larger scale [33] with about 36% of all requests to Google going over IPv6 as of March 2022 [25]. In addition to the IPv6 address space being larger, the addressing itself is also different compared to IPv4 [23]. While in IPv4 most end-user clients get their address via

DHCP [15], in IPv6 clients get addresses either via DHCPv6 [37] or stateless address auto-configuration (SLAAC) [48]. Instead of directly assigning a full address as in DHCP or DHCPv6, with SLAAC a router simply sends a prefix to its clients (i.e., the network part), and the clients then by themselves choose an IPv6 address within that prefix (i.e., the host part). This host part is also called interface identifier or *IID*. Initially, the IID part used an encoding of the interface's MAC address, called *EUI-64* [2]. The unique and consistent nature of MAC addresses lead to devices being trackable over time and across different networks [44]. Consequently, IPv6 *privacy extensions* were proposed, which simply randomize the IID part instead of using a device's MAC address [39]. In addition to user devices being trackable by EUI-64 addresses, ISP subscribers can also be tracked by their prefix. In order to defeat prefix tracking, ISPs can change the prefix of each customer after a certain time (*prefix rotation*). Although there has been a lot of work on IPv6 measurements [1, 3, 5, 6, 8, 11, 16–21, 28, 34–36, 38, 40–42, 44, 47, 49, 50], many of them focused on active measurements or structural properties of the IPv6 space. The work closest to ours was recently published by Rye et al. [43], in which they show that prefix rotation can be defeated by tracerouting customer premise equipment (CPE), which responds with EUI-64 addresses. In our work, we show the privacy implications of EUI-64 usage among devices directly within the end-user network.

3 METHODOLOGY

In this section, we describe our methodology and show how a single device using EUI-64, i.e., not using privacy extensions, can be used to track devices at the subscriber level. In Figure 1, we show how an end-user prefix can be tracked despite the ISP performing frequent prefix rotation. In the example scenario, there are two devices in the end-user prefix, a laptop and a smart TV. Both are using IPv6, the former with privacy extensions, the latter with EUI-64. The CPE device also has IPv6 connectivity on the upstream facing interface. If the CPE device's WAN-facing address is not within the end-user prefix, it can not be used for tracking with our methodology.

Since the smart TV is not using privacy extensions it allows CDNs and other large players in the Internet to track not only the smart TV itself, but all devices within that end-user prefix. In fact, we can use the smart TV's IID part of the IPv6 address as its unique tracking ID since it is derived from a MAC address. Furthermore, we assign this same *tracking ID* to all addresses within the end-user prefix. This way, we can jointly track all devices of a subscriber by relying on a single EUI-64-enabled device. After the initial blue and red flows were observed, the ISP rotates the customer's prefix (time 2), and all customer devices are now using a new IPv6 address. Importantly, as the smart TV is still using the same



Time	Host	IPv6 Address	Tracking ID
1	SmartTV	2001:db80:1111:b000:8e8f:90ff:fe12:3456	8e8f:90ff:fe12:3456
1	Laptop	2001:db80:1111:b000:ddde:abcd:1111:ff11	8e8f:90ff:fe12:3456
1	CPE	2001:db80:2222:b25d:aff0:abff:fe34:5679	aff0:abff:fe34:5679
...			
2	SmartTV	2001:db80:3333:fff1:8e8f:90ff:fe12:3456	8e8f:90ff:fe12:3456
2	Laptop	2001:db80:3333:fff1:1111:1123:ee11:2222	8e8f:90ff:fe12:3456
2	CPE	2001:db80:2222:b266:aff0:abff:fe34:5679	aff0:abff:fe34:5679

Figure 1: Privacy leakage across prefixes.

IID even in this new prefix, any content provider can again associate all devices with the same tracking ID as before. With this technique, a single EUI-64 device in an end-user subnet can spoil the privacy gains of prefix rotation of all other devices, even if they use privacy extensions.

For our method to be effective, the devices in the same end-user prefix must contact a vantage point. In our case, we are in a privileged position to see all the connections and thus be able to track all the devices. However, in the wild, these devices would require to contact the same application, e.g., hypergiants, content delivery networks, search engines, upstream providers, or other popular services such as DNS or NTP. The devices can then simply be tracked by assigning tracking IDs to the red and blue flows as shown in Figure 1.

Recall, the IID part of an EUI-64 IPv6 address is generated by inserting the `'ff:fe'` hex string between the third and fourth bytes of a MAC address and setting the Universal/Local bit. We can extract the MAC address from the EUI-64 part of an IPv6 address and uncover the device manufacturer. To achieve this, we extract the Organization Unique Identifier (OUI) part of the MAC address, i.e., the first three bytes. For the mapping, we use the official IEEE OUI database [32]. This database contains information about the name and address of the manufacturer that has registered the OUI.

4 DATASETS

ISP Profile: We analyze data from a large European Internet Service Provider (ISP) that offers Internet connectivity to more than 15 million broadband subscriber lines in Europe.
IPv6 Assignment at the ISP: The ISP fully supports IPv6 by utilizing dual-stack addressing. Each CPE device gets delegated a /56 IPv6 prefix, out of which it will pick one /64 prefix, which is then used to assign addresses to clients via

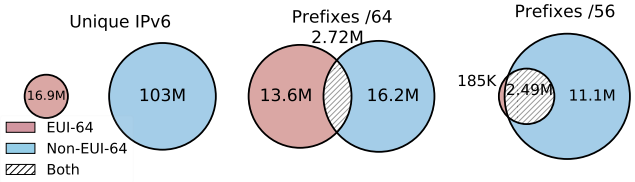


Figure 2: Venn diagram for EUI-64 and non-EUI-64 IPv6 addresses and the overlap between different prefix sizes.

SLAAC. By default, the ISP rotates the /56 prefixes delegated to customers every 24 hours. Generally, the IPv6 prefix used for the upstream-facing CPE interface to the ISP ("periphery prefix" in Figure 1) may or may not share the same prefix as the end-user network. Thus, in the latter case, a /56 prefix that does not contain an upstream-facing CPE interface represents an end-user network. We will show in our analysis in Section 5.2 that the CPE interface and end-user networks of this ISP do not share the same /56 prefixes.

ISP Data: The data is sampled network flow data collected at the ISP using NetFlow [9] to assess the state and operation of its network routinely, a typical operation of ISPs. For our analysis, we apply our method on the NetFlow data at the premises of the ISP, and we do not transfer or have direct access to the NetFlow data. The data was collected on July 14, 2021, and four months later, on November 17, 2021.

Ethical Considerations: The ISP NetFlow data does not contain any payload. Thus, there is no user information. The data is processed on-premise at the ISP, and no data is copied, transferred, or stored outside the server dedicated for NetFlow analysis at the ISP. Because IPv6 can be used as Personal Identifiable Information (PII), we consistently hash the first 56 bits that the subscribers of the ISP use. Following best operational practices, the NetFlow data is deleted at an expiration date set at the data collection time. To avoid blocklisting of products, vendors, manufacturers, and network companies, including hypergiants, we anonymize the names of all companies.

5 PRIVACY VIOLATIONS AT THE EDGE

To assess the prevalence of privacy violations due to devices without privacy extensions, we apply our methodology on NetFlow data of the ISP (see the previous section). Since the ISP rotates the customer prefixes once a day, we analyze one day of data, namely, Wednesday, July 14, 2021, to show the feasibility of tracking devices at home. We also examine the data collected on Wednesday, November 17, 2021, which confirms our initial observations. Unless otherwise mentioned, our results refer to the first dataset.

5.1 Quantifying EUI-64 Prevalence

In Figure 2 (left), we report the number of IPv6 addresses visible in the ISP during one day. Recall that the ISP serves

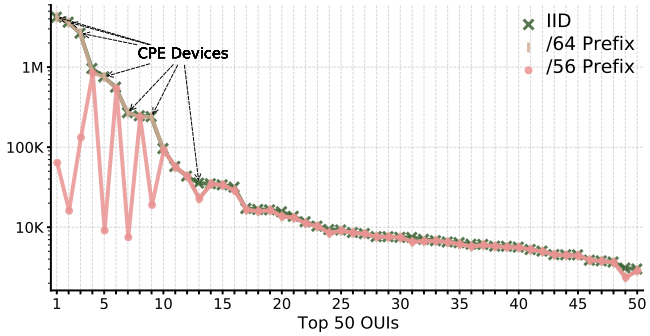


Figure 3: OUI popularity. Note that the y-axis is log-scaled.

around 15 million subscriber lines. The number of non-EUI-64 addresses—in our case those are IPv6 addresses with privacy extensions enabled (see Appendix A.1 for a detailed analysis of non-EUI-64 addresses)—is more than 100 million. This is to be expected as these devices frequently use new IPv6 addresses, and more than one of these devices may be served by a subscriber line. On the other hand, the number of IPv6 addresses for devices that do not use privacy extensions, i.e., EUI-64, is smaller, around 17 million. However, we have strong and consistent identifiers for IPv6 addresses used by these devices, i.e., their IIDs, that we use to track devices even when the ISP performs prefix rotation. In total, we found 14.4 million devices that use EUI-64.

Next, we map all IPv6 addresses to their /64 prefix. We see that the numbers are now quite similar, 13.6M for EUI-64 and 16.2M for prefixes with non-EUI-64 addresses, with an overlap of 2.7M prefixes.

As mentioned in Section 4, the ISP assigns /56 addresses to each subscriber line. In Figure 2 (right), we illustrate the number of prefixes that contain devices that use EUI-64, non-EUI-64 devices that use privacy extensions, and the prefixes that contain both types of addresses(i.e., dual-type prefixes). In total, we observed at least one EUI-64 device in around 2.68 million /56 prefixes out of 11.3 million /56 prefixes. Thus, the number of affected /56 prefixes accounts for about 22.2%. Note that the vast majority (more than 93%) of the host prefixes with EUI-64 devices also host non-EUI-64 devices as well. This shows that the presence of privacy-violating EUI-64 addresses impacts a substantial portion of ISP subscribers. Even within a day, it is still possible for prefix rotation to happen for some subscriber lines. We can detect these rotations for EUI-64 using prefixes by tracking the IIDs across multiple /56 prefixes. We observed that only less than 13% of the EUI-64 using /56 prefixes had prefix rotation within a day. Hence, if the same IID is observed across multiple /56 prefixes, we count the prefixes only once. For non-EUI-64 prefixes, we cannot track them across prefixes after prefix rotation, which is precisely the purpose of using IPv6 privacy extensions.

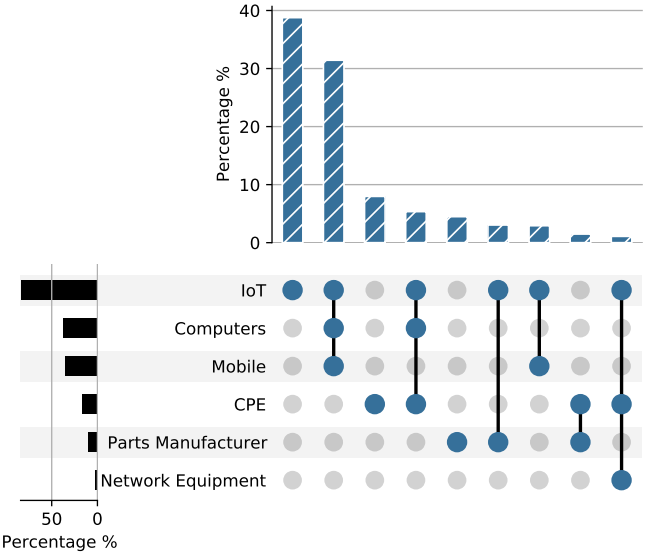


Figure 4: EUI-64 addresses mapped to different device categories. Percentage corresponds to number of /56 prefixes.

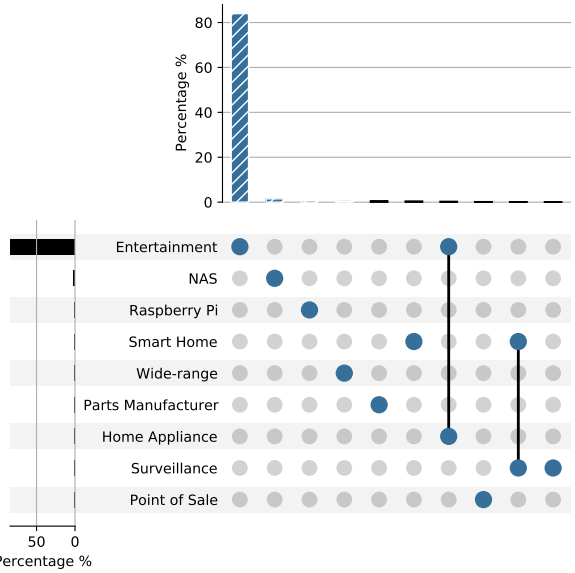


Figure 5: Composition of IoT-only manufacturers. Percentage corresponds to the number of /56 prefixes.

5.2 Popularity of EUI-64 Manufacturers

Based on the IPv6 address for devices that use EUI-64 addresses, we analyze the device manufacturer using the OUI (see Section 3). In total, we find devices with 1216 unique OUIs from 1113 distinct manufacturers. In Figure 3, we show manufacturers sorted by popularity (i.e., number of unique IIDs). We focus on the top 50 manufacturers as these are responsible for more than 99.1% of all IIDs. A closer investigation shows that 6 out of the top 10 are CPE manufacturers. The rest in the top 10 are IoT, smart TV, mobile devices, home appliances, and data storage manufacturers.

Interestingly, the number of covered /56 prefixes or even /64 ones is almost identical with the number of IIDs in most cases. This means that it is expected to be one device from each manufacturer in each /56 or /64 in our dataset. A striking difference is the case of CPEs, where the number of /56 prefixes is substantially lower than the /64 prefixes and the corresponding IIDs. We attribute this to two reasons. First, the WAN (upstream-facing) interfaces of the CPEs in the ISP typically do not share the same /56 prefix as the devices at home, i.e., the periphery prefix is different from the end-user prefix shown in Figure 1. We confirm this with multiple users of the ISP. Second, the IPv6 address of the WAN interface of CPEs are concentrated within a relatively small number of prefixes that it seems the ISP uses for exactly this purpose. Thus, in our methodology, the IPv6 address of the CPE is not sufficient to track the devices at home. On the other hand, it is possible to use this information to defeat the privacy of devices at home with active measurements [43].

Based on these insights, we re-estimate the number of affected prefixes by differentiating between periphery subnets used by CPEs and end-user subnets used by devices at home. We find that around 2.23M prefixes out of a total of 2.6M EUI-64 prefixes are end-user prefixes. Therefore, about 19% of all 11.3M /56 prefixes are at risk of privacy leakage.

5.3 EUI-64 Manufacturer Categorization

To understand what type of devices contribute the most to the leakage of users' privacy due to EUI-64, we characterize the business model and products of the associated manufacturers. Thus, we manually visit the website of top 100 manufacturers found by our method. We consider the following business types and any combinations: IoTs, computers, mobile devices, CPEs, part manufacturers, and network equipment manufacturers (see Appendix A.2 for a detailed description). We assign a weight to each manufacturer with the associated coverage of /56 prefixes. Then, we aggregate the weights for the manufacturers of the same type.

As shown in Figure 4, around 39% of the prefixes that host EUI-64 devices, contain products from manufacturers that only produce IoT devices. The second most popular category, that accounts for 32%, are devices by manufacturers active in different product lines that include IoT devices, computers, mobile devices. All other categories account for 8% or less. Thus, the large majority of subscribers with EUI-64 devices are IoTs or likely IoTs. To our surprise, a large number of subscribers host computers, mobile phones and other equipment that also uses EUI-64. Although large vendors, e.g., Apple, by default enable privacy extensions in their products [31], it seems that other popular vendors do not. This could be related to some operating systems not enabling privacy extensions by default.

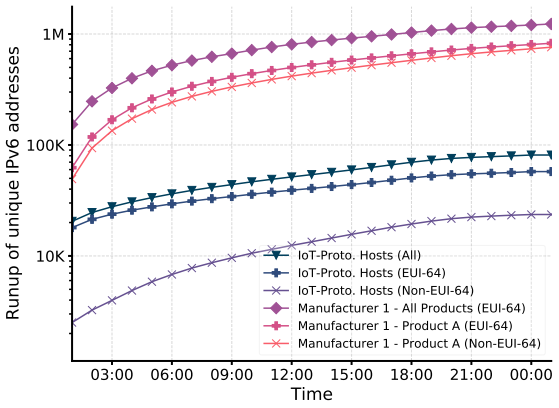


Figure 6: Prevalence of EUI-64 in IoT devices and a case study for a popular IoT product. Note that the y-axis is log-scaled.

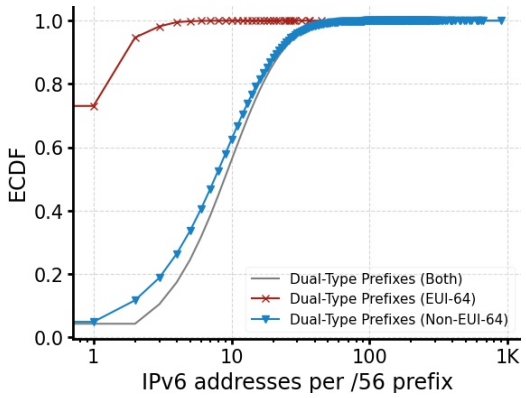


Figure 7: IPs in prefixes with both EUI-64 and non-EUI-64 IPs, i.e., dual-type prefixes. Number of non-EUI-64, EUI-64, and both types of IPs in dual-type prefixes. X-axis is log-scaled.

5.4 EUI-64 Use Among IoT Devices

Next, we focus on the IoT devices that contribute the most to the leakage of users' privacy. We take a conservative approach by only considering manufacturers which exclusively produce IoT devices. We manually investigate their product line and further categorize their products as follows: entertainment (that includes smart TV, voice assistants, streaming devices, media players), network attached storage (NAS), Raspberry Pi, smart home equipment, IoT parts manufacturer, home appliances, surveillance devices, point of sale devices, and varied products (that include multiple categories). See Appendix A.3 for a detailed description of these categories. As Figure 5 shows, the most popular category is entertainment IoT devices, which cover more than 85% of all /56 prefixes with only IoT devices. In this category, we identify more than 19 popular manufacturers. If this relatively small number of manufacturers had adopted best common practices to enhance IPv6 privacy, EUI-64 privacy leaks could have been substantially reduced.

However, even at the level of a manufacturer, it is possible that different products or product versions have different behavior when it comes to privacy leakage. To assess how common this is, we consider the top contributor of EUI-64 IoT devices in our dataset ("manufacturer 1"). Using the methodology that we introduced and validated in our previous work [45], we annotate the products of this IoT manufacturer based on the contacted destinations addresses. We utilize the destination information to annotate the most popular IoT product of this manufacturer ("product A"), and we also infer if a specific device uses EUI-64 or not, based on the IPv6 address. In Figure 6, we show the cumulative unique number of IPv6 addresses for all the products with EUI-64 of the manufacturer and the number of devices with product A with and without EUI-64 with hourly updates. A first observation is that, as expected, within 24 hours, the number of IPv6 addresses that host the EUI-64 devices as well as the IIDs of this manufacturer converge to around 1.2 million and 650k IPv6 addresses for the total and product A, respectively. The number of IPv6 addresses and IIDs that do use and do not use EUI-64 is similar for product A. Even though some of the devices belonging to product A have adopted IPv6 privacy extension, either by updates or because of newer models, the majority of these devices still have the potential to leak user privacy.

Unfortunately, it is not easy to generate signatures for all IoTs based on the visited destinations because the IoT devices have to be purchased, and communication data has to be collected in a lab over longer periods of time [45]. On the other hand, IoT-specific protocols such as MQTT [4] are popular among many IoT manufacturers. Indeed, we notice that port TCP/8883, i.e., the IANA-assigned port for MQTT, is among the top 10 ports by our top manufacturers (see Figure 10 in Appendix A.4 for a detailed view of ports used by different manufacturers). Hence, we use this activity as a proxy to infer what is the percentage of IoT-devices that use EUI-64 vs. any other MQTT activity that does not use EUI-64. In addition, we confirm that more than 95% of these devices contact servers that are exclusively used for IoT cloud services [27, 30]. Therefore, these devices are highly likely to be IoTs. Our analysis in Figure 6 shows that, indeed, more than 83% of the devices that communicate using the common IoT protocol MQTT are also using EUI-64. This is another indicator of the rampant privacy-violating practice of using EUI-64 addresses among IoT devices.

5.5 Collateral Privacy Leakage

In this section, we turn our attention to the popularity of EUI-64 devices in end-user prefixes. As shown in Figure 7, we typically only find one or two EUI-64 devices per end-user prefix. Indeed, more than 90% of end-user prefixes that host both EUI-64 and non-EUI-64 devices, i.e., are dual-type

prefixes, have two or fewer EUI-64 devices. Only about 1% of dual-type prefixes host more than five EUI-64 devices. Recall, from Figure 2, more than 93% of all end-user prefixes with EUI-64 devices also host non-EUI-64 devices.

Also, in Figure 7, we see that number of non-EUI-64 addresses in dual-type prefixes is larger than the number of EUI-64 addresses. However, a single EUI-64 device is sufficient to leak user privacy to a third party if both this device and a non-EUI-64 device contact the same destination. To understand how probable this collateral privacy leakage is, first, we analyze the popular applications that are contacted by EUI-64 devices. Our analysis shows that these devices contact popular applications, e.g., Web (port 443, 80), DNS (port 53), NTP (port 123). For details about the popularity of ports for the top EUI-64 manufacturers, we refer to Figure 10 in Appendix A.4. This is alarming, as other devices that use IPv6 privacy extensions also contact these ports. To estimate the collateral damage, we count the number of dual-type prefixes where EUI-64 and non-EUI-64 devices contact the same third-party provider. Figure 8 shows the number of end-user dual-type prefixes which can be tracked over time by common hypergiants [7]. We find that in total, two million end-user prefixes (around 17% of the total end-user prefixes) are affected by this collateral privacy leakage, with the top hypergiants, i.e., HG1, HG2, and HG3, being able to longitudinally de-anonymize prefix rotation efforts by the ISP. Alarmingly, users do not even need to log in or visit the websites of these hypergiants to be tracked. Tracking can simply happen by accessing one of their services, e.g., loading ads or static files. Some of these hypergiants run popular public DNS services and online advertising platforms that make them very attractive as a destination. A recent study also shows that services such as NTP can collect a vast number of IPv6 addresses [8], thus, breaking IPv6 privacy when sufficient conditions are in place, as we describe in our methodology (cf. Section 3). We note that this form of tracking can not only be facilitated by hypergiants but also at major aggregation points in the network, such as peering locations, Internet exchange points, transit providers, and large data centers.

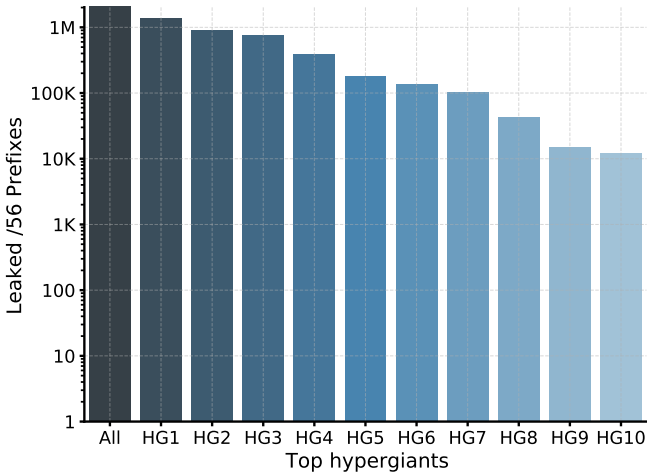


Figure 8: Per hypergiant number of /56 prefixes vulnerable to privacy. Each of these prefixes contains at least one EUI-64 address and one non-EUI-64 address.

6 DISCUSSION

Vendor Self-regulation: Hardware vendors should adequately test their products and make every effort to protect the privacy of their consumers, as currently, there is a gap in legislation regarding IPv6 privacy. This includes all the involved parties, from chip manufacturers to product integrators, software companies, and ISPs. For software companies, e.g., operating system distributors, it is important to enable IPv6 privacy extensions by default. Unfortunately, at the time of writing, many Linux distributions do not activate privacy extensions by default. Products using Linux derivatives in their software are likely unknowingly putting their users' privacy at risk. This could be related to the fact that the original privacy extensions specification [39] contained a recommendation to deactivate them by default. The current standard [24] does not contain this recommendation anymore. We, therefore, recommend that all IPv6-capable software stacks enable IPv6 privacy extensions by default. We are in contact with hardware vendors to make them aware of this issue.

Privacy Badges: The average user is not a privacy expert when purchasing or operating smart home appliances or other Internet-connected devices. Although the end-user may be aware of privacy risks when using such devices, we can not expect end-users to perform experiments to validate which devices use privacy extensions and which do not. The consumer unions and regulators, e.g., the FCC and FTC in the US and the European Commission in the EU could require vendors to certify their products for IPv6 privacy compliance. These badges could affirm the compliance of a product with the relevant future legislation, similar to other certifications, e.g., health, safety, and environmental protection standards [10].

The Role of the ISP: ISPs should continuously improve the privacy that they provide to their customers and could also inform them about potentially privacy risky products in the market and their home network upon customer request. Another possibility would be to introduce a NAT in ISP IPv6 client networks. This would, however, break the end-to-end principle—a primary design goal of IPv6 [12]. Therefore, we refrain from recommending NAT as a practical workaround. Finally, ISPs should also check CPEs for privacy risks before shipping them massively to their customers.

7 CONCLUSION

In this paper, we show a new way to defeat IPv6 privacy even when the ISP does prefix rotation. We find that a single device that uses EUI-64 can be leveraged as a tracking identifier for devices in the same end-user prefix. Our analysis shows that up to a 19% of end-user prefixes in a large ISP can face IPv6 privacy leakage, and up to 17% of them can be monitored by third parties, primarily hypergiants. Closer investigation unveils that IoT devices and popular manufacturers contribute the most to this type of IPv6 privacy leakage. We propose that vendors should enable privacy extensions by default and that regulatory intervention is necessary to protect users' privacy. In the future, we continue to monitor prevalence of EUI-64 devices, and we extend our study by collaborating with other ISPs.

ACKNOWLEDGMENTS

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A APPENDIX

A.1 Analysis of Non-EUI-64 IPv6 Addresses

Non-EUI-64 addresses can be privacy extension addresses, addresses assigned via DHCPv6, or also statically assigned addresses. In order to understand how many of the non-EUI-64 addresses are actually privacy extension addresses, we analyze the interface identifier (IID) of all non-EUI-64 addresses. We use the Hamming weight, i.e., the number of bits set to '1', to analyze the random nature of IIDs. In completely random 64 bit IIDs, i.e., the presence of privacy extensions, we would expect exactly half of the bits being set to '1'. Moreover, the central limit theorem states that the sum of those independent IID Hamming weight distributions tends toward a normal distribution. In Figure 9 we show the Hamming weight distribution of these IIDs along with the normal distribution shifted one bit to the left due to the universal/local bit. As can be seen, the non-EUI-64 Hamming weight distribution perfectly matches the normal distribution. Consequently, non-EUI-64 addresses in our dataset are in fact privacy extension addresses.

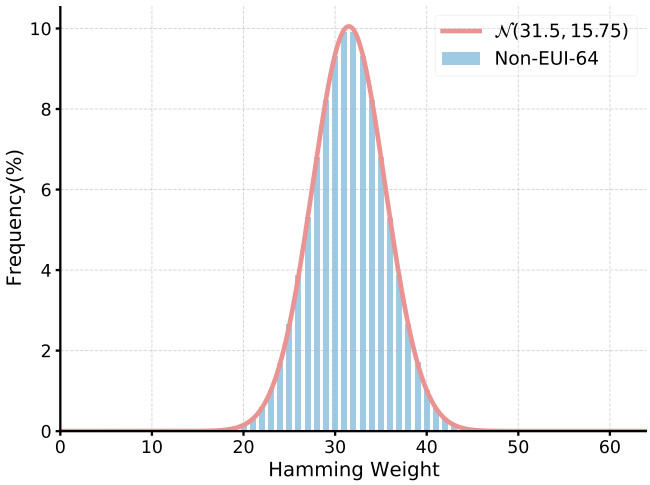

Figure 9: Hamming weight distribution of non-EUI-64 IIDs.

Category	Description
IoT	Manufacturers of internet-connected devices such as sensors, smart TVs, home appliances, security cameras, alarms, smart speakers, etc.
Computers	Laptops, personal computers, and servers
Mobile	Mobile phones and tables
CPE	Devices supporting broadband technologies such DSL, cable modem, and 5G/4G hotspots.
Parts Manufacturer	Network interface cards, CPUs, memory modules, motherboards, WiFi modules, and chipsets that can be embedded into other devices.
Network Equipment	Routers, switches, access points, and firewalls.
Gaming Console	Internet connected devices primarily used for gaming.
Unknown	Manufacturers that we were not able to find their website, or were not providing any information about the type of their products.
Virtual Machine	Vendors that develop virtual machine and hypervisor software.

Table 1: Description of device categories.

A.2 Device Categories

By associating OUIs to their manufacturers, we can, for many OUIs, even identify the type of device. The IEEE OUI database [32] contains details such as the name and address of the company that registers an OUI. Depending on the range

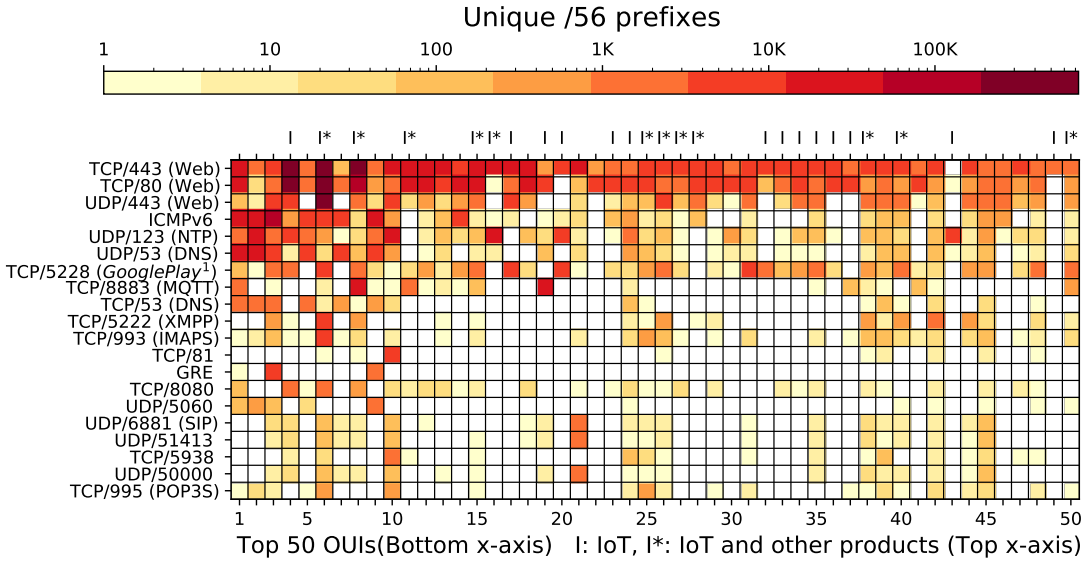

Figure 10: Heatmap showing used application ports for the top 50 OUIs. [1]The Google Play port is not officially registered with IANA.

Manufacturer Type	Description
Entertainment	Manufacturer of smart TVs, over the top streaming devices (OTTs), smart speakers, network-connected media players.
Network Attached Storage	Internet-connected devices used for storing data.
Smart Home	devices such as smart plugs, light bulbs, door openers, alarms, and thermostats.
Varied	Manufacturers with a large portfolio of IoT devices, that not only includes all our categories but span beyond them. For example, robots, industrial devices, highly-specialized medical equipment, etc.
Parts Manufacturer	Chipsets, and modules tailored to be used specifically in IoT devices, e.g. 3G/4G, and Zigbee modules. Note, we tag a manufacturer in this category, only if it explicitly states that it produces IoT-specific modules and chipsets.
Home Appliance	Washing machine, refrigerators, air conditioners, air purifiers, etc.
Surveillance	Security cameras and related surveillance equipment.
Point of Sale	Devices mostly used at retail stores for accepting payments.

Table 2: Description of IoT manufacturer categories.

and type of products of a manufacturer, it is possible to identify the type of a device. For example, if we observe an OUI registered by a company producing only wind turbines, the device generating the traffic is likely a wind turbine. For this purpose, we visited the company's website that registered our OUIs. We categorized their products into one or multiple categories. Some companies produce generic products, e.g., network interface cards (NICs) installed in many devices. In such cases, we mark their OUIs as Parts Manufacturers. Moreover, if a company produces more than one product category, we assign their OUIs into all those categories. Table 1 explains the different types of devices categories that we used in our device classification.

A.3 IoT Manufacturer Categories

Table 2 explains the different types of IoT manufacturer categories that we used in our EUI-64 classification.

A.4 Traffic Profile by Manufacturer

Figure 10 shows the popularity among the top 20 protocols utilized by top 50 manufacturer devices that use EUI-64. These devices utilize protocols that are also popular for other devices, like laptops, smartphones, etc. that may use privacy extension. Thus, it is possible that devices using EUI-64 and other that do not use EUI-64 contact the same CDNs (Web on ports 80 and 443), applications (Google play updates on port 5228 [26], MQTT on port 8883), or other services (NTP on port 123, DNS on port 53).