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Security Guidance for First Responder Mobile and Wearable Devices

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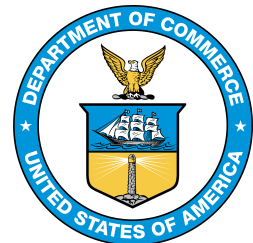
Security Guidance for First Responder Mobile and Wearable Devices

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Reports on Computer Systems Technology

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Abstract

Public safety officials utilizing public safety broadband networks will have access to devices, such as mobile devices, tablets and wearables. These devices offer new ways for first responders to complete their missions but may also introduce new security vulnerabilities to their work environment. To investigate this impact, the security objectives identified in NIST Interagency Report (NISTIR) 8196, *Security Analysis of First Responder Mobile and Wearable Devices*, were used to scope the analysis of public safety mobile and wearable devices and the current capabilities that meet those security objectives [1]. The purpose of this effort is to provide guidance that enables jurisdictions to select and purchase secure devices; and assist industry to design and build secure devices tailored to the needs of first responders.

Keywords

cybersecurity; first responders; internet of things; IoT; mobile security; public safety; wearables.

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Audience

This document is intended for those acquiring mobile devices and wearables for deployment in public safety scenarios. This document may also be useful for those designing public safety mobile devices, tablets, and wearable devices.

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1 Introduction

Public safety first responders are the first at the scene of an emergency incident. Their day-to-day includes life-saving and sometimes life-threatening activities. As commercial and enterprise technology advance, first responders have the opportunity to take advantage of this technology to enhance their efficiency, safety, and capabilities during an incident. The nationwide public safety broadband network (NPSBN), is steadily deployed across the United States. The NPSBN is operated by AT&T under the guidance of the First Responders FirstNet Authority (FirstNet), per the Middle Class Tax Relief and Job Creation Act of 2012 [2]. Networks like those provided by FirstNet by AT&T and the NPSBN will allow first responders to use modern communication technology (e.g., mobile devices) as well as other Internet of Things (IoT) devices (e.g., wearables) to accomplish their public safety mission.

As with any new technology, there are security concerns, such as the vulnerabilities and threats to their data and users. In the case of public safety there are concerns that exploits of vulnerabilities may inhibit first responders from performing their duties and put their safety at risk. NISTIR 8196 *Security Analysis of First Responder Mobile and Wearable Devices*, is a document that was produced in a previous study to understand the specific security needs of mobile and wearable devices for first responders [1]. The document captures the various use cases of public safety mobile and wearable device, the known attacks on public safety mobile and wearable devices, and information received from interviews with actual public safety officials. Due to their unique roles, environments, and situations, the information in NISTIR 8196 is important to grasp the first responder perspective and analyze the security objectives necessary for all first responder devices.

Mass production of mobile and wearable devices makes it easy to find and buy any device that may meet one's wants and needs. Technology is primarily produced for the general consumer or enterprise and not specifically designed with public safety in mind. This could lead to potential repercussions if the appropriate device is procured without consideration of the security and safety of first responders. When it comes to selecting mobile and wearable devices, there is little security guidance that focuses on the particular needs of public safety. During an emergency, a first responder should have some assurance that their devices are reliable and secure.

1.1 Purpose

The purpose of this document is to share a high-level overview of the current capabilities of public safety mobile and wearable devices. This will give insight of the security capabilities available within today's devices. Additionally, this document provides guidance for procuring and designing secure mobile and wearable devices specifically for public safety. This document includes the following:

- A list of tests developed to analyze public safety mobile and wearable devices
 - Each test provides an overview of the outcome and the analysis derived from observation of that outcome
- A collection of best practices and guidance for public safety mobile and wearable devices

1.2 Scope

This research effort focuses primarily on public safety mobile and wearable devices. Securing broadband networks, for instance, the management, and operation of cellular networks are out of scope. An entire class of devices exists under the IoT umbrella; however, this document solely focuses on wearable IoT devices that may be used by public safety. Additionally, mobile applications that ship with a public safety mobile device are considered in scope, as they are often required to perform typical public safety activities, such as voice communication. Backend services and the communication paths utilized by these mobile applications, to include data transmission from an application to supporting infrastructure, are in scope. Finally, public safety officials work in a variety of disciplines, this Interagency Report (IR) is focused on first responders (i.e., fire service, EMS, and law enforcement) and the public safety device administrators that provide devices to first responders. Testing scenarios, gaps, analysis and guidance beyond those found within this document or the needs of first response, may consult supplementary resources such as the NIST Cybersecurity Framework, the NIST Mobile Security Framework, the Open Web Application Security Project (OWASP), and other device specific security hardening resources.

1.3 Document Structure

The document is organized into the following major sections:

- Section 2 provides an overview of the technology analyzed,
- Section 3 outlines the methodology used for analysis
- Section 4 summarizes the test plan and findings
- Section 5 suggests best practices and guidance for public safety mobile and wearable devices
- Section 6 concludes the document with a review of the document, future considerations, and other related NIST work
- Section 7 contains a list of references used in the development of this document

The document also contains appendices with supporting material:

- Appendix A defines selected acronyms and abbreviations used in this publication, and
- Appendix B provides a detailed description of each test, including, procedures, analysis, gaps, and guidance

2 Technology Overview

The following section describes the technologies reviewed throughout this effort. When selecting the public safety devices to analyze, PSCR Engineers searched for public safety-grade technology and devices that could be used in the future to assist first responders. Below is an overview of the types of the devices and why those devices are relevant to this project.

2.1 Public Safety Mobile Devices

The selection of public safety mobile devices was based on knowledge of the upcoming public safety communication systems. The Federal Communications Commission has allocated a portion of the 700 MHz band as the public safety spectrum. This portion of the spectrum is also known as the Band 14 spectrum, which is to be utilized as the national public safety broadband network. This spectrum will allow for device communications to penetrate walls and buildings and prevent congestion issues due to flooded transmissions during an emergency. PSCR Engineers sought out mobile devices that utilized band 14, as well other mobile devices that are not band 14 capable but may be ruggedized or have a secure operating system.

The analyzed public safety mobile devices use rich operating systems supporting downloadable applications, usually based on operating systems found on consumer electronics. Typically, the mobile devices used an Android operating system. The version of the operating system varied per device, some being 4-5 versions behind the latest release.

2.2 Public Safety Wearable Devices

Wearable devices made specifically for public safety are slowly being introduced to the marketplace. Outside of public safety specific wearable devices, PSCR Engineers also acquired wearable devices that may assist first responders in different ways, such as awareness, communication, and data sharing. Examples of wearable devices include the following:

- Bluetooth headset
- body camera
- vital-sign monitors/Body sensors

Most of the wearable devices analyzed, use some variation of Bluetooth and/or Wi-Fi as their wireless communication protocol. These protocols allow for communication between a wearable device and a mobile device or desktop. Wearable devices typically do not have a complex operating system and perform minimal tasks that enable them to process and send information to be interpreted by an application on another system, such as a mobile device or desktop computer. Many of the wearable devices analyzed through this research are dependent on being able to send information to a mobile application to be interpreted, stored, and possibly shared through cloud services.

3 Analysis Methodology

This section gives an overview of the methodology used to develop the best practices and guidance for securing First Responder mobile and wearable devices. The process required thorough understanding of the security objectives from the perspective of first responders. This was accomplished through interviews with public safety officials and development of NISTIR 8196, *Security Analysis of First Responder Mobile and Wearable Devices* [1].

With the information gathered from NISTIR 8196, PSCR Engineers were able to take the steps necessary to analyze the security of current mobile and wearable devices and compare their analysis with the security objectives of first responders. This exercise resulted in this document and ultimately security guidance that describes the security capabilities that should be included in mobile and wearable devices for first responders.

3.1 Test Plan

The previous effort, NISTIR 8196, identified eight (8) security objectives, documented below:

Table 1 - Handset and Wearable Security Objectives

Availability	Confidentiality
Ease of Management	Authentication
Interoperability	Integrity
Isolation	Healthy Ecosystem

Using these security objectives, the first step was to develop a test plan to perform a security analysis of public safety mobile and wearable devices. The security objectives, which focus on the security needs of public safety, are used to define the scope of the tests. Some, not all, security objectives have sub-objectives. A list of these sub-objectives can be found below:

Table 2 - Handset and Wearable Security Sub-objectives

SECURITY OBJECTIVE	SUB-OBJECTIVE(S)
AVAILABILITY	Network Availability Network Agility Data Availability Device Availability
EASE OF MANAGEMENT	N/A

SECURITY OBJECTIVE	SUB-OBJECTIVE(S)
INTEROPERABILITY	Device Configuration Infrastructure Interoperability Network Interoperability Security Technology Interoperability Data Format Interoperability
ISOLATION	Data Isolation Application Isolation
CONFIDENTIALITY	Data In Transit Data At Rest
AUTHENTICATION	Ease of Authentication User to Device Authentication Device to Network Authentication User to Third Party Service/Mobile Device/ Wearables
INTEGRITY	N/A
HEALTHY ECOSYSTEM	Configuration Updates Bundled Applications

Many of the sub-objectives are not in scope for this analysis, as these sub-objectives require a more in-depth analysis and test plan than intended for the purposes of this project. The excluded security objectives are important to the needs of public safety and may be analyzed in future research.

3.2 Testing & Analysis

PSCR Engineers gathered a series of mobile and wearable devices that are advertised for public safety use or could be used to assist first responders. Using the test plan, PSCR Engineers applied the tests to the acquired devices. With the observed results, an analysis was performed that gave understanding of the current security posture of these devices. Using information gathered from the initial research in NISTIR 8196 and the results from this security analysis, a gap analysis was performed to identify any missing features or capabilities within the public safety mobile and wearable devices. The results of all research allowed for the next step in the overall methodology, the development of best practices and guidance for acquiring secure mobile and wearable devices for public safety.

3.3 Develop Guidance

After completion of the security testing and gap analysis, for the final step in the methodology PSCR Engineers developed best practices and guidance. To develop this guidance, PSCR Engineers used information gathered from the test analysis and referenced current security best practices for general information systems that can apply to mobile and wearable devices. These references include the Cybersecurity Framework Version 1.1 [3], NISTIR 8228, *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks* [4], and NISTIR 8259, *Foundational Cybersecurity Activities for IoT Device Manufacturers* [5].

4 Test Overview

The type of testing performed for this analysis demonstrates an understanding of the state of firmware/software that is pre-installed, the vulnerabilities present on the device, and the types of secure technologies included within the devices. This effort will also assist with understanding what type of external certifications and testing occurs for these devices, such as Ingress Protection (IP) codes which rate device ruggedness against environmental elements [6].

This document does not identify specific devices, manufacturers, or service providers. NIST does not condone, endorse, dissuade or dismiss the use of any specific device, manufacturer, service provider or analysis tool utilized for information collection. All test information was gathered at a specific date and time before the writing of this document and may not accurately reflect the current state, condition or availability of information pertaining to a specific device. In this section information will be collated to reflect a summary of information regarding all devices tested.

The following sections provide a summary of the test findings for mobile (section 4.1) and wearable (section 4.2). Each section starts with a table that provides an overview of the tests used to analyze the security capabilities of mobile and wearable devices. The table includes the following:

- *Test Number* – The number associated with each test
- *Test Name* – The test name, which summarizes the purpose of the test
- *Security Objective(s)* – The mapping to one or more of the security objectives from NISTIR 8196 [1]
- *Test Description* – The test description describes the information the test will provide in relation to the security analysis of the mobile and wearable devices

For more information about the test outcomes, including a detailed analysis of potential impacts, future considerations for public safety, and any gaps found as a result of the test, see Appendix B.

4.1 Mobile Test Results Summary

Table 3 - Mobile Device Tests

Test No.	Test Name	Security Objectives	Test Description
1	Obtain General Hardware Information	Ease of Management Data Availability Healthy Ecosystem	This test identifies information about the device, and how easy it is to do so.

Test No.	Test Name	Security Objectives	Test Description
2	Obtain General Software Information	Ease of Management Network Agility Healthy Ecosystem	This test identifies the name and software version of operating system and major applications that are shipped with the device. This will also attempt to understand the protocol versions for the primary wireless protocols (i.e., Wi-Fi, Bluetooth, and Cellular).
3	Device Ruggedization Ratings	Device Availability Ease of Management Healthy Ecosystem	Implementation of ruggedization ensures durability for First Responder applications and survivability of day-to-day use. This test identifies the IP ratings and any ruggedization information available for the device. Physical survivability of First Responder mobile devices ensures the integrity of responder data. IP ratings and certification ensure data integrity by reducing occurrence of device failure in extreme environments as well as reliable communications.
4	Obtaining Vulnerability Information from OS version and known databases	Device Availability Data Availability Integrity Healthy Ecosystem	In this test, PSCR Engineers manually check the software versions of the OS that shipped within the device against a list of vulnerabilities within public databases to understand the types of vulnerabilities already known within the OS. PSCR Engineers look to understand the impact and criticality of all the known vulnerabilities.
5	Vulnerability Scan via Mobile Threat Defense (MTD) Application	Device Availability Data Availability Integrity Healthy Ecosystem	This test uses publicly available mobile threat defense (MTD) applications to identify vulnerabilities within the mobile OS and applications shipped with the device. PSCR Engineers look to understand the impact and criticality of all the known vulnerabilities
6	External Fingerprinting	Confidentiality Integrity	Fingerprinting a device is often an initial stage of information gathering before it is attacked. This test uses a set of common network scanning tools to understand the types of ports and protocols open and running on the device.

Test No.	Test Name	Security Objectives	Test Description
7	External Vulnerability Scan	Data Availability Confidentiality Integrity Healthy Ecosystem	This test uses a set of common vulnerability scanners to understand the types of vulnerabilities within the device. An external vulnerability scan device is often part of an information gathering phase before it is attacked. PSCR Engineers look to understand the impact and criticality of all the known vulnerabilities
8	MAC Address Randomization	Confidentiality	Static device or network identifiers could be used to track a device or user in a physical region. This test determines if a device randomizes these identifiers, including Bluetooth and Wifi MAC addresses.
9	Device Update Policy	Healthy Ecosystem	This test seeks to understand how often the device is scheduled to receive security updates and other software from the vendor. Specifically, the regularity / cadence, type, and reasons for updating the device and applying security patches will be reviewed.
10	Rogue Base station Detection	Availability Confidentiality Integrity	This test identifies if the public safety mobile devices can detect rogue base stations that could affect cellular traffic in malicious ways.
11	Configuration Guidance	Integrity Interoperability Healthy Ecosystem	This test reviews the type of guidance provided from the vendor to the public safety professionals, and if any of this is security guidance dedicated to properly owning, operating, and configuring the device for public safety use.
12	Wi-Fi Person-in-the-Middle (PitM) Detection	Availability Confidentiality Integrity	This test checks to see if the mobile device is able to locally detect PitM attacks when using Wi-Fi.
13	Boot Integrity	Integrity	This test checks to see if the mobile device is performing some form of boot validation. Boot validation is an integrity check on device boot files and processes to verify that the mobile OS has not been modified by an unauthorized entity. If validation succeeds, the device will continue to load the system and may perform additional validation. If validation fails, the device will stop the boot sequence, enter an error state and/or reboot.

Test No.	Test Name	Security Objectives	Test Description
14	Data Isolation	Integrity Isolation	In this test, PSCR Engineers seek to understand if the mobile device is utilizing an isolation technology, such as SELinux.
15	Device Encryption	Confidentiality Ease of Management	In this test, PSCR Engineers seek to understand if the device is using encryption, and how difficult it is to enable.

PSCR Engineers found that most mobile devices have the built-in capabilities and the information necessary to meet the various security objectives of First Responders. Mobile devices have been around for more than 10 years, which has allowed growth in many areas (e.g., functionality and security). With a full OS and screen display, users/administrators can easily find device information within the *Settings* menu (i.e., hardware and software information). Additional information (e.g., configuration guidance and update policies) is easily accessible in the user manuals available online. All of this information is useful for device administrators to use when making risk decisions and deciding whether to use a specific mobile device that meets the First Responder requirements.

Security is not automatically enabled in mobile devices. Although mobile devices have built-in security features, enabling those features requires additional APIs. For example, PSCR Engineers leveraged a free 3rd party mobile application called a Mobile Threat Defense tool to analyze any potential or current vulnerabilities on the mobile device under analysis. A Mobile Threat Defense tool can detect the presence of malicious apps or operating system (OS) software, known vulnerabilities in software or configurations, and connections to denylisted websites/servers or networks [7]. There are other applications/tools that can enable different security features within a mobile device, such as a VPN connection or enforce policies/device configurations.

PSCR Engineers found that a few mobile devices were operating on an outdated OS. Using an outdated OS allowed the device to continue to use Public Safety mobile applications that are only supported by the old OS. OS updates are developed to improve features or patch bugs/vulnerabilities. Using an outdated OS may allow a First Responder to use the Public Safety application they need for their daily activities, but may also leave the phone in a vulnerable state because it has not received the necessary patches.

Lastly, PSCR Engineers found that mobile devices are not able to detect a rogue/fake base station and prevent connection to these base stations. Rogue base stations are not owned or operated by a Mobile Network Operator (MNO), they broadcast cellular network information, and masquerade as a legitimate network [8]. These base stations can be used for PitM attacks to eavesdrop, perform a denial of service, or gather information to track a user's location. A common attack is using a rogue base station as an International Mobile Subscriber Identity (IMSI) catcher. When a mobile device attempts to connect to a rogue base station, they are able to gather that device's IMSI information. With a device's IMSI information, an attacker can track a device as it moves from base station to base station. Recent updates to the 3GPP cellular standards have improved confidentiality of the subscriber identity so that it is more difficult for rogue base stations to track the location a user's device through normal means [9]. Although this may defeat IMSI catchers, this does not resolve the other potential attacks because mobile devices are constantly trying to connect to a cellular network and may connect to a rogue base station if it has the strongest signal. There are ongoing standards activities and research projects to improve mobile device technology and protect devices against rogue base station attacks.

4.2 Wearable Test Results Summary

Table 4 - Wearable Device Tests

Test No.	Test Name	Security Objectives	Test Description
1	Obtain General Hardware Information	Ease of Management Data Availability Healthy Ecosystem	This test identifies information about the device, and how easy it is to obtain that information.
2	Obtain General Software Information	Ease of Management Network Agility Healthy Ecosystem	This test identifies the name and software version of operating system and major applications that are shipped with the device. Note that this is much more difficult on a wearable device than on a mobile device, and NIST engineers will not be performing firmware and binary extraction activities. This will also attempt to understand the protocol versions for the primary wireless protocols (i.e., Wi-Fi, Bluetooth, and Cellular). This test will also investigate the use of wearable specific protocols such as Near field communications (NFC) and long range(LoRa®) technology.
3	Device Ruggedization Ratings	Device Availability Ease of Management Healthy Ecosystem	Implementation of ruggedization ensures durability for First Responder applications and survivability of day-to-day use. This test identifies the Ingress Protection (IP) ratings and any ruggedization information available for the device.

4	Obtaining Vulnerability Information from OS version and known databases	Device Availability Data Availability Integrity Healthy Ecosystem	In this test, PSCR Engineers manually check the software versions of the OS that shipped within the device against a list of vulnerabilities within public databases to understand the types of vulnerabilities already known within the OS. PSCR Engineers look to understand the impact and criticality of all the known vulnerabilities.
5	Device Pairing	Authentication Integrity	This test identifies how the wearable device pairs and authenticates to a mobile device, such as the use of an insecure pairing mechanism. Investigate any encryption, privacy protections, device names, and insecure pairing types.
6	Device Encryption	Confidentiality	This test identifies how the wearable device communicates with a mobile device, specifically using encryption. This will include the use of secure algorithm, reasonable key sizes, and any PitM protection.
7	Configuration Guidance	Integrity Interoperability Healthy Ecosystem	This test reviews the type of guidance provided from the vendor to the public safety professionals, and if any of this is security guidance dedicated to properly owning, operating, and configuring the device for public safety use.
8	MAC Address Randomization	Confidentiality	Static device or network identifiers could be used to track a device or user in a physical region. This test determines if a device randomizes these identifiers, including Bluetooth and Wifi MAC addresses.
9	Device Update Policy	Healthy Ecosystem	This test seeks to understand how often the device is scheduled to receive security updates and other software from the vendor. Specifically, the regularity / cadence, type, and reasons for updating the device and applying security patches will be reviewed.

Through testing and analysis, PSCR Engineers found that most wearable devices have minimal functionality. The limited functionality seems to be partially intentional because the device requires limited processing power which minimizes batter power usage and allows for longer battery life. This also restricts the general capabilities of the device, including the security capabilities. Wearable devices often do not have a screen display and require another application (e.g., mobile application) to interface with the device and gather information about the device. Alternatively, detailed device information can be found in the user manual or on the device manufacturer's website.

When reviewing access to wearable device information, PSCR Engineers found limited and varying information available on each device. Some information required network traffic analysis to identify information such as, the version of the network protocol being used, or the security levels being implemented by the wearable device. Most devices did not provide an update policy or secure configuration guidance.

Network protocols varied amongst the wearable devices, with few using Wi-Fi or Cellular protocols. The most common network protocol used across the wearable devices under test (DUTs), was Bluetooth. Many of the devices were using older versions of the Bluetooth specification or were able to downgrade to an earlier version of the protocol for device compatibility reasons. PSCR Engineers analyzed the authentication and encryption capabilities with regards to the Bluetooth device pairing process.

For authentication, most wearable DUTs use Simple Pairing Mode to request device access, which does not provide PitM protection. This potentially leaves wearable devices vulnerable to eavesdropping, a denial of service, and location tracking. Devices that utilize version Bluetooth 4.0 or greater have the ability to use the latest authentication, encryption, and key pairing mechanism which is utilized by Bluetooth Classic and Bluetooth Low Energy (BLE), which can provide PitM protection if the device can display a number or handle input from a user.. Most wearables do not have a display or a way to input the passkey required for PitM protection. PSCR Engineers found that one device used a pairing mode providing PitM protection, but the PIN was static and could easily be brute forced or found in the device manual. Overall most devices used the older Bluetooth pairing method (Simple Pairing Mode) and auto accepts any connection requests. More information can be found in Appendix B section B.2.5.

The encryption used by the wearable DUTs followed that of devices using older versions of Bluetooth (e.g., Bluetooth version 2.1) and secure simple pairing with security level 2, which uses unauthenticated keys. Some older versions of Bluetooth use encryption algorithms that are no longer approved by the Federal Information Processing Standards (FIPS). Bluetooth versions 4.1 or greater and Bluetooth Low Energy support the use of NIST-approved algorithms [10].

Ultimately, PSCR Engineers concluded that wearables are currently able to adhere to a minimum number of Public Safety security objectives. Wearable devices are built to emphasize usability rather than security. In a field such as Public Safety, usability is vital for a First Responder to perform their life-saving activities, but without the proper hardening this could impact the usability of a wearable device (e.g., Denial-of-Service or transmission of inaccurate data) [11]. Wearable devices may require future improvements to better meet the security needs of First Responders.

5 Best Practices and Guidance

After reviewing the test analysis results, PSCR Engineers gained an understanding of the current state of mobile and wearable devices with regards to their security capabilities. These results were then compared to the First Responder security objectives from NISTIR 8196 [1]. This comparison was done to understand gaps in the current capabilities of these devices vs. what first responders are looking for when it comes to the security of their devices.

In this section, PSCR Engineers provide guidance to assist first responders when acquiring mobile and wearable devices that meet their security needs. This guidance is intended to be beneficial and understandable for all stakeholders within the public safety mobile and wearable device arena. First responders can benefit from this guidance because they are the primary users of these devices and a secure device allows them to focus on their life-saving activities. Also, first responders should have a way to communicate their needs with regards to a secure device. Public safety device administrators are responsible for distribution and configuration of mobile and wearable devices. This guidance will help administrators ensure they are aware of what security features to ask for, how to apply the security features, and train their users for proper use. Finally, this guidance will give device manufacturers insight into the security features and capabilities that first responders are looking for within their mobile and wearable devices. With this information, manufactures can build to meet the security objectives of first responders.

PSCR Engineers used the Cybersecurity Framework version 1.1, to aid in the guidance communication. The Cybersecurity Framework is a tool that can be used to communicate cybersecurity information to various technical levels within an organization. The Cybersecurity Framework defines five functions (Identify, Protect, Detect Respond, and Recover) that are easy to understand and can be used to communicate in plain language to various members within an organization [3]. PSCR Engineers used these functions to provide high-level guidance to take into consideration when aspiring to acquire secure mobile and wearable devices.

5.1 Guidance for Mobile and Wearable Devices

Mobile devices have many built-in security capabilities. This is partially due to their size, storage capability, and fully-fledged operating systems. Somewhat mimicking traditional desktops, a mobile phone has various network capabilities (e.g., Bluetooth, Wi-Fi, and cellular connectivity), along with the ability to update firmware and download software to expand the devices abilities even further. Many mobile devices are capable or have the information necessary to meet the security objectives of first responders.

Wearable devices are very different from mobile devices, in that they are typically built primarily to accomplish a specific use (e.g., communication through a headset or to record vital signs). Due to their often-limited processing power, wearable devices do not have various options when it comes to functionality and security. Device information and capabilities vary per wearable device, and the inconsistency with wearable device information makes it difficult for interested parties to find what they need to make risk-decisions. While there is a variance in capabilities, this could be beneficial if the capabilities meet the needs of first responders using them (i.e., functionally and security-wise). The configuration of wearable device capabilities is not as flexible as with mobile devices. Often wearable devices only come with preset abilities and are not updatable. For some wearable devices that interfaced with a mobile application or other external software application, some areas of functionality/firmware could be updated. There are several areas where wearable devices can better address the security objectives of first responders, and they are highlighted in the guidance provided below.

Below is a chart that includes the following:

- Cybersecurity Framework Function – the Cybersecurity Framework function that provides the plain language term that applies to the guidance
- Guidance – the one-line notion that states guidance of what to consider when it comes to the security of first responder mobile and wearable devices

Table 5 – High-Level Guidance for Securing Mobile and Wearable Devices

Cybersecurity Framework Function	Guidance
Identify	Identify your public safety needs and devices
Protect	Protect yourself by applying security and training users
Detect	Detect issues by logging and monitoring your devices
Respond	Respond with a prepared plan
Recover	Recover by implementing the plan and constantly improving

The following subsections give more information about what should be considered when applying each aspect of the guidance mentioned in the chart above. These subsections also map the guidance to the First Responder security objective(s) that are addressed through the guidance. Lastly, the guidance is mapped to any tests that are relevant to the guidance being discussed.

5.1.1 Identify – your public safety needs and devices

The first step in making decisions about technology acquisition is understanding an organization’s needs. An organization needs may be influenced by the following:

- use cases
- threat modeling/risk assessments
- business policies
- desired security objectives

An example of these influential components can be found in NISTIR 8196 [1]. This information can be used to guide the search for features and capabilities within a device. Here are some example features and capabilities that may be considered necessary for First Responder devices:

- Make & model of the device
- Firmware and software information
- Network protocols (e.g., Wi-Fi, Bluetooth, Cellular)
- Ruggedization ratings (e.g., IP ratings or MIL-STD)
- Security capabilities (e.g., authentication options and encryption)
- Update policies and schedules

Once the organization establishes their device needs, this can be used to identify devices that meet these needs. To identify these devices, device administrators will need to obtain information about their prospective or current devices. A device administrator can use this information to decide whether a device has most of their required features, which may be prioritized by usability and security capabilities [11].

PSCR Engineers found that mobile devices provide most of the information necessary to allow public safety device administrators to make decisions around whether a device has the security features that meets their needs. Wearable devices differed in that the device information provided varied per device. Many wearable devices require additional research or a discussion with the device vendor to find specific details about the device's specifications. Some wearable device information that was not readily available include the security capabilities and limitations (e.g., encryption, PitM protection, degradability) within a specific version of Bluetooth.

This guidance will assist public safety device administrators to identify devices that meet their specific public safety needs. Device information gives insights into device capabilities, including their interoperability with other devices/systems. Also, having information readily available about a device will help device administrators maintain and manage the devices that are used by first responders.

Security Objectives: Availability, Ease of Management, Interoperability, Healthy Ecosystem

Test References in Appendix B: [B.1.1](#), [B.1.2](#), [B.1.3](#), [B.1.9](#), [B.1.11](#), [B.1.13](#), [B.2.1](#), [B.2.2](#), [B.2.3](#), [B.2.9](#)

5.1.2 Protect – yourself by applying security and training users

Once devices are acquired security controls must be applied. The security applied should go along with the public safety security needs identified through the prior guidance given in section 5.1.1. Some devices are built with security features automatically enabled. Most devices require secure configuration to allow an organization to configure to their specific needs (e.g., authentication and encryption requirements). When applying security, public safety device administrators should consider both usability and security [11]. Usability and security are both very important to public safety officials. A device needs to be usable to accomplish the necessary tasks during an emergency incident. Security is important because if not applied, it could leave a device vulnerable to attacks, which could then compromise the usability of the device during an emergency incident.

In addition to applying security, public safety device users should receive training to properly use their devices. User error can impact security if users do not do their part to secure their device. Most security configurations should be applied prior to providing a user with a device, but some security controls require user interaction. For example, a public safety user may be required to create a password or use an authenticator for their device. The user should understand the importance of applying the password and the potential risk to sharing their password or authenticators.

With few exceptions, mobile devices do not apply security by default. Some security features can be enabled manually by a public safety device administrator. Other features require additional third-party services to apply security features such as policy configurations, encrypt data transmissions, or analyze mobile applications. The practice guide, NIST SP 1800-21 *Mobile Device Security: Corporate-owned Personally-enabled*, discusses some of the various mobile device security solutions that can be used to apply security configurations and policies to a mobile device [12]. These solutions include an Enterprise Mobility Management (EMM) solution, Mobile Application Vetting (MAV), and Virtual Private Network (VPN).

PSCR Engineers developing applications for wearables may require an API on a mobile device or other system to update and apply certain features. Most security features were unchangeable, which is why it is very important to be aware of the security features within a wearable device; to ensure the device meets the desired public safety security objectives. If future wearable devices are more configurable with their security capabilities, this would allow a single device to be configured to meet the security needs of various different parties.

The appropriate security applied to First Responder devices helps to mitigate against threats that could harm the security and usability of a device. Any risk to security of a device could put the safety of a first responder at risk. By applying security and training users in advance, first responders can focus on an emergency incident without the unnecessary distraction of interacting with the device.

Security Objectives: Availability, Isolation, Confidentiality, Authentication, Integrity

Test References: [B.1.4](#), [B.1.5](#), [B.1.7](#), [B.1.11](#), [B.1.12](#), [B.1.14](#), [B.1.15](#), [B.2.4](#), [B.2.5](#), [B.2.6](#), [B.2.7](#)

5.1.3 Detect – issues by logging and monitoring your devices

First Responder mobile and wearable devices should be constantly monitored to check for compliance, vulnerabilities, and any other issues. While monitoring, it is also important to log events and general device activities. Compliance monitoring will check for any changes to the device configuration, such as changing the password settings or downloading an unauthorized application to the device. Vulnerability monitoring can check for different types of vulnerabilities that may impact the device (e.g., application vulnerabilities, network vulnerabilities, or OS vulnerabilities). Potential issues related to device health are also important to monitor since they can also have significant consequences for the security and usability of devices (e.g., battery health and overheating).

Using device information (i.e., make/model, OS, network protocol), public safety device administrators can manually monitor devices by performing a web search for potential vulnerabilities. Mobile device security solutions (e.g., EMM and MTD) can monitor mobile devices, log events and device activities, and send notifications to the administrator and/or the user when it finds a potential vulnerability or policy violation. Some solutions can also perform compliance actions if it finds that a mobile device is violating an enforced policy. An example policy violation is a user removing a required authentication method. To address this policy violation, a compliance action could be enforced to restrict the device's access to an organization's resources, until the device is no longer in violation of the policy. Wearable devices do not have easily available monitoring tools and may require manual monitoring through research and analysis. Some devices may provide their own monitoring tools, but this is not consistent across all wearable devices.

By logging and monitoring devices, device administrators are aware of device issues and trends in device activity. This is the information needed to make decisions about how to address issues in the short-term and long-term. With insight into current or potential issues with a device, a device administrator can make risk-based decisions (e.g., likelihood, impact, etc.) for how to address any device concerns. Notification of any anomalous activity allows administrators to address device issues promptly. Lastly, continuous monitoring and logging information provides the ability to monitor cybersecurity incidents and review the effectiveness of the protective measures in place.

Security Objectives: Availability, Integrity, Ease of Management, Healthy Ecosystem

Test References: [B.1.1](#), [B.1.2](#), [B.1.4](#), [B.1.5](#), [B.1.7](#), [B.2.1](#), [B.2.2](#), [B.2.4](#)

5.1.4 Respond – with a prepared plan to address issues

When device issues are found, it is helpful to be prepared with a plan of action to address issues. This may be an immediate plan of action. For example, in the short-term, device issues may be handled by:

- Removing a device from deployment and provide an alternative/back-up device to perform during an emergency incident
- Disconnecting a device's access to public safety resources

A combination of understanding the device issue and making a risk-based decision should be taken into consideration when deciding how to address device issues. For first responders, timing and impact of the remediation plan are a few key things to consider because a first responder may not want their device disconnected in the middle of an emergency incident. Communication of any remediation plans is important to share across the first responder team.

PSCR Engineers found that most mobile devices allowed for device administrators or users to apply some type of immediate response to address certain issues. Mobile tools, such as an EMM, can respond and update a device's configuration settings if there is a policy in place to address a particular issue or event. As mentioned before, an immediate change in device configuration could cause a disruption while a public safety official is responding to an emergency incident. Instead of applying immediate changes, an EMM can send notifications of any issues/anomalous events to the user/device administrator. With these notifications, the device administrator can make decisions to plan how to appropriately address the issue or event. [13]

Wearable devices do not have the same flexibility with regards to updating device configurations. Most of the wearable devices reviewed by PSCR Engineers, do not have a way to immediately apply fixes or update the device configurations. The lack of updatability may require device administrators to do additional planning for how to address wearable device vulnerabilities, when to decommission, and the purchase of new wearable devices. Devices that are able to be maintained, updated, and patched offer longer use and less of a need to purchase new devices.

Having a plan prepares public safety officials with methods to address devices issues when they occur. Using an effective plan will help prevent first responders in the field from using devices potentially vulnerable to attack. Communication of any planned remediation keeps all public safety officials aware and allows everyone to plan/prepare accordingly.

Security Objectives: Ease of Management, Healthy Ecosystem

Test References: [B.1.11](#), [B.2.7](#)

5.1.5 Recover - from issues by implementing the plan and constantly improving

After establishing a plan to handle issues/events, it is important to implement those plans/procedures to restore mobile and wearable devices affected by a cybersecurity issue/event. Additionally, any remediation of issues, should be tested to ensure the issue is resolved as desired and does not impact device functionality. Device administrators should also take note of any lessons learned from the issue/event and from applying the remediation. Once again, communication is key here during and after recovery.

Some device issues require more time and consideration. Some example remediations that may require more planning and preparation include:

- Patch/update of a device and redeployment
- Decommission/dispose of a device and device replacement

Device vendors may provide an update policy and/or schedule. This was commonly provided amongst mobile devices. Updates/Patches to vulnerabilities are typically not applied automatically to mobile and wearable devices unless specified to do-so. First responders may not want automatic updates because this could disrupt activities at an emergency incident. Without automatic updates, public safety device administrators can plan an appropriate schedule to apply changes to a public safety mobile and wearable devices. Wearable devices often did not have an update policy/schedule or were not capable of being updated at all. A risk analysis may be necessary to decide how to handle the wearable device issues/vulnerabilities. If, for example, a wearable device is unable to be updated/patched to address a high-risk issue/vulnerability, then the device may need to be decommissioned. Device administrators will then have to consider device replacement.

Implementing the plan to address device issues assists with protecting first responders and reducing risks to being vulnerable to attack and device malfunctions. Advanced planning for more impactful changes, such device updates and patches ensures that device maintenance doesn't interfere with first responder daily activities. Applying fixes on a schedule and preparing for decommission/device replacement ensures first responders have a device available to use during emergencies. Testing devices will check to see that the issue is remediated as desired and that any changes do not impact the device's functionality. The lessons learned throughout the recovery process can be used to improve your plan to address future device issues, more efficiently or before they occur. The fewer issues first responders need to address, the more they can focus on their daily live saving activities. Communication amongst all public safety officials involved helps with the following:

- Understanding what the device issue and why it is important to make changes to address the issue
- Scheduling an appropriate time for device maintenance that doesn't impact a first responder's work schedule
- Teaching/Learning any significant nuances to device functionality after the remediation is applied
- Ensuring the first responder is confident and comfortable using the device

Security Objectives: Healthy Ecosystem

Test References: [B.1.9](#), [B.1.11](#), [B.2.7](#), [B.2.9](#)

6 Conclusion

Using the public safety security objectives defined in NISTIR 8196, PSCR Engineers analyzed the security capabilities of public safety mobile and wearable devices [1]. The security objectives assisted in framing the test plan used to analyze the devices. The test analysis of devices fed into the development of suggestions and guidance for future public safety mobile and wearable devices.

The guidance derived from the test analysis, leverages the Cybersecurity Framework Functions to summarize and easily communicate the guidance to various levels within public safety organizations. PSCR Engineers suggest the following high-level guidance for public safety officials interested in acquiring mobile and wearable devices: *Identify* your public safety needs and devices; *Protect* yourself by applying security and training users; *Detect* issues by logging and monitoring your devices; *Respond* with a prepared plan; *Recover* by implementing the plan and constantly improving. In addition to this high-level guidance, PSCR Engineers detail specific information and features that should be taken into consideration to accomplish the guidance.

Throughout the analysis of mobile and wearable devices, PSCR Engineers found that mobile devices have advanced greatly over the years and are capable of meeting most of the public safety security objectives. Mobile technology still has room for improvement when it comes to capabilities, such as rogue base station detection. Wearable devices are still being introduced to the public safety market and due to their limited functionality, wearable devices struggle to meet some of the public safety security objectives. Wearable device information was inconsistently provided in manuals and many devices lack the ability to be updated or reconfigured to apply different security settings. Some wearable devices interact with an API, which allows a little more flexibility in gathering information or applying different settings. While Bluetooth specifications are constantly being improved and updated, commercially available wearables still seem to use older versions of Bluetooth, with minimal security levels. Overall, PSCR Engineers found that few devices are built with features that are specific to public safety, such as a ruggedization rating that meets the needs of firefighters.

Through this security analysis and guidance, PSCR Engineers strive to assist public safety officials interested in acquiring mobile and wearable devices that meet their security objectives. This information may also prove informative to device manufacturers that are interested in building devices that meet the public safety security objectives and include features to support our first responders. PSCR Engineers suggests the following publications as supplemental guidance for public safety mobile and wearable devices:

- NISTIR 8196, *Security Analysis of First Responder Mobile and Wearable Devices* [1]
- NISTIR 8080, *Usability and Security Considerations for Public Safety Mobile Authentication* [11]
- NISTIR 8228, *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks* [4]
- NISTIR 8259, *Foundational Cybersecurity Activities for IoT Device Manufacturers* [5]
- NISTIR 8259A, *IoT Device Cybersecurity Capability Core Baseline* [14]
- NIST SP 800-124 Revision 2, *Guidelines for Managing the Security of Mobile Devices in the Enterprise* [7]

- NIST SP 1800-13, *Mobile Application Single Sign-On: Improving Authentication for Public Safety First Responders* [15]
- NISTIR 8181, *Incident Scenarios Collection for Public Safety Communications Research: Framing the Context of Use* [16]

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Appendix A—Acronyms

Selected acronyms and abbreviations used in this paper are defined below.

2G	2 nd Generation
3G	3 rd Generation
3GPP	3 rd Generation Partnership Project
4G	4 th Generation
5G	5 th Generation
AP	Access Point
AES	Advanced Encryption Standard
AES-CCM	Advanced Encryption Standard-Counter with CBC-MAC
AKM	Authentication and Key Management
ANonce	Authenticator number once
APCO	Association of Public Safety Communications Officials
BLE	Bluetooth Low Energy
BSSID	Basic Service Set Identifier
CBC-MAC	Cipher Block Chaining Message Authentication Code
CCMP	Counter Mode Cipher Block Chaining Message Authentication Code Protocol
CVE	Common Vulnerabilities and Exposures
DHCP	Dynamic Host Configuration Protocol
DHS	Department of Homeland Security
EAP	Extensible Authentication Protocol
EAPoL	Extensible Authentication Protocol over Local Area Network
ECDH	Elliptic Curve Diffie–Hellman
EMM	Enterprise Mobility Management
EMS	Emergency Medical Services

EMT	Emergency Medical Technician
ESSID	Extended Service Set Identifier
FILS	Fast Initial Link Setup
FIPS	Federal Information Processing Standards
FT	Fast Transition
GSM	Global System for Mobile Communications
GMK	Group Main Key
GTK	Group Temporal Key
HSTS	HTTP Strict-Transport-Security
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IP	Ingress Protection
IP	Internet Protocol
IR	Interagency Report
IoT	Internet of Things
ITL	Information Technology Laboratory
ISM	Industrial, Scientific, and Medical
KRACK	Key Reinstallation Attack
LAN	Local Area Network
LE	Low Energy
LEO	Law Enforcement Officer
LMR	Land Mobile Radio
LTE	Long Term Evolution
MHz	Megahertz
MIC	Message Integrity Code

MTD	Mobile Threat Defense
MAC	Media Access Control Address
MAV	Mobile Application Vetting
NFC	Near Field Communication
NIST	National Institute of Standards and Technology
NPSBN	Nationwide Public Safety Broadband Network
OS	Operating System
OUI	Organizationally Unique Identifier
PAN	Personal Area Network
PIN	Personal Identification Number
PMF	Protected Management Frame(s)
PMK	Pairwise Main Key
PTK	Pairwise Transient Key
PITM	Person in the Middle
PSCR	Public Safety Communications Research
PSK	Pre-shared Key
RFID	Radio-Frequency Identification
RSN	Robust Security Network
SNonce	Supplicant Number once
SP	Special Publication
SSID	Service Set Identifier
SSL	Secure Sockets Layer
SSO	Single Sign-on
TLS	Transport Layer Security
TPK	Temporal Pairwise Key

UI	User Interface
VPN	Virtual Private Network
WEP	Wired Equivalent Privacy
WLC	Wireless Local Area Network Controller
WNM	Wireless Network Management
WPA	Wi-Fi Protected Access
WPS	Wi-Fi Protected Setup

Appendix B—Tests and Results

The type of testing performed for this analysis includes an understanding of the type and state of the software that is pre-installed, the vulnerabilities residing within the device, and the types of secure technologies included within the devices. This effort will also assist with understanding what type of external certifications and testing occurs for these devices, such as the Ingress Protection (IP) ratings.

This section provides the test plan used to analyze the security capabilities of the device. Below is an outline of the layout for each test case description:

- **Test Number: Test Name** – Each test is numbered and given a name with summarizes the purpose of the test.
- *Security Objective* – The objective of each test is mapped to one or more of the security objectives from NISTIR 8196 [1]
- *Test Description* – The test description describes the information the test will provide concerning the security analysis of the mobile and wearable devices
- *Test Procedures* – PSCR Engineers documented the procedures used to perform each test. These procedures provide insight into how these tests can be replicated for personal analysis
- *Test Outcome* – After completion of each test, the engineers documented the outcome.
- *Analysis* – The results of each test are reviewed for potential impacts and future considerations for public safety. This analysis also includes gaps found as a result of the test.
- *Guidance* – Finally, each test concludes with suggested guidelines for how to address the Security Objective(s) and concerns discussed in the Analysis. This guidance also includes potential benefits to implementing the provided guidance.

B.1 Mobile Test Results

B.1.1 Test 1: Obtain General Hardware Information

Security Objective(s): Ease of management of the mobile device, availability of technical specifications, and the ability to maintain a healthy device ecosystem.

Test Description: Obtaining device documentation is the starting point towards understanding the basic operating functions of a mobile device. In this test, general information is gathered from the accompanying documentation contained in the box of the device, the manufacturer’s website, or the service provider’s website. Specific device information can also be obtained from the device’s “About” or help settings. This test intends to find hardware information/specifications and ease of access to assistive or help documentation.

Test Procedures: Check the accompanying documentation that shipped with the device. Record ease of access to the information and note the presence of quick-start guides, detailed guides, links to online resources. Check online web resources for ease of access, quick start guides, and supplementary links. Check help and about settings on the device for online guides or search features. Note the presence of hardware information or specifications from these sources.

Test Outcome: General hardware information can be obtained directly from manufacturers' websites. All devices tested contained a printed manual that contained information, quick start guides, and/or links to web-related resources. Both new and older devices contained at least one source of information to obtain general hardware information or help functions. A simple web search provided results to online resources to either the manufacturer or service provider of the mobile device. Newer devices had specific links to online help services from the mobile OS settings menu, however, older devices only contained general hardware information from the "About" screen.

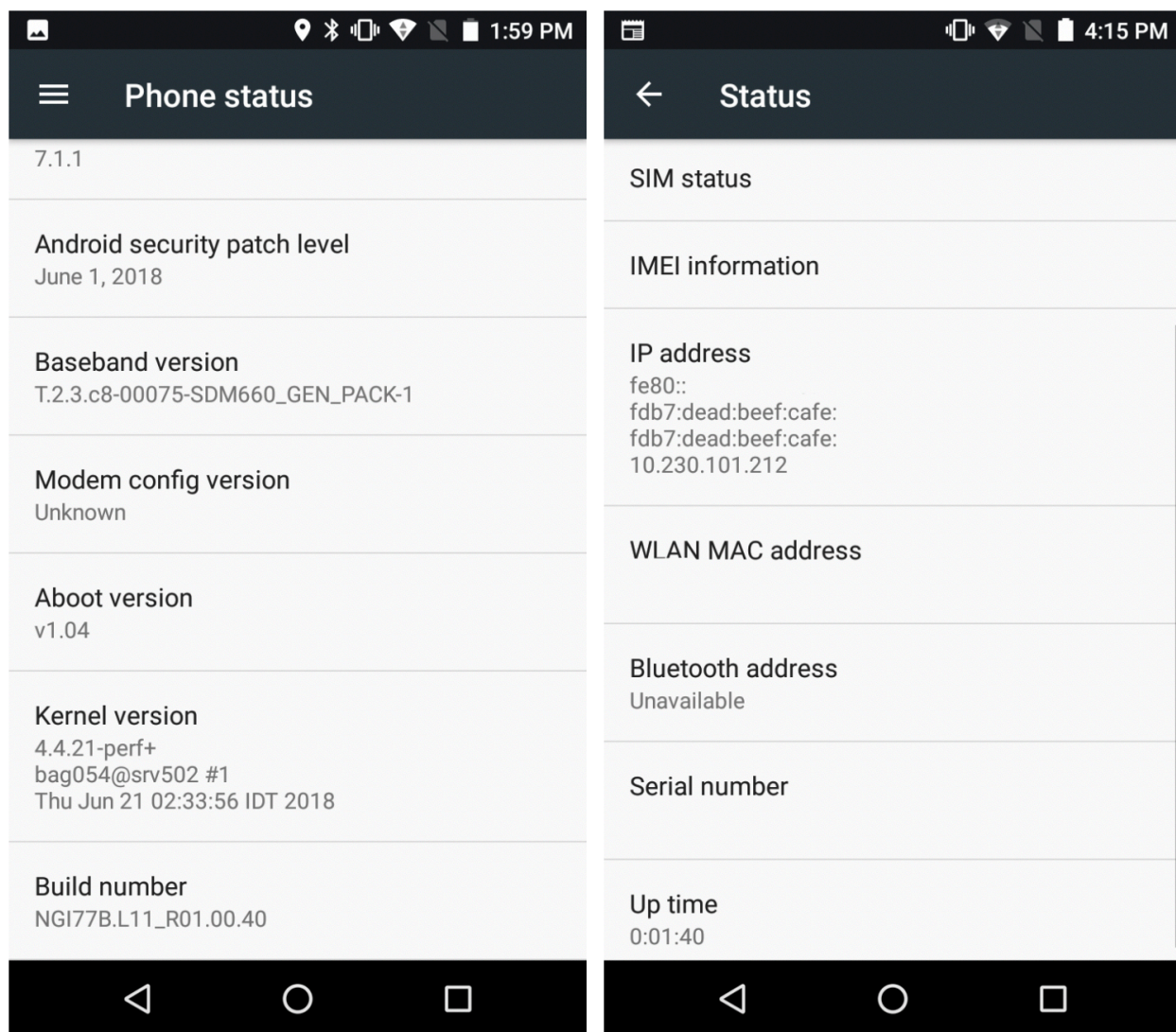


Figure 1 - Example 1: Device Information

Figure 1 shows the "About" and "Phone Status" screen on an Android device. These images show basic phone information including hardware platform, software versions, and builds. This information can be used to obtain further information about the phone, either through web searches, manufacturers' web site or OS vendor web site. This information serves as a base reference for subsequent mobile tests performed in this guidance document.

Analysis: General hardware information for mobile devices is easy to obtain for both new and old mobile devices. With access to the mobile device, a user can find information within the Android “Settings” application under “About device” or “General > About” for iOS devices. This section provides information, such as the make and model of mobile devices. Each device comes with a manual or data sheet within the packaging. Alternatively, a web search using the device’s name and model provides direct links to the device’s manufacturer and the device’s manual and/or specification sheet. Documentation accompanying the device contained general setup guidance that corresponded with the OEM OS and version contained on the device, out-of-the-box. Subsequent device updates from the OEM OS contained variations that did not match the insert documentation, however through intuition, settings often closely matched previous versions.

Gaps: Updates to the device’s operating system may alter results, conflict, or invalidate documentation sources. Device specifications may have slight variations among minor hardware revisions or among service providers that use the same manufacturer and model of a device. More in-depth web searches may be required by referencing the device’s serial number or part number to ensure up-to-date and accurate documentation sources.

Guidance: Manufacturers should continue to provide the general hardware information for mobile devices and public safety users/device administrators should leverage this information as necessary (e.g., inventory, awareness, etc.). Documentation that accompanies the device should reflect the OEM OS contained on the phone, however valid web resources or links should be referenced so the user can obtain the latest update and guidance information.

Benefits: Easy access to the general hardware information allows the user to easily identify the device. Device serial numbers, OS version, and model numbers can be used to gather more information to make configurations to the device, solve technical or usability issues, as well as secure the device. Device hardware on mobile devices is generally considered “non-upgradable” and therefore unlikely to deviate over the device’s lifespan. Occasionally manufacturers may perform minor hardware revisions through the device’s lifespan and are often reflected in the device’s serial or hardware model number.

B.1.2 Test 2: Obtain General Software Information

Security Objective(s): Ease of Management, Network Agility, and Healthy Device Ecosystem

Test Description: This test will identify the name and software version of the operating system and major applications that are shipped with the device. This will also attempt to understand the protocol versions for the primary wireless protocols (i.e., Wi-Fi, Bluetooth, and Cellular).

Test Procedures: Device information is obtained via documentation obtained using the methodology described in Test 1. OS software information can be obtained on Android devices under Settings > About or on iOS General > About. Web searches for the specific OS version to find information from the OS software provider. Network capabilities are obtained via the device’s technical specifications documentation or manufacturer website. Applications that ship with the device are identified under the Settings > Applications (Apps) listing and/or within the "apps" menu. Apple iOS displays a list of apps under the settings menu.

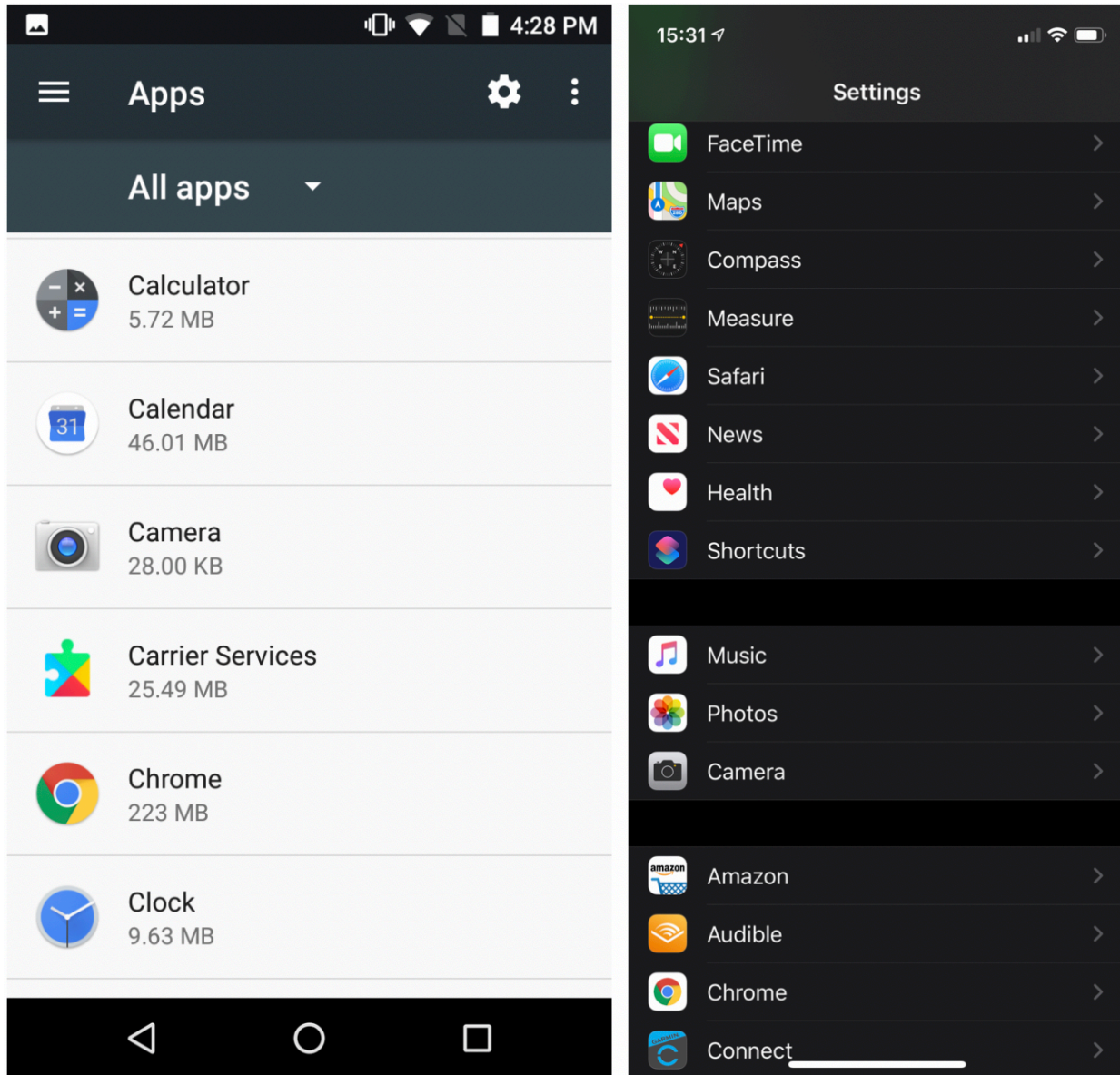


Figure 2 - id applications listing (left), iOS applications listing (right)

Test Outcome: Basic information can be gathered from the device through the use of the mobile's user interface or graphical user interface. Of the devices analyzed, the OEM OS was not at the latest patch level. Upon connecting to the internet, devices automatically downloaded new OS versions and/or patches that corrected most known vulnerabilities and added features. While pre-provisioned devices are at risk upon unboxing, it is commonly accepted risk and part of normal onboarding operations for enterprise and First Responder mobile devices.

Some Pre-installed applications are viewable to the user under the applications listing or under Settings menus. Of the observed applications, only one observed device revealed a remote-management application. Upon further inspection, the application is used as a remote-management and provisioning platform used by enhanced management services. Unlike most general consumer market devices, First Responder devices only included applications such as the default Google applications, First Responder focused applications, and/or service provider installed applications.

All devices observed are capable of Wi-Fi, Bluetooth, and Cellular network capabilities. Of the devices tested, only three mobiles were Band 14 capable, however, all devices but two supported up to Bluetooth version 5 and Wi-Fi 802.11ac also known as Wi-Fi 5. None of the devices tested supported Wi-Fi version 802.11ax also known as Wi-Fi 6.

Analysis: Operating system and application data can be easily obtained through the Settings menu within the mobile device. Application data is found within the applications menu and/or the settings menu. Of the applications observed, those that are not part of the default OS installation are designed to assist or enhance the experience for Public Safety officials. Those applications are specifically designed for mobility services, such as talk groups, remote management, or public safety-specific data services. Complete network capabilities are not easily obtained via the OS settings; however, the general specifications of network capability are contained within the device documentation as described in Test 1. All devices supported protocols and capabilities to operate on cellular and Wi-Fi networks, however, older devices lacked the hardware capability necessary to connect to future network technology protocols and methods.

Gaps: Many of the default OS shipped applications are not necessary or applicable to the First Responder mission or enhance the goals of Public Safety. Likewise, supplementary applications shipped with the device do not reflect the entirety of Public Safety's needs to include Police, Firefighters, or EMS. Also, note that some default OS applications cannot be removed. Similarly, some applications "hide" as background processes or daemons and cannot be easily analyzed without 3rd party tools. Such applications do not appear within the user space of the OS.

Guidance: Software information including OS, general app inventory, and network protocols should be readily available to the Public Safety. To leverage the NSPBN FirstNet Network, Public Safety mobile devices must have band 14 capability. The FirstNet NPSBN contains a certified list of applications and requirements for certification available from the FirstNet developer portal at <https://developer.firstnet.com>. Applications should only be installed from trusted platform providers, such as Android Google Play or Apple iOS App Store. Any applications not relevant to the needs of first responders should be uninstalled, where possible. Onboarding practices vary by organization and mobile device management (MDM) implementations, however, it is recommended that new device onboarding be performed on an isolated network segment. Isolated network segments only contain crucial network connections necessary for device updating, application installation, federation, and device integration. Devices that are onboarded via the cellular interface should utilize private VPN connections for MDM integration.

Benefits: Accessibility to OS, application data and network capability allow the user to understand software and hardware capability of the device. These factors foster comprehension of the device's point in its lifecycle. Similarly, the presence of default applications in first responder devices should reflect the goal or mission of the device. Network capability and performance should adequately support the purpose of default applications to ensure resilience and reliability required of First Responders.

Mobile devices with Band 14 capabilities can utilize the NSPBN FirstNet network, which hosts reserved spectrum for public safety to remediate any concerns of potential congestion due to mass communications transmissions that may occur on the traditional cellular networks. This congestion may be caused due to a heavily populated area without the supporting infrastructure, a major emergency incident where citizens are attempting to contact loved ones all at the same time.

Most mobile devices have multiple network capabilities. This provides network agility by allowing the device to alternate between Wi-Fi, Bluetooth, or cellular if one network protocol is unavailable. Awareness of the network protocols available on a mobile device allows Public Safety Officials to be aware of any potential limitations to their network agility.

B.1.3 Test 3: Device Ruggedization Ratings

Security Objective(s): Device availability and integrity through survivability, healthy mobile ecosystem through continuous operation, and ease of management in day-to-day operations.

Test Description: Implementation of ruggedization ensures durability for First Responder applications and survivability of day-to-day use. This test identifies the Ingress Protection (IP) ratings and any ruggedization information available for the device. IP ratings are followed by two numbers that correspond with the device's protection. The first number defines protection against solid objects. The second number defines the device's protection against liquids. A larger number designates more protection against environmental particulate or liquids. The lowest and highest IP rating for a device is IP00 and IP69 respectively [6]. Physical survivability of First Responder mobile devices ensures the integrity of responder data. IP ratings and certification ensure data integrity by reducing the occurrence of device failure in extreme environments as well as reliable communications.

Test Procedures: Utilizing the methodologies described in Test 1, obtain metrics to determine any certifications of ruggedization. Through local observation, inspect any protective surfaces or covers that enhance device survival in demanding environments. Check any fortifications that ensure battery operation or temperature threshold parameters.

Test Outcome: Device ruggedization metrics and certifications are obtained through a combination of online documentation, product inserts, and queries to the manufacturer's technical support. Physical observations can also determine if a device is built specifically for First Responder applications. Attributes include, but are not limited to, features such as protective glass, fortified case, and high-impact plastics. The most common ruggedization standard utilized is the MIL-STD-810G [17]. Of the phones analyzed, only three handhelds claim conformation to MIL-STD-810G, one rating was self-certified. All devices under analysis conformed to IP67 ruggedization certification. One device is certified IP69, which includes high-temperature, high-pressure ruggedization.

Analysis: Devices that conform to the MIL-STD-810G standard are generally bulky and contain rubber and/or hard plastics to fortify against impacts and drops. Devices that contain IP67 certification are not as easily discernable, however of the devices that contained the certification and contained a removable battery, supplementary seals, screws, and latches are present to enhance protection against water. It may also be noted that of the devices tested, the removable batteries do not correlate to the same temperature thresholds as the mobile device. Survivability of the device does not necessarily correlate to operational ability through a first responder event.



Figure 3 - Example ruggedized device [18]

Figure 3 is an example of a mission-critical handsets that is typically bigger, with ruggedized features adapted for mission-critical applications. Handsets may include additional interfaces than consumer-based handsets, such as buttons for push-to-talk, emergency request buttons, and switches to toggle between talk groups.

Gaps: Although ruggedization rating information is available in some form. There are no specific standards with regards to what is required for a public safety device. The ruggedization rating may differ per public safety personnel (i.e., law enforcement, firefighter, EMS). Ruggedization ratings may only be held at face value due to non-conformality or non-regulation of IP or MIL implementations. Comparison analysis among rating standards may be required (by the user) to determine if a device applies to their need(s).

Guidance: While high-grade ruggedization may be ideal, public safety mobile devices should meet the appropriate ruggedization ratings for their purposes. This information should be easily available for Public Safety to determine whether the ruggedization level of the device meets their desired needs. Such information should be provided within the product documentation or on the manufacturer's website. Mobile carriers often group mission-critical devices as a separate offering and are presented on a different web page than standard consumer mobile devices. Public safety devices that do not require or contain additional OEM ruggedization may benefit from the application of a mobile case and/or screen protector.

Benefits: Ruggedization certification ensures that a mobile device is properly designed with extreme environments in mind. A public-safety-specific ruggedization certification or guide could be beneficial to assist public safety personnel in choosing a device with the appropriate ruggedization grade. For example, a law enforcement officer's device may not require the same heat-resistant capabilities as a firefighter's device. Due to the occupational extremities required of public safety and first responders, ruggedization is required for the day-to-day survivability and operation of the device.

B.1.4 Test 4: Obtaining Vulnerability Information from OS version and known databases

Security Objective(s): Availability of the mobile operating system, the integrity of the mobile and user data, and maintaining a healthy device ecosystem.

Test Description: The Analysis of the OEM software version can be verified against a list of vulnerabilities within public databases describing Common Vulnerabilities and Exposures (CVEs) [19]. While most cellular service providers and device manufacturers provide patching and updates to help mitigate known CVEs, the application of updates are generally initiated by the end-user. Older mobile devices, particularly those that are out of production cycle or end-of-life, may lack necessary updates and patches to ensure operating system integrity. Since many public safety mobile devices are built for longevity and incur higher costs to the user/first responder organization, the likelihood of use beyond the manufacturer's lifetime is higher than normal consumer mobile devices. By comparing the current operating system with known CVE databases, it can be determined if operating system support is being provided and known vulnerabilities are being patched by the user, device manufacturer, or service provider.

Google » Android » 7.1.1: Security Vulnerabilities

Cpe Name: [cpe:/o:google:android:7.1.1](#)

CVSS Scores Greater Than: [0](#) [1](#) [2](#) [3](#) [4](#) [5](#) [6](#) [7](#) [8](#) [9](#)

Sort Results By: [CVE Number Descending](#) [CVE Number Ascending](#) [CVSS Score Descending](#) [Number Of Exploits Descending](#)

Total number of vulnerabilities: 544 Page: [1](#) (This Page) [2](#) [3](#) [4](#) [5](#) [6](#) [7](#) [8](#) [9](#) [10](#) [11](#)

[Copy Results](#) [Download Results](#)

#	CVE ID	CWE ID	# of Exploits	Vulnerability Type(s)	Publish Date	Update Date	Score	Gained Access Level	Access	Complexity	Authentication	Conf.	Integ.	Avail.
1	CVE-2019-14783	264			2019-08-08	2019-09-25	2.1	None	Local	Low	Not required	None	Partial	None
On Samsung mobile devices with N(7.x), and O(8.x), P(9.0) software, FotaAgent allows a malicious application to create privileged files. The Samsung ID is SVE-2019-14764.														
2	CVE-2019-2179	190		Overflow	2019-09-05	2019-09-06	4.3	None	Remote	Medium	Not required	Partial	None	None
In NDEF_MsgValidate of ndef_utils in Android 7.1.1, 7.1.2, 8.0, 8.1 and 9, there is a possible out of bounds read due to an integer overflow. This could lead to local information disclosure with no additional execution privileges needed. User interaction is needed for exploitation.														
3	CVE-2019-2178	787			2019-09-05	2019-09-06	7.2	None	Local	Low	Not required	Complete	Complete	Complete
In rw_t4t_sm_read_ndef in Android 7.1.1, 7.1.2, 8.0, 8.1 and 9, there is a possible out of bounds write due to a missing bounds check. This could lead to local escalation of privilege in the NFC service with no additional execution privileges needed. User interaction is not needed for exploitation.														

Figure 4 - Example Android CVEs [20]

Figure 4 is an example of one of the CVE databases that contain extensive analysis for each Android or Apple iOS version. Many databases rate the severity of the CVE, vulnerability type, and when or if a patch is available. This data can be cross-referenced with the currently running version on the handset under test to ensure it is protected [21].

Test Procedures: Obtain the OS version of the device and search for CVEs on known databases. Where possible, search for the specific OS build number to provide more refined results. Make a specific note of the number of vulnerabilities in critical categories.

In this test, it is important to note that the results reflect the date that the test was conducted. Reiterations of these tests will result in different outcomes due to newly discovered vulnerabilities and the issuance of new CVEs. Likewise, before all tests were performed, all devices under test (DUT) were upgraded and patched to the latest available version from the manufacturer or service provider. It is also important to note that older versions of operating systems do not necessarily mean less patching support. Adequate patching of both new and old operating systems is necessary to ensure device integrity. Gaps in patching, delays in patching, or missing patches were not instigated in this study.

Test Outcome: Of all the devices, only one mobile device contained a patch level within three months of the date of the testing. While this resulted in fewer CVEs, many critical categories remained. Likewise, only one device contained an operating system and patch level that was no longer supported and no longer receiving updates. Two of the devices tested contained Android Version 7.1.1 with different patch levels and one device contained version 6.0.1 with a patch level issued within the past 3 months of testing.

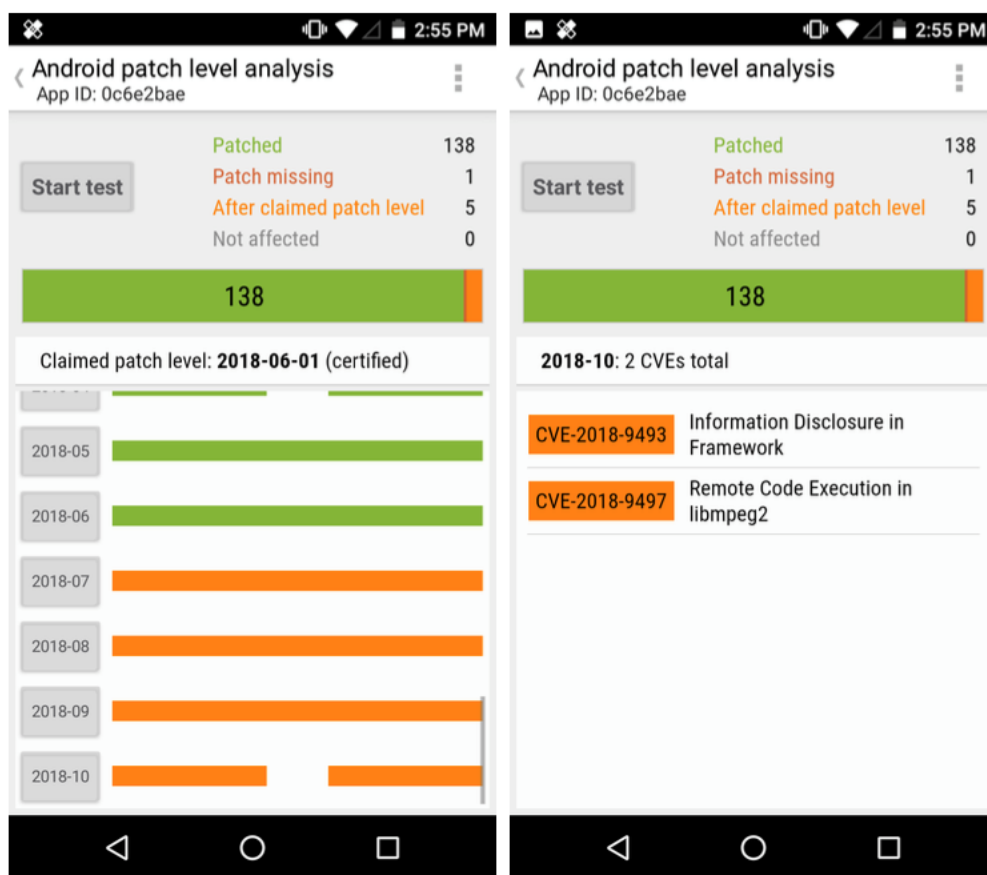


Figure 5 - Vulnerability scanner results [22]

Vulnerability scanners, such as SnoopSnitch in Figure 5, can scan a device and provide patch analysis reports to inform the user of any potential vulnerabilities. The results in the above report, show two potential vulnerabilities. The device under test (DUT) is running Android version 7.1.1, patch level June 1st, 2018. No subsequent updates were available for this device, potentially putting the device at risk.

Analysis: CVE databases are easily accessible through online sources and patch-level analysis tools are available for free use. Most CVEs can be mitigated through regular patching and updates. Those that can't be mitigated through patching must utilize alternative methods of protection, such as mobile threat defense and detection applications. While CVEs are easy to find and identify, the level of threat and user applicability may differ, depending on the device, OS, and build. Some CVEs are listed as informal notifications that affect a large breadth of devices but may not directly affect the DUT.

Gaps: Individual patch levels may further be analyzed to determine if a specific software build contains vulnerabilities. Not all patch levels are publicly disclosed. Software builds may also be specific to a device, vendor, hardware platform, and/or service provider. It may be difficult for a first responder to interpret what CVEs impact their device. The information presented is not always clear and concise for the average user and may require additional research. The requirement of additional time investment may not be feasible for most public safety groups.

Guidance: Enterprise administrators of public safety mobile devices should be aware of CVEs that pertain to current running versions. Since devices typically run under a common administration using mobile device management (MDM) solution in enterprise scenarios, keeping devices up-to-date and patching CVEs is a cumulative task. Individual managed devices and personal devices are administered at the discretion of the first responder and/or mobile ISP service provider. It is recommended to check for device software updates regularly and apply those patches when available. Note that not all CVEs may apply to a specific device, nor may it be possible to address or patch the CVE. OS and patch-level information should be readily available to the device user at any time of inquiry.

CVE-2018-9497 Detail

Current Description

In `impeg2_fmt_conv_yuv420p_to_yuv420sp_uv_av8` of `impeg2_format_conv.s` there is a possible out of bounds write due to missing bounds check. This could lead to remote code execution with no additional execution privileges needed. User interaction is needed for exploitation. Product: Android Versions: Android-7.0 Android-7.1.1 Android-7.1.2 Android-8.0 Android-8.1 Android-9.0 Android ID: A-74078669

Source: MITRE

[+View Analysis Description](#)

Severity	CVSS Version 3.x	CVSS Version 2.0
CVSS 3.x Severity and Metrics:		
 NIST: NVD	Base Score: 7.8 HIGH	Vector: CVSS:3.0/AV:L/AC:L/PR:N/UI:R/S:U/C:H/I:H/A:H

Figure 6 - CVE reference in National Vulnerability Database

Using one of the CVE's found in Figure 5, Figure 6, cross-references the CVE-2018-9497 ID in the NIST National Vulnerability Database to obtain more information about the unpatched vulnerability [23]. Detailed information can be used to determine if a patch is available or if further action is needed to mitigate the risk.

Benefits: Analysis of known vulnerabilities informs the user of potential threats that the device may incur. CVE analysis allows the users to determine the next steps to secure the device, such as if the device can be updated, if further protections are necessary, or supplemental mitigation mechanisms must be employed.

B.1.5 Test 5: Vulnerability Scan via Mobile Threat Defense (MTD) Application

Security Objective(s): Device integrity, availability, and health can be enhanced using a mobile threat defense application.

Test Description: Vulnerability scanning on a mobile device is commonly achieved using a 3rd party application downloaded from a mobile application store. Frequent use of an MTD ensures the integrity of both the mobile device operating system as well as any applications installed by the user, manufacturer, or service provider. MTDs expedite and automate vulnerability scanning reducing time invested into searching for vulnerabilities. This test uses publicly available MTD applications to identify vulnerabilities within the mobile OS and applications shipped with the device. MTD information may be cross-referenced with the results in Test 4 CVEs or via the manufacturer's website to ensure consistency among results. In most cases, the MTD will produce a report and prompt notification of any potential threats to the mobile device.

Test Procedures: Download and install an MTD application that reference CVE databases and provide applications ratings. Observe and compare the results, cross-referencing patch databases.

Test Outcome: Overall, the 3rd party application found that all CVEs were patched at the current level (after the mobile device was updated) for three of the DUTs. The remaining devices contained less than five patched CVEs. The 3rd party application reported many "inconclusive" results for all the DUTs. Inconclusive indicates that the MTD could not find evidence of the patch related to the OS. The number of pre-installed/OEM apps and several files analyzed by the MTD varied among all the devices tested. Only one false-positive result was reported among the OEM applications installed. The MTD reported a potential command and control application. The application in question was used for device remote provisioning and deployment. Referring to Test 2, due to the unique application of First Responder mobile devices, pre-installed applications represented less risk compared to consumer mobile devices.

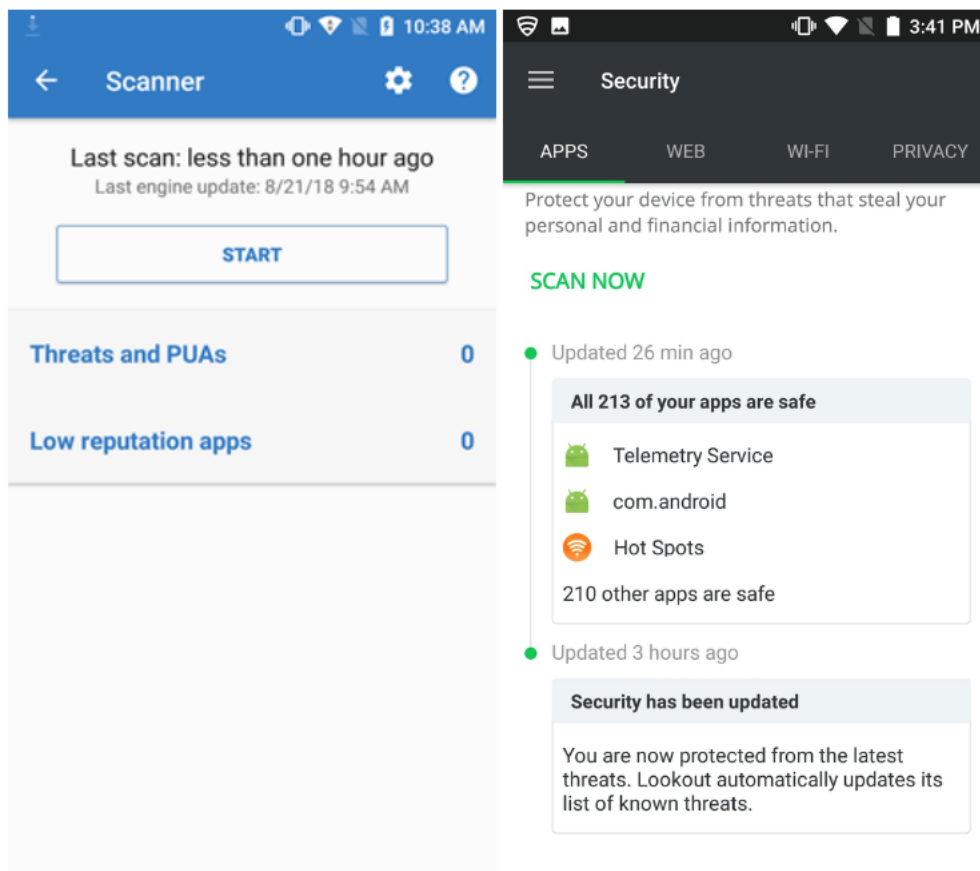


Figure 7 – Sophos MTD scan results [24]

MTD software can scan devices for app-based vulnerabilities in addition to systems scans (see Figure 7). Most MTD applications can be configured to run on a continuous or “active” basis to intercept malicious apps in real-time. Regular, full-system scans should be running daily to ensure existing apps have not been compromised.

Analysis: MTD software is easily obtained through OS application stores and can be configured to scan the device automatically regularly. Most MTD applications will also provide active application analysis, web browsing security, connection monitoring, and privacy settings optimization. When a threat is detected, the application immediately informs the user of the threat and will take action to mitigate the problem. Full system scans give the user a detailed report and accounting log of executed actions. MTD application updates and definition updates occur upon installation of the MTD and check on a regularly preconfigured schedule.

Gaps: Results differ among MTD software providers. MTD definitions must be updated to ensure the latest vulnerabilities are defined and discoverable. Users and administrators must be aware that malware on an infected device may alter results from MTD applications. The occurrence of false-positive results also varies among MTD software providers. MTDs are powerful tools to help the user secure their device, however, human intervention and judgment must be made to determine if an unpatched CVE presents a risk to the device. Analysis of CVEs can be time-consuming and requires familiarity with cybersecurity-related technologies to determine if a CVE presents a risk.

Guidance: For both public safety enterprise administrators and individual first responder users, it is recommended to consider using mobile security tools, such as the MTD application tool used in this test. MTD applications can be used in conjunction with an EMM solution to ensure a complete device health ecosystem. An MTD tool scans the mobile device and alerts the user/administrator of potential vulnerabilities. In addition to EMM, MDM, and MTD solutions, users can also consider Mobile Application Vetting Services. More information can be found in NIST SP 800-124 rev. 2 *Guidelines for Managing the Security of Mobile Devices in the Enterprise* [7]. Daily scans should be performed to ensure no new threats are present. Users and/or administrators should be alerted if a threat is present. A log or summary of the scan information should be presented in the application or remote management software upon request. MTD applications offer protections such as zero-day mitigations and enhanced device management optimizations. First responders should install and run a MTD application to apply additional protections to their first responder device. Most mobile devices include built-in MTD functionality which are enabled by default. The MTD capabilities on Android devices can be checked by opening the Google Play application, tap the user profile icon, tap Play Protect, then Settings. Most mobiles manufactured after 2013 have the latest version of Android OS should support Play Protect.

Benefits: Mobile security tools such as MTDs inform the user of potential vulnerabilities and low reputation applications installed on the mobile device. Information and awareness are beneficial to public safety device administrators by allowing them to take necessary action to address any potential vulnerabilities or concerns. By addressing these vulnerabilities, public safety officials can avoid any potential compromise of a mobile device and its capabilities. Scanned app information can be used to make decisions on an app's trustworthiness or weigh the benefits of the app versus the potential risk of using the app. This decision can prompt further investigation of the app in question and the data that it has access to. Maintaining logs or summaries of information from the mobile security tools can assist with future policy analysis and risk considerations.

B.1.6 Test 6: External Fingerprinting

Security Objective(s): Device integrity and confidentiality can be inspected through the use of network-based scanning tools.

Test Description: Device integrity can be verified by performing external scanning and fingerprinting over a network connection. Most internet-connected devices utilize application sockets to communicate using either Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) transport mechanisms. Open TCP or UDP sockets on a device may indicate a “listening” service or application on the mobile device. Network sockets are typically used for enhanced user experience and network operation/functionality. In some cases, an open socket may be used to exploit a device application or be indicative of malicious applications on the mobile device. Knowledge of open service ports may lead to further analysis of the application or services requesting the service port. Fingerprinting a device is often the initial stage of information gathering before it is attacked over a network.

Test Procedures: Identify the Wi-Fi IP address of the mobile device. Using a network-based scanning tool, such as Nmap, scan the DUT [25]. Determine which, if any network sockets are open, what services are running on the ports, and if the device OS and/or hardware can be identified.

Test Outcome: Analyzed devices displayed open ports via Wi-Fi scanning with Nmap. Open ports did not indicate a listening service to establish a session with the specified TCP/UDP socket. Of the devices tested, DHCPD UDP/67, DHCPD UDP/68, and zeroconf were observed as common open ports. All three ports are typically used for device configuration and IP assignment. Although all three ports were “open” the scan indicated that the devices did not respond or actively closed the connection. One device indicated SIP TCP/5060 service port, commonly used for Voice over IP applications. Two of the devices scanned indicated open IMAP TCP/143 and TCP/993 and pop3 ports, TCP/110 and TCP/995 typically used for email services. Overall, potential findings indicate the presence of applications, such as pop and sip services, that could be further exploited. To minimize exposure, unnecessary applications and services should be disabled or removed. The scan could not indicate what applications used these open ports. Further investigation of running applications should be investigated to determine the need of the application. Device hardware could only be extrapolated by the manufacturer due to the 24-bit Organizationally Unique Identifier (OUI) of the Wi-Fi MAC address.

```
~$ sudo nmap -sS -sU -PN 10.230.101.124

Starting Nmap 7.60 ( https://nmap.org ) at 2018-08-21 17:13 MDT
Nmap scan report for 10.230.101.124
Host is up (0.081s latency).
Not shown: 1996 closed ports
PORT      STATE      SERVICE
5060/tcp  filtered  sip
67/udp    open|filtered dhcps
68/udp    open|filtered dhcpc
5353/udp  open|filtered zeroconf
MAC Address:

Nmap done: 1 IP address (1 host up) scanned in 1010.91 seconds
```

Figure 8 - NMAP port scan

Network-based scanning tools, such as NMAP (see Figure 8), can provide insight into open ports, indicating a potential running service on the device. Other information can be extrapolated from in-depth scans, such as OS type, running applications, and hardware information.

Analysis: Network-based scanning tools utilized in this test returned results indicating that the devices filtered any open network ports. While this does indicate an active running service, the device actively mitigated any attempts to probe or exploit those ports. In general, mobile devices, in their default configuration, protect against network-based attacks using methods built-in to the devices' OS. However, the manufacturer of the device can be easily obtained through the device's MAC OUI if the device does not support MAC address randomization. The device manufacturer of all the tested devices was determined, however detailed information, such as device type and actual running applications, could not be determined.

Gaps: Network-based port scanning does not provide information on the specific application using the open port. Host-based tools may be used to determine the nature of the application and legitimacy of its presence on a device. Accordingly, if a device has multiple network interfaces, e.g. Wi-Fi, Bluetooth, and/or LTE data connection, all interfaces must be analyzed to determine listening service ports. Depending on the network configuration, accurate results may be skewed due to intermediate network devices, filters, firewalls, or other middleware boxes.

Guidance: Devices under a common administration should be routinely scanned over a managed local network for potential network vulnerabilities. Since most broadband mobile devices operate over LTE networks, the opportunity to externally scan the device on a locally controlled Wi-Fi network may not be possible. If a device cannot be regularly scanned over a locally controlled Wi-Fi network, an MTD should be used and a mobile management policy should be implemented to ensure the device can be periodically scanned. MDM solutions, as explained in Test 7, can perform detailed device scans if the mobile can connect to the internet. Devices not under a common administration should run an MTD daily. Only applications required for mission-critical operations should be present on the device.

Benefits: Network scanning allows the user to determine how network-based or "outside" hosts may connect to the mobile device. Scanning reveals potential exploitable sources of entry as well as applications that allow external access to the device.

B.1.7 Test 7: External Vulnerability Scan

Security Objective(s): Mobile device availability, confidentiality, and integrity.

Test Description: Vulnerability scanning is the next step beyond external fingerprinting and is often executed to ensure device integrity. Vulnerability scanning suites utilize scripts and automated methods to determine if an open network port or service can be exploited. This level of scanning is much more intrusive but can provide an in-depth analysis concerning a device's network security posture. An external vulnerability scan is often part of an information-gathering phase before it is attacked.

Test Procedure: Determine the Wi-Fi IP address of the DUT. Using a network-based vulnerability scanner, execute a scan to determine if the open ports in Test 6 are exploitable and if OS information can be enumerated.

Test Outcome: Test results indicated only informative level findings providing network enumeration values, such as hostname, IP address, and network diameter information. No known vulnerabilities were discovered, indicating that the ports discovered in Test 6 were not active listening services. Overall indications reveal that external, network-originated attacks on mobile OS services do not represent a high risk for the DUT. Specific OS information could not be determined without an authenticated scan. The scanner could only determine that the mobile devices run a variant of Linux.

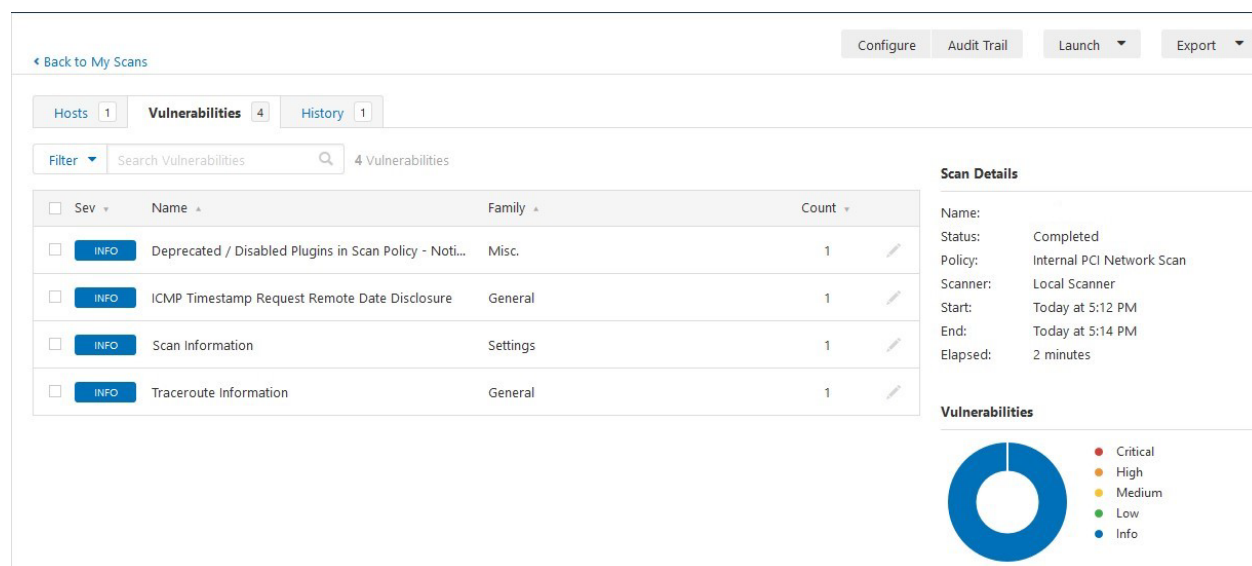


Figure 9 – Tenable Nessus External vulnerability scan results [26]

External vulnerability scanners can perform detailed analysis against networked hosts, including mobile devices (see Figure 9). Authenticated scans can also be performed to provide an administrative level scan against the device. Authenticated scans may require the installation of additional apps and device policy modifications to maximize results. Scans should only be performed over Wi-Fi connections under locally controlled administration.

Analysis: Observed devices produce informational findings using unauthenticated scans. Authenticated scans using an MDM solution produced a detailed analysis that included CVE checks against OS patch levels and application versions. Authenticated scans produced warnings concerning installed applications, including those requiring updating and potential low reputation apps.

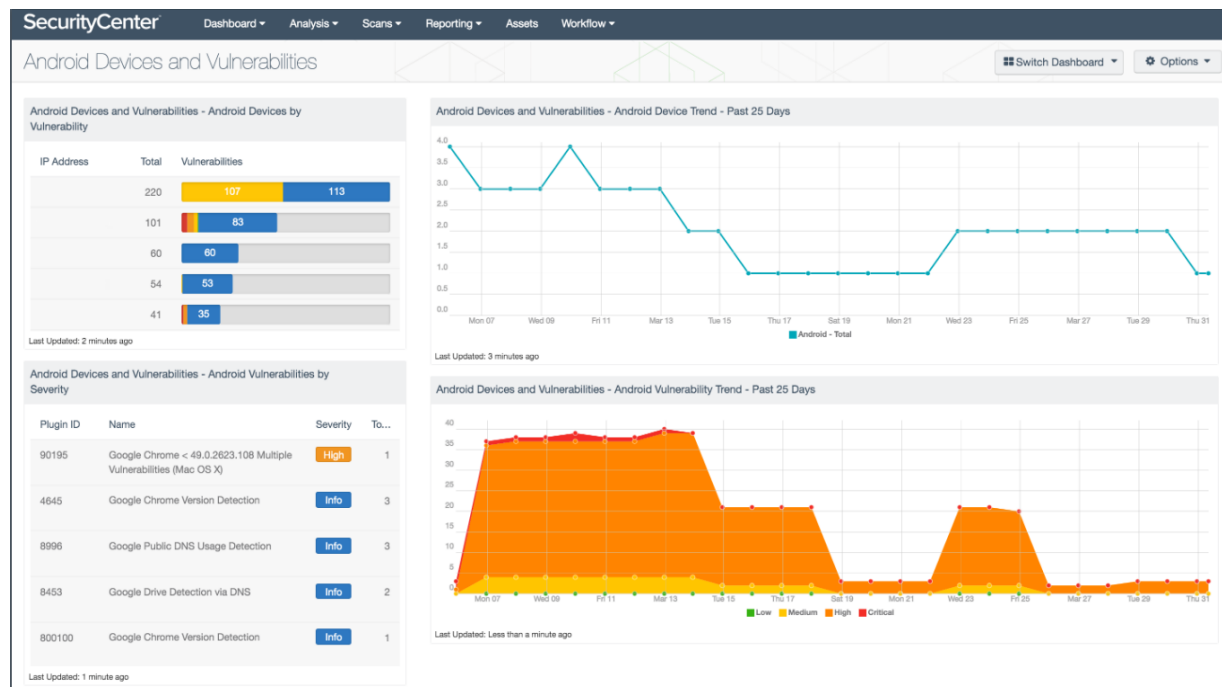


Figure 10 - External vulnerability scan results

Another example of external vulnerability scanning can be found in Figure 10 which is a Nessus Android vulnerability report. [26]

Gaps: Authenticated scans provide enhanced scanning by remotely logging into the DUT. Most mobile devices do not allow authenticated scans without root account access, which is often restricted or prohibited by the manufacturer or service provider. Like Test 6, all network ports should be analyzed to determine a device's integrity.

Guidance: Like guidance in Test 6, devices under a common administration should be routinely scanned over a managed local network using for potential network vulnerabilities. An MDM solution and mobile management policy should be implemented to ensure periodic scanning. Only applications required for mission-critical operations should be present on the device. Non-essential applications should be removed to ensure no external network connections can be made to the device. Authenticated scans are typically performed on devices running an MDM and an associated scanner plugin. The scanner application works in conjunction with the MDM application to provide detailed analysis of device applications and patches. Devices that cannot be scanned or are scanned using unauthenticated methods should have an MTD installed and scheduled to run daily. For more information on MDM implementation, consult NIST SPECIAL PUBLICATION 1800-4, "Mobile Device Security Cloud and Hybrid Builds." This publication includes detailed procedures on how to architect enterprise-class protection for mobile devices accessing corporate resources. [27]

Benefits: External vulnerability scans allow the user to determine if the mobile device is exploitable. When possible, the scanning software will attempt to determine OS type, hardware platform, exploitable applications, services and exploit unpatched systems.

B.1.8 Test 8: MAC Address Randomization

Security Objective(s): Mobile device confidentiality

Test Description: Device confidentiality and autonomy can be maintained using MAC address randomization. Static MAC addresses can be used as a mechanism to track First Responders between networks and potentially build a profile of users, locations, and network activity. MAC address randomization may also be limited due to hardware, OS, and device limitations.

Test Procedure: Check the device’s MAC address under the Settings menu. Connect to a Wi-Fi network and compare the MAC address to the address in the settings menu. Perform the same analysis on different Wi-Fi networks. Using an external Wi-Fi network sniffer, capture traffic to and from the device. Analyze the packets and compare the MAC address in the capture with the MAC address under the Settings menu.

Test Outcome: Over the air packet captures confirmed that MAC address changed between different Wi-Fi networks. Only the devices running Android 8 and IOS 8 or greater performed the MAC address change. Older devices did not have a menu option to use MAC address randomization. Over-the-air captures confirmed that older devices did not change their MAC address.

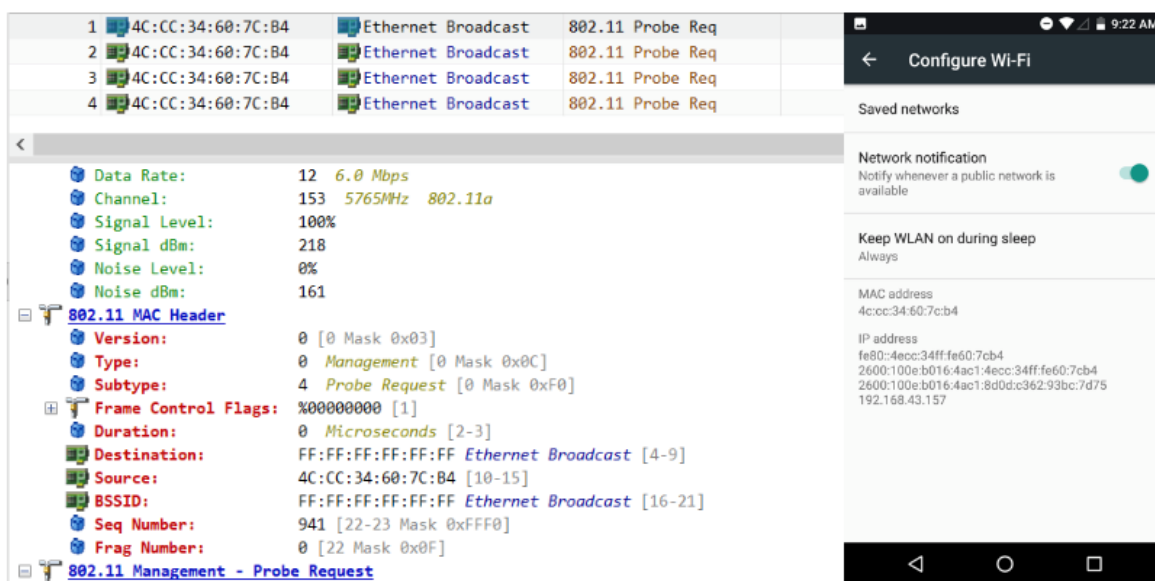


Figure 11 - Mac address randomization analysis

Figure 11’s over-the-air capture shows MAC address an Android device with MAC address unchanged. This device did not support MAC address randomization. Note device MAC address in the 802.11 MAC Header Source (left), matches the device MAC address 4C:CC:34:60:7C:B4 (right)

Analysis: In Android version 8, the MAC address randomization feature was added to devices with supported Wi-Fi chipsets. Similarly, MAC address randomization was enabled starting in iOS version 8, but it is enabled only during specific user configurations. iOS will randomize the MAC address of the device when connecting to a new access point. The below figure displays an Android device running Android version 10, showing MAC address randomization enabled.

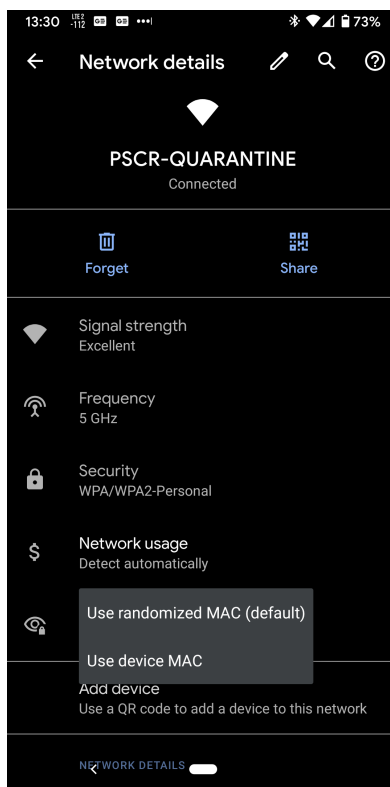


Figure 12 - Optional Mac address randomization setting

Figure 12 shows an Android device's Wi-Fi network settings where a randomized MAC address can be set under the specific Wi-Fi network. As shown in the figure, randomization is enabled by default.

Gaps: Network and systems administrators must take note of the MAC address randomization feature during device enrollment to ensure proper device connectivity and tracking. When a mobile device connects to a Wi-Fi network, it will save the randomized MAC address into a network profile. Subsequent associations to the same Wi-Fi network will utilize the saved network profile information. It is important to recognize if the feature is enabled and which MAC address is the device's permanent and randomized address. Alternative enrollment methods may be required if MAC address based network access controls and/or MDM inventory tracking are used.

Wi-Fi probe requests, device traffic patterns, and frame sequence numbers from the mobile device may be used to profile or fingerprint certain mobile devices, despite enabling MAC address randomization. MAC address randomization alone does not ensure device confidentiality due to advanced heuristic tracking methods.

Guidance: MAC address randomization should be enabled and used when possible. Network access control considerations should be given for devices that authenticate to enterprise wireless networks. The use of authentication methods that depend on static MAC addressing cannot be used. Additional device protections, as discussed in this document, are recommended in addition to MAC address randomization.

Only trusted Wi-Fi networks should be used while using a mission-critical, first responder device. When outside of a trusted network, LTE broadband networks should be used.

Benefits: MAC address randomization ensures confidentiality by preventing the tracking of a device within or between networks. Similarly, a randomized MAC address may prevent identification of the device hardware if the OUI portion of the address is randomized.

B.1.9 Test 9: Device Update Policy

Security Objective(s): Device Ease of Management, Integrity, and Healthy Ecosystem.

Test Description: Verifying the device update policy seeks to understand how often the device is scheduled to receive security updates and other software from the vendor. Specifically, the regularity, cadence, type, and reasons for updating the device and applying security patches are common policies contained in the updated policy.

Test Outcome: Update procedures and implementation are clearly defined within device user guides, however, specific information concerning frequency and scheduling of updates were not easily obtained. Both Android and Apple IOS have defined roadmaps for OS updates and releases at their respective websites, but most mobile providers and mobile device vendors control the actual implementation and release of updates, patches, and features. Since Apple IOS devices are sourced from a single vendor, roadmaps, releases, and patch notes can easily be found from the Apple support site. Specific versions can be found on the Apple website and release notes have specific, clear sections for features that received updates. A specific section for privacy and security contained high-level descriptions for specific security updates or features.

For Android devices, none of the vendor/platform-specific user guides or websites contained information concerning security update roadmaps. Some of the mobile device vendors have software update histories and change reports freely available, while others required support account logins to view update information. Overall, the information for security-related updates are difficult to find for Android devices in vendor-specific handsets. Vendor-produced documentation does not include detailed information concerning security patches. More detailed information can be found through the Android support and developer websites; however, the information only refers to the general Android OS and not the vendor-specific, OEM version of the mission-critical device.

Analysis: Specific device software and security patching roadmaps are not readability available. Device manufacturers did not contain specific information regarding patching but did contain update procedure documentation. The website of cellular providers supporting the device contained the most recent information for device updates. Update information didn't contain road-mapping information to address outstanding patch fixes for security vulnerabilities.

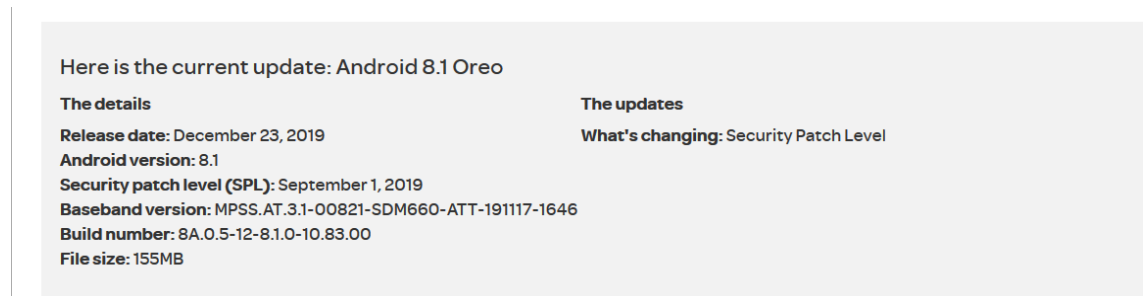


Figure 13 - Example update information

Most cellular service providers implement and control the distribution of software and security patch updates. This information can be found for specific devices on the cellular service provider's website (see Figure 13).

Gaps: Update policies are either non-existent or not consistent among the Android devices tested. Update policies are difficult to find and often do not contain detailed information to make formal decisions.

Guidance: End-users and administrators should configure devices to receive notifications when patches and updates are available. This configuration is commonly the default for both Android and Apple iOS devices but should be verified before initial deployment. Both Android and iOS devices are set to automatically check for updates and notify the user when updates are available. Users and administrators should be aware of the vendor's current support for respective devices. Software versioning and patch levels can be found under the devices about menu on both iOS and Android devices. The specific version and patch level for a device can be cross-referenced with online documentation to ensure the latest software is in use. As discussed in Test 4, OS versions and patch levels can be referenced in CVE databases to check existing vulnerabilities.

End-users and administrators should also consider the schedule/timing of applying software updates. Applying a patch/update during an emergency incident can impact First Responders' ability to perform their public safety activities. Device administrators should also ensure that all public safety applications are compatible with the software before performing an update. Lack of compatibility can prevent a First Responder from accessing public safety resources.

Benefits: A defined device update policy informs the user of ensured continuity of device support. It notifies the user of any potential vulnerabilities or enhancements made to the device OS. Applying patches assist in protecting a first responders' mobile device from known vulnerabilities.

B.1.10 Test 10: Rogue Base Station Detection

Security Objective(s): Availability, Confidentiality, Integrity, and Authentication

Test Description: Long-Term Evolution (LTE) is commonly known as 4G in the 3GPP specification. This test serves to identify the known LTE vulnerabilities and how public safety and first responder groups can protect against these attacks. The analysis will include settings that can be configured by first responders, conditions to observe during an LTE service attack, and appropriate response actions.

There are three general attack methods that bad actors will use when targeting mobile devices utilizing LTE networks.

1. Denial of Service
2. PitM or rogue base station
3. Location Tracking

Denial of service attacks are the most successful because they can be performed in multiple ways. Bad actors can “jam” the operating frequency, denying the use of the mobile spectrum. Another way is to impersonate an LTE base station and send a fabricated network rejection message. Note that rogue base stations are also referred to as rogue eNodeBs or stingrays in some publications or articles.

PitM attacks involve both impersonating an eNodeB as well as causing a “downgrade attack.” In this method, the bad actor will send a rejection message, causing the mobile to disconnect from the trusted network as in the denial of service attack. Secondly, the bad actor will also run a 2G eNodeB that the mobile will believe is a valid service node. 2G services lack mutual authentication and weak encryption methods required in modern communications networks. Once the mobile connects, the bad actor can intercept all traffic the user sends over the network.

Location tracking attacks utilize a weakness in how eNodeBs identify mobiles in each cell. In general, the information gathered from this attack cannot be detected by the user and is gathered by the bad actor using passive sniffing techniques.

Test Outcome: In the default configuration, mobile devices will attach to any “valid” eNodeB providing a mobile connection. The order of preference is to attach to the network providing the topmost tier connection within the provisioned “home” network. For example, if the mobile’s provisioned network has an available 4G LTE signal, the phone will authenticate and connect to that network first. In the event of signal degradation or poor coverage, the handset will connect to the next best service tier. Fallback to 3G or 2G will occur when those services are available in absence of higher quality links and/or access to the mobile’s “home” network. When a rogue eNodeB is introduced, the mobile handset will attach to the rogue base station in scenarios where legitimate services are lost or degraded to an unusable status. This will only occur if the rogue base station is configured to imitate an existing base station and to accept and authenticate with the handset.

Analysis: A tradeoff scenario occurs whilst determining greater protection versus reduce cell signal quality. Out of the box, most mobile devices are provisioned to connect to cellular services of any connection level, if available. This behavior is normal to ensure maximum coverage for cellular subscribers. Some mobile devices can be configured to only connect to specific quality connections, e.g. 5G, 4G, 3G, 2G, or a combination of those services. Similarly, most devices allow the user to configure “home only” connections or disabling roaming when home networks are not available. All of the first responder-specific mobiles that were analyzed gave the user both the option to configure connection type as well as roaming options. However, many of the devices, not designed for first responder needs, only contained options for roaming configuration.

Gaps: Device types and OS may alter user-configurable settings to control cellular connection parameters.

Most cellular vulnerabilities are inherent issues within the LTE standard and cannot be mitigated by the user. Ratifications within the 3GPP LTE standard would have to include methods to hide sensitive identifiers mobile providers use to authenticate and track handsets.

Some mitigations can only occur within the mobile provider network, including encryption of sensitive identifiers of mobile devices.

Guidance: Mobile providers should ensure baseline configurations of LTE network components include maximum security and encryption for public safety and first responder devices. Device users should be aware of the potential behaviors of LTE-based attacks. Many of these attacks are localized, meaning the bad actor is specifically targeting a responder or group of responders with the intent of further mal intent. While targeted campaigns on mobile devices are rare, special events or circumstances may make an LTE-based attack a viable method.

Denial of Service mitigations – Users should observe behaviors in signal drops and outages. A fabricated *Attach Reject* message from a rogue eNodeB causes a mobile device to go into an out-of-service state. *Attach Reject* messages are temporary blocks that can be removed by rebooting the mobile device or toggling off and on Airplane mode. The only way a first responder may know they have been affected by an *Attach Reject* attack is the loss of signal, “no bars” or inability to use network services. Another type of denial of service attack is using signal spectrum jamming. Jamming attacks can only be mitigated by moving into an area not affected by the jam or using alternative signaling channels. Localized controls, such as deployable LTE eNodeBs, may also counteract weaker jamming signals. Alternative protocols, such as LTE over Wi-Fi, or IMS over Wi-Fi can also be utilized if cellular service is unavailable.

PitM or rogue base station mitigations – Like denial of service, observations in signal dropping and outages are inherent to these attacks. Users may also observe a downgrade in service from 4G/3G to 2G GSM. If the downgrade of service occurs in an area where 4G LTE service is inherent, this may be indicative of a downgrade attack. Users can mitigate these attacks by configuring the device to only attach to 4G LTE networks. However, the drawback is that coverage may be limited in areas where legitimate services are available. Configuring the device in 4G LTE only mode will prevent the device from connecting to mobile services in poor reception or coverage areas.

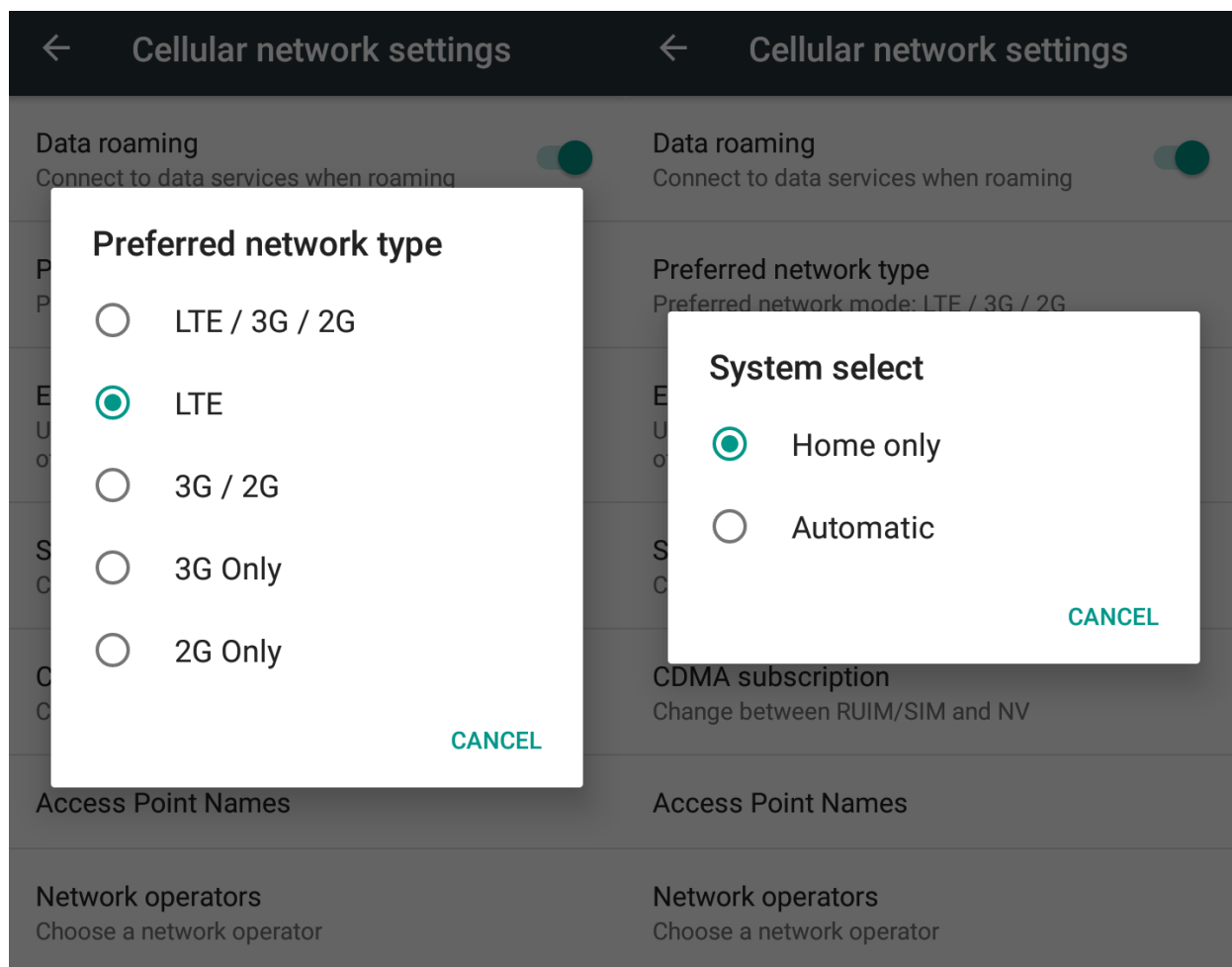


Figure 14 - Preferred network selection on an Android device

The preferred network can be configured to LTE-only mode on some mobile devices (see Figure 14 - Preferred network selection on an Android device). Configuration can set the mobile to only connect to the home subscriber network or automatic mode. The home subscriber setting ensures the device only connects to an NPSBN and the Automatic selection will select the best available network, which can be a non-NPSBN, commercial network, or rogue base station. Be aware that selecting a specific preferred network, e.g. LTE only, and/or home only setting will effectively limit coverage for the device. These settings should only be used in situations where increased security is necessitated over mobile coverage requirements.

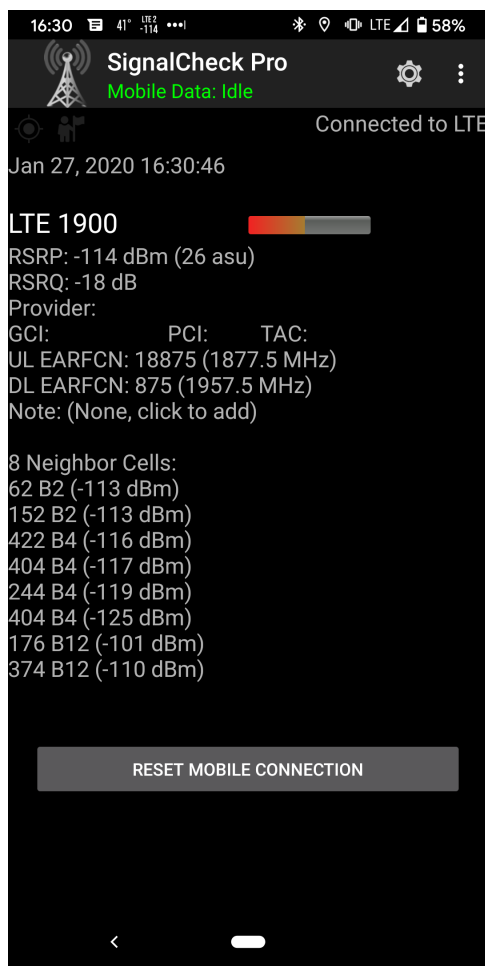


Figure 15 - Mobile network connection monitor [28]

3rd Party applications, such as SignalCheck in Figure 15, can be used to monitor connected LTE networks. Users and administrators may utilize these utilities to determine signal quality and legitimate LTE connections in special operations scenarios.

Location Tracking mitigations – Bad actors can utilize both passive monitoring and the PitM methods to track LTE users. First Responders should use the guidance for mitigating PitM attacks. However, since passive monitoring cannot be mitigated by the user, service providers should ensure that mission-critical networks contain provisioning to prevent tracking of local mobile identifiers, such as international mobile subscriber identities (IMSI) or Cell Random Network Temporary Identifiers (C-RNTI.) These identifiers should be transmitted via encrypted methods to ensure passive monitoring attacks are mitigated.

Benefits: First Responders should have a general situation awareness of LTE mobile devices. While LTE-based attacks are unlikely, they may be used in specific circumstances where the bad actor is savvy with communication technologies. Such circumstances may include investigative cases, SWAT scenarios, or coordinated campaigns.

B.1.11 Test 11: Configuration Guidance

Security Objective(s): Integrity, Device & Ecosystem Health, Interoperability

Test Description: Mobile device configuration guidance provides the user instruction to configuring the device, ensuring integrity, device ecosystem health, and interoperability. This test will review the type of guidance provided by the vendor to the public safety professionals. The analysis will determine if any of the contained information contains security guidance dedicated to properly owning, operating, and configuring the device for public safety use. The procedure of this test utilizes the outcome observed in Test 1; however, this test focuses specifically on user guidance after device unboxing and post-provisioning.

Test Outcome: Devices have specific user guidance in the user manual to secure the mobile device. Configuration settings include enabling/disabling location tracking, account settings, user accounts, unlock settings, and linked accounts. Detailed user guides can also be found online from both the device manufacturer and the cellular service provider.

Analysis: Out-of-the-box devices will go through a setup procedure to secure settings such as location tracking, encryption, and lock screen settings. Application-specific settings are configured after the device is initialized and in some cases after applications are installed. Configuration guidance is easily obtained through the device manufacturer's website, accompanying documentation, and the cellular provider's website. The most accurate guidance information is contained on the cellular service provider's website for Android devices. Guidance for Apple iOS devices is best obtained through Apple's support website. Specific app settings must be obtained through the application's vendor or developer website. MDM solutions and local settings are also available for further device controls, such as camera access and app store access.

Gaps: OS updates and patches may alter the location of specific settings. Likewise, updates and patches can alter previously set configurations and/or add additional settings. Deviations from updates and patches may require the user to either find new settings or search online for additional settings. MDM software can help mitigate settings-induced risk among devices that are under common administration. App-specific settings are variable, and users must refer to the specific app vendor for configuration guidance.

Guidance: It is recommended to perform post-provisioning of devices, especially after installation of additional mission-critical applications. Only the minimum services and permissions should be enabled to allow the functionality of mission-critical applications and perform routine duties. Configurations, such as location tracking should be turned off for non-essential applications, including OS-provided tracking services. Application permissions are configured upon installation or can be changed post-installation in the settings menus.

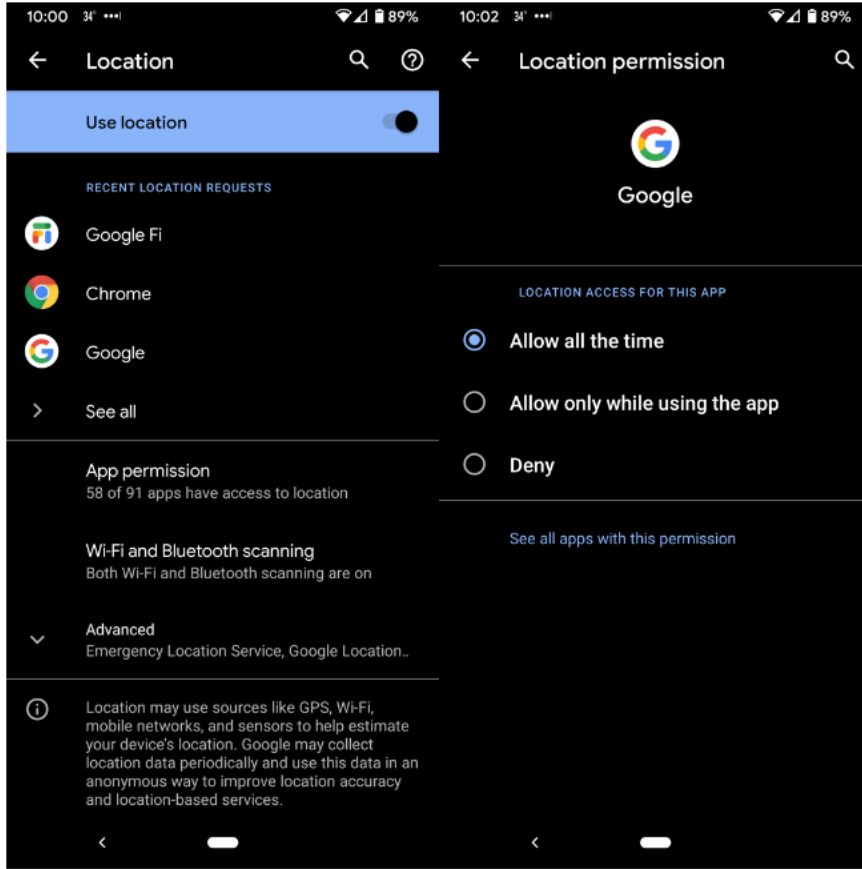


Figure 16 - Android device location permissions

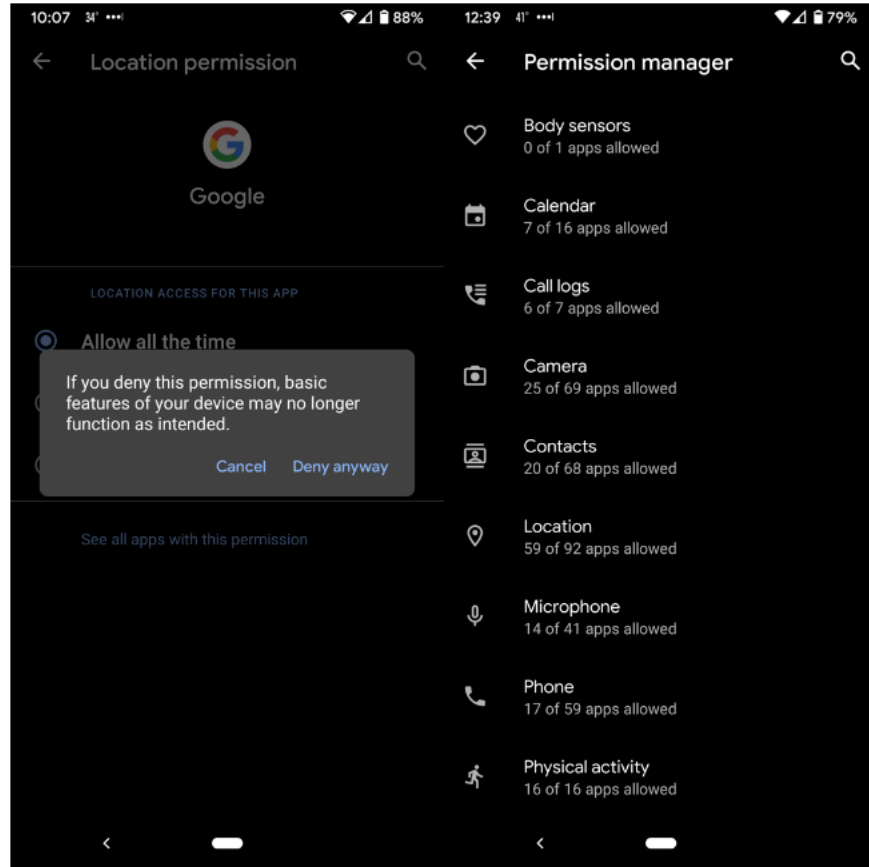


Figure 17 - Android device location permissions

Android contains specific provisioning for location and permissions for each installed app. Figure 16 displays a system-wide setting for location tracking as well as a log of recent tracking requests. The right image of Figure 16 shows specific settings for an individual application. Figure 17 shows a warning message notifying the user that disabling location services for certain apps may negatively affect basic device functionality and permissive variables for device functionality.

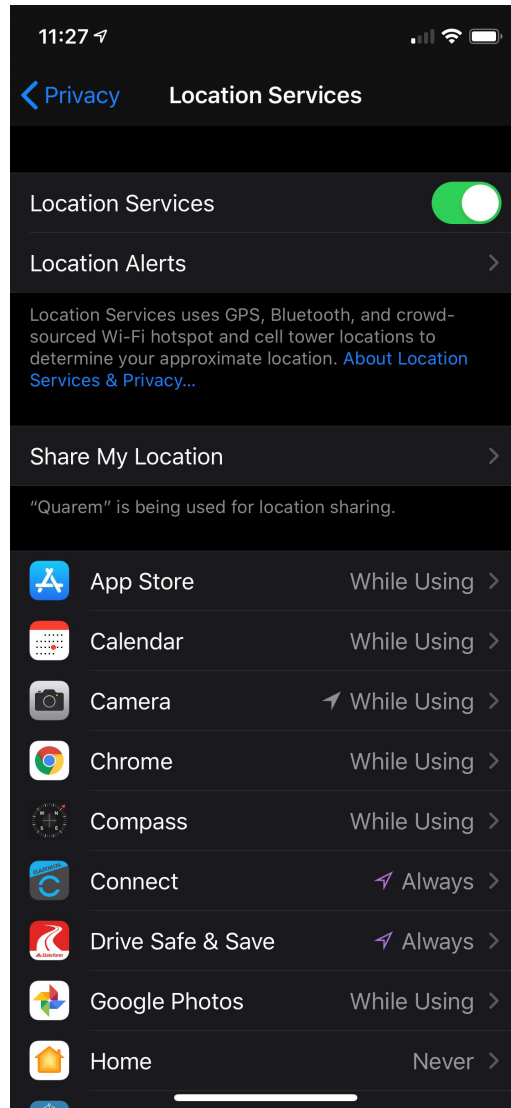


Figure 18 – iOS device location permissions

Figure 18 shows how Apple iOS devices contain a similar menu to control location permissions for the entire device or individual apps.

Mobile devices allow for application-specific settings for various permission. Note that some permissions must be enabled for the device to operate properly. The application will typically re-prompt the user if an application requires additional permissions. Users and administrators should regularly review device permissions and services to ensure device integrity and prevent profile tracking of responders.

Since settings are subject to change with OS versions and device type, it is recommended to utilize web-based resources for configuration guidance for specific devices. Most mobile OSs provide detailed lists of apps and associated permissions as shown in the Android Permissions Manager in the figure above. It is recommended to regularly test applications, especially after updates or permission changes, to ensure that first responder applications remain operational. Policies applied through an MDM solution should be regularly tested to ensure proper policy implementation as well as adequate operation of the responder devices. Negligence in performing regression testing of security policies and operational functionality puts the first responder at risk. For example, a security policy that limits the use of the device's camera may impact the ability to collect incident evidence at a crime scene. In some reported cases, public safety personnel has resorted to using non-secure, personal devices to collect such evidence. These actions prevent the responder from completing their job, exposes their asset to external risk, and may invalidate the evidence and chain-of-custody processes.

Benefits: Post provisioning of device security settings ensure device integrity by securing device permissions. Location services can allow profiling through apps and tracking of First Responder devices. Linked accounts may provide app access to mobile settings, cameras, haptic devices, and databases. Linked accounts may present the potential for remote application execution or device exploitation through the installation of backdoor trojans or solicitation exploitation. Users should be aware of configuration and security settings to ensure the continued health of the mobile device in post-provisioning situations. Post-provisioning, post-policy application regression testing should be performed on test devices before being applied to first responder devices in the field. Field users should be notified of changes and updates so that devices can be operationally verified in a non-emergency setting.

B.1.12 Test 12: Wi-Fi PitM, Denial of Service, and Rogue Access Point Detection

Security Objective(s): Integrity, Confidentiality

Test Description: This test checks to see if the mobile device can locally detect Evil Access Points and/or PitM attacks when using Wi-Fi.

Wireless network selection varies between Android and Apple iOS devices if the screen is off or on, previous user selection, security level/types, etc [29] [30]. The details of the selection process may also change in future OS and hardware iterations. Technologists, IT administrators, and mobile users must always be aware of potential changes and threats that may impact mobile device day-to-day usage. While this document primarily focuses on the mobile device, it is also important to secure and protect the wireless network infrastructure that the mobile device connects to.

Note: Most Wi-Fi networks consist of three main components or devices; the mobile device, the Access Point (AP,) and optionally an authentication server. The mobile device can be any Wi-Fi-capable client, user device, computer, etc. The AP may also consist of a Wireless LAN Controller (WLC) to control several APs under a common administration. The authentication server is any computing device that contains a user database. The authentication server may be built into the AP and/or WLC, however, it may also be a separate server that contains a user database. This document will interchangeably refer to the Wi-Fi-capable client as the supplicant or mobile device. The AP, Wi-Fi controller and/or WLC will be referred to as the authenticator. The authentication server will retain this terminology.

To obtain a better understanding of different Wi-Fi attacks, including PitM, it is important to understand the wireless association and authentication processes. 802.11, Wi-Fi connections typically exist in one of three states:

1. Not Authenticated or associated with an authenticator
2. Authenticated, but not associated
3. Authenticated and associated

Moving through these states is a multi-step process that includes low-level, physical layer checks, followed by higher-level authentication. It's important to note that two authentication sequences typically take place in Wi-Fi networks, even with modern security protocols. The first authentication sequence comprises the three steps mentioned above, and the second sequence involves a 4-way handshake. Both sequences are detailed in the following steps.

1. The supplicant starts as unassociated and may be sending out inquiries probes to find compatible Wi-Fi authenticators. The end-user will typically see this as a list of Wi-Fi networks in their Wi-Fi management application.
2. Authenticators receiving probes will compare received data rates to see if there is a compatible rate. If there is a rate match, the authenticator will respond with its supported parameters and information, such as Service Set Identifier (SSID), encryption types, and other wireless capabilities.
3. The end-user or supplicant will select the desired wireless network or SSID. Once selected, the supplicant will respond to the select SSID with a low-level "authentication" probe with the sequence 0x0001, see Figure 19. This step is only used to provide initial communications between the authenticator and supplicant. Secure authentication methods, such, Wi-Fi Protected Access (WPA), WPA2, WPA3, and/or 802.1X are performed in a later, high-level authentication sequence.

Note: Wired Equivalent Privacy (WEP), WPA, and WPA2 are considered insecure and should not be used when possible. Similarly, Temporal Key Integrity Protocol (TKIP), encryption protocol should also not be used due to known vulnerabilities. WPA and WPA2 support Counter Mode Cipher Block Chaining Message Authentication Code Protocol (CCMP) / Advanced Encryption Standard (AES) and should be used in cases where these protocols must be used. While it is still being used in many deployments, WPA2 is also considered insecure due to a vulnerability known as Key Reinstallation Attack (KRACK.) Where possible, deployments should utilize WPA3 with AES encryption, and mobile devices should be upgraded or replaced to support the new Wi-Fi standard. WPA3 was introduced in January of 2018, so devices manufactured before or around this time may not support WPA3. Public safety organizations must determine use and risk factors by continuing to use older encryption protocols. Most Wi-Fi APs and controllers support mixed mode security for migration purposes, so both older WPA2 and newer WPA3 devices can run concurrently.

Note: There is another Wi-Fi security standard known as Wi-Fi Protected Setup (WPS), that was primarily created to assist home Wi-Fi users to secure their wireless networks. The protocol allows users to add wireless devices to their network without having to remember passphrases. WPS is considered insecure and easily subject to brute-force attacks. WPS should not be used in corporate, first response, or enterprise networks.

4. The authenticator receives the low-level authentication frame and responds with an acknowledgment frame of 0x0002. If the authenticator doesn't receive the 0x0001 frame or receives any other frame from the supplicant, it will return the supplicant's status to unassociated.

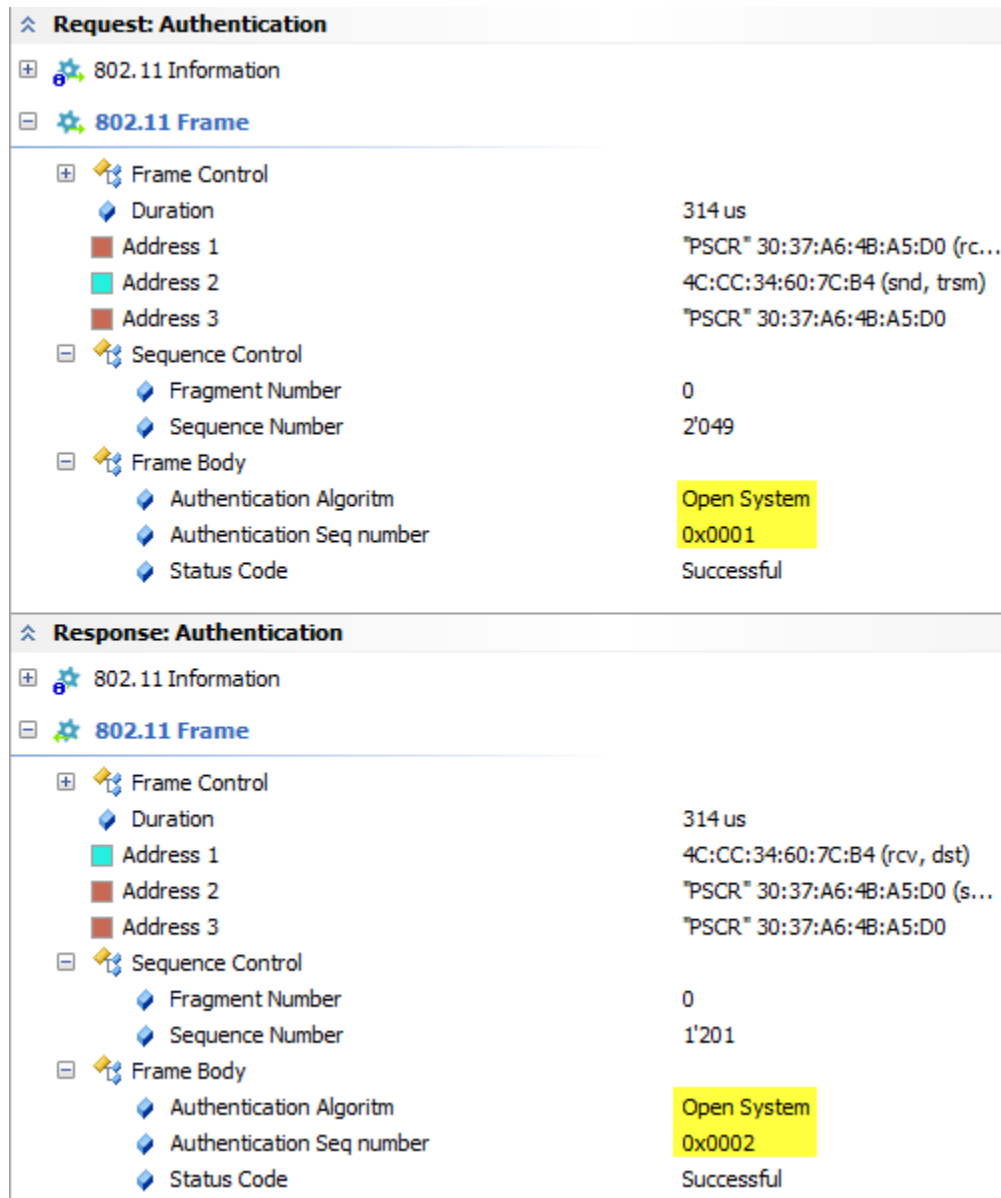


Figure 19: Wi-Fi capture displaying authentication process. Open authentication algorithm and sequence numbers highlighted.

- The supplicant will now be considered authenticated, but unassociated. The supplicant will send an association request to the authenticator with the chosen encryption ciphers and compatible 802.11 capabilities.

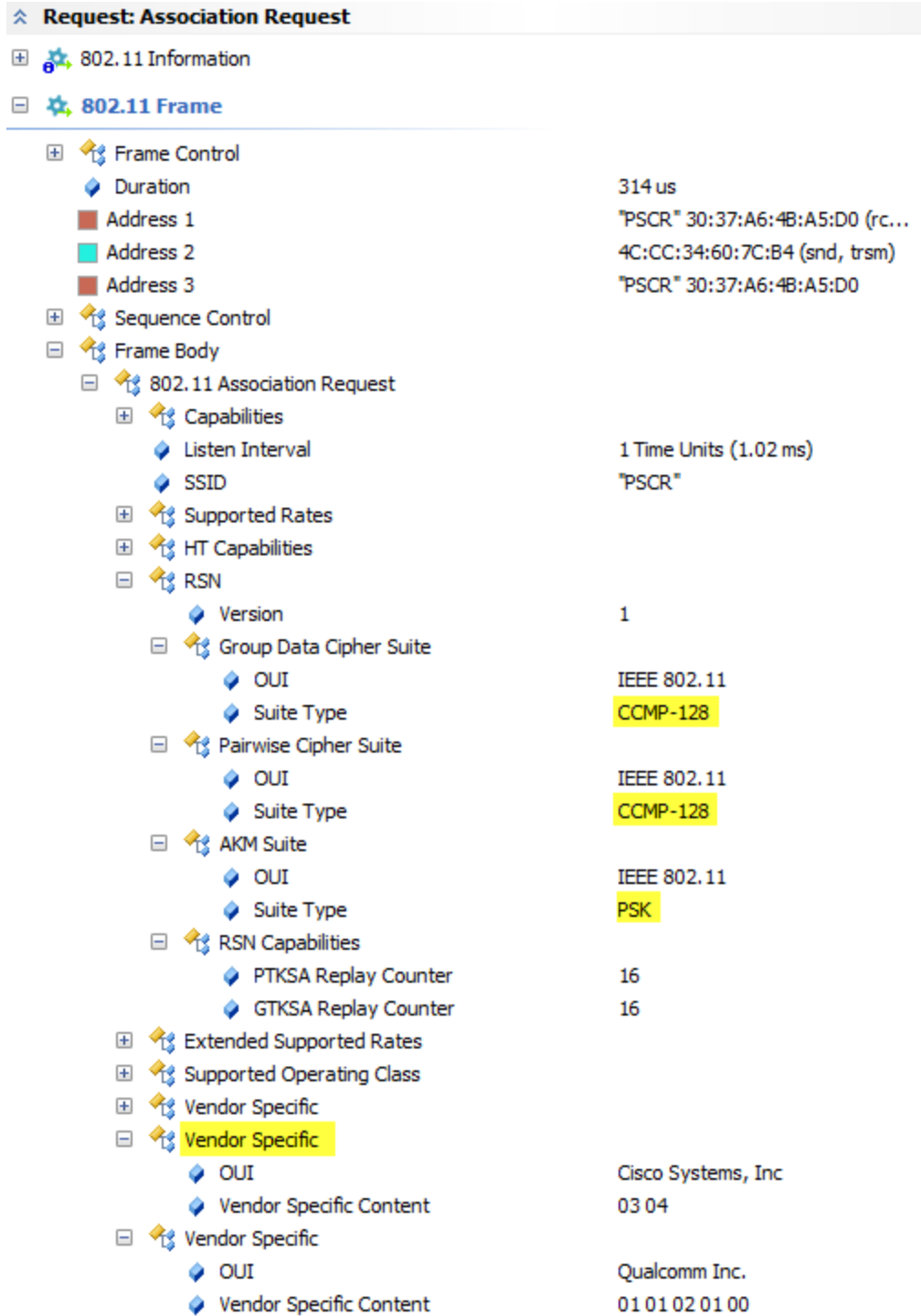


Figure 20: Wi-Fi capture of association frame sent from a mobile device.

Figure 20 shows a frame that contains information that can be useful to a bad actor, such as MAC addresses of sender and receiver and cipher suites. CCMP-128 with Pre-shared Key (PSK) indicates that AES encryption with a pre-shared key is being used, so one can deduce that WPA2-Personal is being used as the encryption protocol suite, which is subject to the KRACK vulnerability. Also, note the Vendor-Specific attributes of the mobile device. This information is normally used to include vendor-specific information in Wi-Fi management frames.

6. The authenticator receives the supplicant’s association request, checks matching capabilities, and will create an association ID for the supplicant. The authenticator will respond with an association response, granting the supplicant to the wireless network. Like step 4, if the authenticator receives any frame other than an association request, the authenticator will move the supplicant back to the unassociated state.
7. While the supplicant is considered associated, if the authenticator requires WPA, WPA2, or WPA3 authentication, an additional 4-way handshake must take place to be fully authenticated. If the authenticator is using Open or WEP authentication (not recommended), then the mobile device will be granted access to the network.

Beacon ("PSCR", 18 Mb/s, x 162)	PSCR (snd,trsm)	Broadcast (rcv,dst)
Association Request (retries=2)	C3:F0:00:2E:AA:AA (snd,trsm)	00:00:A4:53:0E:7A (rcv,dst)
Probe	4C:CC:34:60:7C:B4	PSCR
Authentication (Device=00:00:00:00:00:00, AP=00:00:00:00:00:00)	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Authentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Authentication	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Association (Device=4C:CC:34:60:7C:B4, AP=PSCR)	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Association Request	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Association Response (18 Mb/s)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
4-Way Handshake		
QoS Data	PSCR (snd,trsm,ap)	4C:CC:34:60:7C:B4 (rcv,dst)
QoS Data	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst,ap)
QoS Data	PSCR (snd,trsm,ap)	4C:CC:34:60:7C:B4 (rcv,dst)
QoS Data	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst,ap)
Block Ack Setup (Status=Successful)		
Block Ack Req	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Block Ack (x 6)	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Block Ack Setup (Status=Successful)		
UDP > DHCP Boot Request	0.0.0.0 68	255.255.255.255 67
UDP > DHCP Boot Request	0.0.0.0 68	255.255.255.255 67

Figure 21: Wi-Fi capture showing a collapsed view of the Wi-Fi authentication process.

Figure 21 shows the 4-way handshake and Dynamic Host Configuration Protocol (DHCP) exchange after a successful connection. Note that DHCP packets are unencrypted through the Wi-Fi capture utility for viewer reference. Normally these packets are not viewable without knowledge of the encryption key or PSK.

Note: WPA3 mandates the use of a feature called Protected Management Frames (PMF.) PMF protects management frames that contain sensitive device information as demonstrated in the Wi-Fi captures above. PMF prevents eavesdropping and further reduces the risk to mobile devices and Wi-Fi networks. WPA2 supports PMF, but it is an optional integration component that may not be supported on all devices. Support attributes for PMF are advertised by the AP in beacon broadcasts. However, note that initial management frames used in authentication are not protected since no encryption security mechanism has been established.

8. After a device is associated and authenticated, high-level authentication takes place. Optionally, depending on the Wi-Fi architecture, 802.1X is a network authentication that may be used to form trust relationships between network devices. 802.1X is used with networks that use a remote authentication server or centralized user database. The additional AAA infrastructure in combination with WPA, WPA2, or WPA3 protocol is generally known as Enterprise level authentication, e.g. WPA3-Enterprise used in corporate networks as opposed to WPA3-personal, used in private or home networks. Enterprise Wi-Fi architectures are used in implementations where user scalability and role-based access are required. 802.1X uses an end-to-end encryption protocol called Extensible Authentication Protocol (EAP), to supplement authentication between the supplicant, authenticator, and the authentication server. EAP may utilize Transport Layer Security (TLS), with Public-Private Key Cryptography to establish trust relationships between devices used in 802.1X authentication. Other EAP encryption methods exist, but TLS with Public-Private Key Cryptography is the recommended configuration, as of this publication date.

Note: 802.1X is used often interchangeably with the term Extensible Authentication Protocol through 802.1X (EAPOL) in Wi-Fi technical documentation. Both refer to the authentication framework used in many network connections, to form trust connections.

Note: 802.1X is still used in WPA, WPA2, and WPA3 personal protocols, however, it generally takes place within the authenticator since an authenticator server is not used in WPA personal networks.

9. The last step in the Wi-Fi authentication process is the 4-way handshake. The 4-way handshake is used in both personal and enterprise Wi-Fi networks where any version of WPA is used. The 4-way handshake is the process and exchange of four messages between the supplicant, authenticator, and optionally the authentication server to generate encryption keys used to encrypt and decrypt data over the wireless media. WPA3 is currently the recommended and latest key exchange protocol that secures the 4-way handshake key exchange.

To understand the 4-way handshake some terms need to be defined. The purpose of the 4-way handshake is so the authenticator and supplicant can independently verify each other without disclosing the PSK. See Figure 22 below for handshake chart visual representation.

1. Pairwise Main Key (PMK) – For this document, this is the same as the PSK. When a PSK is entered into the supplicant and authenticator, it is converted from a human-readable passphrase to a bit string. If 802.1X authentication is used, the PMK is derived through the EAP method.
2. Group Temporal Key (GTK) – Encryption key used for exchange between an authenticator and supplicant. The GTK is used to encrypt all broadcast and multicast transmission between the authenticator and multiple supplicants on the same authenticator. Each authenticator in a Wi-Fi network has a different GTK, but all supplicants on the same authenticator have the same GTK.
3. Group Main Key (GMK) – The GMK is used to create the GTK, unique to each authenticator and refreshed periodically to prevent compromise.
4. Message Integrity Code (MIC) – Also sometimes known as Message Authentication Code or tag. MIC is used to verify the sender's message by providing message integrity and authenticity checking.
5. Authenticator nonce-value (ANonce) – Random number generated by the authenticator.
6. Supplicant nonce-value (SNonce) – Random number generated by the supplicant.
7. Pairwise Transient Key (PTK) – Encryption key used for unicast traffic between the authenticator and supplicant.
8. Integrity Group Temporal Key (IGTK) – Used to check the integrity of broadcast/multicast management frames and used to compute the MIC for broadcast/multicast frames. This key is sent in message 3 and generated by the authenticator when broadcast or multicast is used in the 4-way handshake.

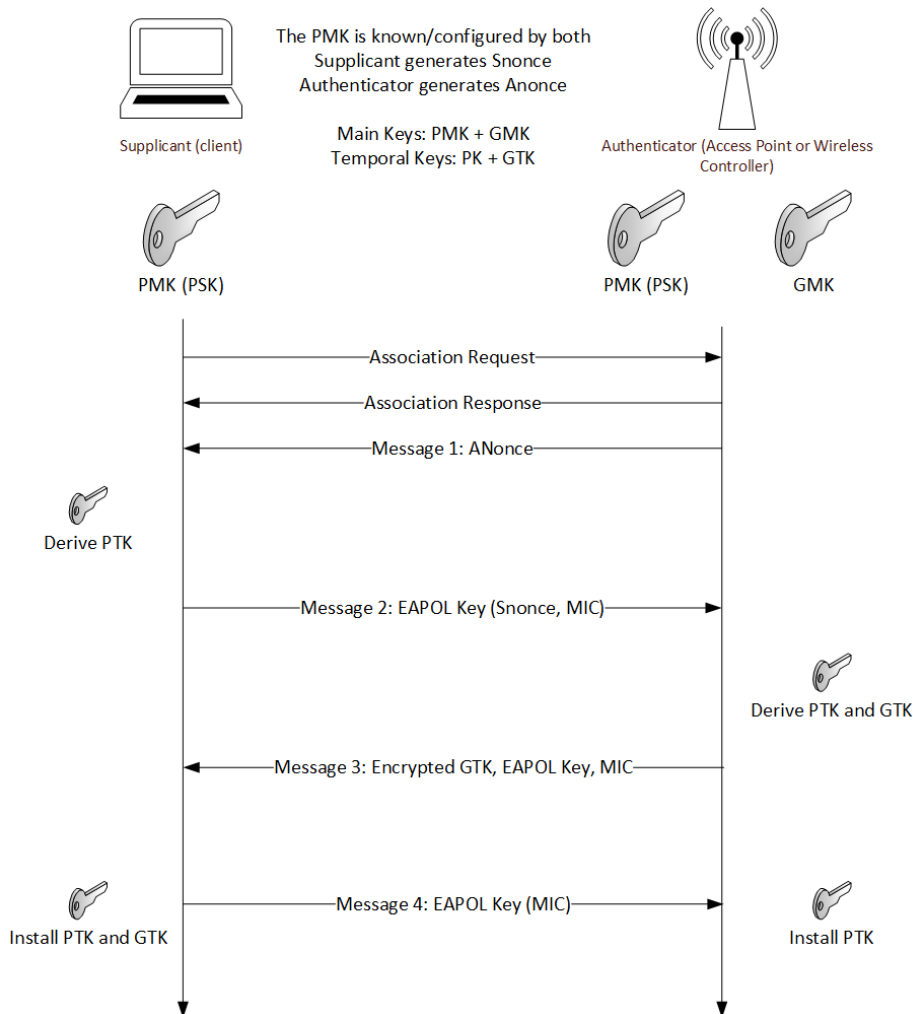


Figure 22: 4-Way handshake, key exchange used in WPA, WPA2, and WPA3 personal protocols.

Wireless attacks usually combine two aspects to perform a PitM attack. One part is the creation of a rogue access point, referred to as an Evil AP, to mimic an existing Wi-Fi access point and the second part is utilizing a signal-jamming mechanism to “capture” a wireless host from the trusted wireless network. Alternatively, the bad actor may also utilize other methods such as Wi-fi deauthentication or brute-force attacks against the authenticator to achieve similar results. Replay vulnerabilities may also be utilized by manipulating and replaying cryptographic handshake messages, tricking the target device into installing already-in-use keys. WPA2 does not check to see if previously used keys are being replayed, however, this has been corrected in WPA3.

PitM attacks can be profiled using a six-phase procedure as follows:

1. A bad actor performs reconnaissance to gather information from the target Wi-Fi network. Of particular interest are the Robust Secure Network (RSN) parameters (see Figure below), which include the preferred authentication method of the target authenticator, and supported cipher suites for key exchange. Other reconnaissance information includes parameters, such as Service Set Identifier (SSID), Basic Service Set Identifier (BSSID,) Extended Service Set Identifier (ESSID,) MAC address of the target authenticator, the signal strength of the target authenticator, operating channel of the target authenticator and other parameters. Much of this information is provided by the target authenticator through Wi-Fi broadcast beacons.

RSN	
Version	1
Group Data Cipher Suite	
OUI	IEEE 802.11
Suite Type	CCMP-128
Pairwise Cipher Suite	
OUI	IEEE 802.11
Suite Type	CCMP-128
AKM Suite	
OUI	IEEE 802.11
Suite Type	PSK
RSN Capabilities	
PTKSA Replay Counter	16
GTKSA Replay Counter	16

Figure 23: Wireless capture of an access point beacon, displaying Robust Security Network (RSN) and 802.11i parameters.

Figure 23 shows RSN attributes such as Authentication and Key Management (AKM), and cipher suite capabilities. PSK is a passphrase that indicates both the Wi-Fi authenticator and mobile client have prior knowledge of the connection. The use of PSK is common, however can be subject to brute-force attacks.

802.11 Frame	
Frame Control	
Type	Management
Sub Type	Beacon
To DS	No
From DS	No
Power Management	Active mode
Duration	0
Address 1	Broadcast (rcv, dst)
Address 2	"PSCR" 30:37:A6:4B:A5:D0 (snd, trsm)
Address 3	"PSCR" 30:37:A6:4B:A5:D0
Sequence Control	
Fragment Number	0
Sequence Number	1'152
Frame Body	
Timestamp	0x000000000EFC2978
Beacon Interval	102 Time Units (104 ms)
Capabilities	
ESS	Yes
Privacy	Yes
Short Preamble	Yes
Short Slot Time	Yes
SSID	"PSCR"
Supported Rates	
Rate	1 Mb/s (basic rate)
Rate	2 Mb/s (basic rate)
Rate	5.5 Mb/s (basic rate)
Rate	6 Mb/s
Rate	9 Mb/s
Rate	11 Mb/s (basic rate)
Rate	12 Mb/s
Rate	18 Mb/s
Current Channel	11

Figure 24: Wireless capture of authenticator beacon information displaying supported 802.11 capabilities.

2. The second, optional step is to gather similar information from the target mobile device that is being targeted. Much of the same information can be gathered from the target mobile probe broadcast, see Figure 24. Probe broadcasts are like authenticator beacons in that they contain connection parameters/capabilities of the mobile device. Even if a mobile device is already connected to a wireless authenticator, it may still send out probe broadcasts to scan for wireless networks, especially if the mobile device user is using the wireless network selection utility. If the timing is correct, the bad actor may capture the 4-way handshake, gathering key information to help perform replay attacks against the handshake. Note that Wi-Fi operation depends on probe broadcasts and authenticator beacons, however, there are mitigation methods to help reduce risk. Mitigations include using strong authentication methods, strong encryption protocols, management frame protection, or turning off the mobile Wi-Fi when not in use.
3. Third, the bad actor will create a rogue authenticator with the same attributes as the legitimate wireless network. For example, the same ESSID, BSSID, same wireless frequency, wireless channel, authentication method, and/or MAC address. Depending on the attack, the bad actor may utilize one or many of these attributes to either hijack, attempt to trick the user into selecting the evil AP, or perform a denial-of-service attack.
4. Optionally, the bad actor may connect the evil AP to the internet. Providing an internet connection allows the evil AP to act as an intermediate proxy, so unsuspecting users don't immediately differentiate between the legitimate AP and the evil AP. This also allows the bad actor to intercept user data or perform further exploitations or data exfiltration.
5. The bad actor may cause the evil AP to initiate a jamming and/or de-authorization attack against the legitimate network to force clients onto the evil AP. Alternatively, the bad actor can jam the target AP to cause a denial-of-service attack and/or force the mobile Wi-Fi user onto the evil AP's mimicked network. The bad actor may also cause temporary disruptions to record and replay the 4-way authentication sequence to decrypt user traffic.
6. Intercept private data by using a proxy, sniff/capture wireless traffic, or cause a denial of service to wireless networks.

Note: The process of implementing a wireless proxy or wireless traffic sniffer in the evil AP is an important consideration when a wireless attack is performed. This goes beyond some of the points discussed in this test, however, a web browser PitM mitigation feature is presented in the guidance section for user awareness and example.

Note: While additional, PitM attack methodologies exist, this test intends to explain basic mobile device PitM detection using built-in OS defenses and observations.

Test Procedure: The test configuration network consists of two Access Points (see Figure below.) One AP is the trusted AP utilizing secure methods of authentication and encryption. The second AP is the Evil AP used to mimic the trusted APs SSID and perform Wi-Fi attacks. For the test to be “successful” the mobile device must be able to locally distinguish between the trusted and untrusted Wi-Fi connections. Two attacks are performed include the deauthentication attack and replay attack.

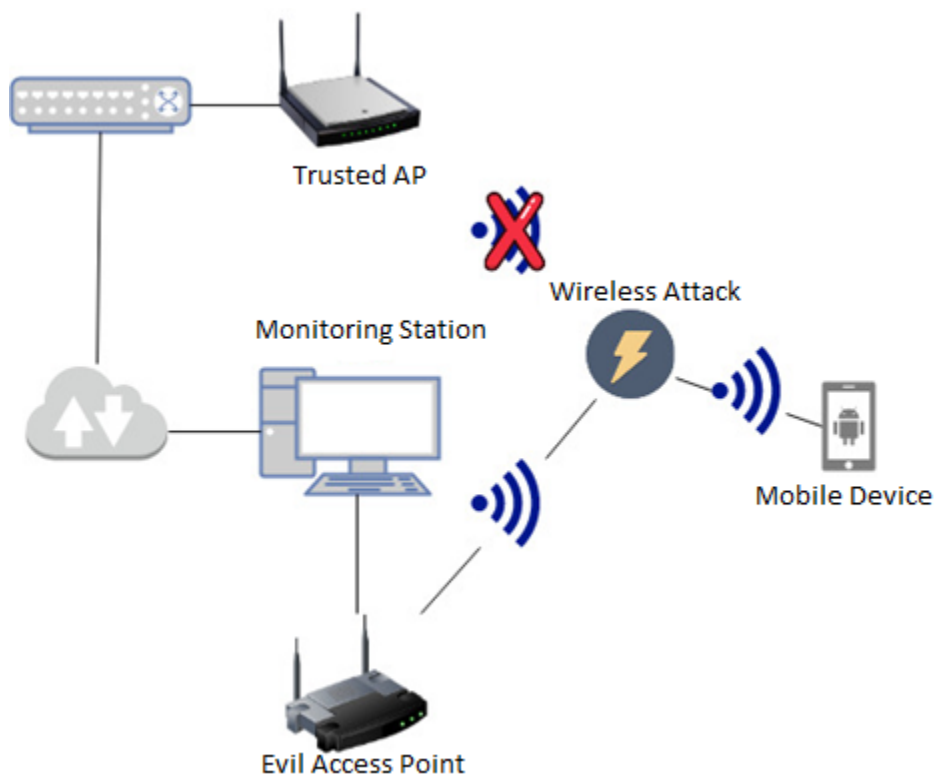


Figure 25 - EvilAP/PitM network configuration

Attack 1: Wi-Fi deauthentication attack

Wi-Fi deauthentication attacks are considered a denial-of-service type attack where the Evil AP sends a deauthentication frame to the target mobile device. Unlike a jamming attack, that disrupts the physical radio frequency of the Wi-Fi channel, the deauthentication attack utilizes the built-in functionality of the Wi-Fi protocol to deny service to Wi-Fi clients. The deauthentication attack targets the mobile device’s MAC address, which can be obtained as clear text through a wireless sniffer. Under normal conditions, a deauthentication frame is sent by the mobile device to the wireless AP to disconnect or end a Wi-Fi session, essentially a user requesting to log off from the network. In this scenario, the Evil AP spoofs the user device and tells the AP to log the real client off the network. Deauthentication attacks can be used to gain additional authentication information, in the case of WEP, WPA, or WPA2 observe and replay authentication phases. It can also be used to hijack a target device into using the Evil AP.

Mobile devices will not automatically connect to the evil AP until manually subjected via user input in some cases. Typically, the mobile device will recognize the Wi-Fi networks as two separate, distinguished networks unless the rogue AP mimics the real AP exactly, see Figure 26.

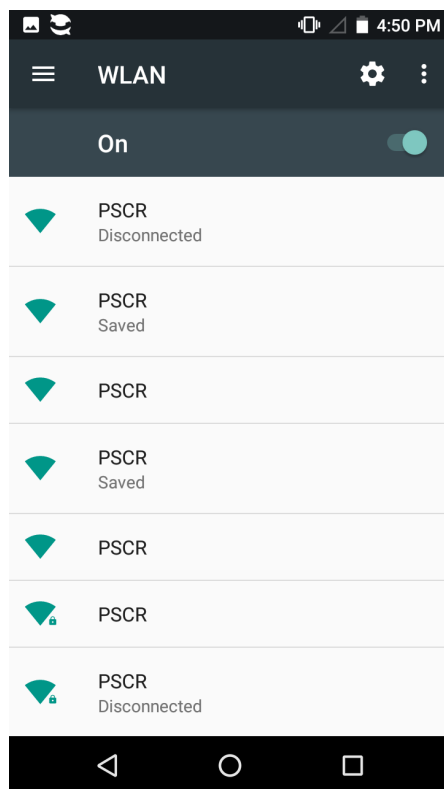


Figure 26: Mobile device Wi-Fi selection screen showing multiple instances of the same SSID.

Both the trusted AP and Evil AP are configured with the same SSID, however, the Evil AP contained some parameters that didn't match the trusted AP. While not shown in Figure 26, the conflicting settings included different authentication types, e.g. Open authentication vs. WPA2, and different BSSID/MAC addresses. The mobile device distinguished the SSIDs as two separate networks. Multiple instances appeared due to the deauthentication attack performed against the mobile device.

Wi-Fi network distinction is typically implemented in the mobile device through network profiles saved to the device. Figure 27 below shows how the mobile responds if configuration parameters match the SSID, BSSID, and MAC of the trusted AP, but not the authentication type.

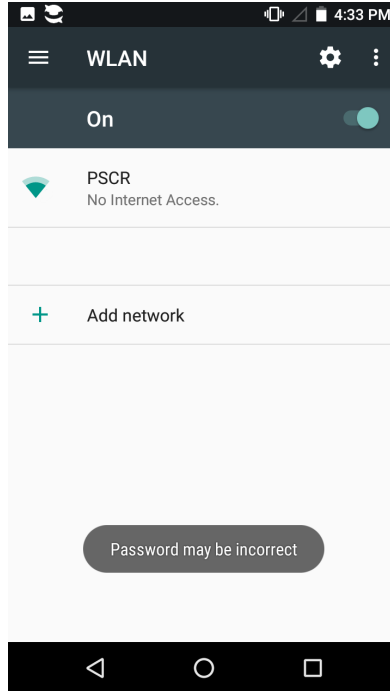


Figure 27: Mobile device showing only a single SSID during a PitM attack.

Figure 27 shows that both the Evil AP and Trusted AP have the same SSID, BSSID, and MAC address. The only different configuration is Open authentication configured on the Evil AP and WPA2 on the Trusted AP. The radio frequency signal of the Evil AP is stronger than the Trusted AP, so the mobile device attempts a connection but fails since the previously saved connection profile contains WPA2 authentication information.

If a previous association is made to both APs, the mobile client would prefer the AP with the best signal strength first. If both APs have sufficient signal strength, then mobile will prefer the AP with better security mechanisms over an AP using Open or no authentication. The connection distinction is important to track since Android and Apple iOS have different Wi-Fi selection algorithms. This selection information is available through both the Android OS and Apple iOS user and developer websites.

Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4E:CC:34:60:7C:B4 (snd,trsm)	30:37:A6:4B:A5:94 (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Deauthentication	4C:CC:34:60:7C:B4 (snd,trsm)	PSCR (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)
Disassociation (retries=8)	PSCR (snd,trsm)	4C:CC:34:60:7C:B4 (rcv,dst)

Figure 28: Wi-Fi capture shows a successful deauthentication attack.

Figure 28 shows the Evil AP sending deauthentication frames aggressively in an attempt to disconnect the mobile client. The flood of deauthentication frames prevent the mobile from auto-reconnecting and allows the bad actor to collect more connection information for further attacks.

To protect against deauthentication attacks, the Wi-Fi AP or wireless controller can be configured to use PMF, which encrypts management frames between the mobile device and AP, see Figure 29.

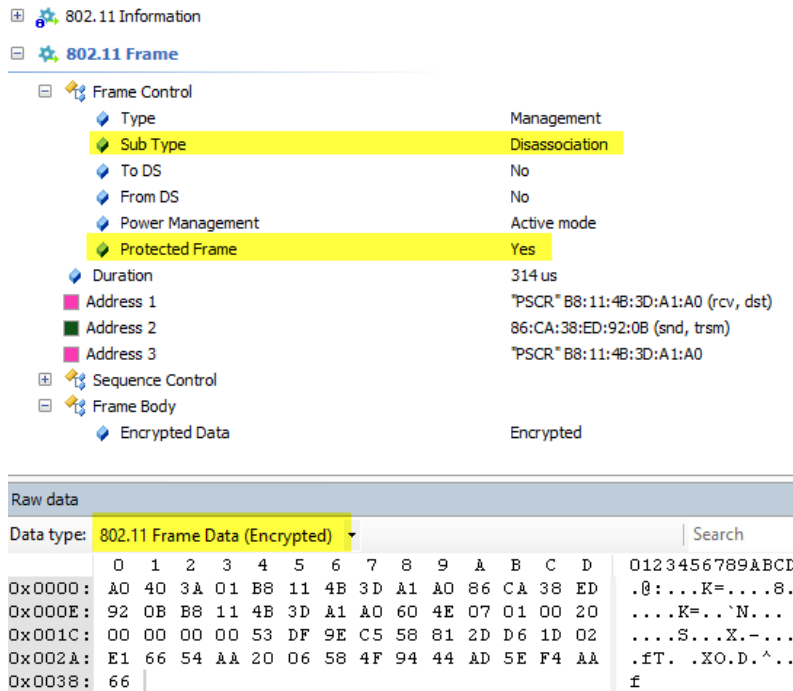


Figure 29: Deauthentication frame utilizing PMF.

The authenticator will only acknowledge dissociation frames that can be decrypted with specific WPA session keys, negotiated between the host and AP. PMF is supported in WPA2 and mandatory in WPA3.

Attack 2: WPA2 Key Reinstallation Attack (KRACK) [31]

The KRACK vulnerability is achieved by manipulating and replaying the 4-way cryptographic handshake. The process is presented by M. Vanhoef and F. Piessens in greater detail in their key reinstallation studies. The M. Vanhoef et al.; method allows an attacker to target victim devices by tricking the device into reinstalling an all-zero Nonce encryption key. This effectively allows the attacker to decrypt client session traffic and can also allow the attacker to perform more advanced PiTM attacks such as SSL Strip or PiTM proxy. KRACK exposes vulnerabilities in the 802.11 protocol, most notably WPA and WPA2 authentication protocols. KRACK has also been shown to expose similar vulnerabilities in 802.11 protocol features, such as Fast Initial Link Setup (FILS,) Wireless Network Management (WNM) power-save, Tunneled direct-link setup PeerKey (TPK,) features and roaming handoff. The FILS protocol is commonly deployed in highly mobile and deployable networks where first responders require expedited network access. It is important to note that key reinstallation attacks can be performed on the client, Wi-Fi infrastructure, or both. To fully leverage the PiTM attack, the bad actor must position their attack platform between both the client device and Wi-Fi infrastructure. CVE identifiers have been created to represent the M. Vanhoef et al.; key reinstallation attacks, which have been assigned as follows:

- CVE-2017-13077: Reinstallation of the pairwise encryption key (PTK) in the 4-way handshake. [32]
- CVE-2017-13078: Reinstallation of the group key (GTK) in the 4-way handshake. [33]
- CVE-2017-13079: Reinstallation of the integrity group key (IGTK) in the 4-way handshake. [34]
- CVE-2017-13080: Reinstallation of the GTK in the group key handshake. [35]
- CVE-2017-13081: Reinstallation of the IGTK in the group key handshake. [36]
- CVE-2017-13082: Accepting a retransmitted Fast BSS Transition (FT) Reassociation Request and reinstalling the PTK while processing it. [37]
- CVE-2017-13084: Reinstallation of the Station-to-Station-Link key in the PeerKey handshake. Affects host-to-host direct connections. [38]
- CVE-2017-13086: Reinstallation of the Tunneled Direct-Link Setup PeerKey (TPK) key in the TDLS handshake. Affects host-to-host connections. [39]
- CVE-2017-13087: Reinstallation of the GTK when processing a Wireless Network Management (WNM) Sleep Mode Response frame. [40]
- CVE-2017-13088: Reinstallation of the IGTK when processing a Wireless Network Management (WNM) Sleep Mode Response frame. [41]

NIST engineers utilized the M. Vanhoef et al.; method to replicate the KRACK attack for lab testing for first responder Wi-Fi devices [42]. Similar testing utilities/methodologies are available to Wi-Fi Alliance members and available through the Wi-Fi Alliance website [43]. Since the scope of this document focuses on first responder “client” mobile devices, NIST engineers only performed tests to check the integrity of end devices, rather than Wi-Fi infrastructure. CVE-2017-13080, CVE-2017-13077, and CVE-2017-13078 address the vulnerabilities presented in the 4-way handshake. Three of the tests presented by M. Vanhoef et al.; check the presence of the KRACK vulnerability within mobile client devices as follows:

1. `./krack-test-client.py --replay-broadcast` . This application tests if the client accepts replayed broadcast frames. If the client accepts broadcast frames test No. 2 will report false positives since the test script will always say the group key is being reinstalled (accepting any broadcast frame), see test No. 2 for more description.
2. `./krack-test-client.py --group` . Tests if the client reinstalls the group key using broadcast Address Resolution Protocol (ARP) requests to the client. The evil AP sends a replayed “nonce = IV” with an all 0’s Nonce packet. If the client accepts the packet and installs all 0’s Nonce, it is susceptible to CVE-2017-13080.
3. `./krack-test-client.py` . This will test reinstallations in the 4-way handshake by resending message 3. CVE-2017-13077 and CVE-2017-13078 are addressed in this test. This test overcomes the issues presented in test No. 1 since messages are sent unicast. This will check if either or both the pairwise key and/or group key are reinstalled.

Attack 2 results:

All first responder devices that were patched to address the CVEs successfully mitigated the three KRACK tests presented in this document. Since all devices tested were running a patched OS to prevent KRACK, all first responder devices successfully mitigated the WPA2 KRACK vulnerability. Devices tested included Android OS versions, 6.0.1 and 7.1.1, and Apple iOS versions 13.1.2 and 15.0 (19A346.)

To display the effectiveness of the presented KRACK tests, an older, first responder Android device, running Android 4.4.4, was selected as a proof-of-concept. This device will be referred to as the “control” device. This was done to ensure the tests were accurately implemented and to highlight the importance of device patching and the retirement of older devices. The following results were derived from the control device, not the tested first response devices:

Test number 1, replayed broadcast frames:

```
(venv) root@pwnix-b8aeedeba229:/home/pwnie/krackattacks-scripts/krackattack# ./krack-test-client.py --replay-broadcas
[16:55:28] Note: disable Wi-Fi in network manager & disable hardware encryption. Both may interfere with this script.
[16:55:28] Starting hostapd ...
Configuration file: /home/pwnie/krackattacks-scripts/krackattack/hostapd.conf
Using interface wlan0 with hwaddr 28:24:ff:46:7e:0c and ssid "testnetwork"
wlan0: interface state UNINITIALIZED->ENABLED
wlan0: AP-ENABLED
[16:55:29] Ready. Connect to this Access Point to start the tests. Make sure the client requests an IP using DHCP!
[16:55:30] Reset PN for GTK
[16:55:33] Reset PN for GTK
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: authenticated
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: associated (aid 1)
wlan0: AP-STA-CONNECTED b0:ec:71:67:72:2d
wlan0: STA b0:ec:71:67:72:2d RADIUS: starting accounting session FF5BA35091173E09
[16:55:34] b0:ec:71:67:72:2d: 4-way handshake completed (RSN)
[16:55:34] b0:ec:71:67:72:2d: DHCP reply 192.168.100.2 to b0:ec:71:67:72:2d
[16:55:35] b0:ec:71:67:72:2d: DHCP reply 192.168.100.2 to b0:ec:71:67:72:2d
[16:55:35] Reset PN for GTK
[16:55:36] b0:ec:71:67:72:2d: client has IP address -> now sending replayed broadcast ARP packets
[16:55:36] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 0 ARPs this interval)
[16:55:37] Reset PN for GTK
[16:55:38] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 1 ARPs this interval)
[16:55:39] Reset PN for GTK
[16:55:40] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 2 ARPs this interval)
[16:55:41] Reset PN for GTK
[16:55:42] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 3 ARPs this interval)
[16:55:43] Reset PN for GTK
[16:55:44] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 4 ARPs this interval)
[16:55:45] Reset PN for GTK
-- Output removed for brevity --
[16:56:26] b0:ec:71:67:72:2d: Client DOESN'T accept replayed broadcast frames (this is good)
```

Figure 30: Terminal output from KRACK broadcast replay vulnerability test.

Output in Figure 30 shows that the control device does not accept replayed broadcast frames, therefore test 2 can be run with the confidence of no false positives. All devices, including the control device, passed this test.

Test number 2, Reinstallation of group key through broadcast ARPs

```
(venv) root@pwnix-b8aeedeba229:/home/pwnie/krackattacks-scripts/krackattack# ./krack-test-client.py --group
[17:08:30] Note: disable Wi-Fi in network manager & disable hardware encryption. Both may interfere with this script.
[17:08:31] Starting hostapd ...
Configuration file: /home/pwnie/krackattacks-scripts/krackattack/hostapd.conf
Using interface wlan0 with hwaddr 28:24:ff:46:7e:0c and ssid "testnetwork"
wlan0: interface state UNINITIALIZED->ENABLED
wlan0: AP-ENABLED
[17:08:32] Ready. Connect to this Access Point to start the tests. Make sure the client requests an IP using DHCP!
[17:08:33] Reset PN for GTK

-- Output removed for brevity --

[17:08:51] Reset PN for GTK
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: authenticated
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: associated (aid 1)
wlan0: AP-STA-CONNECTED b0:ec:71:67:72:2d
wlan0: STA b0:ec:71:67:72:2d RADIUS: starting accounting session 6AA5B3B2DC3DCF37
[17:08:52] b0:ec:71:67:72:2d: 4-way handshake completed (RSN)
[17:08:53] b0:ec:71:67:72:2d: DHCP reply 192.168.100.2 to b0:ec:71:67:72:2d
[17:08:54] Reset PN for GTK
[17:08:55] b0:ec:71:67:72:2d: client has IP address -> now sending replayed broadcast ARP packets
[17:08:55] b0:ec:71:67:72:2d: Send group message 1 for the same GTK and zero RSC
[17:08:55] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 0 ARPs this interval)
[17:08:55] b0:ec:71:67:72:2d: received a new group message 2
[17:08:56] Reset PN for GTK
[17:08:57] b0:ec:71:67:72:2d: Send group message 1 for the same GTK and zero RSC
[17:08:57] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 1 ARPs this interval)
[17:08:57] b0:ec:71:67:72:2d: received a new group message 2
[17:08:58] Reset PN for GTK
[17:08:59] b0:ec:71:67:72:2d: Send group message 1 for the same GTK and zero RSC
[17:08:59] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 2 ARPs this interval)
[17:08:59] b0:ec:71:67:72:2d: received a new group message 2
[17:09:00] Reset PN for GTK
[17:09:01] b0:ec:71:67:72:2d: Send group message 1 for the same GTK and zero RSC
[17:09:01] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 3 ARPs this interval)
[17:09:01] b0:ec:71:67:72:2d: received a new group message 2
[17:09:02] Reset PN for GTK
[17:09:03] b0:ec:71:67:72:2d: Send group message 1 for the same GTK and zero RSC
[17:09:03] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 4 ARPs this interval)
[17:09:03] b0:ec:71:67:72:2d: received a new group message 2

-- Output removed for brevity --

[17:09:40] b0:ec:71:67:72:2d: Client reinstalls the group key in the group key handshake (this is bad).
[17:09:40] Or client accepts replayed broadcast frames (see --replay-broadcast).
[17:09:41] Reset PN for GTK
[17:09:43] Reset PN for GTK
```

Figure 31: Terminal output showing device susceptible to the broadcast group key reinstallation vulnerability.

Figure 31 shows that the mobile device is vulnerable to CVE-2017-13080, by reinstalling the group key in the group key handshake.

Test number 3, reinstallation of the pairwise and/or unicast group key from the 4-way handshake:

```
(venv) root@pwnix-b8aeedeba229:/home/pwnie/krackattacks-scripts/krackattack# ./krack-test-client.py
[17:34:55] Note: disable Wi-Fi in network manager & disable hardware encryption. Both may interfere with this script.
[17:34:56] Starting hostapd ...
Configuration file: /home/pwnie/krackattacks-scripts/krackattack/hostapd.conf
Using interface wlan0 with hwaddr 28:24:ff:46:7e:0c and ssid "testnetwork"
wlan0: interface state UNINITIALIZED->ENABLED
wlan0: AP-ENABLED
[17:34:57] Ready. Connect to this Access Point to start the tests. Make sure the client requests an IP using DHCP!
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: authenticated
wlan0: STA b0:ec:71:67:72:2d IEEE 802.11: associated (aid 1)
wlan0: AP-STA-CONNECTED b0:ec:71:67:72:2d
wlan0: STA b0:ec:71:67:72:2d RADIUS: starting accounting session 2F168238BC5CB245
[17:34:57] b0:ec:71:67:72:2d: 4-way handshake completed (RSN)
[17:34:58] b0:ec:71:67:72:2d: DHCP reply 192.168.100.2 to b0:ec:71:67:72:2d
[17:34:58] Reset PN for GTK
[17:34:58] b0:ec:71:67:72:2d: sending a new 4-way message 3 where the GTK has a zero RSC
[17:34:58] b0:ec:71:67:72:2d: received a new message 4
[17:34:59] b0:ec:71:67:72:2d: client has IP address -> now sending replayed broadcast ARP packets
[17:34:59] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 0 ARPs this interval)
[17:34:59] b0:ec:71:67:72:2d: IV reuse detected (IV=1, seq=4). Client reinstalls the pairwise key in the 4-way handshake (this is bad)
[17:35:00] Reset PN for GTK
[17:35:01] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 1 ARPs this interval)
[17:35:02] Reset PN for GTK
[17:35:03] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 2 ARPs this interval)
[17:35:04] Reset PN for GTK
[17:35:05] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 3 ARPs this interval)
[17:35:06] Reset PN for GTK
[17:35:07] b0:ec:71:67:72:2d: sending broadcast ARP to 192.168.100.2 from 192.168.100.1 (sent 4 ARPs this interval)
[17:35:08] Reset PN for GTK
-- Output omitted for brevity --
[17:35:49] b0:ec:71:67:72:2d: Client DOESN'T reinstall the group key in the 4-way handshake (this is good)
```

Figure 32: Terminal output showing mobile device vulnerable to pairwise key replay attack.

Results in Figure 32 show that the mobile device is vulnerable to CVE-2017-13077, but not CVE-2017-13078. The device reused the pairwise key but did not reinstall the unicast group key.

In conclusion, most devices manufactured or patched after the 2017 exploit were able to successfully mitigate the KRACK replay attack. While the weakness remains in the WPA/WPA2 protocol, hardware devices can mitigate the attack through software modifications. It is important to note that while older mobile devices may receive updates or be retired, infrastructure equipment supporting Wi-Fi networks has a higher likelihood of being vulnerable due to longer expected lifecycles of networking equipment. Like mobile devices, Wi-Fi infrastructure equipment may be software/firmware upgradable to prevent the KRACK attack.

Analysis: Protecting both Wi-Fi mobile devices and the associated Wi-Fi infrastructure is necessary to ensure the integrity of first responder data. While this document focuses primarily on the configuration of mobile devices, it is necessary to evaluate and recommend associated Wi-Fi infrastructure configuration to adequately fulfill the necessary protection of Wi-Fi devices. New Wi-Fi protocols, encryption methods, infrastructure designs, and best practices are routinely implemented and coordinated by the Wi-Fi Alliance and standards organizations. As a Wi-Fi user and/or administrator it is important to understand the security protections necessary to protect mission data and maintain privacy yet be mission ready. Different responder situations may require different levels of Wi-Fi security as well as user training to understand when increased Wi-Fi security protections are needed. At a minimum, it is important to update OS and security patches on both network infrastructure as well as connecting devices, such as mobile devices. Devices that can no longer be updated to mitigate vulnerabilities, such as manufacturer end-of-life and/or end-of-support equipment, should be removed and retired from use.

Mobile devices have built-in mitigations to help prevent Wi-Fi-based attacks, both on the OS level as well as the browser level. Many indicators and warning messages are conveyed to the user to make them aware of a potential attack. These indicators may or may not be directly related to a PiTM, DoS, or jamming attack, but could clue in the user that they are being targeted in a cyber-attack. The user should utilize situational awareness when connecting to Wi-Fi networks, especially in public or open Wi-Fi networked systems. Most mobile devices are designed for ease of use, which may obscure operational/background changes on the mobile device. Most Android and iOS mobile devices contain Wi-Fi profiles for frequently used networks. Network profiles help ensure connections to previously trusted networks are made, however, may obfuscate potential Wi-Fi attacks or connection problems. For example, in PSCR lab testing, multiple indicators were present that indicated potential Wi-Fi connection problems. In one test iteration, NIST engineers configured an evil AP to mimic a trusted Wi-Fi network but failed to configure internet access to clients that connected to the evil AP. Devices claimed to be connected to the Rogue Wi-Fi network but reported “no internet.” This factor indicates that the Wi-Fi client identified a potential misconfiguration since the rogue AP didn’t have an internet connection properly configured. While an evil AP can be configured to allow internet access, a bad actor may make similar mistakes that can reveal their actions.

After NIST engineers configured internet connectivity on the evil AP, another attack misconfiguration was identified by the mobile’s web browser, see Figure 33 below. The mobile browser identified that the destination website utilized HTTPS, but did not receive correct certificate authentication information. The attack was identified due to an improperly configured HTTP proxy used to intercept traffic on the EvilAP. A secure mechanism called HTTP Strict Transport Security (HSTS) is used to prevent SSL downgrade attacks that may be utilized in an intercept HTTP proxy.

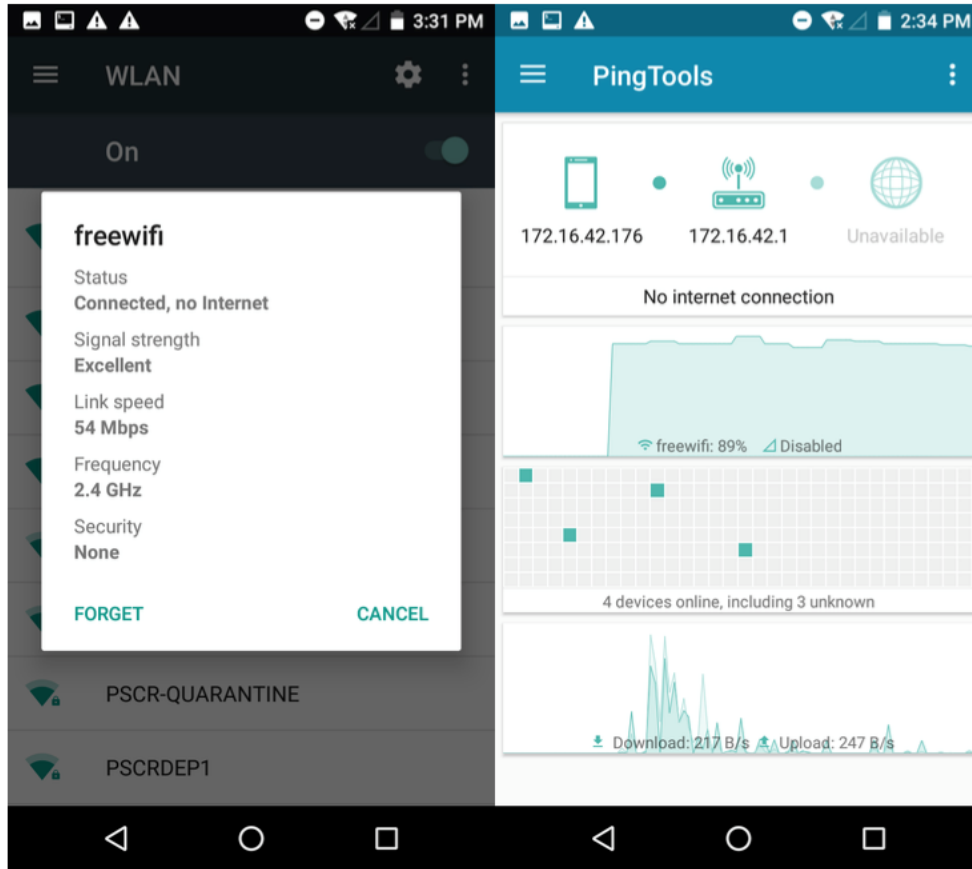


Figure 33: Mobile device connection to AP with no Internet [44]

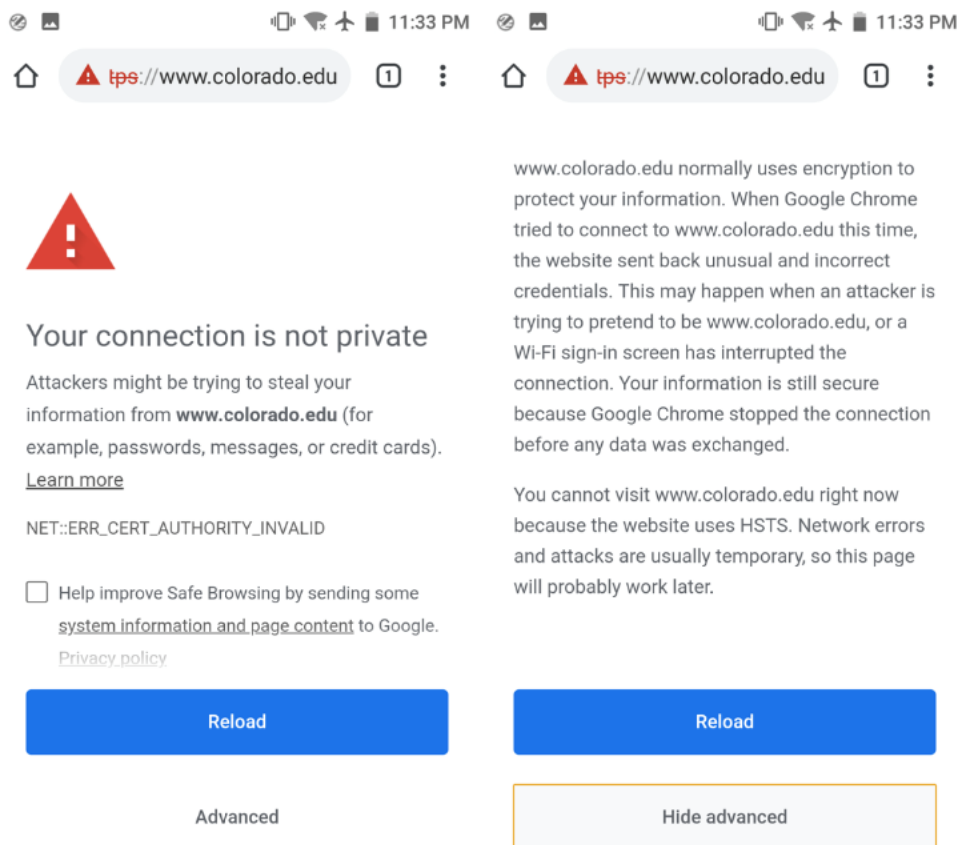


Figure 34: Website detects PitM attack due to invalid certificate response

Figure 34 displays an Android Wi-Fi client that shows a connection to a Wi-Fi network, but no internet. On the right of Figure 33, PingTools (3rd party app) is shown to verify the connectivity status [44]. It shows a browser request to detect a PitM attack due to an invalid certificate response and the advanced information explaining why the connection was not established due to an invalid certificate response.

Note that a properly configured evil AP HTTP proxy could utilize tools such as SSLstrip and/or the KRACK attack to transparently hijack a device and extract HTTP/HTTPS traffic without detection.

Gaps:

Unlike most LTE networks, Wi-Fi networks operate on an unlicensed radio spectrum, also known as the Industrial, Scientific, and Medical (ISM) bands. This allows anyone to operate and broadcast within the allotted ISM radio frequencies without prior permission, certification, or license. Unlicensed radio spectrum provides users, scientists, and administrators with the flexibility to establish wireless internet network connectivity with low capital cost. As a result, the open nature of the unlicensed spectrum, also allows for bad actors to operate with a certain amount of anonymity and greater potential to compromise or damage first responder Wi-Fi networks. While the standards for Wi-Fi are maintained by the Wi-Fi Alliance, each Wi-Fi network is locally configured and maintained. Liability and quality of service of the connection must be maintained by the first responder organization, rather than a network service provider, such as with mobile broadband services. Much of this responsibility falls onto the network or IT administrators to properly train users of the risks of connecting to public Wi-Fi access points, and judgment calls must be made by the user to decide if a Wi-Fi network is safe to connect to. Administrators need to ensure devices used in Wi-Fi infrastructure are up-to-date and patched. In enterprise Wi-Fi architecture, this may also include Wi-Fi-enabled devices, APs, wireless controllers, and authentication servers. Devices and services may span beyond the normal IT network boundary and may even include cloud components, managed off-premises. Mobile devices should be enrolled to include Wi-Fi policies that are appropriate for the device's use. IT administrators must be aware and knowledgeable of multiple technologies to ensure the proper protection of Wi-Fi assets.

The web browser is not locally tied to the OS, instead, the OEM web browser was used in this experiment. Changes in browser technologies and protocols are typically interdependent on the OS. Therefore, it is important to keep browser applications up to date with the latest revisions and patches in addition to the mobile OS.

Guidance: The device user should always check the network connection and access to network services. Awareness of network connectivity and availability is important to validate the Wi-Fi connection to ensure connection to the proper network. The user should be aware of what Wi-Fi networks are safe to connect to and how to properly use public Wi-Fi hotspots or access points. IT administrators should provide user training reflecting agency or organizational policy in addition to device management and access control policies. Update, patching, and device renewal policies should be implemented to reflect data sensitivity, device availability, service availability, and mission purpose. Devices that cannot be patched or updated should be network segmented, isolated, and/or applied network control policies that enhance perimeter defenses [45]. Users that utilize devices that cannot be patched or updated should be trained on how to operate and manage higher-risk devices.

User training, device operation, situational awareness, and cyber incident response are the foremost defenses to protect against Wi-Fi PitM attacks and denial of service attacks. Wi-Fi users and operators should be aware of how Wi-Fi networks normally operate and recognize potential attacks against their devices or Wi-Fi networks. Attacks against the Wi-Fi protocol may be mitigated through upgrades, security patches, device replacement, network access controls, and organizational/agency policy.

Deauthentication attacks can be mitigated using PMF, however, this protocol feature may not be fully implemented in all Wi-Fi networks and mobile devices. Replay attacks, such as the KRACK vulnerability, may be mitigated through software upgrades and device update policy.

Jamming attacks that affect the Wi-Fi radio spectrum, are locally targeted, and can be mitigated primarily through RF congestion avoidance mechanisms. Most Wi-Fi infrastructure devices can broadcast on multiple ISM frequencies with the further capability to avoid congestion or interference within the ISM radio spectrum. When congestion or interference occurs on a Wi-Fi channel, the Wi-Fi access point and mobile device will negotiate and attempt to communicate on a different frequency within a compatible ISM RF band. Typically, RF congestion avoidance mechanisms are enabled by default on both mobile devices and Wi-Fi network equipment and occur automatically with little or no human interaction.

First response organizations and agencies may consider cybersecurity models, such as Defense in Depth, towards implementing layered approaches to protect mission-critical data. Additional cyber defense tools may be utilized to safeguard against data interception in the event of a PitM attack. Device administrators may consider leveraging VPN services on the mobile device as an additional layer of protection. The device user may authenticate to the VPN services to ensure authorized access to public safety resources. VPNs ensure data confidentiality when connecting to public Wi-Fi access points or untrusted networks. VPNs can be configured to only transmit some or all user data over the VPN using a method called split-tunneling. In situations where enhanced device protection and traffic analysis is requiring, administrators can tunnel all traffic through a VPN to the central office. This method allows all traffic, including internet bound, to transverse additional perimeter network devices that can help mitigate internet threats and provide enhance logging and auditing of user traffic. In situations where this level of protection is not required, the VPN tunnel can be “split” to send mission traffic over the VPN, and traffic that does not have a destination to the central office may be sent to the device’s local network or internet gateway.

Antivirus and antimalware software with host-based threat detection software may be installed on mobile devices to defend against targeted threats. Many endpoint protection software suites also contain network monitoring and threat detection features that may help protect users that connect to public Wi-Fi networks.

Network perimeter devices that utilize network threat behavioral analysis may be implemented on controlled Wi-Fi networks and/or VPN gateways. Network perimeter devices, such as advanced or “next-gen” firewalls, provide an additional layer of protection to mobile devices and/or devices that don’t have the computational power to run endpoint threat protection applications.

Benefits: Complete defense against wireless attacks may be a challenge to the public safety organization but utilizing the concepts of defense-in-depth, proper user training and situational awareness may greatly reduce the chances of a Wi-Fi attack. The benefits of user training also improve overall security posture within the public safety organization. Individuals that receive cybersecurity briefings often reconsider their actions when utilizing technology.

Periodic device and network infrastructure updates/upgrades help reduce risk to the public safety organization by implementing the latest security technology, such as WPA3. The benefit of upgrading network and mobile devices also improves device and network performance by taking advantage of new Wi-Fi standards.

B.1.13 Test 13: Boot Integrity

Security Objective(s): Integrity

Test Description: This test will check to see if the mobile device is performing some form of boot validation. Boot validation are integrity checks on device boot files and processes to verify that the mobile OS has successfully executed into a valid state. Boot validation methods on mobile devices require executable kernels and code to be verified via digitally signed cryptographic hashes (of the kernel code). The exact location of the hashes varies between devices, but the operation and methodology are similar in all mobile devices. After the boot executable code is loaded into memory, validation occurs. If validation succeeds, the device will continue to load system executables and may perform additional validation. If validation fails, the device will stop the boot sequence, enter an error state and/or reboot.

Secure boot processes are rooted in a public key that is stored by the device manufacturer in hardware-protected memory regions, typically one-time programmable read-only memory. The boot process uses a series of public keys, beginning with the hardware-protected key, to verify digital signatures on bootloaders, system firmware, and the operating system are sequentially loaded during the boot process. This methodology allows lower levels of the boot operation to verify the next operation in a “chain” of events. If any step in the chain verification fails, the device will stop the boot process, log the error, notify the user and reboot the device. While the boot procedure is like that of any other computer, verification occurs before any code is loaded into system memory or storage. Mobile devices with unlockable bootloaders will bypass the secure chain verification, warn the user of booting an unverified OS, and load the OS.

When selecting mobile technology, the consumer needs to be aware of the differences and selections available between bootloader unlocked versus bootloader locked mobile phones. Starting in Android version 4.4, methods were added for kernel verification during boot and notified the user if deviations occurred. In Android version, 7.0 boot verification was enforced to prevent data corruption and malicious compromise. Subsequent Android releases beyond 7.0 perform boot verification and in some cases have improved these methods to address known exploits or improve boot security methods. Apple iOS devices also cryptographically sign components involved in the booting and startup process in a similar method as Android. Portions of the iOS bootloader is immutable at the chip fabrication level and verified through Apple Root CA verification.[15] The initial bootloader is written to an immutable, read-only memory space during the manufacturing process, and included the Apple-controlled public key that is used to verify the next component of the boot process. The initial BootROM code is implicitly trusted since it is programmed into the phone during manufacturing, therefore trusting the Apple public key.

Test Outcome: All tested devices contained some degree of boot verification. One of the tested devices contained the oldest Android version 4.4, however still contained kernel verification, but could be easily bypassed. Another device contained a special version of Android OS and therefore did not have specific information about boot integrity. Since this device also came bootloader unlocked, boot integrity methods can be bypassed by the user. All the remaining devices in the test contained an Android version greater than 7, contained enforced boot verification methods.

Analysis: Modern mobile devices contain some form of boot integrity verification. Like any technology, older devices may not have the latest protection mechanisms and are more likely to contain exploits to bypass boot verification. Newer devices also contain hardware-level verification methods that check for digital signatures and cross-reference these signatures with trusted manufacturer sources. Overall, factory “locked” devices provide the greatest boot integrity protection and should always be considered over “unlocked” devices.

Gaps : Many older handsets cannot be software upgraded to protect against new exploits. Like any other secure computing device, bootloaders typically run immutable code on read-only memory programmed during the manufacturing process. Future technologies and exploits may reveal weaknesses in current cryptographic algorithms. Since cryptographic keys are programmed during manufacturing into read-only memory, they cannot be remediated or patched because the code is written in read-only memory. Likewise, the public key cannot be updated to either provide stronger security strength or remediate a compromised or lost private signing key. Typically, it is assumed that the lifecycle of the device is shorter than technological advances that may be used to exploit security controls.

Guidance: First responders and public safety organizations should only purchase mobile devices from trusted vendors. Devices should be factory locked to ensure device integrity and that only the mobile provider or device vendor can perform OS updates. Devices that are no longer software upgradable or hardware cannot support the latest boot integrity methods should be retired out-of-service.

Benefits : Boot integrity prevents the loading of an unauthorized OS that could be used to compromise handset devices, potentially leading to data extraction or utilization as a remote attack platform. In Android Verified Boot Version 2.0, system prompts are implemented to warn the user in the event a unverified OS is loaded. Apple iOS devices also provide similar protection mechanisms to prevent the loading of unauthorized iOS boot code.

B.1.14 Test 14: Data Isolation

Objective: Isolation

Description: This test will check to understand if the mobile device is utilizing an isolation technology such as Android Security-Enhanced Linux (SELinux) [46]. Data isolation occurs on individual applications after the device is fully booted and operational. SELinux enforces access control over all device processes as well as their interaction with crucial Linux processes, such as `init`, `dmesg`, `cron`, and others. Data isolation provides device protection by confining and restricting system services and controls access between applications. These protections create sandboxes that allow applications to run within their domain without risk of interfering with other applications or system services. Many mobile device systems run data isolation on an allowlisted basis where processes are denied unless explicitly allowed. However, for development purposes, it is possible to enable special modes that are more permissive. Permissive modes are disabled by default and must be manually enabled by the user or developer. While permissive modes allow greater access to system resources and processes, enabling this mode puts the device at greater risk. However, most modern mobile operating systems, such as Android, still allow sandboxing even while in permissive test modes. Android OS introduced SELinux sandboxing into its operating system in version 4.3. Version 7.0 and 8.0 added features to further restrict applications to sandboxes as well as boot level isolation for vendor-specific images. Apple iOS uses similar data integrity mechanism, simply referred to as “sandboxing.” Much like SELinux, a combination of read-only system permissions, as well as sandboxed runtime environments, separate applications in user spaces to prevent system compromise. Apple further enhances application security by requiring applications to be vetted through an app review process. Once the app passes the review process, it receives a digital signature that is used as a trust verification mechanism before the iPhone installs the app. [47]

Test Outcome: All observed devices contained a form of data isolation for applications. Most of the devices were factory, bootloader locked and developer options were disabled by default. Of the devices that were not factory or bootloader locked, developer options were disabled, and OEM OS images were used in testing. All devices ran in the respective enforced security policy to provide sandboxing of applications and file system protections.

Analysis: Data isolation methods are implemented on most modern devices. Like Boot Integrity methods, older hardware and software may not support the latest protections provided by data isolation methods like SELinux or Apple iOS sandboxing. Data isolation methods can be bypassed through user modification, however, sandboxing of applications creates permissive restrictions for processes and applications. Most users are unaware of data isolation since there is an abstraction level between app operation and user interface (UI). Options for the user to interact with data isolation mechanism must be explicitly implemented by the application developer or through system settings.

Gaps: No vendor guidance is given regarding data isolation in the user documentation or website resources from the vendor. Data isolation is considered a mandatory or common implementation on modern mobile devices, so it’s often assumed that these features are enabled by default. Typical users would have no recollection of data integrity unless explicitly notified of its purpose or in the event of a compromise.

Data isolation does not prevent administrative override to grant user or app permission to system resources. Out-of-the-box, the device owner has complete administrative control over the device to grant application permissions, which could potentially compromise the data integrity of the device. It is important to understand that data integrity does not influence administrative control, these two concepts are not analogous.

Guidance: Most modern handsets and mobile devices contain the latest features and enhancements regarding data integrity protections. Similarly, devices typically have data integrity mechanisms built-in and enabled by default, requiring little or no user intervention. Older devices may lack features to protect against modern attacks, therefore it is important to keep devices up to date with the latest OS patches and upgrades. Devices that are no longer supported by the hardware vendor or OS manufacturer should be retired out of service.

To guarantee data integrity, applications should only be downloaded through a trusted app store. Apps must be digitally signed to ensure the contained code has been properly vetted for public use.

Users that install new applications from the app store should take note of any special permissions required for the application to run. Allowing application permissions grants the use of protected system processes, which could compromise data integrity and put the system or user data at risk. Only applications required to perform first responder duties should be installed to mission-critical handsets. By default, out-of-the-box, the device owner is considered the device administrator and can install apps or make system changes. Device administrators may consider using an application vetting service or working with an application provider that includes the information necessary to address any concerns (app permissions, data collection, privacy concerns, etc.). [48]

Devices that are under common administration should run supplemental device enrollment software to further enforce data integrity policies at the enterprise level. Device enrollment management systems are typically used to secure and manage enterprise mobile devices. These systems enforce device policies to ensure devices are up to date and prevent installation of unwanted or unnecessary applications. Device enrollment systems and software are not included in most factory handset configurations.

Handsets not used in software development environments should have developer and test modes disabled. This setting is commonly found within the device's setting menu but may be hidden from the user, depending on the platform and OS version. By default, most factory distributions have developer or test modes disabled. This setting is typically not included within the normal user documentation but can be found through online web searches or vendor support web pages. Depending on the hardware platform, development environments may only be accessible using supplemental hardware interfaces and software development kits. Devices used for development purposes should not be used daily first responder use.

Application developers should only use software development kits offered by the OS developer. Applications should be vetted through the manufacturer and digitally signed for end-user use and distribution. Any developed application should only request permissions necessary for the application to function. Requested permissions should be clearly explained as to why the permission is required within the app's description on the application store. During installation or application use the user should be prompted to allow special permissions. Allowing excessive or unnecessary permissions can allow an application to bypass data integrity protections, putting the device at risk.

Benefits: Data integrity protects OS processes and user data from potential compromise by enforcing access permission. Data integrity protection mechanisms are a combination of supervisory processes that prevent execution of code, access to system processes, and critical OS file system areas. These supervisory processes prevent the deletion or alteration of critical system files, enforce user process separation, segregate application processes, and enforce application permission to system functions.

B.1.15 Test 15: Device Encryption

Objective: Confidentiality, Ease of Management

Description: This analyzes if the device is locally utilizing device-wide encryption, and how difficult it is to use. Device encryption encodes all user data using symmetric encryption keys. Once encrypted, the user must provide credentials upon boot to decrypt user data. Typically, the user only must provide credentials once and further encryption/decryption occurs automatically upon data read and writes. Modern devices utilize dedicated, chip-based, encryption engines or dedicated security hardware-accelerated processors to support real-time processing. Hardware-level separation allows device encryption to occur in physically separate processors than is used by regular system or user processes. Device encryption mechanisms that perform encryption/decryption in hardware reduce exposing encryption keys in system memory. Physical separation reduces the risk of compromising encryption keys.

Two types of encryption are available for most mobile devices, depending on the mobile OS and hardware support. Device functionality behaves differently depending on the type of encryption used. One is not necessarily better or worse than the other regarding file system security but may alter the user experience. The type of encryption on a mobile device is hardware-dependent and typically not configurable by the user. For more information about Android encryption refer to Android's developer web documentation. [49]

- File-based encryption only encrypts user files, which allows for partial phone functionality before decryption. File-based encryption allows for the device to receive calls and/or make emergency calls before credentials are entered. Multiple keys can be used to provide independent encryption of files, which is useful in multi-user configurations or in high-confidential scenarios where additional protections are required.

- Full-disk encryption uses only a single key to protect user data stored on the device. User data as well as system data is encrypted and can only be unlocked at boot. The device is not usable until an authenticating mechanism, such as a password, is used to unlock the data.

Test Outcome: All of the DUTs supported file-based encryption. Encryption options were prompted upon initial device setup, however, configuration for encryption was present in the device’s security settings.

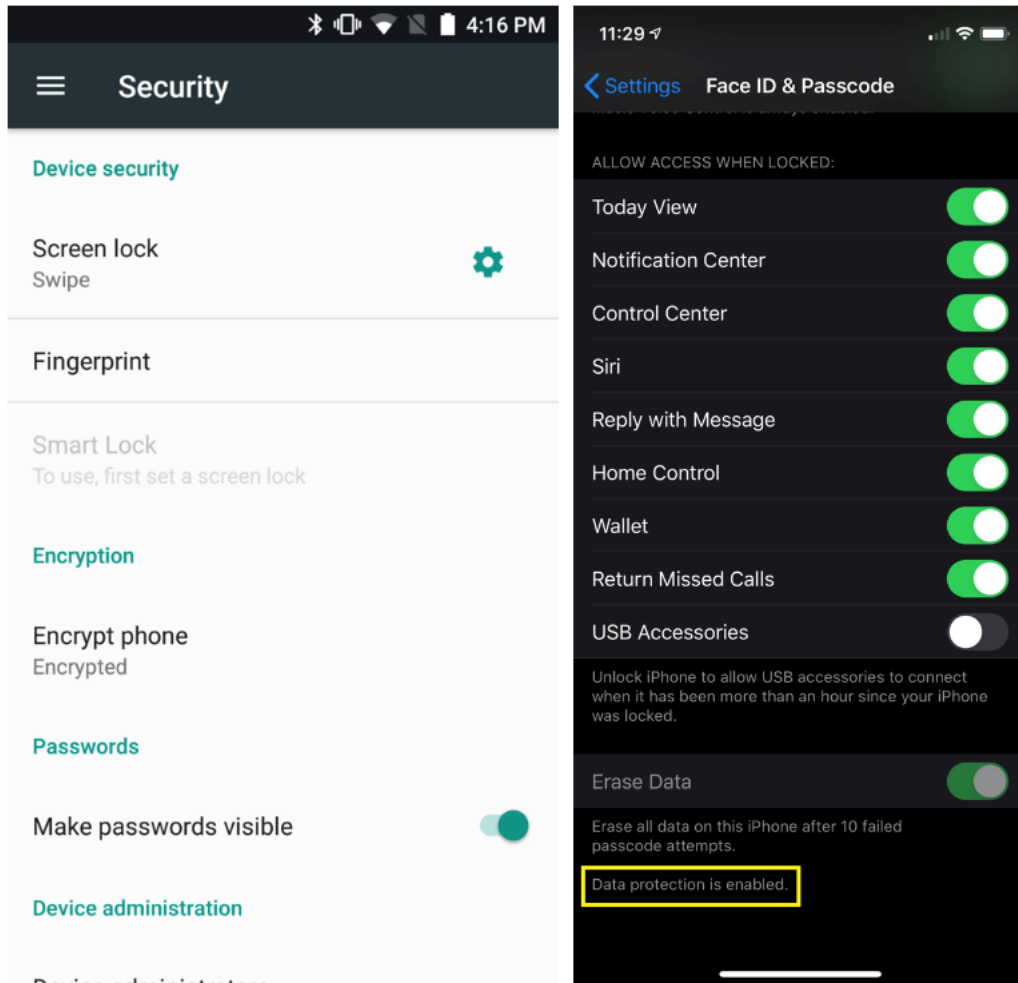


Figure 35 - (Left) Android device encryption settings. (Right) Apple iOS device data protection settings

Figure 36 shows an Android device’s security settings confirming encryption and an Apple iOS device confirming encryption settings “Data protection is enabled.” Neither device specifies what type of encryption is being used.

Analysis: All modern mobile handsets contain some form of device encryption. Apple iOS introduced forms of encryption and digital signing in early versions of its operating system. Digital signing of applications was mimicked after app store implementations were introduced in iPod devices. Encryption was introduced in iOS version 4, such as encryption on lock screen and application-specific data protection. Modern mobile devices include encryption as an initial deployment option and are recommended to the user on initial setup. Encryption is easy to set up, however it requires that the user implement stronger authentication methods. Stronger authentication ensures that encryption cannot be bypassed through brute force. Modern mobile devices incorporate multiple authentication methods. However, it is always important to understand that a strong password or PIN is recommended on most devices. Even if a biometric authentication method is used, such as fingerprint or facial recognition, a PIN or password is required to unlock a device at power-on/reset. Choosing a sufficiently strong password or PIN is important to ensuring strong device encryption. What is suitably strong also depends on device capabilities. Devices that include hardware-backed key stores for device encryption greatly reduce the risk of brute force attacks on the device encryption keys, particularly when these devices automatically delete locally stored mobile data after too many successive failed password/PIN attempts.

Gaps : No observable gaps were found concerning data and device encryption. Vendor guidance provided clear configuration instructions, where possible. Since encryption is offered during device setup, it is easily user-configurable. Online resources through the vendor or OS manufacturer offered clear instructions on how to set up encryption or where to check the status of the device's encryption. App-based encryption and configuration varies according to the app developer, this is not considered a notable gap for the device.

Guidance: Out-of-the-box most devices are encrypted, however, devices that are not encrypted have setup wizards that provide the option to encrypt the device upon initial setup. It is recommended to enable device encryption whenever possible. Application or app-based specific encryption is only recommended in situations where greater data privacy is required, e.g. evidence data, state secrets, or personally identifiable data. App-based encryption is not typical or available for every app and is usually implemented by the app developer. The level and degree of encryption and authentication complexity is also dependent on the device use, user role, and privacy requirements. Device encryption can be enabled through the setup menu of the device, typically under the security configuration section. On Apple IOS devices, encryption configuration can be found under Settings, Touch ID & Passcode, or Face ID & Passcode.

Mobile device data encryption is only as good as the authentication methodology for access control. When possible, complex passwords should be used for encryption. This password should include complex alphanumeric passwords instead of numeric pin. Passwords should contain special characters, both lower and capital letters, numbers and should not contain dictionary-based, easily guessable words. Consider obtaining mobile devices with hardware-embedded key stores for data encryption and enabling features that perform factory resets after 10 failed attempts, if appropriate for the user environment. After the device is fully booted and decrypted, alternative authentication methods can be used to “unlock” the device screen during normal use. For public safety applications, users need to ensure that the device is fully booted and authenticated to ensure rapid access to the device is available.

Benefits : Data Encryption ensures the confidentiality of user or system data if the device is physically compromised. If the device is lost or stolen, data on the device cannot be retrieved unless the proper passcode or key is presented to unencrypt the data. While the device may be reused, the data cannot be retrieved due to the data being encoded. If key passcodes are lost, data cannot be retrieved, and the device must either be factory defaulted or the application reinstalled. Data encryption can also protect app specific data from other potential malicious apps on devices that support file-based encryption.

B.2 Wearable Devices

B.2.1 Test 1: Obtain General Hardware Information

Security Objective: Ease of Management

Test Description: This test will identify information about the device, and how easy it is to obtain that information.

Test Procedures: Search for online datasheets and technical documentation for each wearable device to obtain available hardware information and operating specifications. Most information was obtained using the device manufacturer’s webpages and search engines if the information could not be found through the device manufacturer.

Test Outcome: All devices had specific online resources pertaining to the hardware and software specifications of each device. Some devices had specific datasheets that listed all the hardware components and manufacturer information while others listed the ranges of operating conditions that the device would be able to handle. Overall, the information gathered about each device was sufficient to understand what sensors and components the device had as well as its hardware capabilities.

Analysis: Most of the information about devices was readily available. The information sheets varied in the amount of detail and types of data provided. The data ranged from specifications on the hardware and software to general marketing information about the product. Devices that were accompanied by technical datasheets could be more thoroughly examined since they often included important information about software versions and hardware components that may have been difficult to obtain through other means, since most wearable devices do not have an operating system to interact with.

Gaps: Some devices had more descriptive datasheets than others, so we were not able to get all the important information we would have liked to have about each device through reading these datasheets.

Guidance: Public Safety device administrators should have the device hardware information for asset management and resource awareness. Device manufacturers should ensure hardware information is readily available on the device, online, or in the device manual.

Benefits: Hardware data sheets allow public safety device administrators to be aware of the device information, such as the make and model. This information is important for general awareness, auditing inventory, and asset management. This information is also useful if any issues are identified with a specific make or model of device (e.g., recall or identify information about the device based on hardware datasheets that can give awareness to information (e.g., the device make and model).

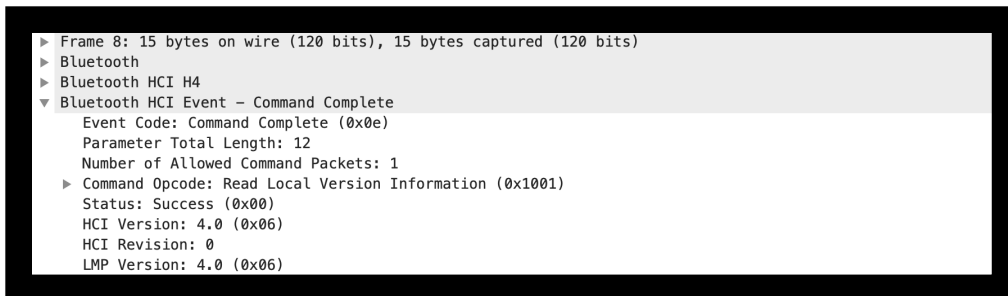
B.2.2 Test 2: Obtain General Software Information

Security Objective: Ease of Management

Test Description: This test will identify the name and software version of operating system and major applications that are shipped with the device. Note that this is much more difficult on a wearable device than on a mobile device, and NIST engineers will not be performing firmware and binary extraction activities. This will also attempt to understand the protocol versions for the primary wireless protocols (i.e., Wi-Fi, Bluetooth, and Cellular). This test will also investigate the use of wearable specific protocols such as Near field communications (NFC) and LoRa.

Test Procedures: Software information about each wearable device was obtained using the device datasheets obtained from the device manufacturer or through packet captures. More recent versions of Bluetooth carry more comprehensive security capabilities, so identifying the version of Bluetooth used by the device is indicative of what security measures the device is capable of supporting. Some devices had the version of Bluetooth and Wi-Fi being used listed in their technical documentation. Other devices did not have this information readily available, so the information needed to be obtained through examining a packet capture for an attempted connection to the device using Bluetooth. Versions of Bluetooth past version 4.0 usually contain a packet that identifies the version of Bluetooth that the device is using even if a successful connection to the device cannot be made.

Test Outcome: All devices examined either used Bluetooth or Wi-Fi, with some devices using both for different purposes. The versions of Bluetooth being used by each device varied since Bluetooth is designed to be backwards compatible with earlier versions. All devices using Bluetooth exclusively used at least Bluetooth version 2.1 which was the first version of Bluetooth to enforce using encrypted key exchange between devices.



```
▶ Frame 8: 15 bytes on wire (120 bits), 15 bytes captured (120 bits)
▶ Bluetooth
▶ Bluetooth HCI H4
▼ Bluetooth HCI Event - Command Complete
  Event Code: Command Complete (0x0e)
  Parameter Total Length: 12
  Number of Allowed Command Packets: 1
  ▶ Command Opcode: Read Local Version Information (0x1001)
    Status: Success (0x00)
    HCI Version: 4.0 (0x06)
    HCI Revision: 0
    LMP Version: 4.0 (0x06)
```

Figure 36 - Example packet capture used to identify Bluetooth version

Analysis: Most of the wearable devices examined do not contain an operating system since they were not designed to be interacted with directly. Therefore, to identify versions of Bluetooth being used you need to examine datasheets that accompany the device or identify the information through attempting to pair with the device. From examining device pairings, we could find the Bluetooth version directly if the exchange contained a ‘Read Remote Version Information’ packet sent by the controller or a ‘Read Local Version Information’ packet sent by the host. Both of these packets contain a “LMP version number” field that corresponds to the Link Manager Protocol (LMP) Version Number. This version number has a corresponding mapping to what version of Bluetooth is being used by the device. If the device pairing did not contain either of these packets, we could check the exchange to see if simple pairing mode was enabled, which indicates that the device is at least using Bluetooth version 2.1.

Gaps: Some older versions of Bluetooth do not require that the device list its version number when pairing, so we were not able to list a specific version of Bluetooth for all devices. However, if the devices were using Secure Simple Pairing, we could assume that the version being used was at least 2.1.

Guidance: Software information should be available to device owners to understand the device capabilities (e.g., available network protocols, compatible applications, operating system). For first responders, additional information about the specifics of the network protocols should be provided. For example, with Bluetooth, the device owner should have the information about what version of Bluetooth is being used and what security levels are enabled within the device.

Benefits: Devices that use newer versions of Bluetooth can utilize more security features that have been built into the pairing mechanisms between devices. Recognizing the differences between versions of Bluetooth can encourage public safety organizations to purchase devices that clearly state the software specifications for the devices they are using to ensure that they have the capabilities necessary to meet their security objectives (e.g., confidentiality, integrity, and availability).

B.2.3 Test 3: Device Ruggedization Ratings

Security Objective: Availability

Test Description: This will identify the IP ratings and any other information available for the device.

Test Procedures: Most devices were accompanied by datasheets and technical documentation that contained ruggedization information, specifically IP ratings and operating temperatures. Examining the IP ratings and operating temperatures in this documentation was sufficient to determine what physical limitations the device had.

Test Outcome: Most wearable devices were accompanied by IP ratings in their technical documentation, with varying capabilities when it came to dust and water protection. The least protected wearable devices had protection against limited dust ingress and low-pressure water jets, while the best protected wearables had protection for total dust ingress and were submersible up to 1 meter in water. Most wearable devices had relatively durable operating temperatures, with some allowing devices to operate at temperatures below 0° F and as high as 122°F. Some of the wearable devices examined contained drop tests as well and had varying results between 6 to 10 feet. Some devices did not contain significant technical documentation information like operating temperatures and IP ratings could not be obtained.

Analysis: Most wearable devices have significant durability because they were built for everyday use. Wearable devices that have little to no protection against dust and water are limited in where and how they can be used effectively, so most wearable devices are required to have a certain level of protection that allow for them to be used by consumers wherever possible. This makes them particularly useful for public safety professionals because wearable devices need to be durable and dependable for public safety professionals to incorporate them into their jobs. Devices that can withstand extreme operating temperatures and have significant protection against water are particularly useful since they can be used in most climates that a public safety professional will experience. It is important for device manufacturers to provide easy access to this information so consumers can evaluate the conditions that the wearable device can handle and decide whether the device will be capable of withstanding the environment that it will be placed in when used.

Gaps: Some devices did not contain IP ratings and operating temperature ranges in their technical documentation, so the durability of these wearable devices could not be evaluated. Providing these details in technical documents can be very important for public safety professionals to determine whether or not they can be used.

Guidance: Public safety device administrators should be aware of their ruggedization ratings for their wearable devices. These devices are typically worn on a first responder's body and may be more exposed to elements than other devices/sensors. It is important to understand what ruggedization ratings mean for wearable devices since they are intended to be used in a variety of conditions so these ratings could directly affect their reliability in the field.

Benefits: Devices that have a wider range of operating temperatures, significant dust ingress protection, and water protection are more dependable for public safety professionals to use in their everyday tasks. Better protection also means that these devices can be used in more significant ways that could help public safety professionals have better tools to work with in situations with bad weather conditions or in unsafe environments.

B.2.4 Test 4: Obtaining Vulnerability Information from OS Information

Security Objective: Integrity, Device & Ecosystem Health

Test Description: This test will have NIST engineers manually check the software versions of the OS that shipped within the device against a list of vulnerabilities within public databases to understand the types of vulnerabilities already known within the OS. These will include the National Vulnerability Database (NVD), VulnDB, and the vulnerability bulletins from Apple, Google, and the public safety handset manufacturers [50]. Engineers will look to understand the impact and criticality of all the known vulnerabilities.

Test Procedures: Researchers could extract version information pertaining to Bluetooth from each device by parsing packet captures using Python. Bluetooth versions earlier than 4.0 do not include the “Low Energy” additions to the protocol so devices that used these earlier versions were identified as having potential vulnerabilities.

Test Outcome: Most devices used versions of Bluetooth that supported Secure Simple Pairing, which would indicate that the device supported at least Bluetooth version 2.1. This version of Bluetooth allows for encryption key sizes to be negotiated, so an attacker can negotiate a smaller key size in an effort to help them break the encryption set up by Secure Simple Pairing. In addition, mutual authentication may not be required with this and versions of Bluetooth prior to 3.1. The “Just Works” pairing method was observed in most devices, since it requires the least number of security features to be enabled, however this method of pairing provides no PitM protection. Devices that use this method for pairing, even in versions of Bluetooth up to 4.2, are susceptible to a PitM where an attacker can obtain the authentication and encryption key(s) from each device and observe and inject Bluetooth packets between devices. Devices using Bluetooth versions prior to 4.0 also use the E0 stream cipher, which is not a FIPS-approved algorithm and is replaced with the FIPS-approved AES-CCM encryption algorithm in later versions.

Analysis: Through observing packet captures, information about the version of Bluetooth being used by the device and security features that were enabled could be extracted to provide insight into what vulnerabilities the device was likely to have. Most devices using Secure Simple Pairing were using Security Mode 4 but did not have PitM protection enabled. Most wearable devices are not built with a display to show a passkey to users, so enabling PitM protection would require the device to have a static pin number that it can use to set up this protection with the controlling device. Devices using a version of Bluetooth greater than 4.0 use the latest authentication, encryption, and key pairing mechanism that contains the same limitation, so device manufacturers need to ensure that PitM protection can be enabled through using a static pin number and the “Passkey” pairing method as opposed to the “Just Works” pairing method. Device manufacturers should use device-specific passkeys that should not be obvious or included in technical documentation since attackers can easily find what the passkey is and disable the PitM protection. If the device is capable of supporting a display, the passkey should vary with each pairing attempt to not be using a static passkey, and if not the static passkey should be specific to the device and provided with the device upon purchase. Bluetooth was designed to be backwards compatible with earlier versions of itself, which means that devices will commonly try to connect using legacy methods that can possibly be less secure than more current implementations.

Gaps: Prior to Bluetooth version 4.0, there was not an explicit packet that designated what version of Bluetooth was being used in the device’s pairing process. Since Secure Simple Pairing was introduced in version 2.1, we can only assume that the devices are using at least version 2.1 when the “Read Remote Version Information” or “Read Local Version Information” packets are not present in a packet capture of a device’s pairing process.

Guidance: Public safety device administrators should be aware of the Bluetooth version used on their wearable devices and the potential vulnerabilities with using a particular version. PSCR Engineers performed packet captures to obtain the Bluetooth version. It would be helpful if this information was provided by the manufacturer within the device manual. With this information, a device administrator can identify and assess the risk of using that device.

Attackers will often intentionally display or use an earlier version of Bluetooth to force the device to authenticate and pair using a less secure process, so device manufacturers need to take this into account when evaluating the security of their wearable devices. Device manufacturers need to carefully observe what “Security Mode” their device will downgrade to when the controlling device does not support a recent or commonly used version of Bluetooth, in order to make sure that there is no situation where the device can be connected to and used with low to no security measures.

Benefits: Identifying a device’s Bluetooth version and pairing mechanisms gives an in-depth view on what security measures the device can support and what measures it has enabled. Earlier versions of Bluetooth have significant vulnerabilities that are somewhat addressed in more recent versions of Bluetooth but are not always enabled or enforced by default. Using packet captures also allows researchers to perform an unbiased analysis of the device and allows for providing additional information about the device’s capabilities along with what may or may not be present in a device’s technical documentation.

B.2.5 Test 5: Bluetooth Pairing

Security Objective: Authentication

Test Description: This test will identify how the wearable device pairs and authenticates to a mobile device, such as the use of an insecure pairing mechanism. Investigate any encryption, privacy protections, device names, and insecure pairing types.

Test Procedures: To examine authentication mechanisms packet captures were examined between wearable devices and the mobile devices that contained software to be able to interact with them. Many wearable devices are accompanied by third party applications, so capturing packets gave the opportunity to examine how the wearable device would attempt to authenticate when being used as intended. To facilitate identifying authentication information in packet captures, automation methods using Python were implemented to extract meaningful information related to device version information and flags that were enabled during pairing such as secure simple pairing, PitM protection, and out of band information. The presence of these fields in each packet determines the level of privacy protection that the wearable device will use and is an indicator for what kind of encryption the device will use as well.

Test Outcome: All of the wearable devices contained an authentication mechanism, although how this mechanism was implemented varied depending on what version of Bluetooth the device was using. Some devices did not use Bluetooth at all, since they contained a wireless networking interface that they could use to access all of their components over the local area network. In this case the devices used WPA2 passwords to handle authentication, but packet payload encryption was not available for all devices. Devices that primarily used Bluetooth to communicate enforced authentication through Bluetooth's simple pairing mode, which will set up a symmetric key between each device upon pairing. Before the symmetric key is established between the devices, the host device sends a user confirmation request packet to the controller device. The controller device then needs to respond with the corresponding link key to authenticate to the host device.

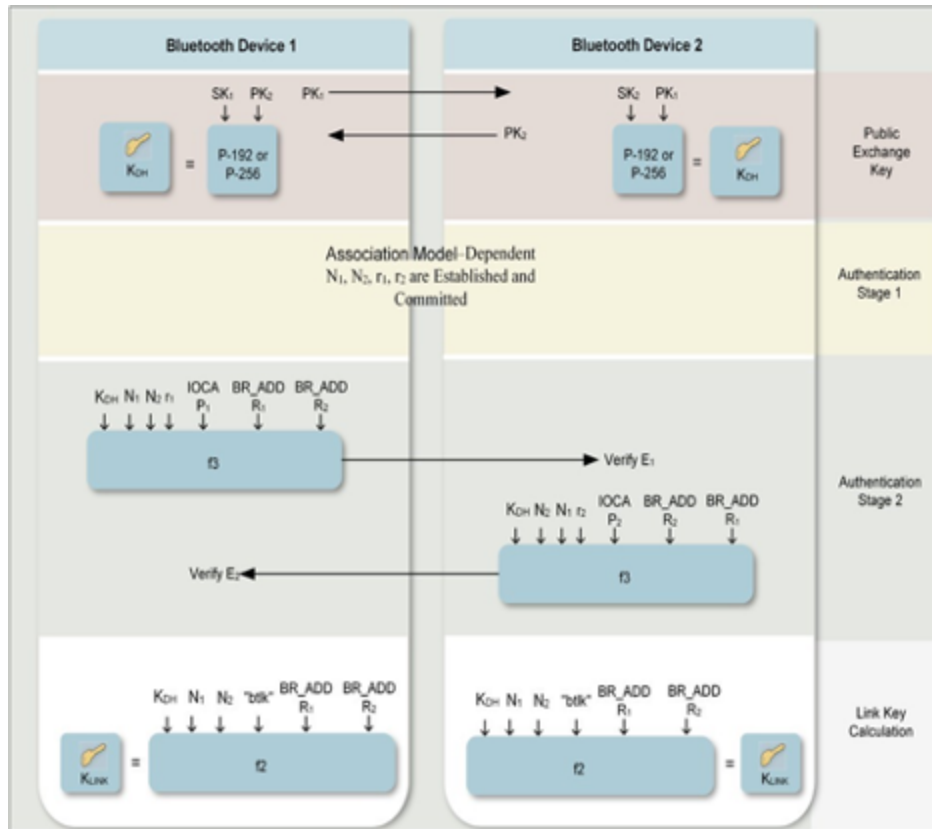


Figure 37 - Link Key Establishment for Secure Simple Pairing (NIST SP 800-121) [51]

If the link key is not provided, then the device will either set up a new connection or refuse to pair with the controller device depending on its authentication requirements. Most of the devices used secure simple pairing to handle authentication, however some appeared to be using Bluetooth's Generic Attribute Profile (GATT) to only handle service level access restrictions. Devices that were compatible with Bluetooth Low Energy (BLE) handled authentication through the low energy pairing process, where identity keys for each device are used among a set of additional keys to calculate a long-term key that is used to verify each device's identity.

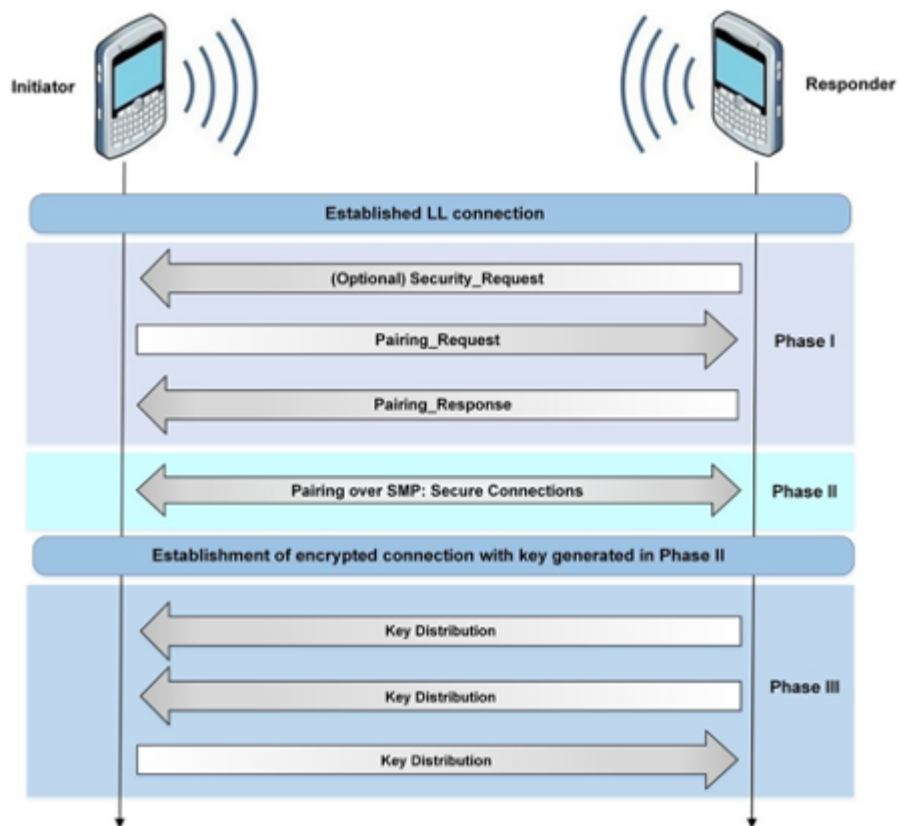


Figure 38 - Bluetooth Low Energy Secure Connections Pairing (NIST SP 800-121) [51]

Analysis: The pairing exchanges for every device could be observed and every device could be successfully paired with, however the version of Bluetooth being used by the device and its input capability determined what kind of authentication would be used. Devices that do not have an interface for a user to interact with cannot require the user to input a PIN number or passcode since there is no way to enter this information, so the device has to either take a predetermined pin code or use an alternative method for handling authentication. Wearable devices using secure simple pairing handle authentication through using a link key and a random number which is calculated during the pairing exchange, so when a host reconnects the controller device can verify its identity. However, the authentication requirements of the controller device can allow for varying restrictions on devices that do not authenticate correctly, from automatically accepting a new connection to refusing a connection with the host device. Secure simple pairing also does not provide PitM protection since a single link key is calculated between the devices, so Bluetooth version 4.0 and above have adapted a more robust pairing mechanism to authenticate devices. This pairing mechanism for host and controller devices and involves creating a “long term key” from a series of key exchanges between the devices. These key exchanges allow the devices to handle authentication by securely sending keys from one device to the other, instead of the devices calculating them individually. Bluetooth versions 4.0 and newer can provide PitM protection if both devices can display a six-digit code that can be verified by the device user(s), but if the controller device has no display capability then no PitM protection is applied. One device examined used a static PIN code with Bluetooth 4.1 which provides PitM protection, but the code was listed in their technical documentation and could be easily guessed to allow for a successful connection to the device.

Gaps: Bluetooth is designed to be able to successfully pair with devices using older versions of Bluetooth, so when examining the pairing between devices the wearable device may use an older method of pairing if the host device is using an older version of Bluetooth. In addition, the authentication requirements of the wearable device can be set to allow automatically accepting new connections. This is common in wearable devices since they do not have an interface to interact with, so some are built to constantly try to accept new connections without a set number of allowed attempts.

Guidance: Public safety device administrators should be aware of the device pairing process for their IoT devices. This pairing process is often based on the network protocols (discussed in Test B.1.2) available within the device (e.g., Wi-Fi, Bluetooth, NFC, etc.). Device manufacturers should include information about the pairing capabilities within the device manuals and also consider providing different pairing options. By providing information on different device pairing options, this allows public safety officials to enable the authentication process that meets their various needs.

Benefits: It is important that wearable devices used by Public Safety are appropriately authenticated to interact with other Public Safety devices (e.g., mobile devices) and/or public safety resources (e.g., computer-aided dispatch (CAD) systems). Evaluating the pairing between devices highlights the important information being passed between devices when the wearable device is being used, and what steps the device will take to protect the confidentiality, integrity, and availability of this information.

Depending on the emergency incident or scenario, a first responder may require immediate access to communications or resources. With this in mind, it is important for device administrators to understand the device authentication/pairing capabilities and consider the risk of implementing different levels of authentication. Certain authentication mechanisms may require more time and interaction from the user, which can negatively impact a first responders response time to an emergency incident.

Devices that use newer versions of Bluetooth have access to more robust security measures that provide better protection from common attacks on wearable devices. Examining the pairing between host devices and wearable devices can give specific information on what requirements for authentication and encryption wearable devices should have to make full use of the security options in newer versions of Bluetooth.

B.2.6 Test 6: Bluetooth Encryption

Security Objective: Confidentiality, Integrity

Test Description: This test will identify how the wearable device communicates with a mobile device, specifically using encryption. This will include the use of secure algorithm, reasonable key sizes, and any PitM protection.

Test Procedures: Similar to the previous authentication testing, automated parsing of packet captures using Python was used to test for encryption mechanisms in wearable devices. When a wearable Bluetooth device pairs with a host device an encryption scheme is determined based on the corresponding versions of each device and the method for authentication. Encryption information could be extracted from packet captures if flags were set during the pairing process such as secure simple pairing, out of band pairing, or PitM protection enabled since a Bluetooth device will examine these flags and choose a certain encryption method in versions under 4.0. Later versions of Bluetooth use a more complicated process which uses multiple temporary encryption keys to calculate a long-term encryption key, so encryption information can be extracted from multiple packets that carry these encryption keys.

Test Outcome: All devices pairing using Secure Simple Pairing enforced link level encryption using a shared link key, with some devices explicitly setting an encryption key size when paired with. The pairing exchanges between devices do not mention specific algorithms being used to generate keys but does indicate whether encryption is enabled and provides a code that indicates what type of encryption key was used to encrypt the data. Secure simple pairing uses Elliptic-Curve Diffie Hellman (ECDH) public key cryptography to generate key pairs between devices starting with version 2.1 and includes four levels of link key authentication that services on Bluetooth devices can enforce (see Figure 27).

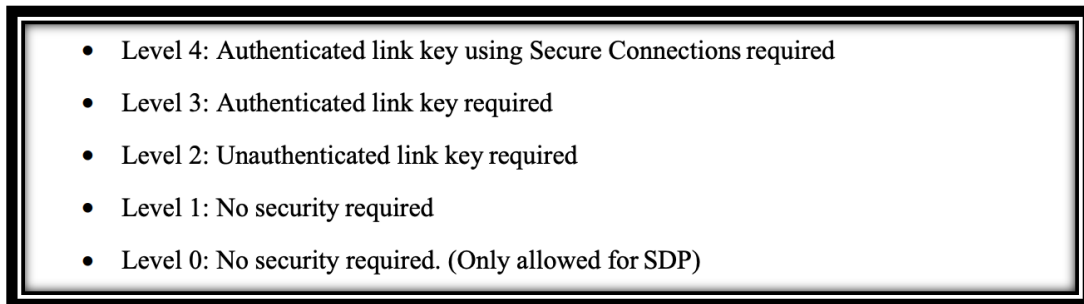
- 
- Level 4: Authenticated link key using Secure Connections required
 - Level 3: Authenticated link key required
 - Level 2: Unauthenticated link key required
 - Level 1: No security required
 - Level 0: No security required. (Only allowed for SDP)

Figure 39 - Security Requirements for Services Protected by Security Mode 4 (NIST SP 800-121) [51]

All of the devices examined using Secure Simple Pairing enforced unauthenticated link keys, which would correspond to Security Level 2. Security Level 1 corresponds to no security at all, Security Level 3 enforces using authenticated link keys, and Security Level 4 enforces using Secure Connections. All devices examined used Bluetooth versions 2.1 to 4.0, which corresponds to using the Bluetooth E0 encryption algorithm, which uses the 128-bit link key, 128-bit random number, and an encryption key to encrypt packet data. Newer versions of Bluetooth do not use the E0 algorithm because it is not FIPS-approved and is considered a weak algorithm for encryption in comparison to newer algorithms developed for use in low power wearable devices. Bluetooth Low Energy (BLE) and versions of Bluetooth after 4.1 use a stronger encryption algorithm called Advanced Encryption Standard-Counter with Cipher Block Chaining Message Authentication Code (AES-CCM) which is FIPS approved and helps to resolve a lot of the shortcomings of the E0 algorithm. PitM protection was not enabled with most of the wearable devices since Bluetooth depends on the user being able to enter or verify a numerical PIN, and most wearable devices do not contain the ability to enter data through a keyboard. One device set a static PIN for use with the BLE Secure Connections pairing, which provides PitM protection but makes the static pin easy to guess through a brute force attack or easily identified in user manuals. Key sizes for devices ranged between 7 and 16 bytes for encryption keys, some of which were set by the controller device during pairing.

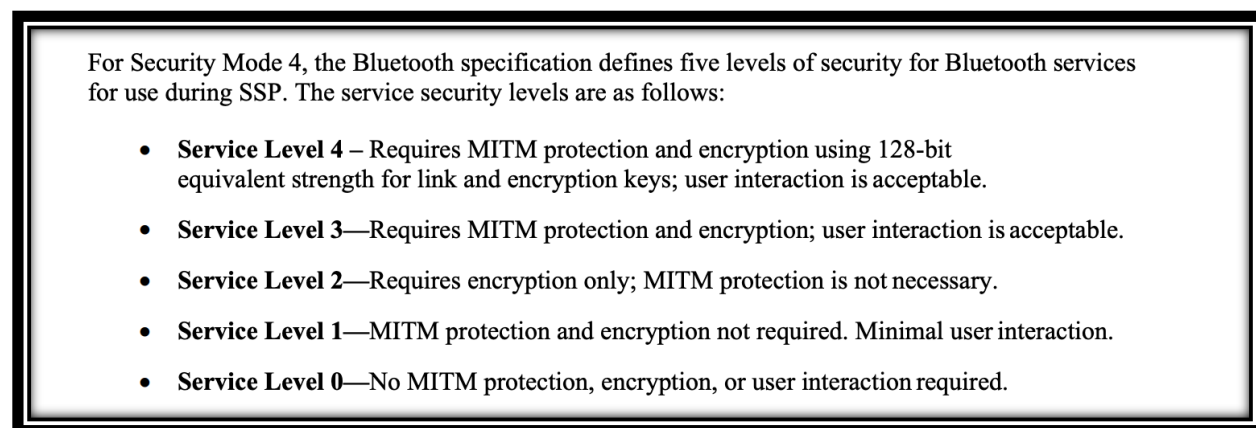


Figure 40 - Secure Simple Pairing Service Levels (NIST SP 800-121) [51]

Analysis: The strength and reliability of Bluetooth encryption algorithms is directly related to the pairing mechanisms being used between devices, and many of the inputs for encryption schemes come from outputs of authentication during pairing. With later versions of Bluetooth come more robust pairing schemes which lead to stronger and more reliable encryption algorithms, so keeping up to date with the latest versions of Bluetooth becomes vitally important for protecting the confidentiality of data passing between wearable and mobile devices. Even between the latest three versions of Bluetooth there have been significant improvements to the encryption algorithm being used as well as the authentication mechanisms that Bluetooth uses.

Using more recent versions of Bluetooth also provides additional capabilities when it comes to protecting data integrity. Devices using Secure Simple Pairing only generate a link key that is used to encrypt and decrypt data, but the ability to cryptographically sign packets to ensure they have not been altered in transit after the pairing process is complete did not become available until Bluetooth Low Energy was introduced in version 4.0. This updated version introduced a Connection Signature Resolving Key (CSRK) that is generated from the same pairing process that creates Long Term Key (LTK) that is used for authentication. This CSRK can be used by the device sending data packets to sign them and the signature can be verified by the receiving device to provide additional data integrity protection.

Gaps: If wearable devices do not have the ability to input a numeric PIN for Security Level 4 then they cannot provide PitM protection and have to fall back to using the “Just Works” pairing mechanism. In addition, the ability to have no limit on the attempts made to pair with a device means that an attacker can continually attempt to pair with a device to try to extract any information about encryption or authentication. To determine the Bluetooth encryption levels, PSCR Engineers performed network traffic analysis. This information was not easily available in the device documentation and would require public safety officials to inquire about the device encryption information.

Guidance: Wearable devices that use the classic implementation of Bluetooth should strive to use the latest version of Bluetooth since it includes significant updates to encryption and authentication that are available in Bluetooth Low Energy capable devices. Where applicable, wearable devices should also use Security Level 4 which implements secure connections for both BLE and BDR implementations but be mindful that using secure connections does not guarantee PitM protection.

Benefits: Strong encryption algorithms help to protect vital user data for wearable devices, such as devices that measure a user’s vital signs or record what a user is doing while working as a public safety professional. First responders, such as law enforcement may need to keep their location and activities confidential during an operation. Using robust pairing and strong encryption algorithms can help to prevent an attacker from being able to gain access to this data without proper authentication to the device.

B.2.7 Test 7: Configuration Guidance

Security Objective: Integrity, Device & Ecosystem Health, Interoperability

Test Description: This will review the type of guidance provided from the vendor to the public safety professionals, and if any of this is security guidance dedicated to properly owning, operating, and configuring the device for public safety use.

Test Procedures: To identify configuration guidance information, researchers examined user guides and manuals that were shipped with the device. Additionally, researchers examined the vendor’s websites and any additional information that could be found through the vendor’s documentation for each device.

Test Outcome: The wearable devices examined that used Bluetooth did not provide secure configurations guidance, while the wearable devices that included a networking component did. The quality of guidance varied between devices, with some containing simple instructions and suggestions to some devoting entire webpages and videos to secure configuration. The devices that used Bluetooth primarily did not provide secure configuration guidance since most of the configuration details are set within the Bluetooth firmware and could not be changed by the user.

Analysis: Most of the wearable devices that primarily use Bluetooth did not provide secure configuration guidance since most of the configuration is already established in the firmware. This highlights the fact that secure configuration and use has not been a major focus in the development of wearable devices since manufacturers place more emphasis on usability than security. However, secure configuration plays a major role in how Bluetooth devices can use the available security options present in the most recent versions of Bluetooth, so providing mechanisms for enforcing strict authentication and encryption requirements can help a great deal to close some of the security gaps present in wearable Bluetooth devices.

Gaps: Most wearable Bluetooth devices examined do not provide a mechanism for altering the authentication and encryption requirements present in the device from outside the device's firmware.

Guidance: Public safety device administrators should identify the necessary device configurations and apply them prior to providing the devices to their users.

Benefits: Secure configuration guidance can help users to become aware of the security capabilities of the wearable devices in use and can help users to extend enforcing security policies to wearable devices. By applying secure configurations prior to device deployment, this provides the first responder with a device that is secure whilst requiring minimal to no additional configuration that may interfere with their response to an emergency.

B.2.8 Test 8: Wearable Device MAC Address Randomization

Security Objective: Confidentiality

Test Description: This test will identify if the wearable device is utilizing MAC address randomization. This includes the Bluetooth MAC address.

Test Procedures: Bluetooth advertisement packets were collected using Python, which contained Bluetooth MAC addresses of the devices sending advertisements within range of the capturing device. The specific Bluetooth address of the DUT was already known, so a program was developed that would check this known address against the addresses found in advertisement packets to determine if the device was sending its real Bluetooth MAC address in advertisement packets.

Test Outcome: Most devices do not utilize address randomization as their Bluetooth addresses can be found in advertising messages broadcasted to all devices in the local area network.

Analysis: Bluetooth devices with a version prior to 4.0 and not using Bluetooth Low Energy (BLE) do not have the option to randomize hardware addresses in advertising messages. Since most of the devices observed were using older versions of Bluetooth, MAC address randomization was not expected to be observed. Bluetooth devices that use version 4.0 or later have a feature called “LE Privacy” that will replace the hardware address with a random value that changes at a varying timing interval.

Gaps: Most devices examined were using a Bluetooth version earlier than 4.0, so devices in the future may be able to overcome this limitation through enabling the LE Privacy feature present in the latest versions of Bluetooth.

Guidance: Device address randomization is recommended for first responders that may be involved in situations where tracking their location is problematic and could put them in danger. Public safety device administrators should consider the use cases for each device and ensure it has the appropriate security capabilities. If a feature like LE Privacy is necessary, Public Safety device administrators should ensure they are using the appropriate version of Bluetooth with that capability enabled. This device information could be included with the device manual for easy awareness to the device owner. Additionally, it would be useful for an IoT Management Solution to be able to easily extract the device capabilities and present it to the device administrator through their console.

Benefits: Including this kind of randomization into future wearable devices will help to prevent problematic tracking of public safety wearable devices using the hardware address. With this information readily available, device administrators can make informed decisions when considering the use of a device.

B.2.9 Test 9: Device Update Policy

Security Objective: Device & Ecosystem Health

Test Description: This will seek to understand how often the device is scheduled to receive security updates and other software from the vendor. Specifically, the regularity / cadence, type, and reasons for updating the device and applying security patches will be reviewed.

Test Procedures: To identify update policy information, researchers examined the device vendor’s user guides and manuals to see what steps they recommended taking to apply updates and upgrades to each device. When this information could not be found through the device’s documentation the vendor’s website and any additional information that vendor provided was examined.

Test Outcome: Most wearable devices examined do not contain update policies that schedule regular updates for security. The devices examined either did not contain any mechanism to update the device, required that the device be sent back in for updates to be applied, or could only be updated manually using additional applications and software packages that needed to be purchased separately. Since most devices primarily used Bluetooth, they did not contain a way to regularly check for updates through an online provider unless the user had access to an application or tool on a separate device that could check for updates.

Analysis: Wearable devices using Bluetooth cannot manage identifying updates on their own since they do not have a network connection, so scheduling security updates for these devices needs to be managed by another device. Many of the devices examined included applications or command line tools for a host device in the local piconet to handle updating the firmware on devices. While these applications could successfully update the firmware on the wearable devices, they rarely included information on what specific updates were being applied, so users could not be made aware of whether specific versions of components were being upgraded.

Gaps: Wearable devices cannot seek out updates on their own and need a separate application or tool to be able to install the newest versions of firmware available.

Guidance: Public safety device administrators should be aware of any devices update policies to be informed of the following:

- Device update schedule – to plan and ensure updates do not conflict with first responder daily work activities
- Device security updates – to patch vulnerabilities that may leave a first responder’s device vulnerable to attack
- Device functionality updates – to address bug fixes and be aware of any new/removed capabilities provided within the device
- Device support period – to know how long a device is supported and prepare for end-of-life, device disposal, and device refresh.
- Device interoperability changes – to be aware if the update impacts the wearable devices compatibility with applications and different device platforms (e.g., Windows, MacOS, iOS, and Android)
- Applying device update – to understand how the device must be updated (e.g., automatically, manually, or through purchase of a new device)

Benefits: Device update policies can help keep wearable devices stay equipped with the latest versions of Bluetooth that implement the most robust and secure pairing and encryption mechanisms available.