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Randomized and Changing MAC Address Use Cases
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Abstract

To limit the association between a device traffic and its user, client vendors have started implementing MAC address rotation. When such rotation happens, some in-network states may break, which may affect network efficiency and the user experience. At the same time, devices may continue sending other stable identifiers, defeating the MAC rotation purposes. This document lists various network environments and a set of network services that may be affected by such rotation. This document then examines settings where the user experience may be affected by in-network state disruption, and settings where other machine identifiers may expose the user privacy. Last, this document examines solutions to maintain user privacy while preserving user quality of experience and network operation efficiency.

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1. Introduction

It has become easier for attackers to track the activity of a personal device, particularly when traffic is sent over a wireless link. Once the association between a device and its user is made, identifying the device and its activity is sufficient to deduce information about what the user is doing, without the user consent.

To reduce the risks of correlation between a device activity and its owner, multiple vendors have started to implement Randomized and Changing MAC addresses (RCM). With this scheme, an end-device implements a different RCM over time when exchanging traffic over a wireless network. By randomizing the MAC address, the association between a given traffic flow and a single device is made more difficult, assuming no other visible unique identifiers are in use.

However, such address change may affect the user experience and the efficiency of legitimate network operations. For a long time, the unicity of the association between a device and a MAC address was assumed, despite the emergence of tools to flush out the MAC address

to bypass some network policies. When this association is broken, elements of network communication may also break. For example, sessions established between the end-device and network services may be lost and packets in translation may suddenly be without clear source or destination. As multiple clients implements fast-paced RCM rotations, network services may be over-solicited by a small number of stations that appear as many clients.

At the same time, some network services rely on the client station providing an identifier, which can be the MAC address or another value. If the client implements MAC rotation but continues sending the same static identifier, then the association between a stable identifier and the station continues despite the RCM scheme. There may be environments where such continued association is desirable, but others where the user privacy has more value than any continuity of network service state.

There is a need to enumerate services that may be affected by RCM, and evaluate possible solutions to maintain both the quality of user experience and network efficiency while RCM happens and user privacy is reinforced. This document presents such assessment and recommendations.

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 RFC 2119 [RFC2119] RFC 8174 [RFC8174] when, and only when, they appear in all capitals, as shown here.

2. MAC Address as an Identity: User vs. Device

Any device member of an IEEE 802 network [IEEE.802-1D.1993] includes several operating layers. Among them, the Media Access Control (MAC) layer defines rules to control how the device accesses the shared medium. In a network where a machine can communicate with one or more other machines, one such rule is that each machine needs to be identified, either as the target destination of a message, or as the source of a message (and thus the target destination of the answer). Initially intended as a 48-bit (6 octets) value, later versions of the Standard [IEEE.802.15.4P_2014] allowed this address to take an extended format of 64 bits (8 octets), thus enabling a larger number of MAC addresses to coexist as the 802 technologies became widely adopted.

Regardless of the address length, different networks have different needs, and several bits of the first octet are reserved for specific purposes. In particular, the first bit is used to identify the destination address either as an individual (bit set to 0) or a group address (bit set to 1). The second bit, called the Universally or Locally Administered (U/L) Address Bit, indicates whether the address has been assigned by a local or universal administrator. Universally administered addresses have this bit set to 0. If this bit is set to 1, the entire address (i.e., 48 bits) has been locally administered [IEEE.802-1Y.1990] Section 5.2.1.

The intent of this provision is important for the present document. The 802 Standard recognized that some devices may never travel and thus, always attaching to the same network, would not need a globally unique MAC address. To accommodate for this relaxed requirement, the second bit of the MAC address first octet the MAC address format was designed to express whether the address was intended to be globally unique, or if significance was only local. The address allocation method was not defined in the Standard in this later case, but the mechanism was defined in the same clause that defined that an address should be unique so as to avoid collision.

It is also important to note that the purpose of the Universal version of the address was to avoid collisions and confusion, as any machine could connect to any network, and each machine needs to determine if it is the intended destination of a message or its response. The same clause 5.2.1 reminds network designers and operators that all potential members of a network need to have a unique identifier (if they are going to coexist in the network). The advantage of a universal address is that a node with such an address can be attached to any Local Area Network (LAN) in the world with an assurance that its address is unique.

With the rapid development of wireless technologies and mobile devices, this scenario became very common. With a vast majority of 802 networks implementing radio technologies at the access, the MAC address of a wireless device can appear anywhere on the planet and collisions should still be avoided. However, the same evolution brought the distinction between two types of devices that the 802 Standard generally referred to as 'nodes in a network'. Their definition is found in the 802E Recommended Practice (clause 6.2). One type is a shared service device, which functions are used by a number of people large enough that the device itself, its functions or its traffic cannot be associated with a single or small group of people. Examples of such devices include switches in a dense network, 802.11 (WLAN) access points in a crowded airport, task-specific (e.g. barcode scanners) devices, etc. Another type is a personal device, which is a machine, a node, primarily used by a

single person or small group of people, and so that any identification of the device or its traffic can also be associated to the identification of the primary user or their traffic. Quite naturally, the unique identification of the device is trivial if the device expresses a universally unique MAC address. Then, the detection of elements directly or indirectly identifying the user of the device (Personally Identifiable Information, or PII) is sufficient to tie the universal MAC address to a user. Then, any detection of traffic that can be associated to the device becomes also associated with the known user of that device (Personally Correlated Information, or PCI).

This possible identification or association presents a serious privacy issue, especially with wireless technologies. For most of them, and in particular for 802.11, the source and destination MAC addresses are not encrypted even in networks that implement encryption (so that each machine can easily detect if it is the intended target of the message before attempting to decrypt its content, and also identify the transmitter, so as to use the right key when multiple unicast keys are in effect).

This unique identification of the user associated to a node was clearly not the intent of the 802 MAC address. A logical solution to remove this association is to use a locally administered address instead, and change the address in a fashion that prevents a temporal association between one MAC address and some PII to be maintained fruitfully. However, other network devices on the same LAN implementing a MAC layer also expect the unicity of the MAC address. When a device changes its MAC address, other devices on the same LAN may fail to recognize that the same machine is attempting to communicate with them. Additionally, multiple layers implemented at upper OSI layers have been designed with the assumption that each node on the LAN, using these services, would have a unique MAC address. This assumption sometimes adds to the PII confusion, for example in the case of Authentication, Association and Accounting (AAA) services authenticating the user of a machine and associating the authenticated user to the device MAC address. Other services solely focus on the machine (e.g. DHCP), but still expect each device to use a single MAC address. Changing the MAC address may disrupt these services.

3. The Actors: Network Functional Entities and Human Entities

The risk of service disruption is thus weighted against the privacy benefits. However, the plurality of actors involved in the exchanges tends to blur the boundaries of what privacy should be protected against. It might therefore be useful to list the actors to the network exchanges. Some actors are functional entities, some others are humans (or related) entities.

3.1. Network Functional Entities

Wireless access network infrastructure devices (e.g. WLAN access points or controllers): these devices participate in 802 LAN operations. As such, they need to uniquely identify machines as a source or destination so as to successfully continue exchanging frames. Part of the identification includes recording, and adapting to, devices communication capabilities (e.g. support for specific protocols). As a device changes its network attachment (roams) from one access point to another, the access points can exchange contextual information (e.g. device MAC, keying material) allowing the device session to continue seamlessly. These access points can also inform devices further in the wired network about the roam, to ensure that OSI model Layer 2 frames are redirected to the new device access point.

Other network devices operating at the MAC layer: many wireless network access devices (e.g., 802.11 access points) are conceived as Layer 2 devices, and as such they bridge a frame from one medium (e.g., 802.11 or Wi-Fi) to another (e.g., 802.3 or Ethernet). This means that a wireless device MAC address often exists on the wire beyond the wireless access device. Devices connected to this wire also implement 802 technologies, and as such operate on the expectation that each device is associated to a unique MAC address for the duration of continuous exchanges. For example, switches and bridges associate MAC addresses to individual ports (so as to know which port to send a frame intended for a particular MAC address). Similarly, authentication, authorization and accounting (AAA) services can validate the identity of a device and use the device MAC address as a first pointer to the device identity (before operating further verification). Similarly, some networking devices offer Layer-2 filtering policies that may rely on the connected MAC addresses. 802.1X-enabled devices may also selectively block the data portion of a port until a connecting device is authenticated. These services then use the MAC address as a first pointer to the device identity to allow or block data traffic. This list is not exhaustive. Multiple services are defined for 802.3 networks, and multiple services defined by the IEEE 802.1 working group are also applicable to 802.3 networks. Wireless access points may also

connect to other mediums than 802.3, which also implements mechanism under the umbrella of the general 802 Standard, and therefore expect the unique association of a MAC address to a device.

Network devices operating at upper layers: some network devices provide functions and services above the MAC layer. Some of them also operate a MAC layer function: for example, routers provide IP forwarding services, but rely on the device MAC address to create the appropriate frame structure. Other devices and services operate at upper layers, but also rely upon the 802 principle of unique MAC-to-device mapping. For example, DHCPv4 services commonly provide a single IP address per MAC address (they do not assign more than one IPv4 address per MAC address, and assign a new IPv4 address to each new requesting MAC address). ARP and reverse-ARP services commonly expect that, once an IP-to-MAC mapping has been established, this mapping is valid and unlikely to change for the cache lifetime. DHCPv6 services commonly do not assign the same IPv6 address to two different requesting MAC addresses. Hybrid services, such as EoIP, also assume stability of the device-to-MAC-and-IP mapping for the duration of a given session.

3.2. Human-related Entities

Over the air (OTA) observers: as the transmitting or receiving MAC address is usually not encrypted in wireless 802-technologies exchanges, and as any protocol-compatible device in range of the signal can read the frame header, OTA observers are able to read individual transmissions MAC addresses. Some wireless technologies also support techniques to establish distances or positions, allowing the observer, in some cases, to uniquely associate the MAC address to a physical device and its associated location. It can happen that an OTA observer has a legitimate reason to monitor a particular device, for example for IT support operations. However, it is difficult to control if another actor also monitors the same station with the goal of obtaining PII or PCI.

Wireless access network operators: some wireless access networks are only offered to users or devices matching specific requirements, such as device type (e.g., IoT-only networks, factory operational networks). Therefore, operators can attempt to identify the devices (or the users) connecting to the networks under their care. They can use the MAC address to represent an identified device.

Network access providers: wireless access networks are often considered beyond the first 2 layers of the OSI model. For example, several regulatory or legislative bodies can group all OSI layers into their functional effect of allowing network communication between machines. In this context, entities operating access

networks can see their liability associated to the activity of devices communicating through the networks that these entities operate. In other contexts, operators assign network resources based on contractual conditions (e.g., fee, bandwidth fair share). In these scenarios, these operators may attempt to identify the devices and the users of their networks. They can use the MAC address to represent an identified device.

Over the wire internal (OTWi) observers: because the device wireless MAC address continues to be present over the wire if the infrastructure connection device (e.g. access point) functions as a Layer 2 bridge, observers may be positioned over the wire and read transmission MAC addresses. Such capability supposes that the observer has access to the wired segment of the broadcast domain where the frames are exchanged. In most networks, such capability requires physical access to an infrastructure wired device in the broadcast domain (e.g. switch closet), and is therefore not accessible to all.

Over the wired external (OTWe) observers: beyond the broadcast domain, frames headers are removed by a routing device, and a new Layer 2 header is added before the frame is transmitted to the next segment. The personal device MAC address is not visible anymore, unless a mechanism copies the MAC address into a field that can be read while the packet travels onto the next segment (e.g. pre-[RFC4941] and pre-[RFC7217] IPv6 addresses built from the MAC address). Therefore, unless this last condition exists, OTWe observers are not able to see the device MAC address.

3.3. The Trust and the Environments

The surface of PII exposures that can drive MAC address randomization depends on the environment where the device operates, on the presence and nature of other devices in the environment, and on the type of network the device is communicating through. Therefore, a device can express an identity (such as a MAC address) that can be stable over time if trust with the environment is established, or that can be temporal if an identity is required for a service in an environment where trust has not been established. Trust is not a binary currency. Thus it is useful to distinguish what trust a personal device may establish with the different entities at play in a L2 domain:

1. Full trust: there are environments where a personal device establishes a trust relationship and can share a stable device identity with the access network devices (e.g., access point and WLC), the services beyond the access point in the L2 broadcast domain (e.g. DHCP, AAA). The personal device (or its user) has confidence that its identity is not shared beyond the L2 broadcast domain boundary.
2. Selective trust: in other environments, the device may not be willing to share a stable identity with some elements of the Layer 2 broadcast domain, but may be willing to share a stable identity with other elements. For example, a device may want to change the MAC address it uses to communicate with the access point while maintaining the same IP address across the MAC address rotation (thus expressing a stable identity to the DHCP server). That stable identity may or may not be the same for different services.
3. Zero trust: in other environments, the device may not be willing to share any stable identity with any entity reachable through the Layer 2 broadcast domain, and may express a temporal identity to each of them. That temporal identity may or not be the same for different services.

This trust relationship naturally depends on the relationship between the user of the personal device and the operator of the service. Thus, it is useful to observe the typical trust structure of common environments:

- A. Residential settings under the control of the user: this is typical of a home network with Wi-Fi in the LAN and Internet connection. In this environment, the MAC address activity may be detectable beyond the home walls. However, if traffic is encrypted (e.g. WPA3), some protection for OTA eavesdropping can be assumed. The wire segment within the broadcast domain is under the control of the user, and is therefore usually not at risk of hosting an eavesdropper. Full trust is typically established at this level. The device trusts the access point and all L2 domain entities beyond the access point. Traffic over the Internet does not expose the MAC address if it is not copied to another field before routing happens.
- B. Managed residential settings: examples of this type of environment include shared living facilities and other collective environments where an operator manages the network for the residents. The OTA exposure is similar to that of a home. A number of devices larger than in a standard home may be present, and the operator may be requested to provide IT support to the

residents. Therefore, the operator may need to identify a device activity in real time, but may also need to analyze logs so as to understand a past reported issue. For both activities, a device identification associated to the session is needed. Full trust is often established in this environment, at the scale of a series of a few sessions.

- C. Public guest networks: public hotspots, such as in shopping malls, hotels, stores, trains stations and airports are typical of this environment. The guest network operator may be legally mandated to identify devices or users or may have the option to leave all devices and users untracked. In this environment, trust is commonly not established with any element of the L2 broadcast domain (Zero trust model by default).
- D. Enterprises (with BYOD): users may be provided corporate devices or may bring their own devices. The devices are not directly under the control of a corporate IT team. Trust may be established as the device joins the network. Some enterprise models will mandate full trust, others, considering the BYOD nature of the device, will allow selective trust.
- E. Managed enterprises: in this environment, users are typically provided with corporate devices, and all connected devices are managed, for example through a Mobile Device Management (MDM) profile installed on the device. Full trust is created as the MDM profile is installed.

3.4. The Purpose of Device Identification and Associated Problems

Many network functional devices offering a service to a personal device use the device MAC address to maintain service continuity.

Wireless access points and controllers use the MAC address to validate the device connection context, including protocol capabilities, confirmation that authentication was completed, QoS or security profiles, encryption key material. Some advanced access points and controllers also include upper layer functions which purpose is covered below. A device changing its MAC address, without another recorded device identity, would cause the access point and the controller to lose these parameters. As such, the Layer 2 infrastructure does not know that the device (with its new MAC address) is authorized to communicate through the network. The encryption keying material is not identified anymore (causing the access point to fail decrypting the device traffic, and fail selecting the right key to send encrypted traffic to the device). In short, the entire context needs to be rebuilt, and a new session restarted. The time consumed by this procedure breaks any flow that

needs continuity or short delay between packets on the device (e.g. real-time audio, video, AR/VR etc.) The 802.11i Standard recognizes that a device may leave the network and come back after a short time window. As such, the standard suggests that the infrastructure should keep the context for a device up to one hour after the device was last seen. MAC address rotation in this context can cause resource exhaustion on the wireless infrastructure and the flush of contexts, including for devices that are simply in temporal sleep mode.

Other devices in the Layer 2 broadcast domain also use the MAC address to know whether and where to forward frames. MAC rotation can cause these devices to exhaust their resources, holding in memory traffic for a device which port location can no longer be found. As these infrastructure devices also implement a cache (to remember the port position of each known device), too frequent MAC rotation can cause resources exhaustion and the flush of older MAC addresses, including for devices that did not rotate their MAC. For the RCM device, these effects translate into session discontinuity and return traffic losses.

In wireless contexts, 802.1X authenticators rely on the device and user identity validation provided by a AAA server to open their port to data transmission. The MAC address is used to verify that the device is in the authorized list, and the associated key used to decrypt the device traffic. A change in MAC address causes the port to be closed to the device data traffic until the AAA server confirms the validity of the new MAC address. Therefore, MAC rotation can interrupt the device traffic, and cause a strain on the AAA server.

DHCP servers, without a unique identification of the device, lose track of which IP address is validly assigned. Unless the RCM device releases the IP address before the rotation occurs, DHCP servers are at risk of scope exhaustion, causing new devices (and RCM devices) to fail to obtain a new IP address. Even if the RCM device releases the IP address before the rotation occurs, the DHCP server typically holds the released IP address for a certain duration, in case the leaving MAC would return. As the DHCP server cannot know if the release is due to a temporal disconnection or a MAC rotation, the risk of scope address exhaustion exists even in cases where the IP address is released.

Routers keep track of which MAC address is on which interface. MAC rotation can cause MAC address cache exhaustion, but also the need for frequent ARP and inverse ARP exchanges.

In residential settings (environments type A), policies can be in place to control the traffic of some devices (e.g. parental control, block-list devices). These policies are often based on the device MAC address. Rotation of the MAC address removes the possibility for such control.

In residential settings (environments type A) and in enterprises (environments types D and E), device recognition and ranging may be used for IoT-related functionalities (door unlock, preferred light and temperature configuration, etc.) These functions often rely on the detection of the device wireless MAC address. MAC address rotation breaks the services based on such model.

In managed residential settings (environments types B) and in enterprises (environments types D and E), the network operator is often requested to provide IT support. With MAC address rotation, real time support is only possible if the user is able to provide the current MAC address. Service improvement support is not possible if the MAC address that the device had at the (past) time of the reported issue is not known at the time the issue is reported.

3.5. Scenario Mapping Table

Section 3.4 discusses different environments, different settings, and the expectations of users and network operators. Table 1 summarizes the expected degree of trust, network admin responsibility, complexity of supported network services and network support expectation from the user

| Network Location | Trust Degree | Network Admin | Network Services | Network Support Expectation |
|------------------|--------------|---------------|------------------|-----------------------------|
| Home | High | User | Medium | Low |
| Campus (BYOD) | Medium | IT | Complex | Medium |
| Enterprise (MDM) | High | IT | Complex | High |
| Hospitality | Low | IT | Simple | Medium |
| Public WiFi | Low | ISP | Simple | Low |

Table 1: Scenario Mapping Table

For example: a Home network is considered to be trusted and safe. Users expect a simple procedure to connect to their home network. All devices in the home network trust each other. Privacy within the Layer 2 domain is not a major concern. The Home network can also include many IoT devices, which need to be simple to onboard and manage. The home user commonly expects the network operator to protect the home network from external threats (attacks from the Internet). The home user also commonly expects simple policy features (e.g., Parental Control). Most home users do not expect to need networking skills to manage their home network.

On the other end of the spectrum, Public Wi-Fi is often considered to be untrusted. Privacy is the number one concern for the user. Most users connect to Public Wi-Fi only require simple Internet connectivity service, and expect only limited to no technical support.

3.6. Requirements Formulation

The section describes the requirements for Randomized MAC-Address Changes:

- REQ1 The network must not make any assumption about client MAC address persistence. MAC address change must happen while allowing for service continuity. If a service is interrupted during the RCM process, there must be a formal mechanism for the client and the network to exchange about the interruption.
- REQ2 During duration of the services, the device should not change the identity. Any change of identity may result re-authentication and interrupt of the current network services.
- REQ3 Survey the current standards that use MAC address as a device identifier in the protocol. Make recommendation to the working groups to remove the dependency.
- REQ4 Work as liaison with external standard bodies such as IEEE, BBF and WBA to align with use cases and requirements.
- REQ5 Identify a secure mechanism to authenticate and exchange network identity to the device.
- REQ6 Identify a secure mechanism to inform the device about the type of network the device is connecting to (e.g. public Wi-Fi, enterprise, home), allowing the user to select the device identity (or identities) accordingly.

REQ7 Identify a secure mechanism for the network to request device identity. Upon successful authentication, the network may provide the device a temporary network-based marker to use the network services.

REQ8 Identify a secure mechanism for the device to notify the network prior to update the MAC address.

4. IANA Considerations

This memo includes no request to IANA.

5. Security Considerations

Privacy considerations are discussed throughout this document.

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Abstract

Internet privacy has become a major concern over the past few years. Users are becoming more aware that their online activity leaves a vast digital footprint, that communications are not always properly secured, and that their location and actions can be easily tracked. One of the main factors for the location tracking issue is the wide use of long-lasting identifiers, such as MAC addresses.

There have been several initiatives at the IETF and the IEEE 802 standards committees to overcome some of these privacy issues. This document provides an overview of these activities, with the intention to inform the technical community about them, and help coordinate between present and futures standardization activities.

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1. Introduction

Internet privacy is becoming a huge concern, as more and more mobile devices are getting directly (e.g., via cellular or Wi-Fi) or indirectly (e.g., via a smartphone using Bluetooth) connected to the Internet. This ubiquitous connectivity, together with not very secure protocol stacks and the lack of proper education about privacy make it very easy to track/monitor the location of users and/or eavesdrop their physical and online activities. This is due to many factors, such as the vast digital footprint that users leave on the Internet, for instance sharing information on social networks, cookies used by browsers and servers to provide a better navigation

experience, connectivity logs that allow tracking of a user's Layer-2 (L2/MAC) or Layer-3 (L3) address, web trackers, etc.; and/or the weak (or even null in some cases) authentication and encryption mechanisms used to secure communications.

This privacy concern affects all layers of the protocol stack, from the lower layers involved in the actual access to the network (e.g., the MAC/Layer-2 and Layer-3 addresses can be used to obtain the location of a user) to higher layer protocol identifiers and user applications [wifi_internet_privacy]. In particular, IEEE 802 MAC addresses have historically been an easy target for tracking users [wifi_tracking].

There have been several initiatives at the IETF and the IEEE 802 standards committees to overcome some of these privacy issues. This document provides an overview of these activities, with the intention to inform the community and help coordinate between present and futures standardization activities.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

The following terms are used in this document:

MAC: Medium Access Control

3. Background

3.1. MAC address usage

Most mobile devices used today are Wi-Fi enabled (i.e. they are equipped with an IEEE 802.11 wireless local area network interface). Wi-Fi interfaces, as any other kind of IEEE 802-based network interface, like Ethernet (i.e. IEEE 802.3) have a Layer-2 address also referred to as MAC address, which can be seen by anybody who can receive the signal transmitted by the network interface. The format of these addresses is shown in Figure 1.

Figure 1: IEEE 802 MAC Address Format (TBD)

MAC addresses can either be universally administered or locally administered. Universally administered and locally administered addresses are distinguished by setting the second-least-significant bit of the most significant byte of the address (the U/L bit).

A universally administered address is uniquely assigned to a device by its manufacturer. Most physical devices are provided with a universally administered address, which is composed of two parts: (i) the Organizationally Unique Identifier (OUI), which are the first three octets in transmission order and identify the organization that issued the identifier, and (ii) Network Interface Controller (NIC) Specific, which are the following three octets, assigned by the organization that manufactured the NIC, in such a way that the resulting MAC address is globally unique.

Locally administered addresses override the burned-in address, and they can either be set-up by the network administrator, or by the Operating System (OS) of the device to which the address pertains. However, as explained in further sections of this document, there are new initiatives at the IEEE 802 and other organizations to specify ways in which these locally administered addresses should be assigned, depending on the use case.

3.2. MAC address randomization

Since universally administered MAC addresses are by definition globally-unique, when a device uses this MAC address to transmit data -especially over the air- it is relatively easy to track this device by simple medium observation. Since a device is usually directly associated to an individual, this poses a privacy concern [link_layer_privacy].

MAC addresses can be easily observed by a third party, such as a passive device listening to communications in the same network. In an 802.11 network, a station exposes its MAC address in two different situations:

- o While actively scanning for available networks, the MAC address is used in the Probe Request frames sent by the device (aka IEEE 802.11 STA).
- o Once associated to a given Access Point (AP), the MAC address is used in frame transmission and reception, as one of the addresses used in the address fields of an IEEE 802.11 frame.

One way to overcome this privacy concern is by using randomly generated MAC addresses. As described in the previous section, the IEEE 802 addressing includes one bit to specify if the hardware address is locally or globally administered. This allows generating local addresses without the need of any global coordination mechanism to ensure that the generated address is still unique within the local network. This feature can be used to generate random addresses, which decouple the globally-unique identifier from the device and

therefore make it more difficult to track a user device from its MAC/L2 address [enhancing_location_privacy].

3.3. Privacy Workshop, Tutorial and Experiments at IETF and IEEE 802 meetings

As an outcome to the STRINT W3C/IAB Workshop [strint], on July 2014 a Tutorial on Pervasive Surveillance of the Internet - Designing Privacy into Internet Protocols was given at the IEEE 802 Plenary meeting in San Diego [privacy_tutorial]. The Tutorial provided an update on the recent developments regarding Internet privacy, the actions that other SDOs such as IETF were taking, and guidelines that were being followed when developing new Internet protocol specifications (e.g. [RFC6973]). The Tutorial highlighted some Privacy concerns applicable specifically to Link Layer technologies and provided suggestions on how IEEE 802 could help addressing them.

Following the discussions and interest within the IEEE 802 community, on 18 July 2014 the IEEE 802 Executive Committee (EC) created an IEEE 802 EC Privacy Recommendation Study Group (SG) [ieee_privacy_ecsg]. The work and discussions from the group have generated multiple outcomes, such as: 802E PAR: Recommended Practice for Privacy Considerations for IEEE 802 Technologies [IEEE_802E], and the 802c PAR: Standard for Local and Metropolitan Area Networks - Overview and Architecture Amendment - Local Medium Access Control (MAC) Address Usage [IEEE_802c].

In order to test the effects of MAC address randomization, major trials were conducted at the IETF and IEEE 802 meetings between November 2014 and March 2015 - IETF91, IETF92 and IEEE 802 Plenary in Berlin. The purpose of the experiments was to evaluate the use of MAC address randomization from two different perspectives: (i) the effect on the connectivity experience of the end-user, also checking if applications and operating systems (OSs) were affected; and (ii) the potential impact on the network infrastructure itself. Some of the findings were published in [wifi_internet_privacy].

During the experiments it was observed that the probability of address duplication in a network with this characteristics is negligible. The experiments also showed that other protocol identifiers can be correlated and therefore be used to still track an individual. Hence, effective privacy tools should not work in isolation at a single layer, but they should be coordinated with other privacy features at higher layers.

Since then, MAC randomization has further been implemented by mobile operating systems to provide better privacy for mobile phone users

when connecting to public wireless networks [privacy_ios], [privacy_windows], [privacy_android].

4. Recent RCM activities at the IEEE 802

Practical experiences of Randomized And Changing MAC Addresses (RCM) in live devices helped researchers fine-tune their understanding of attacks against randomization mechanisms [when_mac_randomization_fails]. At IEEE 802.11 these research experiences eventually formed the basis for a specified mechanism introduced in the IEEE 802.11aq in 2018 which randomize MAC addresses that recommends mechanisms to avoid pitfalls [IEEE_802_11_aq].

More recent developments include turning on MAC randomization in mobile operating systems by default, which has an impact on the ability of network operators to personalize or customize services [rcm_user_experience_csd]. Therefore, follow-on work in the IEEE 802.11 mapped effects of potentially large uptake of randomized MAC identifiers on a number of commonly offered operator services in 2019[rcm_tig_final_report]. In the summer of 2020 this work emanated in two new standards projects with the purpose of developing mechanisms that do not decrease user privacy and enable an optimal user experience when the MAC address of a device in an Extended Service Set is randomized or changes [rcm_user_experience_par] and user privacy solutions applicable to IEEE Std 802.11 [rcm_privacy_par].

The IEEE 802.1 working group has also published a specification that defines a local MAC address space structure, known as the Structured Local Address Plan (SLAP). This structure designates a range of local MAC addresses for protocols using a Company ID (CID) assigned by the IEEE Registration Authority. Another range of local MAC addresses is designated for assignment by administrators. The specification recommends a range of local MAC addresses for use by IEEE 802 protocols [IEEE_802c].

Work within the IEEE 802.1 Security task group on privacy recommendations for all IEEE 802 network technologies has also looked into general recommendations on identifiers, reaching the conclusion that temporary and transient identifiers are preferably in network technology design if there are no compelling reasons of service quality for a newly introduced identifier to be permanent. This work has been specified in the recently published IEEE P802E: Recommended Practice for Privacy Considerations for IEEE 802 Technologies [IEEE_802E]. The IEEE P802E specification will form part of the basis for the review of user privacy solutions applicable to IEEE Std 802.11 (aka Wi-Fi) devices as part of the RCM [rcm_privacy_csd] efforts.

Currently, two task groups in IEEE 802.11 are dealing with issues related to RCM:

- o The IEEE 802.11bh task group, looking at mitigating the repercussions that RCM creates on 802.11 networks and related services, and
- o The IEEE 802.11bi task group, which will define modifications to the IEEE Std 802.11 medium access control (MAC) specification to specify new mechanisms that address and improve user privacy.

5. Recent MAC randomization-related activities at the WBA

At the Wireless Broadband Alliance (WBA), the Testing and Interoperability Work Group has been looking at the issues related to MAC address randomization and has identified a list of potential impacts of these changes to existing systems and solutions, mainly related to Wi-Fi identification.

As part of this work, WBA has documented a set of use cases that a Wi-Fi Identification Standard should address in order to scale and achieve longer term sustainability of deployed services. A first version of this document has been liaised with the IETF as part of the MAC Address Device Identification for Network and Application Services (MADINAS) activities through the "Wi-Fi Identification In a post MAC Randomization Era v1.0" paper [wba_paper].

6. MAC randomization-related activities at the IETF

Several IP address assignment mechanisms such as the IPv6 stateless autoconfiguration techniques (SLAAC) [RFC4862] generate the Interface Identifier (IID) of the address from its MAC address (via EUI64), which then becomes visible to all IPv6 communication peers. This potentially allows for global tracking of a device at L3 from any point on the Internet. Besides, the prefix part of the address provides meaningful insights of the physical location of the device in general, which together with the MAC address-based IID, makes it easier to perform global device tracking.

There are some solutions that might mitigate this privacy threat, such as the use of temporary addresses [RFC4191], the use of opaque IIDs [RFC7217], [I-D.gont-6man-deprecate-eui64-based-addresses]. Next, we briefly describe how these solutions work.

[RFC4191] identifies and describes the privacy issues associated with embedding MAC stable addressing information into the IPv6 addresses (as part of the IID) and describes some mechanisms to mitigate the associated problems. The specification is meant for IPv6 nodes that

auto-configure IPv6 addresses based on the MAC address (EUI-64 mechanism). It defines how to create additional addresses (generally known as "temporary addresses") based on a random interface identifier for the purpose of initiating outgoing sessions. These "random" or temporary addresses are meant to be used for a short period of time (hours to days) and would then be deprecated. Deprecated addresses can continue to be used for already established connections, but are not used to initiate new connections. New temporary addresses are generated periodically to replace temporary addresses that expire. In order to do so, a node produces a sequence of temporary global scope addresses from a sequence of interface identifiers that appear to be random in the sense that it is difficult for an outside observer to predict a future address (or identifier) based on a current one, and it is difficult to determine previous addresses (or identifiers) knowing only the present one. The main problem with the temporary addresses is that they should not be used by applications that listen for incoming connections (as these are supposed to be waiting on permanent/well-known identifiers). Besides, if a node changes network and comes back to a previously visited one, the temporary addresses that the node would use will be different, and this might be an issue in certain networks where addresses are used for operational purposes (e.g., filtering or authentication). [RFC7217], summarized next, partially addresses the problems aforementioned.

[RFC7217] defines a method for generating IPv6 IIDs to be used with IPv6 Stateless Address Autoconfiguration (SLAAC), such that an IPv6 address configured using this method is stable within each subnet, but the corresponding IID changes when the host moves from one network to another. This method is meant to be an alternative to generating Interface Identifiers based on MAC addresses, such that the benefits of stable addresses can be achieved without sacrificing the security and privacy of users. The method defined to generate the IPv6 IID is based on computing a hash function which takes as input information that is stable and associated to the interface (e.g., MAC address or local interface identifier), stable information associated to the visited network (e.g., IEEE 802.11 SSID), the IPv6 prefix, and a secret key, plus some other additional information. This basically ensures that a different IID is generated when any of the input fields changes (such as the network or the prefix), but that the IID is the same within each subnet.

In addition to the former documents, [I-D.ietf-dhc-mac-assign] proposes an extension to DHCPv6 that allows a scalable approach to link-layer address assignments where preassigned link-layer address assignments (such as by a manufacturer) are not possible or unnecessary. [I-D.ietf-dhc-slap-quadrant] proposes extensions to DHCPv6 protocols to enable a DHCPv6 client or a DHCPv6 relay to

indicate a preferred SLAP quadrant to the server, so that the server may allocate MAC addresses in the quadrant requested by the relay or client.

Not only MAC and IP addresses can be used for tracking purposes. Some DHCP options carry unique identifiers. These identifiers can enable device tracking even if the device administrator takes care of randomizing other potential identifications like link-layer addresses or IPv6 addresses. [RFC7844] introduces anonymity profiles, designed for clients that wish to remain anonymous to the visited network. The profiles provide guidelines on the composition of DHCP or DHCPv6 messages, designed to minimize disclosure of identifying information. [RFC7844] also indicates that the link-layer address, IP address, and DHCP identifier shall evolve in synchrony.

Lately, the MAC Address Device Identification for Network and Application Services (MADINAS) IETF BoF has discussed the need to examine the effect of RCM schemes on network and application services in several scenarios identified as relevant.

7. OS current practices

Most modern OSes (especially mobile ones) do implement by default some MAC address randomization policy. Table 1 summarizes current practices for Android and iOS, as the time of writing this document (original source: <https://www.fing.com/news/private-mac-address-on-ios-14>, updated based on findings from the authors).

| Android 10+ | iOS 14+ |
|--|--|
| The randomized MAC address is bound to the SSID | The randomized MAC address is bound to the BSSID |
| The randomized MAC address is stable across reconnections for the same network | The randomized MAC address is stable across reconnections for the same network |
| The randomized MAC address is reset when the device forgets a WiFi network | The randomized MAC address is reset when the device forgets a WiFi network |
| MAC address randomization is enabled by default for all the new WiFi networks. But if the device previously connected to a WiFi network identifying itself with the real MAC address, no randomized MAC address will be used (unless manually enabled) | MAC address randomization is enabled by default for all the new WiFi networks |

Table 1: Android and iOS MAC address randomization practices

8. IANA Considerations

N/A.

9. Security Considerations

TBD.

10. Acknowledgments

TBD.

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