Surveilling the Masses with Wi-Fi-Based Positioning Systems

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***Abstract*—Wi-Fi -based Positioning Systems (WPSes) are used by modern mobile devices to learn their position using nearby Wi-Fi access points as landmarks. In this work, we show that Apple's WPS can be abused to create a privacy threat on a global scale. We present an attack that allows an unprivileged attacker to amass a worldwide snapshot of Wi-Fi BSSID geolocations in only a matter of days. Our attack makes few assumptions, merely exploiting the fact that there are relatively few dense regions of allocated MAC address space. Applying this technique over the course of a year, we learned the precise locations of over 2 billion BSSIDs around the world.**

The privacy implications of such massive datasets become more stark when taken longitudinally, allowing the attacker to track devices' movements. While most Wi-Fi access points do not move for long periods of time, many devices—like compact travel routers—are specifically designed to be mobile.

We present several case studies that demonstrate the types of attacks on privacy that Apple's WPS enables: We track devices moving in and out of war zones (specifically Ukraine and Gaza), the effects of natural disasters (specifically the fires in Maui), and the possibility of targeted individual tracking by proxy—all by remotely geolocating wireless access points.

We provide recommendations to WPS operators and Wi-Fi access point manufacturers to enhance the privacy of hundreds of millions of users worldwide. Finally, we detail our efforts at responsibly disclosing this privacy vulnerability, and outline some mitigations that Apple and Wi-Fi access point manufacturers have implemented both independently and as a result of our work.

1. Introduction

Mobile devices increasingly rely on frequent, precise geolocation, both for location-based services (e.g., driving directions, advertising, gaming, localized search) as well as for tracking one's devices in the case of loss or theft [31] (e.g., Apple's Find My service). Due to its high power consumption, GPS is not a viable solution for such frequent geolocation needs. Instead, Apple and Google operate *Wi-Fi-based Positioning Systems* (WPSes), which allow mobile devices to query a server for their location based on the Wi-Fi access points they see.

At a high level[1]: mobile devices that have used GPS to ascertain their location periodically report to the WPS the Wi-Fi access points' MAC addresses—known as BSSIDs—that they observe, along with their GPS coordinates. The WPS stores the reported locations of the BSSIDs at a server. Then, other mobile devices who are unable or unwilling to use GPS can query the server, providing a set of BSSIDs it sees and receiving an estimated geolocation in return.

1. We provide more details of Apple's WPS in §2.

As prior work has noted [35], [12], popular WPSes (especially Apple's and Google's) are publicly accessible, and they do not require devices querying the database to prove they actually see the BSSIDs they claim to see. In other words, one can query for *any* arbitrary MAC address and, if it is in the WPS's database, then it will return its location. This design lends itself to relatively obvious *individually-targeted* attacks. For instance, if a victim of intimate partner violence were to move to an undisclosed location, their ex-partner could periodically query the WPS with the BSSID of the victim's Wi-Fi access point (or travel modem, Wi-Fi enabled TV, etc.) until its location appears, thereby divulging the victim's location. While dangerous, individually-targeted attacks like this require an attacker to have *a priori* knowledge about their targets, thereby limiting the potential threat.

In this paper, we show that an unprivileged, weak attacker can take advantage of Apple's WPS to perform *mass surveillance* of users' Wi-Fi access points virtually anywhere in the world, without any *a priori* knowledge. We present novel ways to query Apple's WPS that allow us to learn about devices worldwide, and to exhaustively track devices into and out of target geographic regions. We perform a systematic empirical evaluation of the data available from WPSes, finding that they span hundreds of millions of devices, and that they allow us to monitor the movement of Wi-Fi access points and other devices.

To demonstrate the potential our attack has at using WPSes for open-source intelligence (OSINT), we present several case studies, including:

Russia-Ukraine War First, we use Apple's WPS to analyze device movements into and out of Ukraine and Russia, gaining insights into their ongoing war that, to the best of our knowledge, have yet to be made public. We find what appear to be personal devices being brought by military personnel into war zones, exposing pre-deployment sites and military positions. Our results also show individuals who have left Ukraine to a wide range of countries, validating public reports of where Ukrainian refugees have resettled.

Israel-Hamas War in Gaza Second, we use Apple's WPS to track movements out of and within Gaza, as well as the disappearance of devices throughout the Gaza Strip. This case study shows that it is possible to use WPS data to track extensive outages and loss of devices.

Making matters worse, users whose devices are being tracked never opted in to Apple's WPS in the first place, nor did they have a way to opt out when we conducted this study. Merely being within Wi-Fi range of an Apple device can lead to a device's location and movements being made widely and publicly available. Indeed, we identify devices from over 10,000 distinct vendors in Apple's WPS. Fortunately, in response to our responsible disclosure (§10), Apple now provides a way for users to opt their devices out. We discuss additional potential mitigations in §9.

Contributions To summarize, this paper makes the following contributions:

- We introduce the first known techniques for using Wi-Fi-based Positioning Services to perform *mass surveillance* of Wi-Fi access point locations, movements, and outages. (§4)
- We perform an extensive and systematic evaluation of the extent to which an unprivileged attacker can perform mass surveillance using Apple's WPS, building from no *a priori* knowledge a corpus of 490,940,552 BSSIDs in virtually all locations around the world. (§7)
- We present several case studies of the mass surveillance attack: movements in and out of military locations (within Ukraine and Gaza) as well as the aftermath of a natural disaster (the fires in Maui, Hawaii). (§8)
- We present several possible ways that various stakeholders could mitigate these attacks. (§9)
- We disclosed our findings to Apple and Google—both of which operate their own WPS—as well as two of the most salient manufacturers in our case studies: SpaceX and GL.iNet. We report on this disclosure process and the remediations Apple and SpaceX have taken in response. (§10)

2. Background

In this section we discuss 802.11 hardware identifiers, commonly known as Media Access Control (MAC) addresses, and the operation of Wi-Fi Positioning Systems (WPSes), which are systems that assist in geolocation by using 802.11 identifiers as landmarks.

2.1. MAC Addresses and BSSIDs

MAC addresses are 48-bit link-layer identifiers used to identify a network interface on a local network. MAC addresses are typically written as 12 hexadecimal digits, with each pair separated by colons or hyphens, e.g., `08:4A:93:2F:B1:07`. When a Wi-Fi access point (AP) creates an 802.11 network, the AP and the devices connected to it form a *Basic Service Set (BSS)*. The MAC address the Wi-Fi AP uses for that BSS is called a Basic Service Set Identifier (BSSID). Note that there is a many-to-one relationship between BSSIDs and APs; one AP can form several 802.11 Wi-Fi networks (e.g., an employee network and a guest network) by using different BSSIDs for each.

Some bits of MAC addresses have semantic meaning. The lowest order bit of the first byte, for example, indicates whether the MAC address is unicast (when the bit is unset) or multicast (when set). Of particular note, the second lowest order bit of the first byte—the so-called Universal/Local (U/L) bit—indicates whether the MAC address is globally assigned to a manufacturer by the IEEE (when the bit is unset), or if the MAC address is locally assigned by the device. Locally-assigned MAC addresses are often used for peer-to-peer applications (which typically invert the U/L bit of the globally-assigned MAC address) or by Wi-Fi APs advertising multiple 802.11 Wi-Fi networks by creating virtual interfaces using the same physical hardware. When devices choose random MAC addresses, as most modern mobile 802.11 clients do for anti-tracking protection, they also set the U/L bit.

2.2. Wi-Fi Positioning Systems (WPSes)

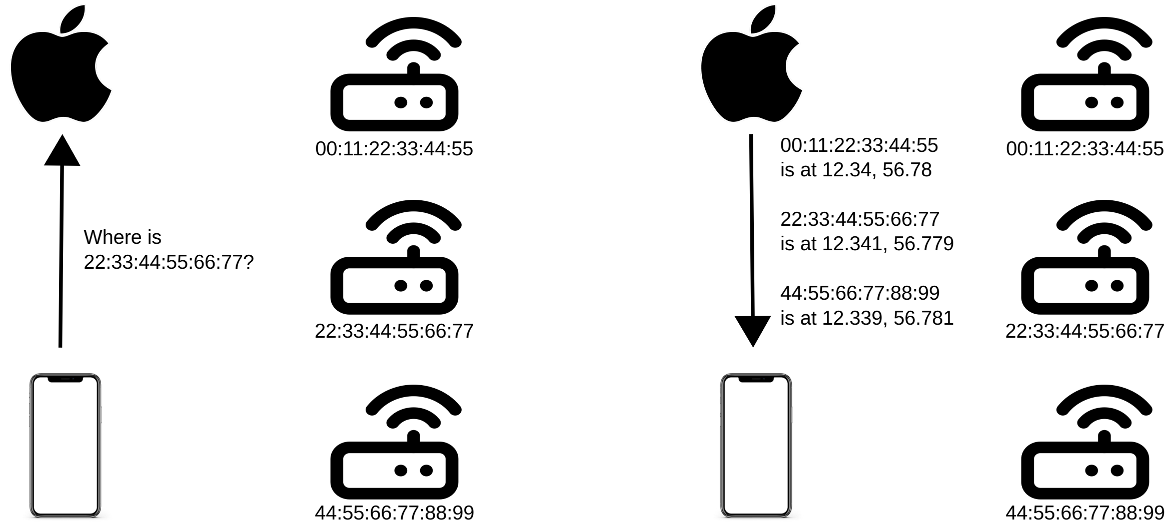
WPSes, which use BSSIDs as landmarks by which to geolocate devices, are central to this work. WPSes are typically queried via an API. These APIs are backed by large-scale databases that contain the geolocations of hundreds of millions of Wi-Fi routers.

WPSes obtain the locations of the BSSIDs in their databases through a crowd-sourced network of sensors. In the case of Google and Apple, the devices that populate their WPSes are mobile phones and other devices running their operating systems. Periodically, these devices will forward their locations (obtained through GPS or trilateration using cell towers as landmarks) along with nearby AP BSSIDs and their received signal strengths. If enough sensors detect a BSSID for a long enough period of time, the BSSID and its estimated location are made entries in the WPS.

These WPSes typically operate in one of two ways. First, a client may submit a list of nearby Wi-Fi AP BSSIDs and signal strengths through the API. The positioning system then calculates the position of the client that observed the APs, and responds to the client with the computed position. Google's Wi-Fi Geolocation API [14] works in this manner, requiring at least 2 BSSIDs in order to calculate a client's position.

Conversely, other Wi-Fi geolocation systems put the onus of trilateration on the client. These APIs also accept a list of nearby AP BSSIDs; instead of computing the client's location based off the set of observed APs and their received signal strengths, the API returns the geolocations of the BSSIDs the client submitted.

Apple's Wi-Fi geolocation API [4] works in the latter manner, but with an added twist: In addition to the geolocations of the BSSIDs the client submits, Apple's API opportunistically returns the geolocations of up to *several hundred more* BSSIDs nearby the one requested. These unrequested BSSID geolocations are presumably then cached by the client, which no longer needs to request the locations



(a) An Apple device queries the Apple WPS for BSSIDs it detects in 802.11 scans to geolocate itself.

(b) The Apple WPS responds with the BSSID's geolocation as well as the geolocations of up to 400 additional nearby BSSIDs.

Figure 1: An Apple device querying and receiving BSSID geolocations from the Apple WPS. The WPS is populated by other Apple devices that report their geolocations (derived from e.g. GPS) and nearby BSSIDs, which the WPS then uses as landmarks. This figure shows 3 decimal digits of precision, though Apple routinely provides up to 8.

of the nearby BSSIDs it may soon encounter, e.g., as the user walks down a city street.

Figure 1 demonstrates the operation of Apple's WPS. A device that needs to trilaterate its own position based on nearby BSSIDs queries Apple's WPS for the locations of the BSSIDs it detects (Figure 1(a)); multiple BSSIDs' geolocations can be requested in the same query. When it knows a BSSID's geolocation, Apple's WPS, unlike Google's, also responds with the locations of up to 400 additional nearby BSSIDs for the querying device to cache (Figure 1(b)).

Apple's WPS API is free and places few restrictions on its use. It requires neither an API key, authentication, nor an Apple device; our measurement software is written in Go and runs on Linux. Moreover, Apple appears to make no attempt to filter physically impossible queries. The BSSIDs submitted to the WPS need not be physically proximate to each other nor to the device submitting the query; Apple's WPS will respond with geolocations for BSSIDs on two different continents in the same request to a querier on a third.

The operation of Apple's WPS was first described in 2012 [3] and has since been used in other work to geolocate *known* BSSIDs—those observed nearby [19] or computed from IPv6 addresses [32]. We extend prior work by efficiently discovering large numbers of previously *unknown* BSSIDs.

3. Related Work

There is some prior work that has investigated WPSes and their accompanying security and privacy concerns.

The earliest such work is a 2009 study by Tippenhauer et al. [35] that investigated the Skyhook WPS [34]. At that time, the Skyhook WPS was used by Apple devices to calculate their own positions. They did this by submitting nearby BSSIDs to Skyhook servers, which would look the BSSIDs up in location lookup tables (LLTs). For BSSIDs whose locations are known, the Skyhook system would then return the geolocations of these BSSIDs for the local device to compute its own location. Although Apple ceased using Skyhook the following year in favor of using its own Wi-Fi geolocation database [33], its devices continue to compute their own locations in essentially the same manner.

Tippenhauer et al. demonstrated several attacks against the Skyhook Wi-Fi geolocation service. First, they used another Wi-Fi geolocation database, WiGLE [37], to obtain BSSIDs of APs in a geographically-distant city. They then set up rogue APs spoofing the BSSIDs of the remote APs. This had the effect of tricking Apple devices in the vicinity of the spoofed BSSIDs into incorrectly believing they were in the remote location. They also discovered that they could inject false information into Skyhook's geolocation database by spoofing the location of Apple devices using rogue APs, while also transmitting from APs using BSSIDs unknown to the Skyhook service. These new BSSIDs were eventually added to Skyhook's LLTs after broadcasting for some time.

Our attacks leverage Apple's WPS, which works in much the same way as the Skyhook system is described. Unlike Tippenhauer et al., we are primarily concerned with discovering the locations of APs worldwide and studying their movement over time.

Several years later, Feng et al. extended Tippenhauer's approach to location services systems beyond Skyhook, including Google's, Apple's, and Microsoft's WPSes [12]. They show that all four of these services can be tricked into providing the client device with an incorrect location by setting up rogue APs from the location to be spoofed, while simultaneously jamming nearby legitimate APs.

Boutet and Cunche examined privacy concerns inherent in WPSes [8]. However, their threat model assumed the adversary was the operator of the Wi-Fi location provider (e.g., Google, Apple, or Skyhook), which can learn the location of the device using the system from the BSSIDs it queries. In contrast, our threat model assumes the adversary is an unprivileged user of a Wi-Fi geolocation API.

Han et al. reverse-engineered Google's WPS's method of operation [17]. Google's WPS functions differently than Skyhook's and Apple's insofar as Google's service attempts to geolocate the device submitting the query, providing it with only the device's computed position given a list of BSSIDs from the client. They used this knowledge to improve the effectiveness of the location spoofing attack introduced in previous work.

One related work used Apple's WPS to geolocate Wi-Fi routers, as does our own study. In *IPvSeeYou*, Rye and Beverly extracted MAC addresses from a legacy form of IPv6 addresses they obtained in large-scale active Internet measurements [32]. Then, they used data from Apple's WPS, along with BSSIDs from wardriving databases [27], [28], [29], as an oracle to find closely-related BSSIDs (i.e. within a few bits from the IPv6-extracted MAC address). Their observation was that closely-related BSSIDs are a strong indicator that both MAC addresses belong to different interfaces on the same device.

Rye and Beverly's attack differs from ours in several key ways. First, the authors used Apple's WPS solely to geolocate all-in-one combination devices that have both a WAN and WLAN interface with MAC addresses at small offsets from each other. By contrast, our work has no such requirements—its efficacy relies only on an AP being powered on and stationary for long enough to appear in Apple's WPS. Second, our work focuses on building a worldwide corpus of Wi-Fi geolocation data for the purpose of observing location changes over time. By contrast, Rye and Beverly's work is naturally skewed toward countries with large IPv6 deployments, and did not study the privacy problems that result from BSSID movement over time—a central focus of our work.[2]

In sum, while prior work is concerned with providing a spoofed location to unwitting client devices or geolocating IPv6 addresses, our goal in this work is to amass a large-scale, longitudinal corpus of BSSID locations, and examine the privacy concerns this raises. The next section describes the range of attacks that can be mounted with such a corpus.

4. Mass Surveillance Using WPSes

In this section, we describe a novel way to use a WPS to perform mass surveillance without any *a priori* knowledge. We focus the details of our attack on Apple's WPS, but the high-level approach generalizes to other WPSes, as well.

4.1. Threat Model

We assume an unprivileged, low-resource adversary who has no prior knowledge of in-use BSSIDs. The adversary need not have a device from any particular manufacturer (e.g., Apple or Google), nor does it need to be geographically proximal to any specific target. The central goal of the attacker we consider is to gather location and movement data about a large number of devices, either globally or pertaining to a specific region of interest. Such information gathering can enable a wide range of information-leaking attacks; we present several such case studies in §8.

4.2. Mass Surveillance Attack

We assume that our adversary initially knows nothing about the geographic locations of any Wi-Fi BSSIDs, and uses the Apple Wi-Fi geolocation API as an oracle to detect online BSSIDs.

In the most naïve variant of this attack, the adversary simply generates BSSIDs at random and queries the WPS for them. To get a sense of the likelihood that querying for a random BSSID would result in returning an actual device's location, first recall that as MAC addresses, BSSIDs are 48 bits. Second, note that WiGLE reports 1.19 billion unique Wi-Fi networks in its 20-year corpus. Using this as an estimate for the number of active APs, this would result in a probability of 0.0004% that a random BSSID corresponds to a live device.

An adversary can drastically reduce the number of queries it has to make by *seeding* their guesses using the list of allocated Organizationally Unique Identifiers (OUIs) published by the IEEE [21]. The IEEE allocates 24-bit OUIs[3] to organizations that need to allocate MAC addresses to network interfaces, for which they pay a small fee. MAC addresses are used in the 802.3 Ethernet, Bluetooth, and 802.11 Wi-Fi protocols to provide link-layer identifiers. An organization that has been allocated an OUI can then allocate the remaining 24 bits of the MAC address to individual network interfaces as they choose. The relationship between organizations and OUIs is one-to-many; large organizations may have tens or hundreds of OUIs registered.

Importantly, however, allocated OUIs provide a starting point from which to test for active BSSIDs, which are MAC addresses used for the wireless interface on APs. At the time of writing, the IEEE has made 34,322 OUI allocations that are listed in its public OUI database [21]. In addition to the IEEE-assigned OUIs, an attacker can also include the IEEE-assigned OUIs with the U/L bit set to 1 (see §2.1). The U/L bit, when 0, indicates that the MAC address is from an OUI assigned by the IEEE and should be globally-unique. All IEEE-assigned OUIs have the U/L bit set to

2. In fact, their study ignored movement altogether; whenever they saw a device in multiple locations, they chose one randomly as the "canonical" location [32, §7.3].

3. OUIs are also referred to by the IEEE as MAC Address Block Large (MA-L) allocations.

Algorithm 1: Mass Information Gathering with WPSes

1) $\mathsf{GeolocatedBSSIDS} \leftarrow \emptyset$
2) **Seed** an initial set of OUIs:
   $\mathsf{OUIs} \leftarrow$ IEEE-assigned OUIs (U/L = $\{0, 1\}$)
3) Until OUIs is exhausted:
   a) Choose an o from OUIs
   b) Generate 2^{14} distinct BSSIDs with OUI o
   c) Query the WPS for each random BSSID b
   d) For each successful response, comprising the location for b and the locations of up to 400 nearby BSSIDs:
      i) Add b's location to $\mathsf{GeolocatedBSSIDs}$.
      ii) Add each nearby BSSID's location to $\mathsf{GeolocatedBSSIDs}$.

0. When the U/L bit is set to 1, however, it indicates that the MAC address is "locally-administered," and the MAC address should not be considered globally-unique. APs will sometimes use MAC addresses from their assigned OUI with the U/L bit set to 1 when creating multiple virtual interfaces on the same physical hardware.

With both IEEE-assigned OUIs and their locally-administered variants, there are 68,644 potential OUIs to use to bootstrap BSSID discovery using Apple's Wi-Fi geolocation API. This is a dramatic reduction of the search space. A naïve attacker guessing random BSSIDs from the 48-bit MAC address space is in effect guessing randomly from each of the 2^{24} = 16,777,216 possible OUIs. By restricting random BSSID guessing to IEEE-assigned OUIs and their locally-administered variants, an attacker narrows the search space by 99.6%. After this search space winnowing, the attacker then chooses random BSSIDs to query. In our own implementation (§6), we query for 2^{14} random BSSIDs from each of the 68,644 IEEE-assigned and locally-administered OUIs.

These queried BSSIDs represent a naïve understanding of the allocated MAC address space that any reasonably-informed attacker could gather with little-to-no difficulty. As we will see in §7, this leads to rapid discovery of live devices. We will also show that, while there are indeed APs with OUIs that are *not* from this small set of prefixes, our technique is able to learn these, as well, because Apple's WPS provides up to 400 nearby BSSIDs with each successful request.

We summarize how an attacker can perform mass information gathering in Algorithm 1.

After obtaining a large collection of random BSSIDs' locations, an adversary can then use that collection to explore specific geographic regions of interest. To do this, the attacker can simply identify which BSSIDs are in the target geographic region (or keep querying with random BSSIDs until it finds some), and then repeatedly issue queries for the locations of the nearby BSSIDs it returns, thereby getting another list of nearby BSSIDs, and so on.

Note that the attack outlined here, and the specific case studies in §8, require only minimal technical sophistication and can be carried out by individuals with consumer-grade hardware, with no additional charges or subscriptions. Before evaluating the attack's capabilities, we first consider ethical issues raised by WPSes and the ability to conduct these attacks.

5. Ethical Considerations

Any work that has the potential to track individuals remotely naturally raises ethical questions. As a preliminary step, we consulted with our institution's IRB, which determined that this work is not human subjects research. However, we believe that our conduct of this work and our aims further adhere to the principles of beneficence and respect for persons.

To demonstrate the feasibility of our attack, we make use of Apple's crowd-sourced WPS via an API. This API is used by Apple products to trilaterate their own location through the geolocations of nearby AP BSSIDs; our queries mimic those that iOS and macOS devices routinely make. Apple provides this API free of charge without the requirement to register for the service or obtain an API key; furthermore, the use of this API appears to be unrestricted in the query rate or number of queries allowed. During this study, we issued approximately 30 queries per second; at this rate, we did not encounter rate-limiting or observe service interruptions or outages. Each API call can itself contain multiple BSSIDs to query, and in practice, we included 100 BSSIDs per API request.

To the best of our knowledge, there is no official Apple policy restricting the use of this API. While no official documentation for this API exists, it has been publicly documented in academic [32], [3] and security community [19] work over the last decade. Google's WPS, which we do not examine, has also been the subject of privacy research [17].

This work identifies the potential for harm to befall owners of Wi-Fi APs, particularly those among vulnerable and sensitive populations, that can be tracked using WPSes. The threat applies even to users that do not own devices for which the WPSes are designed—individuals who own no Apple products, for instance, can have their AP in Apple's WPS merely by having Apple devices come within Wi-Fi transmission range.

In §7 and 8, we demonstrate the ability to track both individuals and groups of people over time and space. Because the precision of Apple's WPS is on the order of meters, this allows us to, in many cases, identify individual homes or businesses where APs are located. Out of respect for user privacy, we do not include examples that could publicly identify individuals in the case studies we examine in this work. However, determining the identities of individuals or groups they are a part of—down to individual names, military units and bases, or RV parking spots—is eminently possible using the techniques we describe in this work, and is a major motivating factor for our disclosure of this vulnerability. As such, we have disclosed this vulnerability to Apple and router manufacturers that feature prominently in our case studies (§8). We discuss our communication with these companies and remediation measures they have taken in §10.

The data collected during this study is stored on the authors' machines and will not be publicly released. After follow-on work to improve user privacy has concluded, we will destroy the data.

6. Data Collection Methodology

This section describes the datasets we collected; we analyze them in §7 and §8. All of our data was collected from a single vantage point located in an access network in the United States.[4]

6.1. Month-Long Longitudinal Dataset

While the global corpus collection experiment outlined in §4.2 provides a snapshot of the world-wide distribution of BSSIDs, a fundamental privacy issue with the existence of Wi-Fi geolocation APIs is the potential for user movement to be captured as these APIs are queried over extended periods of time.

To measure the potential for user tracking over time, we sample 10 million BSSIDs from the global corpus we amass by randomly guessing BSSIDs within known OUIs. Then, we query the Apple WPS for these BSSIDs on a daily basis to detect movements in the BSSID geolocations as reported by the API.

With this knowledge, we then characterize the type and amount of movement in our sample. We examine the locations from which and to which APs (and potentially their owners) are migrating.

The results of our month-long querying the Apple geolocation API for the 10 million sampled BSSIDs are reported in §7.2

6.2. Year-Long Longitudinal Dataset

Next, we use a longitudinal dataset collected between November 2022 and November 2023 as the basis for demonstrating several practical privacy attack case studies in §8. This corpus, which consists of over 2 billion distinct BSSIDs, was additionally focused on various hotspots throughout the year (e.g., Russia's invasion of Ukraine and the August 2023 wildfires on the Hawaiian island of Maui). Its purpose is to highlight the types of practical privacy attacks a motivated attacker can mount, rather than to demonstrate the ability to develop a worldwide BSSID geolocation database.

However, collecting BSSIDs from a specific geographic area requires knowledge of "seed" BSSIDs located in that area, so that a more comprehensive picture of the APs in that location. We used an initial dataset developed using methodology similar to that outlined in §4.2 to build an initial, worldwide BSSID view. Then, when we wanted to focus on specific regions, we first filtered for BSSIDs within that geographic region from our global dataset before repeatedly querying for our areas of interest.

6.3. WiGLE Data Validation

Last, to validate our geolocation collection methodology, we compare the results of querying Apple's WPS with data retrieved from WiGLE.

WiGLE [37] is a 20-year-old crowdsourced Wi-Fi, cellular tower, and Bluetooth wardriving project. Wardriving is the term for wireless surveying, often done while mobile, and typically involves annotating the location the wardriver is at when her equipment receives the wireless signals [6], [20]. WiGLE contains records of more than 1 billion Wi-Fi BSSIDs and their geolocations, and is queryable through a rate-limited API. WiGLE is well-known in the wireless security community for being a source of Wi-Fi geolocation data, so we compare the results of querying the Apple WPS with WiGLE data for 60,000 BSSIDs selected from popular Customer Premises Equipment (CPE) equipment and IoT vendor OUIs—TP-Link, Roku, Technicolor, and Vantiva. The 60,000 BSSID sample we selected from WiGLE was filtered for BSSIDs that had been updated within the last two months (on or after 1 October 2023) to ensure relative temporal consistency

Of the 60,000 BSSIDs we retrieved from WiGLE, we removed 178 that were geolocated by WiGLE to 0,0 latitude and longitude, the so-called "Null Island" in the Atlantic Ocean. These were likely due to misconfigured equipment, GPS devices without an accurate fix, or some other data corruption. We then requested the geolocations for the remaining 59,822 BSSIDS from the Apple WPS. Of these, 5,951 (10%) BSSIDs were unknown to the Apple WPS, which responds with a `-180, -180` latitude and longitude for these BSSIDs. The remaining 53,871 (90%) were geolocatable by the Apple WPS. Of these, the vast majority (52,946 or 98% of the Apple-geolocatable BSSIDs) were located within 1 kilometer of the WiGLE geolocation. We discuss BSSID movement in more detail in §7 and 8.

7. Systematic Analysis of a Global Corpus

In this section we describe the results of our global corpus collection, and detail a month-long study in which we queried 10 million BSSIDs daily.

7.1. Global Corpus Collection

The attack we demonstrate in this work is the ability to curate a worldwide view of geolocated BSSIDs, from

4. To verify that using only a single vantage point did not introduce bias, we issued a set of queries for 100 test BSSIDs with known geolocations from five geographically disparate locations: Mumbai, India; Melbourne, Australia; Warsaw, Poland; Paris, France; and Washington, DC. Apple's WPS returned identical geolocations (to eight decimal places) to each vantage point. Therefore, we determined that with the possible exception of mainland China—which rarely appears in our data—vantage point location appears not to impact the results returned by the WPS.

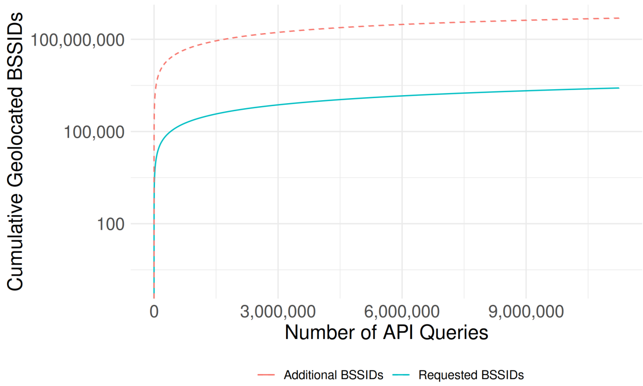


Figure 2: Number of BSSIDs discovered by guessing randomly among IEEE-assigned OUIs and their locally-administered versions versus the additional BSSIDs the Apple Wi-Fi geolocation API returns. Note that the y-axis is log-scale.

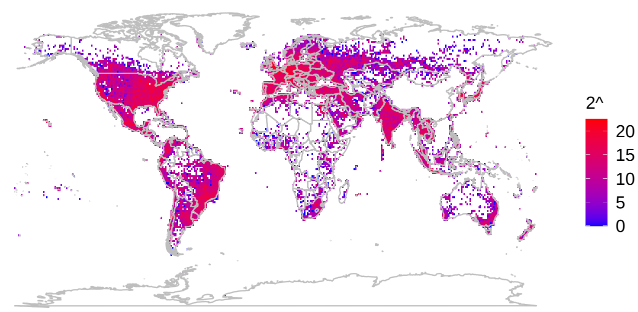


Figure 3: Heatmap of BSSIDs discovered by guessing randomly among IEEE-assigned OUIs and their locally-assigned variants.

which we can gain a number of insights, as we discuss in §8. We build this corpus by querying the Apple WPS for random BSSIDs within IEEE-assigned OUIs and their locally-assigned analogs.

Of the 1,124,663,296 BSSIDs for which we queried the Apple WPS, only 2,834,067 (0.25%) were successful—that is, were BSSIDs known by the Apple WPS. In the event that the WPS does not have a record of a requested BSSID, it returns a `-180, -180` latitude and longitude pair. When the Apple WPS does have a geolocation for a BSSID, it returns the latitude and longitude of the BSSID as inferred from measurements made previously by Apple devices to populate the WPS database.

While only ∼3 million BSSIDs we randomly chose from within the 68,644 OUIs were known by the Apple Wi-Fi geolocation API, we learned the geolocations of substantially more BSSIDs due to how Apple's WPS operates. When an API request is made for a BSSID that Apple's WPS knows the geolocation of, it additionally returns *up to 400 additional, nearby geolocated BSSIDs.*

In theory, this opportunistic BSSID caching is desirable feature. An Apple device that queries for the geolocations of nearby BSSIDs in order to trilaterate its own location will not need to do so again in the future if the API responds with many BSSIDs near its location—it need only consult its cache of geolocated BSSIDs when the user walks down the block. However, to an attacker, the additional BSSIDs returned by the API offer a wealth of information and comprise the vast majority of BSSIDs discovered in our experiment.

While we correctly guessed only 2,834,067 valid BSSIDs at random from our set of 68,644 known OUIs, we learned 488,677,543 geolocated BSSIDs—172 times more BSSIDs—from the additional geolocation data that the Apple API returns (a small number were both requested and learned in the additional BSSIDs returned from a different request).

Figure 2 displays the cumulative number of BSSID geolocations learned from the Apple WPS during our global corpus collection. The distance between the curves indicate that the knowledge gained from the additional nearby BSSIDs remains relatively constant as the number of queries grows (each API query contained 100 BSSIDs to be geolocated). Further, the number of new BSSIDs learned continues to grow linearly over time (Figure 2's y-axis is log-scale).

The geographic distribution of the corpus we compile through OUI-based random BSSID guessing is global in scope. Figure 3 displays a global heatmap of the number of unique BSSIDs discovered, aggregated into 4-character geohash bins. The distribution of wireless APs we discover largely mirrors the global distribution of human population, with one major exception.

China is significantly underrepresented in the BSSID geolocation corpus, with the exception of the special autonomous regions (SARs) of Hong Kong and Macau. We speculate that this is an artifact of Chinese legislation that restricts collecting and publishing China's (but not their SARs') geographic information [1]. It is possible that, as with some other Apple data [26], Chinese BSSID location data would be accessible from a vantage point within China (recall that ours was in the US). In either case, despite the surprising sparseness, we do observe *some* Wi-Fi AP geolocations in mainland China (on the order of thousands). We conjecture that these geolocations, which typically arise only for brief periods of time, are geolocated by tourists or foreigners whose devices report the geolocation of Chinese APs. That even a nationwide policy not to be included in this dataset can be so regularly violated underscores the challenges of opting out of a WPS.

Next, we analyze the BSSIDs we discover by manufacturer, using the first three bytes (the OUI) of the BSSID to determine the manufacturer. When the Universal/Locally-Administered (U/L) bit in the BSSID is set, we clear it before looking up the OUI, as all IEEE-registered OUIs have the U/L bit set to 0.

TABLE 1: Number of unique geolocated BSSIDs organized by the most common OUIs (left) and most common vendors (right). Some vendors are listed under multiple names in the IEEE OUI database file; we made a best effort to consolidate counts under a single vendor name.

Count	%	OUI	Vendor	Count	%	Vendor
1,119,296	0.23	12:59:32	Roku	63,628,162	12.96	Unlisted
1,082,808	0.22	8e:49:62	Roku	42,351,581	8.63	TP-Link
998,529	0.20	1c:3b:f3	TP-Link	28,407,586	5.79	Huawei
968,367	0.20	40:ca:63	Seongji Industries	19,556,964	3.98	Vantiva
965,516	0.20	00:31:92	TP-Link	17,251,657	3.51	Sagemcom
485,806,036	98.95	2,401,736 others	—	319,744,602	65.13	15,302 others
490,940,552	100	—	**Total**	490,940,552	100	**Total**

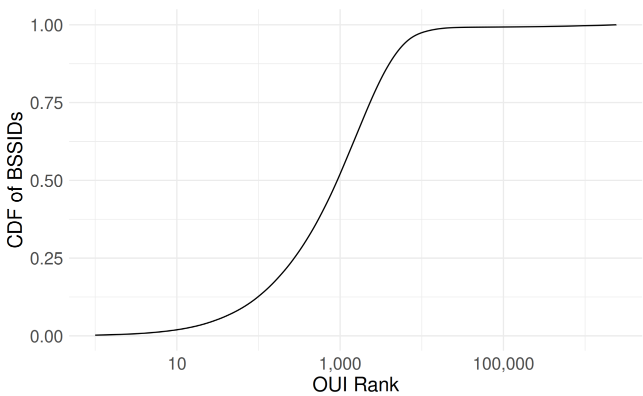


Figure 4: CDF of geolocated BSSIDs versus OUI ranked by decreasing number of geolocated BSSIDs. Note that the x-axis is log-scale.

Table 1 details the most common OUIs and equipment manufacturers in our corpus obtained from randomly guessing among IEEE-allocated OUIs and their locally-assigned variants.

Two of the five most commonly-observed OUIs from the BSSIDs we obtained belong to the streaming television equipment manufacturer Roku, while another two are assigned to the home-router manufacturer TP-Link. Over 2 million unique "OUIs" were observed in our data; because only about 30,000 OUIs have been assigned by the IEEE, the vast majority of OUIs in our are likely mobile phones. Mobile devices running iOS 17 or Android 14, current at the time of writing, choose a random BSSID when put into hotspot mode. This is further supported by the fact that most of the "OUIs" that do not resolve to a manufacturer have only one BSSID observation. Figure 4 shows that more than 90% of all BSSIDs in our corpus belong to one of the top 10,000 OUIs, while the remaining $<$10% is accounted for in the more than 2 million other OUIs.

Next, we aggregate the number of BSSIDs by OUI manufacturer. In some cases, this is a manual and error-prone process, as manufacturers may specify whatever name they wish when they register new allocations with the IEEE, and variations in company names exist between different allocation registrations. Regardless, we made an attempt to normalize and aggregate discovered BSSID by manufacturer on the right side of Table 1. The most common vendor our BSSIDs mapped to was no vendor at all, meaning that the BSSID's OUI had no listed manufacturer. Again, we believe these are primarily mobile phones, which choose a random BSSID when placed into hotspot mode in order to prohibit device tracking. While the most common vendor, this occurred for only about 13% of BSSIDs.

The most common true vendors in our dataset were TP-Link, Huawei, Vantiva, and Sagemcom. All four of these companies manufacturer CPE-grade routers for home and small business purposes. No single manufacturer accounts for more than 10% of the dataset, with TP-Link accounting for the largest fraction of the geolocated BSSIDs at 8.6%.

7.2. Month-Long Longitudinal Study

The privacy threats of massive Wi-Fi geolocation datasets are arguably most severe when wireless APs move. To determine the prevalence of AP movement and characterize the phenomenon, we randomly sampled 10 million geolocated BSSIDs from the corpus of 490 million we amassed in §7.1.

Over the course of a month, we queried the Apple WPS for these 10 million BSSIDs each day in the same order at approximately the same time. This month-long study allows us to answer questions about the longevity of BSSIDs in our corpus, in addition to learning how APs move over time and where they move from and to.

Figure 5 displays the fraction of the original 10 million that are still geolocatable each day that we query the API. This figure demonstrates several interesting artifacts of Apple's WPS. First, between the beginning and end of the month, approximately 8% of the sampled BSSIDs were no longer able to be geolocated (that is, the API returned a `-180,-180` latitude and longitude for the BSSID). While we do not possess ground truth for any of the devices in our 10 million BSSID sample, we suspect that there are several factors that contribute to the decay in geolocatable BSSIDs.

First, some devices are turned off, whether temporarily or permanently, for a period of time long enough to be reflected in Apple's WPS. We demonstrated in a laboratory setting that it takes roughly a week for a device to appear in the geolocation database when first powered on, as well as to be expunged from the database when powered off. It is possible that some devices have simply been off for long enough to be removed from the location API because

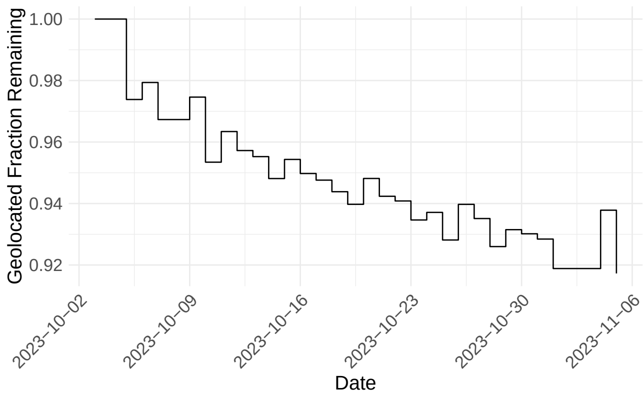


Figure 5: Fraction of geolocated BSSIDs (of 10,000,000 tested) remaining each day following an initial sweep of the OUI space.

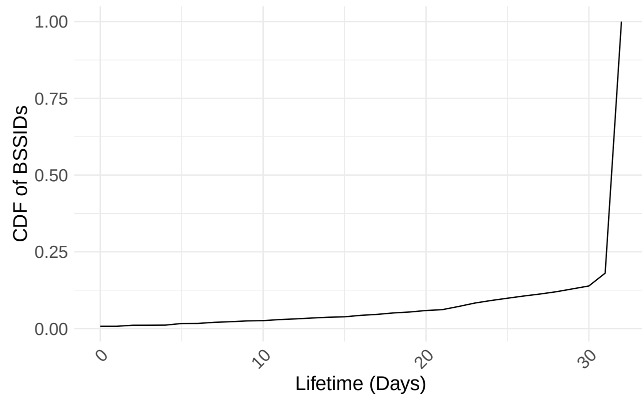


Figure 6: Distribution of lifetimes of geolocated BSSIDs from daily querying for 10 million randomly sampled BSSIDs.

they have been replaced, destroyed, or powered off due to a long-term power outage.

It is possible that some devices, while still powered and active, are no longer near enough Apple devices to have their location reported and are therefore “aged out” at some point. While we believe that removing BSSIDs from the geolocation service for this reason is possible, due to the remoteness of some BSSIDs we discover (e.g., in Antarctica or Tristan Da Cunha Island), we believe that the threshold for number of “finding” Apple devices for a BSSID to be entered into the geolocation service to be relatively low.

Finally, we suspect that some BSSIDs in the geolocation database are random MAC addresses, which are used by both modern Android and iOS devices when users put them into hotspot mode. These BSSIDs are identifiable because they have the U/L bit set to indicate that they are locally-administered, and when the bit is unset, the resulting OUI does not map to any assigned by the IEEE.

We also note that some BSSIDs “drop out” of the Apple WPS, only to later “return” and be geolocatable again. These events manifest as rises in the fraction geolocatable in Figure 5. We believe that these are Wi-Fi APs that, for whichever of the preceding reasons, have been removed from the WPS. Assuming that the device has not been physically destroyed, it stands to reason that it can again be plugged in and used as a geolocation landmark—perhaps after being sold to a new owner, or after power has been restored following a power outage that kept it offline for an extended period of time. Further, certain classes of AP—travel routers—are designed to move with the user, which implies periods in which they are off and not present in Apple’s WPS.

Figure 6 displays the lifetimes of the 10 million BSSIDs that were part of our month-long longitudinal study. The lifetime of a BSSID is the total number of days it was geolocatable, even if one or more breaks occurred over the course of the month. More than 85% of BSSIDs remain geolocatable for the entire month, indicating that most of the BSSIDs in the 10 million BSSID sample are stable.

Next, we characterize the amount of movement we see in our 10 million BSSID sample. Changes in the locations of the BSSIDs reported by the Apple Wi-Fi geolocation service is indicative of the AP the BSSIDs are tied to changing geographic locations, and are potential indications that the owner of the AP has moved. This movement is at the heart of the privacy vulnerability that Wi-Fi geolocation services present, and underlies all of the threats we present in §4 and demonstrate in §8.

Most BSSIDs in our geolocation corpus change positions over time. These changes are typically small and are probably due to updates in Apple’s computation of the AP’s position. Therefore, we apply a conservative filter of 1 kilometer total distance moved during the month-long longitudinal experiment to identify BSSIDs that have moved.

Of the 10 million total BSSIDs in our sample, 6,002 move more than 1 kilometer during our month-long experiment. While 0.06% is a small percentage of our initial sample, this indicates that many thousands of BSSIDs move when considering a larger dataset (such as our corpus from randomly-guessing BSSIDs within OUIs) over a longer time frame than a month. Figure 7 is a CDF of the distance BSSIDs in the 10 million BSSID sample travel, restricted to only those that travel more than 1 kilometer. The median distance traveled is approximately 4.5 kilometers.

In §8, we delve deeper into some case studies that illuminate the privacy issues inherent with WPSes, all of which involve BSSIDs that move over time, or disappear from the Apple WPS entirely.

8. Case Studies

In this section, we demonstrate how the results from longitudinal WPS queries can be used by an adversary to track Wi-Fi APs and their owners over time. In contrast to §7, in this section we use a corpus of BSSID geolocations obtained from the Apple WPS between November 2022 and November 2023. This corpus contains more than 2 billion unique geolocated BSSIDs. Much of the data collection

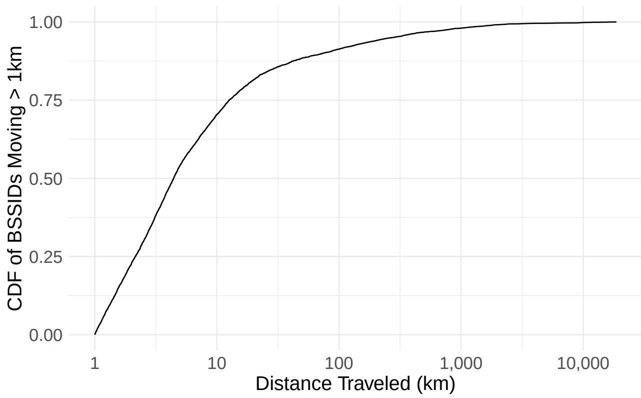


Figure 7: Distances traveled by BSSIDs from the 10 million BSSID sample; BSSIDs that traveled less than 1 kilometer are excluded ($N = 6,002$).

in this corpus was focused on either specific geographic regions or OUI vendors. To collect geolocation data specific to a region, we filtered known BSSIDs from a global corpus that were within a specified geographic bound (e.g., Hawaii or Ukraine). With this initial "seed" set of BSSIDs within the geographic area of interest, we then queried Apple's WPS for these BSSIDs, from which we learned more BSSIDs within the geographic region due to how the Apple API returns up to an additional 400 geolocated BSSIDs nearby the queried BSSIDs. We repeated this process until we learned most of the BSSIDs the Apple WPS knows for a geographic region.

8.1. Maui Wildfires

The Hawaiian island Maui was devastated by a large fire in August 2023, which destroyed much of the town of Lahaina. During the wildfires, we queried Apple's WPS for BSSIDs we had previously observed in and nearby Lahaina. Many BSSIDs were "forgotten" by the Apple WPS after a period of several days, presumably after they had been destroyed by the fire.

Figure 8 depicts BSSID from Lahaina before and after the fire. Black dots are BSSIDs that were in the Apple WPS before the fire started as well a month after. Red dots indicate BSSIDs that were removed from the Apple WPS between the fire starting and mid-October. We suspect that most of the APs associated with these BSSIDs were destroyed in the fire. This is not purely speculation; our map of BSSIDs that disappeared from the Apple WPS substantially aligns with open-source reporting and maps of the damage produced following the fire [11].

This case study demonstrates that real-world phenomena manifest in the data we retrieve from the Apple WPS. In addition to studying the effects of natural disasters like fires and hurricanes, a remote attacker might also use an WPS in this manner to conduct a battle damage assessment following a military strike or terrorist attack.

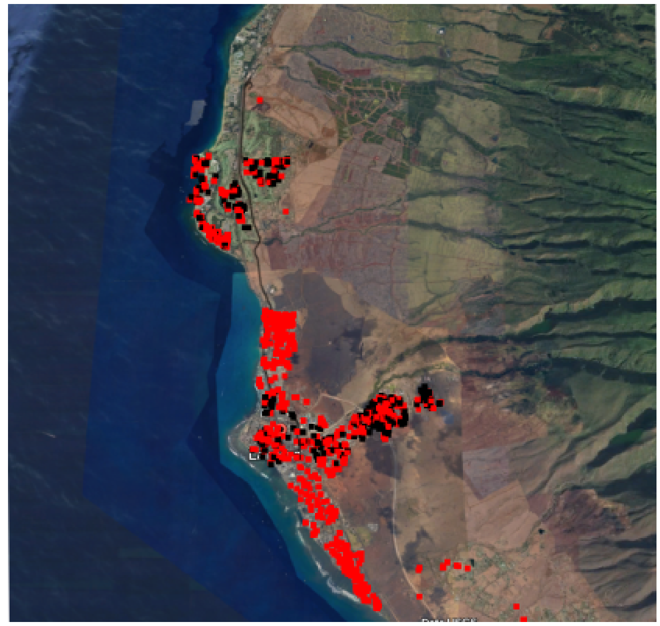


Figure 8: A view of damage from the August 2023 Maui fires. Red points are BSSIDs that were in Lahaina, Hawai'i prior to the fire but were not geolocatable in the Apple WPS as of mid-October. Black points were geolocatable prior to and one month after the fires.

8.2. User Tracking

In §7, we found that by querying 10 million BSSIDs daily only 0.06% moved more than one kilometer over the course of a month. Many of the AP vendors from that sample manufacture infrastructure that seldom moves—both commercial and residential Wi-Fi deployments are rarely taken down and set back up once they are installed.

However, certain types of APs *are designed for mobility*. For example, the router manufacturer GL.iNet [2] produces a variety of small "travel routers" designed to be used for e.g., in hotels, boats, and recreational vehicles.

Of 511,935 GL.iNet BSSIDs we geolocated at any point over the yearlong corpus collection, 23,396 BSSIDs moved more than 1 kilometer, our conservative threshold to detect AP mobility. This 4.6% BSSID movement rate is 76 times greater than the mobility observed in our 10 million randomly sampled corpus, and highlights the different use cases of different router types.

Figure 9 shows that the GL.iNet routers move significantly farther than the movers in the month-long sample. While $\geq$ 1 kilometer moving routers in the 10 million BSSID sample have a median distance traveled of 4 kilometers, moving GL.iNet routers over the same time period traveled a median 97 kilometers. Over the six months during which we tracked GL.iNet travel routers, the median distance traveled grew to 120 kilometers.

This suggests that when general-use routers move, such as those rented or lent to customers by Internet Service Providers (ISPs), their movements are less pronounced than

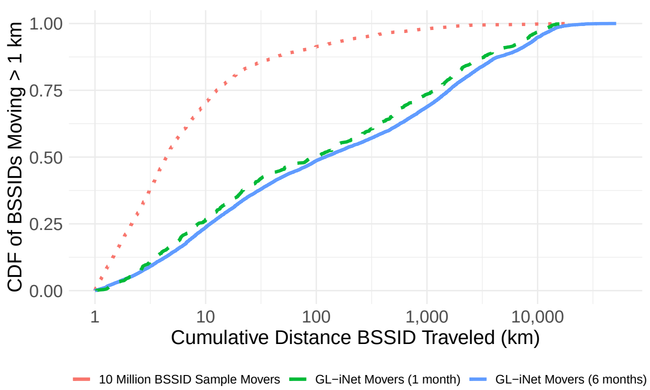


Figure 9: Comparison of the cumulative distances traveled between BSSIDs that moved in our 10 million BSSID sample, GL.iNet travel routers restricted to the same timeframe as the 10 million BSSID sample, and GL.iNet travel routers over six months. x-axis is log-scale.

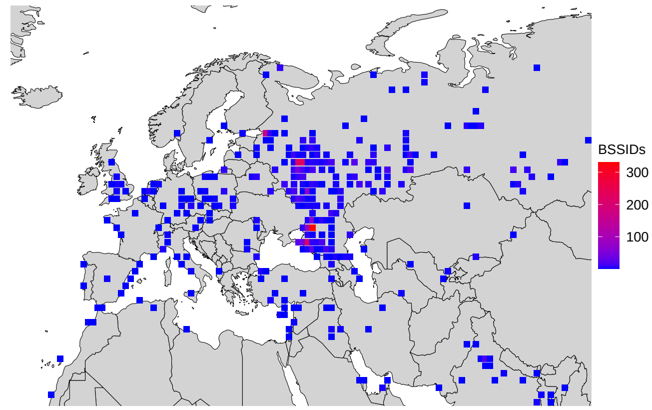


Figure 10: Heatmap of where BSSIDs that enter the Donbas and Crimea regions of Ukraine originate.

routers that are specifically designed for movement. While we do not have ground truth, we surmise that these types of routers, when they do move, are often redistributed to customers of the same ISP that live in the same general area from a local customer support office.

While we omit specific details to protect the users we were able to track, movement from BSSIDs represents a serious privacy problem. We observe routers move between cities and countries, potentially representing their owner's relocation or a business transaction between an old and new owner. While there is not necessarily a 1-to-1 relationship between Wi-Fi routers and users, home routers typically only have several. If these users are vulnerable populations, such as those fleeing intimate partner violence or a stalker, their router simply being online can disclose their new location.

Travel routers, like many GL.iNet devices, compound the problem. Because travel routers are frequently used on campers or boats, we see a significant number of GL.iNet devices move between campgrounds, RV parks, and marinas. They are used by vacationers who move between residential dwellings and hotels. We have evidence of their use by military members as they deploy from their homes and bases to war zones.

The ability to detect router movement is a grave threat to individuals who wish to not be tracked. In the next section, we discuss privacy threats to entire populations of sensitive populations and vulnerable people – military members and civilians living through the wars in Ukraine and Gaza.

8.3. Russia-Ukraine War

The ongoing Russian invasion of Ukraine provides further examples of privacy threats presented by WPSes.

First, we examine where BSSIDs that are seen in Russian-occupied Ukranian territory (the Donbas region in the east and the Crimean Pennisula to the south) originate, if they were seen outside of those two regions.

Figure 10 is a heatmap of the locations that BSSIDs observed in the Donbas or Crimea were seen *before* they entered Ukraine. Four primary Russian hotspots emerge at Moscow, St. Petersburg, Rostov-on-Don, and Krasnodar. While Crimea remains open for Russian tourism, movement of BSSIDs to these regions, and especially to the Donbas, is suggestive of military movement. For BSSIDs not previously in Russia, we speculate that the owners of these devices are perhaps humanitarian assistance workers, or volunteers with Ukraine's Foreign Legion. It is also possible that the devices were sold secondhand before ending up in Ukraine.

Ukraine's use of SpaceX's Starlink satellite Internet service has been widely reported [23], [30], [22], [18]. The Wi-Fi APs provided with the Starlink terminals have BSSIDs drawn from the "TIBRO Corp" `74:24:9F` OUI ("TIBRO" is "ORBIT" backwards). During the course of our study, we discovered 1,500,506 Starlink BSSIDs. Of these, 3,722 were geolocated at one point to Ukraine.

Figure 11 is a heatmap of the Starlink BSSIDs in Ukraine. Major hotspots exist in Kyiv, Lviv, Odesa, and Dnipro, the last of which is closest to the front lines in Ukraine's east.

Ukraine's Starlink use is reportedly restricted from functioning on Russian-occupied Ukrainian territory [9]. Figure 11 largely confirms this, with the contours of the Donbas region's front lines evident east of Dnipro.

Interestingly, one Starlink BSSID did appear in Russian-occupied city of Simferopol, Crimea during our study. However, it is worth noting that the Starlink AP can be operational without having a connection to the Internet through the Starlink satellite terminal, which is a potential explanation for this phenomenon.

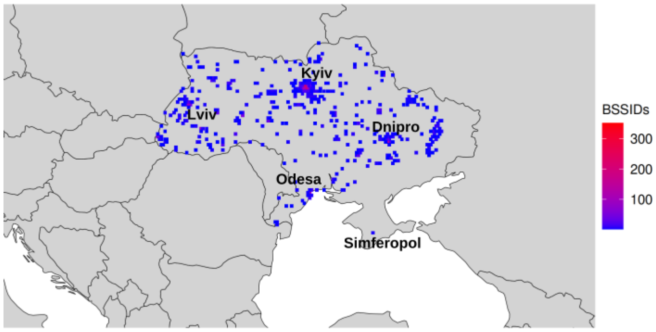


Figure 11: Heatmap of Starlink routers in Ukraine.

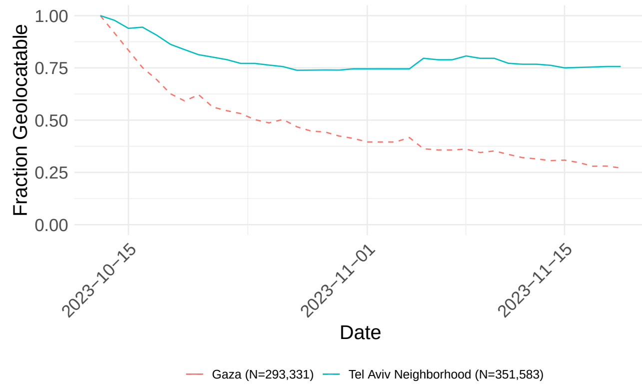


Figure 12: Comparison of the decay in geolocated BSSIDs in Gaza and Tel Aviv, Israel.

8.4. Gaza

On 7 October 2023, Hamas launched an attack on Israeli settlements from the Gaza Strip. In response, Israel initiated a major air and ground war in Gaza.

We are able to view the effects of Israel's war in Gaza through the lens of geolocated BSSIDs in Apple's WPS. Shortly after the Hamas attacks, Israel ceased providing electricity to the Gaza Strip. While some fuel aid is allowed into Gaza by relief organizations, the Israeli power cut severed a large fraction of the power used by Gazans to power basic household items, like Wi-Fi APs [10].

Beginning shortly after the Hamas attack on Israel, we queried for both Gazan and Israeli BSSIDs to understand the effects of the Israel-Gaza War. Each day, we queried about 300,000 Gazan BSSIDs to see whether they are still known to Apple's WPS, and as a control, we queried a similar number of BSSIDs from a neighborhood in Tel Aviv, Israel.

Figure 12 demonstrates the effects of the Gaza power cut. Within one week, the percentage of Gazan BSSIDs that were geolocatable at the outset of the Israel-Gaza war had dropped to 62%. In contrast, the number of Tel Aviv BSSIDs that continued to be geolocatable was nearly 20% higher, with 81% still known to Apple's Wi-Fi geolocation API.

As time progressed, the number of Gazan BSSIDs that are geolocatable continued to decline. By the end of the month, only 28% of the original BSSIDs were still found in the Apple WPS. In contrast, the number of BSSIDs in the Tel Aviv control group leveled off after initially declining, and stayed relatively consistent after an initial drop within the first 10 days. At the end of the month, 76% of the Tel Aviv BSSIDs were still geolocatable, having lost only an additional 5% since the end of the first week.

Figure 13 displays the drop-off in geolocatable BSSIDs by geographic region inside Gaza. On 13 October 2023 (Figure 13(a)), after the initial Hamas attack and before the beginning of the Israeli ground war, major hotspots of dense BSSID geolocations exist, but are most pronounced in northern Gaza. Figure 13(b) depicts the BSSID density on 19 November 2023. Significantly weaker hotspots still exist, but northern and southern Gaza's BSSID density has largely normalized.

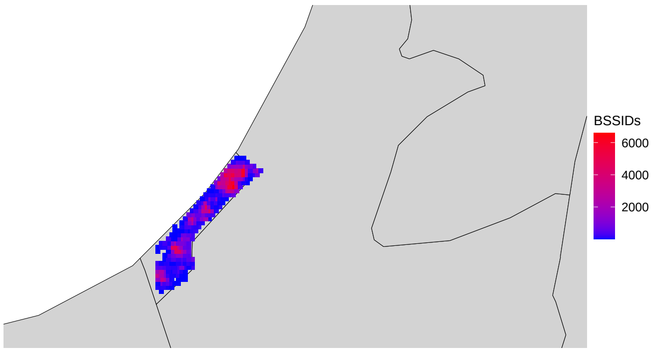
Finally, we considered the BSSIDs that were in Gaza on 7 October—when the war between Hamas and Israel began—that moved more than 1 kilometer. Only 14 BSSIDs were detected on or after 7 October within Gaza that were detected again after moving. Of these, the majority (10) moved within Gaza. Several moved from North Gaza, where the initial Israeli offensive occurred, to South Gaza, where people living in the north were instructed by the Israelis to move at the war's outset. One BSSID moved from Gaza to each of Romania, Poland, Côte d'Ivoire, and Israel. Note that because BSSIDs linger in the WPS for several days after being taken offline, it is possible that some of the BSSIDs detected on 7 October had already begun moving by that date. Nevertheless, the timeframe and movement of the BSSIDs from north to south within Gaza suggests that this relocation was in response to the war.

9. Remediation

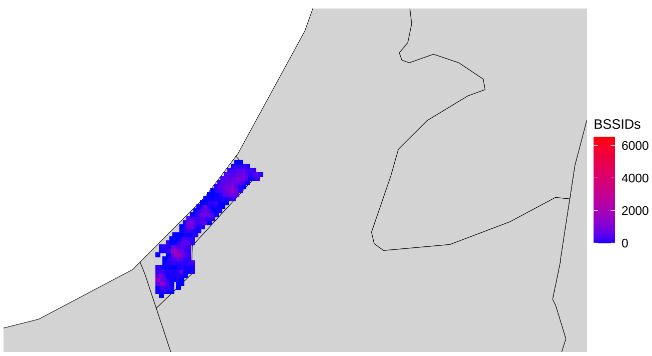
There are policy-based, technical, and legal solutions to remediate the privacy concerns created by the presence of large-scale Wi-Fi geolocation APIs. They range in effectiveness from preventing only a weak, non-state adversary from performing global tracking of Wi-Fi APs while permitting targeted tracking, to eliminating most AP tracking if implemented correctly.

Wi-Fi Positioning System Remediations The type of unlimited and unregulated access to Wi-Fi geolocation data Apple currently permits via its API should be prohibited. There are a number of controls that Apple might implement in order to restrict access to this data.

Perhaps the most straightforward solution to limit information disclosure is to implement a per-device rate limit. The number of queries legitimate Apple products issue to the WPS for its intended purpose—self-geolocation—is likely orders of magnitude lower than an attacker would need to amass a worldwide BSSID geolocation corpus in a tractable



(a) Heat map of the BSSIDs in Gaza on 13 October 2023. Several hotspots are present in dense urban environments.



(b) Heat map of the BSSIDs in Gaza on 19 November 2023. Significantly lower density is seen in previous hotspots.

Figure 13: Heatmaps of BSSID density within the Gaza strip following the attack on Israel and Israel's response.

time, especially when combined with other mitigations (e.g., not returning additional, nearby BSSID locations). This rate limit could be enforced by modifying the API to tie queries to specific Apple IDs, which would also allow Apple to ban or further limit abusive users.

To wit, Google's WPS requires the use of an API key by which they manage billing for geolocation queries that a user performs. The cost is nominal when the number of queries is small; at the time of writing, Google's geolocation API query billing rate begins at $5.00 per 1,000 requests, with further discounts applied for bulk lookups in excess of 100,000 requests [16]. Attempting to enumerate the allocated OUI space, however, would cost millions of dollars—likely prohibitively expensive for all but very powerful adversaries. [5]

As noted previously, Apple's WPS opportunistically returns up to 400 unrequested BSSIDs and their geolocations that are near requested BSSIDs. This greatly facilitated the breadth and speed at which our attack was able to operate. We recommend that Apple's WPS cease providing unrequested nearby BSSID geolocations. While this would not in theory prevent an attacker from amassing a global BSSID geolocation corpus, it would significantly increase the difficulty, particularly for random OUIs. We suspect that limiting the number of returned BSSID geolocations returned need not adversely affect Apple's geolocation API; after all, Google's WPS returns only a single geolocation—that of the device that ostensibly sensed those nearby BSSIDs. This distinction not only obscures the locations of the BSSIDs in question by returning the trilaterated requester's position, but also provides nowhere near the benefit that the Apple API provides in unrequested nearby BSSIDs. Discontinuing the inclusion of nearby BSSIDs with active queried BSSIDs would not prevent an attacker from performing a targeted tracking attack by querying the API for a specific BSSID or set of BSSIDs over time.

Finally, the volunteer-sourced wardriving website WiGLE has instituted policy restrictions associated with sensitive areas. Following the Russian invasion of Ukraine in 2022, Wi-Fi spottings in Ukraine have been removed from the WiGLE map and API query results. Operators of other WPSes could institute similar policies for sensitive geographic areas, such as war zones. However, we recognize that implementing such policies might prove problematic for large corporations in practice. Selectively implementing privacy protections for some areas, while choosing not to implement them for others, could lead to accusations of bias or of ignoring the plight of certain populations.

AP Manufacturer Remediations The most comprehensive solution to the range of privacy attacks Wi-Fi geolocation APIs present that we outline in this paper is to implement MAC address randomization for Wi-Fi APs.

Randomizing the source MAC address field in 802.11 probe requests became standard among 802.11 client devices in the mid-2010s, with all major operating systems now implementing this privacy technique. While some implementation issues were initially uncovered [25], [36], [24], *pre-association* MAC address randomization is now an effective mechanism to prevent tracking mobile 802.11 clients [13]. In 2020, both Android and iOS also began randomizing clients' source MAC addresses during authentication and after they join an 802.11 network. *Post-association* MAC address randomization prevents network operators and rogue APs from tracking users based on their hardware MAC address, which was previously exposed any time the device attempted to join or joined a network.

We are strongly advocating for a similar privacy measure for wireless APs. Wireless APs should choose new BSSIDs each time they are powered on. Some APs already implement this privacy measure—modern iOS and some Android mobile devices choose a random BSSID each time they are placed into hotspot mode. This feature is presumably to safeguard against the type of tracking attacks mobile device manufacturers have guarded against for nearly a decade with probe request randomization, and later, post-association client MAC address randomization.

5. While Google does impose a geolocation API query rate limit, it is 100 queries per second per user—more than three times higher than our query rate in this work.

Yet, due to the privacy attacks we outlined in §4 and demonstrated in §7 and 8 we believe these privacy protections should be afforded to all APs. There is no technical or usability reason why an AP should maintain the same BSSID for long periods of time, or across reboots. Users would not have to reconfigure their clients; Wi-Fi clients typically will associate with any network that advertises an SSID and Authentication and Key Management (AKM) mode (open, Pre-Shared Key (PSK) or 802.1X Extensible Authentication Protocol (EAP)) they have saved—without respect to the BSSID. Indeed, Extended Service Sets (ESSs), like many campus or corporate networks, rely on the 802.11 client *not* caring about the BSSID in order to transition between wireless APs.

User Remediations While the average user's privacy is largely at the mercy of WPS operators and the equipment vendor that manufactures their AP, there are some practical steps they can take in order to limit their exposure to the attacks we outline in this work.

First, users concerned about being tracked via their BSSIDs over time as they change locations (e.g., moving homes or traveling) should avoid using the same AP at each location if possible. Many home and business subscribers lease CPE equipment from their ISP; if given the option to retain their equipment or turn their equipment in and receive a new device at the destination, a privacy-conscious user should opt for the latter.

Second, WPSes require BSSIDs to exhibit some degree of stability before adding them to their database of landmarks. Anecdotally, we find that an AP running in a suburban area will appear in Apple's Wi-Fi geolocation system after two to seven days of continuous operation. While we do not know the exact mechanics of any WPS, establishing some lower bound on AP trustworthiness (whether in terms of time or number of observers) is intuitive—there is no use navigating by an unreliable landmark. Users with privacy concerns may thus wish to limit how long they use their AP in order to prevent it from appearing in a WPS.

Finally, the most technically-savvy, privacy-conscious users with the ability to modify the operation of their AP software, like `hostapd`, should randomize their BSSID when they operate their AP. In a `hostapd` configuration file, the `bssid` directive will change the BSSID used (presuming hardware support) by the AP for that network. By randomizing the network's BSSID at each boot or time the router moves, the user in effect achieves BSSID randomization without operating system-level support.

Legal Remediations As Figure 3 shows, China is almost entirely absent from the Apple WPS, with the exception of its SARs Macau and Hong Kong. We do not believe that the Chinese law preventing the Apple WPS from storing Chinese BSSID geolocations foresaw this specific privacy vulnerability. However, this work demonstrates that WPS operators largely comply with the laws of the nations in which they operate, and Chinese law in practice protects Chinese BSSIDs from being tracked on a large scale, at least from outside China.

If other nations or municipalities implement similar laws or policies, we believe that WPS operators will comply with these mandates as well. It is possible that WPS operators might be willing to work with governments to remove particularly sensitive geographic locations, like war zones or government and military facilities, or specific OUIs that correspond with sensitive equipment. Based on our data, we do not believe that any such policies are currently being implemented.

10. Responsible Disclosure

Having given careful consideration to mitigations of our attack in §9, we responsibly disclosed this vulnerability to several concerned parties. While Apple's WPS clearly permits the global information gathering we rely on to track large numbers of users around the world, it was less clear to us who besides Apple should be informed prior to the publication of this work. All Wi-Fi routers and their owners are potentially affected, because BSSIDs become entries in a WPS merely by being nearby "finding" devices for that WPS (e.g., a neighbor's iPhone might report the BSSIDs of an AP, even when the owner possesses no Apple products herself).

Because of this ambiguity and large population of potentially-affected users, we disclosed our findings to Apple and Google as operators of large-scale WPSes. We also contacted the product security teams for SpaceX and GL.iNet, two of the router manufacturers highlighted extensively in our case studies in §8.

Apple has indicated that they are on track to make several changes to their WPS in order to better protect user privacy. At the time of writing, they have given AP operators the ability to opt out of inclusion in Apple's WPS by appending the string `_nomap` to a Wi-Fi network's SSID [5]. This change brings it in line with Google's WPS and WiGLE, which have also excluded SSIDs with `_nomap` (Google) and `_nomap` and `_optout` (WiGLE) since at least 2016 [15], [7].

We contacted SpaceX's product security team to inform them of the ability to geolocate Starlink routers through Apple's WPS, given the sensitivity of the locations of these devices in the ongoing Russia-Ukraine War. SpaceX's security team informed us that, while Starlink routers originally used static BSSIDs based on an assigned OUI, they had begun in early 2023 to roll out software updates that randomize the BSSID. These updates are "being deployed fleet-wide on a region-by-region basis"; most likely, the devices in our dataset that we identified as Starlink were to devices that have not yet received the software updates.

Based on this response, we are encouraged that a major router manufacturer is beginning to implement BSSID randomization, particularly because of the security concerns of Starlink users in Ukraine. We hope that other router manufacturers will follow their example in the near future, and that BSSID randomization will become the norm rather than the exception.

Finally, we contacted GL.iNet's product security team due to our case studies that demonstrate its users can be easily tracked over time and space. Unfortunately, while they do plan to randomize their *client* MAC addresses, the GL.iNet's team indicated that they have no plans to randomize the products' BSSIDs.

11. Conclusion

In this work, we demonstrated the large-scale privacy threat presented by Apple's WPS. A remote, unprivileged adversary, possessing only the knowledge of which parts of the MAC address space have been assigned by the IEEE, can quickly build a corpus of hundreds of millions of geolocated BSSIDs, spanning all seven continents and extending to even the most remote corners of the Earth.

The ability to obtain this worldwide view of Wi-Fi AP distribution is a privacy vulnerability. Because people often move with their AP, querying a WPS for the same BSSIDs over time reveals when routers—and by proxy their owners—move. We demonstrated that this attack could be applied to individual users, such as travel router owners, as they move from location to location. We also showed that WPSes could be used to find sensitive equipment, like Starlink routers in Ukraine.

There are practical steps to take to limit this vulnerability. WPS operators can limit access to their APIs, governments can legislate that their citizen's devices not be used as geolocation landmarks, and users wary of tracking can be sure to not use the same AP at multiple locations.

However, the most robust solution to this problem is to implement the same privacy protections that were implemented in mobile devices in Wi-Fi APs. BSSID randomization at each boot, or when the device changes locations prevents user tracking even in a world in which WPS operators permit open access to their APIs.

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