NIST SPECIAL PUBLICATION 1800-15B

Securing Small-Business and Home Internet of Things (IoT) Devices

Mitigating Network-Based Attacks Using Manufacturer Usage Description (MUD)

Volume B:
Approach, Architecture, and Security Characteristics

Douglas Montgomery
Tim Polk
Mudumbai Ranganathan
Murugiah Souppaya
NIST

William C. Barker
Dakota Consulting

Drew Cohen
Kevin Yeich
MasterPeace Solutions

Darshak Thakore
Mark Walker
CableLabs

Dean Coclin
Clint Wilson
DigiCert

Yemi Fashina
Parisa Grayeli
Joshua Harrington
Joshua Klosterman
Blaine Mulugeta
Susan Symington
The MITRE Corporation

Eliot Lear
Brian Weis
Cisco

Tim Jones
Forescout

Adnan Baykal
Global Cyber Alliance

Jaideep Singh
Molex

November 2019

PRELIMINARY DRAFT

This publication is available free of charge from
https://www.nccoe.nist.gov/projects/building-blocks/mitigating-iot-based-ddos

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National Institute of Standards and Technology Special Publication 1800-15B, Natl. Inst. Stand. Technol. Spec. Publ. 1800-15B, 169 pages, (November 2019), CODEN: NSPUE2

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You can improve this guide by contributing feedback. As you review and adopt this solution for your own organization, we ask you and your colleagues to share your experience and advice with us.

Comments on this publication may be submitted to: mitigating-iot-ddos-nccoe@nist.gov.

Public comment period: November 21, 2019 through January 21, 2020

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

National Cybersecurity Center of Excellence
National Institute of Standards and Technology
100 Bureau Drive
Mailstop 2002
Gaithersburg, MD 20899
Email: nccoe@nist.gov

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The documents in this series describe example implementations of cybersecurity practices that businesses and other organizations may voluntarily adopt. These documents do not describe regulations or mandatory practices, nor do they carry statutory authority.

ABSTRACT

The goal of the Internet Engineering Task Force's Manufacturer Usage Description (MUD) specification is for Internet of Things (IoT) devices to behave as intended by the manufacturers of the devices. This is done by providing a standard way for manufacturers to indicate the network communications that a device requires to perform its intended function. When MUD is used, the network will automatically permit the IoT device to send and receive only the traffic it requires to perform as intended, and the network will prohibit all other communication with the device, thereby increasing the device's resilience to network-based attacks. In this project, the NCCoE has demonstrated the ability to ensure that when an IoT device connects to a home or small-business network, MUD can be used to automatically permit

the device to send and receive only the traffic it requires to perform its intended function. This NIST Cybersecurity Practice Guide explains how MUD protocols and tools can reduce the vulnerability of IoT devices to botnets and other network-based threats as well as reduce the potential for harm from exploited IoT devices. It also shows IoT device developers and manufacturers, network equipment developers and manufacturers, and service providers who employ MUD-capable components how to integrate and use MUD to satisfy IoT users' security requirements.

KEYWORDS

botnets; Internet of Things; IoT; Manufacturer Usage Description; MUD; router; server; software update server; threat signaling.

DOCUMENT CONVENTIONS

The terms "shall" and "shall not" indicate requirements to be followed strictly to conform to the publication and from which no deviation is permitted.

The terms "should" and "should not" indicate that, among several possibilities, one is recommended as particularly suitable without mentioning or excluding others or that a certain course of action is preferred but not necessarily required or that (in the negative form) a certain possibility or course of action is discouraged but not prohibited.

The terms "may" and "need not" indicate a course of action permissible within the limits of the publication.

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Acronyms used in figures can be found in the Acronyms appendix.

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Such statements should be addressed to mitigating-iot-ddos-nccoe@nist.gov.

ACKNOWLEDGMENTS

We are grateful to the following individuals for their generous contributions of expertise and time.

Name	Organization
Allaukik Abhishek	Arm
Michael Bartling	Arm
Ashwini Kadam	CableLabs
Craig Pratt	CableLabs
Tao Wan	CableLabs
Russ Gyurek	Cisco
Peter Romness	Cisco
Rob Cantu	CTIA
Katherine Gronberg	Forescout
Rae'-Mar Horne	MasterPeace Solutions
Nate Lesser	MasterPeace Solutions
Tom Martz	MasterPeace Solutions
Daniel Weller	MasterPeace Solutions
Mo Alhroub	Molex
Bill Haag	NIST

Name	Organization
Bryan Dubois	Patton Electronics
Stephen Ochs	Patton Electronics
Karen Scarfone	Scarfone Cybersecurity
Matt Boucher	Symantec
Petros Efstathopoulos	Symantec
Bruce McCorkendale	Symantec
Susanta Nanda	Symantec
Yun Shen	Symantec
Pierre-Antoine Vervier	Symantec
Nancy Correll	The MITRE Corporation
Sallie Edwards	The MITRE Corporation
Drew Keller	The MITRE Corporation
Sarah Kinling	The MITRE Corporation
Karri Meldorf	The MITRE Corporation
Mary Raguso	The MITRE Corporation
Allen Tan	The MITRE Corporation
John Bambenek	ThreatSTOP
Paul Watrobski	University of Maryland

Name	Organization
Russ Housley	Vigil Security

The Technology Partners/Collaborators who participated in this project 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 these example solutions. We worked with:

Technology Partner/Collaborator	Build Involvement
Arm	Subject matter expertise
CableLabs	Micronets Gateway Service provider server Partner and service provider server Prototype medical devices–Raspberry Pi
Cisco	Cisco Catalyst 3850S MUD manager
CTIA	Subject matter expertise
DigiCert	Private Transport Layer Security certificate Premium Certificate
Forescout	Forescout appliance–VCT-R Enterprise manager–VCEM-05
Global Cyber Alliance	Quad9 threat agent and Quad 9 MUD manager (integrated in Yikes! router) Quad9 Domain Name System Quad9 Threat Application Programming Interface ThreatSTOP threat MUD file server

Technology Partner/Collaborator	Build Involvement
MasterPeace Solutions	Yikes! router Yikes! cloud Yikes! mobile application
Molex	Molex light-emitting diode light bar Molex Power over Ethernet Gateway
Patton Electronics	Subject matter expertise
Symantec	Subject matter expertise

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1 Summary

The Manufacturer Usage Description Specification (Internet Engineering Task Force [IETF] Request for Comments [RFC] 8520) provides a means for increasing the likelihood that Internet of Things (IoT) devices will behave as intended by the manufacturers of the devices. This is done by providing a standard way for manufacturers to indicate the network communications that the device requires to perform its intended function. When the Manufacturer Usage Description (MUD) is used, the network will automatically permit the IoT device to send and receive only the traffic it requires to perform as intended, and the network will prohibit all other communication with the device, thereby increasing the device's resilience to network-based attacks. This project is focused on the use of IoT devices in home and small-business environments. Its objective is to show how MUD can be used practically and effectively to reduce the vulnerability of IoT devices to network-based threats, and how MUD can be used to limit the usefulness of any compromised IoT devices to malicious actors.

This volume describes a reference architecture that is designed to achieve the project's objective, the laboratory architecture employed for the demonstrations, and the security characteristics supported by the reference design. Three implementations of the reference design are demonstrated. A fourth implementation is under development. These implementations are referred to as *builds*, and this volume describes three of them in detail:

- Build 1 uses products from Cisco Systems, DigiCert, Forescout, and Molex.
- Build 2 uses products from MasterPeace Solutions Ltd., Global Cyber Alliance (GCA), ThreatSTOP, and DigiCert.
- Build 3 uses products from CableLabs. Because it is still under development, it is not described in detail in this version of the practice guide.
- Build 4 uses software developed at the National Institute of Standards and Technology (NIST) Advanced Networking Technologies laboratory and products from DigiCert.

The primary technical elements of this project include components that are designed and configured to support the MUD protocol. We describe these components as being *MUD-capable*. The components used include MUD-capable network gateways, routers, and switches that support wired and wireless network access; MUD managers; MUD file servers; MUD-capable Dynamic Host Configuration Protocol (DHCP) servers; update servers; threat-signaling servers; and MUD files and their corresponding signature files. We also used devices that are not capable of supporting the MUD protocol, which we call *non-MUD-capable* or *legacy* devices, to demonstrate the security benefits of the demonstrated approach that are independent of the MUD protocol, such as threat signaling. Non-MUD-capable devices used include laptops, phones, and IoT devices that cannot emit a uniform resource locator (URL) for a MUD file as described in the MUD specification.

The demonstrated approach, which deploys MUD as an additional security tool rather than as a replacement for other security mechanisms, shows that MUD can make it more difficult to compromise IoT devices on a home or small-business network by using a network-based attack. While MUD can be used to protect networks of any size, the scenarios examined by this National Cybersecurity Center of Excellence (NCCoE) project involve IoT devices being used in home and small-business networks. Owners of such networks cannot be assumed to have extensive network administration experience. This makes plug-and-play deployment a requirement. Although the focus of this project is on home and small-business network applications, the home and small-business network users are not the guide's intended audience. This guide is intended primarily for IoT device developers and manufacturers, network equipment developers and manufacturers, and service providers whose services may employ MUD-capable components. MUD-capable IoT devices and network equipment are not yet widely available, so home and small-business network owners are dependent on these groups to make it possible for them to obtain and benefit from MUD-capable equipment and associated services.

1.1 Challenge

The term *IoT* is often applied to the aggregate of single-purpose, internet-connected devices, such as thermostats, security monitors, lighting control systems, and smart television sets. The IoT is experiencing what some might describe as hypergrowth. Gartner forecasts that there will be 20.4 billion IoT devices by 2020 and that the total will reach 25 billion by 2021, while Forbes forecasts the market to be $457 billion by 2020 (a 28.5 percent compounded annual growth rate). As IoT devices become more commonplace in homes and businesses, security concerns are also increasing. IoT devices may have unpatched or easily discoverable software flaws, and many have minimal security, are unprotected, or are difficult to secure. The full-featured devices such as web servers, personal or business computers, and mobile devices with which users are familiar often have state-of-the-art security software protecting them from most known threats. Conversely, many IoT devices are challenging to secure because they are designed to be inexpensive and to perform a single function—resulting in processing, timing, memory, and power constraints. Nevertheless, the consequences of not addressing security concerns of IoT devices can be catastrophic. For instance, in typical networking environments, malicious actors can detect an IoT device within minutes of it being connected and then, unbeknownst to the user, launch an attack on that device. They can also commandeer a group of compromised devices, called a *botnet,* that can be used to launch large-scale attacks. One example of such an attack is a distributed denial of service (DDoS) attack, which involves multiple computing devices in disparate locations sending repeated requests to a server with the intent to overload it and ultimately render it inaccessible. On October 12, 2016, a botnet consisting of more than 100,000 devices, called Mirai, launched a large DDoS attack on the internet infrastructure firm Dyn. Mirai interfered with Dyn's ability to provide domain name system (DNS) services to many large websites, effectively taking those websites offline for much of a day.

A DDoS or other network-based attack may result in substantial revenue losses and potential liability exposure, which can degrade a company's reputation and erode customer trust. Victims of a DDoS attack can include

- businesses that rely on the internet, who may suffer if their customers cannot reach them
- IoT device manufacturers, who may suffer reputational damage if their devices are exploited
- service providers, who may suffer service degradation that affects their customers
- users of IoT devices, who may suffer service degradation and potentially incur extra costs due to increased activity by their compromised machines

1.2 Solution

This project demonstrates how to use MUD to strengthen security while deploying IoT devices on home and small-business networks. The demonstrated approach uses MUD to constrain the communication abilities of MUD-capable IoT devices, thereby reducing the potential for these devices to be attacked as well as reducing the potential for them to be used to launch network-based attacks—both attacks that could be launched across the internet and attacks on the MUD-capable IoT device's local network. Using MUD combats IoT-based, network-based attacks by providing a standardized and automated method for making access control information available to network control devices capable of prohibiting unauthorized traffic to and from IoT devices. When MUD is used, the network will automatically permit the IoT device to send and receive the traffic it requires to perform as intended, and the network will prohibit all other communication with the device. Even if an IoT device becomes compromised, MUD prevents it from being used in any attack that would require the device to send traffic to an unauthorized destination.

In developing the demonstrated approach, the NCCoE sought existing technologies that use the MUD specification (RFC 8520). The NCCoE envisions using MUD as one of many possible tools that can be deployed, in accordance with best practices, to improve IoT security. This practice guide describes three implementations of the MUD specification that support MUD-capable IoT devices. It describes how one build (Build 2) uses threat signaling to prevent both MUD-capable and non-MUD-capable IoT devices from connecting to internet locations that are known to be potentially malicious. It also describes the importance of using update servers to perform periodic updates to all IoT devices so that the devices will be protected with up-to-date software patches. It shows IoT device developers and manufacturers, network equipment developers and manufacturers, and service providers who employ MUD-capable components how to integrate and use MUD to help make home and small-business networks more secure.

1.3 Benefits

The demonstrated approach offers specific benefits to several classes of stakeholders:

- Organizations and others who rely on the internet, including businesses that rely on their customers being able to reach them over the internet, can understand how MUD can be used to protect internet availability and performance against network-based attacks.
- IoT device manufacturers can see how MUD can protect against reputational damage resulting from their devices being easily exploited to support DDoS or other network-based attacks.
- Service providers can benefit from a reduction of the number of IoT devices that can be easily used by malicious actors to participate in DDoS attacks against their networks and degrade service for their customers.
- Users of IoT devices, including small businesses and homeowners, can better understand what to ask for with respect to the set of tools available to protect their internal networks from being subverted by malicious actors. They will also better understand what they can expect regarding reducing their vulnerability to threats to their businesses that can result from such subversion. By protecting their networks, they also avoid suffering increased costs and bandwidth saturation that could result from having their machines captured and used to launch network-based attacks.

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 deployment of the MUD protocol to mitigate the threat of IoT devices being used to perform DDoS and other network-based attacks. This reference design is modular and can be deployed in whole or in part.

This guide contains three volumes:

- NIST SP 1800-15A: *Executive Summary*
- NIST SP 1800-15B: *Approach, Architecture, and Security Characteristics*—what we built and why **(you are here)**
- NIST SP 1800-15C: *How-To Guides*—instructions for building the example solutions

It is intended for IoT device developers and manufacturers, network equipment developers and manufacturers, and service providers who employ MUD-capable components. 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 1800-15A, which describes the following topics:

- challenges that enterprises face in mitigating IoT-based DDoS threats
- example solution built at the NCCoE
- benefits of adopting the demonstrated approach

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 1800-15B, which describes what we did and why. The following sections will be of particular interest:

- Section 3.4.3, Risk, provides a description of the risk analysis we performed
- Section 5.2, Security Control Map, maps the security characteristics of this example solution to cybersecurity standards and best practices

You might share the *Executive Summary,* NIST SP 1800-15A, with your leadership team members to help them understand the importance of adopting standards-based mitigation of network-based distributed denial of service by using MUD protocols.

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 1800-15C, to replicate all or parts of the builds created in our lab. The how-to guide provides specific product installation, configuration, and integration instructions for implementing the example solutions. We do not re-create the product manufacturers' documentation, which is generally widely available. Rather, we show how we incorporated the products together in our environment to create each example solution.

This guide assumes that IT professionals have experience implementing security products within the enterprise. While we have used a suite of commercial and open-source 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 parts of the MUD protocol. 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 5, Security Characteristic Analysis, maps the characteristics of the demonstrated approach to the cybersecurity controls provided by this reference solution.

A NIST Cybersecurity Practice Guide does not describe "the" solution, but a possible solution. This is a draft guide. We seek feedback on its contents and welcome your input. Comments, suggestions, and success stories will improve subsequent versions of this guide. Please contribute your thoughts to mitigating-iot-ddos-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 language use and style guidance, see the *NCCoE Style Guide.*
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`**

Typeface/ Symbol	Meaning	Example
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

The NCCoE issued an open invitation to technology providers to participate in demonstrating an approach to deploying IoT devices in home and small-business networks in a manner that provides higher security than is typically achieved in today's environments. In this project, the MUD specification (RFC 8520) is applied to home and small-business networks that are composed of both IoT and fully featured devices (e.g., personal computers and mobile devices). Use of MUD constrains the communication abilities of MUD-capable IoT devices, thereby reducing the potential for these devices to be attacked as well as the potential for them to be used to launch attacks. Network gateway components and IoT devices leverage MUD to ensure that IoT devices send and receive only the traffic they require to perform their intended function. The resulting constraints on the MUD-capable IoT device's communication abilities reduce the potential for MUD-capable devices to be the victims of network-based attacks, as well as reducing the ability for these devices to be used in a DDoS or other network-based attack. In addition, in one build (Build 2), network-wide access controls based on threat signaling are provided to protect legacy IoT devices, MUD-capable IoT devices, and fully featured devices (e.g., personal computers). Automatic secure updates are also recommended for all devices.

The NCCoE prepared a Federal Register Notice inviting technology providers to provide products and/or expertise to compose prototypes. Components sought included MUD-capable routers or switches; MUD managers; MUD file servers; MUD-capable DHCP servers; IoT devices capable of emitting a MUD URL; and network access control based on threat signaling. Cooperative Research and Development Agreements (CRADAs) were established with qualified respondents, and build teams were assembled. The build teams fleshed out the initial architectures, and the collaborators' components were composed into example implementations, i.e., builds. The build teams documented the architecture and design of each build. As each build progressed, the team documented the steps taken to install and configure each component of the build. The team then conducted functional testing of the builds, including demonstrating the ability to retrieve a device's MUD file and use it to determine what traffic the device will be permitted to send and receive. We verified that attempts to perform prohibited communications would be blocked. The team conducted a risk assessment and a security characteristics analysis and documented the results, including mapping the security contributions of the demonstrated approach to the *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity

Framework) and other relevant standards. Finally, the NCCoE worked with industry collaborators to suggest considerations for enhancing future support for MUD.

3.1 Audience

The focus of this project is on home and small-business deployments. Its solution is targeted to address the needs of home and small-business networks, which have users who cannot be assumed to have extensive network administration experience and who therefore require plug-and-play functionality. Although the focus of this project is on home and small-business network applications, home and small-business network users are not intended to be this guide's primary audience. This guide is intended for the following types of organizations that provide products and services to homes and small businesses:

- IoT device developers and manufacturers
- network equipment developers and manufacturers
- service providers that employ MUD-capable components

3.2 Scope

The scope of this NCCoE project is IoT deployments in those home and small-business applications where plug-and-play deployment is required. The demonstrated approach includes MUD-capable IoT devices that interact with traditional computing devices, as permitted by their MUD files, and also interact with external systems to access update servers and various cloud services. It employs both MUD-capable and non-MUD-capable IoT devices, such as smart lighting controllers, cameras, smartphones, printers, baby monitors, digital video recorders, and smart assistants.

The primary focus of this project is on the technical feasibility of implementing MUD to mitigate network-based attacks. We show use of threat signaling to protect both MUD-capable devices and devices that are not MUD capable from known threats.

The reference architecture for the demonstrated approach includes support for automatic secure software updates. All builds include a server that is meant to represent an update server to which MUD will permit devices to connect. However, demonstrations of actual IoT device software updates and patching were not included in the scope of the project.

Providing security protections for each of the components deployed in the demonstrated approach is important. However, demonstrating these protections are outside the scope of this project. It is assumed that network owners deploying the architecture will implement best practices for securing it. Also, governance, operational, life cycle, cost, legal, and privacy issues are outside the project's current scope.

3.3 Assumptions

It is assumed that:

- IoT devices, by definition, are not general-purpose devices.
- Each IoT device has an intended function, and this function is specific enough that the device's communication requirements can be defined accurately and completely.
- An IoT device's communication should be limited to only what is required for the device to perform its function.
- Cost is a major factor affecting consumer purchasing decisions and consequent product development decisions. Therefore, it is assumed that IoT devices will not typically include organic support for all their own security needs and would therefore benefit from protections provided by outside mechanism, such as MUD.
- IoT device manufacturers will use the MUD file mechanism to indicate the communications that each device needs.
- Network routers can be automatically configured to enforce these communications so that
    - intended communications are permitted
    - unintended communications are prohibited
- If all MUD-capable network components are deployed and functioning as intended, a malicious actor would need to compromise one of the systems with which an IoT device is permitted to communicate to launch a network-based attack on the device. If a device were to be compromised, it could be used in a network-based attack only against systems with which it is permitted to communicate.
- Network owners who want to provide the security protections demonstrated in this project will:
    - be able to acquire and deploy all necessary components of the architecture on their own network, including MUD-capable IoT devices, a MUD manager, a MUD-capable gateway/router/switch, and a threat-signaling-capable gateway/router/switch
    - have access to MUD file servers that host the MUD files for their IoT devices, update servers, threat-signaling servers, and current threat intelligence
- All deployed architecture components are secure and can be depended upon to perform as designed.
- Best practices for administrative access and security updates will be implemented, and these will reduce the success rate of compromise attempts.

3.4 Risk Assessment

NIST SP 800-30 Revision 1, *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 event 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, *Risk Management Framework for Information Systems and Organizations*—material that is available to the public. The Risk Management Framework (RMF) guidance, as a whole, proved to be invaluable in giving us a baseline to assess risks, from which we developed the project, the security characteristics of the builds, and this guide.

Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks, NIST Interagency or Internal Report (NISTIR) 8228, identified security and privacy considerations and expectations that, together with the *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity Framework) and *Security and Privacy Controls for Federal Information Systems and Organizations* (NIST SP 800-53) informed our risk assessment and subsequent recommendations from which we developed the security characteristics of the builds, and this guide.

3.4.1 Threats

Historically, internet devices have enjoyed full connectivity at the network and transport layers. Any pair of devices with valid internet protocol (IP) addresses was, in general, able to communicate by using transmission control protocol (TCP) for connection-oriented communications or user datagram protocol (UDP) for connectionless protocols. Full connectivity was a practical architectural option for fully featured devices (e.g., servers and personal computers) because the identity of communicating hosts depended largely on the needs of inherently unpredictable human users. Requiring a reconfiguration of hosts to permit communications to meet the needs of system users as they evolved was not a scalable solution. However, a combination of whitelisting device capabilities and blacklisting devices or domains that are considered suspicious allowed network administrators to mitigate some threats.

With the evolution of internet hosts from multiuser systems to personal devices, this security posture became impractical, and the emergence of IoT has made it unsustainable. In typical networking environments, a malicious actor can detect an IoT device and launch an attack on that device from any system on the internet. Once compromised, that device can be used to attack any other system on the internet. Anecdotal evidence indicates that a new device will be detected and will experience its first attack within minutes of deployment. Because the devices being deployed often have known security flaws, the success rate for compromising detected systems is very high. Typically, malware is designed to compromise a list of specific devices, making such attacks very scalable. Once compromised, an IoT device can be used to compromise other internet-connected devices, launch attacks on any victim device on the internet, or launch attacks on devices within the local network hosting the device.

3.4.2 Vulnerabilities

The vulnerability of IoT devices in this environment is a consequence of full connectivity, exacerbated by the large number of security vulnerabilities in complex software systems. Modern systems ship with millions of lines of code, creating a target-rich environment for malicious actors. Some vendors provide patches for security vulnerabilities and an efficient means for securely updating their products. However, patches are often unavailable or nearly impossible to install on many other products, including many IoT devices. In addition, poorly designed and implemented default configuration baselines and administrative access controls, such as hard-coded or widely known default passwords, provide a large attack surface for malicious actors. Many IoT devices include those types of vulnerabilities. The Mirai malware, which launched a large DDoS attack on the internet infrastructure firm Dyn that took many of the Internet's top destinations offline for much of a day, relied heavily on hard-coded administrative access to assemble botnets consisting of more than 100,000 devices.

3.4.3 Risk

The demonstrated approach implements a set of protocols designed to permit users and product support staff to constrain access to MUD-capable IoT devices. A network that includes IoT devices will be vulnerable to exploitation if some but not all IoT devices are MUD-capable. MUD may help prevent a compromised IoT device from doing harm to other systems on the network, and a device acting out of profile may indicate that it is compromised. However, MUD does not necessarily help owners to find and identify already-compromised systems, and it does not help owners correct compromised systems without replacing or reprogramming existing system components. For example, if a system is compromised so that it emits a new URL referencing a MUD file that permits malicious actors to send traffic to and from the IoT device, MUD may not be able to help owners detect such compromised systems and stop the communications that should be prohibited. However, if a system is compromised but it is still emitting the correct MUD URL, MUD can detect and stop any unauthorized communications that the device attempts. Such attempts would also indicate potential compromises.

If a network is set up so that it uses legacy IoT devices that do not emit MUD URLs, these devices could be associated with MUD URLs or with MUD files themselves by using alternative means, such as a device serial number or a public key. If the device is compromised and attempts unauthorized communication, the attempt should be detected, and the device would be subjected to the constraints specified in its MUD file. Under these circumstances, MUD can permit the owner to find and identify already-compromised systems. Moreover, where threat signaling is employed, a compromised system that reaches back to a known malicious IP address can be detected, and the connection can be refused.

4 Architecture

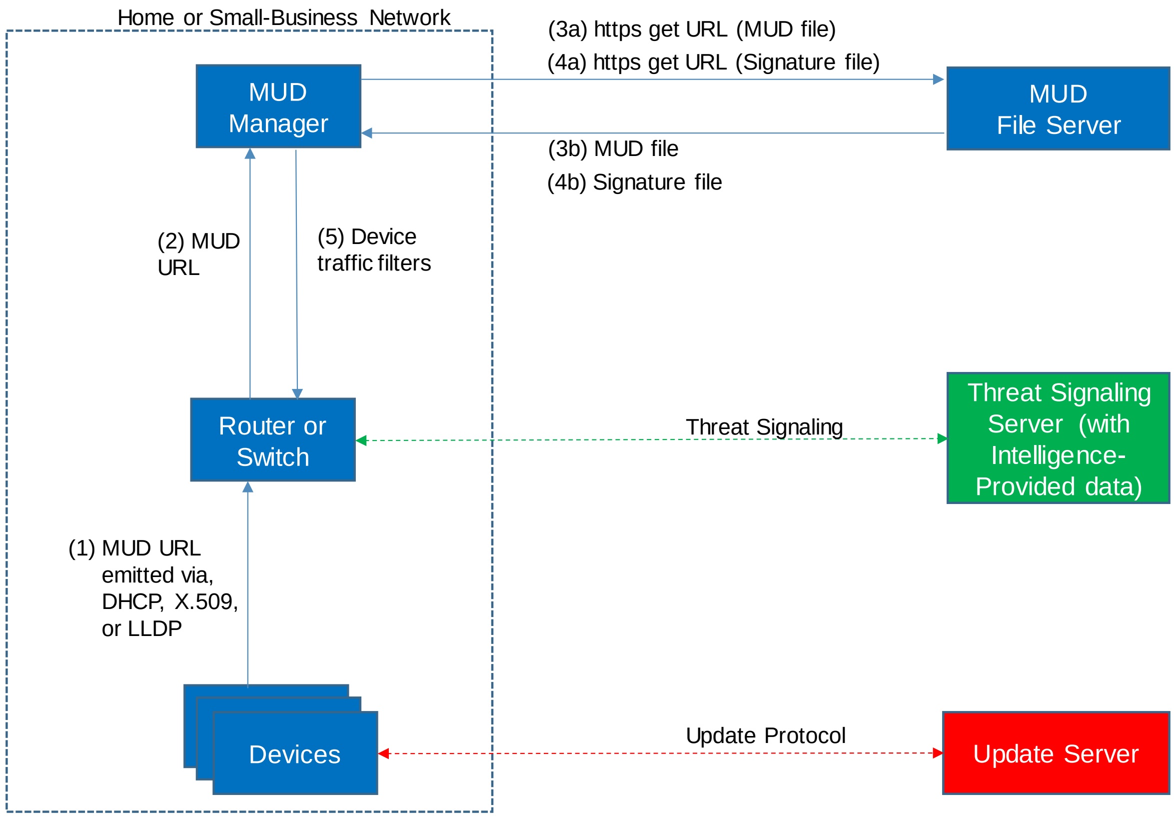
The project architecture is intended for home and small-business networks that are composed of both IoT components and fully featured devices (e.g., personal computers). The architecture is designed to provide three forms of protection:

- use of the MUD specification to automatically permit an IoT device to send and receive only the traffic it requires to perform as intended, thereby reducing the potential for the device to be the victim of a communications-based malware exploit or other network-based attack, and reducing the potential for the device, if compromised, to be used in a DDoS or other network-based attack
- use of network-wide access controls based on threat signaling to protect legacy (non-MUD-capable) IoT devices and fully featured devices, in addition to MUD-capable IoT devices, from connecting to domains that are known current threats
- automated secure software updates to all devices to ensure that operating system patches are installed promptly

4.1 Reference Architecture

Figure 4-1 depicts the logical architecture of the reference design. It consists of three main components: support for MUD, support for threat signaling, and support for periodic updates.

Figure 4-1 Reference Architecture



4.1.1 Support for MUD

A new functional component, the MUD manager, is introduced to augment the existing networking functionality offered by the home/small-business network router or switch. Note that the MUD manager is a logical component. Physically, the functionality that the MUD manager provides can and often is combined with that of the network router in a single device.

IoT devices must somehow be associated with a MUD file. The MUD specification describes three possible mechanisms through which the IoT device can provide the MUD file URL to the network: inserting the MUD URL into DHCP address requests that they generate when they attach to the network (e.g., when powered on), providing the MUD URL in a Link Layer Discovery Protocol (LLDP) frame, or providing the MUD URL as a field in an X.509 certificate that the device provides to the network via a protocol such as Tunnel Extensible Authentication Protocol (TEAP). Each of these MUD URL emission mechanisms is listed as a possibility in Figure 4-1. In addition, the MUD specification provides flexibility to enable other mechanisms by which MUD file URLs can be associated with IoT devices.

Figure 4-1 uses labeled arrows to depict the steps involved in supporting MUD:

- The IoT device emits a MUD URL by using a mechanism such as DHCP, LLDP, or X.509 certificate (step 1).
- The router extracts the MUD URL from the protocol frame of whatever mechanism was used to convey it and forwards this MUD URL to the MUD manager (step 2).
- Once the MUD URL is received, the MUD manager uses https to request the MUD file from the MUD file server by using the MUD URL provided in the previous step (step 3a); if successful, the MUD file server at the specified location will serve the MUD file (step 3b).
- Next, the MUD manager uses https to request the signature file associated with the MUD file (step 4a) and upon receipt (step 4b) verifies the MUD file by using its signature file.
- The MUD file describes the communications requirements for the IoT device. Once the MUD manager has determined the MUD file to be valid, the MUD manager converts the access control rules in the MUD file into access control entries (e.g., access control lists—ACLs, firewall rules, or flow rules) and installs them on the router or switch (step 5).

Once the device's access control rules are applied to the router or switch, the MUD-capable IoT device will be able to communicate with approved local hosts and internet hosts as defined in the MUD file, and any unapproved communication attempts will be blocked.

As described in the MUD specification, the MUD file rules can limit both traffic between the device and external internet domains (north/south traffic), as well as traffic between the device and other devices on the local network (east/west traffic). East/west traffic can be limited using the following constructs:

- controller—class of devices known to be controllers (could describe well-known services such as DNS or Network Time Protocol [NTP])
- my-controller—class of devices that the local network administrator admits to the class
- local-networks—class of IP addresses that are scoped within some local administrative boundary
- same-manufacturer—class of devices from the same manufacturer as the IoT device in question
- manufacturer—class of devices made by a particular manufacturer as identified by the authority component of its MUD URL

It is worth noting that while MUD requires use of a MUD-capable router on the local network, whether this router is standalone equipment provided by a third-party network equipment vendor (as is the case in Builds 1, 2, and 4) or integrated with the service provider's residential gateway equipment (Build 3) is not relevant to the ability of MUD to protect the network. While a service provider will be free to provide support for MUD in its internet gateway equipment and infrastructure, such ISP support is not necessary. A home or small business network can benefit from the protections that MUD has to offer without ISPs needing to make any changes or provide any support other than basic internet connectivity.

4.1.2 Support for Updates

To provide additional security, the reference architecture also supports periodic updates. All builds include a server that is meant to represent an update server to which MUD will permit devices to connect. Each device on an operational network should be configured to periodically contact its update server to download and apply security patches, ensuring that it is running the most up-to-date and secure code available. To ensure that such updates are possible, an IoT device's MUD file must explicitly permit the IoT device to receive traffic from the update server. Although regular manufacturer updates are crucial to security, the builds described in this practice guide demonstrate only the ability for IoT devices to receive faux updates from a notional update server. Communications between IoT devices and their corresponding update servers are not standardized.

4.1.3 Support for Threat Signaling

To provide additional protection for both MUD-capable and non-MUD-capable devices, the reference architecture also envisions support for threat signaling. The router or switch can receive threat feeds from a notional threat-signaling server to use as a basis for restricting certain types of network traffic. For example, both MUD-capable and non-MUD-capable devices can be prevented from connecting to internet domains that have been identified as being potentially malicious. Communications between the threat-signaling server and the router/switch are not standardized.

4.1.4 Build-Specific Features

The reference architecture depicted in Figure 4-1 is intentionally general. Each build instantiates this reference architecture in a unique way, depending on the equipment used and the capabilities supported. While all three builds support MUD and the ability to receive faux updates from a notional update server, only Build 2 currently supports threat signaling. In addition, Build 1 and Build 2 include nonstandard device discovery technology to discover, inventory, profile, and classify attached devices. Such classification can be used to validate that the access that is being granted to each device is consistent with that device's manufacturer and model. In Build 2, a device's manufacturer and model can be used as a basis for identifying and enforcing that device's traffic profile.

The four builds of the reference architecture that have been undertaken, three of which are complete and have been demonstrated, are as follows:

- Build 1 uses products from Cisco Systems, DigiCert, Forescout, and Molex. The Cisco MUD manager is used to support MUD, and the Forescout virtual appliances and enterprise manager are used to perform non-MUD-related device discovery on the network. Molex Power over Ethernet (PoE) Gateway and Light Engine is used as a MUD-capable IoT device. Certificates from DigiCert are also used.
- Build 2 uses products from MasterPeace Solutions Ltd., GCA, ThreatSTOP, and DigiCert. The MasterPeace Solutions Yikes! router, cloud service, and mobile application support MUD as

well as perform device discovery on the network and apply additional traffic rules to both MUD-capable and non-MUD-capable devices based on device manufacturer and model. The Yikes! router also integrates with the GCA Quad9 DNS service and the ThreatSTOP threat MUD file server to prevent devices (MUD-capable or not) from connecting to domains that have been identified as potentially malicious based on current threat intelligence. Certificates from DigiCert are also used.

- Build 3, which is still under development, uses products supplied by CableLabs to support MUD. It will leverage the Wi-Fi Alliance Easy Connect specification to securely onboard devices to the network. It will also use software-defined networking to create separate trust zones (e.g., network segments) to which devices are assigned according to their intended network function. Although limited functionality of a preliminary version of this build was demonstrated as part of this project, Build 3 is not yet complete. Therefore, it has not yet been subjected to functional evaluation or demonstration. A brief preview of the architecture and functional elements planned for Build 3 is provided in this practice guide. Full documentation of Build 3 is planned for inclusion in the next phase of this project.
- Build 4 uses software developed at the NIST Advanced Networking Technologies laboratory. This software supports MUD and is intended to serve as a working prototype of the MUD RFC to demonstrate feasibility and scalability. Certificates from DigiCert are also used.

The logical architectures and detailed descriptions of Builds 1, 2, and 4 can be found in Section 6 (Build 1), Section 7 (Build 2), and Section 9 (Build 4). Build 3 is described briefly in Section 8.

4.2 Physical Architecture

Figure 4-2 depicts the high-level physical architecture of the NCCoE laboratory environment. This implementation currently supports four builds and has the flexibility to implement additional builds in the future. As depicted, the NCCoE laboratory network is connected to the internet via the NIST data center. Access to and from the NCCoE network is protected by a firewall. The NCCoE network includes a shared virtual environment that houses an update server, a MUD file server, an unapproved server (i.e., a server that is not listed as a permissible communications source or destination in any MUD file), a Message Queuing Telemetry Transport (MQTT) broker server, and a Forescout enterprise manager. These components are hosted at the NCCoE and are used across builds where applicable. The Transport Layer Security (TLS) certificate and Premium Certificate used by the MUD file server are provided by DigiCert.

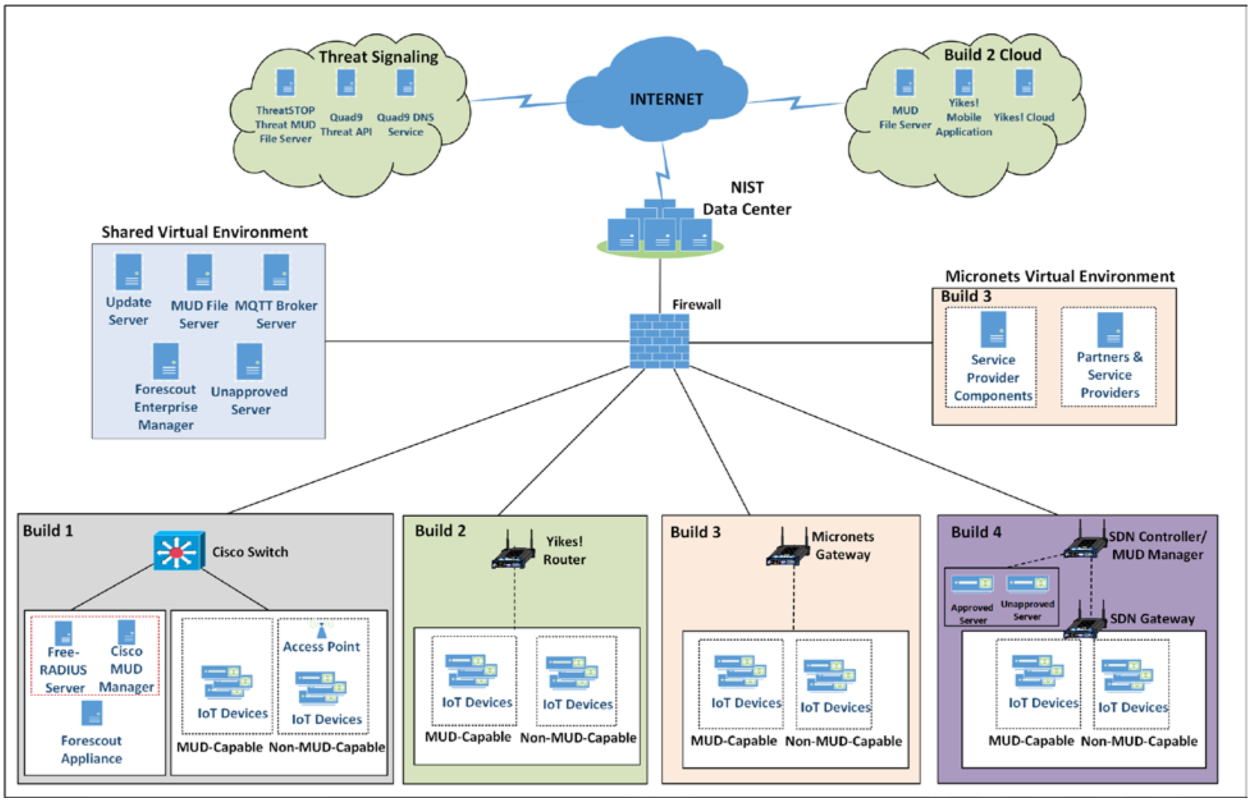
All four builds, as depicted in the diagram, have been implemented, but only three are complete:

- Build 1 network components consist of a Cisco Catalyst 3850-S switch, a Cisco MUD manager, a FreeRADIUS server, and a virtualized Forescout appliance on the local network. Build 1 also requires support from all components that are in the shared virtual environment, including the Forescout enterprise manager.

- Build 2 network components consist of a MasterPeace Solutions Ltd. Yikes! router on the local network. Build 2 requires support from the MUD file server, Yikes! cloud, and a Yikes! mobile application that are resident on the Build 2 cloud. The Yikes! router includes threat-signaling capabilities (not depicted) that have been integrated with it. Build 2 also requires support from threat-signaling cloud services that consist of the ThreatSTOP threat MUD file server, Quad9 threat application programming interface (API), and Quad9 DNS service. Build 2 uses only the update server and unapproved server components that are in the shared virtual environment.
- Build 3 is still under development and is expected to be completed by the next phase of this project. As of this writing, this build's network components consist of a CableLabs Micronets Gateway/wireless access point (AP) that resides on the local network and that operates in conjunction with various service provider components and partner/service provider offerings that reside in the Micronets virtual environment.
- Build 4 network components consist of a software-defined networking (SDN)-capable gateway/switch on the local network, and an SDN controller/MUD manager and approved and unapproved servers that are located remotely from the local network. Build 4 also uses the MUD file server that is resident in the shared virtual environment.

IoT devices used in all four builds include both MUD-capable and non-MUD-capable. The MUD-capable IoT devices used, which vary across builds, include Raspberry Pi, ARTIK, u-blox, Intel UP Squared, BeagleBone Black, NXP i.MX 8M (devkit), and the Molex Light Engine controlled by PoE Gateway. Non-MUD-capable devices used, which also vary across builds, include a wireless access point, cameras, a printer, smartphones, lighting devices, a smart assistant device, a baby monitor, and a digital video recorder. Each of the completed builds and the roles that their components play in their architectures are explained in more detail in Section 6 (Build 1), Section 7 (Build 2), and Section 9 (Build 4). Build 3 is described briefly in Section 8.

Figure 4-2 Physical Architecture



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 the ability to identify IoT components to MUD managers and manage access to those components while limiting unauthorized access to and from the components. In addition, it seeks to understand the security benefits of the demonstrated approach.

5.1 Assumptions and Limitations

The security characteristic analysis has the following limitations:

- It is neither a comprehensive test of all security components nor a red-team exercise.
- It cannot identify all weaknesses.
- It does not include the lab infrastructure. It is assumed that devices are hardened. Testing these devices would reveal only weaknesses in implementation that would not be relevant to those adopting this reference architecture.

5.2 Security Control Map

One aspect of the security characteristic analysis involved assessing how well the reference design addresses the security characteristics that it was intended to support. The NIST Cybersecurity Framework Subcategories were used to provide structure to the security assessment. We consulted the specific sections of each standard that are cited in reference to a Subcategory. The cited sections provide validation points that the example implementations would be expected to exhibit. Using the Cybersecurity Framework Subcategories as a basis for organizing our analysis allowed us to systematically consider how well the reference design supports the intended security characteristics.

The characteristics analysis was conducted in the context of home network and small-business usage scenarios.

The capabilities demonstrated by the architectural elements described in Section 4 and used in the home networks and small-business environments are primarily intended to address requirements, best practices, and capabilities described in the following NIST documents: *Framework for Improving Critical Infrastructure Cybersecurity* (NIST Cybersecurity Framework), *Security and Privacy Controls for Federal Information Systems and Organizations* (NIST Special Publication [SP] 800-53), and *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks* (NIST Interagency or Internal Report 8228). NISTIR 8228 identifies a set of 25 security and privacy expectations for IoT devices and subsystems. These include expectations regarding meeting device protection, data protection, and privacy protection goals. The reference architecture directly addresses the PR.AC-1, PR.AC-2, PR.AC-3, PR.AC-7, and PR.PT-3 Cybersecurity Framework Subcategories and supports activities addressing the ID.AM-1, ID.AM-2, ID.AM-3, ID.RA-2, ID.RA-3, PR.AC-5, PR.AC-4, PR.DS-5, PR.DS-6, PR.IP-1, PR.IP-3, and DE.CM-8 Subcategories. Also, the security platform directly addresses NIST SP 800-53 controls AC-3, AC-18, CM-7, SC-5, SC-7, SC-23, and SI-2, and it supports activities addressing NIST SP 800-53 controls AC-4, AC-6, AC-24, CM-7, CM-8, IA-2, IA-5, IA-8, PA-4, PM-5, RA-5, SC-8, and SI-5. In addition, seven of the NISTIR 8228 expectations are addressed by the example implementation. Table 5-1 describes how MUD-specific example implementation characteristics address NISTIR 8228 expectations, NIST SP 800-53 controls, and NIST Cybersecurity Framework Subcategories.

Table 5-1 Mapping Characteristics of the Demonstrated Approach, as Instantiated in at Least One of Builds 1-4, to NISTIR 8228 Expectations, NIST SP 800-53 Controls, and NIST Cybersecurity Framework Subcategories

Applicable Project Description Element That Addresses the Expectation	Applicable NISTIR 8228 Expectations	NIST SP 800-53 Controls Supported	Cybersecurity Framework Subcategories Supported
There exists some mechanism for associating each device with a URL that can be used to identify and locate its MUD file. The device itself may emit the MUD file URL in one of three ways: • IoT devices insert the MUD URL into DHCP address requests when the device attaches to the network (e.g., power on) (Build 1, Build 2, and Build 4) • MUD URL is provided in LLDP (Build 1) • MUD URL is included in X.509 certificate (Build 3) However, there may be other means for a MUD URL to be learned by a network, and the MUD specification is designed to allow flexibility in this regard.	Device has a built-in identifier.	Supports CM-8 System Component Inventory PM-5 System Inventory	Supports ID.AM-1 Physical devices and systems within the organization are inventoried.
The MUD file URL, which identifies the device type, among other things, is passed to the MUD manager, which retrieves a MUD file by using https. The MUD file describes the communications requirements for this device. The MUD manager converts the requirements into access control information for enforcement by the router or switch. (all builds)	Device can interface with enterprise asset management systems.	Provides AC-3 Access Enforcement AC-18 Wireless Access CM-7 Least Functionality SC-5 Denial of Service Protection SC-7 Boundary Protection	Provides PR.PT-3 The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. Supports ID.AM-1 Physical devices and systems within the organization are inventoried.

Applicable Project Description Element That Addresses the Expectation	Applicable NISTIR 8228 Expectations	NIST SP 800-53 Controls Supported	Cybersecurity Framework Subcategories Supported
		Supports AC-4 Information Flow Enforcement AC-6 Least Privilege AC-24 Access Control Decisions CM-8 System Component Inventory PM-5 System Inventory	ID.AM-2 Software platforms and applications within the organization are inventoried. ID.AM-3 Organizational communication and data flows are mapped. PR.AC-4 Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. PR.AC-5 Network integrity is protected (e.g., network segregation, network segmentation). PR.DS-5 Protections against data leaks are implemented. DE.AE-1 A baseline of network operations and expected data flows for users

Applicable Project Description Element That Addresses the Expectation	Applicable NISTIR 8228 Expectations	NIST SP 800-53 Controls Supported	Cybersecurity Framework Subcategories Supported
			and systems is established and managed.
IoT devices periodically contact the appropriate update server to download and apply security patches. (all builds)	The manufacturer will provide patches or upgrades for all software and firmware throughout each device's life span.	Provides SI-2 Flaw Remediation	Supports PR.IP-1 A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). PR.IP-3 Configuration change control processes are in place.
The router or switch receives threat feeds from the threat-signaling server to use as a basis for restricting certain types of network traffic. (Build 2)	The device either supports the use of vulnerability scanners or provides built-in vulnerability identification and reporting capabilities.	Supports AC-24 Access Control Decisions RA-5 Vulnerability Scanning SI-5 Security Alerts, Advisories, and Directives	Supports ID.RA-2 Cyber threat intelligence is received from information-sharing forums and sources. ID.RA-3 Threats, both internal and external, are identified and documented. DE.CM-8 Vulnerability scans are performed.

Applicable Project Description Element That Addresses the Expectation	Applicable NISTIR 8228 Expectations	NIST SP 800-53 Controls Supported	Cybersecurity Framework Subcategories Supported
The MUD file URL is passed to the MUD manager, which retrieves a MUD file from the designated website (denoted as the MUD file server) by using https. The MUD file server must have a valid TLS certificate, and the MUD file itself must have a valid signature. The MUD file describes the communications requirements for this device. The MUD manager converts the requirements into access control information for enforcement by the router or switch. (all builds)	The device can use existing enterprise authenticators and authentication mechanisms.	Supports IA-2 Identification and Authentication (Organizational Users) IA-5 Authenticator Management IA-8 Identification and Authentication (Non-Organizational Users)	Provides PR.AC-1 Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes. PR.AC-3 Remote access is managed. PR.AC-7 Users, devices, and other assets are authenticated commensurate with the risk of the transaction.
There exists some mechanism for associating each device with a URL that can be used to identify and locate its MUD file. The MUD file URL is passed to the MUD manager, which retrieves a MUD file from the designated website (denoted as the MUD file server) by using https. The MUD file describes the communications requirements for this device. The MUD manager converts the requirements into access control information for enforcement by the router or switch. (all builds)	Device can prevent unauthorized access to all sensitive data transmitted from it over networks.	Provides SC-23 Session Authenticity Supports AC-18 Wireless Access SC-8 Transmission Confidentiality and Integrity	Provides PR.PT-3 The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. Supports PR.DS-5 Protections against data leaks are implemented. PR.DS-6 Integrity-checking

Applicable Project Description Element That Addresses the Expectation	Applicable NISTIR 8228 Expectations	NIST SP 800-53 Controls Supported	Cybersecurity Framework Subcategories Supported
			mechanisms are used to verify software, firmware, and information integrity.
There exists some mechanism for associating each device with a URL that can be used to identify and locate its MUD file. The MUD file URL is passed to the MUD manager, which retrieves a MUD file from the designated website (denoted as the MUD file server) by using https. The MUD file describes the communications requirements for this device. The MUD manager converts the requirements into access control information for enforcement by the router or switch. (all builds) The router or switch periodically receives threat feeds from the threat-signaling server to use as a basis for restricting certain types of network traffic. (Build 2)	There is sufficient centralized control to apply policy or regulatory requirements to personally identifiable information.	Supports PA-4 Information Sharing with External Parties	None

Table 5-2 details Cybersecurity Framework Identify, Protect, and Detect Categories and Subcategories that the example implementations directly address or for which the example implementations may serve a supporting role. Those Subcategories that are directly addressed are highlighted in green. Informative references are made for each subcategory. The following sources are used for informative references: Center for Internet Security (CIS), Control Objectives for Information and Related Technology (COBIT), International Society of Automation (ISA), International Organization for Standardization/International Electrotechnical Commission (ISO/IEC), and NIST SP 800-53. While some of the references provide general guidance that informs implementation of referenced Cybersecurity Framework Core Functions, the NIST SP and Federal Information Processing Standard (FIPS) references provide specific recommendations that should be considered when composing and configuring security platforms. (Note that not all of the informative references apply to this example implementation.)

Table 5-2 Mapping Project Objectives to the Cybersecurity Framework and Informative Security Control References

Cybersecurity Framework Category	Cybersecurity Framework 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.	**CIS** 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, PM-5
	ID.AM-2: Software platforms and applications within the organization are inventoried.	**CIS** CSC 2 **COBIT 5** BAI09.01, BAI09.02, BAI09.05 **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, A.12.5.1 **NIST SP 800-53 Rev. 4** CM-8, PM-5
	ID.AM-3: Organizational communication and data flows are mapped.	**CIS** CSC 12 **COBIT 5** DSS05.02 **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, A.12.5.1 **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8
Risk Assessment (ID.RA): The organization understands the cybersecurity risk to organizational operations (including mission, functions, image, or reputation), organizational assets, and individuals.	**ID.RA-2:** Cyber threat intelligence is received from information-sharing forums and sources.	**CIS** CSC 4 **COBIT 5** BAI08.01 **ISA 62443-2-1:2009** 4.2.3, 4.2.3.9, 4.2.3.12 **ISO/IEC 27001:2013** A.6.1.4 **NIST SP 800-53 Rev. 4** SI-5, PM-15, PM-16
	ID.RA-3: Threats, both internal and external, are identified and documented.	**CIS** CSC 4 **COBIT 5** APO12.01, APO12.02, APO12.03, APO12.04 **ISA 62443-2-1:2009** 4.2.3, 4.2.3.9, 4.2.3.12

Cybersecurity Framework Category	Cybersecurity Framework Subcategory	Informative References
		ISO/IEC 27001:2013 Clause 6.1.2 **NIST SP 800-53 Rev. 4** RA-3, SI-5, PM-12, PM-16
Identity Management, Authentication, and Access Control (PR.AC): Access to physical and logical assets and associated facilities is limited to authorized users, processes, and devices and is managed consistent with the assessed risk of unauthorized access to authorized activities and transactions.	**PR.AC-1:** Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users, and processes.	**CIS** CSC 1, 5, 15, 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.9.2.3, A.9.2.4, A.9.2.6, A.9.3.1, A.9.4.2, A.9.4.3 **NIST SP 800-53 Rev. 4** AC-1, AC-2, IA-1, IA-2, IA-3, IA-4, IA-5, IA-6, IA-7, IA-8, IA-9, IA-10, IA-11
	PR.AC-3: Remote access is managed.	**CIS** CSC 12 **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.6.2.1, A.6.2.2, A.11.2.6, A.13.1.1, A.13.2.1 **NIST SP 800-53 Rev. 4** AC-1, AC-17, AC-19, AC-20, SC-15
	PR.AC-4: Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties.	**CIS** CSC 3, 5, 12, 14, 15, 16, 18 **COBIT 5** DSS05.04 **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, A.9.4.5 **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24
	PR.AC-5: Network integrity is protected, incorporating network segregation where appropriate.	**CIS** CSC 9, 14, 15, 18 **COBIT 5** DSS01.05, DSS05.02 **ISA 62443-2-1:2009** 4.3.3.4 **ISA 62443-3-3:2013** SR 3.1, SR 3.8 **ISO/IEC 27001:2013** A.13.1.1, A.13.1.3, A.13.2.1, A.14.1.2, A.14.1.3

Cybersecurity Framework Category	Cybersecurity Framework Subcategory	Informative References
		NIST SP 800-53 Rev. 4 AC-4, AC-10, SC-7
	PR.AC-7: Users, devices, and other assets are authenticated (e.g., single-factor, multifactor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks).	**CIS** CSC 1, 12, 15, 16 **COBIT 5** DSS05.04, DSS05.10, DSS06.10 **ISA 62443-2-1:2009** 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 **ISA 62443-3-3:2013** SR 1.1, SR 1.2, SR 1.5, SR 1.7, SR 1.8, SR 1.9, SR 1.10 **ISO/IEC 27001:2013** A.9.2.1, A.9.2.4, A.9.3.1, A.9.4.2, A.9.4.3, A.18.1.4 **NIST SP 800-53 Rev. 4** AC-7, AC-8, AC-9, AC-11, AC-12, AC-14, IA-1, IA-2, IA-3, IA-4, IA-5, IA-8, IA-9, IA-10, IA-11
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.	**CIS** CSC 13 **COBIT 5** APO01.06, DSS05.04, DSS05.07, DSS06.02 **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.10.1.1, A.11.1.4, A.11.1.5, A.11.2.1, A.13.1.1, 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
	PR.DS-6: Integrity-checking mechanisms are used to verify software, firmware, and information integrity.	**ISA 62443-3-3:2013** SR 3.1, SR 3.3, SR 3.4, SR 3.8 **ISO/IEC 27001:2013** A.12.2.1, A.12.5.1, A.14.1.2, A.14.1.3 **FIPS 140-2** Sec. 4 **NIST SP 800-45 Ver. 2** 2.4.2, 3, 4.2.3, 4.3, 5.1, 6.1, 7.2.2, 8.2, 9.2 **NIST SP 800-49** 2.2.1, 2.3.2, 3.4

Cybersecurity Framework Category	Cybersecurity Framework Subcategory	Informative References
		NIST SP 800-52 Rev. 1 3, 4, D1.4 **NIST SP 800-53 Rev. 4** SI-7 **NIST SP 800-57 Part 1 Rev. 4** 5.5, 6.1, 8.1.5.1, B.3.2, B.5 **NIST SP 800-57 Part 2** 1, 3.1.2.1.2, 4.1, 4.2, 4.3, A.2.2, A.3.2, C.2.2 **NIST SP 800-81-2** All **NIST SP 800-130** 2.2, 4.3, 6.2.1, 6.3, 6.4, 6.5, 6.6.1 **NIST SP 800-152** 6.1.3, 6.2.1, 8.2.1, 8.2.4, 9.4 **NIST SP 800-177** 2.2, 4.1, 4.4, 4.5, 4.7, 5.2, 5.3
Information Protection Processes and Procedures (PR.IP): Security policies (that address purpose, scope, roles, responsibilities, management commitment, and coordination among organizational entities), processes, and procedures are maintained and used to manage protection of information systems and assets.	**PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality).	**CIS** CSC 1 **COBIT 5** BAI10.01, BAI10.02, BAI10.03, BAI10.05 **ISA 62443-2-1:2009** 4.3.4.3.2, 4.3.4.3.3 **ISA 62443-3-3:2013** SR 7.6 **ISO/IEC 27001:2013** A.12.1.2, A.12.5.1, A.12.6.2, A.14.2.2, A.14.2.3, A.14.2.4 **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10
	PR.IP-3: Configuration change control processes are in place.	**CIS** CSC 3, 11 **COBIT 5** BAI01.06, BAI06.01 **ISA 62443-2-1:2009** 4.3.4.3.2, 4.3.4.3.3 **ISA 62443-3-3:2013** SR 7.6 **ISO/IEC 27001:2013** A.12.1.2, A.12.5.1, A.12.6.2, A.14.2.2, A.14.2.3, A.14.2.4 **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10

Cybersecurity Framework Category	Cybersecurity Framework 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-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities.	**CIS** CSC 3, 11, 14 **COBIT 5** DSS05.02, DSS05.05, DSS06.06 **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
Security Continuous Monitoring (DE.CM): The information system and assets are monitored to identify cybersecurity events and verify the effectiveness of protective measures.	**DE.CM-8:** Vulnerability scans are performed.	**CIS** CSC 4, 20 **COBIT 5** BAI03.10, DSS05.01 **ISA 62443-2-1:2009** 4.2.3.1, 4.2.3.7 **ISO/IEC 27001:2013** A.12.6.1 **NIST SP 800-53 Rev. 4** RA-5

Additional resources required to develop this solution are identified in Appendix C. The core standards, secure update standards, industry best practices for software quality, and best practices for identification and authentication are generally stable, well understood, and available in the commercial off-the-shelf market. Standards associated with the MUD protocol are in an advanced level of development by the IETF.

5.3 Scenarios

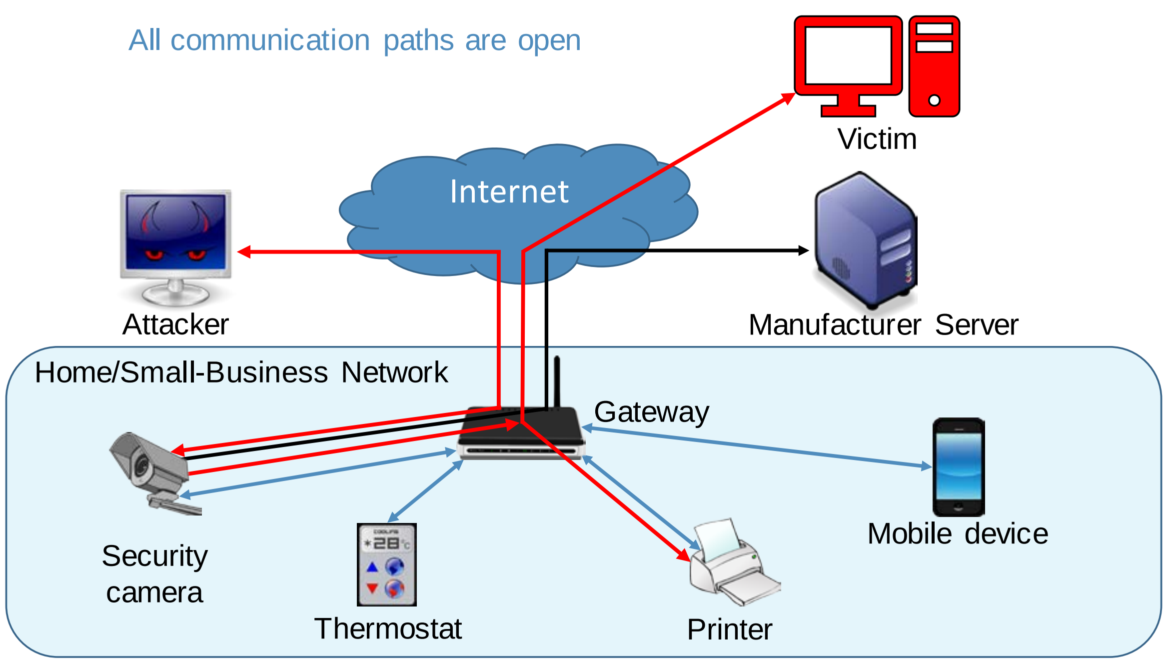
This section presents two scenarios involving home and small-business networks that have IoT devices. In the first scenario, MUD is not deployed on the network, so IoT devices are vulnerable to being port scanned and are not restricted from exchanging traffic with either external sites or other devices on the local network. IoT devices in this first scenario are highly vulnerable to attack. Threat signaling is not deployed either, so none of the devices on the local network are being protected from traffic sent from known malicious actors.

In the second scenario, both MUD and threat signaling are deployed on the network. The MUD files are being used to restrict traffic from being sent between the local IoT devices and some external internet domains (i.e., north/south traffic) as well as traffic among the local IoT devices themselves (i.e., east/west traffic). MUD ensures that the IoT devices are permitted to exchange traffic with only external domains and internal devices that are explicitly specified in their MUD file. Use of threat signaling protects all devices, not just IoT devices, from communicating with sites that are known to be malicious.

5.3.1 Scenario 1: No MUD or Threat-Signaling Protection

In the No MUD or Threat-Signaling Protection scenario, as shown in Figure 5-1, the home/small-business network (depicted by the light blue rectangular box) does not have MUD deployed to provide security for its IoT devices, nor does it use threat signaling.

Figure 5-1 No MUD or Threat-Signaling Protection

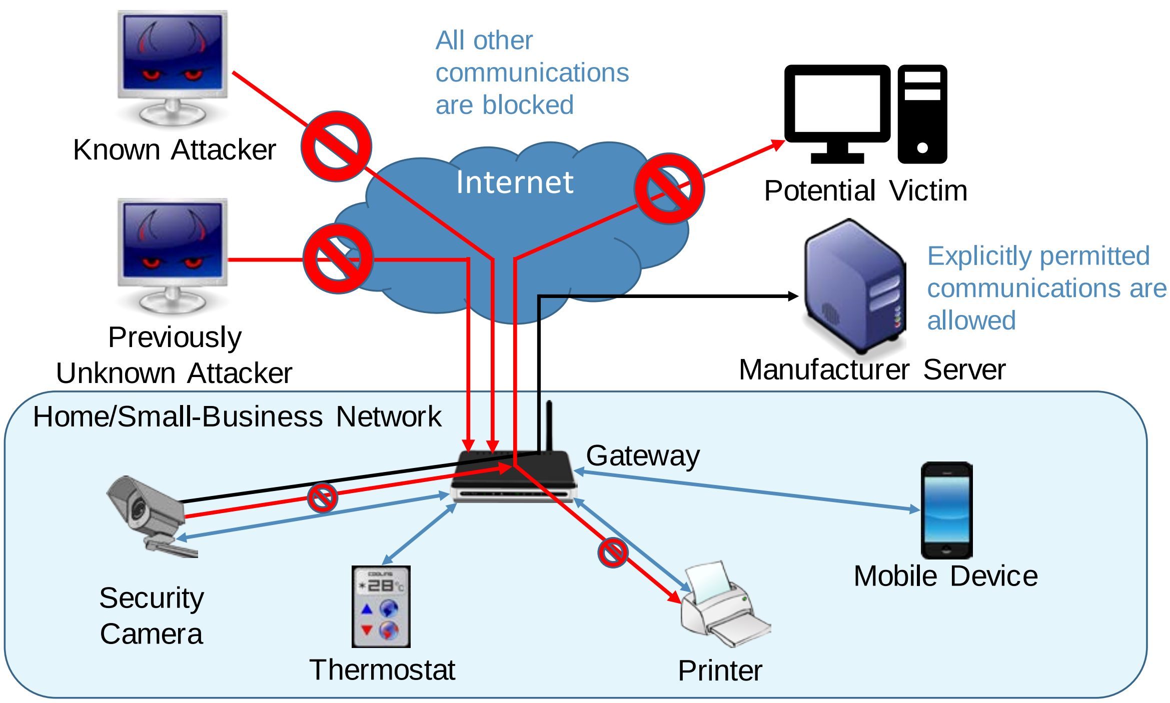


All communication paths are open. The IoT devices on the network can be port scanned (and perhaps hijacked) by an attacker on the internet. IoT devices are permitted to communicate to and from intended services, such as a manufacturer update server as desired. However, the IoT devices are also reachable by malicious external devices and by compromised devices that are on their local network, making them vulnerable to attacks from these malicious and compromised devices. In addition, if an IoT device on the local network becomes compromised, there are no protections in place to stop it from launching an attack on outside or local devices, creating additional potential victims. As shown in Figure 5-1, an external malicious actor can attack a security camera on the local network, compromise that camera, and use it to launch additional attacks on both local and remote targets.

5.3.2 Scenario 2: MUD and Threat-Signaling Protection

In the MUD and Threat-Signaling Protection scenario, as shown in Figure 5-2, the home/small-business network (depicted by the light blue rectangle) has both MUD and threat signaling deployed. (For simplicity, the components of the MUD deployment such as the MUD manager and MUD file server are not depicted, nor are the components of the threat-signaling deployment.) The MUD file for each MUD-capable IoT device lists the domains of all external services with which the MUD-capable device is permitted to exchange traffic. All external domains that are not explicitly permitted in the MUD file are denied. Therefore, each MUD-capable IoT device on the network can freely communicate with its intended external services, but all other attempted communications between that MUD-capable IoT device and external sites are blocked. The MUD-capable IoT device cannot be port scanned or receive traffic from external malicious domains if communication with those domains is not explicitly permitted in the IoT device's MUD file, even if those domains are not known to be malicious. Furthermore, even if the MUD-capable IoT device is compromised in some way after it has connected to the local network, it will not be permitted to attack any external domains if communication with those domains is not explicitly permitted in the MUD-capable IoT device's MUD file.

Figure 5-2 MUD and Threat-Signaling Protection



In Figure 5-2, the symbol prohibiting traffic sent from the previously unknown attacker depicts the fact that MUD prevents MUD-capable devices from receiving traffic from external sites that are not listed in those device's MUD files. The symbol prohibiting traffic sent from the security camera to the potential external victim depicts the fact that MUD prevents MUD-capable devices from sending traffic to external targets that are not explicitly permitted in their MUD files.

One of the external sites with which a MUD-capable IoT device is permitted to communicate is a manufacturer update server, from which the IoT device receives regular software updates to ensure that it installs the most recent security patches as needed.

In addition to listing external domains with which each MUD-capable device is permitted to communicate, the MUD file for each MUD-capable device restricts the local devices each MUD-capable IoT device is permitted to exchange traffic with based on characteristics such as those devices' manufacturer or model or whether those other devices are controllers for the IoT device in question. If a local device is not from the specified manufacturer, for example, it will not be permitted to exchange traffic with the MUD-capable IoT device. So, if a device on the local network attempts to attack another device on the local network that is MUD-capable, the traffic will not be received by that MUD-capable device if the attacking device is not from a manufacturer specified in the MUD-capable device's MUD file. Conversely, if a MUD-capable IoT device becomes compromised, it will not be permitted to attack any local devices that are not from a manufacturer specified in the MUD-capable IoT device's MUD file.

In Figure 5-2, the symbol prohibiting traffic received at the printer depicts the fact that MUD prevents MUD-capable devices from receiving traffic from all local devices that are not permitted in their MUD files. The symbol prohibiting traffic sent from the security camera to the printer depicts the fact that MUD prevents MUD-capable devices from sending traffic to other local devices that are not explicitly permitted in their MUD files.

In addition to MUD, threat signaling is deployed. Threat signaling prevents all devices on the local network from communicating with external domains that are known to be malicious. It protects not just MUD-capable IoT devices but also non-MUD-capable IoT devices and fully functional devices such as cell phones and laptops. This protection is depicted in Figure 5-2 by the symbol prohibiting receipt of traffic sent from the known malicious actor.

6 Build 1

The Build 1 implementation uses products from Cisco Systems, DigiCert, Forescout, and Molex. Cisco equipment is used to support MUD. Build 1 uses the Cisco MUD manager, which is available as open-source software; and the Cisco Catalyst 3850-S switch, which has been customized to work with the MUD manager, to provide switching, DHCP, and LLDP services. Build 1 also uses the Forescout virtual appliances and enterprise manager to perform discovery of all types of devices on the network—both MUD-capable and non-MUD-capable. Build 1 uses Molex PoE Gateway and Light Engine as a MUD-capable IoT device. Build 1 also uses certificates from DigiCert.

6.1 Collaborators

Collaborators that participated in this build are described briefly in the subsections below.

6.1.1 Cisco Systems

Cisco Systems is a provider of enterprise, telecommunications, and industrial networking solutions. The work in this project is being undertaken within Cisco's Enterprise Central Software Group with an eye toward improving the product offering over time. Cisco has provided a proof-of-concept MUD manager as well as a Catalyst 3850-S switch with Power over Ethernet. Learn more about Cisco Systems at https://www.cisco.com.

6.1.2 DigiCert

DigiCert is a major provider of scalable TLS/Secure Sockets Layer (SSL), and PKI solutions for identity and encryption. The company is known for its expertise in identity and encryption for web servers and Internet of Things devices. DigiCert supports TLS/SSL and other digital certificates for PKI deployments at any scale through its certificate life-cycle management platform, CertCentral®. The company provides enterprise-grade certificate management platforms, responsive customer support, and advanced security solutions. Learn more about DigiCert at https://www.digicert.com.

6.1.3 Forescout

Forescout Technologies is an industry leader in device visibility and control. Forescout's unified security platform enables enterprises and government agencies to gain complete situational awareness of their extended enterprise environment and orchestrate actions to reduce cyber and operational risk. Forescout products deploy quickly with agentless, real-time discovery and classification of every connected device, as well as continuous posture assessment. As of June 30, 2019, 3400 customers in more than 85 countries rely on Forescout's infrastructure-agnostic solution to reduce the risk of business disruption from security incidents or breaches, demonstrate security compliance, and increase security operations productivity. Learn more about Forescout at https://www.forescout.com.

6.1.4 Molex

Molex brings together innovation and technology to deliver electronic solutions to customers worldwide. With a presence in more than 40 countries, Molex offers a full suite of solutions and services for many markets, including data communications, consumer electronics, industrial, automotive, commercial vehicle, and medical. Learn more about Molex at https://www.molex.com.

6.2 Technologies

Table 6-1 lists all the products and technologies used in Build 1 and provides a mapping among the generic component term, the specific product used to implement that component, and the security control(s) that the product provides. Some functional Subcategories are described as being directly provided by a component. Others are supported but not directly provided by a component. Refer to Table 5-1 for an explanation of the NIST Cybersecurity Framework Subcategory codes.

Table 6-1 Products and Technologies

Component	Product	Function	Cybersecurity Framework Subcategories
MUD manager	Cisco MUD manager (open source) and a FreeRADIUS server	Fetches, verifies, and processes MUD files from the MUD file server; configures router or switch with traffic filters to enforce access control based on the MUD file	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 DE.AE-1

Component	Product	Function	Cybersecurity Framework Subcategories
MUD file server	NCCoE-hosted Apache server	Hosts MUD files; serves MUD files to the MUD manager by using https	ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
MUD file maker	MUD file maker (https://www.mudmaker.org/)	Yet Another Next Generation (YANG) script graphical user interface (GUI) used to create MUD files	ID.AM-1
MUD file	A YANG model instance that has been serialized in javascript object notation (JSON) [RFC 7951]. The manufacturer of a MUD-capable device creates that device's MUD file. MUD file maker (see previous row) can be used to create MUD files. Each MUD file is also associated with a separate MUD signature file.	Specifies the communications that are permitted to and from a given device	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3
DHCP server	Cisco IOS (Catalyst 3850-S)	Dynamically assigns IP addresses; recognizes MUD URL in DHCP DISCOVER message; should notify MUD manager if the device's IP address lease expires or has been released	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1

Component	Product	Function	Cybersecurity Framework Subcategories
LLDP	Cisco IOS (Catalyst 3850-S)	Supports capability for devices to advertise their identity and capabilities to neighbors on a local area network segment; provides capability to receive MUD URL in IoT device LLDP type length value (TLV) frame as an extension	ID.AM-1
Router or switch	Cisco Catalyst 3850-S (IOS XE software version 16.09.02)	Provides MUD URL to MUD manager; gets configured by the MUD manager to enforce the IoT device's communication profile; performs per-device access control	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
Certificates	DigiCert certificates (TLS and premium)	Authenticates MUD file server and secures TLS connection between MUD manager and MUD file server; used to sign MUD files and generate corresponding signature file	PR.AC-1 PR.AC-3 PR.AC-5 PR.AC-7
MUD-capable IoT device	Raspberry Pi Model 3B (devkit) u-blox C027-G35 (devkit) Samsung ARTIK 520 (devkit) Intel UP Squared Grove (devkit) Molex PoE Gateway and Light Engine	Emits a MUD URL as part of its DHCP DISCOVER message; requests and applies software updates	ID.AM-1

Component	Product	Function	Cybersecurity Framework Subcategories
Non-MUD-capable IoT device	Camera Smartphones Smart lighting devices Smart assistant Printer Baby monitor Wireless access point Digital video recorder	Acts as typical IoT device on a network; creates network connections to cloud services	ID.AM-1
Update server	NCCoE-hosted Apache server Molex update agent	Acts as a device manufacturer's update server that would communicate with IoT devices to provide patches and other software updates	PR.IP-1 PR.IP-3
Unapproved server	NCCoE-hosted Apache server	Acts as an internet host that has not been explicitly approved in a MUD file	DE.DP-3 DE.AM-1
MQTT broker server	NCCoE-hosted MQTT server	Receives and publishes messages to/from clients	ID.AM-3 DE.AE-3
IoT device discovery	Forescout virtual appliances and enterprise manager	Discover IoT devices on network	ID.AM-1 PR.IP-1 DE.AM-1

Each of these components is described more fully in the following sections.

6.2.1 MUD Manager

The MUD manager is a key component of the architecture. It fetches, verifies, and processes MUD files from the MUD file server. It then configures the router or switch with an access list to control communications based on the contents of the MUD files.

The Cisco MUD manager is an open-source implementation. For this project, the Cisco MUD manager was used to support IoT devices that emit their MUD URLs via DHCP messages and other IoT devices that emit their MUD URLs via the Institute of Electrical and Electronics Engineers (IEEE) 802.1AB LLDP.

The Cisco MUD manager is supported by an open-source implementation of an authentication, authorization, and accounting (AAA) server that communicates by using the remote authentication dial-in user service (RADIUS) protocol (i.e., a RADIUS server) called FreeRADIUS. When the MUD URL is emitted via DHCP or LLDP, it is extracted from the corresponding message, and the switch thereafter provides these MUD URLs to the MUD manager via RADIUS messages. The MUD manager then retrieves MUD files associated with those URLs and configures the Catalyst 3850-S switch to enforce the IoT devices' communication profiles based on these MUD files. The switch implements an IP access control list-based policy for src-dnsname, dst-dnsname, my-controller, and controller constructs that are specified in the MUD file, and it uses virtual local area networks (VLANs) to enforce same-manufacturer, manufacturer, and local-networks constructs that are specified in the MUD file. The system supports both lateral east/west protection and appropriate access to internet sites (north/south protection).

When supporting MUD URL emission by LLDP TLV, LLDP TLV must be enabled on both the Cisco switch and the IoT device. A policy-map configuration and a corresponding template are used to cause Media Access Control (MAC) authentication bypass (MAB) to happen. This will trigger an access-session attribute that will cause LLDP TLVs (including the MUD URL) to be forwarded in an accounting message to the RADIUS server.

Some manual preconfiguration of VLANs on the switch is required. The Cisco MUD manager supports a default policy for IPv4. It implements a static mapping between domain names and IP addresses inside a configuration file.

The version of the Cisco MUD manager used in this project is a proof-of-concept implementation that is intended to introduce advanced users and engineers to the MUD concept. It is not a fully automated MUD manager implementation, and some protocol features are not present. These are described in Section 10.1, Findings.

6.2.2 MUD File Server

In the absence of a commercial MUD file server for this project, the NCCoE implemented its own MUD file server by using an Apache web server. This file server signs and stores the MUD files along with their corresponding signature files for the IoT devices used in the project. Upon receiving a GET request for the MUD files and signatures, it serves the request to the MUD manager by using https.

6.2.3 MUD File

Using the MUD file maker component referenced above in Table 6-1, it is possible to create a MUD file with the following contents:

- internet communication class—access to cloud services and other specific internet hosts:
    - host: updateserver (hosted internally at the NCCoE)
        - protocol: TCP

        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- controller class—access to **classes** of devices that are known to be controllers (could describe well-known services such as DNS or NTP):
    - host: mqttbroker (hosted internally at the NCCoE)
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 1883
- local-networks class—access to/from **any** local host for specific services (e.g., http or https):
    - host: any
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- my-controller class—access to controllers specific to this device:
    - controllers: null (to be filled in by the network administrator)
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- same-manufacturer class—access to devices of the same manufacturer:
    - same-manufacturer: null (to be filled in by the MUD manager]
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- manufacturer class—access to devices of a specific manufacturer (identified by MUD URL):
    - manufacturer: devicetype (URL decided by the device manufacturer)

  - protocol: TCP
  - direction-initiated: from IoT device
  - source port: any
  - destination port: 80

6.2.4 Signature File

According to the IETF MUD specification, “a MUD file MUST be signed using CMS as an opaque binary object.” The MUD file *(ciscopi2.json)* was signed with the OpenSSL tool by using the command described in the specification (which will be detailed in Volume C of this publication). A Premium Certificate, requested from DigiCert, was leveraged to generate the signature file *(ciscopi2.p7s).* Once created, the signature file is stored on the MUD file server.

6.2.5 DHCP Server

The DHCP server in the architecture is MUD-capable. In addition to dynamically assigning IP addresses, it recognizes the DHCP option (161) and extracts the MUD URL from the IoT device’s DHCP message. The MUD URL is provided to the MUD manager. The DHCP server is typically embedded in a router/switch. This project uses the DHCP server that is embedded in the Cisco Catalyst 3850-S.

Cisco IOS provides a basic DHCP server that is useful in small/medium-business and home network environments, where centralized address management is not required. As described in the previous section, the DHCP server in this case is configured to allocate addresses for the test network, provide a default router, and configure a domain name server. It is **not** used to deliver MUD URLs to the MUD manager.

6.2.6 Link Layer Discovery Protocol

The Cisco Catalyst 3850-S switch also supports a MUD-capable version of the LLDP that provides the MUD URL in the LLDP TLV frame as an extension. When a MUD-capable IoT device uses LLDP to convey its MUD URL, the Cisco Catalyst 3850-S extracts the MUD URL from the LLDP frame and provides it to the MUD manager via a RADIUS message.

6.2.7 Router/Switch

This project uses the Cisco Catalyst 3850-S switch. The Cisco Catalyst 3850-S is an enterprise-class layer 3 switch capable of Universal PoE for digital building solutions. The optional PoE feature means it can be configured to supply power to capable devices over Ethernet through its ports. In addition to providing DHCP services, the switch acts as a broker for connected IoT devices for AAA through the FreeRADIUS server. The LLDP is enabled on ports that MUD-capable devices are plugged into to help facilitate recognition of connected IoT device features, capabilities, and neighbor relationships at layer 2.

Additionally, an access session policy is configured on the switch to enable port control for multihost authentication and port monitoring. The combined effect of these switch configurations is a dynamic access list, which has been generated by the MUD manager, being active on the switch to permit or deny access to and from MUD-capable IoT devices. The version of the Cisco Catalyst switch used in this project is a proof-of-concept implementation that is intended to introduce advanced users and engineers to the MUD concept. Some protocol features are not present. These are described in Section 10.1, Findings.

6.2.8 Certificates

DigiCert's CertCentral web-based platform allows provisioning and managing publicly trusted X.509 certificates for TLS and code signing as well as a variety of other purposes. After establishing an account, clients can log in, request, renew, and revoke certificates by using only a browser. Multiple roles can be assigned within an account, and a discovery tool can be used to inventory all certificates within the enterprise. In addition to certificate-specific features, the platform offers baseline enterprise software-as-a-service capabilities, including role-based access control, Security Assertion Markup Language (SAML), single sign-on, and security policy management and enforcement. All account features come with full parity between the web portal and a publicly available API. For this implementation, two certificates were provisioned: a private TLS certificate for the MUD file server to support the https connection from the MUD manager to the MUD file server, and a Premium Certificate for signing the MUD files.

6.2.9 IoT Devices

This section describes the IoT devices used in the laboratory implementation. There are two distinct categories of devices: devices that can emit a MUD URL in compliance with the MUD specification, i.e., MUD-capable IoT devices; and devices that are not capable of emitting a MUD URL in compliance with the MUD specification, i.e., non-MUD-capable IoT devices.

6.2.9.1 *MUD-Capable IoT Devices*

The project used several MUD-capable IoT devices: NCCoE Raspberry Pi (devkit), u-blox C027-G35 (devkit), Samsung ARTIK 520 (devkit), Intel UP Squared Grove (devkit), Molex PoE Gateway, and Molex Light Engine. The devkits were modified by the NCCoE to simulate IoT devices. All of the MUD-capable IoT devices demonstrate the ability to emit a MUD URL as part of a DHCP transaction or LLDP message and to request and apply software updates.

6.2.9.1.1 Molex PoE Gateway and Light Engine

This set of IoT devices was developed by Molex. The PoE Gateway acts as a network endpoint and manages lights, sensors, and other devices. One of the devices managed by the PoE Gateway is a light engine that was provided by Molex.

6.2.9.1.2 NCCoE Raspberry Pi (Devkit)

The Raspberry Pi devkit runs the Raspbian 9 operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction. The NCCoE developed a Python script that allowed the Raspberry Pi to receive and process on and off commands by using the MQTT protocol, which were sent to the light-emitting diode (LED) bulb connected to the Raspberry Pi.

6.2.9.1.3 NCCoE u-blox C027-G35 (Devkit)

The u-blox C027-G35 devkit runs the ARM Mbed operating system. The NCCoE modified several of the Mbed-OS libraries to configure the devkit to include a MUD URL that it emits during a typical DHCP transaction. The u-blox devkit is also configured to initiate network connections to test network traffic throughout the MUD process.

6.2.9.1.4 NCCoE Samsung ARTIK 520 (Devkit)

The Samsung ARTIK 520 devkit runs the Fedora 24 operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction. The same Python script mentioned earlier was used to simulate a smart lock. This Python script allowed the ARTIK devkit to receive on and off commands by using the MQTT protocol.

6.2.9.1.5 NCCoE Intel UP Squared Grove (Devkit)

The Intel UP Squared Grove devkit runs the Ubuntu 16.04 LTS operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction. The same Python script mentioned earlier was used to simulate a smart lighting device. This allowed the UP Squared Grove devkit to receive on and off commands by using the MQTT protocol.

6.2.9.2 *Non-MUD-Capable IoT Devices*

The laboratory implementation also includes a variety of legacy, non-MUD-capable IoT devices that are not capable of emitting a MUD URL. These include cameras, smartphones, lighting, a smart assistant, a printer, a baby monitor, a wireless access point, and a digital video recorder (DVR).

6.2.9.2.1 Cameras

The three cameras utilized in the laboratory implementation are produced by two different manufacturers. They stream video and audio either to another device on the network or to a cloud service. These cameras are controlled and managed by a smartphone.

6.2.9.2.2 Smartphones

Two types of smartphones are used for setting up, interacting with, and controlling IoT devices.

6.2.9.2.3 Lighting

Two types of smart lighting devices are used in the laboratory implementation. These smart lighting components are controlled and managed by a smartphone.

6.2.9.2.4 Smart Assistant

A smart assistant is utilized in the laboratory implementation. The device is used to demonstrate and test the wide range of network traffic generated by a smart assistant.

6.2.9.2.5 Printer

A smart printer is connected to the laboratory network wirelessly to demonstrate smart printer usage.

6.2.9.2.6 Baby Monitor

A baby monitor with remote control plus video and audio capabilities is connected wirelessly to the laboratory network. This baby monitor is controlled and managed by a smartphone.

6.2.9.2.7 Wireless Access Point

A smart wireless access point is used in the laboratory implementation to demonstrate the network activity and functionality of this type of device.

6.2.9.2.8 Digital Video Recorder

A smart DVR is connected to the laboratory implementation network. This is also controlled and managed by a smartphone.

6.2.10 Update Server

The update server is designed to represent a device manufacturer or trusted third-party server that provides patches and other software updates to the IoT devices. This project used an NCCoE-hosted update server that provides faux software update files.

6.2.10.1 *NCCoE Update Server*

The NCCoE implemented its own update server by using an Apache web server. This file server hosts faux software update files to be served as software updates to the IoT device devkits. When the server receives an http request, it sends the corresponding faux update file.

6.2.10.2 *Molex Update Agent*

The process for updating the firmware on a Molex PoE Gateway is currently a manual process, with the firmware update taking place over the CoAP, UDP, and trivial file transfer protocol protocols. The update process is initiated by an update agent on the local network connecting to the PoE Gateway and sending the firmware update information.

6.2.11 Unapproved Server

The NCCoE implemented its own unapproved server by using an Apache web server. This web server acts as an unapproved internet host, i.e., an internet host that is not explicitly approved in the MUD file. This was created to test the communication between a MUD-capable IoT device and an internet host that is not included in the MUD file and should thus be denied. To verify that the traffic filters were applied as expected, communication to and from the unapproved server and the MUD-capable IoT device was tested.

6.2.12 MQTT Broker Server

The NCCoE implemented an MQTT broker server by using the open-source tool Mosquitto. The server communicates messages among multiple clients. For this project, it allows mobile devices to set up with the appropriate application to communicate with the MQTT-enabled IoT devices in the build. The messages exchanged by the devices are on and off messages, which allow the mobile device to control the LED light on the IoT device.

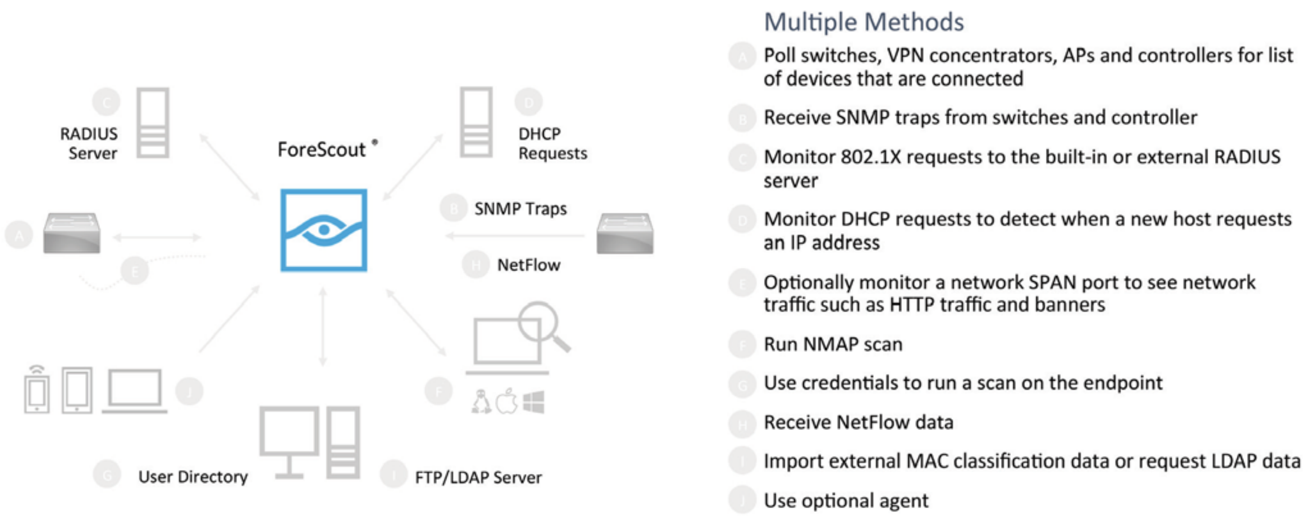
6.2.13 IoT Device Discovery

This project uses Forescout appliance and enterprise manager to provide an IoT device discovery service for the demonstration network. The Forescout appliance can discover, inventory, profile, and classify all attached devices to validate that the access that is being granted to each device is consistent with that device's type. Forescout can also continuously monitor the actions of these assets as they join and leave the network. While Forescout provides a wide range of data collection capabilities, items this project focuses on include:

- device information
    - device type
    - manufacturer
    - connection type
    - hardware information
    - MAC and IP addresses
    - operating system
        - network services
- network configuration
    - wired or wireless

The Forescout appliance detects IoT devices in real time as they connect to the network. It uses both passive monitoring and integration with the network infrastructure. As a device connects to the network, Forescout may learn about that device via a variety of different techniques to discover and classify it without requiring agents, as shown in Figure 6-1. The methods demonstrated in this project included Forescout passive discovery of devices by using switch polling, importation of MAC classification data, and TCP fingerprinting. Due to the passive nature of the device discovery, neither performance nor reliability of the IoT devices is impacted.

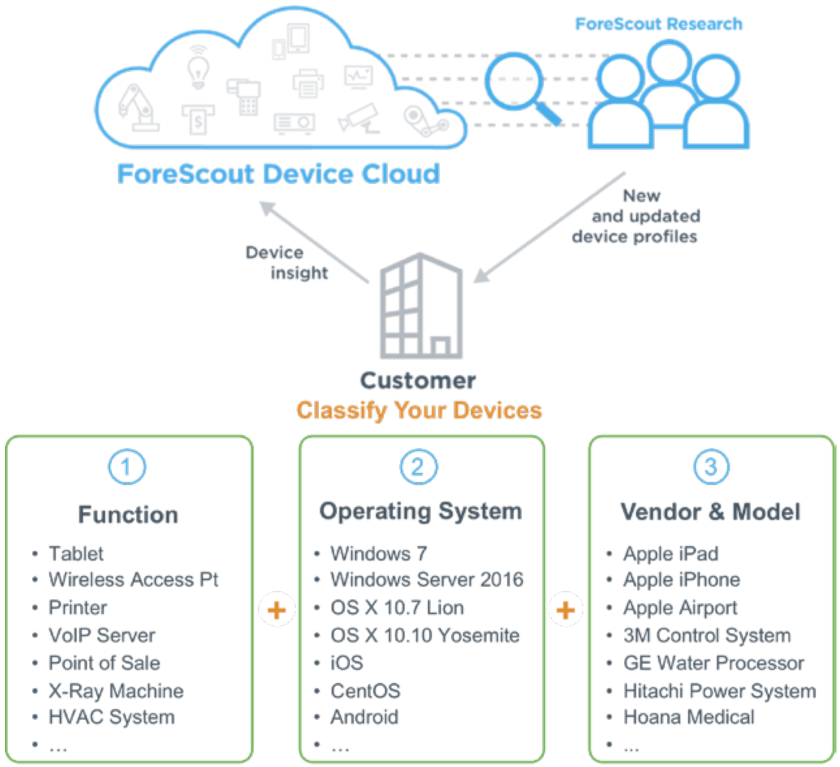
Figure 6-1 Methods the Forescout Platform Can Use to Discover and Classify IP-Connected Devices



Forescout is deployed as virtual appliances on the NCCoE laboratory network and managed by a single enterprise manager. After discovering IoT devices and collecting relevant information, classification is the next step.

To automatically classify discovered devices, the Forescout platform includes Forescout Device Cloud. Device Cloud allows users to benefit from crowdsourced device insight to auto-classify their devices, as shown in Figure 6-2. It also auto-classifies the devices by their type and function, operating system and version, and manufacturer and model. Users can leverage new and updated auto-classification profiles published by Forescout. In addition, they can create custom classification policies to auto-classify devices unique to their environments. At the time of this writing, the Forescout appliance cannot identify whether an IoT device on the network is MUD-capable.

Figure 6-2 Classify IoT Devices by Using the Forescout Platform



6.3 Build Architecture

In this section we present the logical architecture of Build 1 relative to how it instantiates the reference architecture depicted in Figure 4-1. We also describe Build 1's physical architecture and present message flow diagrams for some of its processes.

6.3.1 Logical Architecture

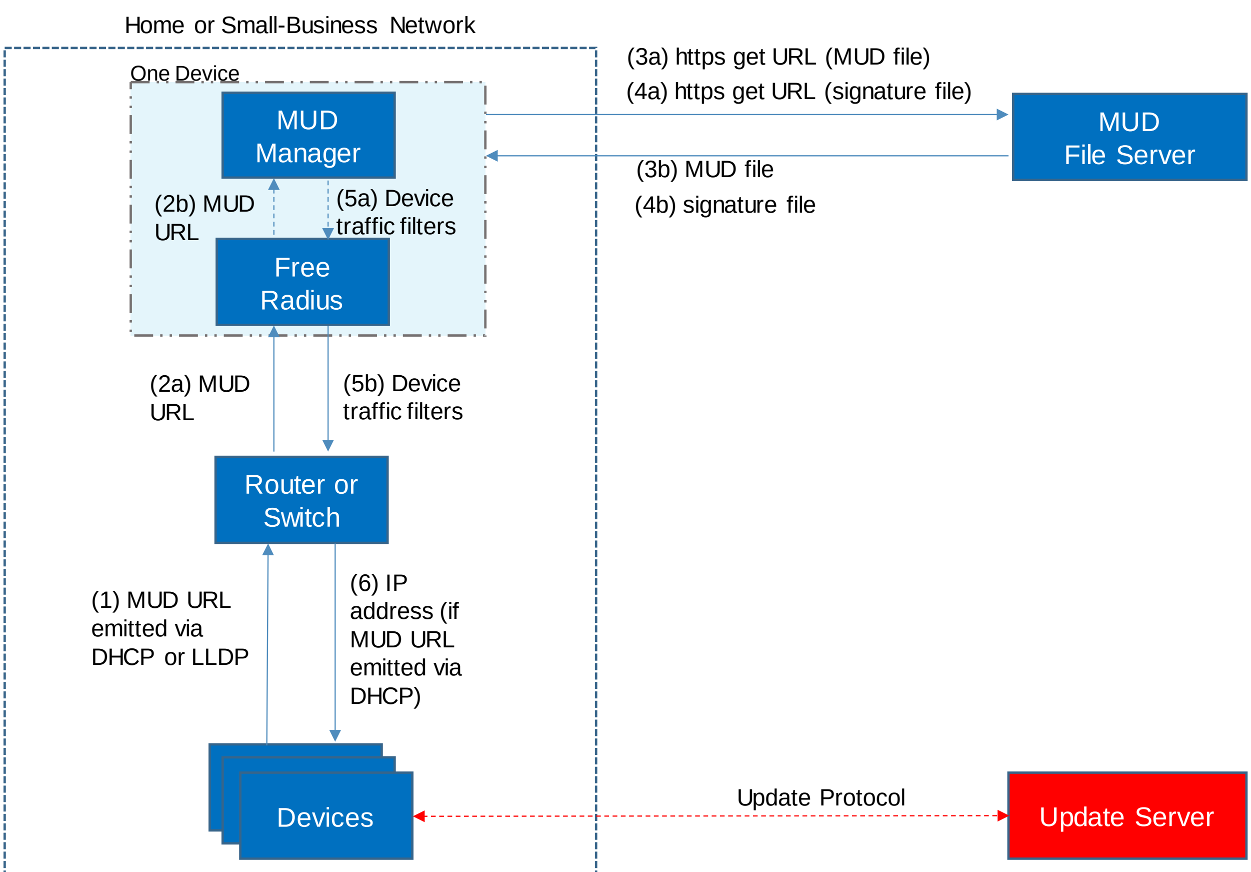
Figure 6-3 depicts the logical architecture of Build 1. Build 1 is designed with a single device serving as the MUD manager and FreeRADIUS server that interfaces with the Catalyst 3850-S switch over TCP/IP. It supports two mechanisms for MUD URL emission: DHCP and LLDP. Only the steps performed when using DHCP emission are depicted in Figure 6-3. The Catalyst 3850-S switch contains a DHCP server that is configured to extract MUD URLs from IPv4 DHCP transactions.

- Upon connecting a MUD-capable device, the MUD URL is emitted via either DHCP or LLDP (step 1).
- The Catalyst 3850-S switch sends the MUD URL to the FreeRADIUS server (step 2a); this is passed from the FreeRADIUS server to the MUD manager (step 2b).

- Once the MUD URL is received, the MUD manager fetches the MUD file from the MUD file server by using the MUD URL provided in the previous step (step 3a); if successful, the MUD file server at the specified location will serve the MUD file (step 3b).
- Next, the MUD manager requests the signature file associated with the MUD file (step 4a) and upon receipt (step 4b) verifies the MUD file by using its signature file.
- Once the MUD file has been verified successfully, the MUD manager passes the device's traffic filters to the FreeRADIUS server (step 5a), which in turn sends the device's traffic filters to the router or switch, where they are applied (step 5b).
- The device is finally assigned an IP address (step 6).

Once the device's traffic filters are applied to the router or switch, the MUD-capable IoT device will be able to communicate with approved local hosts and internet hosts as defined in the MUD file, and any unapproved communication attempts will be blocked.

Figure 6-3 Logical Architecture–Build 1

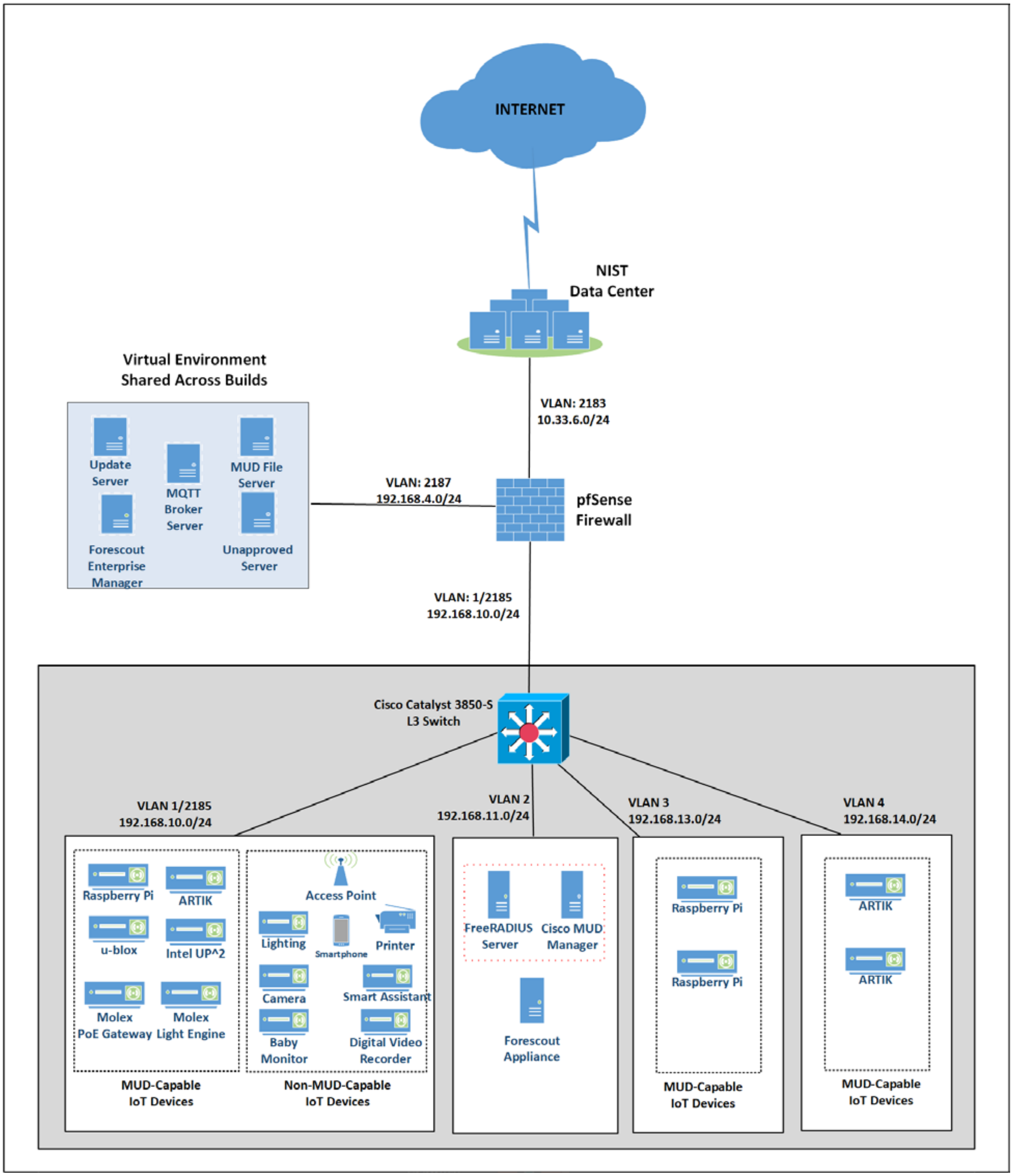


6.3.2 Physical Architecture

Figure 6-4 describes the physical architecture of Build 1. The Catalyst 3850-S switch is configured to host four VLANs. The first VLAN, VLAN 1, hosts many IoT devices. Three separate instances of DHCP servers are configured for VLANs 1, 3, and 4 to dynamically assign IPv4 addresses to each IoT device that connects to the switch on each of these VLANs. VLAN 2 is configured on the Catalyst switch to host the Cisco MUD manager, the FreeRADIUS server, and the Forescout appliance. VLAN 3 and VLAN 4 are configured to host IoT devices from the same manufacturer. Specifically, VLAN 3 hosts two Raspberry Pi devices, while VLAN 4 hosts two u-blox devices. The network infrastructure as configured utilizes the IPv4 protocol for communication both internally and to the internet.

In addition, Build 1 utilized a portion of the virtual environment that was shared across builds. Services hosted in this environment included an update server, MUD file server, MQTT broker, Forescout enterprise manager, and unapproved server.

1224 **Figure 6-4 Physical Architecture–Build 1**



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A full description of Cisco's proof-of-concept MUD manager implementation can be found at https://github.com/CiscoDevNet/MUD-Manager. The Cisco MUD manager is built as a callout from FreeRADIUS and uses MongoDB to store policy information. The MUD manager is configured from a JSON file that will vary slightly based on the installation. This configuration file provides several static bindings and directives as to whether both egress and ingress ACLs should be applied, and it identifies the definition of the local network class on the network.

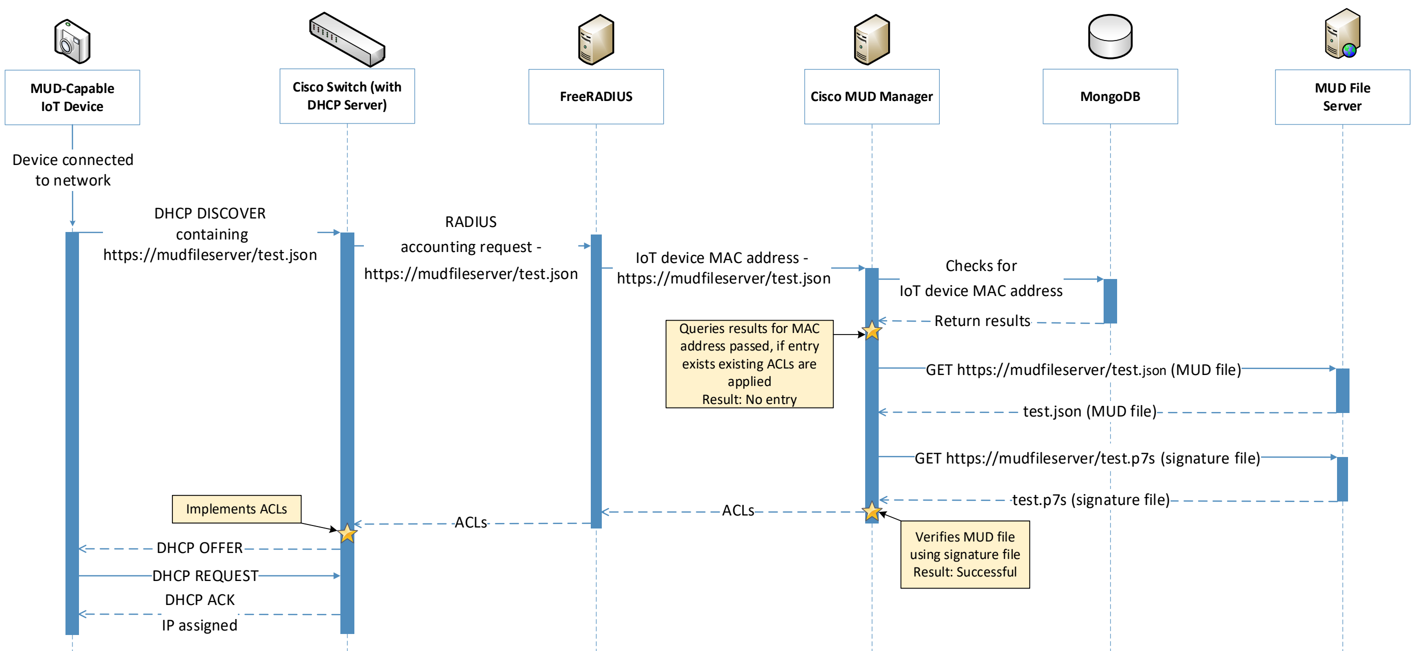
6.3.3 Message Flow

This section presents the message flows used in Build 1 during several different processes of note.

6.3.3.1 *Onboarding MUD-Capable Devices*

Figure 6-5 shows the message flow of the process of onboarding a MUD-capable IoT device that emits a MUD URL via DHCPv4.

Figure 6-5 MUD-Capable IoT Device Onboarding Message Flow–Build 1



As shown in Figure 6-5, the message flow is as follows:

- A MUD-capable IoT device is connected to the network.
- The MUD-capable IoT device begins a DHCPv4 transaction in which DHCP option 161, the Internet Assigned Numbers Authority (IANA)-assigned value for MUD, is transmitted as part of

a DHCP DISCOVER message. It is possible to transmit the option in both DISCOVER and REQUEST messages.

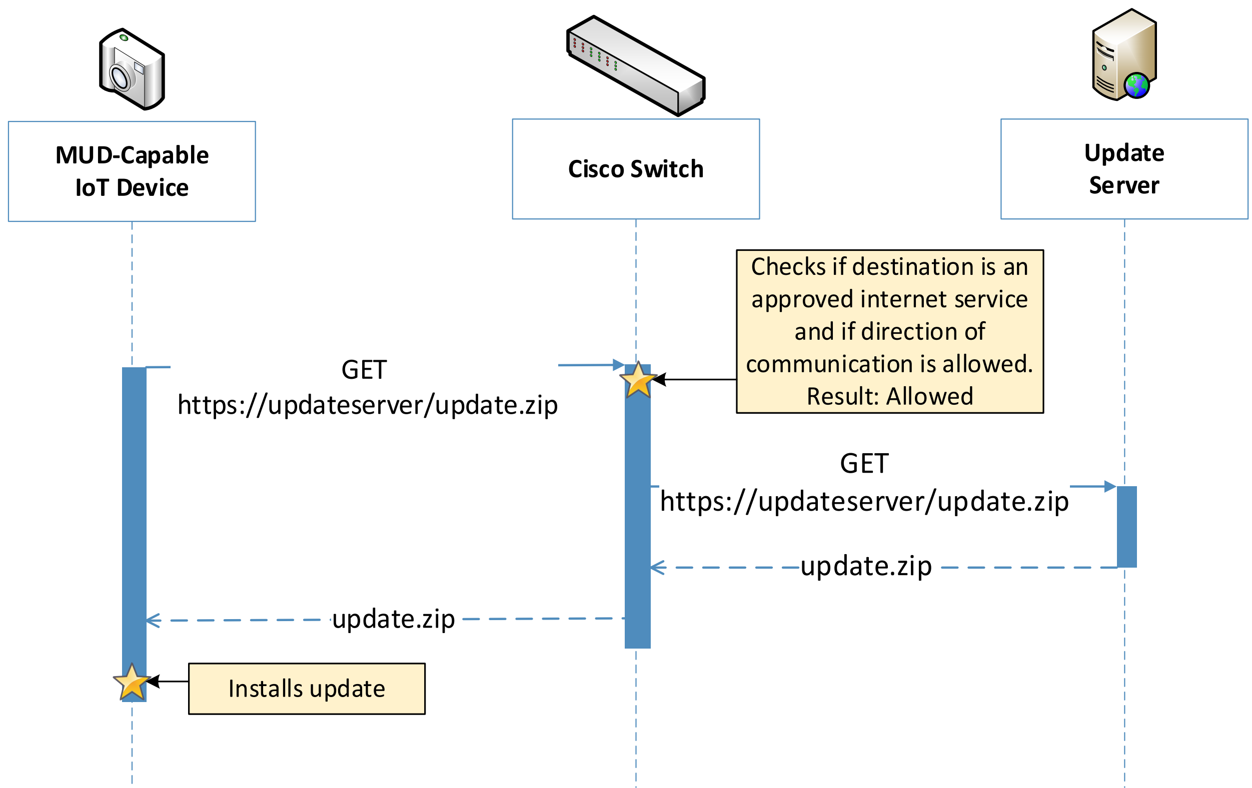
- The DHCP server on the Cisco switch recognizes that option and extracts the MUD URL from the DHCP message, which is sent from the switch to the FreeRADIUS server in the associated accounting request. From this point, the FreeRADIUS server sends the MAC address and MUD URL for the newly onboarded device to the MUD manager.
- Next, the MUD manager does a query for the MAC address in its database, searching for any cached MUD files associated with the MAC address and MUD URL. If an entry does not exist, as depicted in the figure, the MUD manager fetches the MUD file and signature file from the MUD file server.
- The MUD manager verifies the MUD file with the corresponding signature file and translates the contents into ACLs, which are passed through the FreeRADIUS server to the Cisco switch, where they are applied.
- The MUD-capable IoT device is assigned an IP address and is ready to be used on the network. When the MUD-capable IoT device is in use, access of all traffic to and from the IoT device is controlled by the Cisco switch, which will enforce the MUD ACLs for that device.

As an example, the subsections below address several different types of traffic that might apply to an IoT device. The message flow diagram in each subsection shows how this traffic would interact with Build 1’s infrastructure.

6.3.3.2 *Updates*

After a device has been permitted to connect to the home/small-business network, it should periodically check for updates. The message flow for updating the IoT device is shown in Figure 6-6 Update Process Message Flow–Build 1.

Figure 6-6 Update Process Message Flow–Build 1



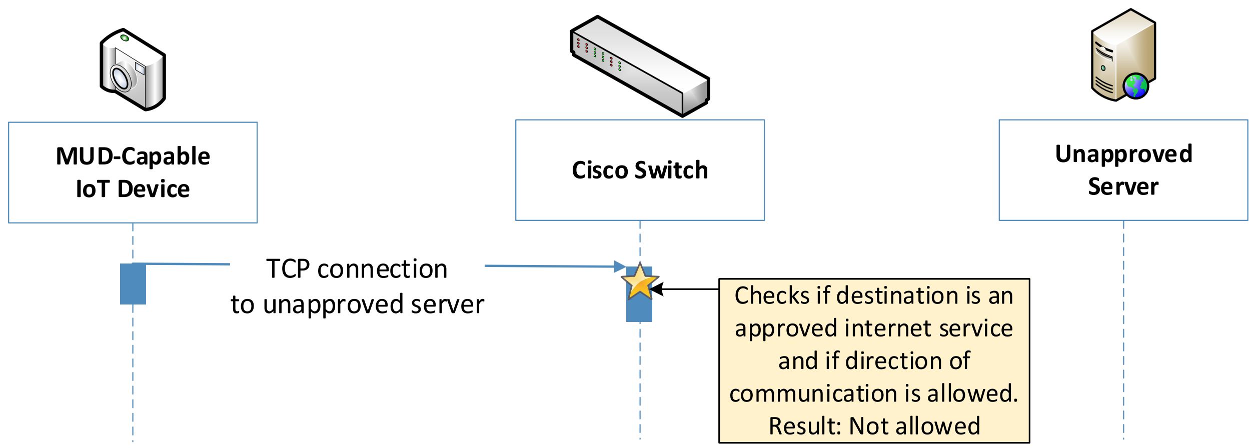
As shown in Figure 6-6 Update Process Message Flow–Build 1, the message flow is as follows:

- A MUD-capable IoT device initiates an https request to the update server.
- The Cisco switch checks its ACLs to determine if the destination and direction of communication should be allowed for the IoT device and allows the request after verification.
- The update server completes the process by sending the requested update package to the IoT device.

6.3.3.3 *Prohibited Traffic*

Figure 6-7 shows the message flows used to handle prohibited traffic in Build 1's infrastructure.

Figure 6-7 Prohibited Traffic Message Flow–Build 1



As shown in Figure 6-7, when an IoT device attempts to send traffic to an external domain, the message flow is as follows:

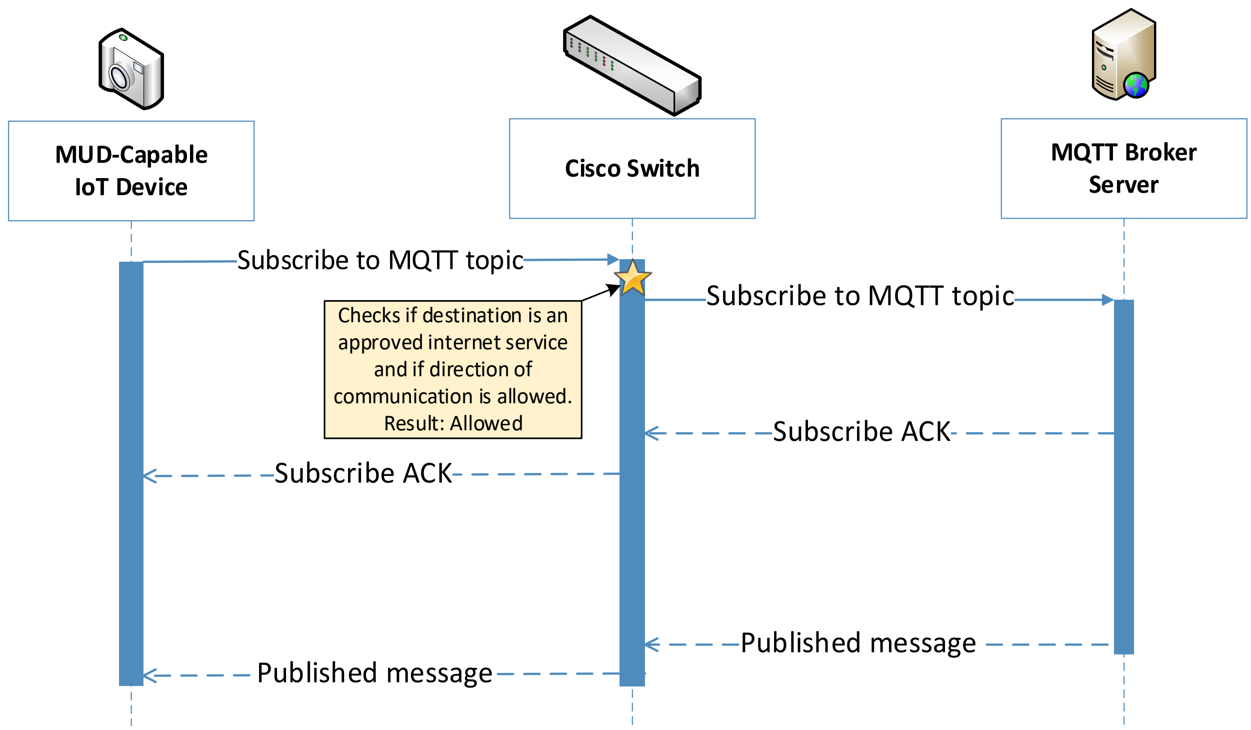
- The MUD-capable IoT device initiates a TCP request to an unapproved server.
- The Cisco switch checks its ACLs to determine if the destination and direction of communication should be allowed for the IoT device and blocks the unapproved communication.

At the time of publication, ingress access control was not yet supported in Build 1. That is, if an unapproved server attempts to send traffic to an IoT device on the local network, this traffic will currently not be blocked. However, responses from the IoT device will still be blocked. Specifics can be found in Section 10.1, Findings.

6.3.3.4 *MQTT Protocol Example*

Figure 6-8 shows the message flows used to handle MQTT communication in Build 1’s infrastructure.

Figure 6-8 MQTT Protocol Process Message Flow–Build 1



As shown in Figure 6-8, the message flow is as follows:

- The MUD-capable IoT device initiates a Subscribe message to the MQTT broker.
- The Cisco switch checks its ACLs to determine if the destination and direction of communication should be allowed for the IoT device and allows the Subscribe message after verification.
- The MQTT broker server sends a Subscribe ACK to the IoT device.
- The MQTT broker server sends a Published message to the IoT device.

6.4 Functional Demonstration

A functional evaluation and a demonstration of Build 1 were conducted that involved two types of activities:

- Evaluation of conformance to the MUD RFC. Build 1 was tested to determine the extent to which it correctly implements basic functionality defined within the MUD RFC.
- Demonstration of additional (non-MUD-related) capabilities. It did not verify the example implementation’s behavior for conformance to a standard or specification or any other expected set of capabilities; rather, it demonstrated advertised capabilities of the example

implementation related to its ability to increase device and network security in ways that are independent of the MUD RFC. These capabilities may provide security for both non-MUD-capable and MUD-capable devices. Examples of this type of activity include device discovery, attribute identification, and monitoring.

Table 6-2 summarizes the tests that were performed to evaluate Build 1's MUD-related capabilities, and Table 6-3 summarizes the exercises that were performed to demonstrate Build 1's non-MUD-related capabilities. Both tables list each test or exercise identifier, the test or exercise's expected and observed outcomes, and the applicable Cybersecurity Framework Subcategories and NIST SP 800-53 controls for which each test or exercise is designed to verify support. The tests and exercises that are listed in the table are detailed in a separate supplement for functional demonstration results. Boldface text is used to highlight the gist of the information that is being conveyed.

Table 6-2 Summary of Build 1 MUD-Related Functional Tests

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
IoT-1	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data	A **MUD-capable IoT device is configured to emit a MUD URL within a DHCP message.** The DHCP server extracts the MUD URL, which is sent to the MUD manager. The MUD manager requests the MUD file and signature from the MUD file server, and the MUD file server serves the MUD file to the MUD manager. The MUD file explicitly permits traffic to/from some internet services and hosts and implicitly denies traffic to/from all other internet services. **The MUD manager translates the**	Upon connection to the network, the MUD-capable IoT device has its MUD **policy enforcement point (PEP) router/switch automatically configured according to the MUD file's route filtering policies.**	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	flows for users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.	**MUD file information into local network configurations that it installs on the router or switch that is serving as the MUD PEP for the IoT device.**		

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
IoT-2	**PR.AC-7:** Users, devices, and other assets are authenticated (e.g., single-factor, multifactor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks). **NIST SP 800-53 Rev. 4** AC-7, AC-8, AC-9, AC-11, AC-12, AC-14, IA-1, IA-2, IA-3, IA-4, IA-5, IA-8, IA-9, IA-10, IA-11	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **MUD file server that is hosting that file does not have a valid TLS certificate. Local policy has been configured to ensure that if the MUD file for an IoT device is located on a server with an invalid certificate, the router/switch will be configured to deny all communication to/from the device.**	When the MUD-capable IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-capable IoT device. Therefore, the **MUD PEP router/switch will be configured to block all traffic to and from the IoT device.**	Pass
IoT-3	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **certificate that was used to sign the MUD file had already expired at the time of signing. Local policy has been configured to ensure that if the MUD file for a device has a signature that was signed by a certificate that had already expired at the time of signature, the device's MUD PEP**	When the MUD-capable IoT device is connected to the network and the MUD file and signature are fetched, the MUD manager will detect that the MUD file's signature was created by using a certificate that had already expired at the time of signing. According to local	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
		router/switch will be configured to deny all communication to/from the device.	policy, the **MUD PEP will be configured to block all traffic to/from the device.**	
IoT-4	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **signature of the MUD file is invalid. Local policy has been configured to ensure that if the MUD file for a device is invalid, the router/switch will be configured to deny all communication to/from the IoT device.**	When the MUD-capable IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-capable IoT device. Therefore, the **MUD PEP router/switch will be configured to block all traffic to and from the IoT device.**	Pass
IoT-5	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some internet locations and implicitly denies traffic**	When the MUD-capable IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the route filter-**	Pass (for testable procedure, ingress cannot be tested)

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.IP-1: A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7	**to/from all other internet locations.**	**ing that is described in the device's MUD file** with respect to traffic being permitted to/from some internet locations, and traffic being implicitly blocked to/from all remaining internet locations.	
IoT-6	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality).	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some lateral hosts and implicitly denies traffic to/from all other lateral hosts.** (The MUD file does not explicitly identify the hosts as lateral hosts; it identifies classes of hosts to/from which traffic should be denied, where one or more hosts of this class happen to be lateral hosts.)	When the MUD-capable IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the access control information that is described in the device's MUD file** with respect to traffic being permitted to/from some lateral hosts, and traffic being implicitly blocked to/from all remaining lateral hosts.	Pass (for testable procedure, ingress cannot be tested)

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.IP-3:** Configuration change control processes are in place. **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition.			
IoT-7	**PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition. **NIST SP 800-53 Rev. 4** CM-8, MP-6	Test IoT-1 has run successfully, meaning that the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. Next, have **the IoT device change DHCP state by explicitly releasing its IP address lease, causing the device's policy configuration to be removed from the MUD PEP router/switch.**	When the MUD-capable **IoT device explicitly releases its IP address lease,** the MUD-related configuration for that IoT device will be removed from its MUD PEP router/switch.	Failed
IoT-8	**PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10	Test IoT-1 has run successfully, meaning that the MUD PEP **router/switch has been configured based on the MUD**	When the MUD-capable **IoT device's IP address lease expires,** the MUD-related configuration for	Failed (not supported)

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.DS-3: Assets are formally managed throughout removal, transfers, and disposition. **NIST SP 800-53 Rev. 4** CM-8, MP-6	**file** for a specific MUD-capable device in question. Next, have **the IoT device change DHCP state by waiting until the IoT device's address lease expires, causing the device's policy configuration to be removed from the MUD PEP router/switch.**	that IoT device will be removed from its MUD PEP router/switch.	
IoT-9	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed.	Test IoT-1 has run successfully, meaning the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. The MUD file contains domains that resolve to multiple IP addresses. The MUD PEP router/switch should be configured to permit communication to or from all IP addresses for the domain.	A domain in the MUD file resolves to two different IP addresses. The MUD manager will create ACLs that permit the MUD-capable device to send traffic to both IP addresses. The MUD-capable device attempts to send traffic to each of the IP addresses, and the MUD PEP router/switch permits the traffic to be sent in both cases.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 AC-4, CA-3, CM-2, SI-4 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-17, AC-19, AC-20, SC-15 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-8, MP-6 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-8, MP-6 **PR.DS-2:** Data in transit is protected. **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10			
IoT-10	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5	A MUD-capable IoT device is configured to emit a MUD URL. Upon being connected to the network, its MUD file is retrieved,	Upon reconnection of the IoT device to the network, **the MUD manager does not contact**	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	ID.AM-2: Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating	and the PEP is configured to enforce the policies specified in that MUD URL for that device. **Within 24 hours (i.e., within the cache-validity period for that MUD file), the IoT device is reconnected to the network.** After 24 hours have elapsed, the same device is reconnected to the network.	**the MUD file server. Instead, it uses the cached MUD file.** It translates this MUD file's contents into appropriate route-filtering rules and installs these rules onto the PEP for the IoT device. Upon reconnection of the IoT device to the network, after 24 hours have elapsed, the MUD manager does fetch a new MUD file.	

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.			
IoT-11	**ID.AM-1:** Physical devices and systems within the organization are inventoried.	A **MUD-capable IoT device is capable of emitting a MUD URL.** The device should leverage one of the specified manners for emitting a MUD URL.	Upon initialization, the MUD-capable IoT device broadcasts a DHCP message on the network, including at most one **MUD URL, in https scheme, within the DHCP transaction.** OR Upon initialization, the MUD-capable IoT device **emits a MUD URL as an LLDP extension.**	Pass

In addition to supporting MUD, Build 1 demonstrates capabilities with respect to device discovery, attribute identification, and monitoring, as shown in Table 6-3.

Table 6-3 Non-MUD-Related Functional Capabilities Demonstrated

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
CnMUD-1	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CM-2, SI-4 **DE.CM-1:** The network is monitored to detect potential cybersecurity events. **NIST SP 800-53 Rev. 4** AC-2, AU-12, CA-7, CM-3, SC-5, SC-7, SI-4	A **visibility/monitoring component** is connected to the local IoT network. It **is configured to detect all devices connected to the network, discover attributes of these devices, categorize the devices, and monitor the devices** for any change of status.	Upon being connected to the network, the **visibility/monitoring component detects all connected devices, identifies their attributes** (e.g., type, IP address, OS), and categorizes them. **When an additional device is powered on, it is also detected and its attributes identified. When a device is powered off, its change of status is detected.**	As expected

6.5 Observations

We observed the following limitations to Build 1 that are informing improvements to its current proof-of-concept implementation:

- MUD manager (version 3.0.1):
    - In previous versions (version 1.0), DNS resolution of internet host names in the MUD file was performed manually and remained static. Dynamic resolution of Fully Qualified Domain Names has since been added and is currently supported.
    - Translation and implementation of the model construct from the MUD file was not supported at the time of testing. However, this should be addressed in newer versions.
- Catalyst 3850-S Switch (IOS version 16.09.02):
    - The MUD URL cannot be extracted when emitted via DHCPv6. Hence, the switch is only able to support MUD-capable IoT devices that use DHCPv4 and IPv4. This version of the switch does not yet support MUD-capable IoT devices when they are configured to use IPv6. IPv6 functionality is expected to be supported in the future.
    - The DHCP server does not notify the MUD manager of changes in DHCP state for MUD-capable IoT devices on the network. According to the MUD specification, the DHCP server should notify the MUD manager if the MUD-capable IoT device's IP address lease expires or has been released. However, this version of the DHCP server does not do so at the time of testing. This is expected to be addressed in the future.
    - Ingress Dynamic ACLs (DACLs) (i.e., DACLs that pertain to traffic that is received from sources external to the network and directed to local IoT devices) are not supported with this version. Consequently, even if a MUD-capable IoT device's MUD file indicates that the IoT device is not authorized to receive traffic from an external domain, the DACL that is needed to prohibit that ingress traffic will not be configured on the switch. As a result, unless there is some other layer of security in place, such as a firewall that is configured to block this incoming traffic, the IoT device will still be able to receive incoming packets from that unauthorized external domain, which means it will still be vulnerable to attacks originating from that domain, despite the fact that the device's MUD file makes it clear that the device is not authorized to receive traffic from that domain. Because egress DACLs (i.e., DACLs that pertain to traffic that is sent from IoT devices to an external domain) are supported, however, even though packets that are sent from an outside domain are not stopped from being received at the IoT device, return traffic from the device to the external domain will be stopped. This means, for example, that if an attacker is able to get packets to an IoT device from an outside domain, it will not be possible for the attacker to establish a TCP connection with the device from that outside domain, thereby limiting the range of attacks that can be launched against the IoT device. This is expected to be addressed in the future.

7 Build 2

The Build 2 implementation uses a product from MasterPeace Solutions called Yikes! to support MUD. Yikes! is a commercial router/cloud service solution focused on consumer and small-business markets. It consists of a Yikes! router, a cloud service, and a mobile application that interfaces with the cloud service. In addition to supporting MUD, the Yikes! router and cloud service are used to perform device discovery on the network and to apply additional traffic rules to both MUD-capable and non-MUD-capable devices based on device manufacturer and model.

Also integrated with the Yikes! router in Build 2 is open-source software called Quad9 Active Threat Response (Q9Thrt), which builds on the Quad9 DNS service provided by Global Cyber Alliance. Q9Thrt enables the Yikes! router to take advantage of threat-signaling intelligence that is available through the Quad9 DNS service. Build 2 can use this information to block access, first to domains and, subsequently, to related IP addresses, that have been determined to be dangerous. This threat-signaling capability can be used to protect both MUD-capable and non-MUD-capable devices. Build 2 also uses certificates from DigiCert.

7.1 Collaborators

Collaborators that participated in this build are described briefly in the subsections below.

7.1.1 MasterPeace Solutions

MasterPeace Solutions Ltd. is a cybersecurity company in Columbia, Maryland that focuses on serving federal intelligence community agencies. MasterPeace also operates the MasterPeace LaunchPad start-up studio, chartered with launching cyber-oriented technology product companies. A current LaunchPad start-up portfolio company, Yikes!, has developed a solution that includes both a MUD manager and cloud-based support for non-MUD IoT device security. Yikes! was created to bring automated enterprise-level security to consumer and small-business networks. Those networks are typically flat (unsegmented), predominantly connected via Wi-Fi-enabled devices, and managed by individuals who possess relatively little IT or cyber background compared with enterprise IT and cyber teams. Learn more about MasterPeace at https://www.masterpeaceltd.com.

7.1.2 Global Cyber Alliance

The GCA is an international, cross-sector effort dedicated to eradicating cyber risk and improving our connected world. It achieves its mission by uniting global communities, implementing concrete solutions, and measuring the effect. GCA, a 501(c)3, was founded in September 2015 by the Manhattan District Attorney’s Office, the City of London Police, and the Center for Internet Security. Learn more about GCA at https://www.globalcyberalliance.org.

7.1.3 DigiCert

See Section 6.1.2 for a description of DigiCert.

7.2 Technologies

Table 7-1 lists all of the products and technologies used in Build 2 and provides a mapping among the generic component term, the specific product used to implement that component, and the security control(s) that the product provides. Some functional Subcategories are described as being directly provided by a component. Others are supported but not directly provided by a component. Refer to Table 5-1 for an explanation of the NIST Cybersecurity Framework Subcategory codes.

Table 7-1 Products and Technologies

Component	Product	Function	Cybersecurity Framework Subcategories
MUD manager	MasterPeace Yikes! router	Fetches, verifies, and processes MUD files from the MUD file server; configures router or switch with traffic filters to enforce firewall rules based on the MUD file	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 DE.AE-1
MUD file server	MasterPeace-hosted Apache server	Hosts MUD files; serves MUD files to the MUD manager by using https	ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
MUD file maker	MUD file maker (https://www.mud-maker.org/)	YANG script GUI used to create MUD files	ID.AM-1
MUD file	A YANG model instance that has been serialized in JSON [RFC 7951]. The manufacturer of a MUD-capable device creates that device's MUD file. MUD file maker (see previous row) can be used to create	Specifies the communications that are permitted to and from a given device	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3

Component	Product	Function	Cybersecurity Framework Subcategories
	MUD files. Each MUD file is also associated with a separate MUD signature file.		
DHCP server	MasterPeace Yikes! router (Linksys WRT 3200ACM)	Dynamically assigns IP addresses; recognizes MUD URL in DHCP DISCOVER message; should notify MUD manager if the device's IP address lease expires or has been released	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
Router or switch	MasterPeace Yikes! router (Linksys WRT 3200ACM)	Provides MUD URL to MUD manager; gets configured by the MUD manager to enforce the IoT device's communication profile; performs per-device firewall rule enforcement	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
Certificates	DigiCert Premium Certificate	Used to sign MUD files and generate corresponding signature file	PR.AC-1 PR.AC-3 PR.AC-5 PR.AC-7
MUD-capable IoT device	Raspberry Pi Model 3B (devkit) Samsung ARTIK 520 (devkit) BeagleBone Black (devkit) NXP i.MX 8M (devkit)	Emits a MUD URL as part of its DHCP DISCOVER message; requests and applies software updates	ID.AM-1
Non-MUD-capable IoT device	Camera Smartphones Smart lighting devices Smart assistant Printer Digital video recorder	Acts as typical IoT devices on a network; creates network connections to cloud services	ID.AM-1

Component	Product	Function	Cybersecurity Framework Subcategories
Update server	NCCoE-hosted Apache server	Acts as a device manufacturer's update server that would communicate with IoT devices to provide patches and other software updates	PR.IP-1 PR.IP-3
Unapproved server	NCCoE-hosted Apache server	Acts as an internet host that has not been explicitly approved in a MUD file	DE.DP-3 DE.AM-1
IoT device discovery, categorization, and traffic policy enforcement	MasterPeace Yikes! router (Linksys WRT 3200ACM) and Yikes! cloud service	Discovers, classifies, and constrains traffic to/from IoT devices on network based on information such as DHCP header, MAC address, operating system, manufacturer, and model	ID.AM-1 PR.IP-1 DE.AM-1
Display and configuration of device information and traffic policies	MasterPeace Yikes! mobile application	Interacts with the Yikes! cloud to receive, display, and change information about the Yikes! router traffic policies and identification and categorization information about connected devices	ID.AM-1 PR.IP-1 DE.AM-1
Threat agent	GCA Quad9 threat agent, which is part of the open-source software Q9Thrt and is integrated into the Yikes! router	Monitors DNS traffic to/from devices on the local network and detects when domains are not resolved. When domains are not resolved, it queries the Quad9 threat API regarding whether the	ID.RA-1 ID.RA-2 ID.RA-3

Component	Product	Function	Cybersecurity Framework Subcategories
		domain is dangerous and, if so, what threat intelligence provider has flagged it as such. If a domain is determined to be dangerous, it notifies the Quad9 MUD manager of this threat.	
Threat-signaling MUD manager	GCA Quad9 MUD manager, which is part of the open-source software Q9Thrt and is integrated into the Yikes! router	Requests, receives, and parses the threat MUD file provided by the threat-signaling service's threat MUD file server, and applies its rules to create configurations to the Yikes! router's DNS service and its firewall rules that prohibit all devices from accessing the locations listed in the threat MUD file	ID.RA-1 ID.RA-2 ID.RA-3
Threat-signaling DNS services	GCA Quad9 DNS service	Receives input from several threat intelligence providers (including ThreatSTOP). Receives DNS resolution queries from local DNS service. For domains that are not known to be a threat, it simply resolves those domains to their IP address and provides this address to the requesting device. For domains that have been flagged as dangerous,	ID.RA-1 ID.RA-2 ID.RA-3

Component	Product	Function	Cybersecurity Framework Subcategories
		it does not perform address resolution and instead returns a NULL response.	
Threat-signaling API	GCA Quad9 threat API	Receives queries from the threat-signaling agent on the local network regarding domains that were not resolved. If a domain was not resolved because it had been flagged as dangerous, it responds with the name of the threat intelligence provider that had flagged the domain as dangerous.	ID.RA-1 ID.RA-2 ID.RA-3
Threat MUD file server	ThreatSTOP threat MUD File Server	Receives requests from the threat-signaling MUD manager on the local network for the threat MUD file corresponding to a domain that has been flagged as dangerous. Responds by providing the threat MUD file (and the MUD file's signature file) that is associated with the threat that has made this domain dangerous. This threat file will contain not just the domain and IP address of the domain that the router had tried, un-	ID.RA-1 ID.RA-2 ID.RA-3

Component	Product	Function	Cybersecurity Framework Subcategories
		successfully, to resolve; it will also include the list of all domains and IP addresses that are associated with the threat in question, i.e., all domains and IP addresses that are associated with this threat campaign.	
Threat MUD File	Threat file in MUD file format provided by ThreatSTOP listing all dangerous domains and IP addresses associated with any given threat	This is a file that has the exact same format as a MUD file, thus providing a standardized format for conveying the domains and IP addresses of all dangerous sites that are associated with a given threat and should therefore be blocked. Unlike a typical MUD file, however, this file does not contain usage description information regarding the permitted communication profile of some specific type of device. Instead, the information in this file is intended to be applied to the entire network (both MUD-capable and non-MUD-capable devices). Furthermore, it will list only external sites to and from which traffic should be	ID.RA-1 ID.RA-2 ID.RA-3

Component	Product	Function	Cybersecurity Framework Subcategories
		prohibited because the sites are associated with a given threat, not sites with which communication should be permitted, and it will not provide any rules regarding local network traffic that should be permitted or prohibited. Also, any given threat may be associated with a number of different domains and/or IP addresses. This threat file is designed to list all domains and IP addresses that are associated with any given threat that should be blocked. The file will also differ from a typical MUD file insofar as its mfg-name field will contain the name of the threat intelligence provider rather than the name of a device manufacturer, and its model-name field will typically contain the name of the threat that the file is associated with rather than model information about any IoT device.	

Each of these components is described more fully in the following sections.

7.2.1 MUD Manager

The MUD manager is a key component of the architecture. It fetches, verifies, and processes MUD files from the MUD file server. It then configures the router with firewall rules to control communications based on the contents of the MUD files. The Yikes! MUD manager is a logical component within the physical Yikes! router. The Yikes! router supports IoT devices that emit their MUD URLs via DHCP messages. When the MUD URL is emitted via DHCP, it is extracted from the DHCP message and provided to the MUD manager, which then retrieves the MUD file and signature file associated with that URL and configures the Yikes! router to enforce the IoT device's communication profile based on the MUD file. The router implements firewall rules for src-dnsname, dst-dnsname, my-controller, controller, same-manufacturer, manufacturer, and local-networks constructs that are specified in the MUD file. The system supports both lateral east/west protection and appropriate access to internet sites (north/south protection).

By default, Yikes! prohibits each device on the network from communicating with all other devices on the network unless explicitly permitted either by the MUD file or by local policy rules that are configurable within the Yikes! router.

The version of the Yikes! MUD manager used in this project is a prerelease implementation that is intended to introduce home and small-business network users to the MUD concept. It is intended to be a fully automated MUD manager implementation that includes all MUD protocol features.

7.2.2 MUD File Server

In the absence of a commercial MUD file server for use in this project, the NCCoE used a MUD file server hosted by MasterPeace that is accessible via the internet. This file server stores the MUD files along with their corresponding signature files for the IoT devices used in the project. Upon receiving a GET request for the MUD files and signatures, it serves the request to the MUD manager by using https.

7.2.3 MUD File

Using the MUD file maker component referenced above in Table 7-1, it is possible to create a MUD file with the following contents:

- internet communication class—access to cloud services and other specific internet hosts:
  - host: www.osmud.org
    - protocol: TCP
    - direction-initiated: from IoT device
    - source port: any
    - destination port: 443

- controller class—access to **classes** of devices that are known to be controllers (could describe well-known services such as DNS or NTP):
    - host: www.getyikes.com
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 443
- local-networks class—access to/from **any** local host for specific services (e.g., http or https):
    - host: any
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- my-controller class—access to controllers specific to this device:
    - controllers: null (to be filled in by the network administrator)
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- same-manufacturer class—access to devices of the same manufacturer:
    - same-manufacturer: null (to be filled in by the MUD manager)
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any
        - destination port: 80
- manufacturer class—access to devices of a specific manufacturer (identified by MUD URL):
    - manufacturer: Google (URL decided by the device manufacturer)
        - protocol: TCP
        - direction-initiated: from IoT device
        - source port: any

  - destination port: 80

7.2.4 Signature File

According to the IETF MUD specification, “a MUD file MUST be signed using CMS as an opaque binary object.” All the MUD files in use (e.g., *yikesmain.json*) were signed with the OpenSSL tool by using the command described in the specification (detailed in Volume C of this publication). A Premium Certificate, requested from DigiCert, was leveraged to generate the signature file (e.g., *yikesmain.p7s*). Once created, the signature file is stored on the MUD file server.

7.2.5 DHCP Server

The DHCP server in the architecture is MUD-capable and, like the MUD manager, is a logical component within the Yikes! router. In addition to dynamically assigning IP addresses, it recognizes the DHCP option (161) and extracts the MUD URL from the IoT device’s DHCP message. It then provides the MUD URL to the MUD manager. The DHCP server provided by the Yikes! router is useful in small/medium-business and home network environments where centralized address management is not required.

7.2.6 Router/Switch

This project uses the MasterPeace Yikes! router. The Yikes! router is a customized original equipment manufacturer product, which at the time of this implementation is a preproduction product developed on a Linksys WRT 3200ACM router. It is a self-contained router, Wi-Fi access point, and firewall that communicates locally with Wi-Fi devices and wired devices. The Yikes! router initially isolates all devices connected to the router from each other. When devices connect to the router, the Yikes! router provides the device’s DHCP header, MAC address, operating system, and connection characteristics to the Yikes! cloud service, which attempts to identify and categorize each device based on this information. The Yikes! router receives from the Yikes! cloud service rules for north/south and east/west filtering based on the Yikes! cloud processing (see Section 7.2.11) and any custom user settings that may have been configured in the Yikes! mobile application (see Section 7.2.12). These rules may apply to both MUD-capable and non-MUD-capable devices.

In addition to this category-based traffic policy enforcement that the Yikes! router provides for all devices, the Yikes! router also provides MUD support for MUD-capable IoT devices that emit MUD URLs via DHCP. Future work may be done to support MUD-capable devices that emit MUD URLs via X.509 or LLDP. The Yikes! router receives the MUD URL emitted by the device, retrieves the MUD file associated with that URL, and configures traffic filters (firewall rules) on the router to enforce the communication limitations specified in the MUD file for each device. The Yikes! router requires access to the internet to support secure API access to the Yikes! cloud service.

Last, the Yikes! router also provides integrated support for threat signaling by incorporating GCA Quad9 threat agent (see Section 7.2.13) and GCA Quad9 MUD manager (see Section 7.2.14) capabilities. Both the Quad9 threat agent and the Quad9 MUD manager are components of the open-source software Q9Thrt. See Section 7.3.1.3 for a description of Build 2's threat-signaling architecture and more information on Q9Thrt.

7.2.7 Certificates

DigiCert provisioned a Premium Certificate for signing the MUD files. The Premium Certificate supports the key extensions required to sign and verify Cryptographic Message Syntax (CMS) structures as required in the MUD specification. Further information about DigiCert's CertCentral web-based platform, which allows for provisioning and managing publicly trusted X.509 certificates, can be found in Section 6.2.8.

7.2.8 IoT Devices

This section describes the IoT devices used in the laboratory implementation. There are two distinct categories of devices: devices that can emit a MUD URL in compliance with the MUD specification, i.e., MUD-capable IoT devices; and devices that are not capable of emitting a MUD URL in compliance with the MUD specification, i.e., non-MUD-capable IoT devices.

7.2.8.1 *MUD-Capable IoT Devices*

The project used several MUD-capable IoT devices: NCCoE Raspberry Pi (devkit), Samsung ARTIK 520 (devkit), BeagleBone Black (devkit), and NXP i.MX 8m (devkit). The devkits were modified by the NCCoE to simulate MUD capability within IoT devices. All of the MUD-capable IoT devices demonstrate the ability to emit a MUD URL as part of a DHCP transaction and to request and apply software updates.

7.2.8.1.1 NCCoE Raspberry Pi (Devkit)

The Raspberry Pi devkit runs the Raspbian 9 operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction.

7.2.8.1.2 NCCoE Samsung ARTIK 520 (Devkit)

The Samsung ARTIK 520 devkit runs the Fedora 24 operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction.

7.2.8.1.3 NCCoE BeagleBone Black (Devkit)

The BeagleBone Black devkit runs the Debian 9.5 operating system. It is configured to include a MUD URL that it emits during a typical DHCP transaction.

7.2.8.1.4 NCCoE NXP i.MX 8m (Devkit)

The NXP i.MX 8m devkit runs the Yocto Linux operating system. The NCCoE modified a Wi-Fi start-up script on the device to configure it to emit a MUD URL during a typical DHCP transaction.

7.2.8.2 *Non-MUD-Capable IoT Devices*

The laboratory implementation also includes a variety of legacy, non-MUD-capable IoT devices that are not capable of emitting a MUD URL. These include cameras, smartphones, smart lighting, a smart assistant, a printer, and a DVR.

7.2.8.2.1 Cameras

The three cameras utilized in the laboratory implementation are produced by two different manufacturers. They stream video and audio either to another device on the network or to a cloud service. These cameras are controlled and managed by a smartphone.

7.2.8.2.2 Smartphones

Two types of smartphones are used for setting up, interacting with, and controlling IoT devices.

7.2.8.2.3 Lighting

Two types of smart lighting devices are used in the laboratory implementation. These smart lighting components are controlled and managed by a smartphone.

7.2.8.2.4 Smart Assistant

A smart assistant is utilized in the laboratory implementation. The device is used to demonstrate and test the wide range of network traffic generated by a smart assistant.

7.2.8.2.5 Printer

A smart printer is connected to the laboratory network wirelessly to demonstrate smart printer usage.

7.2.8.2.6 Digital Video Recorder

A smart DVR is connected to the laboratory implementation network. This is also controlled and managed by a smartphone.

7.2.9 Update Server

The update server is designed to represent a device manufacturer or trusted third-party server that provides patches and other software updates to the IoT devices. This project used an NCCoE-hosted update server that provides faux software update files.

7.2.9.1 *NCCoE Update Server*

The NCCoE implemented its own update server by using an Apache web server. This file server hosts faux software update files to be served as software updates to the IoT device devkits. When the server receives an http request, it sends the corresponding faux update file.

7.2.10 Unapproved Server

As with Build 1, the NCCoE implemented and used its own unapproved server for Build 2. Details can be found in Section 6.2.11.

7.2.11 IoT Device Discovery, Categorization, and Traffic Policy Enforcement– Yikes! Cloud

The Yikes! cloud uses proprietary techniques and machine learning to analyze information about each device that is provided to it by the Yikes! router. The Yikes! cloud uses the DHCP header, MAC address, operating system, and connection characteristics of devices to automatically classify each device, including make, model, and Yikes! device category. Yikes! has a comprehensive list of categories that includes these examples:

- mobile: phone, tablet, e-book, smart watch, wearable, car
- home and office: computer, laptop, printer, IP phone, scanner
- smart home: IP camera, smart device, smart plug, light, voice assistant, thermostat, doorbell, baby monitor
- network: router, Wi-Fi extender
- server: network attached storage, server
- engineering: Raspberry Pi, Arduino

The Yikes! cloud then uses the Yikes! category to define specific east/west rules for that device and every other device on the Yikes! router's network. It also looks up the device in the Yikes! proprietary IoT device library, and, if available, provides specialized north/south filtering rules for that device. The east/west and north/south rules are then configured on the Yikes! router for local enforcement.

The Yikes! cloud also provides information about the device, whether it is MUD-capable, its categorization, and filtering rules to the Yikes! mobile application (see Section 7.2.12). This information is presented to the user in a graphical user interface, and the user can make specific changes. These changes are also configured on the Yikes! router for enforcement.

7.2.12 Display and Configuration of Device Information and Traffic Policies–Yikes! Mobile Application

Yikes! also provides a mobile application for additional capabilities, which at the time of publication was accessed through a web user interface (UI). The Yikes! mobile application allows users further fine-grained device filtering control. The Yikes! mobile application interacts with the Yikes! cloud to receive and display information about the traffic policies that are configured on the Yikes! router as well as the identification and categorization information about devices connected to the network. The Yikes!

mobile application enables device information that is populated automatically by the Yikes! cloud to be overridden, and it enables users to configure traffic policies to be enforced by the router.

7.2.13 Threat Agent

Build 2 has a threat-signaling agent integrated into the Yikes! router. This threat-signaling agent is part of the open-source software called Q9Thrt, which builds on and extends the Quad9 DNS service provided by GCA. More information on Q9Thrt may be found at https://github.com/osmud/q9thrt.

7.2.13.1 *GCA Quad9 Threat Agent*

The GCA Quad9 threat agent monitors DNS traffic to/from devices on the local network and detects when domains are not resolved by the Quad9 DNS service. When a domain is not resolved, it could mean one of two things: either the domain has been flagged as potentially unsafe, or the domain does not exist (perhaps because it was mistyped, for example). The Quad9 threat agent eavesdrops on DNS responses that are sent from the Quad9 DNS service in the cloud to the Yikes! router's local DNS services. If the Quad9 threat agent detects a null response, it queries the Quad9 threat API to inquire as to whether the domain is dangerous and, if so, which threat intelligence provider has flagged it as such. If it receives a response indicating that a domain has been determined to be unsafe, it informs the Quad9 MUD manager (see Section 7.2.18) component (which is also integrated into the Yikes! router).

7.2.14 Threat-Signaling MUD Manager

Build 2 has a second MUD manager integrated into the Yikes! router that is designed to retrieve and parse the threat MUD file (see Section 7.2.18) retrieved from the threat intelligence provider. This threat-signaling MUD manager is part of the open-source software called GCA Q9Thrt, which builds on and extends the Quad9 DNS service provided by GCA. More information on Q9Thrt may be found at https://github.com/osmud/q9thrt.

7.2.14.1 *GCA Quad9 MUD Manager*

The GCA Quad9 MUD manager retrieves and parses threat MUD files. Threat MUD files are files that are written in MUD file format that list the domains and IP addresses of locations on the internet that have been determined to be unsafe and should be blocked because they are associated with a known threat. When the Quad9 threat agent (which is also integrated into the Yikes! router) learns that a threat has been found, it informs the Quad9 MUD manager and provides the Quad9 MUD manager with the URL of the threat MUD file. The Quad9 MUD manager uses https to request the threat MUD file and the threat MUD file's signature file. Assuming the signature file indicates that the threat MUD file is valid, the Quad9 MUD manager parses the threat MUD file and uses the threat MUD file rules to configure both the firewall and the local DNS services in the Yikes! router. It configures the firewall to prohibit all devices from accessing the domains and IP addresses listed in the threat MUD file, and it configures the local DNS services to return null responses when asked to resolve domain names listed in the threat MUD file.

7.2.15 Threat-Signaling DNS Services

Build 2 accesses external DNS services that receive input from several internet threat intelligence providers and are thus able to respond to domain name resolution requests for unsafe domains by signaling that the requested domain is potentially unsafe. These DNS services are provided by GCA.

7.2.15.1 *GCA Quad9 DNS Service*

GCA Quad9 DNS service receives input from several threat intelligence providers, making them aware of which domains have been determined to be unsafe. One of the threat intelligence providers that provides input to Quad9 DNS service is ThreatSTOP. For domains that are not known to be a threat, Quad9 DNS service behaves like any other DNS service would by resolving those domain names to their IP address(es) and providing those addresses to the requesting device. For domains that have been flagged as dangerous, however, Quad9 DNS service does not perform domain name resolution; instead, it returns a null response to the requesting device.

7.2.16 Threat-Signaling API

Build 2 accesses an external threat-signaling API that, when queried regarding specific domain names, responds by indicating whether the domain has been determined to be unsafe and, if so, the name of the threat intelligence provider responsible for the threat information. This threat-signaling API is provided by GCA.

7.2.16.1 *GCA Quad9 Threat API*

When a device on the local network makes a DNS request for a domain that does not get resolved, this means either that the domain does not exist or that it is unsafe. To determine which is the case for any given domain, the Quad9 threat agent on the Yikes! router queries the Quad 9 Threat API regarding that domain. If the domain is considered unsafe, the Quad9 threat API responds with the name of the threat intelligence provider that had flagged the domain as dangerous and other information that is needed to retrieve the associated threat MUD file.

7.2.17 Threat MUD File Server

Build 2 accesses an external threat MUD file server containing threat MUD files (see Section 7.2.18) for threats that a threat intelligence provider has identified and documented. The threat MUD file server used in Build 2 hosts threat MUD files provided by the threat intelligence provider ThreatSTOP.

7.2.17.1 *ThreatSTOP Threat MUD File Server*

When the Quad9 MUD manager on the Yikes! router is informed by the Quad9 threat agent that a threat has been found, the Quad9 MUD manager contacts the ThreatSTOP threat MUD file server to retrieve the threat MUD file associated with that threat. This threat MUD file server hosts threat MUD files (see Section 7.2.18) for threats that ThreatSTOP has identified and documented. When it receives a request from the Quad9 MUD manager for a threat file corresponding to a domain, the ThreatSTOP threat MUD file server responds by providing the threat file that is associated with the threat that has made this domain unsafe. This threat file will contain not just the domain and IP address of the domain that the router had tried unsuccessfully to resolve; it will also include all domains and IP addresses that are associated with the threat in question.

7.2.18 Threat MUD File

Build 2 uses threat MUD files provided by the threat intelligence provider ThreatSTOP. Threat MUD files have the same format as MUD files, thus providing a standardized format for conveying the domains and IP addresses of all dangerous sites that are associated with a given threat and should therefore be blocked. Unlike a typical MUD file, however, a threat MUD file does not contain manufacturer usage description information regarding the communication profile of some specific type of device. Instead, the information in this file is intended to be applied to the entire network (both MUD-capable and non-MUD-capable devices). Furthermore, the threat MUD file will list only external sites to and from which traffic should be prohibited because the sites are associated with a given threat, not sites with which communication should be permitted, and it will not provide any rules regarding local network traffic that should be permitted or prohibited. Also, any given threat may be associated with several different domains and/or IP addresses. The threat MUD file is designed to list all domains and IP addresses that are associated with any given threat that should be blocked. The file will also differ from a typical MUD file insofar as its mfg-name field will typically contain the name of the threat intelligence provider rather than the name of a device manufacturer, and its model-name field will typically contain the name of the threat that the file is associated with rather than model information about a particular IoT device.

7.3 Build Architecture

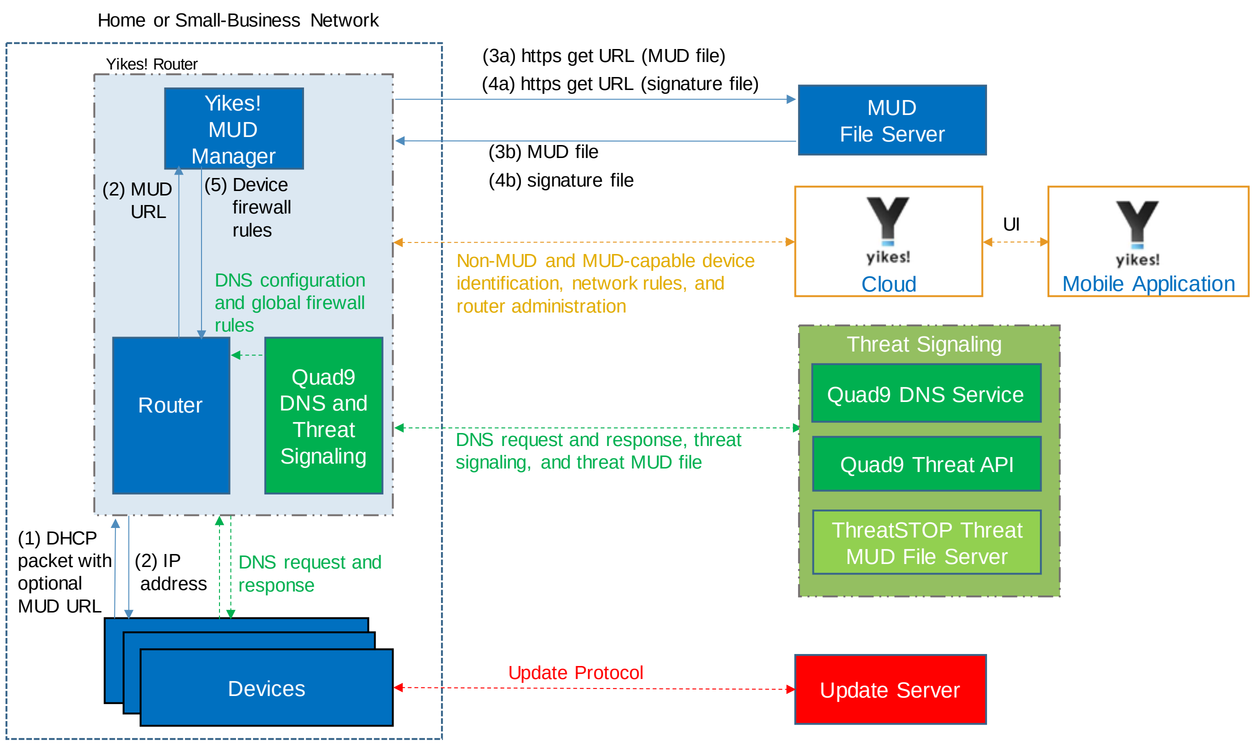
In this section we present the logical architecture of Build 2 relative to how it instantiates the reference architecture depicted in Figure 4-1. We also describe Build 2's physical architecture and present message flow diagrams for some of its processes.

7.3.1 Logical Architecture

Figure 7-1 depicts the logical architecture of Build 2. Figure 7-1 uses numbered arrows to depict in detail the flow of messages needed to support onboarding a MUD-capable device. The other key aspects of the Build 2 architecture (i.e., the Yikes! cloud, the Yikes! mobile application, threat signaling, and the update server) are depicted but not described in the same depth as MUD.

Yikes! is designed to run as a router with a connection to the Yikes! cloud and to be managed via the Yikes! mobile application. The Yikes! cloud provides traffic rules to the Yikes! router that apply to devices based on device category. The Yikes! router also supports threat-signaling capabilities that enable it to refrain from connecting to domains that threat intelligence services have flagged as potentially dangerous. The logical architecture for Build 2 also includes the notion of ensuring that all IoT devices can access update servers so they can remain up-to-date with the latest security patches. MUD, Yikes! cloud, and threat-signaling support are each described in their respective subsections below.

Figure 7-1 Logical Architecture—Build 2



7.3.1.1 *MUD Capability*

As shown in Figure 7-1, the Yikes! router includes integrated support for MUD in the form of a Yikes! MUD manager component and a MUD-capable DHCP server (not depicted). Support for MUD also requires access to a MUD file server that hosts MUD files for the MUD-capable IoT devices being onboarded.

The Yikes! router currently supports DHCP as the mechanism for MUD URL emission. It contains a DHCP server that is configured to extract MUD URLs from IPv4 DHCP transactions.

As shown in Figure 7-1, the flow of messages needed to support onboarding a MUD-capable device is as follows:

- Upon connecting a MUD-capable device, the MUD URL is emitted via DHCP (step 1).
- The Yikes! DHCP server on the router receives the request from the device and assigns it an IP address (step 2).
- At the same time, the DHCP server sends the MUD URL to the Yikes! MUD manager (step 2).
- Once the MUD URL is received, the MUD manager uses it to fetch the MUD file from the MUD file server (step 3a); if successful, the MUD file server at the specified location will serve the MUD file (step 3b).
- Next, the MUD manager requests the signature file associated with the MUD file (step 4a) and upon receipt (step 4b) verifies the MUD file by using its signature file.
- Assuming the MUD file has been verified successfully, the MUD manager translates the traffic rules that are in the MUD file into firewall rules that it installs onto the Yikes! router (step 5). Once the firewall rules are installed on the router, the MUD-capable IoT device will be able to communicate with approved local hosts and internet hosts as defined in the MUD file, and any unapproved communication attempts will be blocked.

7.3.1.2 *Yikes! Cloud Capability*

The Yikes! cloud includes the ability to identify and categorize both MUD-capable and non-MUD-capable devices that join the network, and it serves as the repository of traffic policies that can be applied to categories of devices regardless of whether those devices are MUD-capable. The Yikes! router communicates with the Yikes! cloud via a secure API. This communication is required for the router to send information related to the network to the Yikes! cloud service as well as to receive network rules and router administration from the Yikes! cloud. Network rules and router administration are configured through the Yikes! mobile application.

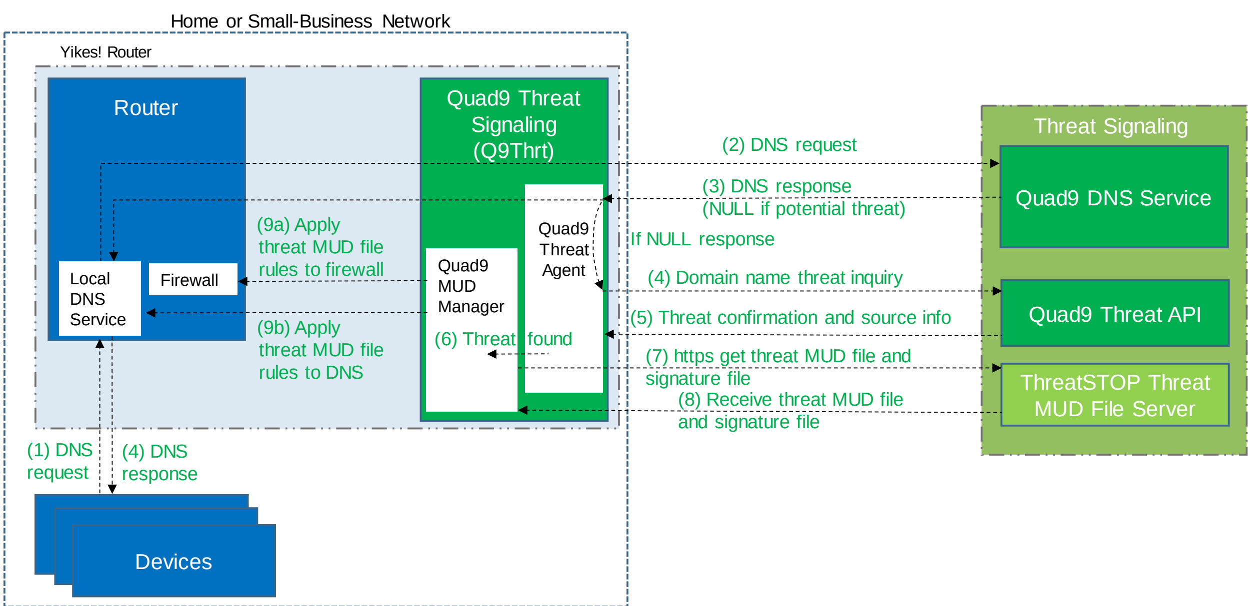
It is possible that both Yikes! cloud traffic policies and MUD file traffic policies could both apply to any given device in the network. For any given device, if these policies conflict, MUD file policies are given precedence over Yikes! traffic policies. If the policies do not conflict, they are both applied to the device. If a device is not MUD-capable, the Yikes! cloud policies that apply to it will be applied. If a device is MUD-capable but its MUD file is not applied (because, for example, the TLS certificate of the MUD file server is not valid or the MUD file is determined to be invalid), the Yikes! cloud rules that apply to the MUD-capable device will still be applied.

7.3.1.3 *Threat-Signaling Capability*

Build 2 integrates a threat-signaling capability that protects both MUD-capable and non-MUD-capable devices from the latest cybersecurity threats that have been detected by threat intelligence services. It prevents devices from accessing external domains and IP addresses that are associated with known current cybersecurity threats.

Figure 7-2 depicts a detailed view of Build 2's threat-signaling architecture. As shown, GCA's Quad9 threat agent and Quad9 MUD manager (which are both part of Q9Thrt) are integrated into the Yikes! router to support threat signaling. Additionally, the Yikes! router requires the use of several external components to support threat signaling: Quad9 DNS service, which receives threat information feeds from a variety of threat intelligence services; Quad9 threat API, which confirms a threat as well as information regarding how to find the threat MUD file for that threat; and the ThreatSTOP threat MUD file server, which provides the threat MUD file for the threat.

Figure 7-2 Threat-Signaling Logical Architecture–Build 2



The messages that are exchanged among architectural components to support threat signaling are depicted by arrows and numbered in sequence in Figure 7-2. The result of this message flow is to protect a local device from connecting to a domain that has been identified as unsafe by a threat intelligence service from which Quad9 DNS service receives information which, in this case, is ThreatSTOP.

As depicted in Figure 7-2, the steps are as follows:

- A local device (which may or may not be an IoT device and may or may not be MUD-capable) sends a DNS resolution requests to its local DNS service, which is hosted on the Yikes! router (step 1).
- If the local DNS service cannot resolve the request itself, it will forward the request to the Quad9 DNS service (step 2).
- The Quad9 DNS service will return a DNS response to the Yikes! router's local DNS service. The Quad9 DNS service receives input from several threat intelligence providers (not depicted in the diagram), so it is aware of whether the domain in question has been identified to be unsafe. If the domain has not been identified as unsafe, the Quad9 DNS service will respond with the IP address(es) corresponding to the domain (as would any normal DNS service). If the domain has been flagged as unsafe, however, the Quad9 DNS service will not resolve the domain. Instead, it will return an empty (null) DNS response message to the local DNS service (step 3).
- The local DNS service will forward the DNS response to the device that originally made the DNS resolution request (step 4).
- Meanwhile, the Quad9 Threat Agent that is running on the Yikes! router monitors all DNS requests and responses. When it sees a domain that does not get resolved, it sends a query to the Quad9 Threat API asking whether the domain is dangerous and, if so, what threat intelligence provider had flagged it as such and with what threat it is associated (step 4).
- The Quad9 Threat API responds with this information, which, in this case, informs the threat agent that the domain is indeed dangerous and if it wants more information about the blocked domain, it should contact ThreatSTOP (a threat intelligence provider) and request a particular threat MUD file. This threat MUD file will list domains and IP addresses that should be blocked because they are all associated with the same threat campaign as this threat (step 5).
- The Quad9 threat agent provides this information to the Quad9 MUD manager (step 6).
- The Quad9 MUD manager requests the threat MUD file (and the threat MUD file's signature file) from the ThreatSTOP threat MUD file server (step 7).
- The Quad9 MUD manager receives the threat MUD file (and the threat MUD file's signature file) from the ThreatSTOP threat MUD file server and uses the signature file to verify that the threat MUD file is valid (step 8).
- Assuming the threat MUD file is valid, the Quad9 MUD manager uses the threat MUD file to configure the router's firewall to block all domains and IP addresses listed in this threat MUD file (step 9a).
- The Quad9 MUD manager also configures the router's local DNS services to provide empty responses for DNS requests that are made for all domain names that are listed in the threat MUD file (step 9b).

Threat-signaling rules have higher precedence than MUD rules, which, in turn, have higher precedence than Yikes! category rules. This means that if a domain is flagged as dangerous by threat-signaling intelligence, none of the devices on the local network will be permitted to communicate with it—even MUD-capable devices whose MUD files list that domain as permissible.

Threat-signaling rules time out after 24 hours, at which time the firewall rules associated with those rules are removed from the router. If, after 24 hours, a device tries to connect to that domain but is still considered dangerous, the firewall rules will no longer be in place in the router to prevent access to the domain. However, when the device attempts to access the domain, the same DNS resolution process as depicted in Figure 7-2 will be performed all over again: when the device requests resolution of the domain name, the Quad9 DNS service will return an empty DNS response message, and the threat MUD file for that domain will be retrieved and its rules installed on the router firewall for another 24 hours.

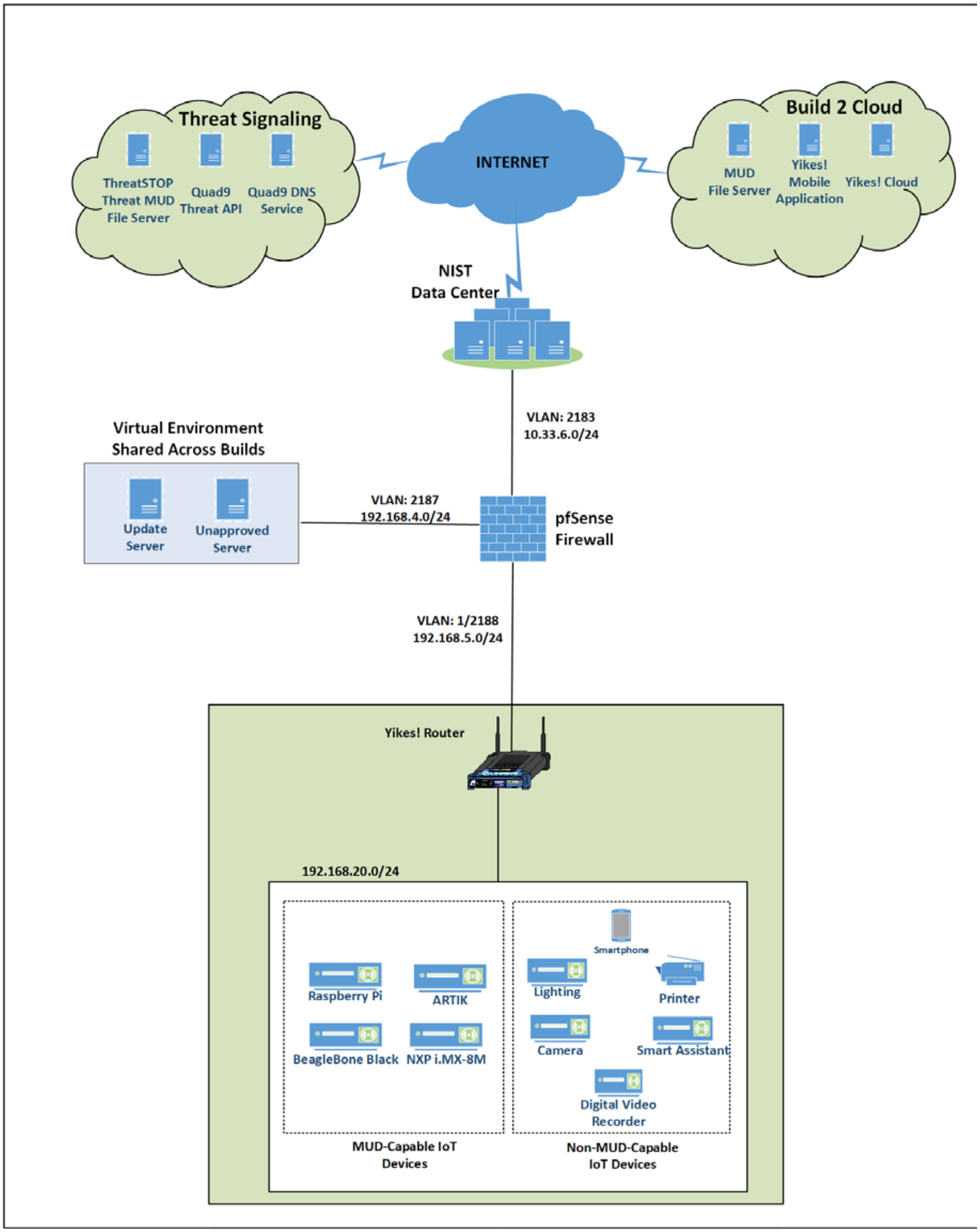
7.3.2 Physical Architecture

Figure 7-3 depicts the physical architecture of Build 2. A single DHCP server instance is configured for the local network to dynamically assign IPv4 addresses to each IoT device that connects to the Yikes! router. This single subnet hosts both MUD-capable and non-MUD-capable IoT devices. The network infrastructure as configured utilizes the IPv4 protocol for communication both internally and to the internet.

In addition, this build uses a portion of the virtual environment that is shared across builds. Services hosted in this environment include an update server and an unapproved server.

Internet-accessible cloud services are also supported in Build 2. This includes a MUD file server and Yikes! cloud services. To support threat-signaling functionality, a ThreatSTOP threat MUD file server, Quad9 threat API, and Quad9 DNS service were utilized.

1815 **Figure 7-3 Physical Architecture—Build 2**



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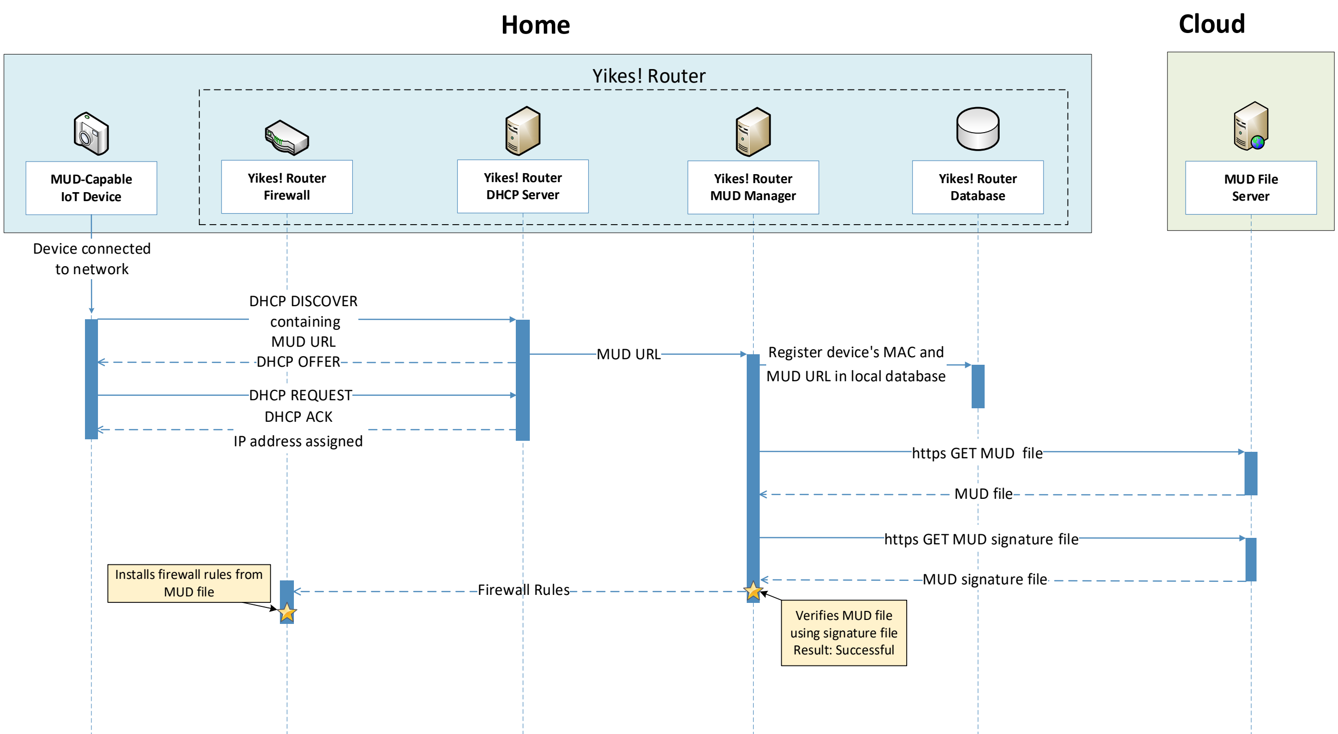
7.3.3 Message Flow

This section presents the message flows used in Build 2 during several different processes of note.

7.3.3.1 *Onboarding MUD-Capable Devices*

Figure 7-4 MUD-Capable IoT Device Onboarding Message Flow - Build 2 depicts the message flows involved in the process of onboarding a MUD-capable IoT device in Build 2.

Figure 7-4 MUD-Capable IoT Device Onboarding Message Flow—Build 2



The components used to support Build 2 are deployed across the home/small-business network (shown in blue) and the cloud (shown in green). A single device called the Yikes! router on the home/small-business network hosts five logical components: the Yikes! router firewall, the Yikes! router DHCP server, the Yikes! router MUD manager, the Yikes! router database, and the Yikes! router agent. (The Yikes! agent is not depicted in Figure 7-4 MUD-Capable IoT Device Onboarding Message Flow—Build 2 because it is not involved in onboarding the MUD-capable device.) The MUD file server is in the cloud, as are the device's update server and the Yikes! cloud service. (Again, only the MUD file server is depicted in Figure 7-4 MUD-Capable IoT Device Onboarding Message Flow—Build 2 because it is the only cloud component that is involved in onboarding the MUD-capable device.)

As shown in Figure 7-4 MUD-Capable IoT Device Onboarding Message Flow—Build 2, the message flow is as follows:

- When a MUD-capable IoT device is connected to the home/small-business network in Build 2, it exchanges DHCP protocol messages with the DHCP server on the router to obtain an IP address. The IoT device provides its MUD file URL within the DHCP DISCOVER message, as specified in the MUD RFC.
- The DHCP server forwards the MUD file URL and the MAC address of the connecting device to the MUD manager.
- The MUD manager registers the MAC address and MUD file URL of the device in the database that is located on the router.
- The MUD manager fetches the MUD file and the MUD file signature file from the MUD file server.
- After verifying that the MUD file is valid, the MUD manager installs the access control rules that correspond to the MUD file rules onto the router's firewall.

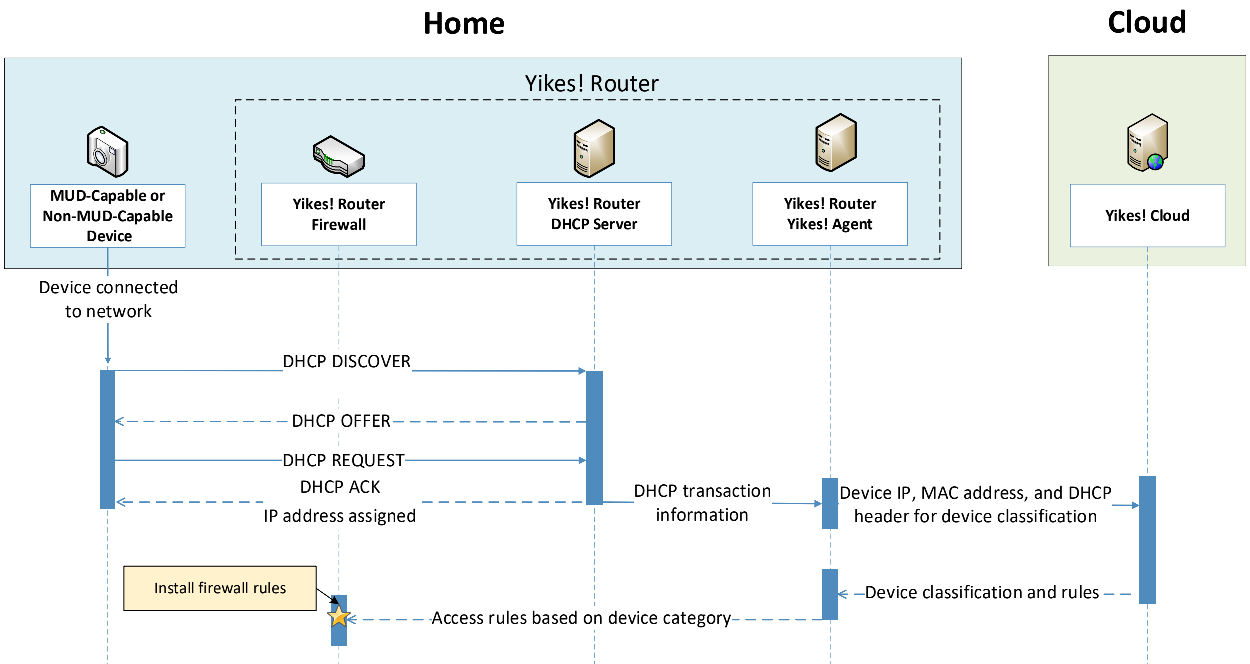
7.3.3.2 *Onboarding All Devices*

Figure 7-5 depicts the message flows involved in the process of onboarding all devices in Build 2 (both MUD-capable and non-MUD-capable devices), which are as follows:

- When a device is connected to the home/small-business network in Build 2, it exchanges DHCP protocol messages with the DHCP server to obtain an IP address. If it is a MUD-capable device, it also includes a MUD URL in this DHCP protocol exchange, and the onboarding message flow depicted in Figure 7-4 occurs in addition to the following message flow that is depicted in Figure 7-5. If it is a non-MUD-capable device, it does not include a MUD URL in this DHCP protocol exchange, and only the following message flow occurs.
- The DHCP server forwards information relevant to the connecting device such as IP address, MAC address, and DHCP header to the Yikes! router agent.
- The Yikes! router agent, in turn, forwards this information to the Yikes! cloud so the cloud can try to identify and classify the device.
- The Yikes! cloud sends the Yikes! router agent its determination of the device's category and associated traffic rules.
- The Yikes! router agent then configures the router with firewall rules for the device based on the device's category. Note that for this process to work, it is assumed that the Yikes! cloud has been preconfigured with various categories and traffic profile rules pertaining to each category. These rules can be configured by a user at any time by using the Yikes! mobile application.

- Note that if a device is MUD-capable and its MUD file rules conflict with its Yikes! category rules, both the device MUD rules and Yikes! category rules are installed, but the MUD rules take precedence and are enforced first.

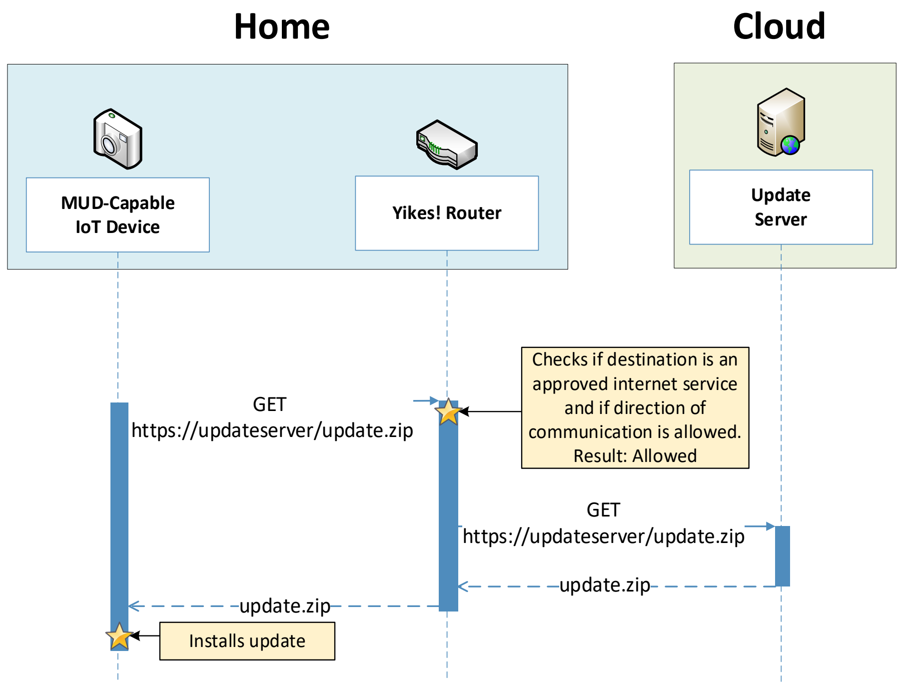
Figure 7-5 Device Onboarding Message Flow—Build 2



7.3.3.3 *Updates*

After a device has been permitted to connect to the home/small-business network, it should periodically check for updates. The message flow for updating the IoT device is shown in Figure 7-6 Update Process Message Flow—Build 2.

Figure 7-6 Update Process Message Flow—Build 2



As shown in Figure 7-6 Update Process Message Flow—Build 2, the message flow is as follows:

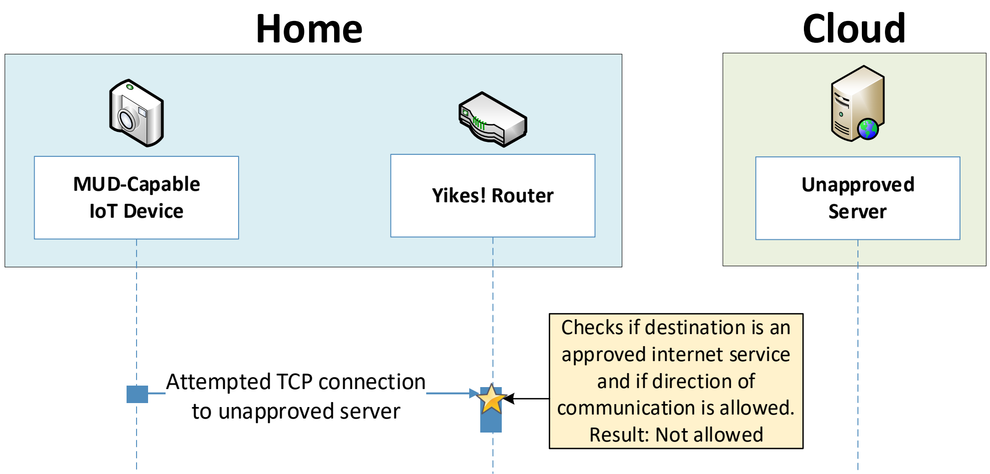
- The device generates an https GET request to its update server.
- The Yikes! router will consult the firewall rules for this device to verify that it is permitted to send traffic to the update server. Assuming there were explicit rules in the device's MUD file enabling it to send messages to this update server, the Yikes! router will forward the request to the update server.
- The update server will respond with a zip file containing the updates.
- The Yikes! router will forward this zip file to the device for installation.

7.3.3.4 *Prohibited Traffic*

Figure 7-7 shows an attempt to send traffic that is prohibited by the MUD file and so is blocked by the Yikes! router.

- A connection attempt is made from a local IoT device to an unapproved server. (The unapproved server is located at a domain to which the MUD file does not explicitly permit the IoT device to send traffic.)
- This connection attempt is blocked because there is no firewall rule in the Yikes! router that permits traffic from the IoT device to the unapproved server.

Figure 7-7 Unapproved Communications Message Flow—Build 2

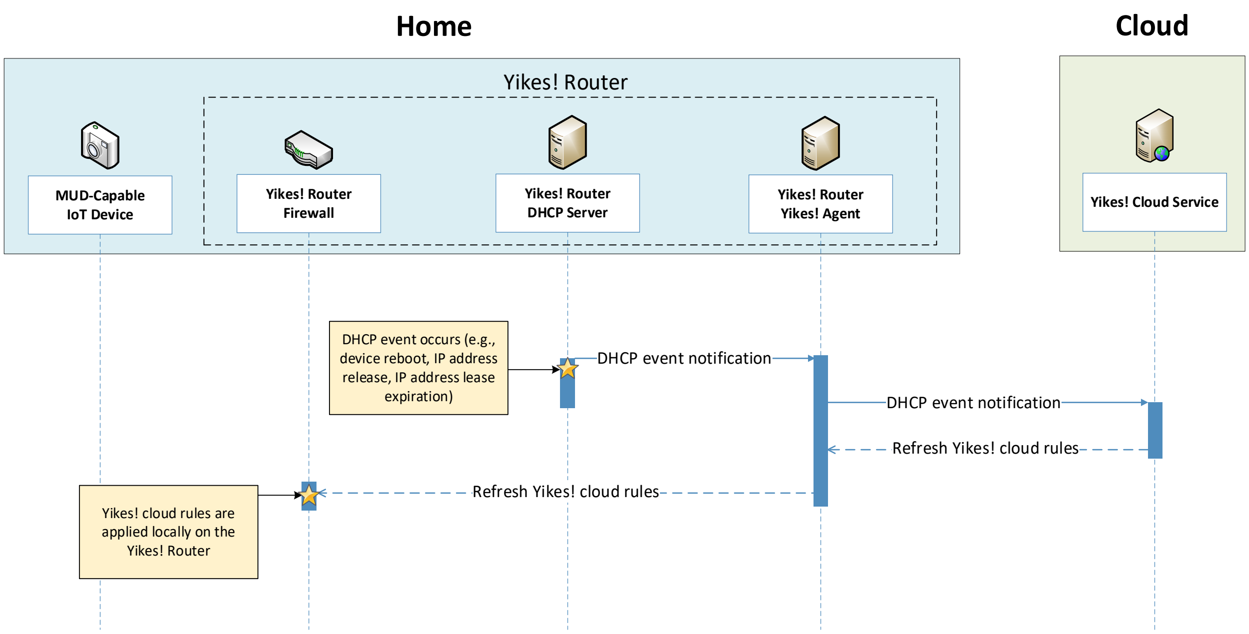


7.3.3.5 *DHCP Events*

Figure 7-8 shows the message flow when a change of DHCP state occurs, for example, when a device's IP address is assigned to a newly onboarded device, a lease expires, or a lease is explicitly released by the device. The Yikes! agent is triggered to send a notification to the Yikes! cloud to update or refresh the Yikes! cloud rules on the router when a DHCP event occurs. This update refreshes the firewall rules defined at the device category level that have been configured through the Yikes! cloud to be applied onto the Yikes! router. Figure 7-8 shows the following message flow:

- The DHCP event triggers a notification that is sent to the Yikes! router Yikes! agent.
- The Yikes! router Yikes! agent forwards the notification to the Yikes! cloud service.
- The Yikes! cloud service responds by sending a refresh of all Yikes! cloud rules to the Yikes! router agent.
- The Yikes! router Yikes! agent installs these refreshed rules onto the Yikes! router firewall.

Figure 7-8 DHCP Event Message Flow—Build 2



7.3.3.6 *Threat Signaling*

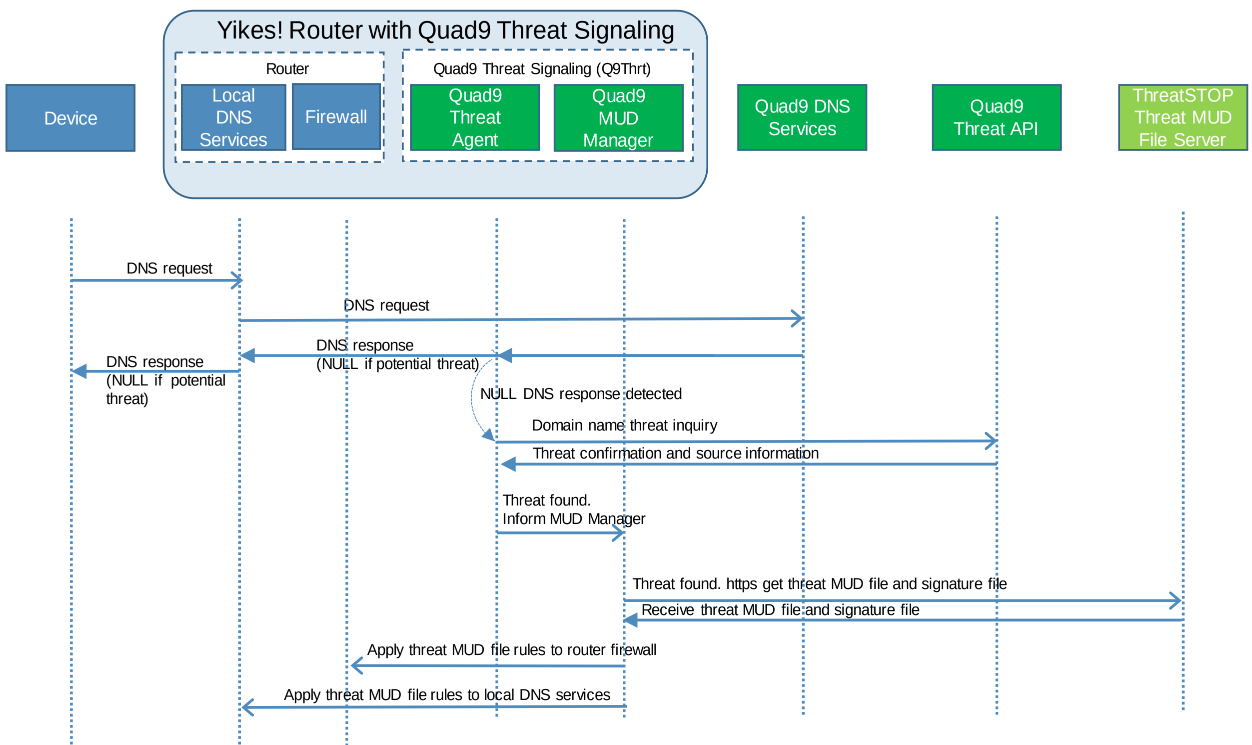
Figure 7-9 shows the message flow required to support threat signaling in Build 2.

- A local device (which may or may not be an IoT device and may or may not be MUD-capable) sends a DNS resolution request to its local DNS service, which is hosted on the Yikes! router.
- If the local DNS service cannot resolve the request itself, it will forward the request to the Quad9 DNS service.
- The Quad9 DNS service receives input from several threat intelligence providers (not depicted in the diagram) so the providers are aware of whether the domain in question has been identified to be unsafe. If the domain has not been identified as unsafe, the Quad9 DNS service will respond with the IP address(es) corresponding to the domain (as would any normal DNS service). If the domain has been flagged as unsafe, however, the Quad9 DNS service will not resolve the domain. Instead, it will return an empty (null) DNS response message to the local DNS service.
- The local DNS service will forward the DNS response to the device that originally made the DNS resolution request.
- Meanwhile, the Quad9 threat agent that is running on the Yikes! router monitors all DNS requests and responses. When it sees a domain that does not get resolved, it sends a query to the Quad9 threat API asking whether the domain is dangerous and, if so, which threat

intelligence provider had flagged it as such and with what threat it is associated (this query is labeled “Domain name threat inquiry” in Figure 7-9).

- The Quad9 threat API responds with this information, which, in this case, informs the threat agent that if it wants more information about the blocked domain, it should contact ThreatSTOP (a threat intelligence provider) and request a threat MUD file. This threat MUD file will list domains and IP addresses that should be blocked because they are all associated with the same threat campaign as this threat.
- Next, the Quad9 threat agent provides this information to the Quad9 MUD manager.
- The Quad9 MUD manager requests and receives this threat MUD file and the threat MUD file signature file from the ThreatSTOP threat MUD file server.
- After ensuring that the threat MUD file is valid, the Quad9 MUD manager uses the threat MUD file to configure the router’s firewall to block all domains and IP addresses listed in this threat MUD file.
- The Quad9 MUD manager also configures the router’s local DNS services to provide empty responses for DNS requests that are made for all domains that are listed in the threat MUD file.

Figure 7-9 Message Flow for Protecting Local Devices Based on Threat Intelligence—Build 2



7.4 Functional Demonstration

A functional evaluation and a demonstration of Build 2 were conducted that involved two types of activities:

- Evaluation of conformance to the MUD RFC—Build 2 was tested to determine the extent to which it correctly implements basic functionality defined within the MUD RFC.
- Demonstration of additional (non-MUD-related) capabilities—It did not verify the example implementation's behavior for conformance to a standard or specification; rather, it demonstrated advertised capabilities of the example implementation related to its ability to increase device and network security in ways that are independent of the MUD RFC. These capabilities may provide security for both non-MUD-capable and MUD-capable devices. Examples of this type of activity include device discovery, identification and classification, and support for threat signaling.

Table 7-2 summarizes the tests used to evaluate Build 2's MUD-related capabilities, and Table 7-3 summarizes the exercises used to demonstrate Build 2's non-MUD-related capabilities. Both tables list each test or exercise identifier, a summary of the test or exercise, the test or exercise's expected and observed outcomes, and the applicable Cybersecurity Framework Subcategories and NIST SP 800-53 controls for which each test or exercise verifies support. The tests and exercises listed in the table are detailed in a separate supplement for functional demonstration results. Boldface text is used to highlight the gist of the information that is being conveyed.

Table 7-2 Summary of Build 2 MUD-Related Functional Tests

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
IoT-1	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8	A **MUD-capable IoT device is configured to emit a MUD URL within a DHCP message.** The DHCP server assigns its IP address and extracts the MUD URL, which is sent to the MUD manager. The MUD manager requests the MUD file and signature from the MUD file server, and the MUD file server	Upon connection to the network, the MUD-capable IoT device has its MUD **PEP router/switch automatically configured according to the MUD file's route filtering policies.**	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.DS-5: Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10	serves the MUD file to the MUD manager. The MUD file explicitly permits traffic to/from some internet services and hosts and implicitly denies traffic to/from all other internet services. **The MUD manager translates the MUD file information into local network configurations that it installs on the router or switch that is serving as the MUD PEP for the IoT device.**		

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.PT-3: The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.			
IoT-2	**PR.AC-7:** Users, devices, and other assets are authenticated (e.g., single-factor, multifactor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks). **NIST SP 800-53 Rev. 4** AC-7, AC-8, AC-9, AC-11, AC-12, AC-14, IA-1, IA-2, IA-3, IA-4, IA-5, IA-8, IA-9, IA-10, IA-11	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **MUD file server that is hosting that file does not have a valid TLS certificate. Local policy has been configured to ensure that if the MUD file for an IoT device is located on a server with an invalid certificate, the router/switch will be configured by local policy to allow all communication to/from the device.**	When the MUD-capable IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-capable IoT device. Therefore, the **MUD PEP router/switch will be configured to allow all traffic to and from the IoT device.**	Pass
IoT-3	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **certificate that was used to sign the MUD file had already expired at the time of signing. Local policy has been configured to ensure that if the MUD file for a device has a signature that was signed by a**	When the MUD-capable IoT device is connected to the network and the MUD file and signature are fetched, the MUD manager will detect that the MUD file's signature was created by using a certificate that had already expired at the time of sign-	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
		certificate that had already expired at the time of signature, the device's MUD PEP router/switch will be configured by local policy to either allow or deny all communication to/from the device.	ing. According to local policy, the **MUD PEP will be configured to either allow or block all traffic to/from the device.**	
IoT-4	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-capable IoT device is configured to emit a URL for a MUD file, but the **signature of the MUD file is invalid. Local policy has been configured to ensure that if the MUD file for a device is invalid, the router/switch will be configured by local policy to allow all communication to/from the IoT device.**	When the MUD-capable IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-capable IoT device. Therefore, the **MUD PEP router/switch will be configured to allow all traffic to and from the IoT device.**	Pass
IoT-5	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **PR.IP-1:** A baseline configuration of information technology/industrial	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some internet locations and implicitly denies traffic to/from all other internet locations.**	When the MUD-capable IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the route filtering that is described in the device's MUD file** with	Pass (for testable procedure, ingress cannot be tested due to Network Address

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7		respect to traffic being permitted to/from some internet locations, and traffic being implicitly blocked to/from all remaining internet locations.	Translation [NAT])
IoT-6	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition. **PR.DS-5:** Protections against data leaks are implemented. **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 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **PR.IP-3:** Configuration change control processes are in place.	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some lateral hosts and implicitly denies traffic to/from all other lateral hosts.** (The MUD file does not explicitly identify the hosts as lateral hosts; it identifies classes of hosts to/from which traffic should be denied, where one or more hosts of this class happen to be lateral hosts.)	When the MUD-capable IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the access control information that is described in the device's MUD file** with respect to traffic being permitted to/from some lateral hosts, and traffic being implicitly blocked to/from all remaining lateral hosts.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7			
IoT-7	**PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition.	Test IoT-1 has run successfully, meaning that the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. Next, have **the IoT device change DHCP state by explicitly releasing its IP address lease, causing the device's policy configuration to be removed from the MUD PEP router/switch.**	When the MUD-capable **IoT device explicitly releases its IP address lease,** the MUD-related configuration for that IoT device will be removed from its MUD PEP router/switch.	Pass
IoT-8	**PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition.	Test IoT-1 has run successfully, meaning that the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. Next, have **the IoT device change DHCP state by waiting until the IoT device's address lease expires,**	When the MUD-capable **IoT device's IP address lease expires,** the MUD-related configuration for that IoT device will be removed from its MUD PEP router/switch.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
		causing the device's policy configuration to be removed from the MUD PEP router/switch.		
IoT-9	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CM-2, SI-4 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate.	Test IoT-1 has run successfully, meaning the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. The MUD file contains domains that resolve to multiple IP addresses. The MUD PEP router/switch should be configured to permit communication to or from all IP addresses for the domain.	A domain in the MUD file resolves to two different IP addresses. The MUD manager will create firewall rules that permit the MUD-capable device to send traffic to both IP addresses. The MUD-capable device attempts to send traffic to each of the IP addresses, and the MUD PEP router/switch permits the traffic to be sent in both cases.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-2, CM-3, SA-10 **PR.DS-2:** Data in transit is protected. **NIST SP 800-53 Rev. 4** SC-8, SC-11, SC-12			
IoT-10	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for	A MUD-capable IoT device is configured to emit a MUD URL. Upon being connected to the network, its MUD file is retrieved, and the PEP is configured to enforce the policies specified in that MUD URL for that device. **Within 24 hours (i.e., within the cache-validity period for that MUD file), the IoT device is reconnected to the network.** After 24 hours have elapsed, the same device is reconnected to the network.	Upon reconnection of the IoT device to the network, **the MUD manager does not contact the MUD file server. Instead, it uses the cached MUD file.** It translates this MUD file's contents into appropriate route-filtering rules and installs these rules onto the PEP for the IoT device. Upon reconnection of the IoT device to the network, after 24 hours have elapsed, the MUD manager	Not testable in preproduction implementation

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.		does fetch a new MUD file.	
IoT-11	**ID.AM-1:** Physical devices and systems within the organization are inventoried.	A **MUD-enabled IoT device is capable of emitting a MUD URL.**	Upon initialization, the MUD-enabled IoT device broad-	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
		The device should leverage one of the specified manners for emitting a MUD URL.	casts a DHCP message on the network, including at most one **MUD URL, in https scheme, within the DHCP transaction.**	

In addition to supporting MUD, Build 2 can identify a device's make (i.e., manufacturer) and model, categorize devices based on their make and model, and associate device categories with traffic policies that affect both internal and external traffic transmissions, as shown in Table 7-3.

Table 7-3 Non-MUD-Related Functional Capabilities Demonstrated

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
YnMUD-1	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CM-2, SI-4	A device identification and a categorization capability are supported by the router and cloud services. The **router is designed to detect all devices connected to the network and leverage cloud services to identify the devices using attributes associated with them, as well as categorize the devices by type when possible. If unable to identify and categorize them, devices are designated as uncategorized.**	Upon being connected to the network, the **router detects all connected devices and leverages a cloud service, which identifies each device's make and model using attributes** (e.g., type, IP address, OS), and **categorizes them** (e.g., cell phone, printer, smart appliance).	As expected

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
	DE.CM-1: The network is monitored to detect potential cybersecurity events. **NIST SP 800-53 Rev. 4** AC-2, AU-12, CA-7, CM-3, SC-5, SC-7, SI-4			
YnMUD-2	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped.	After executing YnMUD-1 successfully, the **UI is used to modify make, model, and/or category of onboarded devices.**	Onboarded devices have been identified and categorized automatically upon being connected to the network. Using the UI, show that the make and model of a device can be modified, and that the category of the device can be assigned manually.	As expected
YnMUD-3	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **ID.AM-4:** External information systems are catalogued. **NIST SP 800-53 Rev. 4** AC-20, SA-9 **PR.AC-1:** Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users and processes. **NIST SP 800-53 Rev. 4** AC-1, AC-2, IA-1, IA-2, IA-3, IA-4, IA-5, IA-6, IA-7, IA-8, IA-9, IA-10, IA-11 **NIST SP 800-53 Rev. 4** PE-2, PE-3, PE-4, PE-5, PE-6, PE-8 **PR.AC-3:** Remote access is managed.	**The router can apply traffic policies to categories of devices that restrict initiation of (south-to-north) communications to internet sites** by all devices in the specified category. Communication **can be configured to (a) allow all internet communication, (b) deny all internet communication to devices of a specific make and model, or (c) permit communication only to/from specified internet domains and**	Through the UI, device category rules can be defined to permit connectivity to every internet location by selecting “Allow All Internet Traffic” or to device-specific sites by selecting “IoT specific sites.” Set rules for the **computer category to permit all internet traffic,** and attempt to initiate communication from laptop to any internet host. **All internet communication from laptop**	As expected

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 AC-1, AC-17, AC-19, AC-20, SC-15 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC- 5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected (e.g., network segregation, network segmentation). **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7	**devices of a specific make and model.**	**will be approved.** Next, set rules for **Smart Appliance category to permit IoT-specific site,** and attempt to initiate communication to specific sites permitted for the make and model of the device being tested. **All specified sites for device make and model should be permitted, and any other communication outside these specified hosts should be blocked.** Last, set rules for **a third type of device category (cell phone) to permit IoT-specific sites, but do not specify any sites as permissible. The device should not be permitted to initiate communication with any internet sites.**	
YnMUD-4	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8	The router can apply **policies to categories of devices** (as defined by a user through the UI) to **specify rules regarding initiation of lateral (east/west)**	**Through the UI,** device category rules can be defined to **permit connectivity between categories of devices.** Set rules for **category x to**	As expected

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
	ID.AM-4: External information systems are catalogued. **NIST SP 800-53 Rev. 4** AC-20, SA-9 **PR.AC-1:** Identities and credentials are issued, managed, verified, revoked, and audited for authorized devices, users, and processes. **NIST SP 800-53 Rev. 4** AC-1, AC-2, IA-1, IA-2, IA-3, IA-4, IA-5, IA-6, IA-7, IA-8, IA-9, IA-10, IA-11 **PR.AC-3:** Remote access is managed. **NIST SP 800-53 Rev. 4** AC-1, AC-17, AC-19, AC-20, SC-15 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC- 5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected (e.g., network segregation, network segmentation). **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7	**communications to other categories of devices on the local network. All traffic is enforced according to** rules associated with **the device's category.**	**permit communication with category y but not to category z.** After rules have been set, **attempt to communicate from a device in category x to a device in category y;** the router will **permit this communication** to occur. Next, **attempt to communicate from a device in category x to a device in category z;** the router **will not permit this communication** to occur.	
YnMUD-5	**ID.RA-2:** Cyber threat intelligence is received from information-sharing forums and sources. **NIST SP 800-53 Rev. 4** SI-5, PM-15, PM-16 **ID.RA-3:** Threats, both internal and external, are identified and documented. **NIST SP 800-53 Rev. 4** RA-3, SI-5, PM-12, PM-16	The router is capable of querying a threat intelligence provider and receiving threat information related to domains that devices on the network are attempting to access. In **response to threat information, all devices on the local network**	A **device on the network sends a DNS request for a malicious domain** to which it is attempting to navigate. The **router receives a response indicating that the domain is potentially malicious. The router**	As expected

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
	ID.RA-5: Threats, vulnerabilities, likelihoods, and impacts are used to determine risk. **NIST SP 800-53 Rev. 4** RA-2, RA-3, PM-16 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties.	**are prohibited from visiting specific domains and IP addresses.**	**queries** threat **services** regarding the domain and receives back the URL for the threat MUD file that is associated with the domain. The router retrieves the threat MUD file and installs its rules as global firewall rules. As a result, the **device that attempted to communicate with the dangerous domain is blocked from communicating with that domain as well as all other domains associated with that same threat.**	
YnMUD-6	**PR.AC-3:** Remote access is managed. **NIST SP 800-53 Rev. 4** AC-1, AC-17, AC-19, AC-20, SC-15 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC- 5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected (e.g., network segregation, network segmentation). **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7	YnMUD-5 was successfully completed, i.e., **in response to threat information received in YnMUD-5, all devices on the local network are prohibited from visiting not only the domains that are associated with the identified threat but also with all IP addresses associated with these domains.**	A **different device on the network attempts to communicate with the malicious domain identified in test YnMUD-5 via its IP address instead of its domain.** Router firewall rules prohibiting access to this IP address should already be present as a result of test **YnMUD-5. As** a result, the **device that attempted to**	As expected

Exercise	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Exercise Summary	Expected Outcome	Observed Outcome
	ID.RA-2: Cyber threat intelligence is received from information-sharing forums and sources. **NIST SP 800-53 Rev. 4** SI-5, PM-15, PM-16 **ID.RA-3:** Threats, both internal and external, are identified and documented. **NIST SP 800-53 Rev. 4** RA-3, SI-5, PM-12, PM-16		**communicate to the IP address is prevented from initiating communication**.	
YnMUD-7	**PR.AC-3:** Remote access is managed. **NIST SP 800-53 Rev. 4** AC-1, AC-17, AC-19, AC-20, SC-15 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC- 5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected (e.g., network segregation, network segmentation). **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **ID.RA-2:** Cyber threat intelligence is received from information-sharing forums and sources. **NIST SP 800-53 Rev. 4** SI-5, PM-15, PM-16 **ID.RA-3:** Threats, both internal and external, are identified and documented. **NIST SP 800-53 Rev. 4** RA-3, SI-5, PM-12, PM-16	YnMUD-5 was successfully completed, resulting in the router being configured with threat intelligence rules**. The threat intelligence was received more than 24 hours earlier.** It indicated domains and IP addresses that should not be trusted, and those domains and IP addresses were blocked by firewall rules installed on the router. **After 24 hours, these firewall rules have been removed from the router.**	Log in to the router and verify that the firewall rules that prohibited communication to malicious domains (and that were verified as present in the previous two tests) are no longer present.	As expected

7.5 Observations

Build 2 was able to successfully permit and block traffic to and from MUD-capable IoT devices as specified in the MUD files for the devices. It was also able to constrain communications to and from all devices (both MUD-capable and non-MUD-capable) based on the traffic profile associated with the device's category in the Yikes! cloud.

We observed the following limitations to Build 2 that are informing improvements to its current proof-of-concept implementation:

- MUD manager (version 1.1.3):
  - MUD file caching is not supported in this version of the MUD manager. The MUD manager fetches a new MUD file for every MUD request that occurs, regardless of the cache-validity of the current MUD file.
- Yikes! cloud:
  - Yikes! performs device identification using data available at the time a device requests an IP address during the network onboarding process. Future versions of the product may collect additional information about a device to improve the specificity of device identification.
- Yikes! mobile application:
  - At the time of demonstration, the Yikes! mobile application was under development. For this reason, Yikes! provided a web-hosted replica of the mobile application under development. This was accessible via web browsers on both mobile and computer platforms.
- Yikes! router (version 1.1.3):
  - At the time of demonstration, DHCP was the only MUD URL emission method supported. LLDP and X.509 MUD URL emission methods are not supported by the current version of the Yikes! router.
  - When MUD-capable devices are first connected and introduced to the network, the default policy in this version of the Yikes! router is to allow communications while the MUD file is being requested and processed. This results in a short period of time during which the device has received an IP address and is able to communicate unconstrained on the network before the MUD rules related to the device are applied.
  - In some situations, when a MUD-capable IoT device is onboarded, the base router configurations may contend with the MUD rules. This can result in the initial instances of unapproved attempted communication from the MUD-capable device to other devices on the local network being permitted until the router reconciles the configuration. Traffic to

or from locations outside the local network is not impacted and only approved traffic is ever allowed.

- At the time of demonstration, the automated process to associate the Yikes! router with the Yikes! cloud service was still under development, and association had to be done manually by MasterPeace.

- threat signaling (version 0.4.0):
    - Access to threat-signaling information is triggered when a device on the local network makes a DNS resolution request for a domain that has been flagged as dangerous because it is associated with some known threat. If a device attempts to connect to a dangerous site using that site's IP address rather than its domain name without first attempting to resolve a domain name that is associated with the same threat that is associated with the dangerous site, the threat-signaling mechanism provided in Build 2 will not block access to that IP address. Therefore, users are cautioned to use domain names rather than IP addresses when attempting outbound communication to ensure that they can take full advantage of the threat-signaling protections offered by Build 2.

8 Build 3

Build 3, which is still under development, uses equipment supplied by CableLabs to support MUD. It will leverage the Wi-Fi Alliance Easy Connect specification to securely onboard devices to the network. It will also use SDN to create separate trust zones (e.g., network segments) to which devices are assigned according to their intended network function. The Build 3 network platform is called Micronets, and there is an open-source reference implementation of Micronets available on GitHub. CableLabs is in the process of developing and adding new features and functionality to its open-source reference implementation of Micronets.

Although limited functionality of a preliminary version of Micronets was demonstrated as part of this project, Build 3 is not yet complete and has not yet been subjected to functional evaluation or demonstration. Full documentation of Build 3 is planned for inclusion in the next phase of this project. In the remainder of this section we provide a brief preview of the architecture and functional elements planned for Build 3. A more detailed description of Micronets can be found in CableLabs' Micronets white paper.

8.1 Collaborators

Collaborators currently participating in this build are described briefly in the subsections below. More collaborators may be added once the build is completed.

8.1.1 CableLabs

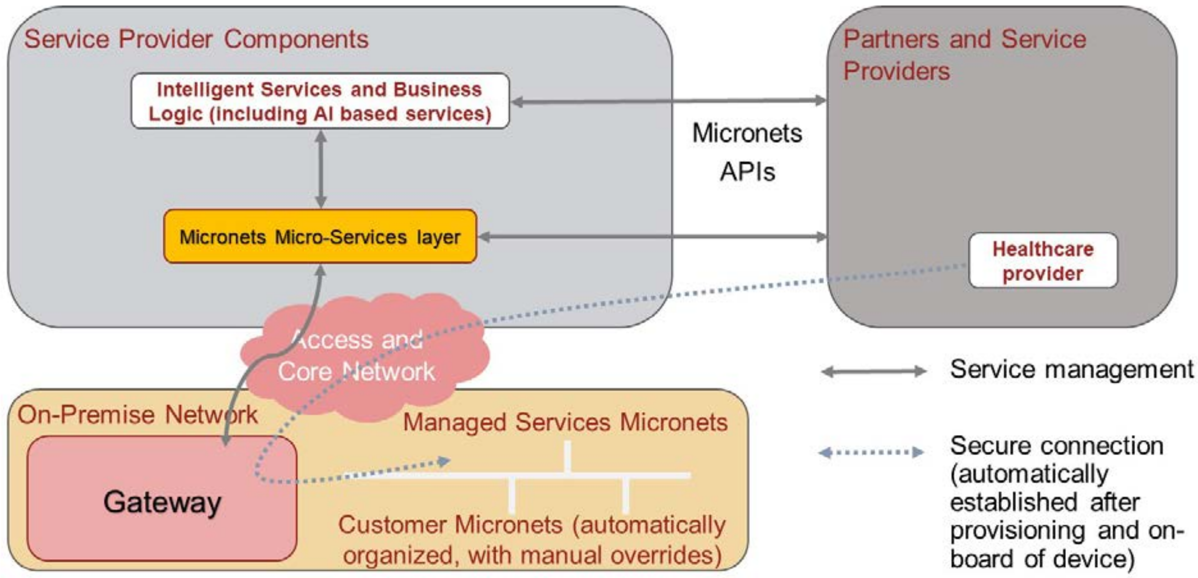
CableLabs is a nonprofit product innovation and research and development enterprise in the cable industry. It includes more than 60 cable-network-operator members around the world, representing approximately 180 million subscribers and roughly 500 million individuals. In November 2018, CableLabs publicly announced Micronets, a next-generation on-premise network platform focused on providing adaptive security for all devices connecting to a residential or small-business network through dynamic micro-segmentation and management of connectivity to those devices. Micronets is designed to provide seamless and transparent security to users without burdening them with the technical aspects of configuring the network. Micronets incorporates and leverages MUD as one technology component to help identify and manage the connectivity of devices, in support of the broader Micronets on-premise network platform. In addition, Micronets can provide enhanced security for high-value or sensitive devices, further reducing the risk of compromise for these devices and their applications. Learn more about CableLabs at https://www.cablelabs.com.

8.2 Micronets Architecture

As illustrated in Figure 8-1 and described in more detail in the subsections below, Micronets' logical architecture currently consists of the following components:

- Intelligent Services and Business Logic layer (e.g., machine-learning-based services), which resides in the cloud and is operated by the service provider
- Micronets Micro-Services layer (e.g., SDN controller, Micronets Manager, MUD manager), which also resides in the cloud and is operated by the service provider. The most important component of this layer is the Micronets Manager, which coordinates the entire state of the Micronets-enabled on-premises network.
- On-premises Micronets, which reside on the home/small-business network. These include the Micronets Gateway, managed services Micronets (i.e., micro-networks), and customer Micronets. The micro-networks can be used to group devices together into trust domains and isolate them from other devices.
- Micronets APIs allow partners and service providers to interface with a customer's micro-networks environment to provision and deliver specific customer-requested services.

Figure 8-1 Logical Architecture—Build 3



8.2.1 Intelligent Services and Business Logic

This architectural component is the interface for the Micronets platform to interact with the rest of the world. It functions as a receiver of the user's intent and business rules from the user's services, and combines them into operational decisions that are handed over to the Micronets micro-services for execution. It may receive information from various Micronets' micro-services (such as the SDN controller) and in turn use that information to dynamically update the access rules for connected IoT devices. For example, to support devices that do not emit a MUD URL, a "synthetic" MUD file generator and MUD server may be provided that can host crowdsourced MUD files that are provided to the Micronets micro-services. Another example is an IoT fingerprinting service that could allow detection of devices in the network or an artificial intelligence/machine-learning-based malware detection service that can provide updated MUD files or access policies based on actively detected threats in the network.

8.2.2 Micronets Micro-Services

The Micronets Micro-Services layer hosts several network management-related micro-services that interact with the on-premises gateway to manage local devices and network connectivity. One of the core micro-services, the Micronets Manager, coordinates the entire state of the Micronets-enabled on-premises network. It orchestrates the overall delivery of services to the IoT devices and ultimately to the user. Several micro-services are engaged and managed by the Micronets Manager, including the SDN controller, DHCP/DNS manager, AAA (RADIUS) server, and MUD manager.

8.2.3 On-Premises Micronets

The Micronets Gateway is responsible for creating and enforcing the Micronets on the home/small-business network. Each Micronet represents a distinct trust domain and at the minimum represents a distinct IP subnet. IoT devices that are not permitted to exchange traffic with other IoT devices will be placed in separate Micronets to isolate them from each other. The Micronets Gateway is also an SDN-capable switch that is controlled by the SDN controller that is part of the Micronets Micro-Services layer in the cloud. The Micronets Gateway is integrated with a Wi-Fi access point, but it supports both wired and wireless connectivity.

8.2.3.1 *MUD-Driven Policies*

The Micronets definition and the placement of devices within a given Micronet are governed by the Micronets Manager and are driven by specific policies. In Build 3, a MUD-based policy will drive the assignment of devices to specific Micronets.

8.2.3.2 *Customer Micronets*

Customers acquire and connect their own devices. They may even integrate entire service-oriented networks, such as a smart home lighting system. In the future, customer-networked devices may be fingerprinted or authenticated by using an ecosystem certificate (e.g., an Open Connectivity Foundation certified device) and automatically placed into an appropriate Micronet.

8.2.4 Micronets API Framework

Each component (the micro-services as well as the gateway services) exposes a set of APIs that form the Micronets API framework. Some of the APIs can be exposed to allow partners and service providers to interface with the customer's Micronets environment to provision and deliver specific services that the customer has requested.

8.3 Build 3 Use Case

Build 3 is expected to make use of the following elements:

- a Micronets Gateway and access point to be located on premises at the home/small-business network
- a cloud-based Micronets Manager, SDN controller, identity server, and RADIUS server dedicated to the home/small-business network
- the service provider's cloud-based infrastructure that includes a proxy for the cable service operator, an authentication server, and a MUD manager
- an offsite onboarding clinic that includes a registration server and a MUD file server that holds versions of MUD files that have been customized by the onboarding clinic

Build 3 is expected to use the above components in combination to support MUD. Build 3 is expected to differ from the other builds in this project insofar as it plans to perform device onboarding at an onboarding clinic that is separate from the home/small-business network. Under this paradigm, the MUD file rules will be installed on the home/small-business network's Micronets Gateway during the onboarding process before the device connects to the home/small-business network. Later, when the device connects to the home/small-business network, the MUD rules will already be in place.

The off-premises onboarding clinic is expected to be equipped with a registration server that will associate each device with a version of its MUD file that has been customized by the onboarding clinic. This registration server will invoke the service provider's infrastructure and the home/small-business network's cloud infrastructure to provision a certificate onto the device. This certificate will enable the device to be authenticated and associated with its MUD file traffic profile upon connection to the home/small-business network. The on-premises Micronets Gateway, which is connected to the cloud, will be configured by the MUD manager with the device's MUD file rules during the onboarding process. Later, when the device connects to the home/small-business network, the Micronets Gateway will already be configured to enforce MUD-based traffic constraints for that device based on the certificate that had been provisioned onto the device during its registration process at the offsite onboarding clinic. The Micronets Gateway is also expected to be designed to support dynamic micro-segmentation and incorporate device identity and fingerprinting techniques to enable real-time detection and quarantining of compromised IoT devices.

9 Build 4

The Build 4 implementation uses software developed at the NIST Advanced Networking Technologies laboratory that is called NIST-MUD. The purpose of this implementation is to serve as a working prototype of the MUD RFC to demonstrate feasibility and scalability. NIST-MUD is intended to provide a platform for research and development by industry and academia. It is released as a simple, minimal, open-source reference implementation of an SDN controller/MUD manager on Github.

The NIST MUD manager is implemented as a feature that is running on an OpenDaylight SDN controller. The SDN controller/MUD manager uses the OpenFlow (1.3) protocol to configure the MUD rules on an SDN-capable switch that is deployed on the home/small-business network. Build 4 also uses certificates from DigiCert.

9.1 Collaborators

Collaborators that participated in this build are described briefly in the subsections below.

9.1.1 NIST Advanced Networking Technologies Laboratory

The NIST Advanced Networking Technologies lab mission is networking research and advanced prototyping of emerging standards.

9.1.2 DigiCert

See Section 6.1.2 for a description of DigiCert.

9.2 Technologies

Table 9-1 lists all of the products and technologies used in Build 4 and provides a mapping among the generic component term, the specific product used to implement that component, and the security control(s) that the product provides. Some functional Subcategories are described as being directly provided by a component. Others are supported but not directly provided by a component. Refer to Table 5-1 for an explanation of the NIST Cybersecurity Framework Subcategory codes.

Table 9-1 Products and Technologies

Component	Product	Function	Cybersecurity Framework Subcategories
SDN controller	OpenDaylight SDN Controller	Used to manage the SDN switch on the home/small-business network. Provides a protocol stack on top of which the MUD manager is built; includes an OpenFlow plug-in that is used to send flow rules to the SDN switch.	Provides ID.AM-3 PR.PT-3
MUD manager	NIST-MUD SDN controller/MUD manager (implemented as a feature on an OpenDaylight open-source SDN controller)	Fetches, verifies, and processes MUD files from the MUD file server maintained by the manufacturer; can also receive MUD files through a Representational State Transfer (REST) API if a manufacturer does not provide a MUD file server. Parses MUD files and converts them to	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 DE.AE-1

Component	Product	Function	Cybersecurity Framework Subcategories
		flow rules. Eaves-drops on IoT device DNS requests to obtain the IP address values to insert into flow rules when instantiating MUD file access control entries (ACEs).	
MUD file server	NCCoE-hosted Python (requests)-based https server	Hosts MUD files and signature files; serves MUD files to the MUD manager by using https	ID.AM-1 ID.AM-2 ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
MUD file maker	MUD file maker (https://www.mud-maker.org/)	GUI used to create example MUD files	ID.AM-1
MUD file	A YANG model instance that has been serialized in JSON (RFC 7951). The manufacturer of a MUD-capable device creates that device's MUD file. MUD file maker (see previous row) can be used to create MUD files. Each MUD file is also associated with a separate MUD signature file.	Specifies the communications that are permitted to and from a given device	Provides PR.PT-3 Supports ID.AM-1 ID.AM-2 ID.AM-3
DHCP server	DNSmasq DHCP server	Functions as a generic DHCP server; does not provide any MUD-specific functions	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1

Component	Product	Function	Cybersecurity Framework Subcategories
Router or switch	Northbound Networks wireless SDN switch	Routes traffic on the home/small-business network. Gets configured with Open-Flow 1.3 flow rules that enforce MUD file ACEs.	ID.AM-3 PR.AC-4 PR.AC-5 PR.DS-5 PR.PT-3 DE.AE-1
Certificates	DigiCert Premium Certificate	Used to sign MUD files and generate corresponding signature file	PR.AC-1 PR.AC-3 PR.AC-5 PR.AC-7
MUD-capable IoT device 1 (has MUD file profile1)	Raspberry Pi Model 3	Emits a MUD URL as part of its DHCP REQUEST	ID.AM-1
Second MUD-capable IoT device (has MUD file profile1)	Raspberry Pi model 3	Emits a MUD URL as part of the DHCP REQUEST. Acts as the second device made by the same manufacturer as device 1.	ID.AM-1
Third MUD-capable IoT device (has MUD file profile2)	Raspberry Pi Model 3	Emits a MUD URL as part of the DHCP REQUEST. Acts as a device made by another manufacturer (so we can test interactions between the first type of device and the second type of device).	ID.AM-1
Non-MUD-capable IoT device	Raspberry Pi without a MUD profile	Acts as a typical IoT device on the home/small-business network; does not emit a MUD URL and does not have an associated MUD file.	ID.AM-1

Component	Product	Function	Cybersecurity Framework Subcategories
		Its traffic is unrestricted.	
Controller	Raspberry Pi without a MUD profile	Acts as a device controller for the first MUD-enabled device	
Update server	NCCoE-hosted Raspberry Pi Python (request)-based servers (two are used)	Acts as a device manufacturer's update server that would communicate with IoT devices to provide patches and other software updates	PR.IP-1 PR.IP-3
Unapproved server	Raspberry Pi running a web server	Acts as an internet host that has not been explicitly approved in a MUD file	DE.DP-3 DE.AM-1

9.2.1 SDN Controller

The switch on the home/small-business network is an SDN switch that is managed by an OpenDaylight SDN controller. OpenDaylight provides protocol stacks on top of which the MUD manager is built. In Build 4, the protocol stack used is a southbound protocol plug-in for the OpenFlow 1.3 protocol that is used by OpenDaylight applications (e.g., the MUD manager) to send flow rules to the OpenFlow-enabled SDN switch on the home/small-business network. OpenDaylight also allows applications to export "northbound" RESTCONF/YANG model APIs that are primarily used for configuration purposes.

9.2.2 MUD Manager

The MUD manager is an OpenDaylight application written in Java. OpenDaylight uses the Apache Karaf Open Service Gateway Initiative container. The MUD manager is a Karaf feature that uses OpenDaylight libraries and bundles. The IETF-published YANG model for MUD is imported into OpenDaylight directly for the MUD manager implementation.

The MUD manager receives the MUD URL for an IoT device, fetches that MUD file and its corresponding signature file, and uses the signature file to verify the validity of the MUD file. If signature verification succeeds, the MUD manager generates SDN flow rules corresponding to the ACEs that are in the MUD file and pushes them to the SDN switch on the home/small-business network by using the OpenFlow protocol. The instantiation of some flow rules (i.e., those relating to DNS names that have not yet been resolved) may have to be deferred because the IP addresses to be inserted into the flow rules corresponding to these ACEs depend on domain name resolution as seen by the IOT device, which may not yet have been performed. If domain name resolution is performed by a device on the home/small-business network for any domain name that is referenced by a flow rule, the flow rule will be instantiated and sent to the SDN switch.

If signature verification fails or if the MUD file is not retrievable (for example, if the manufacturer website is down or does not have a valid TLS certificate), the MUD manager sends packet classification flow rules to the SDN switch that cause the device to be blocked. In a blocked state, the device may only access DHCP, DNS, and NTP services on the network. This effectively quarantines the device until the MUD file may be verified.

The MUD manager can manage multiple switches. The system achieves memory scalability by a multiple flow table design that uses O(N) flow rules for N distinct MAC addresses seen at the switch.

9.2.3 MUD File Server

In the absence of a commercial MUD file server for use in this project, the NCCoE implemented its own MUD file server by using a Python (requests)-based web server. This file server serves the MUD files along with their corresponding signature files for the IoT devices used in the project. Upon receiving a GET request for the MUD files and signatures, it serves the request to the MUD manager by using https.

9.2.4 MUD File

We test interactions between two manufacturers and between two devices made by the same manufacturer. To accomplish this, two MUD files are defined (referred to as “profile1” and “profile2” in the table above).

9.2.5 Signature File

According to the IETF MUD specification, “a MUD file MUST be signed using CMS as an opaque binary object.” The MUD files were signed with the OpenSSL tool by using the command described in the specification (as detailed in Volume C of this guide). A Premium Certificate, requested from DigiCert, was leveraged to generate the signature files. Once created, the signature files are stored on the MUD file server along with the MUD files. The certificate is added to the trust store of the Java Virtual Machine running the MUD manager to enable signature verification.

9.2.6 DHCP Server

NIST-MUD is a Layer-2 implementation. Devices are identified by MAC addresses. NIST-MUD is designed to work with devices that join the network by issuing a DHCP request.

DHCP requests for MUD-enabled devices may contain a MUD URL. The DHCP request (with embedded MUD URL) is sent to the SDN switch, which forwards it simultaneously to the SDN controller/MUD manager and the DHCP server. This is accomplished via an SDN flow rule that is inserted by the MUD manager into the switch flow table when the switch connects to the MUD manager. After extracting the MUD URL from the DHCP packet, the MUD manager proceeds to retrieve the MUD file that is pointed to by the MUD URL.

Because the SDN switch forwards the DHCP request to the MUD manager rather than the DHCP server forwarding the DHCP request to the MUD manager, no modifications to the DHCP server are needed. The MUD manager instead of the DHCP server is responsible for stripping the MUD URL out of the DHCP request. Therefore, Build 4 can use a generic DHCP server that is not required to support any MUD-specific capabilities.

9.2.7 Router/Switch

The switch used on the home/small-business network is a wireless SDN switch that comes bundled with the Northbound Networks Wireless Access Point. The access point bundles a NAT router, DNS server, and DHCP server. The SDN controller/MUD manager is connected to the public-facing side of the switch's NAT component. The switch is OpenFlow-enabled and interacts with its SDN controller/MUD manager via the OpenFlow 1.3 protocol. The SDN switch serves as the enforcement point for MUD policy. Packets sent between devices, between devices and controllers referenced in MUD files, and between devices and the internet must pass through the switch, which is where enforcement occurs.

9.2.8 Certificates

DigiCert provisioned a Premium Certificate for signing the MUD files. The Premium Certificate supports the key extensions required to sign and verify CMS structures as required in the MUD specification. Further information about DigiCert's CertCentral web-based platform, which allows for provisioning and managing publicly trusted X.509 certificates, can be found in Section 6.2.8.

9.2.9 IoT Devices

This section describes the IoT devices used in the laboratory implementation. There are two distinct categories of devices: devices that can emit a MUD URL in compliance with the MUD specification, i.e., MUD-capable IoT devices; and devices that are not capable of emitting a MUD URL in compliance with the MUD specification, i.e., non-MUD-capable IoT devices.

9.2.9.1 *MUD-Capable IoT Devices*

Three Raspberry Pi devkits used on the home/small-business network are designated as MUD-capable. Two emit the same MUD URL (corresponding to profile1) and the third emits a different MUD URL (corresponding to profile2).

9.2.9.2 *Non-MUD-Capable IoT Devices*

A fourth Raspberry Pi on the home/small-business network functions as a non-MUD-capable IoT device. Because it does not have an associated MUD file, its communications are not restricted.

9.2.10 Controller and My-Controller

A fifth Raspberry Pi device on the home/small-business network is designated as controller and my-controller. Note that a host cannot simultaneously be designated as a controller and be part of the local network. Hence, the Raspberry Pi that performs this function is not part of the local network category.

9.2.11 Update Server

The update server is designed to represent a device manufacturer or trusted third-party server that provides patches and other software updates to the IoT devices. This project used an NCCoE-hosted update server that provides faux software update files.

9.2.11.1 *NCCoE Update Server*

The NCCoE implemented its own update server by using an Apache web server. This file server hosts faux software update files to be served as software updates to the IoT device devkits. When the server receives an http request, it sends the corresponding faux update file.

In Build 4, there are two update servers, both of which are Raspberry Pi hosts on the public side of the switch. The DNS server on the switch is configured to return two addresses corresponding to the DNS name of the update server (e.g., www.nist.local maps to two IP addresses). This enables us to test access control when multiple addresses are returned from a DNS lookup.

9.2.12 Unapproved Server

A Raspberry Pi running a web server acts as an unapproved internet host and is used to test the communication between a MUD-capable IoT device and an internet host that is not included in the device's MUD file, so the IoT device should not be permitted to send traffic to it. To verify that the traffic filters were applied as expected, communication to and from the unapproved server and the first MUD-capable IoT device (with profile1) was tested. This unapproved server (www.antd.local) maps to a single IP address and is set up on the public side of the switch.

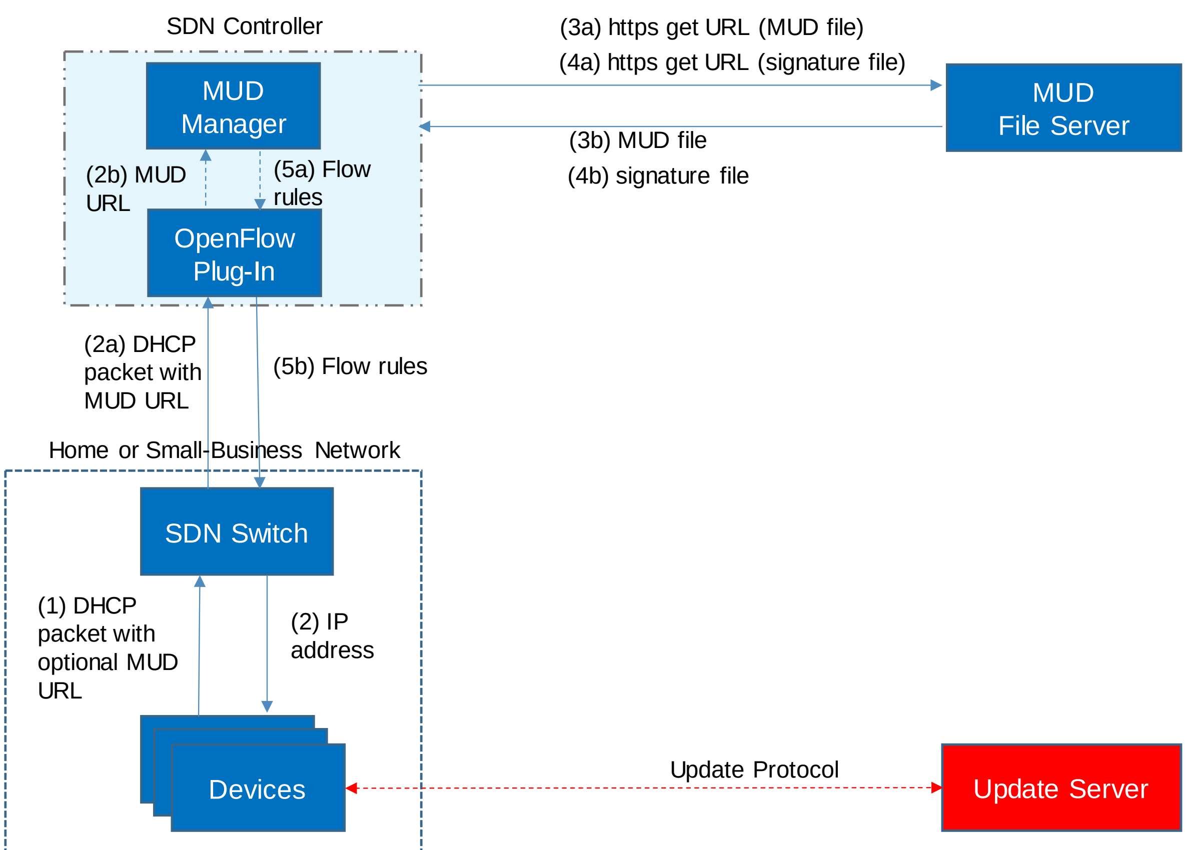
9.3 Build Architecture

In this section we present the logical architecture of Build 4 relative to how it instantiates the reference architecture depicted in Figure 4-1. We also describe Build 4's physical architecture and present message flow diagrams for some of its processes.

9.3.1 Logical Architecture

Figure 9-1 depicts the logical architecture of Build 4. It includes a single device that serves as the SDN controller/MUD manager, which is assumed to be cloud-resident. This SDN controller/MUD manager controls and manages an OpenFlow-enabled SDN switch on the home/small-business network. The SDN switch serves as the MUD policy enforcement point for MUD-capable IoT devices that connect to the home/small-business network. The only automatic MUD URL discovery capability that Build 4 supports is emission of the MUD URL via DHCP. Build 4 does not support LLDP-based or certificate-based MUD URL discovery. However, it is also possible to associate a MUD file with a device that is not capable of emitting a MUD URL by manually associating that device's MAC address with a MUD file URL when using Build 4.

Figure 9-1 Logical Architecture—Build 4



As shown in Figure 9-1, the steps that occur when a MUD-capable IoT device connects to the home/small-business network using Build 4 are as follows:

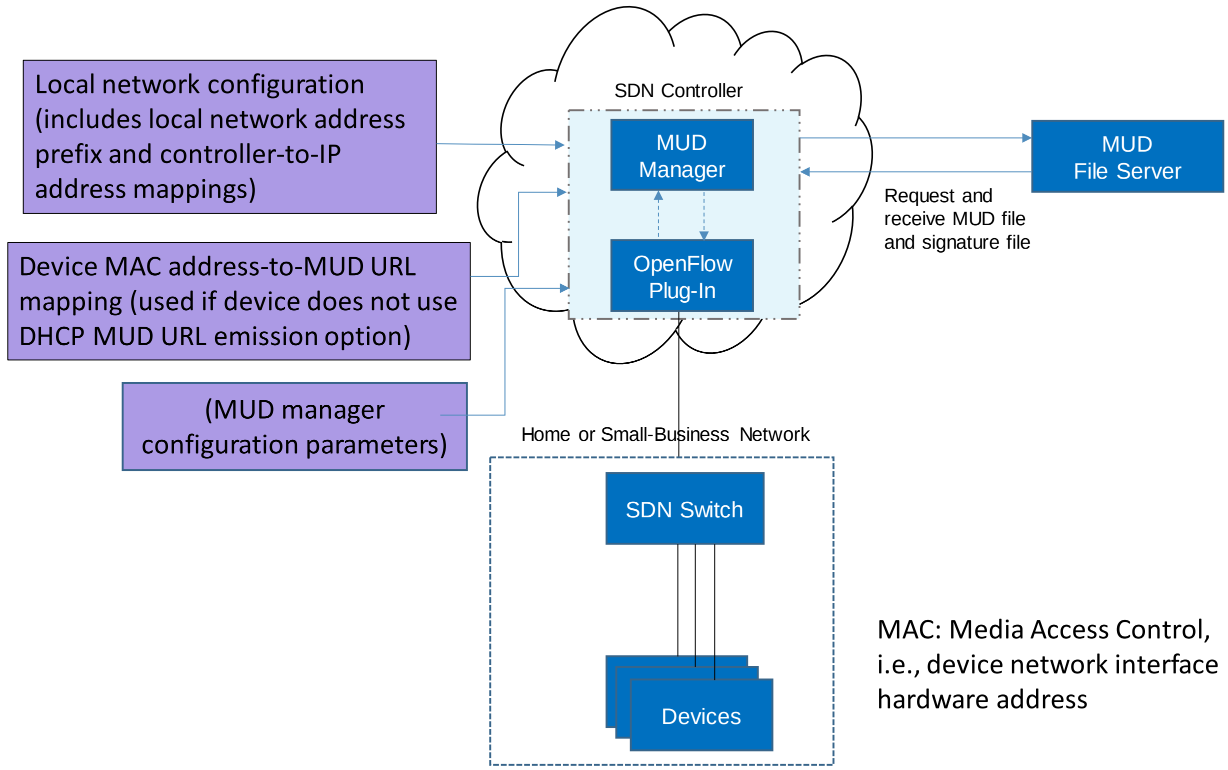
- Upon connecting a MUD-capable device, the MUD URL is emitted via DHCP (step 1).

- The SDN switch sends the DHCP packet containing the MUD URL to the SDN controller/MUD manager via the OpenFlow protocol (step 2a); this is passed from the OpenFlow plug-in to the MUD manager (step 2b).
- Simultaneously, the device is assigned an IP address (step 2).
- Once the DHCP packet is received at the MUD manager, the MUD manager extracts the MUD URL from the DHCP packet and requests the MUD file from the MUD file server by using the MUD URL (step 3a); if successful, the MUD file server at the specified location will serve the MUD file (step 3b).
- Next, the MUD manager requests the signature file associated with the MUD file (step 4a) and upon receipt (step 4b) verifies the MUD file by using its signature file.
- After the MUD file has been verified successfully, the MUD manager creates flow rules corresponding to the MUD file ACEs and provides these to the OpenFlow plug-in (step 5a), which in turn sends the flow rules to the SDN switch, where they are applied (step 5b).

Once the device's flow rules are installed at the SDN switch, the MUD-capable IoT device will be able to communicate with approved local hosts and internet hosts as defined in the MUD file, and any unapproved communication attempts will be blocked. Devices that are not MUD-capable will not have their communications restricted in any way by the MUD manager, assuming they have not been manually associated with a MUD file.

Figure 9-2 depicts some configuration information that can be provided to the Build 4 SDN controller/MUD manager via its REST API.

Figure 9-2 Example Configuration Information for Build 4



As shown in Figure 9-2, the MUD manager exports a YANG-based REST API to allow administrators to configure the SDN controller/MUD manager. This API is not exposed to the network users. It provides the following capabilities:

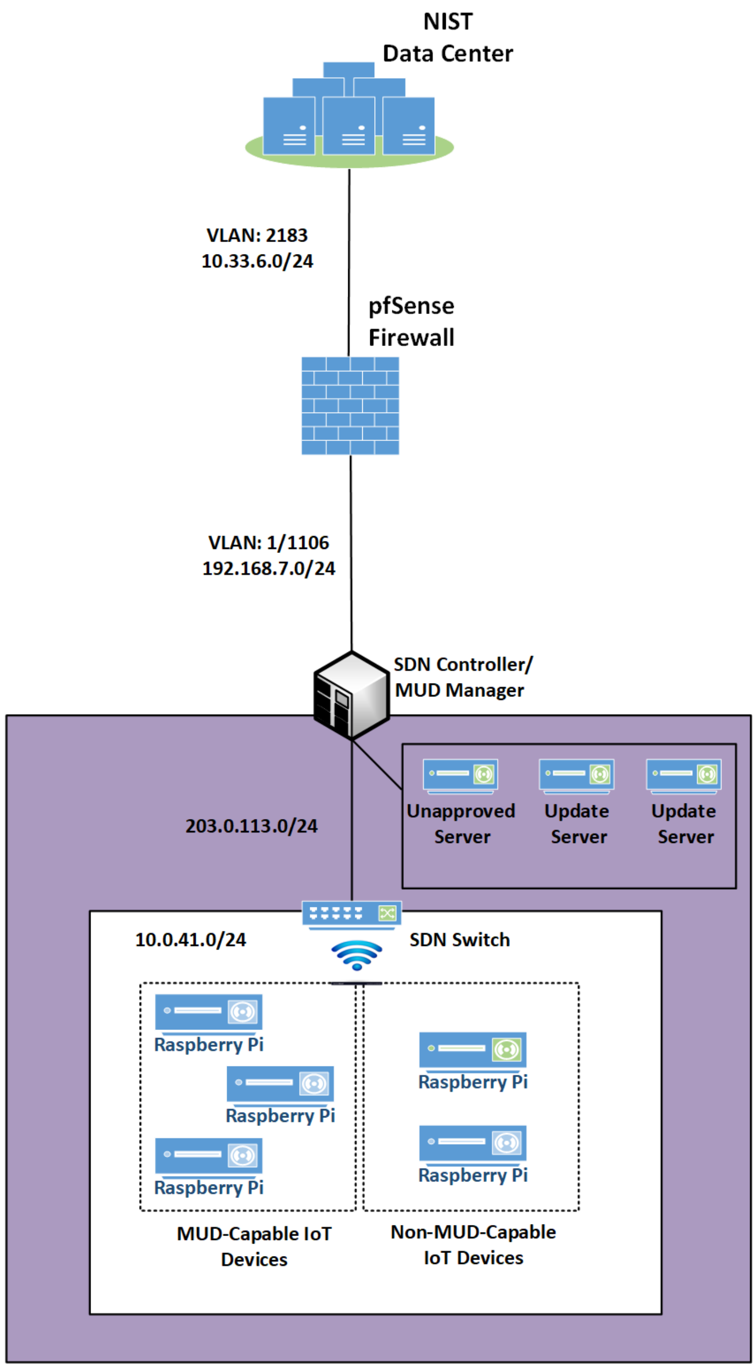
- application configuration—This allows the network administrator to define parameters for the application. The SDN controller/MUD manager must be provided with configuration information for the home and small-business networks that it manages. In addition, configuration parameters for the MUD manager must be supplied.
- controller-class mapping API—This allows the network administrator to define "well-known" network services such as DNS, NTP, and DHCP on the local network and the address prefix used for "local networks."
- device-association—In Build 4, the MUD file URL can be provided to the MUD manager by using the normal DHCP-based MUD URL emission mechanism that is depicted in Figure 9-1. Alternatively, to support devices that are not able to emit a MUD URL, the network administrator can use the REST API to optionally define an association between a device MAC address and a MUD URL.
- MUD file supplied directly—A network administrator can optionally provide a MUD file to the MUD manager by copying it directly into the controller cache in case the manufacturer does not provide a MUD file server.

9.3.2 Physical Architecture

Figure 9-3 depicts the physical architecture of Build 4. A single DHCP server instance is configured for the local network to dynamically assign IPv4 addresses to each IoT device that connects to the SDN switch. This single subnet hosts both MUD-capable and non-MUD-capable IoT devices. The network infrastructure as configured utilizes the IPv4 protocol for communication both internally and to the internet.

The SDN switch is connected across a Wide Area Network (WAN) to the SDN controller/MUD manager. This connection allows the SDN switch to be managed by the SDN controller/MUD manager and enables network flow rules to be updated appropriately. The update servers and unapproved server for Build 4 are also located in this WAN.

2338 **Figure 9-3 Physical Architecture—Build 4**



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9.3.3 Message Flow

This section presents the message flows used in Build 4 during several different processes of note.

NIST MUD works by using six flow tables containing flow rules that are applied to each packet in the following order:

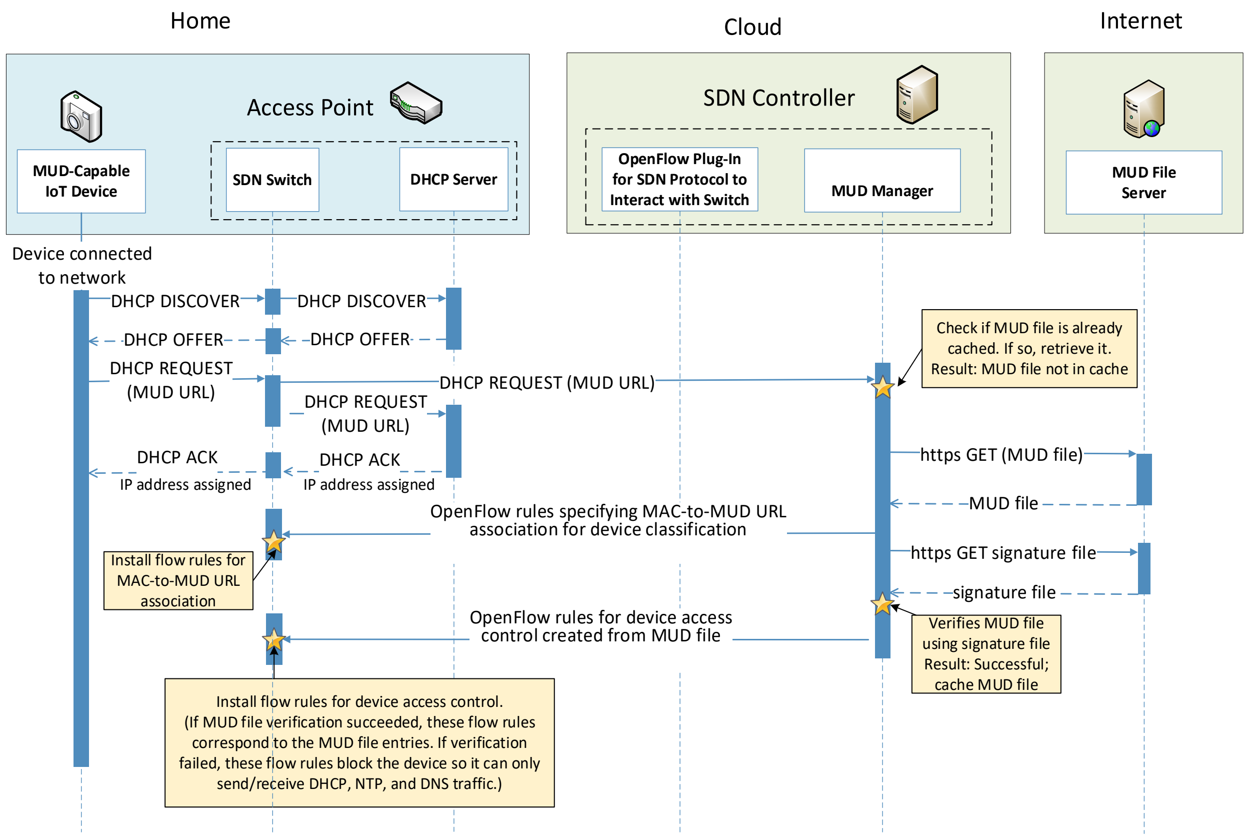
- Table 0, Source MAC address classification table, classifies a packet based on its source IP/MAC address.
- Table 1, Destination MAC address classification table, classifies a packet based on its destination IP/MAC address.
- Table 2, From-Device flow rules table, associates ACEs with the packet based on the packet's source classification, if such ACEs exist. ACEs in this table correspond to the From-Device policy in the MUD file. The MUD-specific ACEs that are applied in this table are matched to the packet based on metadata assigned in the first two tables.
- Table 3, To-Device flow rules table, associates ACEs with the packet based on the packet's destination classification, if such ACEs exist. ACEs in this table correspond to the To-Device policies in the MUD file. The MUD-specific ACEs that are applied in this table are matched to the packet based on metadata assigned in the first two tables.
- Table 4, Pass-Through table—If a packet has an ACE associated with it (i.e., if it has had a MUD-specific ACE applied to it by table 2 or by table 3 that indicates that it should be permitted), it will be sent to this table and the SDN switch will forward it. (For device-to-device communication based on the manufacturer, model, or local network constructs, there must be both a From-Device rule (in table 2) and a To-Device rule (in table 3) for the communication to be allowed. Otherwise the packet is dropped.)
- Table 5, Drop table—All packets from MUD-enabled devices are by default sent to the Drop table unless there is a MUD rule (and therefore a MUD-specific ACE) that applies to the packet indicating that the packet should be permitted (in which case the packet would have been sent to the Pass-Through table). Unprotected devices are metadata-associated with the reserved MUD URL "UNCLASSIFIED," which allows all packets to and from these devices to be permitted (i.e., there are rules in tables 2 and 3 that permit all traffic to these unprotected devices).

Note that a packet may have just one classification based on source and destination MAC/IP address. Packets originating from devices with assigned MUD URLs are not considered to be part of the local network. Hosts with controller classifications (including those with "well-known" controller classifications such as DHCP, DNS, and NTP servers) are not considered to be part of the local network.

9.3.3.1 *Onboarding MUD-Capable Devices*

Figure 9-4 shows the message flow that occurs when a MUD-capable device connects to the home/small-business network in Build 4.

Figure 9-4 MUD-Capable IoT Device Onboarding Message Flow—Build 4



As shown in Figure 9-4, the message flow is as follows:

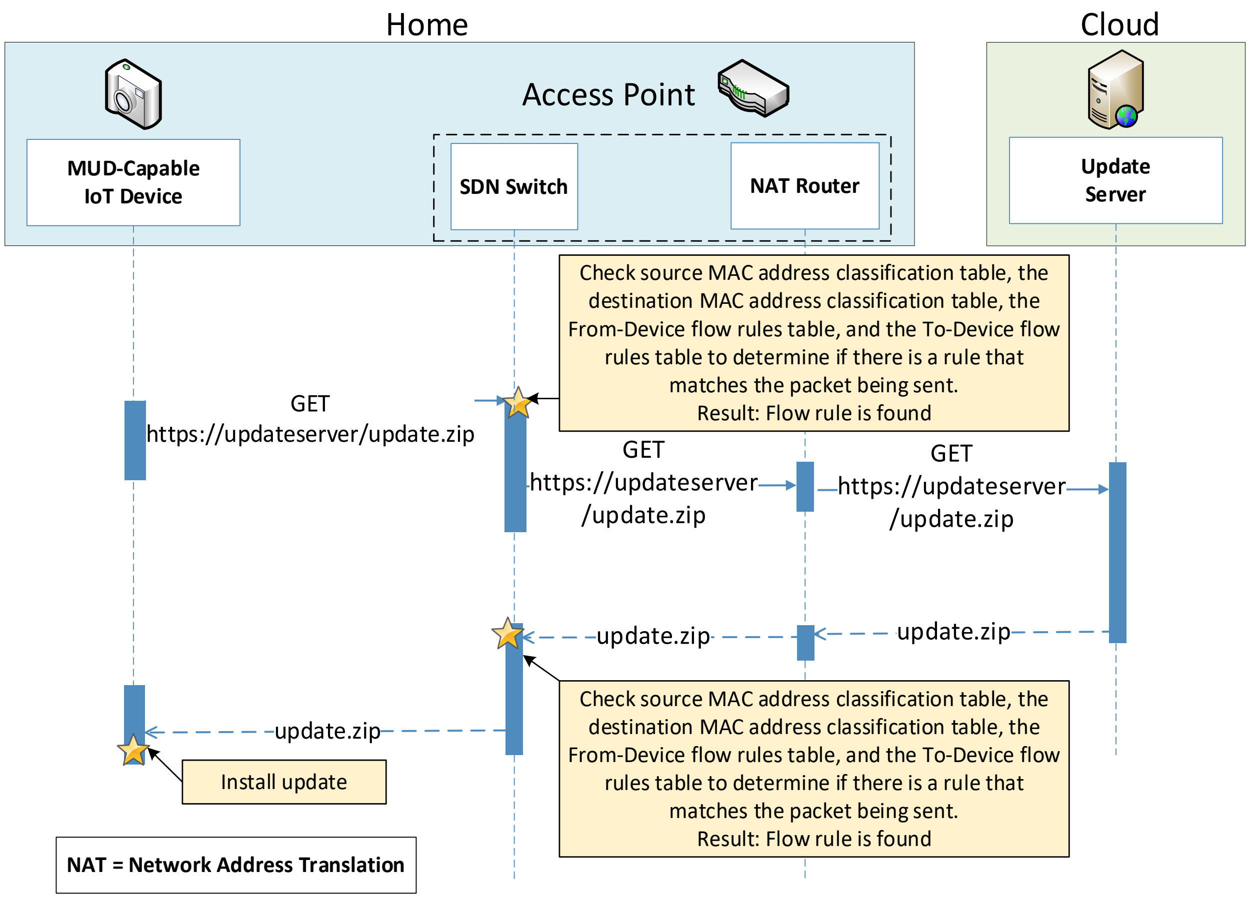
- The IoT device sends out a DHCP DISCOVER message to the SDN switch.
- The AP resident DHCP server sends back a DHCP offer that gets sent back to the device via the SDN switch.
- The device then sends out a DHCP request containing the MUD URL, which gets sent simultaneously to the AP resident DHCP server by the SDN switch and to the MUD manager.
- The AP resident DHCP server sends an IP address to the device in a DHCP ACK message via the switch.
- Based on the MUD URL presented in the DHCP request, the MUD manager checks to see if the corresponding MUD file is already cached. In the example depicted, the MUD file is not in the cache.
- The MUD manager retrieves the MUD file from the manufacturer server.

- The MUD manager installs packet classification flow rules into flow tables 0 and 1 (see Section 9.3.3.4) on the SDN switch. These classification rules associate the MAC address of the device interface with the MUD URL. Other classification information such as whether the packet belongs to the local network is also assigned in the first two tables. Table 0 is for source classification and table 1 is for destination classification. If the device had previously sent out packets, i.e., before it was associated with a MUD file, they would have been classified as UNCLASSIFIED in tables 0 and 1. Hence, the entries in tables 0 and 1 that correspond to the device must be cleared at this point and repopulated so subsequent packets are associated with the MUD URL.
- The MUD manager installs the MUD file ACEs as a set of flow rules in tables 2 and 3 (see Section 9.3.3.4).

9.3.3.2 *Updates*

After a device has been permitted to connect to the home/small-business network, it should periodically check for updates. The message flow for updating the IoT device is shown in Figure 9-5.

Figure 9-5 Update Process Message Flow—Build 4



As shown in Figure 9-5, the message flow is as follows:

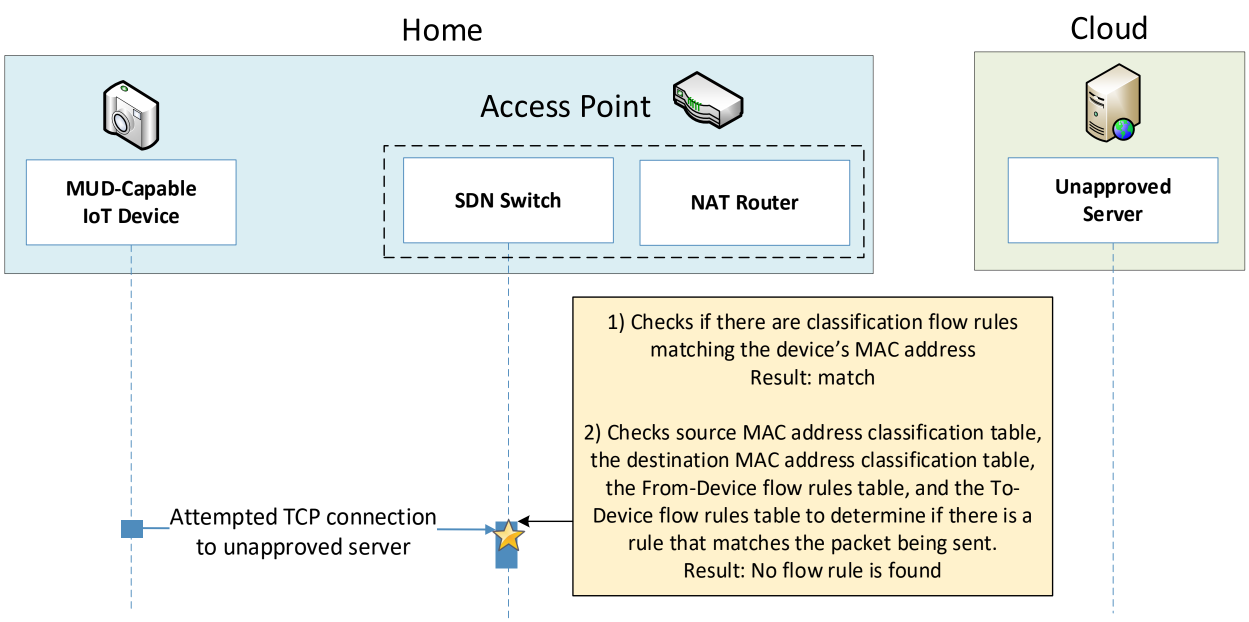
- The device generates an https GET request to its update server.
- The SDN switch will consult its flow rules for this device to verify that it is permitted to send traffic to the update server. Assuming there were explicit rules in the device's MUD file enabling it to send messages to this update server, the SDN switch will forward the request to the NAT router, which will then forward it to the update server.
- The update server will respond with a zip file containing the updates.
- The return traffic will be sent via the NAT router to the switch.
- The destination MAC address of the packet identifies the device, and appropriate metadata is assigned in table 1.

- The source MAC and IP are UNCLASSIFIED, and appropriate metadata is assigned in table 0.
- The packet is forwarded through table 2 and finds a matching flow rule in table 3 from where it is forwarded to the Pass-Through table (4). Two-way communication is thus established.
- The SDN switch will forward this zip file to the device for installation.

9.3.3.3 *Prohibited Traffic*

Figure 9-6 shows the message flow that occurs when an IoT device attempts to send traffic that is not permitted by its MUD file.

Figure 9-6 Unapproved Communications Message Flow—Build 4



As shown in Figure 9-6, the message flow is as follows:

- A TCP packet is originated from the IoT device with a source MAC address of the device’s switch-facing interface and a destination MAC address that is set to the AP-resident router’s switch-facing interface. The source IP address is set to the device IP address and destination IP address is set to the unapproved server IP address.
- The packet arrives at the SDN switch, at which point it:
    - enters flow tables 0 and 1, where it is classified and receives the following metadata assignment as a result:
        - <<source-manufacturer, source-model, is-local> <dest-manufacturer, dest-model, is-local>> is assigned in tables 0 and 1

The <source-manufacturer, source-model> are obtained from the MUD URL assigned to the packet. The is-local flag will be set to False because devices with MUD URLs assigned are not considered to be part of the local network.

The destination manufacturer and model assignments will be UNCLASSIFIED, UNCLASSIFIED and is-local is false because the router MAC address is UNCLASSIFIED, and the destination IP address is not part of the local network. Thus, the metadata assignment after table 0 and 1 are traversed will be

<<source-manufacturer,source-model,False><UNCLASSIFIED,UNCLASSIFIED,False>>

- enters flow table 2, where source metadata-based flow rules have been previously inserted
    - If there is a flow rule that allows the communication, the packet is sent to table 4 (the Pass-Through table), which allows the communication. In the example scenario that is depicted in Figure 9-6, there is no flow rule in table 3 that allows the communications.
    - However, there is a flow rule in table 2 that matches the <source-manufacturer,source-model> that sends the packet to the Drop table (table 5).

- In the example scenario depicted, there is no flow rule found that matches the packet that the IoT device is attempting to send. Therefore, the SDN switch sends the packet to table 5 where there is a single rule that drops the packet.

9.3.3.4 *Installation of Timed-Out Flow Rules and Eventual Consistency*

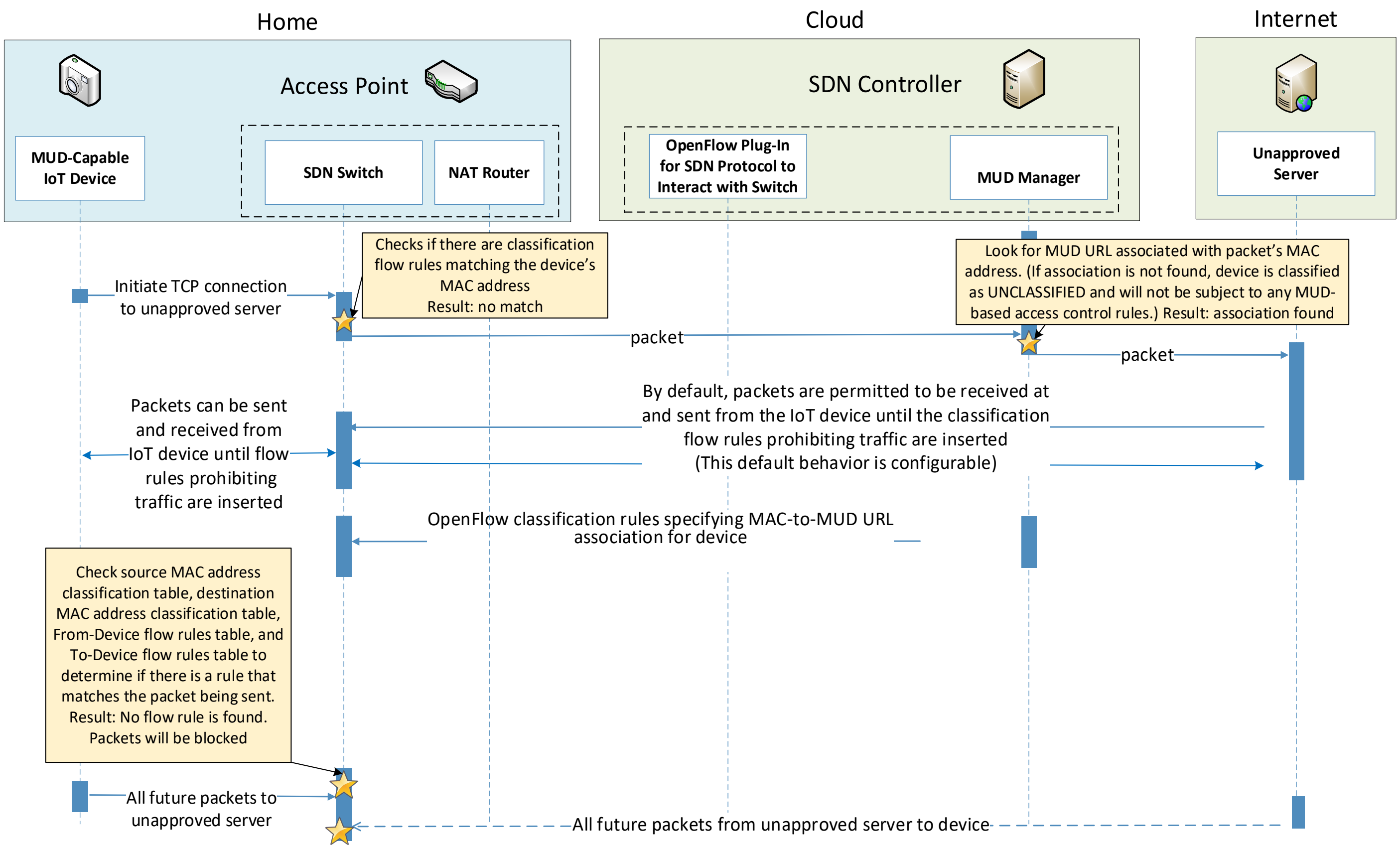
Insertion of flow rules onto the SDN switch on the home/small-business network is dynamic. Rules are computed at the SDN controller/MUD manager and installed on the SDN switch. Flow rules are configured to time out on inactivity to avoid having the SDN switch's flow table fill up. (If an IoT device disconnects from the home/small-business network, there is no need to continue to maintain flow rules for that device on the switch. However, if a device's IP address lease times out, the DHCP server, which has not been modified at all, will not alert the SDN controller/MUD manager of this event. Thus, having the rules time out is an alternative to ensure that rules for disconnected devices will eventually be removed from the switch.)

If an IoT device tries to send a packet, if a packet intended for that device is received at the switch and the source or destination MAC address of the packet does not yet have classification flow rules on the switch, or if the classification flow rules for one or both of those MAC addresses have timed out, the flow rules will need to be sent from the SDN controller/MUD manager to the switch. In this situation, the default OpenFlow rule at the switch (which is inserted in tables 0 and 1 when the switch connects) sends the packet to the MUD manager, and consequently a packet-in event encapsulating the packet is generated at the MUD manager. The packet classification flow rules are then computed and pushed to the switch by the MUD manager during processing of the packet-in event. During this period, additional packets may arrive at the switch.

A design decision had to be made regarding whether to permit the IoT device to send and receive traffic during the window of time while its flow rules are being computed and pushed to the switch. The decision was made to allow an “eventually consistent” model. That is, packets sent by or intended for the IoT device are permitted to proceed through the switch while the SDN flow rules for packet classification are being computed at the SDN controller/MUD manager and sent to the switch. This may result in a few packets that are prohibited by the MUD file ACEs getting through before such violating flows are eventually blocked. This can happen the first time a device sends a packet and every time the flow rules time out due to inactivity. Thus, a misbehaving device or an attacker can have small windows of time during which packets that the MUD file intends to prohibit will be permitted to be exchanged with the device. The alternative is to block the packets while flow rules are computed and inserted. While this alternative behavior can be configured in NIST-MUD, it is not a recommended configuration because it blocks the processing pipeline (resulting in packet drops) while the flow rules are being computed and pushed.

Figure 9-7 shows the message flow that occurs when a device whose flow rules have timed out attempts to initiate communications with an unapproved external server, i.e., a server that is not explicitly listed as a permissible destination in the device’s MUD file.

Figure 9-7 Installation of Timed-Out Flow Rules and Eventual Consistency Message Flow—Build 4



As shown in Figure 9-7, the message flow is as follows:

- The MUD-capable IoT device sends a packet attempting to initiate a TCP connection to an unapproved server.
- The SDN switch checks to see if it has packet classification flow rules for this device (which it determines by looking for rules that match the device's MAC address in tables 0 and 1). In this case, no flow rules are found for this device.
- The SDN switch sends the packet to the SDN controller/MUD manager as a result of the default rule. This is delivered in a packet-in event at the MUD manager.
- The MUD manager receives the packet-in event and looks to see if there is a MUD URL associated with the device's MAC address. (If the device does not have an associated MUD file, it will not be subject to any MUD-based access control rules and will be assigned a reserved MUD URL of UNCLASSIFIED.) In the example scenario depicted in Figure 9-7, the device was found to be associated with a MUD file.

- Even though the flow rules corresponding to the sending device's MUD file are not currently installed on the switch, the SDN controller/MUD manager forwards the packet to the unapproved server.
- The unapproved server responds with an acknowledgment packet.
- The IoT device and the unapproved server are permitted to exchange packets for the time being.
- Meanwhile, the MUD manager computes the SDN flow rules that correspond to the device's MUD file and installs them on the SDN switch.
- After the flow rules have been installed on the switch, when the IoT device attempts to send a packet to the unapproved server, the switch will check each of its flow tables in order (i.e., it will check the Source MAC address classification table [table 0], Destination MAC address classification table [table 1], From-Device flow rules table [table 2], and To-Device flow rules table [table 3]) to determine if there is an ACE that matches the packet being sent. In the example scenario depicted, the switch will find packet classification flow rules for the device in tables 0 and 1, but it will not find any matching flow rules in table 2, indicating that the IoT device's MUD file did not contain an ACE that permits the packet to be sent. As a result, the switch will drop the packet.
- In addition, any subsequent packets that may be sent by the unapproved server and received at the SDN switch will be similarly blocked as a result of the switch consulting its flow rules and determining that there are no ACEs that permit the unapproved server to send packets to the IoT device.

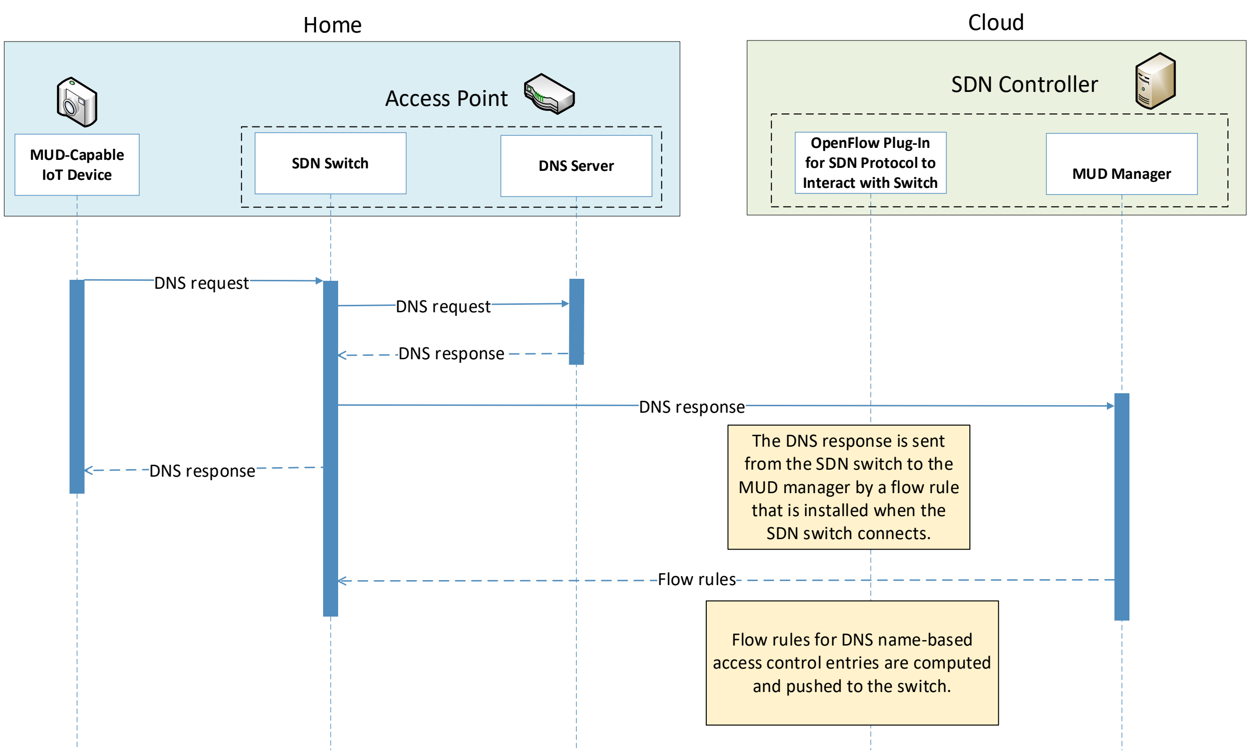
9.3.3.5 *DNS Events*

MUD allows traffic flow rules to be based on domain names. However, the corresponding SDN flow rules configured in the SDN switch must be based on IP addresses rather than domain names. The MUD manager needs to resolve each host name that is in a MUD file ACE rule to the same value to which it would be resolved by the MUD-enabled IoT device. NIST-MUD is built on the assumption that the SDN controller/MUD manager, which is assumed to be in the cloud, does not necessarily have access to the same DNS resolver as the home/small-business network. Therefore, the SDN controller/MUD manager cannot simply issue DNS queries to resolve domain names that are in MUD files and populate the SDN switch's flow table with the IP addresses that it receives back because the IP addresses that the SDN controller/MUD manager would receive back may not be the same as those that the IoT device would receive back. Instead, as DNS packets are sent from the IoT devices through the SDN-enabled switch, they are also sent to the SDN controller/MUD manager, enabling the SDN controller/MUD manager to snoop on DNS queries and responses that occur on the home/small-business network. The SDN controller/MUD manager extracts the IP address resolution information from each DNS response and uses that information to populate the flow table with the appropriate IP address for rules in the MUD file.

Each time a domain name is resolved for a device on the home/small-business network, the MUD manager must check to determine if there are any flow rules that use that domain name that had previously been deferred (i.e., that have not yet been instantiated and sent to the switch) because the IP address corresponding to that domain name had not yet been known. If so, the MUD manager must instantiate those flow rules by inserting the IP address that corresponds to that domain name in place of that domain name and sending the flow rules to the SDN switch.

Figure 9-8 shows the message flow that occurs when the MUD-capable device does a DNS name lookup and the SDN controller/MUD manager uses the IP address returned in the DNS response to instantiate deferred flow rules for installation on the SDN switch.

Figure 9-8 DNS Event Message Flow—Build 4



As shown in Figure 9-8, the message flow is as follows:

- The IoT device (or any device on the network managed by the switch) does a name lookup by sending a DNS request to the SDN switch, which has a default rule that allows access to DNS.
- The SDN switch forwards the DNS request to a DNS server. In our experiment, this DNS server is resident on the access point.

- The DNS server sends a DNS response back to the SDN switch. The response contains a domain name resolution. Note that if the access point were configured to use an upstream DNS server, the response would be returned from that server and routed back to the device via the switch. For simplicity and control of our experimental setup, we use the AP-resident DNS server so there is no routing of DNS request and response.
- The SDN switch sends the DNS response to the MUD manager, which caches the name resolution information for the switch and updates any DNS-name-based ACEs for MUD files that it manages.
- Concurrently with the previous step, the SDN switch also sends the DNS response to the device that originally generated the DNS request.
- The MUD manager instantiates flow rules corresponding to these DNS-name-based ACEs by substituting each domain's IP address for its domain name and installing the flow rules into flow tables 2 and 3 on the SDN switch.

9.4 Functional Demonstration

A functional evaluation and a demonstration of Build 4 were conducted that involved evaluation of conformance to the MUD RFC. Build 4 was tested to determine the extent to which it correctly implements basic functionality defined within the MUD RFC.

Table 9-2 summarizes the tests that were performed to evaluate Build 4's MUD-related capabilities. It lists each test identifier, the test's expected and observed outcomes, and the applicable Cybersecurity Framework Subcategories and NIST SP 800-53 controls for which each test is designed to verify support. The tests that are listed in the table are detailed in a separate supplement for functional demonstration results. Boldface text is used to highlight the gist of the information that is being conveyed.

Table 9-2 Summary of Build 4 MUD-Related Functional Tests

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
IoT-1	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5	A **MUD-enabled IoT device is configured to emit a MUD URL.** The MUD manager requests the MUD file and signature from the MUD file server, and the MUD file server serves the MUD file to the MUD manager. The	Upon connection to the network, the MUD-enabled IoT device has its MUD **PEP router/switch automatically configured according to the MUD file's route filtering policies.**	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	ID.AM-3: Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place.	MUD file explicitly permits traffic to/from some internet services and hosts, and implicitly denies traffic to/from all other internet services. **The MUD manager translates the MUD file information into local network configurations that it installs on the router or switch that is serving as the MUD PEP for the IoT device.**		

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	NIST SP 800-53 Rev. 4 CM-3, CM-4, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.			
IoT-2	**PR.AC-7:** Users, devices, and other assets are authenticated (e.g., single-factor, multifactor) commensurate with the risk of the transaction (e.g., individuals' security and privacy risks and other organizational risks). **NIST SP 800-53 Rev. 4** AC-7, AC-8, AC-9, AC-11, AC-12, AC-14, IA-1, IA-2, IA-3, IA-4, IA-5, IA-8, IA-9, IA-10, IA-11	A MUD-enabled IoT device is configured to emit a URL for a MUD file, but the **MUD file server that is hosting that file does not have a valid TLS certificate. Local policy has been configured to ensure that if the MUD file for an IoT device is located on a server with an invalid certificate, the router/switch will be configured to deny all communication to/from the device.**	When the MUD-enabled IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-enabled IoT device. Therefore, the **MUD PEP router/switch will be configured to block all traffic to and from the IoT device.**	Pass
IoT-3	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-enabled IoT device is configured to emit a URL for a MUD file, but the **certificate that was used to sign the MUD file had already expired at the time of signing. Local policy has been configured to ensure that if the MUD file for a device has a signature**	When the MUD-enabled IoT device is connected to the network and the MUD file and signature are fetched, the MUD manager will detect that the MUD file's signature was created by using a certificate that had already expired	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
		that was signed by a certificate that had already expired at the time of signature, the device's MUD PEP router/switch will be configured to deny all communication to/from the device.	at the time of signing. According to local policy, the **MUD PEP will be configured to block all traffic to/from the device.**	
IoT-4	**PR.DS-6:** Integrity-checking mechanisms are used to verify software, firmware, and information integrity. **NIST SP 800-53 Rev. 4** SI-7	A MUD-enabled IoT device is configured to emit a URL for a MUD file, but the **signature of the MUD file is invalid. Local policy has been configured to ensure that if the MUD file for a device is invalid, the router/switch will be configured to deny all communication to/from the IoT device.**	When the MUD-enabled IoT device is connected to the network, the MUD manager sends locally defined policy to the router/switch that handles whether to allow or block traffic to the MUD-enabled IoT device. Therefore, the **MUD PEP router/switch will be configured to block all traffic to and from the IoT device.**	Pass
IoT-5	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **PR.IP-1:** A baseline configuration of information technology/industrial	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some internet locations and implicitly denies traffic to/from all other internet locations.**	When the MUD-enabled IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the route filtering that is described in the device's MUD file** with	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7		respect to traffic being permitted to/from some internet locations, and traffic being implicitly blocked to/from all remaining internet locations.	
IoT-6	**ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place.	Test IoT-1 has run successfully, meaning that the MUD PEP router/switch has been configured based on a **MUD file that permits traffic to/from some lateral hosts and implicitly denies traffic to/from all other lateral hosts.** (The MUD file does not explicitly identify the hosts as lateral hosts; it identifies classes of hosts to/from which traffic should be denied, where one or more hosts of this class happen to be lateral hosts.)	When the MUD-enabled IoT device is connected to the network, its MUD PEP **router/switch will be configured to enforce the access control information that is described in the device's MUD file** with respect to traffic being permitted to/from some lateral hosts, and traffic being implicitly blocked to/from all remaining lateral hosts.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.PT-3: The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-3:** Assets are formally managed throughout removal, transfers, and disposition.			
IoT-9	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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 **DE.AE-1:** A baseline of network operations and expected data flows for users and systems is established and managed. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CM-2, SI-4 **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24	Test IoT-1 has run successfully, meaning the MUD PEP **router/switch has been configured based on the MUD file** for a specific MUD-capable device in question. The MUD file contains domains that resolve to multiple IP addresses. The MUD PEP router/switch should be configured to permit communication to or from all IP addresses for the domain.	A domain in the MUD file resolves to two different IP addresses. The MUD manager will create firewall rules that permit the MUD-capable device to send traffic to both IP addresses. The MUD-capable device attempts to send traffic to each of the IP addresses, and the MUD PEP router/switch permits the traffic to be sent in both cases.	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	PR.AC-5: Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM- 5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.DS-2:** Data in transit is protected. **NIST SP 800-53 Rev. 4** SC-8, SC-11, SC-12			
IoT-10	**ID.AM-1:** Physical devices and systems within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-2:** Software platforms and applications within the organization are inventoried. **NIST SP 800-53 Rev. 4** CM-8, PM-5 **ID.AM-3:** Organizational communication and data flows are mapped. **NIST SP 800-53 Rev. 4** AC-4, CA-3, CA-9, PL-8 **PR.DS-5:** Protections against data leaks are implemented. **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	A MUD-capable IoT device is configured to emit a MUD URL. Upon being connected to the network, its MUD file is retrieved, and the PEP is configured to enforce the policies specified in that MUD URL for that device. **Within 24 hours (i.e., within the cache-validity period for that MUD file), the IoT device is reconnected to the network.** After 24 hours have	Upon reconnection of the IoT device to the network, **the MUD manager does not contact the MUD file server. Instead, it uses the cached MUD file.** It translates this MUD file's contents into appropriate route-filtering rules and installs these rules onto the PEP for the IoT device. Upon reconnection of the IoT device to the network, after 24	Pass

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
	DE.AE-1: A baseline of network operations and expected data flows for users and systems is established and managed. **PR.AC-4:** Access permissions and authorizations are managed, incorporating the principles of least privilege and separation of duties. **NIST SP 800-53 Rev. 4** AC-1, AC-2, AC-3, AC-5, AC-6, AC-14, AC-16, AC-24 **PR.AC-5:** Network integrity is protected, incorporating network segregation where appropriate. **NIST SP 800-53 Rev. 4** AC-4, AC-10, SC-7 **PR.IP-1:** A baseline configuration of information technology/industrial control systems is created and maintained, incorporating security principles (e.g., concept of least functionality). **NIST SP 800-53 Rev. 4** CM-2, CM-3, CM-4, CM-5, CM-6, CM-7, CM-9, SA-10 **PR.IP-3:** Configuration change control processes are in place. **NIST SP 800-53 Rev. 4** CM-3, CM-4, SA-10 **PR.PT-3:** The principle of least functionality is incorporated by configuring systems to provide only essential capabilities. **NIST SP 800-53 Rev. 4** AC-3, CM-7 **PR.DS-2:** Data in transit is protected.	elapsed, the same device is reconnected to the network.	hours have elapsed, the MUD manager does fetch a new MUD file.	

Test	Applicable Cybersecurity Framework Subcategories and NIST SP 800-53 Controls	Test Summary	Expected Outcome	Observed Outcome
IoT-11	**ID.AM-1:** Physical devices and systems within the organization are inventoried.	A **MUD-enabled IoT device is capable of emitting a MUD URL.** The device should leverage one of the specified manners for emitting a MUD URL.	Upon initialization, the MUD-enabled IoT device broadcasts a DHCP message on the network, including at most one **MUD URL, in https scheme, within the DHCP transaction OR as an LLDP extension.**	Pass

9.5 Observations

NIST-MUD was able to successfully permit and block traffic to and from MUD-capable IoT devices as specified in the MUD files for the devices.

NIST-MUD does not implement LLDP extensions or certificate-based device authentication. (An authentication server can, however, inform the MUD manager of the MAC to MUD URL association using the API provided by NIST-MUD.) The current implementation supports devices that emit their MUD URL using the MUD DHCP extension or that are associated with their MUD URL by the provided API (i.e., the administrator or network authentication server configures the association).

NIST-MUD does not implement secure device onboarding. A device may “lie” about its identity by issuing a spurious DHCP request with a MUD URL embedded. There are no certificate-based onboarding checks.

As was discussed in Section 9.3.3.4, a misbehaving device or an attacker can have small windows of time where illegal packets can be exchanged with a device the first time the device sends or receives packets after its flow rules have timed out. This is because the design decision was made to permit packets sent by or intended for the IoT device to proceed through the switch while the SDN flow rules for packet classification are being computed at the SDN controller/MUD manager and pushed to the switch. The alternative is to block the packets while classification rules are inserted. While this can be configured, it is not a recommended configuration because it disrupts correct behavior.

10 General Findings, Security Considerations, and Recommendations

This section introduces findings based on the build implementations and demonstrations, security considerations, and recommendations.

10.1 Findings

Based on our experiences with the various builds considered and demonstrated in this project, we offer the following findings:

- It is possible to achieve significantly better security than is typically achieved in today's (non-MUD-capable) home and small-business networks by deploying and using MUD on those networks to constrain the communications of IoT devices.
- MUD is designed to protect devices that have a clear purpose and whose communication needs can be clearly defined. These communication needs are defined in terms of not only what ports and protocols the devices are permitted to use, but also the destinations with which the IoT devices can use those ports and protocols to communicate. If a device is not special-purpose and instead has very general communication requirements that cannot be clearly defined (e.g., a laptop or a phone), then the device does not lend itself to protection by MUD.
- The demonstrated approach, as implemented in each of the builds, shows that by using MUD-capable IoT devices on networks where support for MUD has been deployed, it is possible to manage access to MUD-capable IoT devices in a manner that maintains device functionality while
    - preventing access to the MUD-capable IoT device from other components on the internal network that are not from authorized manufacturers or authorized device classes
    - preventing the MUD-capable IoT device from being used to access unauthorized external domains
    - preventing the MUD-capable IoT device from being used to access other components on the internal network that are not from authorized manufacturers or that are not authorized device types
- MUD can help prevent MUD-capable IoT devices from being used to launch DDoS and other network-based attacks that are typically made possible by commandeering non-MUD-capable IoT devices found on today's home and small-business networks. For MUD to provide this protection, it must be deployed correctly, networks must use MUD-capable IoT devices, and MUD files must be written and available for these devices so that the files authorize only the outgoing communications that each MUD-capable IoT device needs to maintain its intended functionality.

- There are commercially available network visibility/monitoring technologies that can detect connected devices and identify certain device attributes (e.g., type, IP address, OS) throughout the duration of a device's connection to the network. These technologies are also able to detect when the devices leave the network or are powered off and to note their change of status accordingly.
- Setup and configuration of the components needed to deploy MUD on a network (MUD-capable router/switch and MUD manager) should ideally be able to be performed easily, right out of the box, to enable typical home or small-business users to deploy MUD successfully. While Build 2 is a plug-and-play solution that is designed to be easily deployable, setup and configuration of the other builds are not currently sufficiently user-friendly to enable the typical, nontechnical user to easily and seamlessly deploy these implementations. For MUD to be widely deployed on home/small-business networks, emphasis on ease of use will be crucial.
- MUD has the potential to help with the security of even those IoT devices that have been deprecated and are no longer receiving regular updates. Eventually, most IoT devices will reach a point at which they will no longer be updated by their manufacturer. This is a dangerous point in any device's life cycle because it means that any of its security vulnerabilities that become known after this point will not be protected against, leaving the device open to attack. For MUD-capable devices that reach this end-of-life stage, however, the use of MUD provides additional protection that is not available to non-MUD-capable devices. Even if a MUD-capable device can no longer be updated, its MUD file will still limit the other devices with which that MUD-capable device is able to communicate, thereby limiting what other devices could be used to attack it and what other devices it could be used to attack. In the future, there are expected to be many IoT devices that are no longer being updated by their manufacturers but will continue to be used. The ability to leverage MUD to limit the communication profiles of such unsupported devices will be important for protecting these highly vulnerable devices from attack by unauthorized endpoints and for protecting the internet from attack by these vulnerable devices.
- Even when using components that are fully conformant to the MUD specification, there are still some behaviors that will be determined by local policy. If the default policy that is provided by a specific product out of the box is not sufficient, user action will be required to configure the device according to a different and desired policy. User-friendly interfaces will be needed to enable the typical, nontechnical user of a home or small-business network to interact with the MUD components to modify their default settings when needed. For example, the MUD specification does not dictate what action to take (e.g., block or permit traffic to the IoT device) if the MUD manager is not able to validate the device's MUD file server's TLS certificate or if the MUD manager is not able to validate the device's MUD file's certificate. In either of these cases, if the default behavior that the device is configured to perform is not acceptable, the user would need to configure the device to perform the desired behavior. Ideally the device would provide a user-friendly interface through which to do so.
- There is still a dearth of MUD-capable IoT devices. Users wanting to deploy MUD do not yet have the option to do so because of a lack of availability of MUD-capable IoT devices. More

vendor buy-in is required to encourage IoT device manufacturers to implement support for MUD in their devices.

- Communications between the MUD manager and the router/switch, between the threat-signaling server and the MUD manager/router, and between the IoT devices and their corresponding update servers are not standardized. This lack of standardization has the potential to inhibit interoperability of components that are obtained from different manufacturers, thereby limiting the choice that consumers have to mix architectural components from different vendors in their MUD deployments.
- RFC 8520 states clearly that if the cache-validity timer has not expired, the MUD manager must not check for a new MUD file and should use the cached file instead. It also clearly states that expiration of the cache-validity timer does not require the MUD manager to discard the MUD file. It does not, however, state that if the cache-validity timer has expired, the MUD manager should check for a new MUD file, even though this is the behavior that the RFC authors had intended to specify. It is our understanding that this will be submitted as an erratum for clarification. In the meantime, implementations wishing to conform to the desired behavior should be designed such that if the cache-validity timer has expired, the MUD manager checks for a new MUD file.
- MUD rules are defined in terms of domain names, but when MUD rules are instantiated on routers, IP addresses, rather than domain names, are used. However, the IP address to which any given domain resolves may change. So, if a domain is listed in a MUD file rule and device traffic filters that instantiate this MUD file rule have been installed on the router, when the domain begins resolving to a different address, the device will initially not behave as intended. If the device attempts to communicate with this new IP address, it will not be permitted to do so because there will not yet be device traffic filters in its router that permit it to access this new IP address. The device traffic filters in the router will still be permitting access to the old IP address. In other words, the device will not be permitted to communicate with the desired domain, despite this communication being permitted by the device's MUD file. This undesirable situation will persist until the device traffic filters in the router are updated to use the new IP address to which the domain now resolves.

  To minimize the effect of such a situation, the MUD implementation (e.g., the MUD manager) should periodically generate DNS resolution requests for each of the domains listed in the MUD file and, if any of these domains now resolve to different IP addresses than previously, the device traffic filters using the old IP address should be deleted from the router or switch, and the device traffic filters using the new IP address should be installed. Regarding how often a MUD implementation might want to perform this periodic checking of domain name resolution values, one suggestion is to do so at intervals of TTL+V, where TTL is the time to live value in the A record of the domain's DNS entry, and V might be as long as 86,400 seconds (i.e., 24 hours). (The TTL value specifies how long a resolver is supposed to cache the DNS query before the query expires and the domain should be resolved again. If a DNS record for a domain changes, a new lookup will not be done until the cache expires.) Users should be cautioned that if the IP address to which a domain name resolves changes, the IoT device may be prohibited from communicating with that domain for some period (i.e., V) after the TTL for the domain's DNS entry has expired.

- When a MUD-capable IoT device performs a domain name lookup, it is important that the IP address to which the domain name gets resolved matches the IP addresses that that domain name got resolved to when the MUD rule containing that domain was installed at the router or switch. If they do not match, then the device would be prohibited from communicating with the desired domain despite the existence of a MUD rule explicitly permitting the device to do so.

  If the router or switch itself does a domain name lookup when the MUD rule is installed on it, and if the device and the router or switch are colocated, then the device and the router or switch will be in the same region and would be expected to have their domain name lookups resolved to the same IP addresses. Therefore, if the router or switch itself performs the domain name lookup when translating a MUD rule to device traffic filters, the IP address that is returned to the IoT device when it performs a domain name lookup should be the same as the IP address that was configured in the device traffic filters.

  However, if some other component, such as a MUD manager or controller that is in the cloud, performs a domain name lookup and sends the resulting device traffic filters to the router or switch for installation, then it is possible that the controller/MUD manager and the router or switch could be in a different region, which could mean that their domain name lookups for a given domain do not resolve to the same IP addresses. For MUD rules to be enforced as expected, measures need to be taken to ensure that the IP addresses that are used in the device traffic filters match the IP addresses that the IoT device would in fact use. Some possible ways of ensuring address alignment include:

  - requiring that the IoT device and the entity that is instantiating the MUD rules as device traffic filters use the same DNS server
  - having the entity that is instantiating the MUD rules as device traffic filters eavesdrop on the DNS queries made by the IoT device so it can learn what IP addresses the IoT device receives back in the DNS responses
  - having the router or switch occasionally send DNS queries for the list of domains it used in MUD files and updating the device traffic filters based on those queries

- In working with project collaborators, the NCCoE determined that MUD is only one of several foundational elements that are important to IoT security. First and foremost, it is imperative that IoT device manufacturers follow best practices for security when designing, building, and supporting their devices. Manufacturers should, for example, understand and manage the security and privacy risks posed by their devices as discussed in NISTIR 8228, *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks,* as well as the more general guidelines for identifying, assessing, and managing security risks that are discussed in the *Framework for Improving Critical Infrastructure Cybersecurity* (Cybersecurity Framework). In addition, they should continue to support their devices throughout their full life cycle, from initial availability through eventual decommissioning, with regular patches and updates. Cisco has proposed the following four elements as necessary for IoT security:

- device security by design: certifiable device capabilities
- device intent: MUD
- device network onboarding: secure, scalable, automated—bootstrapping remote secure key infrastructure/autonomic networking integrated model approach
- life-cycle management: behavior, software patches/updates

- There are numerous ways in which support for MUD can be provided within a home/small-business network. Build 3 is expected to demonstrate support for MUD in residential gateway equipment and infrastructure. However, this does not imply any requirement that service providers bear the responsibility for implementing MUD. Builds 1, 2, and 4 simply require that customers acquire and use third-party routers and other related components that are MUD-capable. Integrating MUD capability into residential gateway equipment supplied by service providers, along with strong advocacy and education of customers to explain the benefits of using MUD, represents one approach to encouraging widespread adoption of MUD in home and small-business environments. Factors affecting determination of how and where MUD should be supported include infrastructure and support requirements, cost, and privacy. These are some issues that should be considered:
    - Upgrading all existing internet gateways to be MUD-capable would be a large undertaking, so service providers might perform cost-benefit analyses to determine whether it makes economic sense for them to provide and support MUD-capable internet gateways in homes and small businesses.
    - Providing and supporting MUD-capable internet gateways could potentially cast service providers into a situation in which they might be perceived as responsible for troubleshooting problems with the IoT devices themselves. This is a function that is generally outside the service provider's control.
    - In addition to upgrading internet gateways to be MUD capable, service providers might choose to make changes to the upstream network to support MUD. A service provider's analysis regarding whether it should integrate support for MUD into the residential gateway or simply encourage its customers to use MUD-capable third-party routers should consider any additional upstream network changes that may be needed.
    - The MUD manager, by its very nature, is aware of all MUD-capable IoT devices that are attached to the network and of what domains and other types of local devices they are permitted to communicate with. Such information could have privacy ramifications. Whatever entity controls the MUD manager will have access to this information. If this entity is a service provider, as in the planned Build 3 implementation, the service provider will be privy to this personal information.

10.2 Security Considerations

Use of MUD, when implemented correctly, allows manufacturers to constrain communications to and from IoT devices to only those sources and destinations intended by the device's manufacturer. By restricting an IoT device's communications to only those that it needs to fulfill its intended function, MUD reduces both the communication vectors that can be used to attack a vulnerable IoT device and the communication vectors that a compromised IoT device can use to attack other devices. MUD does not, however, provide any inherent security protections to IoT devices themselves. If a device's MUD file permits an IoT device to receive communications from a malicious domain, traffic from that domain can be used to attack the IoT device. Similarly, if the MUD file permits an IoT device to send communications to other domains, and if the IoT device is compromised, it can be used to attack those other domains. Users implementing MUD are advised to keep the following security considerations in mind.

- It is important to ensure that the MUD implementation itself is secure and not vulnerable to attack. If the MUD implementation itself were to be compromised, the compromised MUD infrastructure would serve as a venue for attack. As stated in the Security Considerations section of the MUD specification (RFC 8520), "the basic purpose of MUD is to configure access, and so by its very nature can be disruptive if used by unauthorized parties." Protecting the MUD infrastructure includes ensuring the security of the IoT device MUD URL emission, the MUD manager, the DHCP server, the MUD file server, the router, and the private key used to sign the MUD file. If the MUD implementation itself is compromised—e.g., if an IoT device emits an incorrect MUD file URL; if a different MUD file URL is sent to the MUD manager than that provided by the IoT device; if a well-formed, signed MUD file is malicious; if a malicious actor creates a compromised MUD manager; or if a router is compromised so that it does not enforce its device traffic filters—then MUD can be used to enable rather than prevent potentially damaging communications between affected IoT devices and other domains.
- If a malicious actor can create a well-formed, signed, malicious MUD file, the undesirable communications that will be permitted by that MUD file will be readily visible by reading the MUD file. Therefore, for added protection, users implementing MUD should review the MUD file for their IoT devices to ensure it specifies communications that are appropriate for the device. Unfortunately, on home and small-business networks, where users are not likely to have the technical expertise to understand how to read MUD files, users will be required to trust that the MUD files specify communications appropriate for the device or rely on a third party to perform this review for them.
- MUD implementation depends on the existence and secure operation of a MUD file server from which a device's MUD file can be retrieved. If the manufacturer goes out of business or does not conform to best common practices for patching, the MUD file server domain would be vulnerable to having malware deployed on it and thereby being transformed into an attack vector. To safeguard against such a scenario, a mechanism needs to be defined to enable the domain of the manufacturer to be invalidated so that the MUD manager can be protected

from connecting to the compromised MUD file server, despite the fact that IoT devices may continue to emit the URL of the compromised domain. Use of threat-signaling information is one example of such a mechanism.

- To protect all IoT devices on a network, both MUD-capable and non-MUD-capable, users may want to consider investigating mechanisms for supplying MUD files for legacy (non-MUD-capable) devices.
- By emitting a MUD URL, a device reveals information about itself, thereby potentially providing an attacker with guidance on what vulnerabilities it might have and how it might be attacked.
- An attacker could spy on the MUD manager to determine what devices are connected to the network and then use this information to plan an attack.
- If an attacker can gain access to the local network, they may be able to use the MUD manager in a reflected denial of service attack by emitting a large amount of MUD URLs (e.g., from spoofed MAC addresses) and forcing the MUD manager to make connection attempts to retrieve files from those MUD URLs. Safeguards to counter this, such as throttling connection attempts of the MUD manager, should be considered.
- MUD users should understand that the main benefit of MUD is its ability to limit an IoT device's communication profile; it does not necessarily permit owners to find, identify, and correct already-compromised IoT devices.
    - If a system is compromised but it is still emitting the correct MUD URL, MUD can detect and stop any unauthorized communications that the device attempts. Such attempts may also indicate potential compromises.
    - On the other hand, a system could be compromised so that it emits a new URL referencing a MUD file that a malicious actor has created to enable the compromised device to engage in communications that should be prohibited. In this case, whether the compromised system will be detected depends on how the MUD manager is configured to react to such a change in MUD URL. According to the MUD specification, if a MUD manager determines that an IoT device is sending a different MUD URL, the MUD manager should not use this new URL without some additional validation, such as a review by a network administrator.
        - If the MUD manager requires an administrator to accept the new URL but the administrator does not accept it, MUD would help owners detect the compromised system and limit the ability of the compromised system to be used in an attack.
        - However, if the MUD manager does not require an administrator to accept the new URL or if it requires an administrator to accept the new URL and the administrator does accept the new URL, MUD would not help owners detect the compromised system, nor would it limit the ability of the compromised system to be used in an attack.
        - As a third possibility, a compromised system could be subjected to a more sophisticated attack that enables it to dynamically change its identity (e.g., its MAC address) along with emitting a new URL. In this case, the compromised system would not be detected

unless the MUD manager were configured to require the administrator to explicitly add each new identity to the network.

- The following security considerations are specific to the MUD deployment and configuration process:
  - When an IoT device emits its MUD URL by using DHCP or LLDP rather than using an X.509 certificate that can be used to provide strong authentication of the device, the device may be able to lie about its identity and thereby gain network access it should not have. If a network includes IoT devices that emit their MUD URL by using one of these insecure mechanisms, as does the MUD build implemented in this project, network administrators should take additional precautions to try to improve security. For example, the MUD implementation should be configured to:
    - prevent devices that have not been authenticated from being in the same class as devices that have been strongly authenticated to prevent the nonauthenticated devices from getting possibly elevated permissions that are granted to the authenticated devices
    - prevent devices that have not been authenticated from being able to use the same MUD URL as devices that have been strongly authenticated
    - whenever possible, bind communications to the authentication that has been used, e.g., IEEE 802.1X, 802.1AE (MACsec), 802.11i (WPA2), or future authentication types
    - remove state if an unauthenticated method of MUD URL emission is being used and any form of break in that session is detected
    - not include unauthenticated devices into the manufacturer grouping of any specific manufacturer without additional validation
    - use additional discovery and classification components that may be on the network to try to fingerprint devices that have not been authenticated to try to verify that they are of the type they are asserting to be by their MUD URLs
    - raise an alert and require administrator approval if the MUD manager detects that the signer of a MUD file has changed, in order to protect against rogue Certificate Authorities
    - raise an alert and require administrator approval if the MUD manager detects that a device's MUD file has changed, in order to protect compromised IoT devices that seek to be associated with malevolent MUD files
    - To protect against domain name ownership changes that would permit a malicious actor to provide MUD files for a device, MUD managers should be configured to cache certificates used by the MUD file server. If a new certificate is retrieved, the MUD manager should check to see if ownership of the domain has changed and, if so, it should raise an alert and require administrator approval.

The points above provide only a summary of the security considerations discussed in the MUD specification (RFC 8520). Users deploying a MUD implementation are encouraged to consult that document directly for more detailed discussion.

Additionally, please refer to NISTIR 8228, *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks,* for more details related to IoT cybersecurity and privacy considerations.

10.3 Recommendations

The following are recommendations for using MUD:

- Home and small-business network owners should make clear to vendors that both IoT devices and network components need to be MUD-capable. They should use MUD-capable IoT devices on their networks and enable MUD on their networks by deploying all of the MUD-capable network components needed to compose a MUD-capable infrastructure.
- Service providers should consider either providing and supporting or encouraging their customers to use MUD-capable routers on their home and small-business networks. (Note: MUD requires the use of a MUD-capable router; this router could be either standalone equipment provided by a third-party network equipment vendor or integrated with the service provider's residential gateway equipment. While service providers are not required to do so, some may choose to make their residential gateway equipment MUD-capable.)
- IoT device manufacturers should configure their devices to emit a MUD URL by default.
- IoT device manufacturers should write MUD files for their devices. By doing so, they will be able to provide network administrators the confidence to know what sort of access their device needs (and what sort of access it does not need), and they will do so in a way that someone trained to operate and install the device does not need to understand network administration.
- IoT device manufacturers should ensure that the MUD files for their devices remain continuously available by hosting these MUD files at their specified MUD URLs throughout the devices' life cycles.
- IoT device manufacturers should update each of their MUD files over the course of their devices' life cycles, as needed, if the communication profiles for their devices evolve.
- Even after an IoT device manufacturer deprecates an IoT device so that it will no longer be supported, the manufacturer should continue to make the device's MUD file available so the device's communication profile can continue to be enforced. This will be especially important for deprecated IoT devices that have unpatched vulnerabilities.
- IoT device manufacturers should provide regular updates to patch security vulnerabilities and other bugs that are discovered throughout the life cycle of their devices, and they should make these updates available at a designated URL that is explicitly named in the device's MUD file as being a permissible endpoint with which the device may communicate.

- Manufacturers of MUD managers, MUD-capable DHCP servers, and MUD-capable routers that are targeted for use on home and small-business networks should strive to make deployment and configuration of these devices as easy to understand and as user-friendly as possible to increase the probability that they will be deployed and configured correctly and securely, even when the person performing the deployment has limited understanding of network administration.
- Home and small-business network owners should have visibility into every device on their network. Any device is a potential attack or reconnaissance point that must be discovered and secured. Non-MUD-capable devices are inviting targets.
- Home and small-business network owners should segment their networks where possible. In small-business and home environments it may not be possible to apply good segmentation policies. But at a minimum, where there are IoT devices that are known to have security risks, e.g., non-MUD-capable devices, keep these on a separate network segment from the everyday computing devices that are afforded with a higher level of cybersecurity protection via regular updates and security software. This is an important step to contain any threats that may emerge from the IoT devices.
- Home and small-business network owners should use the information presented in the Security Considerations section of the MUD specification (RFC 8520) to enhance protection of MUD deployments.
- Standards development organizations should standardize communications between the MUD manager and the router, between the threat-signaling server and the MUD manager/router, and between the IoT devices and their corresponding update servers.
- Home and small-business network owners should consider their deployment of MUD to be only one pillar in the overall security of their network and IoT devices. Deployment of MUD is not a substitute for performing best practices to ensure overall, comprehensive security for their network.
- Manufacturers of MUD-capable network components and MUD-capable IoT devices should consider MUD to be only one pillar in helping users secure their networks and IoT devices. Manufacturers should, for example, understand the security and privacy risks posed by their devices as discussed in NISTIR 8228, *Considerations for Managing Internet of Things (IoT) Cybersecurity and Privacy Risks,* as well as the guidelines for identifying, assessing, and managing security risks that are discussed in the *Framework for Improving Critical Infrastructure Cybersecurity* (Cybersecurity Framework). They should use this information as they make decisions regarding both how they design their MUD-capable components and the default configurations with which they provide these components, being mindful of the fact that home and small-business network users of their components may have only a limited understanding of network administration and security.

The following recommendations are suggestions for continuing activity with the collaboration team:

- Continue work with collaborators to enhance MUD capabilities in their commercial products (see Section 10.1).
- Perform additional work that builds on the broader set of security controls identified in Section 5.2.
- Work with collaborators to demonstrate MUD deployments that are configured to address the security considerations that are raised in the MUD specification, such as
    - configuring IoT devices to emit their MUD URLs in a secure fashion by providing the IoT devices with credentials and binding the device's MUD URLs with their identities
    - restricting the access control permissions of IoT devices that do not emit their MUD URLs in a secure fashion, so they are not elevated beyond those of devices that do not present a MUD policy
    - configuring the MUD manager to raise an exception and seek administrator approval if the signer of a MUD file or the MUD file itself changes
    - for IoT devices that do not emit their MUD URLs in a secure fashion, if their MUD files include rules based on the "manufacturer" construct, performing additional validation measures before admitting the devices to that manufacturer class. For example, look up each device's MAC address and verify that the manufacturer associated with that MAC address is the same as the manufacturer specified in the "manufacturer" construct in that device's MUD file.
- Explore the possibility of using crowdsourcing and analytics to perform traffic flow analysis and thereby adapt and evolve traffic profiles of MUD-capable devices over the course of their use. Instead of simply dropping traffic that is received at the router if that traffic is not within the IoT device's profile, this traffic could be quarantined, recorded, and analyzed for further study. An analytics application that receives such traffic from many sources would be able to analyze the traffic and determine whether there may be valid reasons to expand the device's communication profile.
- Work with collaborators to define a blueprint to guide IoT device manufacturers as they build MUD support into their devices, from initial device availability to eventual decommissioning. Provide guidance on required and recommended manufacturer activities and considerations.

11 Future Build Considerations

The number of network components that support the MUD protocol continues to grow rapidly. As more MUD-capable IoT devices become available, these too should be demonstrated. In addition, IPv6, for which no MUD-capable products were available for the initial demonstration sequences, adds a new dimension to using MUD to help mitigate IoT-based DDoS and other network-based attacks. As discussed in Section 11.2, inclusion of IPv6-capability should be considered for future builds.

In addition, operationalization, IoT device onboarding, and IoT device life-cycle issues in general are promising areas for further work. With respect to onboarding, additional mechanisms for devices to securely provide their MUD URL, such as use of the Wi-Fi Device Provisioning Protocol, can be investigated and developed as proof-of-concept implementations.

The following features, which are enhancements that are being implemented in Build 4, are potential candidates for inclusion in future IETF MUD drafts:

- The MUD manager implements device quarantine. A device may enter a "quarantine" state when a packet originating from the device triggers an access violation (i.e., does not match any MUD rules). When the device is in a quarantine state, its access is limited to only those ACEs that are allowable under quarantine.
- The MUD manager implements a MUD reporting capability for manufacturers to be able to get feedback on how their MUD-capable devices are doing in the field. To protect privacy, no identifying information about the device or network is included.

11.1 Extension to Demonstrate the Growing Set of Available Components

ARM, CableLabs, Cisco, CTIA, DigiCert, Forescout, Global Cyber Alliance, MasterPeace Solutions, Molex, Patton Electronics, and Symantec have signed CRADAs and are collaborating in the project. There is also strong interest from additional industry collaborators to participate in future builds, particularly if we expand the project scope to include onboarding. Some collaborators have also expressed interest in our demonstrating the enterprise use case. Several of these new potential collaborators may submit letters of interest leading to CRADAs for participation in tackling the challenge of integrating MUD and other security features into enterprise or industrial IoT use cases.

11.2 Recommended Demonstration of IPv6 Implementation

Due to product limitations, the initial phases of this project involved support for only IPv4 and did not include investigation of IPv6 issues. Additionally, due to the absence of NAT in IPv6, all IPv6 devices are directly addressable. Hence, the potential for DDoS and other attacks against IPv6 networks could potentially be worse than it is against IPv4 networks. Consequently, we recommend that demonstration of MUD in an IPv6 environment be performed as part of follow-on work.

Appendix A List of Acronyms

AAA	Authentication, Authorization, and Accounting
ACE	Access Control Entry
ACK	Acknowledgement
ACL	Access Control List
API	Application Programming Interface
CIS	Center for Internet Security
CMS	Cryptographic Message Syntax
CoAP	Constrained Application Protocol
COBIT	Control Objectives for Information and Related Technology
CRADA	Cooperative Research and Development Agreement
DACL	Dynamic Access Control List
DB	Database
DDoS	Distributed Denial of Service
Devkit	Development Kit
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
DVR	Digital Video Recorder
FIPS	Federal Information Processing Standard
FTP	File Transfer Protocol
GCA	Global Cyber Alliance
GUI	Graphical User Interface
http	Hypertext Transfer Protocol
https	Hypertext Transfer Protocol Secure
IETF	Internet Engineering Task Force
IOS	Cisco's Internetwork Operating System
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ISA	International Society of Automation
ISO/IEC	International Organization for Standardization/International Electrotechnical Commission
ISP	Internet Service Provider
IT	Information Technology
ITL	National Institute of Standards and Technology's Information Technology Laboratory
JSON	JavaScript Object Notation
LDAP	Lightweight Directory Access Protocol
LED	Light-Emitting Diode
LLDP	Link Layer Discovery Protocol (Institute of Electrical and Electronics Engineers 802.1AB)

MAB	MAC Authentication Bypass
MAC	Media Access Control
MQTT	Message Queuing Telemetry Transport
MUD	Manufacturer Usage Description
NAT	Network Address Translation
NCCoE	National Cybersecurity Center of Excellence
NIST	National Institute of Standards and Technology
NISTIR	NIST Interagency or Internal Report
NTP	Network Time Protocol
OS	Operating System
PEP	Policy Enforcement Point
PoE	Power over Ethernet
RADIUS	Remote Authentication Dial-In User Service
REST	Representational State Transfer
RFC	Request for Comments
RMF	Risk Management Framework
SDN	Software Defined Networking
SNMP	Simple Network Management Protocol
SP	Special Publication
SSL	Secure Sockets Layer
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TLS	Transport Layer Security
TLV	Type Length Value
UDP	User Datagram Protocol
URL	Uniform Resource Locator
VLAN	Virtual Local Area Network
VPN	Virtual Private Network
WAN	Wide Area Network
WPA3	Wi-Fi Protected Access 3 Security Certificate protocol
YANG	Yet Another Next Generation

Appendix B Glossary

Audit — Independent review and examination of records and activities to assess the adequacy of system controls, to ensure compliance with established policies and operational procedures (National Institute of Standards and Technology (NIST) Special Publication (SP) 800-12 Rev. 1)

Best Practice — A procedure that has been shown by research and experience to produce optimal results and that is established or proposed as a standard suitable for widespread adoption (Merriam-Webster)

Botnet — The word “botnet” is formed from the words “robot” and ”network.” Cyber criminals use special Trojan viruses to breach the security of several users’ computers, take control of each computer, and organize all the infected machines into a network of “bots” that the criminal can remotely manage. (https://usa.kaspersky.com/resource-center/threats/botnet-attacks)

Control — A measure that is modifying risk (Note: Controls include any process, policy, device, practice, or other actions that modify risk.) (NIST Interagency or Internal Report [NISTIR] 8053)

Denial of Service — The prevention of authorized access to a system resource or the delaying of system operations and functions (NIST SP 800-82 Rev. 2)

Distributed Denial of Service (DDoS) — A denial of service technique that uses numerous hosts to perform the attack (NISTIR 7711)

Managed Devices — Personal computers, laptops, mobile devices, virtual machines, and infrastructure components require management agents, allowing information technology staff to discover, maintain, and control them. Those with broken or missing agents cannot be seen or managed by agent-based security products.

Mapping — Depiction of how data from one information source maps to data from another information source

Mitigate — To make less severe or painful or to cause to become less harsh or hostile (Merriam-Webster)

Manufacturer Usage Description (MUD)	A component-based architecture specified in Request for Comments (RFC) 8250 that is designed to provide a means for end devices to signal to the network what sort of access and network functionality they require to properly function
MUD-Capable	An Internet of Things (IoT) device that is capable of emitting a MUD uniform resource locator in compliance with the MUD specification
Network Address Translation (NAT)	A function by which internet protocol addresses within a packet are replaced with different IP addresses. This function is most commonly performed by either **routers** or firewalls. It enables private IP networks that **use** unregistered IP addresses to connect to the internet. **NAT** operates on a router, usually connecting two networks together, and translates the private (not globally unique) addresses in the internal network into legal addresses before packets are forwarded to another network.
Non-MUD-Capable	An IoT device that is not capable of emitting a MUD URL in compliance with the MUD specification (RFC 8250)
Onboarding	The process by which a new device gains access to the wired or wireless network for the first time
Operationalization	Putting MUD implementations into operational service in a manner that is both practical and effective
Policy	Statements, rules, or assertions that specify the correct or expected behavior of an entity. For example, an authorization policy might specify the correct access control rules for a software component. (NIST SP 800-95 and NISTIR 7621 Rev. 1)
Policy Enforcement Point	A network device on which policy decisions are carried out or enforced
Risk	The net negative impact of the exercise of a vulnerability, considering both the probability and the impact of occurrence. Risk management is the process of identifying risk, assessing risk, and taking steps to reduce risk to an acceptable level. (NIST SP 800-30)
Router	A computer that is a gateway between two networks at open system interconnection layer 3 and that relays and directs data packets through that internetwork. The most common form of router operates on IP packets (NIST SP 800-82 Rev. 2)

Server	A computer or device on a network that manages network resources. Examples include file servers (to store files), print servers (to manage one or more printers), network servers (to manage network traffic), and database servers (to process database queries). (NIST SP 800-47)
Security Control	A safeguard or countermeasure prescribed for an information system or an organization designed to protect the confidentiality, integrity, and availability of its information and to meet a set of defined security requirements (NIST SP 800-53 Rev. 4)
Shall	A requirement that must be met unless a justification of why it cannot be met is given and accepted (NISTIR 5153)
Should	This term is used to indicate an important recommendation. Ignoring the recommendation could result in undesirable results. (NIST SP 800-108)
Threat	Any circumstance or event with the potential to adversely impact organizational operations (including mission, functions, image, or reputation), organizational assets, or individuals through an information system via unauthorized access, destruction, disclosure, modification of information, and/or denial of service. Also, the potential for a threat-source to successfully exploit a particular information system vulnerability (Federal Information Processing Standards 200)
Threat Signaling	Real-time signaling of DDoS-related telemetry and threat-handling requests and data between elements concerned with DDoS attack detection, classification, trace back, and mitigation (https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/cybersecurity-network-and-information-security)
Traffic Filter	An entry in an access control list that is installed on the router or switch to enforce access controls on the network
Uniform Resource Locator (URL)	A reference to a web resource that specifies its location on a computer network and a mechanism for retrieving it. A typical URL could have the form http://www.example.com/index.html, which indicates a protocol (http), a host name (www.example.com), and a file name (index.html). Also sometimes referred to as a web address.

Update	New, improved, or fixed software, which replaces older versions of the same software. For example, updating an operating system brings it up-to-date with the latest drivers, system utilities, and security software. Updates are often provided by the software publisher free of charge. (https://www.computerhope.com/jargon/u/update.htm)
Update Server	A server that provides patches and other software updates to IoT devices
VLAN	A broadcast domain that is partitioned and isolated within a network at the data link layer. A single physical local area network (LAN) can be logically partitioned into multiple, independent VLANs; a group of devices on one or more physical LANs can be configured to communicate within the same VLAN, as if they were attached to the same physical LAN.
Vulnerability	Weakness in an information system, system security procedures, internal controls, or implementation that could be exploited or triggered by a threat source (NIST SP 800-37 Rev. 2)

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