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Mobile Application Single Sign-On:

Improving Authentication for Public Safety First Responders

Volume B:
Approach, Architecture, and Security Characteristics

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The first and second drafts of this publication are available free of charge from
https://www.nccoe.nist.gov/library/mobile-application-single-sign-nist-sp-1800-13-practice-guide

DISCLAIMER

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FEEDBACK

As a private-public partnership, we are always seeking feedback on our practice guides. We are particularly interested in seeing how businesses apply NCCoE reference designs in the real world. If you have implemented the reference design, or have questions about applying it in your environment, please email us at psfr-nccoe@nist.gov.

All comments are subject to release under the Freedom of Information Act.

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NATIONAL CYBERSECURITY CENTER OF EXCELLENCE

NIST CYBERSECURITY PRACTICE GUIDES

ABSTRACT

On-demand access to public safety data is critical to ensuring that public safety and first responder (PSFR) personnel can deliver the proper care and support during an emergency. This necessitates heavy reliance on mobile platforms while in the field, which may be used to access sensitive information. However, complex authentication requirements can hinder the process of providing emergency services, and any delay—even seconds—can become a matter of life or death. In collaboration with NIST'S Public Safety Communications Research (PSCR) Division and industry stakeholders, the NCCoE aims to help PSFR personnel efficiently and securely gain access to mission data via mobile devices and applications.

This practice guide describes a reference design for multifactor authentication (MFA) and mobile single sign-on (MSSO) for native and web applications while improving interoperability among mobile platforms, applications, and identity providers, regardless of the application development platform used in their construction. This guide discusses major architecture design considerations, explains security characteristics achieved by the reference design, and maps the security characteristics to applicable

standards and security control families. For parties interested in adopting all or part of the reference architecture, this guide includes a detailed description of the installation, configuration, and integration of all components.

KEYWORDS

access control; authentication; authorization; identity; identity management; identity provider; relying party; single sign-on

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The Technology Partners/Collaborators who participated in this build submitted their capabilities in response to a notice in the Federal Register. Respondents with relevant capabilities or product components were invited to sign a Cooperative Research and Development Agreement (CRADA) with NIST, allowing them to participate in a consortium to build this example solution. We worked with:

Technology Partner/Collaborator	Build Involvement
Ping Identity	Federation Server
Motorola Solutions	Mobile Applications
Yubico	External Authenticators
Nok Nok Labs	Fast Identity Online (FIDO) Universal Authentication Framework (UAF) Server
StrongKey	FIDO Universal Second Factor (U2F) Server

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1 Summary

The National Cybersecurity Center of Excellence (NCCoE), with the National Institute of Standards and Technology's (NIST's) Public Safety Communications Research lab, is helping the public safety and first responder (PSFR) community address the challenge of securing sensitive information accessed on mobile applications. The Mobile Application Single Sign-On (SSO) Project is a collaborative effort with industry and the information technology (IT) community, including vendors of cybersecurity solutions.

This project aims to help PSFR personnel efficiently and securely gain access to mission-critical data via mobile devices and applications through mobile SSO, identity federation, and multifactor authentication (MFA) solutions for native and web applications by using standards-based commercially available and open-source products.

The reference design herein

- provides a detailed example solution and capabilities that address risk and security controls
- demonstrates standards-based MFA, identity federation, and mobile SSO for native and web applications
- supports multiple authentication methods, considering unique environmental constraints faced by first responders in emergency medical services, law enforcement, and fire services

1.1 Challenge

On-demand access to public safety data is critical to ensuring that PSFR personnel can protect life and property during an emergency. Mobile platforms offer a significant operational advantage to public safety stakeholders by providing access to mission-critical information and services while deployed in the field, during training and exercises, or when participating in day-to-day business and preparing for emergencies during nonemergency periods. These advantages can be limited if complex authentication requirements hinder PSFR personnel, especially when a delay—even seconds—is a matter of containing or exacerbating an emergency. PSFR communities are challenged with implementing efficient and secure authentication mechanisms to protect access to this sensitive information while meeting the demands of their operational environment.

Many public safety organizations (PSOs) are in the process of transitioning from conventional land-based mobile communications to high-speed, regional or nationwide wireless broadband networks (e.g., First Responder Network Authority [FirstNet]). These emerging 5G systems employ internet protocol-based communications to provide secure and interoperable public safety communications to support initiatives such as Criminal Justice Information Services; Regional Information Sharing Systems; and international justice and public safety services, such as those provided by Nlets. This transition will foster critically needed interoperability within and among jurisdictions but will create a significant increase in the number of mobile Android and iPhone operating system (iOS) devices that PSOs will need to manage.

Current PSO authentication services may not be sustainable in the face of this growth. There are needs to improve security assurance, limit authentication requirements that are imposed on users (e.g., avoid the number of passwords that are required), improve the usability and efficiency of user account management, and share identities across jurisdictional boundaries. There is no single management or administrative hierarchy spanning the PSFR population. PSFR organizations operate in a variety of environments with different authentication requirements. Standards-based solutions are needed to support technical interoperability and this diverse set of PSO environments.

1.1.1 Easing User Authentication Requirements

Many devices that digitally access public safety information employ different software applications to access different information sources. Single-factor authentication processes, usually passwords, are most commonly required to access each of these applications. Users often need different passwords or personal identification numbers (PINs) for each application used to access critical information. Authentication prompts, such as entering complex passwords on a small touchscreen for each application, can hinder PSFRs. There is an operational need for the mobile systems on which they rely to support a single authentication process that can be used to access multiple applications. This is referred to as single sign-on, or SSO.

1.1.2 Improving Authentication Assurance

Single-factor password authentication mechanisms for mobile native and web applications may not provide sufficient protection for control of access to law enforcement-sensitive information, protected health information, and personally identifiable information (PII). Replacement of passwords by multifactor technology (e.g., a PIN plus some physical token or biometric) is widely recognized as necessary for access to sensitive information. Technology for these capabilities exists, but budgetary, contractual, and operational considerations have impeded implementation and use of these technologies. PSOs need a solution that supports differing authenticator requirements across the community (e.g., law enforcement, fire response, emergency medical services) and a “future-proof” solution allowing for adoption of evolving technologies that may better support PSFRs in the line of duty.

1.1.3 Federating Identities and User Account Management

PSFRs need access to a variety of applications and databases to support routine activities and emergency situations. These resources may be accessed by portable mobile devices or mobile data terminals in vehicles. It is not uncommon for these resources to reside within neighboring jurisdictions at the federal, state, county, or local level. Even when the information is within the same jurisdiction, it may reside in a third-party vendor’s cloud service. This environment results in issuance of many user accounts to each PSFR that are managed and updated by those neighboring jurisdictions or cloud service providers. When a PSFR leaves or changes job functions, the home organization must ensure that accounts are deactivated, avoiding any orphaned accounts managed by third parties. PSOs need a solution that reduces the number of accounts managed and allows user accounts and credentials issued by a PSFR's home organization to access information across jurisdictions and with cloud services. The ability of one organization to accept the identity and credentials from another organization in the form of an identity assertion is called *identity federation*. Current commercially available standards support this functionality.

1.2 Solution

This NIST Cybersecurity Practice Guide demonstrates how commercially available technologies, standards, and best practices implementing SSO, identity federation, and MFA can meet the needs of PSFR communities when accessing services from mobile devices.

In our lab at the NCCoE, we built an environment that simulates common identity providers (IdPs) and software applications found in PSFR infrastructure. In this guide, we show how a PSFR entity can leverage this infrastructure to implement SSO, identity federation, and MFA for native and web applications on mobile platforms. SSO, federation, and MFA capabilities can be implemented independently, but implementing them together would achieve maximum improvement with respect to usability, interoperability, and security.

At its core, the architecture described in Section 4 implements the Internet Engineering Task Force's (IETF's) Best Current Practice (BCP) guidance found in Request for Comments (RFC) 8252, *OAuth 2.0 for Native Apps* [1]. Leveraging technology newly available in modern mobile operating systems (OSes), RFC 8252 defines a specific flow allowing for authentication to mobile native applications without exposing user credentials to the client application. This authentication can be leveraged by additional mobile native and web applications to provide an SSO experience, avoiding the need for the user to manage credentials independently for each application. Using the Fast Identity Online (FIDO) Universal Authentication Framework (UAF) [2] and Universal Second Factor (U2F) [3] protocols, this solution supports MFA on mobile platforms that use a diverse set of authenticators. The use of Security Assertion Markup Language (SAML) 2.0 [4] and OpenID Connect (OIDC) 1.0 [5] federation protocols allows PSOs to share identity assertions between applications and across PSO jurisdictions. Using this architecture allows PSFR personnel to authenticate once—say, at the beginning of their shift—and then leverage that single authentication to gain access to many other mobile native and web applications while on duty, reducing the time needed for authentication.

The PSFR community comprises tens of thousands of different organizations across the United States, many of which may operate their own IdPs. Today, most IdPs use SAML 2.0, but OIDC is rapidly gaining market share as an alternative for identity federation. As this build architecture demonstrates, an OAuth authorization server (AS) can integrate with both OIDC and SAML IdPs.

The guide provides:

- a detailed example solution and capabilities that may be implemented independently or in combination to address risk and security controls
- a demonstration of the approach, which uses commercially available products
- how-to instructions for implementers and security engineers on integrating and configuring the example solution into their organization's enterprise in a manner that achieves security goals with minimal impact on operational efficiency and expense

Organizations can adopt this solution or a different one that adheres to these guidelines in whole, or an organization can use this guide as a starting point for tailoring and implementing parts of a solution.

Note that since May 2018, when this project build was initially completed at the NCCoE laboratory, some of the products used in the build have migrated to new platforms. In addition, new specifications and standards used by the products have been published and revised. While the general integration concepts demonstrated in this guide still apply, implementers using newer or different products will have to tailor their implementation to meet the specific requirements of those products and specifications. Thus, the implementation details will be different.

1.3 Benefits

The NCCoE, in collaboration with our stakeholders in the PSFR community, identified the need for a mobile SSO and MFA solution for native and web applications. This NCCoE practice guide, *Mobile Application Single Sign-On*, can help PSOs:

- define requirements for mobile application SSO and MFA implementation
- improve interoperability among mobile platforms, applications, and IdPs, regardless of the application development platform used in their construction
- enhance the efficiency of PSFRs by reducing the number of authentication steps, the time needed to access critical data, and the number of credentials that need to be managed
- support a diverse set of credentials, enabling a PSO to choose an authentication solution that best meets its individual needs
- enable cross-jurisdictional information sharing by identity federation

2 How to Use This Guide

This NIST Cybersecurity Practice Guide demonstrates a standards-based reference design and provides users with the information they need to replicate an MFA and mobile SSO solution for mobile native and web applications. This reference design is modular and can be deployed in whole or in part.

This guide contains three volumes:

- NIST Special Publication (SP) 1800-13A: *Executive Summary*
- NIST SP 1800-13B: *Approach, Architecture, and Security Characteristics*—what we built and why **(you are here)**
- NIST SP 1800-13C: *How-To Guides*—instructions for building the example solution

Depending on your role in your organization, you might use this guide in different ways:

Business decision makers, including chief security and technology officers, will be interested in the *Executive Summary* (NIST SP 1800-13A), which describes the following topics:

- challenges that enterprises face in MFA and mobile SSO for native and web applications
- example solution built at the NCCoE
- benefits of adopting the example solution

Technology or security program managers who are concerned with how to identify, understand, assess, and mitigate risk will be interested in this part of the guide, NIST SP 1800-13B, which describes what we did and why. The following sections will be of particular interest:

- Section 3.5, Risk Assessment, provides a description of the risk analysis we performed.
- Appendix A, Mapping to Cybersecurity Framework Core, maps the security characteristics of this example solution to cybersecurity standards and best practices.

You might share the *Executive Summary,* NIST SP 1800-13A, with your leadership team members to help them understand the importance of adopting a standards-based MFA and mobile SSO solution for native and web applications.

Information technology (IT) professionals who want to implement an approach like this will find the whole practice guide useful. You can use the how-to portion of the guide, NIST SP 1800-13C, to replicate all or parts of the build created in our lab. The how-to portion of the guide provides specific product installation, configuration, and integration instructions for implementing the example solution. We do not re-create the product manufacturer's documentation, which is generally widely available. Rather, we show how we incorporated the products together in our environment to create an example solution.

This guide assumes that IT professionals have experience implementing security products within the enterprise. While we have used a suite of commercial products to address this challenge, this guide does not endorse these particular products. Your organization can adopt this solution or one that adheres to these guidelines in whole, or you can use this guide as a starting point for tailoring and implementing SSO or MFA separately. Your organization's security experts should identify the products that will best integrate with your existing tools and IT system infrastructure. We hope you will seek products that are congruent with applicable standards and best practices. Section 3.7, Technologies, lists the products we used and maps them to the cybersecurity controls provided by this reference solution.

A NIST Cybersecurity Practice Guide does not describe "the" solution, but a possible solution. Comments, suggestions, and success stories will improve subsequent versions of this guide. Please contribute your thoughts to psfr-nccoe@nist.gov.

2.1 Typographic Conventions

The following table presents typographic conventions used in this volume.

Typeface/Symbol	Meaning	Example
Italics	file names and pathnames, references to documents that are not hyperlinks, new terms, and placeholders	For detailed definitions of terms, see the *NCCoE Glossary.*
Bold	names of menus, options, command buttons, and fields	Choose **File > Edit.**
`Monospace`	command-line input, onscreen computer output, sample code examples, and status codes	`mkdir`
`Monospace Bold`	command-line user input contrasted with computer output	**`service sshd start`**
blue text	link to other parts of the document, a web URL, or an email address	All publications from NIST's NCCoE are available at https://www.nccoe.nist.gov.

3 Approach

In conjunction with the PSFR community, the NCCoE developed a project description identifying MFA and SSO for mobile native and web applications as a critical need for PSFR organizations. The NCCoE then engaged subject matter experts from industry organizations, technology vendors, and standards bodies to develop an architecture and reference design leveraging new capabilities in modern mobile OSes and best current practices in SSO and MFA.

3.1 Audience

This guide is intended for individuals or entities that are interested in understanding the mobile native and web application SSO and MFA reference designs that the NCCoE has implemented to allow PSFR personnel to securely and efficiently gain access to mission-critical data by using mobile devices. Though the NCCoE developed this reference design with the PSFR community, any party interested in SSO and MFA for native mobile and web applications can leverage the architecture and design principles implemented in this guide.

The overall build architecture addresses three different audiences with somewhat separate concerns:

- IdPs—PSFR organizations that issue and maintain user accounts for their users. Larger PSFR organizations may operate their own IdP infrastructures and may federate by using SAML or OIDC services, while others may seek to use an IdP service provider. IdPs are responsible for identity proofing, account creation, account and attribute management, and credential management.
- Relying parties (RPs)—organizations providing application services to multiple PSFR organizations. RPs may be software-as-a-service (SaaS) providers or PSFR organizations providing shared services consumed by other organizations. The RP operates an OAuth 2.0 AS, which integrates with users' IdPs and issues access tokens to enable mobile applications to make requests to the back-end application servers.
- Application developers—mobile application developers. Today, mobile client applications are typically developed by the same software provider as the back-end RP applications. However, the OAuth framework enables interoperability between RP applications and third-party client applications. In any case, mobile application development is a specialized skill with unique considerations and requirements. Mobile application developers should consider implementing the AppAuth library for IETF RFC 8252 to enable standards-based SSO.

3.2 Scope

The focus of this project is to address the need for secure and efficient mobile native and web application SSO. The NCCoE drafted a use case that identified numerous desired solution characteristics. After an open call in the Federal Register for vendors to help develop a solution, we chose participating technology collaborators on a first-come, first-served basis. We scoped the project to produce the following high-level desired outcomes:

- Provide a standards-based solution architecture that selects an effective and secure approach to implementing mobile SSO, leveraging native capabilities of the mobile OS.
- Ensure that mobile applications do not have access to user credentials.
- Support MFA and multiple authentication protocols.
- Support multiple authenticators, considering unique environmental constraints faced by first responders in emergency medical services, law enforcement, and fire services.
- Support cross-jurisdictional information sharing through identity federation.

To maintain the project's focus on core SSO and MFA requirements, the following subjects are out of scope. These technologies and practices are critical to a successful implementation, but they do not directly affect the core design decisions.

- Identity proofing—The solution creates synthetic digital identities that represent the identities and attributes of public safety personnel to test authentication assertions. This includes the usage of a lab-configured identity repository—not a genuine repository and schema provided by any PSO. This guide will not demonstrate an identity proofing process.
- Access control—This solution supports the creation and federation of attributes but will not discuss or demonstrate access control policies that an RP might implement to govern access to specific resources.
- Credential storage—This solution is agnostic to where credentials are stored on the mobile device. For example, this use case is not affected by storing a certificate in software versus hardware, such as a trusted platform module.
- Enterprise Mobility Management (EMM)—The solution assumes that all applications involved in the SSO experience are allowable via an EMM. This implementation may be supported by using an EMM (for example, to automatically provision required mobile applications to the device), but it does not strictly depend on using an EMM.
- Fallback authentication mechanisms—This solution involves the use of multifactor authenticators, which may consist of physical authentication devices or cryptographic keys stored directly on mobile devices. Situations may arise where a user's authenticator or device has been lost or stolen. This practice guide recommends registering multiple authenticators for each user as a partial mitigation, but in some cases, it may be necessary to either enable users to fall back to single-factor authentication or provide other alternatives. Such fallback mechanisms must be evaluated considering the organization's security and availability requirements.

3.3 Assumptions

Before implementing the capabilities described in this practice guide, organizations should review the assumptions underlying the NCCoE build. These assumptions are detailed in Appendix B. Though not in scope for this effort, implementers should consider whether the same assumptions can be made based on current policy, process, and IT infrastructure. As detailed in Appendix B, applicable and appropriate guidance is provided to assist this process for the following functions:

- identity proofing
- mobile device security
- mobile application security
- EMM
- FIDO enrollment process

3.4 Business Case

Any decision to implement IT systems within an organization must begin with a solid business case. This business case could be an independent initiative or a component of the organization's strategic planning cycle. Individual business units or functional areas typically derive functional or business unit strategies from the overall organization's strategic plan. The business drivers for any IT project must originate in these strategic plans, and the decision to determine if an organization will invest in mobile SSO, identity federation, or MFA by implementing the solution in this practice guide will be based on the organization's decision-making process for initiating new projects.

Important inputs to the business case are the risks to the organization from mobile authentication and identity management, as outlined in Section 3.5. Apart from addressing cybersecurity risks, SSO also improves the user experience and alleviates the overhead associated with maintaining and using passwords for multiple applications. This provides a degree of convenience to all types of users, but reducing the authentication overhead for PSFR users and reducing barriers to getting the information and applications that they need could have a tremendous effect. First responder organizations and application providers also benefit by using interoperable standards that provide easy integration across disparate technology platforms. In addition, the burden of account management is reduced by using a single user account managed by the organization to access multiple applications and services.

3.5 Risk Assessment

NIST SP 800-30 Revision 1 [6], *Guide for Conducting Risk Assessments,* states that risk is "a measure of the extent to which an entity is threatened by a potential circumstance or event, and typically a function of (i) the adverse impacts that would arise if the circumstance or even occurs; and (ii) the likelihood of occurrence." The guide further defines risk assessment as "the process of identifying, estimating, and prioritizing risks to organizational operations (including mission, functions, image, reputation), organizational assets, individuals, other organizations, and the Nation, resulting from the operation of an information system. Part of risk management incorporates threat and vulnerability analyses, and considers mitigations provided by security controls planned or in place."

The NCCoE recommends that any discussion of risk management, particularly at the enterprise level, begins with a comprehensive review of NIST SP 800-37 Revision 2, *Guide for Applying the Risk Management Framework to Federal Information Systems* [7]—material that is available to the public. The risk management framework guidance, as a whole, proved invaluable in giving us a baseline to assess risks, from which we developed the project, the security characteristics of the build, and this guide.

3.5.1 PSFR Risks

As PSFR communities adopt mobile platforms and applications, organizations should consider potential risks that these new devices and ecosystems introduce that may negatively affect PSFR organizations and the ability of PSFR personnel to operate. These are some of the risks:

- The reliance on passwords alone by many PSFR entities effectively expands the scope of a single application/database compromise when users fall back to reusing a small set of easily remembered passwords across multiple applications.
- Complex passwords are harder to remember and input to IT systems. Mobile devices exacerbate this issue with small touchscreens that may not work with gloves or other PSFR equipment, and with three separate keyboards among which the user must switch. In an emergency response, any delay in accessing information may prove critical to containing a situation.
- Social engineering, machine-in-the-middle attacks, replay attacks, and phishing all present real threats to password-based authentication systems.
- Deterministic, cryptographic authentication mechanisms have security benefits, yet come with the challenge of cryptographic key management. Loss or misuse of cryptographic keys could undermine an authentication system, leading to unauthorized access or data leakage.
- Biometric authentication mechanisms may be optimal for some PSFR personnel, yet organizations need to ensure that PII, such as fingerprint templates, is protected.
- Credentials exposed to mobile applications could be stolen by malicious applications or misused by nonmalicious applications. Previously, it was common for native applications to use embedded user-agents (commonly implemented with web views) for OAuth requests. That approach has many drawbacks, including the host application being able to copy user credentials and cookies, as well as the user needing to authenticate again in each application.

3.5.2 Mobile Ecosystem Threats

Any discussion of risks and vulnerabilities is incomplete without considering the threats that are involved. NIST SP 800-150, *Guide to Cyber Threat Information Sharing* [8], states that a cyber threat is "any circumstance or event with the potential to adversely impact organizational operations (including mission, functions, image, or reputation), organizational assets, individuals, other organizations, or the Nation through an information system via unauthorized access, destruction, disclosure, or modification of information, and/or denial of service."

To simplify this concept, a *threat* is anything that can exploit a *vulnerability* to damage an *asset*. Finding the intersection of these three will yield a *risk*. Understanding the applicable threats to a system is the first step in determining its risks.

However, identifying and delving into mobile threats is not the primary goal of this practice guide. Instead, we rely on prior work from NIST's Mobile Threat Catalogue (MTC), along with its associated NIST Interagency Report (IR) 8144, *Assessing Threats to Mobile Devices & Infrastructure* [9]. Each entry in the MTC contains several pieces of information: an identifier, a category, a high-level description, details on its origin, exploit examples, examples of common vulnerabilities and exposures, possible countermeasures, and academic references. For the purposes of this practice guide, we are primarily interested in threat identifiers, categories, descriptions, and countermeasures.

In broad strokes, the MTC covers 32 threat categories that are grouped into 12 distinct classes, as shown in Table 3-1. Of these categories, three in particular, highlighted in green in the table, are covered by the guidance in this practice guide. If implemented correctly, this guidance will help mitigate those threats.

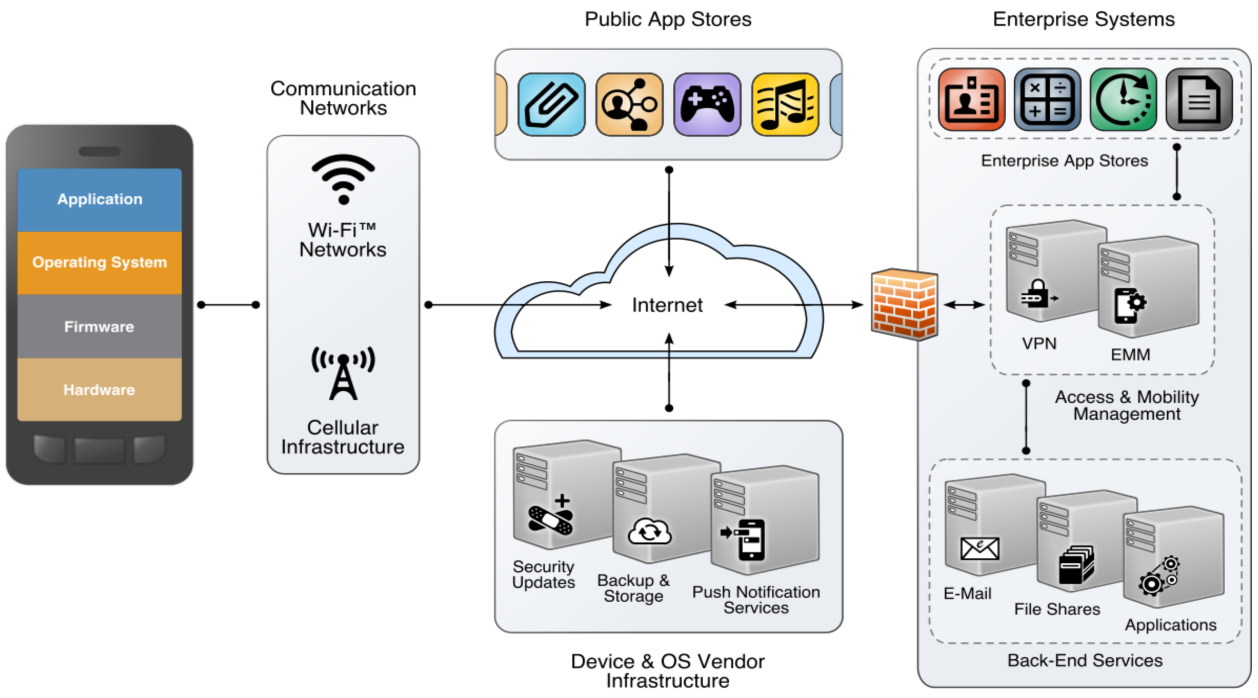
Table 3-1 Threat Classes and Categories

Threat Class	Threat Category
Application	Malicious or Privacy-Invasive Applications
	Vulnerable Applications
Authentication	Authentication: User or Device to Network
	Authentication: User or Device to Remote Service
	Authentication: User to Device
Local Area Network and Personal Area Network	Network Threats: Bluetooth
	Network Threats: Near Field Communication (NFC)
	Network Threats: Wi-Fi
Payment	Application-Based
	In-Application Purchases

Threat Class	Threat Category
Cellular	Carrier Infrastructure
	Carrier Interoperability
	Cellular Air Interface
	Consumer-Grade Femtocell
	Short Message Service (SMS)/Multimedia Messaging Service (MMS)/Rich Communication Services (RCS)
	Unstructured Supplementary Service Data (USSD)
	Voice over Long-Term Evolution (VoLTE)
Ecosystem	Mobile Application Store
	Mobile OS & Vendor Infrastructure
EMM	EMM
Global Positioning System (GPS)	GPS
	NFC-Based
Physical Access	Physical Access
Privacy	Behavior Tracking
Supply Chain	Supply Chain
Stack	Baseband Subsystem
	Boot Firmware
	Device Drivers
	Isolated Execution Environments
	Mobile Operating System
	Secure Digital (SD) Card
	Universal Subscriber Identity Module (USIM)/Subscriber Identity Module (SIM)/Universal Integrated Circuit Card (UICC) Security

The other categories, while still important elements of the mobile ecosystem and critical to the health of an overall mobility architecture, are out of scope for this document. The entire mobile ecosystem should be considered when analyzing threats to the architecture; this ecosystem is depicted in Figure 3-1, taken from NIST IR 8144. Each player in the ecosystem—the mobile device user, the enterprise, the network operator, the application developer, and the original equipment manufacturer (OEM)—can find suggestions to deter other threats by reviewing the MTC and NIST IR 8144. Many of these share common solutions, such as using EMM software to monitor device health, and installing applications from only authorized sources.

Figure 3-1 The Mobile Ecosystem



3.5.3 Authentication and Federation Threats

The MTC is a useful reference from the perspective of mobile devices, applications, and networks. In the context of mobile SSO, specific threats to authentication and federation systems must also be considered. Table 8-1 in NIST SP 800-63B [10] lists several categories of threats against authenticators:

- theft—stealing a physical authenticator, such as a smart card or U2F device
- duplication—unauthorized copying of an authenticator, such as a password or private key
- eavesdropping—interception of an authenticator secret when in use
- offline cracking—attacks on authenticators that do not require interactive authentication attempts, such as brute-force attacks on passwords used to protect cryptographic keys
- side-channel attack—exposure of an authentication secret through observation of the authenticator's physical characteristics

- phishing or pharming—capturing authenticator output through impersonation of the RP or IdP
- social engineering—using a pretext to convince the user to subvert the authentication process
- online guessing—attempting to guess passwords through repeated online authentication attempts with the RP or IdP
- end point compromise—malicious code on the user's device, which is stealing authenticator secrets, redirecting authentication attempts to unintended RPs, or otherwise subverting the authentication process
- unauthorized binding—binding an attacker-controlled authenticator with the user's account by intercepting the authenticator during provisioning or impersonating the user in the enrollment process

These threats undermine the basic assumption that use of an authenticator in an authentication protocol demonstrates that the user initiating the protocol is the individual referenced by the claimed user identifier. Mitigating these threats is the primary design goal of MFA, and the FIDO specifications address many of these threats.

An additional set of threats concerns federation protocols. Authentication threats affect the process of direct authentication of the user to the RP or IdP, whereas federation threats affect the assurance that the IdP can deliver assertions that are genuine and unaltered, only to the intended RP. Table 8-1 in NIST SP 800-63C [11] lists the following federation threats:

- assertion manufacture or modification—generation of a false assertion or unauthorized modification of a valid assertion
- assertion disclosure—disclosure of sensitive information contained in an assertion to an unauthorized third party
- assertion repudiation by the IdP—IdP denies having authenticated a user after the fact
- assertion repudiation by the subscriber—subscriber denies having authenticated and performed actions on the system
- assertion redirect—subversion of the federation protocol flow to enable an attacker to obtain the assertion or to redirect it to an unintended RP
- assertion reuse—attacker obtains a previously used assertion to establish his own session with the RP
- assertion substitution—attacker substitutes an assertion for a different user in the federation flow, leading to session hijacking or fixation

Federation protocols are complex and require interaction among multiple systems, typically under different management. Implementers should carefully apply best security practices relevant to the federation protocols in use. Most federation protocols can incorporate security measures to address these threats, but this may require specific configuration and enabling optional features.

3.6 Systems Engineering

Some organizations use a systems engineering-based approach to plan and implement their IT projects. Organizations wishing to implement IT systems should develop robust requirements, taking into consideration the operational needs of each system stakeholder. Standards such as International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) ISO/IEC/IEEE 15288:2015, *Systems and software engineering—System life cycle processes* [12] and NIST SP 800-160, *Systems Security Engineering: Considerations for a Multidisciplinary Approach in the Engineering of Trustworthy Secure Systems* [13] provide guidance for applying security in systems development. With both standards, organizations can choose to adopt only those sections of the standard that are relevant to their development approach, environment, and business context. NIST SP 800-160 recommends a thorough analysis of alternative solution classes accounting for security objectives, considerations, concerns, limitations, and constraints. This advice applies to both new system developments and integration of components into existing systems, the focus of this practice guide. Section 4.1, General Architecture Considerations, may assist organizations with this analysis.

3.7 Technologies

Table 3-2 lists all of the technologies used in this project and provides a mapping among the generic application term, the specific product used, and the NIST Cybersecurity Framework Subcategory that the product provides. For a mapping of Cybersecurity Framework Subcategories to security controls, please refer to Appendix A, Mapping to Cybersecurity Framework Core. Refer to Table A-1 for an explanation of the Cybersecurity Framework Category and Subcategory codes.

Table 3-2 Products and Technologies

Component	Specific Product Used	How the Component Functions in the Build	Applicable Cybersecurity Framework Subcategories
Federation Server	Ping Federate 8.2	OAuth 2.0 AS OIDC provider SAML 2 IdP	PR.AC-3: Remote access is managed.
FIDO U2F Server	StrongKey Crypto Engine (SKCE) 2.0	FIDO U2F server	PR.AC-1: Identities and credentials are managed for authorized devices and users.

Component	Specific Product Used	How the Component Functions in the Build	Applicable Cybersecurity Framework Subcategories
External Authenticator	YubiKey Neo	FIDO U2F token supporting authentication over NFC	PR-AC-1: Identities and credentials are managed for authorized devices and users.
FIDO UAF Server	Nok Nok Labs FIDO UAF Server	UAF authenticator enrollment, authentication, and transaction confirmation	PR.AC-1: Identities and credentials are managed for authorized devices and users.
Mobile Applications (including SaaS back-end)	Custom demo applications developed by the build team; Motorola Solutions Public Safety Experience (PSX) Cockpit, PSX Messenger, and PSX Mapping 5.2	Provide application programming interfaces (APIs) for mobile client applications to access cloud-hosted services and data; consume OAuth tokens	PR.AC-3: Remote access is managed.
SSO Implementing Best Current Practice	AppAuth Software Development Kit (SDK) for iOS and Android	Library used by mobile applications, providing an IETF RFC 8252-compliant OAuth 2.0 client implementation; implements authorization requests, Proof Key for Code Exchange (PKCE), and token refresh	PR.AC-3: Remote access is managed.

4 Architecture

The NCCoE worked with industry subject matter experts to develop an open, standards-based, commercially available architecture demonstrating three main capabilities:

- SSO to RP applications using OAuth 2.0 implemented in accordance with RFC 8252 (the *OAuth 2.0 for Native Apps* BCP)
- identity federation to RP applications using both SAML 2.0 and OIDC 1.0
- MFA to mobile native and web applications using FIDO UAF and U2F

Though these capabilities are implemented as an integrated solution in this guide, organizational requirements may dictate that only a subset of these capabilities be implemented. The modular approach of this architecture is designed to support such use cases.

Additionally, the authors of this document recognize that PSFR organizations will have diverse IT infrastructures, which may include previously purchased authentication, federation, or SSO capabilities, and legacy technology. For this reason, Section 4.1 and Appendix C outline general considerations that any organization may apply when designing an architecture tailored to organizational needs. Section 4.2 follows with considerations for implementing the architecture specifically developed by the NCCoE for this project.

Organizations are encouraged to read Section 3.2, Section 3.3, Section 3.5, and Appendix B to understand context for this architecture design.

4.1 General Architectural Considerations

The PSFR community is large and diverse, comprising numerous state, local, tribal, and federal organizations with individual missions and jurisdictions. PSFR personnel include police, firefighters, emergency medical technicians, public health officials, and other skilled support personnel. There is no single management or administrative hierarchy spanning the PSFR population. PSFR organizations operate in a variety of environments with different technology requirements and wide variations in IT staffing and budgets.

Cooperation and communication among PSFR organizations at multiple levels is crucial to addressing emergencies that span organizational boundaries. Examples include coordination among multiple services within a city (e.g., fire and police services), among different state law enforcement agencies to address interstate crime, and among federal agencies like the Department of Homeland Security and its state and local counterparts. This coordination is generally achieved through peer-to-peer interaction and agreement or through federation structures, such as the National Identity Exchange Federation. Where interoperability is achieved, it is the result of the cooperation of willing partners rather than adherence to central mandates.

Enabling interoperability across the heterogeneous, decentralized PSFR user base requires a standards-based solution; a proprietary solution might not be uniformly adopted and could not be mandated. The solution must also support identity federation and federated authentication, as user accounts and authenticators are managed by several different organizations. The solution must also accommodate organizations of different sizes, levels of technical capabilities, and budgets. Compatibility with the existing capabilities of fielded identity systems can reduce the barrier to entry for smaller organizations.

Emergency response and other specialized work performed by PSFR personnel often require that they wear personal protective equipment, such as gloves, masks, respirators, and helmets. This equipment renders some authentication methods impractical or unusable. Fingerprint scanners cannot be used with gloves, authentication using a mobile device camera to analyze the user's face or iris may be hampered by masks or goggles, and entering complex passwords on small virtual keyboards is also impractical for gloved users. In addition, PSFR work often involves urgent and hazardous situations requiring the ability to quickly perform mission activities like driving, firefighting, and administering urgent medical aid. Therefore, the solution must support a variety of authenticators in an interoperable way so that individual user groups can select authenticators suited to their operational constraints.

In considering these requirements, the NCCoE implemented a standards-based architecture and reference design. Section 4.1.1 through Section 4.1.3 detail the primary standards used, while Appendix C goes into great depth on architectural consideration when implementing these standards.

4.1.1 SSO with OAuth 2.0, IETF RFC 8252, and AppAuth Open-Source Libraries

SSO enables a user to authenticate once and subsequently access different applications without having to authenticate again. SSO on mobile devices is complicated by the sandboxed architecture, which makes it difficult to share the session state with back-end systems between individual applications. EMM vendors have provided solutions through proprietary SDKs, but this approach requires integrating the SDK with each individual application and does not scale to a large and diverse population, such as the PSFR user community.

OAuth 2.0 is an IETF standard that has been widely adopted to provide delegated authorization of clients accessing representational state transfer interfaces, including mobile applications. OAuth 2.0, when implemented in accordance with RFC 8252 (the *OAuth 2.0 for Native Apps* BCP), provides a standards-based SSO pattern for mobile applications. The OpenID Foundation's AppAuth libraries [14] can facilitate building mobile applications in full compliance with IETF RFC 8252, but any mobile application that follows RFC 8252's core recommendation of using a shared external user-agent for the OAuth authorization flow will have the benefit of SSO. OAuth considerations and recommendations are detailed in Section C.1 of Appendix C.

4.1.2 Identity Federation

SAML 2.0 [4] and OIDC 1.0 [5] are two standards that enable an application to redirect users to an IdP for authentication and to receive an assertion of the user's identity and other optional attributes. Federation is important in a distributed environment like the PSFR community, where user management occurs in numerous local organizations. Federated authentication relieves users of having to create accounts in each application that they need to access, and it frees application owners from managing user accounts and credentials. OIDC is a more recent protocol, but many organizations have existing SAML deployments. The architecture supports both standards to facilitate adoption without requiring upgrades or modifications to existing SAML IdPs. Federation considerations and recommendations are detailed in Section C.2 of Appendix C.

4.1.3 FIDO and Authenticator Types

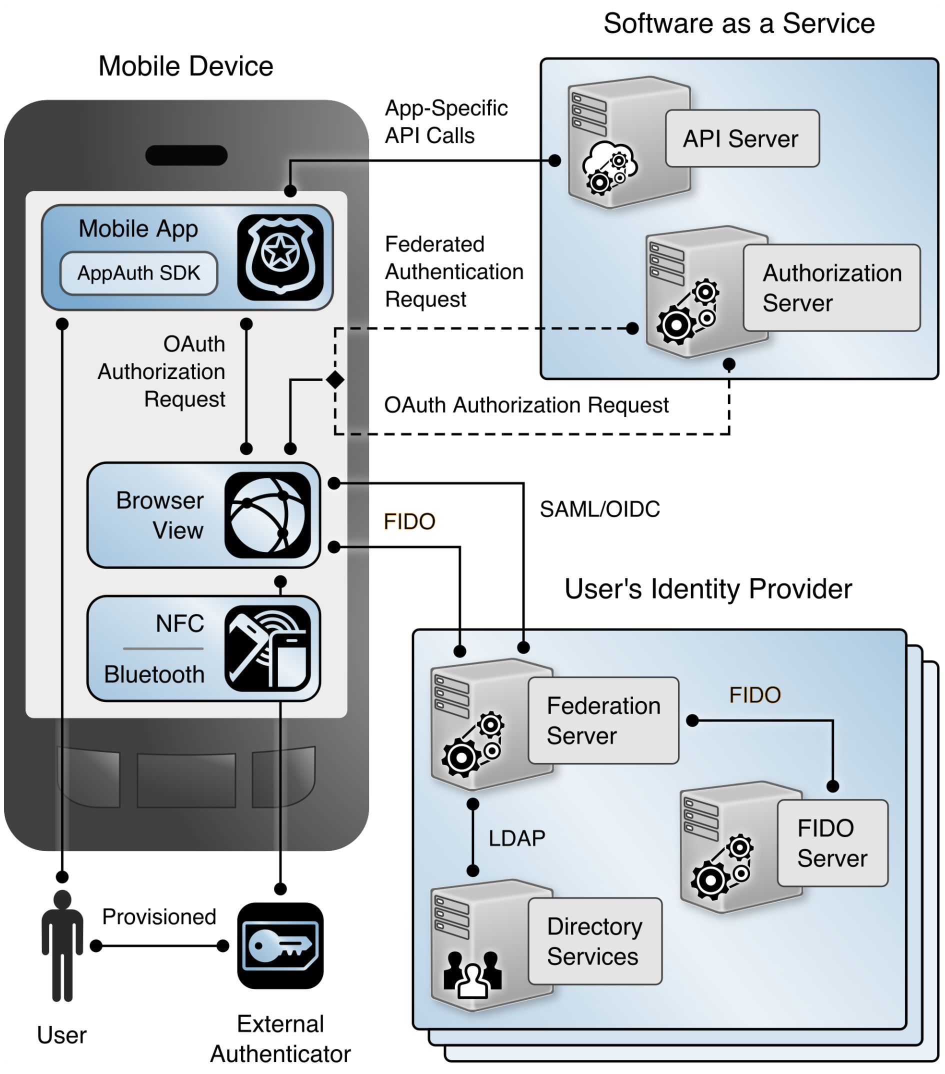
When considering MFA implementations, PSFR organizations should carefully consider organizationally defined authenticator requirements. These requirements are detailed in Section C.3 of Appendix C.

FIDO provides a standard framework within which vendors have produced a wide range of interoperable biometric, hardware, and software authenticators. This will enable PSFR organizations to choose authenticators suitable to their operational constraints. The FIDO Alliance has published specifications for two types of authenticators based on UAF and U2F. These protocols operate agnostic of the FIDO authenticator, allowing PSOs to choose any FIDO-certified authenticator that meets operational requirements and to implement it with this solution. The protocols, FIDO key registration, FIDO authenticator attestation, and FIDO deployment considerations are also detailed in Section C.3 of Appendix C.

4.2 High-Level Architecture

The NCCoE implemented both FIDO UAF and U2F for this project. The high-level architecture varies somewhat between the two implementations. Figure 4-1 depicts the interactions between the key elements of the build architecture with the U2F implementation.

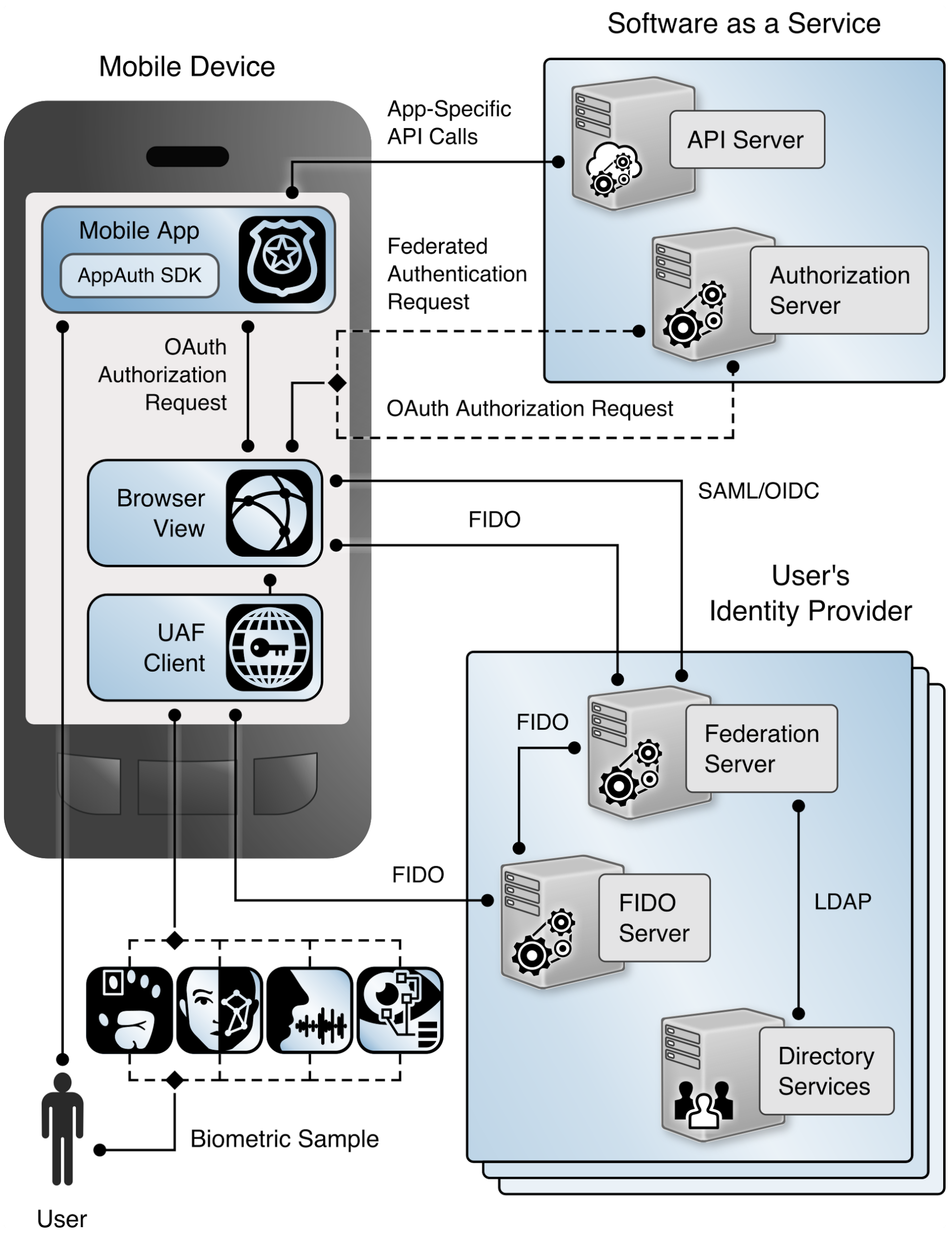
Figure 4-1 High-Level U2F Architecture



On the mobile device, the mobile application includes the OpenID Foundation's AppAuth library, which streamlines implementation of the OAuth client functionality in accordance with the IETF RFC 8252, *OAuth 2.0 for Native Apps*, guidance. AppAuth orchestrates the authorization request flow by using the device's native browser capabilities, including in-application browser tabs on devices that support them. The mobile device also supports the two FIDO authentication schemes, UAF and U2F. UAF typically involves an internal (on-device) authenticator that authenticates the user directly to the device by using biometrics, other hardware capabilities, or a software client. U2F typically involves an external hardware authenticator token, which communicates with the device over NFC or Bluetooth.

Figure 4-2 shows the corresponding architecture view with the FIDO UAF components.

Figure 4-2 High-Level UAF Architecture



The SaaS provider hosts application servers that provide APIs consumed by mobile applications, as well as an OAuth AS. The browser on the mobile device connects to the AS to initiate the OAuth authorization code flow. The AS redirects the browser to the IdP of the user's organization to authenticate the user. Once the user has authenticated, the AS will issue an access token, which is returned to the mobile application through a browser redirect and can be used to authorize requests to the application servers.

The user's IdP includes a federation server that implements SAML or OIDC, directory services containing user accounts and attributes, and a FIDO authentication service that can issue authentication challenges and validate the responses that are returned from FIDO authenticators. The FIDO authentication service may be built into the IdP but is more commonly provided by a separate server.

A SaaS provider may provide multiple applications, which may be protected by the same AS. For example, for our build Motorola Solutions provided both the PSX Mapping and PSX Messaging applications, which were protected by a shared AS. Users may also use services from different SaaS providers, which would have separate ASes. This build architecture can provide SSO between applications hosted by a single SaaS provider as well as across applications provided by multiple SaaS vendors.

Support for these two scenarios differs between the Android and iOS platforms. When the build team implemented this project, U2F was not supported on iOS devices, while UAF was supported on both Android and iOS. The build team has only built and tested the U2F implementation on Android devices.

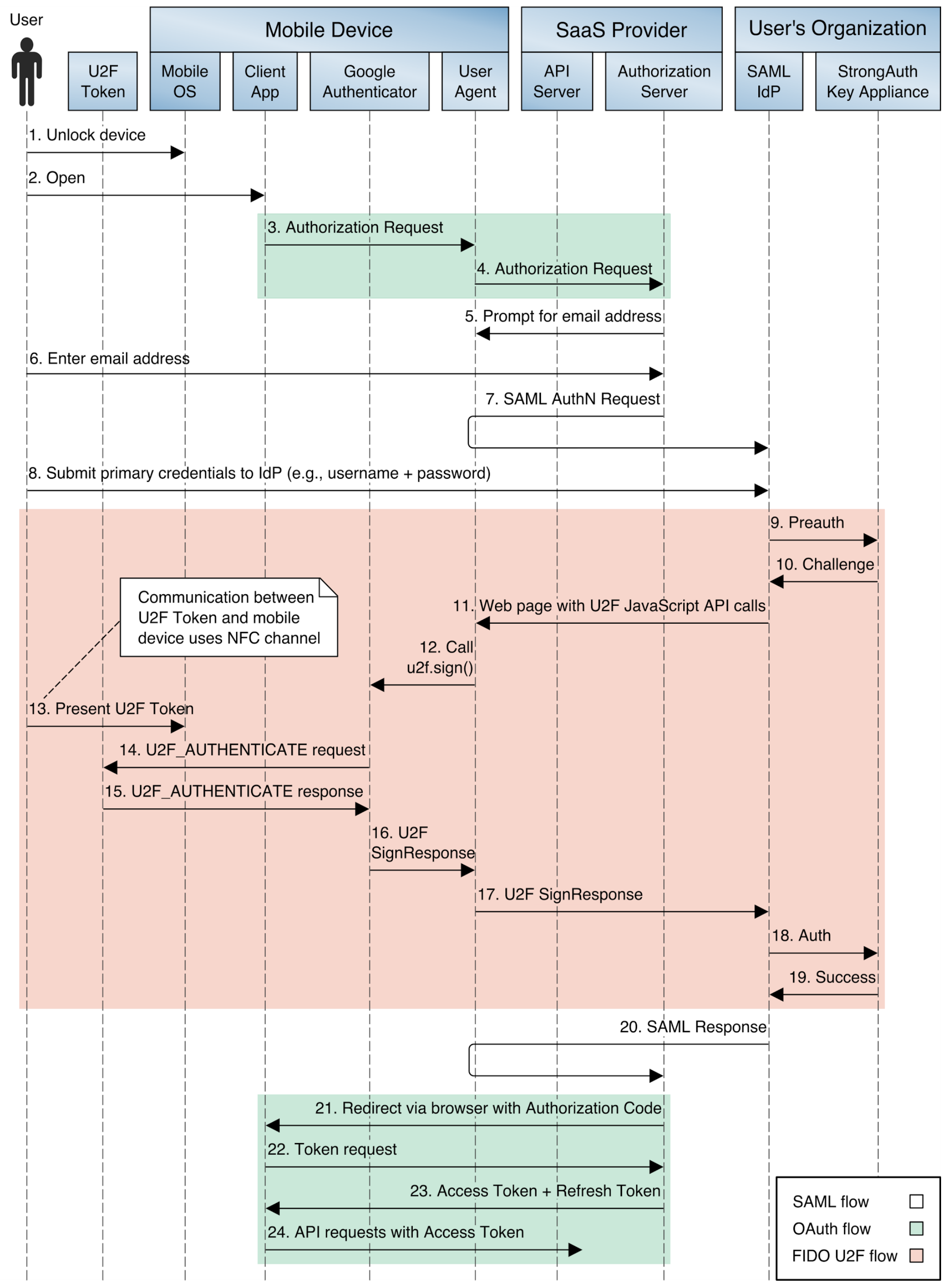
4.3 Detailed Architecture Flow

The mobile SSO lab implementation demonstrates two authentication flows: one in which the user authenticates to a SAML IdP with a YubiKey Neo U2F token and a PIN, and one in which the user authenticates to an OIDC IdP by using UAF with a fingerprint. These pairings of federation and authentication protocols are purely arbitrary; U2F could just as easily be used with OIDC, for example.

4.3.1 SAML and U2F Authentication Flow

The authentication flow using SAML and U2F is depicted in Figure 4-3. As explained in Section 4.2, at the time of publication this implementation is not supported on iOS devices. This figure depicts the message flows among different components on the mobile device or hosted by the SaaS provider or user organization. In the figure, colored backgrounds differentiate the SAML, OAuth, and FIDO U2F protocol flows. Prior to this authentication flow, the user must have registered a FIDO U2F token with the IdP, and the AS and IdP must have exchanged metadata and established an RP trust.

Figure 4-3 SAML and U2F Sequence Diagram



The detailed steps are as follows:

1. The user unlocks the mobile device. Any form of lock-screen authentication can be used; it is not directly tied to the subsequent authentication or authorization.
2. The user opens a mobile application that connects to the SaaS provider's back-end services. The mobile application determines that an OAuth token is needed. This may occur because the application has no access or refresh tokens cached or it has an existing token known to be expired based on token metadata, or it may submit a request to the API server with a cached bearer token and receive an HTTP 401 status code in the response.
3. The mobile application initiates an OAuth authorization request using the authorization code flow by invoking the system browser (or an in-application browser tab) with the uniform resource locator (URL) of the SaaS provider AS's authorization end point.
4. The browser submits the request to the AS over a Hypertext Transfer Protocol Secure (HTTPS) connection. This begins the OAuth 2 authorization flow.
5. The AS returns a page that prompts for the user's email address.
6. The user submits the email address. The AS uses the domain of the email address for IdP discovery. The user needs to specify the email address only one time; the address is stored in a cookie in the device browser and will be used to automatically determine the user's IdP on subsequent visits to the AS.
7. The AS redirects the device browser to the user's IdP with a SAML authentication request. This begins the SAML authentication flow.
8. The IdP returns a login page. The user submits a username and PIN. The IdP validates these credentials against the directory service. If the credentials are invalid, the IdP redirects back to the login page with an error message and prompts the user to authenticate again. If the credentials are valid, the IdP continues to step 9.
9. The IdP submits a "preauth" API request to the StrongKey SKCE server. The preauth request includes the authenticated username obtained in step 8. This begins the FIDO U2F authentication process.
10. The SKCE responds with a U2F challenge that must be signed by the user's registered key in the U2F token to complete authentication. If the user has multiple keys registered, the SKCE returns a challenge for each key so that the user can authenticate with any registered authenticator.
11. The IdP returns a page to the user's browser that includes Google's JavaScript U2F API and the challenge obtained from the SKCE in step 10. The user taps a button on the page to initiate U2F authentication, which triggers a call to the u2f.sign JavaScript function.
12. The u2f.sign function invokes the Google Authenticator application, passing it the challenge, the appId (typically the domain name of the IdP), and an array of the user's registered key.
13. Google Authenticator prompts the user to hold the U2F token against the NFC radio of the mobile device, which the user does.

14. Google Authenticator connects to the U2F token over the NFC channel and sends an applet selection command to activate the U2F applet on the token. Google Authenticator then submits a U2F_AUTHENTICATE message to the token.
15. Provided that the token has one of the keys registered at the IdP, it signs the challenge and returns the signature in an authentication success response over the NFC channel.
16. Google Authenticator returns the signature to the browser in a SignResponse object.
17. The callback script on the authentication web page returns the SignResponse object to the IdP.
18. The IdP calls the “authenticate” API on the SKCE, passing the SignResponse as a parameter.
19. The SKCE validates the signature of the challenge by using the registered public key and verifies that the appId matches the IdP’s and that the response was received within the configured time-out. The API returns a response to the IdP, indicating success or failure and any error messages. This concludes the U2F authentication process; the user has now authenticated to the IdP, which sets a session cookie.
20. The IdP returns a SAML response indicating the authentication success or failure to the AS through a browser redirect. If authentication has succeeded, the response will include the user’s identifier and, optionally, additional attribute assertions. This concludes the SAML authentication flow. The user is now authenticated to the AS, which sets a session cookie. Optionally, the AS could prompt the user to approve the authorization request, displaying the scopes of access being requested at this step.
21. The AS sends a redirect to the browser with the authorization code. The target of the redirect is the mobile application’s redirect_uri, a link that opens in the mobile application through a mechanism provided by the mobile OS (e.g., custom request scheme or Android AppLink).
22. The mobile application extracts the authorization code from the URL and submits it to the AS’s token end point.
23. The AS responds with an access token and, optionally, a refresh token that can be used to obtain an additional access token when the original token expires. This concludes the OAuth authorization flow.
24. The mobile application can now submit API requests to the SaaS provider’s back-end services by using the access token in accordance with the bearer token authorization scheme defined in RFC 6750, *The OAuth 2.0 Authorization Framework: Bearer Token Usage* [15].

4.3.2 OpenID Connect and UAF Authentication Flow

The authentication flow involving OIDC and UAF is depicted in Figure 4-4.

Figure 4-4 OIDC and UAF Sequence Diagram

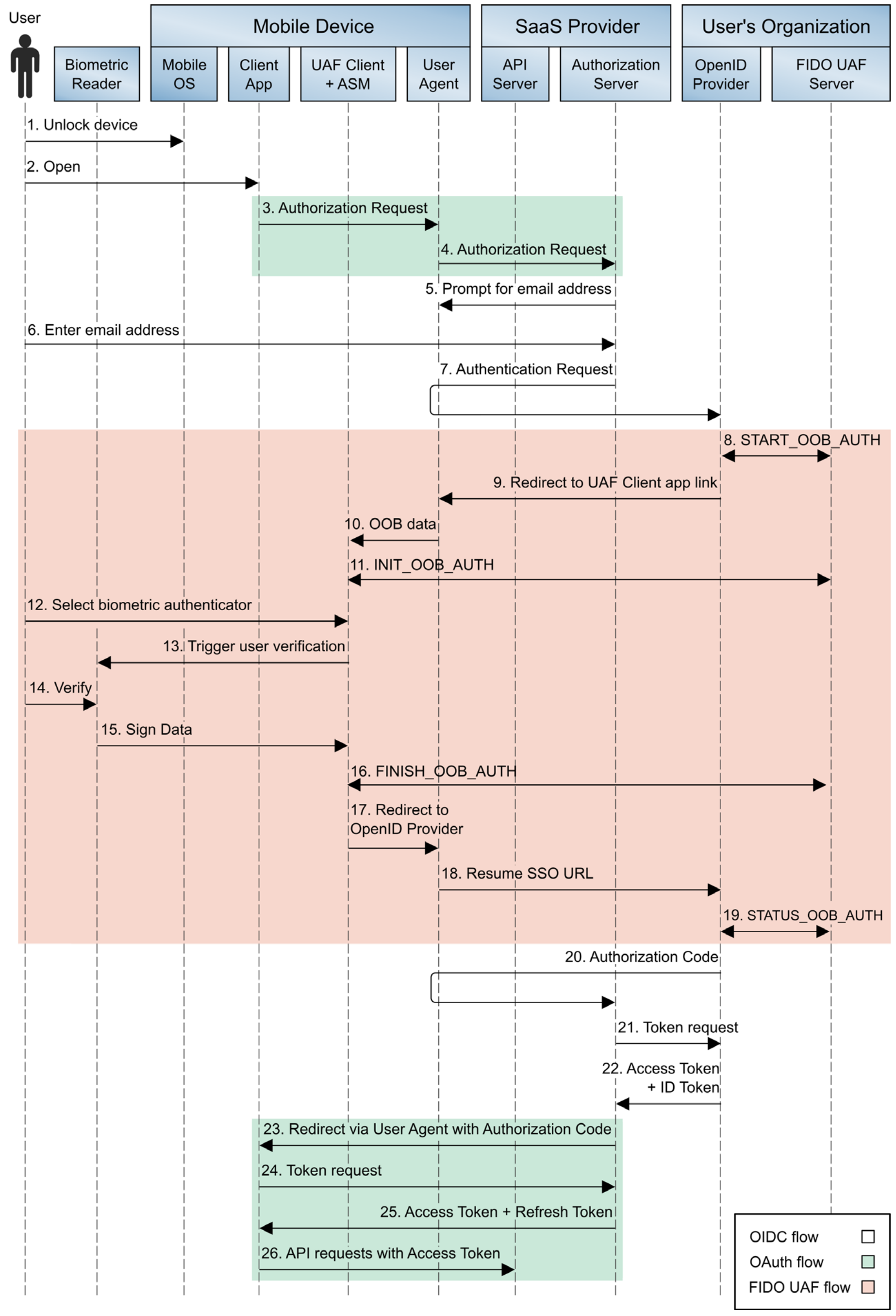


Figure 4-4 uses the same conventions and color coding as the earlier SAML/U2F diagram (Figure 4-3) to depict components on the device, at the SaaS provider, and at the user's organization. Prior to this authentication flow, the user must have registered a FIDO UAF authenticator with the IdP, and the AS must be registered as an OIDC client at the IdP. The detailed steps are listed below. For ease of comparison, steps that are identical to the corresponding step in Figure 4-3 are shown in italics.

1. *The user unlocks the mobile device. Any form of lock-screen authentication can be used; it is not directly tied to the subsequent authentication or authorization.*
2. *The user opens a mobile application that connects to the SaaS provider's back-end services. The mobile application determines that an OAuth token is needed. This may occur because the application has no access or refresh tokens cached or it has an existing token known to be expired based on token metadata, or it may submit a request to the API server with a cached bearer token and receive an HTTP 401 status code in the response.*
3. *The mobile application initiates an OAuth authorization request by using the authorization code flow by invoking the system browser (or an in-application browser tab) with the URL of the SaaS provider AS's authorization end point.*
4. *The in-application browser tab submits the request to the AS over an HTTPS connection. This begins the OAuth 2 authorization flow.*
5. *The AS returns a page that prompts for the user's email address.*
6. *The user submits the email address. The AS uses the domain of the email address for IdP discovery. The user needs to specify the email address only one time; the address is stored in a cookie in the device browser and will be used to automatically determine the user's IdP on subsequent visits to the AS.*
7. The AS redirects the device browser to the user's IdP with an OIDC authentication request. This begins the OIDC authentication flow.
8. The IdP submits a START_OOB_AUTH request to the UAF authentication server. The server responds with a data structure containing the necessary information for a UAF client to initiate an Out-of-Band (OOB) authentication, including a transaction identifier linked to the user's session at the IdP.
9. The IdP returns an HTTP redirect to the browser. The redirect target URL is an application link that will pass the OOB data to the Nok Nok Labs Passport application on the device.
10. The Nok Nok Passport application opens and extracts the OOB data from the application link URL.

11. Passport sends an INIT_OOB_AUTH request to the UAF authentication server, including the OOB data and a list of authenticators available on the device that the user has registered for use at the IdP. The server responds with a set of UAF challenges for the registered authenticators.
12. If the user has multiple registered authenticators (e.g., fingerprint and voice authentication), Passport prompts the user to select which authenticator to use.
13. Passport activates the authenticator, which prompts the user to perform the required steps for verification. For example, if the selected authenticator is the Android Fingerprint authenticator, the standard Android fingerprint user interface (UI) overlay will pop over the browser and prompt the user to scan an enrolled fingerprint. The authenticator UI may be presented by Passport (for example, the PIN authenticator), or it may be provided by an OS component such as Apple Touch ID or Face ID.
14. The user completes the biometric scan or other user verification activity. Verification occurs locally on the device; biometrics and secrets are not transmitted to the server.
15. The authenticator signs the UAF challenge by using the private key that was created during initial UAF enrollment with the IdP. The authenticator returns control to the Passport application through an application link with the signed UAF challenge.
16. The Passport application sends a FINISH_OOB_AUTH API request to the UAF authentication server. The server extracts the username and registered public key and validates the signed response. The server can also validate the authenticator's attestation signature and check that the security properties of the authenticator satisfy the IdP's security policy. The server caches the authentication result.
17. The Passport application closes, returning control to the browser, which is redirected to the "resume SSO" URL at the IdP. This URL is defined on the Ping server to enable multistep authentication flows and allow the browser to be redirected back to the IdP after completing required authentication steps with another application.
18. The browser requests the Resume SSO URL at the IdP.
19. The IdP sends a STATUS_OOB_AUTH API request to the UAF authentication server. The UAF server responds with the success/failure status of the out-of-band authentication and any associated error messages. (Note: The IdP begins sending STATUS_OOB_AUTH requests periodically, following step 9 in the flow, and continues to do so until a final status is returned or the transaction times out.) This concludes the UAF authentication process; the user has now authenticated to the IdP, which sets a session cookie.
20. The IdP returns an authorization code to the AS through a browser redirect.

21. The AS submits a token request to the IdP's token end point, authenticating with its credentials and including the authorization code.

22. The IdP responds with an identification (ID) token and an access token. The ID token includes the user's identifier and, optionally, additional attribute assertions. The access token can optionally be used to request additional user claims at the IdP's user information end point. This concludes the OIDC authentication flow. The user is now authenticated to the AS, which sets a session cookie. Optionally, the AS could prompt for the user to approve the authorization request, displaying the scopes of access being requested at this step.

23. *The AS sends a redirect to the browser with the authorization code. The target of the redirect is the mobile application's redirect_uri, a link that opens in the mobile application through a mechanism provided by the mobile OS (e.g., custom request scheme or Android AppLink).*

24. *The mobile application extracts the authorization code from the URL and submits it to the AS's token end point.*

25. *The AS responds with an access token and, optionally, a refresh token that can be used to obtain an additional access token when the original token expires. This concludes the OAuth authorization flow.*

26. *The mobile application can now submit API requests to the SaaS provider's back-end services by using the access token in accordance with the bearer token authorization scheme.*

Both authentication flows end with a single application obtaining an access token to access back-end resources. At this point, conventional OAuth token life-cycle management would begin. Access tokens have an expiration time. Depending on the application's security policy, refresh tokens may be issued along with the access token and used to obtain a new access token when the initial token expires. Refresh tokens and access tokens can continue to be issued in this manner for as long as the security policy allows. When the current access token has expired and no additional refresh tokens are available, the mobile application would submit a new authorization request to the AS.

Apart from obtaining an access token, the user has established sessions with the AS and IdP that can be used for SSO.

Implementation details for this scenario were slightly different on iOS and Android devices. On Android devices, a Chrome Custom Tab was used as the user-agent. On iOS, however, the team encountered issues using the custom tabs implementation in iOS 12 (provided by the ASWebAuthenticationSession API) in conjunction with Passport. At step 17 in the above sequence, where the Passport application should close and control should return to the in-application browser tab, instead a second Safari window opened, and the user was prompted again to authenticate using Passport. The team determined that ASWebAuthenticationSession did not seem to support opening a different application like Passport and then returning to the same ASWebAuthenticationSession instance once the other application closes. This issue was resolved by configuring AppAuth to use Safari instead of ASWebAuthenticationSession.

4.4 Single Sign-On with the OAuth Authorization Flow

When multiple applications invoke a common user-agent to perform the OAuth authorization flow, the user-agent maintains the session state with the AS and IdP. In the build architecture, this can enable SSO in two scenarios.

In the first case, assume that a user has launched a mobile application, been redirected to an IdP to authenticate, and completed the OAuth flow to obtain an access token. Later, the user launches a second application that connects to the same AS used by the first application. The application will initiate an authorization request using the same user-agent as the first application. Provided that the user has not logged out at the AS, this request will be sent with the session cookie that was established when the user authenticated in the previous authorization flow. The AS will recognize the user's active session and issue an access token to the second application without requiring the user to authenticate again.

In the second case, again assume that the user has completed an OAuth flow, including authentication to an IdP, while launching the first application. Later, the user launches a second application that connects to an AS that is different from the first application. Again, the second application initiates an authorization request using the same user-agent as the first application. The user has no active session with the second AS, so the user-agent is redirected to the IdP to obtain an authentication assertion. Provided that the user has not logged out at the IdP, the authentication request will include the previously established session cookie, and the user will not be required to authenticate again at the IdP. The IdP will return an assertion to the AS, which will then issue an access token to the second application.

This architecture can also provide SSO across native and web applications. If the web application is an RP to the same SAML or OIDC IdP used in the authentication flow described above, the application will redirect the browser to the IdP and resume the user's existing session without the need to reauthenticate, provided that the browser used to access the web application is the same one used in the authorization flow described above. For example, if a Google Chrome Custom Tab is used in the native-application OAuth flow, accessing the web application in Chrome will provide a shared cookie store and SSO. If the web application uses the OAuth 2.0 implicit grant, SSO could follow either of the above workflows, depending on whether the user is already authenticated at the AS used by the application.

When applications use embedded web views instead of the system browser or in-application tabs for the OAuth authorization flow, each individual application's web view has its own cookie store, so there is no continuity of the session state as the user transitions from one application to another, and the user must authenticate each time.

4.5 Application Developer Perspective of the Build

The following paragraphs provide takeaways from an application developer's perspective regarding the experience of the build team, inclusive of FIDO, the AppAuth library, PKCE, and Chrome Custom Tabs.

AppAuth was integrated as described in Section C.1 of Appendix C. From an application developer perspective, the primary emphasis in the build was integrating AppAuth. The authentication technology was basically transparent to the developer. In fact, the native application developers for this project had no visibility to the FIDO U2F or UAF integration. This transparency was achieved through the AppAuth pattern of delegating the authentication process to the in-application browser tab capability of the OS. Other application developer effects are listed below:

- Several pieces of information must be supplied by an application in the OAuth authorization request, such as the scope and the client ID, which an OAuth AS might use to apply appropriate authentication policy. These details are obtained during the OAuth client registration process with the AS.
- The ability to support multiple IdPs without requiring any hard-coding of IdP URLs in the application itself was achieved by using Hypertext Markup Language (HTML) forms hosted by the IdP to collect information from end users (e.g., domain) during login, which was used to perform IdP discovery.

4.6 Identity Provider Perspective of the Build

The IdP is responsible for account and attribute creation and maintenance, as well as credential provisioning, management, and deprovisioning. Some IdP concerns for this architecture are listed below:

- Enrollment/registration of authenticators: IdPs should consider the enrollment process and life-cycle management for MFA. For this NCCoE project, FIDO UAF enrollment was launched by the user via tapping a native enrollment application (Nok Nok Labs' Passport application). During user authentication, the same application (Passport) was invoked programmatically (via AppLink) to perform FIDO authentication. In a production implementation, the IdP would need to put processes in place to enroll, retire, or replace authenticators when needed. A process for responding when authenticators are lost or stolen is particularly important to prevent unauthorized access.
- For UAF, a FIDO UAF client must be installed (e.g., we installed Nok Nok Labs' NNL Passport).
- For U2F, download and install Google Authenticator (or equivalent) because mobile browsers do not support FIDO U2F 1.1 natively (as do some desktop browsers). This situation is evolving with ratification of the World Wide Web Consortium's Web Authentication (WebAuthn) standard [16] and mobile browser support for it. For implementations supporting U2F integration in the browser, such as the one described in this practice guide, Google Authenticator is still required

on Android devices. For implementations using WebAuthn, native browser support may eliminate the need for Google Authenticator.

4.7 Token and Session Management

RP application owners have two separate areas of concern when it comes to token and session management. They have authorization tokens to manage on the client side and identity tokens/sessions to receive and manage from the IdP side. Each of these functions has its own separate concerns and requirements.

When dealing with the native application's access to RP application data, RP operators need to make sure that appropriate authorization is in place. The architecture in Section 4.2 uses OAuth 2.0 and authorization tokens for this purpose, following the guidance from IETF RFC 8252. Native-application clients present a special challenge, as mentioned earlier, especially when it comes to protecting the authorization code being returned to the client. To mitigate a code interception threat, RFC 8252 requires that both clients and servers use PKCE for public native-application clients. ASes should reject authorization requests from native applications that do not use PKCE. The lifetime of the authorization tokens depends on the use case, but the general recommendation from the OAuth working group is to use short-lived access tokens and long-lived refresh tokens. The reauthentication requirements in NIST SP 800-63B [10] can be used as guidance for maximum refresh token lifetimes at each authenticator assurance level. All security considerations from RFC 8252 apply here as well, such as making sure that attackers cannot easily guess any of the token values or credentials.

The RP may directly authenticate the user, in which case all of the current best practices for web session security and protecting the channel with Transport Layer Security (TLS) apply. However, if there is delegated or federated authentication via a third-party IdP, then the RP must also consider the implications for managing the identity claims received from the IdP, whether it be an ID token from an OIDC provider or a SAML assertion from a SAML IdP. This channel is used for authentication of the user, which means that potential PII may be obtained. Care must be taken to obtain user consent prior to authorization for release and use of this information in accordance with relevant regulations. If OIDC is used for authentication to the RP, then all of the OAuth 2.0 security applies again here. In all cases, all channels between parties must be protected with TLS encryption.

5 Security Characteristic Analysis

The purpose of the security characteristic analysis is to understand the extent to which the project meets its objective of demonstrating MFA and mobile SSO for native and web applications. In addition, it seeks to document the security benefits and drawbacks of the example solution.

5.1 Assumptions and Limitations

This security characteristics analysis is focused on the specific design elements of the build, consisting of MFA, SSO, and federation implementation. It discusses some elements of application development, but only the aspects that directly interact with the SSO implementation. It does not focus on potential underlying vulnerabilities in OSes, application run times, hardware, or general secure coding practices. It is assumed that risks to these foundational components are managed separately (e.g., through asset and patch management). As with any implementation, all layers of the architecture must be appropriately secured, and it is assumed that implementers will adopt standard security and maintenance practices to the elements not specifically addressed here.

This project did not include a comprehensive test of all security components or “red team” penetration testing or adversarial emulation. Cybersecurity is a rapidly evolving field where new threats and vulnerabilities are continually discovered. Therefore, this security guidance cannot be guaranteed to identify every potential weakness of the build architecture. It is assumed that implementers will follow risk management procedures as outlined in the NIST Risk Management Framework.

5.2 Threat Analysis

The following subsections describe how the build architecture addresses the threats discussed in Section 3.5.

5.2.1 Mobile Ecosystem Threat Analysis

In Section 3.5.2, we introduced the MTC, described the 32 categories of mobile threats that it covers, and highlighted the three categories that this practice guide addresses: Vulnerable Applications, Authentication: User or Device to Network, and Authentication: User or Device to Remote Service.

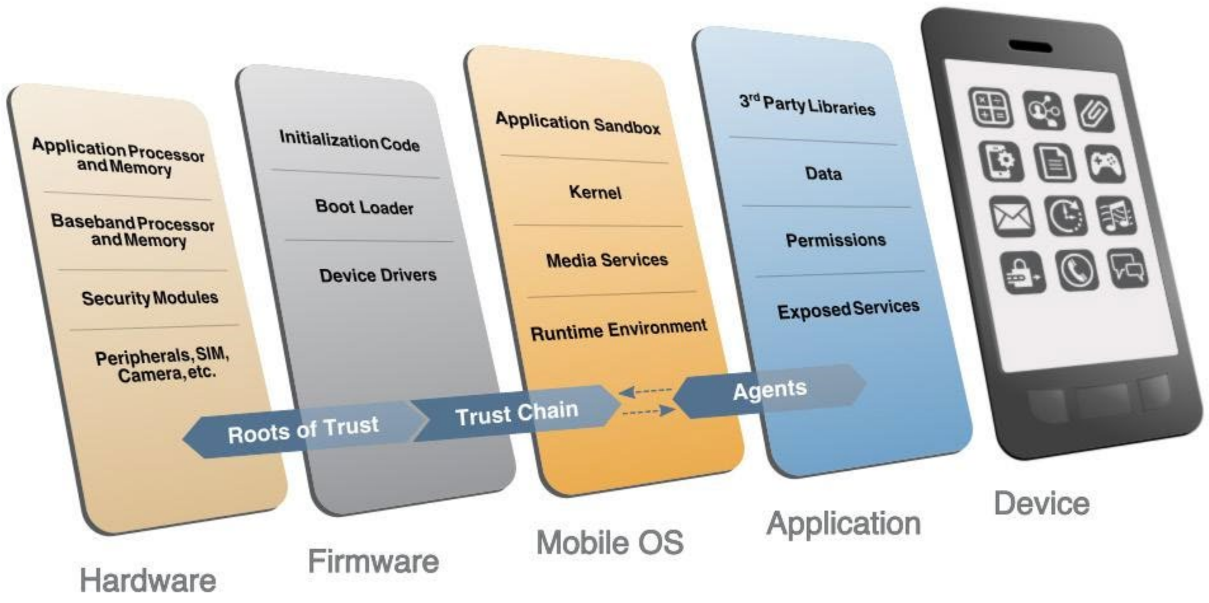
At the time of this writing, these categories encompass 18 entries in the MTC. However, the MTC is a living catalog, which is continually being updated. Instead of addressing each threat, we describe in general how these types of threats are mitigated by the architecture laid out in this practice guide:

- Use encryption for data in transit: The IdP and AS enforce HTTPS encryption by default, which the application is required to use during SSO authentication.
- Use newer mobile platforms: Volume C of this guide (NIST SP 1800-13C) calls for using at least Android 5.0 or iOS 8.0 or newer, which mitigates weaknesses of older versions (e.g., applications can access the system log in Android 4.0 and older).
- Use built-in browser features: The AppAuth for Android library utilizes the Chrome Custom Tabs feature, which activates the device’s native browser. This allows the application to leverage built-in browser features, such as identifying and avoiding known malicious web pages. AppAuth for iOS supports using the SFSafariViewController and SFAuthenticationSession APIs or the Safari browser.

- Avoid hard-coded secrets: The AppAuth guidance recommends and supports the use of PKCE. This allows developers to avoid using a hard-coded OAuth client secret.
- Avoid logging sensitive data: The AppAuth library, which handles the OAuth 2 flow, does not log any sensitive data.
- Use sound authentication practices: By using SSO, the procedures outlined in this guide allow application developers to rely on the IdP's implementation of authentication practices, such as minimum length and complexity requirements for passwords, maximum authentication attempts, and periodic reset requirements. In addition, the IdP can introduce new authenticators without any downstream effect to applications.
- Use sound token management practices: Again, this guide allows application developers to rely on the IdP's implementation of authorization tokens and good management practices, such as replay-resistance mechanisms and token expirations.
- Use two-factor authentication: Both FIDO U2F and UAF, as deployed in this build architecture, provide multifactor cryptographic user authentication. The U2F implementation requires the user to authenticate with a password or PIN and with a single-factor cryptographic token. However, the UAF implementation utilizes a key pair stored in the device's hardware-backed key store that is unlocked through user verification consisting of a biometric (e.g., fingerprint or voice match) or a password or PIN.
- Protect cryptographic keys: FIDO U2F and UAF authentication leverage public key cryptography. In this architecture, U2F private keys are stored external to the mobile device in a hardware-secure element on a YubiKey Neo. UAF private keys are stored on the mobile device's hardware-backed key store. These private keys are never sent to external servers.
- Protect biometric templates: When using biometric authentication mechanisms, organizations should consider storage and use of user biometric templates. This architecture relies on the native biometric mechanisms implemented by modern mobile devices and OSes, which verify biometric templates locally and store them in protected storage.

To fully address these threats and threats in other MTC categories, additional measures should be taken by all parties involved in the mobile ecosystem: the mobile device user, the enterprise, the network operator, the application developer, and the OEM. A figure depicting this ecosystem in total is shown in Section 3.5.2. In addition, the mobile platform stack should be understood in great detail to fully assess the threats that may be applicable. An illustration of this stack, taken from NISTIR 8144 [9], is shown in Figure 5-1.

Figure 5-1 Mobile Device Technology Stack



Several tools, techniques, and best practices are available to mitigate these other threats. EMM software can allow enterprises to manage devices more fully and to gain a better understanding of device health; one example of this is detecting whether a device has been *rooted* or *jailbroken*, which compromises the security architecture of the entire platform. Application security-vetting software (commonly known as app-vetting software) can be utilized to detect vulnerabilities in first-party applications and to discover potentially malicious behavior in third-party applications. Using app-vetting software in conjunction with EMM software prevents the installation of unauthorized applications and reduces the attack surface of the platform. For more guidance on these threats and mitigations, refer to the MTC and NISTIR 8144 [9].

5.2.2 Authentication and Federation Threat Analysis

Section 3.5.3 discussed threats specific to authentication and federation systems, which are cataloged in NIST SP 800-63-3 [17]. MFA, provided in the build architecture by FIDO U2F and UAF, is designed to mitigate several authentication risks:

- Theft of physical authenticator: Possessing an authenticator, which could be a YubiKey (in the case of U2F) or the mobile device itself (in the case of UAF), does not in itself enable an attacker to impersonate the user to an RP or IdP. Additional knowledge or a biometric factor is needed to authenticate.

- Eavesdropping: Some MFA solutions, including many one-time password (OTP) implementations, are vulnerable to eavesdropping attacks. FIDO implements cryptographic authentication, which does not involve transmission of secrets over the network.
- Social engineering: A typical social engineering exploit involves impersonating a system administrator or other authority figure under some pretext to convince users to disclose their passwords over the phone, but this comprises only a single authentication factor.
- Online guessing: Typical password authentication schemes may be vulnerable to online guessing attacks, although lockout and throttling policies can reduce the risk. Cryptographic authentication schemes are not vulnerable to online guessing.

FIDO also incorporates protections against phishing and pharming attacks. When a FIDO authenticator is registered with an RP, a new key pair is created and associated with the RP's application ID, which is derived from the domain name in the URL where the registration transaction was initiated. During authentication, the application ID is again derived from the URL of the page that is requesting authentication, and the authenticator will sign the authentication challenge only if a key pair has been registered with the matching application ID. The FIDO Facet specification enables sites to define a list of domain names that should be treated as a single application ID to accommodate service providers that span multiple domain names, such as google.com and gmail.com.

The application ID verification effectively prevents the most common type of phishing attack, in which the attacker creates a new domain and tricks users into visiting that domain instead of an intended RP where the user has an account. For example, an attacker might register a domain called "google-accts.com" and send emails with a pretext to get users to visit the site, such as a warning that the user's account will be disabled unless some action is taken. The attacker's site would present a login screen identical to Google's login screen to obtain the user's password (and OTP, if enabled) credentials and to use them to impersonate the user to the real Google services. With FIDO, the authenticator would not have an existing key pair registered under the attacker's domain, so the user would be unable to return a signed FIDO challenge to the attacker's site. If the attacker could convince the user to register the FIDO authenticator with the malicious site and then sign an authentication challenge, the signed FIDO assertion could not be used to authenticate to Google because the RP can also verify the application ID associated with the signed challenge, and it would not be the expected ID.

A more advanced credential theft attack involves an active machine-in-the-middle that can intercept the user's requests to the legitimate RP and act as a proxy between the two. To avoid TLS server certificate validation errors, in this case, the attacker must obtain a TLS certificate for the legitimate RP site that is trusted by the user's device. This could be accomplished by exploiting a vulnerability in a commercial certificate authority; it presents a high bar for the attacker but is not unprecedented. Application ID validation is not sufficient to prevent this attacker from obtaining an authentication challenge from the RP, proxying it to the user, and using the signed assertion that they get back from the user to authenticate to the RP. To prevent this type of attack, the FIDO specifications permit token binding to protect the signed assertion that is returned to the RP by including information in the assertion about the TLS channel over which it is being delivered. If there is a machine in the middle (or a proxy of any kind) between the user and the RP, the RP can detect it by examining the token-binding message included in the assertion and comparing it with the TLS channel over which it was received. Token binding is not widely implemented today, but with finalization of the token-binding specification in RFC 8471 [18] and related RFCs, adoption is expected to increase.

Many of the federation threats discussed in Section 3.5.3 can be addressed by signing assertions, ensuring their integrity and authenticity. An encrypted assertion can also provide multiple protections, preventing disclosure of sensitive information contained in the assertion and providing strong protection against assertion redirection because only the intended RP will have the key required to decrypt the assertion. Most mitigations to federation threats require application of protocol-specific guidance for SAML and OIDC. These considerations are not specific to the mobile SSO use case; application of a security-focused profile of these protocols can mitigate many potential issues.

In addition to RFC 8252, application developers and RP service providers should consult the *OAuth 2.0 Threat Model and Security Considerations* documented in RFC 6819 [19] for best practices for implementing OAuth 2.0. The AppAuth library supports a secure OAuth client implementation by automatically handling details like PKCE. Key protections for OAuth and OIDC include those listed below:

- Requiring HTTPS for protocol requests and responses protects access tokens and authorization codes and authenticates the server to the client.
- Using the mobile operating system browser or in-application browser tabs for the authentication flow, in conformance with RFC 8252, protects user credentials from exposure to the mobile client application or the application service provider.
- OAuth tokens are associated with access scopes, which can be used to limit the authorizations granted to any given client application, which somewhat mitigates the potential for misuse of compromised access tokens.
- PKCE, as explained previously, prevents interception of the authorization code by malicious applications on the mobile device.

5.3 Scenarios and Findings

The overall test scenario on Android devices involved launching the Motorola Solutions PSX Cockpit mobile application, authenticating, and then subsequently launching additional PSX applications and validating that the applications could access the back-end APIs and reflected the identity of the authenticated user. To enable testing of the two authentication scenarios, two separate "user organization" infrastructures were created in the NCCoE lab, and both were registered as IdPs to the test PingFederate instance acting as the PSX AS. A "domain selector" was created in PingFederate to perform IdP discovery based on the domain of the user's email address, enabling the user to trigger authentication at one of the IdPs.

On iOS devices, two demonstration applications—a chat application and a mapping application, with corresponding back-end APIs—were developed to demonstrate SSO. The iOS demo used the same authentication infrastructure in the NCCoE lab as the Android demo. The demo consisted of launching either application and authenticating to the IdP that supported OpenID Connect and FIDO UAF, then launching the additional demo application to demonstrate SSO and access to the back-end APIs with the identity of the authenticated user.

Prior to testing the authentication infrastructure, users had to register U2F and UAF authenticators at the respective IdPs. FIDO authenticator registration requires a process that provides high assurance that the authenticator is in possession of the claimed account holder. In practice, this typically requires a strongly authenticated session or an in-person registration process overseen by an administrator. In the lab, a notional enrollment process was implemented with the understanding that real-world processes would be different and subject to agency security policies. Organizations should refer to NIST SP 800-63B [10] for specific considerations regarding credential enrollment. From a FIDO perspective, however, the registration data used would be the same.

Lab testing showed that the build architecture consistently provided SSO between applications. Two operational findings were uncovered during testing:

- Knowing the location of the NFC radio on the mobile device greatly improves the user experience when authenticating with an NFC token, such as the YubiKey Neo. The team found that NFC radios are in different locations on different devices; on the Nexus 6P, for example, the NFC radio is near the top of the device, near the camera, whereas on the Galaxy S6 Edge, the NFC radio is slightly below the vertical midpoint of the device. After initial experimentation to locate the radio, team members could quickly and reliably make a good NFC connection with the YubiKey by holding it in the correct location. Device manufacturers provide NFC radio location information via device technical specifications.
- Time synchronization between servers is critical. In lab testing, intermittent authentication errors were found to be caused by clock drift between the IdP and the AS. This manifested as the AS reporting JavaScript Object Notation Web Token validation errors when attempting to validate ID tokens received from the IdP. All participants in the federation scheme should synchronize their clocks to a reliable Network Time Protocol (NTP) source, such as the NIST NTP pools [20]. Implementations should allow for a small amount of clock skew—on the order of a few seconds—to account for the unpredictable latency of network traffic.

Appendix A Mapping to Cybersecurity Framework Core

Table A-1 maps informative National Institute of Standards and Technology (NIST) and consensus security references to the Cybersecurity Framework core Subcategories that are addressed by this practice guide. The references do not include protocol specifications that are implemented by the individual products that compose the demonstrated security platforms. While some of the references provide general guidance that informs implementation of referenced Cybersecurity Framework core Functions, the references also provide specific recommendations that should be considered when composing and configuring security platforms and technologies described in this practice guide.

Table A-1 Cybersecurity Framework Categories

Category	Subcategory	Informative References
Asset Management (ID.AM): The data, personnel, devices, systems, and facilities that enable the organization to achieve business purposes are identified and managed consistent with their relative importance to business objectives and the organization's risk strategy.	**ID.AM-1:** Physical devices and systems within the organization are inventoried.	**CCS CSC** 1 **COBIT 5** BAI09.01, BAI09.02 **ISA 62443-2-1:2009** 4.2.3.4 **ISA 62443-3-3:2013** SR 7.8 **ISO/IEC 27001:2013** A.8.1.1, A.8.1.2 **NIST SP 800-53 Rev. 4** CM-8
Access Control (PR.AC): Access to assets and associated facilities is limited to authorized users, processes, or devices, and to authorized activities and transactions.	**PR.AC-1:** Identities and credentials are managed for authorized devices and users.	**CCS CSC** 16 **COBIT 5** DSS05.04, DSS06.03 **ISA 62443-2-1:2009** 4.3.3.5.1 **ISA 62443-3-3:2013** SR 1.1, SR 1.2, SR 1.3, SR 1.4, SR 1.5, SR 1.7, SR 1.8, SR 1.9 **ISO/IEC 27001:2013** A.9.2.1, A.9.2.2, A.9.2.4, A.9.3.1, A.9.4.2, A.9.4.3 **NIST SP 800-53 Rev. 4** AC-2, Information Assurance Family

Category	Subcategory	Informative References
	PR.AC-3: Remote access is managed.	**COBIT 5** APO13.01, DSS01.04, DSS05.03 **ISA 62443-2-1:2009** 4.3.3.6.6 **ISA 62443-3-3:2013** SR 1.13, SR 2.6 **ISO/IEC 27001:2013** A.6.2.2, A.13.1.1, A.13.2.1 **NIST SP 800-53 Rev. 4** AC-17, AC-19, AC-20
	PR.AC-4: Access permissions are managed, incorporating the principles of least privilege and separation of duties.	**CCS CSC** 12, 15 **ISA 62443-2-1:2009** 4.3.3.7.3 **ISA 62443-3-3:2013** SR 2.1 **ISO/IEC 27001:2013** A.6.1.2, A.9.1.2, A.9.2.3, A.9.4.1, A.9.4.4 **NIST SP 800-53 Rev. 4** AC-2, AC-3, AC-5, AC-6, AC-16
Data Security (PR.DS): Information and records (data) are managed consistent with the organization's risk strategy to protect the confidentiality, integrity, and availability of information.	**PR.DS-5:** Protections against data leaks are implemented.	**CCS CSC** 17 **COBIT 5** APO01.06 **ISA 62443-3-3:2013** SR 5.2 **ISO/IEC 27001:2013** A.6.1.2, A.7.1.1, A.7.1.2, A.7.3.1, A.8.2.2, A.8.2.3, A.9.1.1, A.9.1.2, A.9.2.3, A.9.4.1, A.9.4.4, A.9.4.5, A.13.1.3, A.13.2.1, A.13.2.3, A.13.2.4, A.14.1.2, A.14.1.3 **NIST SP 800-53 Rev. 4** AC-4, AC-5, AC-6, PE-19, PS-3, PS-6, SC-7, SC-8, SC-13, SC-31, SI-4

Category	Subcategory	Informative References
Protective Technology (PR.PT): Technical security solutions are managed to ensure the security and resilience of systems and assets, consistent with related policies, procedures, and agreements.	**PR.PT-1:** Audit/log records are determined, documented, implemented, and reviewed in accordance with policy.	**CCS CSC** 14 **COBIT 5** APO11.04 **ISA 62443-2-1:2009** 4.3.3.3.9, 4.3.3.5.8, 4.3.4.4.7, 4.4.2.1, 4.4.2.2, 4.4.2.4 **ISA 62443-3-3:2013** SR 2.8, SR 2.9, SR 2.10, SR 2.11, SR 2.12 **ISO/IEC 27001:2013** A.12.4.1, A.12.4.2, A.12.4.3, A.12.4.4, A.12.7.1 **NIST SP 800-53 Rev. 4** Audit and Accountability Family
	PR.PT-2: Removable media is protected and its use restricted according to policy.	**COBIT 5** DSS05.02, APO13.01 **ISA 62443-3-3:2013** SR 2.3 **ISO/IEC 27001:2013** A.8.2.2, A.8.2.3, A.8.3.1, A.8.3.3, A.11.2.9 **NIST SP 800-53 Rev. 4** MP-2, MP-4, MP-5, MP-7
	PR.PT-3: Access to systems and assets is controlled, incorporating the principle of least functionality.	**COBIT 5** DSS05.02 **ISA 62443-2-1:2009** 4.3.3.5.1, 4.3.3.5.2, 4.3.3.5.3, 4.3.3.5.4, 4.3.3.5.5, 4.3.3.5.6, 4.3.3.5.7, 4.3.3.5.8, 4.3.3.6.1, 4.3.3.6.2, 4.3.3.6.3, 4.3.3.6.4, 4.3.3.6.5, 4.3.3.6.6, 4.3.3.6.7, 4.3.3.6.8, 4.3.3.6.9, 4.3.3.7.1, 4.3.3.7.2, 4.3.3.7.3, 4.3.3.7.4 **ISA 62443-3-3:2013** SR 1.1, SR 1.2, SR 1.3, SR 1.4, SR 1.5, SR 1.6, SR 1.7, SR 1.8, SR 1.9, SR 1.10, SR 1.11, SR 1.12, SR 1.13, SR 2.1, SR 2.2, SR 2.3, SR 2.4, SR 2.5, SR 2.6, SR 2.7 **ISO/IEC 27001:2013** A.9.1.2 **NIST SP 800-53 Rev. 4** AC-3, CM-7

Category	Subcategory	Informative References
	PR.PT-4: Communications and control networks are protected.	**CCS CSC** 7 **COBIT 5** DSS05.02, APO13.01 **ISA 62443-3-3:2013** SR 3.1, SR 3.5, SR 3.8, SR 4.1, SR 4.3, SR 5.1, SR 5.2, SR 5.3, SR 7.1, SR 7.6 **ISO/IEC 27001:2013** A.13.1.1, A.13.2.1 **NIST SP 800-53 Rev. 4** AC-4, AC-17, AC-18, CP-8, SC-7

Appendix B Assumptions Underlying the Build

This project is guided by the following assumptions. Implementers are advised to consider whether the same assumptions can be made based on current policy, process, and IT infrastructure. Where applicable, appropriate guidance is provided to assist this process as described in the following subsections.

B.1 Identity Proofing

NIST SP 800-63A, *Enrollment and Identity Proofing* [21] addresses how applicants can prove their identities and become enrolled as valid subjects within an identity system. It provides requirements for processes by which applicants can both proof and enroll at one of three different levels of risk mitigation, in both remote and physically present scenarios. NIST SP 800-63A contains both normative and informative material. An organization should use NIST SP 800-63A to develop and implement an identity proofing plan within its enterprise.

B.2 Mobile Device Security

Mobile devices can add to an organization's productivity by providing employees with access to business resources at any time. Not only has this reshaped how typical tasks are accomplished, but organizations are also devising entirely new ways to work. However, mobile devices may be lost or stolen. A compromised mobile device may allow remote access to sensitive on-premises organizational data or any other data that the user has entrusted to the device. Several methods exist to address these concerns (e.g., using a device lock screen, setting shorter screen timeouts, forcing a device wipe in case of too many failed authentication attempts). It is up to the organization to implement these types of security controls, which can be enforced with EMM software (see Section B.4).

NIST SP 1800-4, *Mobile Device Security: Cloud and Hybrid Builds* [22] demonstrates how to secure sensitive enterprise data that is accessed by and/or stored on employees' mobile devices. The NIST *Mobile Threat Catalogue* [23] identifies threats to mobile devices and associated mobile infrastructure to support development and implementation of mobile security capabilities, best practices, and security solutions to better protect enterprise IT. We strongly encourage organizations implementing this practice guide in whole or in part to consult these resources when developing and implementing a mobile device security plan for their organizations.

B.3 Mobile Application Security

The security qualities of an entire platform can be compromised if an application exhibits vulnerable or malicious behavior. Application security is paramount in ensuring that the security controls implemented in other architecture components can effectively mitigate threats. The practice of making sure that an application is secure is known as software assurance (SwA). This is defined as "the level of confidence that software is free from vulnerabilities, either intentionally designed into the software or accidentally inserted at any time during its lifecycle, and that the software functions in the intended manner" [24].

In an architecture that largely relies on third-party—usually closed-source—applications to handle daily user functions, good SwA hygiene can be difficult to implement. To address this problem, NIST has released guidance on how to structure and implement an application-vetting process (also known as *app vetting*) [25]. This takes an organization through the following steps:

1. understanding the process for vetting the security of mobile applications
2. planning for implementation of an app-vetting process
3. developing application security requirements
4. understanding types of application vulnerabilities and testing methods used to detect those vulnerabilities
5. determining whether an application is acceptable for deployment on the organization's mobile devices

PSOs should carefully consider their application-vetting needs. Though major mobile-application stores, such as Apple's iTunes Store and Google's Play Store, have vetting mechanisms to find vulnerable and malicious applications, organizations may have needs beyond these proprietary tools. Per NIST SP 800-163, *Vetting the Security of Mobile Applications* [25]:

> App stores may perform app vetting processes to verify compliance with their own requirements. However, because each app store has its own unique, and not always transparent, requirements and vetting processes, it is necessary to consult current agreements and documentation for a particular app store to assess its practices. Organizations should not assume that an app has been fully vetted and conforms to their security requirements simply because it is available through an official app store. Third party assessments that carry a moniker of "approved by" or "certified by" without providing details of which tests are performed, what the findings were, or how apps are scored or rated, do not provide a reliable indication of software assurance. These assessments are also unlikely to take organization specific requirements and recommendations into account, such as federal-specific cryptography requirements.

FirstNet provides an application store specifically geared toward first responder applications. Through the FirstNet Developer Portal [26], application developers can submit mobile applications for evaluation against its published development guidelines. The guidelines include security, scalability, and availability. Compliant applications can be selected for inclusion in the FirstNet App Store. This provides first responder agencies with a repository of applications that have been tested to a known set of standards.

PSOs should avoid the unauthorized "side loading" of mobile applications that are not subject to organizational vetting requirements.

B.4 Enterprise Mobility Management

The rapid evolution of mobile devices has introduced new paradigms for work environments, along with new challenges for enterprise IT to address. EMM solutions, as part of an EMM program, provide a variety of ways to view, organize, secure, and maintain a fleet of mobile devices. EMM solutions can vary greatly in form and function, but in general, they use platform-provided application programming interfaces. Sections 3 and 4 of NIST SP 800-124 [27] describe the two basic approaches of EMM, along with components, capabilities, and their uses. One approach, commonly known as *fully managed*, controls the entire device. Another approach, usually used for bring-your-own-device situations, wraps or "containerizes" applications inside a secure sandbox so that they can be managed without affecting the rest of the device.

EMM capabilities can be grouped into four general categories:

1. General policy—centralized technology to enforce security policies of particular interest for mobile device security, such as accessing hardware sensors like GPS, accessing native OS services like a web browser or email client, managing wireless networks, monitoring when policy violations occur, and limiting access to enterprise services if the device is vulnerable or compromised
2. Data communication and storage—automatically encrypting data in transit between the device and the organization (e.g., through a virtual private network); strongly encrypting data at rest on internal and removable media storage; and wiping the device if it is being reissued to another user, has been lost, or has surpassed a certain number of incorrect unlock attempts
3. User and device authentication—requiring a device password/passcode and parameters for password strength, remotely restoring access to a locked device, automatically locking the device after an idle period, and remotely locking the device if needed
4. Applications—restricting which application stores may be used, restricting which applications can be installed, requiring specific application permissions (such as using the camera or GPS), restricting use of OS synchronization services, verifying digital signatures to ensure that applications are unmodified and sourced from trusted entities, and automatically installing/updating/removing applications according to administrative policies

PSFR organizations will have different requirements for EMM. This document does not prescribe any specific processes or procedures but assumes that they have been established in accordance with agency requirements. However, sections of this document refer to the NIST Mobile Threat Catalogue [23], which does list the use of EMM solutions as mitigations for certain types of threats.

B.5 FIDO Enrollment Process

FIDO provides a framework for users to register a variety of different multifactor authenticators and use them to authenticate to applications and identity providers. Before an authenticator can be used in an online transaction, it must be associated with the user's identity. This process is described in NIST SP 800-63B [10] as *authenticator binding*. NIST SP 800-63B specifies requirements for binding authenticators to a user's account both during initial enrollment and after enrollment, and recommends that relying parties support binding multiple authenticators to each user's account to enable alternative strong authenticators in case the primary authenticator is lost, stolen, or damaged.

Authenticator binding may be an in-person or remote process, but in both cases, the user's identity and control over the authenticator being bound to the account must be established. This is related to identity proofing, discussed in Section B.1, but requires that credentials be issued in a manner that maintains a tight binding with the user identity that has been established through proofing. PSFR organizations will have different requirements for identity and credential management; this document does not prescribe any specific processes or procedures but assumes that they have been established in accordance with agency requirements.

As an example, in-person authenticator binding could be implemented by having administrators authenticate with their own credentials and authorize the association of an authenticator with an enrolling user's account. Once a user has one enrolled authenticator, it can be used for online enrollment of other authenticators at the same assurance level or lower. Allowing users to enroll strong multifactor authenticators based on authentication with weaker credentials, such as username and password or knowledge-based questions, can undermine the security of the overall authentication scheme and should be avoided.

Appendix C Architectural Considerations for the Mobile Application Single Sign-On Build

This appendix details architectural considerations relating to SSO with OAuth 2.0; IETF RFC 8252; and AppAuth open-source libraries, federation, and types of MFA.

C.1 SSO with OAuth 2.0, IETF RFC 8252, and AppAuth Open-Source Libraries

As stated above, SSO streamlines the user experience by enabling a user to authenticate once and to subsequently access different applications without having to authenticate again. SSO on mobile devices is complicated by the sandboxed architecture, which makes it difficult to share the session state with back-end systems between individual applications. EMM vendors have provided solutions through proprietary SDKs, but this approach requires integrating the SDK with each individual application and does not scale to a large and diverse population, such as the PSFR user community.

OAuth 2.0, when implemented in accordance with RFC 8252 (the *OAuth 2.0 for Native Apps* Best Current Practice), provides a standards-based SSO pattern for mobile applications. The OpenID Foundation's AppAuth libraries [14] can facilitate building mobile applications in full compliance with IETF RFC 8252, but any mobile application that follows RFC 8252's core recommendation of using a shared external user-agent for the OAuth authorization flow will have the benefit of SSO.

To implement SSO with OAuth 2.0, this practice guide recommends that application developers choose one of the following options:

- Implement IETF RFC 8252 themselves. This RFC specifies that OAuth 2.0 authorization requests from native applications should be made only through external user-agents, primarily the user's browser. This specification details the security and usability reasons for why this is the case and how native applications and authorization servers can implement this best practice. RFC 8252 also recommends the use of PKCE, as detailed in RFC 7636 [28], which protects against authorization code interception attacks.
- Integrate the AppAuth open-source libraries (that implement RFC 8252 and RFC 7636) for mobile SSO. The AppAuth libraries make it easy for application developers to enable standards-based authentication, SSO, and authorization to application programming interfaces. This was the option chosen by the implementers of this build.

When OAuth is implemented in a native application, it operates as a *public client;* this presents security concerns with aspects like client secrets and redirected uniform resource identifiers (URIs). The AppAuth pattern mitigates these concerns and provides several security advantages for developers. The primary benefit of RFC 8252 is that native applications use an external user-agent (e.g., the Chrome for Android web browser) instead of an embedded user-agent (e.g., an Android WebView) for their OAuth authorization requests.

An embedded user-agent is demonstrably less secure and user-friendly than an external user-agent. Embedded user-agents potentially allow the client to log keystrokes, capture user credentials, copy session cookies, and automatically submit forms to bypass user consent. In addition, session information for embedded user-agents is stored on a per-application basis. This does not allow for SSO functionality, which users generally prefer and which this practice guide sets out to implement. Recent versions of Android and iPhone operating systems (iOS) both provide implementations of “in-application browser tabs” that retain the security benefits of using an external user-agent while avoiding visible context-switching between the application and the browser; RFC 8252 recommends their use where available. In-application browser tabs are supported in Android 4.1 and higher and in iOS 9 and higher.

AppAuth also requires that public client applications eschew client secrets in favor of PKCE, which is a standard extension to the OAuth 2.0 framework. When using the AppAuth pattern, the following steps are performed:

1. The user opens the client application and initiates a sign-in.
2. The client uses a browser to initiate an authorization request to the AS.
3. The user authenticates to the IdP.
4. The OIDC/SAML flow takes place, and the user authenticates to the AS.
5. The browser requests an authorization code from the AS.
6. The browser returns the authorization code to the client.
7. The client uses its authorization code to request and obtain an access token.

There is a possible attack vector at the end user’s device in this workflow if PKCE is not enabled. During step 6, so that the client application can receive the authorization code, the AS redirects the browser to a URI on which the client application is listening. However, a malicious application could register for this URI and attempt to intercept the code so that it may obtain an access token. PKCE-enabled clients use a dynamically generated random *code verifier* to ensure proof of possession for the authorization code. If the grant is intercepted by a malicious application before being returned to the client, the malicious application will be unable to use the grant without the client’s secret verifier.

AppAuth also outlines several other actions to consider, such as three types of redirect URIs, native-application client registration guidance, and reverse domain-name-based schemes. These are supported and/or enforced with secure defaults in the AppAuth libraries. The libraries are open-source and include sample code for implementation. In addition, if U2F or UAF is desired, that flow is handled entirely by the external user-agent, so client applications do not need to implement any of that functionality.

The AppAuth library takes care of several boilerplate tasks for developers, such as caching access tokens and refresh tokens, checking access-token expiration, and automatically refreshing access tokens. To implement the AppAuth pattern in an Android application by using the provided library, a developer needs to perform the following actions:

- Add the Android AppAuth library as a Gradle dependency.
- Add a redirect URI to the Android manifest.
- Add the Java code to initiate the AppAuth flow and to use the access token afterward.
- Register the application's redirect URI with the AS.

Using the AppAuth library in an iOS application is a similar process:

- Add the AppAuth library by using either Pods or Carthage.
- Configure a custom URL scheme in the info.plist file.
- Update the view controllers and application delegate to initiate the AppAuth flow and to use the access token afterward.
- Register the application's redirect URI with the AS.

To implement the AppAuth pattern *without* using a library, the user will need to follow the general guidance laid out in RFC 8252, review and follow the operating system-specific guidance in the AppAuth documentation [14], and adhere to the requirements of both the OAuth 2.0 framework documented in RFC 6749 [29] and the PKCE.

C.1.1 Attributes and Authorization

Authorization, in the sense of applying a policy to determine the rights and privileges that apply to application requests, is beyond the scope of this practice guide. OAuth 2.0 provides delegation of user authorizations to mobile applications acting on their behalf, but this is distinct from the authorization policy enforced by the application. This guide is agnostic to the specific authorization model (e.g., role-based access control [RBAC], attribute-based access control [ABAC], capability lists) that applications will use, and the SSO mechanism documented here is compatible with virtually any back-end authorization policy.

While applications could potentially manage user roles and privileges internally, federated authentication provides the capability for the IdP to provide user attributes to RPs. These attributes might be used to map users to defined application roles or used directly in an ABAC policy (e.g., to restrict access to sworn law enforcement officers). Apart from authorization, attributes may provide identifying information useful for audit functions, contact information, or other user data.

In the build architecture, the AS is an RP to the user's IdP, which is either a SAML IdP or an OIDC provider. SAML IdPs can return attribute elements in the SAML response. OIDC providers can return attributes as claims in the ID token, or the AS can request them from the user information end point. In both cases, the AS can validate the IdP's signature of the asserted attributes to ensure their validity and integrity. Assertions can also optionally be encrypted, which both protects their confidentiality in transit and enforces audience restrictions because only the intended RP will be able to decrypt them.

Once the AS has received and validated the asserted user attributes, it could use them as issuance criteria to determine whether an access token should be issued for the client to access the requested scopes. In the OAuth 2.0 framework, *scopes* are individual access entitlements that can be granted to a client application. In addition, the attributes could be provided to the protected resource server to enable the application to enforce its own authorization policies. Communications between the AS and protected resource are internal design concerns for the SaaS provider. One method of providing attributes to the protected resource is for the AS to issue the access token as a JavaScript Object Notation (JSON) Web Token (JWT) containing the user's attributes. The protected resource could also obtain attributes by querying the AS's token introspection end point, where they could be provided as part of the token metadata in the introspection response.

C.2 Federation

The preceding section discussed the communication of attributes from the IdP to the AS for use in authorization decisions. In the build architecture, it is assumed that the SaaS provider may be an RP of many IdPs supporting different user organizations. Several first responder organizations have their own IdPs, each managing its own users' attributes. This presents a challenge if the RP needs to use those attributes for authorization. Local variations in attribute names, values, and encodings would make it difficult to apply a uniform authorization policy across the user base. If the SaaS platform enables sharing of sensitive data between organizations, participants would need some assurance that their partners were establishing and managing user accounts and attributes appropriately—promptly removing access for terminated employees and performing appropriate validation before assigning attributes that enable privileged access. Federations attempt to address this issue by creating common profiles and policies governing use and management of attributes and authentication mechanisms, which members are expected to follow. This facilitates interoperability, and members are also typically audited for compliance with the federation's policies and practices, enabling mutual trust in attributes and authentication.

As an example, the National Identity Exchange Federation (NIEF) is a federation serving law enforcement organizations and networks, including the Federal Bureau of Investigation, the Department of Homeland Security, the Regional Information Sharing System, and the Texas Department of Public Safety. NIEF has established SAML profiles for both web-browser and system-to-system use cases, and a registry of common attributes for users, resources, and other entities. NIEF attributes are grouped into attribute bundles, with some designated as mandatory, meaning that all participating IdPs must provide those attributes, and participating RPs can depend on their presence in the SAML response.

The architecture documented in this build guide is fully compatible with NIEF and other federations, though this would require configuring IdPs and RPs in compliance with the federation's policies. The use of SAML IdPs is fully supported by this architecture, as is the coexistence of SAML IdPs and OIDC providers.

NIST SP 800-63-3 [17] defines Federation Assurance Levels (FALs) and their implementation requirements. FALs are a measure of the assurance that assertions presented to an RP are genuine and unaltered, pertain to the individual presenting them, are not subject to replay at other RPs, and are protected from many additional potential attacks on federated authentication schemes. A high-level summary of the requirements for FALs 1-3 is provided in Table C-1.

Table C-1 FAL Requirements

FAL	Requirement
1	Bearer assertion, signed by IdP
2	Bearer assertion, signed by IdP, and encrypted to RP
3	Holder of key assertion, signed by IdP, and encrypted to RP

IdPs typically sign assertions, and this functionality is broadly supported in available software. For SAML, the IdP's public key is provided in the SAML metadata. For OIDC, the public key can be provided through the discovery end point, if supported; otherwise, the key would be provided to the RP out of band. Encrypting assertions is also relatively trivial and requires providing the RP's public key to the IdP. The build architecture in this guide can support FAL-1 and FAL-2 with relative ease.

The requirement for holder of key assertions makes FAL-3 more difficult to implement. A SAML holder of key profile exists but has never been widely implemented in a web-browser SSO context. The OIDC core specification does not include a mechanism for a holder of key assertions; however, the forthcoming token binding over the Hypertext Transfer Protocol (HTTP) specification [30] and related RFCs may provide a pathway to supporting FAL-3 in an OIDC implementation.

C.3 Authenticator Types

When considering MFA implementations, PSFR organizations should carefully consider organizationally defined authenticator requirements. These requirements may include:

- the sensitivity of data being accessed and the commensurate level of authentication assurance needed
- environmental constraints, such as gloves or masks, that may limit the usability and effectiveness of certain authentication modalities

- costs throughout the authenticator life cycle, such as authenticator binding, loss, theft, unauthorized duplication, expiration, and revocation
- policy and compliance requirements, such as the Health Insurance Portability and Accountability Act (HIPAA) [31], the Criminal Justice Information System Security Policy [32], or other organizationally defined requirements
- support of current IT infrastructure, including mobile devices, for various authenticator types

The new, third revision of NIST SP 800-63, *Digital Identity Guidelines* [17] is a suite of documents that provide technical requirements and guidance for federal agencies implementing digital identity services, and it may assist PSFR organizations when selecting authenticators. The most significant difference from previous versions of NIST SP 800-63 is the retirement of the previous assurance rating system, known as the Levels of Assurance (LOA), established by Office of Management and Budget (OMB) Memorandum M-04-04, *E-Authentication Guidance for Federal Agencies*. In the new NIST SP 800-63-3 guidance, digital identity assurance is split into three ordinals as opposed to the single ordinal in LOA. The three ordinals are listed below:

- identity assurance level (IAL)
- authenticator assurance level (AAL)
- FAL

This practice guide is primarily concerned with AALs and how they apply to the reference architecture outlined in Table 3-2.

The strength of an authentication transaction is measured by the AAL. A higher AAL means stronger authentication and requires more resources and capabilities by attackers to subvert the authentication process. We discuss a variety of multifactor implementations in this practice guide. NIST SP 800-63-3 gives us a reference to map the risk reduction of the various implementations recommended in this practice guide.

The AAL is determined by authenticator type and combination, verifier requirements, reauthentication policies, and security control baselines, as defined in NIST SP 800-53, *Security and Privacy Controls for Federal Information Systems and Organizations* [33]. A summary of requirements at each of the levels is provided in Table C-2.

A memorized secret (most commonly implemented as a password) satisfies AAL1, but this alone is not enough to reach the higher levels shown in Table C-2. For AAL2 and AAL3, some form of MFA is required. MFA comes in many forms. The architecture in this practice guide describes two examples. One example is a multifactor software cryptographic authenticator, where a biometric authenticator application is installed on the mobile device—the two factors being possession of the private key and the biometric. The other example is a combination of a memorized secret and a single-factor cryptographic device, which performs cryptographic operations via a direct connection to the user end point.

Reauthentication requirements also become more stringent for higher levels. AAL1 requires reauthentication only every 30 days, but AAL2 and AAL3 require reauthentication every 12 hours. At AAL2, users may reauthenticate by using a single authentication factor, but at AAL3, users must reauthenticate by using both of their authentication factors. At AAL2, 30 minutes of idle time is allowed, but only 15 minutes is allowed at AAL3.

For a full description of the different types of multifactor authenticators and AAL requirements, please refer to NIST SP 800-63B [10].

Table C-2 AAL Summary of Requirements

Requirement	AAL1	AAL2	AAL3

Permitted authenticator types	Memorized Secret;
	Lookup Secret;
	Out of Band;
	Single Factor (SF) One-Time Password (OTP) Device;
	Multifactor (MF) OTP Device;
	SF Crypto Software;
	SF Crypto Device;
	MF Crypto Software;
	MF Crypto Device
		MF OTP Device;
		MF Crypto Software;
		MF Crypto Device;
		or Memorized Secret plus:
		▪ Lookup Secret
		▪ Out of Band
		▪ SF OTP Device
		▪ SF Crypto Software
		▪ SF Crypto Device
			MF Crypto Device;
			SF Crypto Device plus Memorized Secret;
			SF OTP Device plus MF Crypto Device or Software;
			SF OTP Device plus SF Crypto Software plus Memorized Secret

Federal Information Processing Standard (FIPS) 140-2 verification	Level 1 (government agency verifiers)	Level 1 (government agency authenticators and verifiers)	Level 2 overall (MF authenticators) Level 1 overall (verifiers and SF Crypto Devices) Level 3 physical security (all authenticators)
Reauthentication	30 days	12 hours, or after 30 minutes of inactivity; MAY use one authentication factor	12 hours, or after 15 minutes of inactivity; SHALL use both authentication factors

Requirement	AAL1	AAL2	AAL3
Security controls	NIST SP 800-53 Low Baseline (or equivalent)	NIST SP 800-53 Moderate Baseline (or equivalent)	NIST SP 800-53 High Baseline (or equivalent)
Machine-in-the-middle resistance	Required	Required	Required
Verifier-impersonation resistance	Not required	Not required	Required
Verifier-compromise resistance	Not required	Not required	Required
Replay resistance	Not required	Required	Required
Authentication intent	Not required	Recommended	Required
Records retention policy	Required	Required	Required
Privacy controls	Required	Required	Required

The FIDO Alliance has published specifications for two types of authenticators based on UAF and U2F. These protocols operate agnostic of the FIDO authenticator, allowing PSOs to choose any FIDO-certified authenticator that meets operational requirements and to implement it with this solution. As new FIDO-certified authenticators become available in the marketplace, PSOs may choose to migrate to these new authenticators if they better meet PSFR needs in their variety of duties.

C.3.1 UAF Protocol

The UAF protocol [2] allows users to register their device to the online service by selecting a local authentication mechanism, such as swiping a finger, looking at the camera, speaking into the microphone, or entering a PIN. The UAF protocol allows the service to select which mechanisms are presented to the user. Once registered, the user simply repeats the local authentication action whenever they need to authenticate to the service. The user no longer needs to enter their password when authenticating from that device. UAF also allows experiences that combine multiple authentication mechanisms, such as fingerprint plus PIN. Data used for local user verification, such as biometric templates, passwords, or PINs, is validated locally on the device and is not transmitted to the server. Authentication to the server is performed with a cryptographic key pair, which is unlocked after local user verification.

C.3.2 U2F Protocol

The U2F protocol [3] allows online services to augment the security of their existing password infrastructure by adding a strong second factor to user login, typically an external hardware-backed cryptographic device. The user logs in with a username and password as before and is then prompted to present the external second factor. The service can prompt the user to present a second-factor device at any time that it chooses. The strong second factor allows the service to simplify its passwords (e.g., four-digit PIN) without compromising security. During registration and authentication, the user presents the second factor by simply pressing a button on a universal serial bus (USB) device or tapping over NFC.

The user can use their FIDO U2F device across all online services that support the protocol. On desktop operating systems, the Google Chrome and Opera browsers currently support U2F. U2F is also supported on Android through the Google Authenticator application, which must be installed from the Play Store.

C.3.3 FIDO 2

The FIDO 2 project comprises a set of related standardization efforts undertaken by the FIDO Alliance and the World Wide Web Consortium (W3C). The second iteration of the FIDO standards will support the W3C's Web Authentication standard [16]. As a W3C recommendation, Web Authentication is expected to be widely adopted by web browser developers and to provide out-of-the-box FIDO support without the need to install additional client applications or extensions.

In addition, the proposed FIDO Client-to-Authenticator Protocol (CTAP) standard will support new authenticator functions, including the ability to set a PIN on authenticators such as YubiKeys. By requiring a PIN at authentication time, a CTAP-compliant authenticator can provide MFA in a manner similar to a smart card. This would eliminate the need to pair an external authenticator with an existing knowledge factor such as username/password authentication against an LDAP database, as was used in the U2F implementation of this build.

C.3.4 FIDO Key Registration

From the perspective of an IdP, enabling users to authenticate themselves with FIDO-based credentials requires that users register a cryptographic key with the IdP and associate the registered key with the username or distinguished name known to the IdP. FIDO registration must be repeated for each authenticator that the user chooses to associate with their account. FIDO protocols are different from most authentication protocols in that they permit registering multiple cryptographic keys (from different authenticators) to use with a single account. This is convenient for end users as it provides a natural backup solution to lost, misplaced, or forgotten authenticators—users may use any one of their registered authenticators to access their applications.

The process of a first-time FIDO key registration is fairly simple:

1. A user creates an account for themselves at an application site, or one is created for them as part of a business process.
2. The user registers a FIDO key with the application through one of the following processes:
    a. as part of the account self-creation process
    b. upon receiving an email with an invitation to register
    c. as part of a registration process, after an authentication process within an organization application
    d. A FIDO authenticator with a temporary, preregistered key is provided so that the user can strongly authenticate to register a new key with the application, at which point the temporary key is deleted permanently. Authenticators with preregistered keys may be combined with shared secrets given/sent to the user out of band to verify their identity before enabling them to register a new FIDO key with the organization's application.
    e. as part of a custom process local to the IdP

Policy at the organization dictates what might be considered most appropriate for a registration process.

C.3.5 FIDO Authenticator Attestation

To meet AAL requirements, RPs may need to restrict the types of FIDO authenticators that can be registered and used to authenticate. They may also require assurances that the authenticators in use are not counterfeit or vulnerable to known attacks. The FIDO specifications include mechanisms that enable the RP to validate the identity and security properties of authenticators, which are provided in a standard metadata format.

Each FIDO authenticator has an attestation key pair and certificate. To maintain FIDO's privacy guarantees, these attestation keys are not unique for each device but are typically assigned on a manufacturing batch basis. During authenticator registration, the RP can check the validity of the attestation certificate and validate the signed registration data to verify that the authenticator possesses the private attestation key.

For software authenticators, which cannot provide protection for a private attestation key, the UAF protocol allows for surrogate basic attestation. In this mode, the key pair generated to authenticate the user to the RP is used to sign the registration data object, including the attestation data. This is analogous to the use of self-signed certificates for HTTPS in that it does not actually provide cryptographic proof of the security properties of the authenticator. A potential concern is that the RP could not distinguish between a genuine software authenticator and a malicious look-alike authenticator that could provide registered credentials to an attacker. In an enterprise setting, this concern could be mitigated by delivering the valid authenticator application using EMM or another controlled distribution mechanism.

Authenticator metadata would be most important in scenarios where an RP accepts multiple authenticators with different assurance levels and applies authorization policies based on the security properties of the authenticators (e.g., whether they provide FIPS 140-2-validated key storage [34]). In practice, most existing enterprise implementations use a single type of authenticator.

C.3.6 FIDO Deployment Considerations

To support any of the FIDO standards for authentication, some integration needs to happen on the server side. Depending on how the federated architecture is set up—whether with OIDC or SAML—this integration may look different. In general, there are two servers where a FIDO server can be integrated: the AS (also known as the RP) and the IdP.

FIDO Integration at the IdP

Primary authentication already happens at the IdP, so logic follows that FIDO authentication (e.g., U2F, UAF) would as well. This is the most common and well-understood model for using a FIDO authentication server and, consequently, there is solid guidance for setting up such an architecture. The IdP already has detailed knowledge of the user and directly interacts with the user (e.g., during registration), so it is not difficult to insert the FIDO server into the registration and authentication flows. In addition, this gives PSOs the most control over the security controls that are used to authenticate their users. However, there are a few downsides to this approach:

- The PSO must now budget, host, manage, and/or pay for the cost of the FIDO server.
- The only authentication of the user at the AS is the bearer assertion from the IdP, so an assertion intercepted by an attacker could be used to impersonate the legitimate user at the AS.

FIDO Integration at the AS

Another option is to integrate FIDO authentication at the AS. One benefit of this is that PSOs will not be responsible for the expenses of maintaining a FIDO server. In addition, an attacker who intercepted a valid user's SAML assertion or ID token could not easily impersonate the user because of the requirement to authenticate to the AS as well. This approach assumes that some mechanism is in place for tightly binding the FIDO authenticator with the user's identity, which is a nontrivial task. In addition, this approach has several downsides:

- Splitting authentication into a two-stage process that spans the IdP and AS is a less well understood model for authentication, which may lead to subtle issues.
- The AS does not have detailed knowledge of—or direct action with—users, so enrollment is more difficult.

- Users would have to register their FIDO authenticators at every AS that is federated to their IdP, which adds complexity and frustration to the process.
- PSOs would lose the ability to enforce which kinds of FIDO token(s) their users utilize.

Appendix D Acronyms

AAL	Authenticator Assurance Level
ABAC	Attribute-Based Access Control
API	Application Programming Interface
AS	Authorization Server
BCP	Best Current Practice
CJIS	Criminal Justice Information Services
CNSS	Committee on National Security Systems
CRADA	Cooperative Research and Development Agreement
CTAP	Client-to-Authenticator Protocol
EMM	Enterprise Mobility Management
FAL	Federation Assurance Level
FIDO	Fast Identity Online
FIPS	Federal Information Processing Standard
FirstNet	First Responder Network Authority
GPS	Global Positioning System
HIPAA	Health Insurance Portability and Accountability Act
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IA	Information Assurance
IAL	Identity Assurance Level
ID	Identification
IdP	Identity Provider
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
iOS	iPhone Operating System
ISO	International Organization for Standardization
IT	Information Technology
JSON	JavaScript Object Notation
JWT	JSON Web Token
LOA	Level of Assurance
MF	Multifactor
MFA	Multifactor Authentication
MMS	Multimedia Messaging Service
MSSO	Mobile Single Sign-On

MTC	Mobile Threat Catalogue
NCCoE	National Cybersecurity Center of Excellence
NFC	Near Field Communication
NIEF	National Identity Exchange Federation
NIST	National Institute of Standards and Technology
NTP	Network Time Protocol
OEM	Original Equipment Manufacturer
OIDC	OpenID Connect
OMB	Office of Management and Budget
OOB	Out of Band
OS	Operating System
OTP	One-Time Password
PII	Personally Identifiable Information
PIN	Personal Identification Number
PKCE	Proof Key for Code Exchange
PSCR	Public Safety Communications Research Division
PSFR	Public Safety and First Responder
PSO	Public Safety Organization
PSX	Public Safety Experience
RBAC	Role-Based Access Control
RCS	Rich Communication Services
RFC	Request for Comments
RP	Relying Party
SaaS	Software as a Service
SAML	Security Assertion Markup Language
SD	Secure Digital
SDK	Software Development Kit
SF	Single Factor
SIM	Subscriber Identity Module
SKCE	StrongKey Crypto Engine
SMS	Short Message Service
SP	Special Publication
SSO	Single Sign-On
SwA	Software Assurance
TLS	Transport Layer Security
U2F	Universal Second Factor
UAF	Universal Authentication Framework

UI	User Interface
UICC	Universal Integrated Circuit Card
URI	Uniform Resource Identifier
URL	Uniform Resource Locator
USB	Universal Serial Bus
USIM	Universal Subscriber Identity Module
USSD	Unstructured Supplementary Service Data
VoLTE	Voice over Long-Term Evolution
W3C	World Wide Web Consortium

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