Toward Identification and Characterization of IoT Software Update Practices

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Abstract—Software update systems are critical for ensuring systems remain free of bugs and vulnerabilities while they are in service. While many Internet of Things (IoT) devices are capable of outlasting desktops and mobile phones, their software update practices are not yet well understood. This paper discusses efforts toward characterizing the IoT software update landscape through network analysis of IoT device traffic. Our results suggest that vendors do not currently constrain follow security best practices, and that software update standards, while available, are not being deployed. We discuss our findings and give a research agenda for improving the overall security and transparency of software updates on IoT.

Index Terms—IoT, Software Updates, Update Detection

I. INTRODUCTION

Consumer Internet of Things (IoT) devices have gained significant popularity in recent years resulting in a revolution of IoT devices used in many applications. These devices are typically resource-constrained and require specialized operating systems and software stacks depending on their application. Due to the unique resource constraints and operating conditions of IoT devices, device vendors have to either design their own software update infrastructure and supporting applications from scratch, or use an integrated third-party solution such as AWS IoT [1], Google Cloud IoT [2], or Azure IoT [3], which may be inconsistent and vulnerable [4]. Software update systems are well understood and widely available on general-purpose computers and servers; however, there is very little insight and research into how these vendor-specific IoT software update systems work due to a lack of standardization in the IoT space [5], [6]. Our research aims to characterize how typical consumer IoT devices query for and retrieve software updates, and evaluate the security of these techniques as used by prominent IoT vendors.

IoT devices have another unique operating constraint for vendors to consider: their lifespan. A typical personal computer has a relatively short lifespan compared to an IoT device, which is expected to behave in an appliance-like fashion with minimal (if any) downtime. A personal computer may get replaced if the updated software or operating system requires more resources than those available on the system, causing slowness or simply refusing to install. In contrast, an IoT device such as a smart thermostat may be expected to run for decades before being replaced. With how rapidly technology changes, device vendors have the additional challenge of providing a secure implementation of their software on potentially outdated hardware.

We hypothesize that the suboptimal update intervals from IoT device vendors may further weaken IoT update systems. For example, device libraries such as the crucial OpenSSL library was analyzed during a study of 122 IoT device firmware files, which revealed several vendors failing to patch OpenSSL in their IoT devices after critical vulnerabilities were released [7]. Several vendors took months to supply an updated system image with a patched OpenSSL version, and one vendor took nearly 1,500 days to provide an update that patched the critical vulnerability. Failing to keep key libraries up to date allows these devices to gain a larger attack surface that could potentially be leveraged by bad actors to trick the device into downloading malware [8] or to bypass security measures that are in place to prevent the device from loading modified firmware [6], [9].

In recent years there have been several proposals for secure software update systems that are designed for IoT [7], [10], [11] and embedded systems [12], [13]; however, there has not been much research (to our knowledge) aiming to broadly understand the IoT software/firmware update landscape. Does this device check for updates on a regular basis? Does this vendor digitally sign firmware update files? How many days elapse between updates for IoT light bulbs? This paper presents a preliminary analysis of IoT software update practices, shedding light on specific security behaviors, and attempting to establish a framework for answering the questions above.

In this paper, our primary focus is on the identification of updates being requested and taking place. Being able to identify IoT device updates at the network level is beneficial in several contexts. First, network-level update detection can be used as independent feedback to end users that their devices are being updated regularly – an IoT device vendor may promise to publish security patches for their IoT devices, but not deliver on that promise. Second, in a enterprise context administrators may want to apply the principle of

1For example, a longitudinal study of device firmware files by Zhang et al. found that device vendors often take around 6 months to many years to patch critical libraries (e.g., OpenSSL) in their IoT devices after a critical vulnerability was released [11].
least privilege to fleets of IoT devices. Certain IoT devices do not need access to the open internet all the time, for most devices they are capable of working exclusively with LAN connectivity to a central hub or other devices. The only edge case to this is checking for updates and downloading them. If a smart firewall can detect update-related traffic from IoT devices, it can adjust rules to (1) allow the IoT device to download an update from the internet, and (2) log the update instance. Finally, update detection can help with asset management. At a glance, a system administrator would be able to see which IoT devices on their network are updating, which can assist them in finding devices that are running outdated firmware.

The research contributions in this paper are:

- The initial design of a system for real-time detection of IoT device updates. Our design can be extended to train a data-driven model for use in network appliances.
- Analysis of IoT network traffic from one of the largest IoT studies to date [14] to identify update-related traffic. We identified several common design patterns used in several IoT devices, and found vulnerabilities that could be exploited.
- A case study of software update schemes that we identified through our methodology. Devices featured in our case study distribute software updates over HTTP with no tamper-resistant protection mechanisms added on. One of the devices identified in the case study provides a happy medium between update transparency and security.
- A research agenda for improving IoT update systems regarding proposed update system designs, how TLS cannot be relied upon as a single source of firmware protection, and how future update system designs can be integrated with our identification system.

II. METHODOLOGY

Our research objective is to design a system that identifies software update requests and responses from/to IoT devices. We aim for the system to be vendor agnostic, requiring no a priori knowledge about the IoT vendor’s infrastructure or devices. The system should also identify updates across multiple independent cloud vendors, which are relied upon heavily in IoT.

Our methodology involves passive analysis of captured network traffic (using the pcap standard) from a 2019 Internet Measurements Conference (IMC) paper by Ren et al. [14] which actively captured traffic from 81 IoT devices. These 81 devices were located in two geographic regions: 46 in the US, 35 in the UK, and 26 common devices across both regions. In other words, the dataset contains packet captures from 55 unique devices. Collected data was harvested at network gateways, but no form of middle-person attack was done on TLS traffic which precludes peering into an encrypted device communication. Therefore, in this paper, we rely exclusively on extractable HTTP traffic along with other metadata such as TLS handshakes. Devices are inherently excluded from the scope of this study if they do not leverage HTTP or TLS.

Thus, if a vendor created an application-specific protocol that does not conform to common identifiable standards, the device is excluded as there is no extractable data. In our dataset, 11 devices (20%) did not have any extractable HTTP traffic or TLS handshakes, therefore they are inherently excluded from our study.

A. Data Extraction

In total, Ren et al.’s dataset of packet captures is 13GB in size, which includes 37,744 packet captures recorded by the automated test system and 611 unsupervised experiment packet captures, yielding a total of 38,355 packet captures. We do not separate traffic by geographic region as Ren et al. found very negligible differences in region-specific traffic [14].

In order to identify network traffic related to software updates, we hypothesize that update interactions between an IoT device and vendor cloud follow a structured schema. If the schema is human-readable (e.g., JSON, XML, etc.) there will be keywords contained inside indicating some update-related information, such as a firmware version. We initially searched for a single keyword “update” using file search tools, which led us to identify several other update-related keywords that we list below:
Given a packet capture, we generate a UUID Assignment such as Apache Spark, and works on the dataset as follows:

1. Traffic Metadata and HTTP Object Extraction: We create an output directory with files that will serve as the unit of work in the parallel execution portion of the pipeline. The HTTP objects are of particular interest as they provide us insight into any files transferred along with the HTTP request/response in the packet capture to the system interactions, we load the metadata generated from Section II-A and search through the directories of HTTP objects for analyzing extracted TLS metadata. To infer IoT update system interactions, we load the metadata generated from Section II-A and search through the directories of HTTP objects to identify keywords that we found to be update-related. The analysis pipeline aggregates the update keywords along with various pieces of metadata from the original experiments, such as device information and the interaction event that took place in order to perform TLS offloading, this is not feasible in practice with embedded devices, especially a large number of embedded devices. Any attempt at tampering with the device will likely change the device behavior, and therefore, will not be indicative of how these devices normally behave.

**TLS Handshake Extraction:** We then extract TLS client and server hello data using a modified version of pyshark [15]. Our modified version of pyshark supports extracting more TLS handshake metadata, including the ciphers advertised in the TLS client hello and server hello handshake. In total, we return a list containing every TLS handshake, including TLS version, TLS handshake type, and a list of cipher suites. The TLS cipher suite data is used to determine if devices are adequately securing communication channels against TLS-related attacks.

**Keyword Extraction:** For each of the extracted HTTP objects, we scan for the aforementioned update-related keywords by performing a case-insensitive search for all of the keywords. A keyword occurrence flags a packet capture related to a software update. Counts of keyword occurrences are saved to the metadata DB for future analysis.

The data-extraction pipeline operates per packet capture in parallel. On our test VM with 24 virtual processors, 64GB of RAM, and a solid-state drive, we were able to run the extraction pipeline on 38,355 packet captures in just over 60 minutes (approx. 10 packet captures processed per second). Without a parallelized approach, our extraction pipeline would have taken over 24 hours to process. There is room for future optimization for this pipeline to achieve faster speeds – each extraction of the packet capture happens independently. In other words, tshark ends up being executed once to extract the packet contents, then twice to filter the packet capture for client hello and server hello packets. The time to execute each tshark process, read the results into a buffer, then unmarshal the results takes significant time compared to directly using native pcap processing libraries.

**B. Data Analysis**

We developed a parallel analysis pipeline to parse the extracted HTTP objects and metadata from the extraction pipeline. Our data analysis pipeline is separated into two parts: one for inferring IoT update system interactions, and the other for analyzing extracted TLS metadata. To infer IoT update system interactions, we load the metadata generated from Section II-A and search through the directories of HTTP objects to identify keywords that we found to be update-related. The analysis pipeline aggregates the update keywords along with various pieces of metadata from the original experiments, such as device information and the interaction event that took place (e.g. device power on, device activation, etc.) to generate the results in Section III-

Using the metadata that corresponds to the packet capture, we can trace the packet capture that had been flagged as having update-related traffic. After identification of these packet captures, we manually inspect the HTTP response data to look for any endpoints we can connect to, or we look through...
extracted HTTP response data for any update service-related artifacts such as firmware update files. It is highly unlikely that update artifacts are present in HTTP response data, as this would imply the update artifacts were transmitted over an insecure HTTP channel which would place an additional burden on device vendors to provide some protection (digital signatures on update files, cryptographic hashes, etc.) on their firmware files. It is worth noting that device vendors should be protecting their firmware from being tampered with regardless of the transfer protocol being used: if a vendor uses only TLS to secure their updates in transit, the compromise of a single cryptographic key is the only requirement to jeopardize the integrity of the vendor’s update system [16].

Analyzing IoT update interactions by raw traffic is misleading as it does not tell us about the context that triggers a device to update, only that the device checked for an update. To further characterize update interaction, we look at event-related information to provide more context to the various conditions that cause IoT devices to update. All of the packets captured from the Ren et al. study are labeled with various event-related information such as power events, app interaction, or idle events. Therefore, we analyze these crucial pieces of context to see if there are any detectable events that we can use to see if an IoT device is updating. For example, if an IoT device checks for an update when powered on, an adaptive firewall can use temporal data of an IoT device’s network connectivity to provide more context to classify if an IoT device may be requesting and applying a software update.

Aside from the update traffic we extracted, we also extract and analyze all TLS handshake data from all the packet captures (independent of update keyword traffic) to assess the overall strength of the communication channels in use. To interpret the set of cipher suites advertised between clients and servers, we converted the cipher suite’s hexadecimal value to the IANA cipher suite name by leveraging a cipher suite information API provided by ciphersuite.info [17] which aggregates all IANA cipher suites along with IANA cipher suite security classifications. Cipher suites are then categorized into four buckets: insecure, weak, secure, and recommended. Insecure cipher suites have easily exploitable security flaws and thus should never be used, while weak cipher suites may have proof-of-concept vulnerabilities that are more difficult to exploit in practice. The classes of secure and recommended cipher suites have no known vulnerabilities, and all recommended cipher suites are a subset of secure cipher suites. The only differentiating factor is recommended cipher suites support Perfect Forward Secrecy (PFS).

III. RESULTS

In this section, we discuss our preliminary results in identifying update-related traffic. At the network level, software updates are difficult to detect if the update communications are taking place over an encrypted connection, as we do not have the means to perform TLS offloading. Even with this limitation, our HTTP object extraction pipeline successfully extracted HTTP objects from 5,766 of 38,356 packet captures, which is 15% of the packet captures in the dataset. In other words, 85% of packet captures use some form of encryption, or a protocol other than HTTP. In terms of device counts, we extracted HTTP data for 35 out of 55 devices[2] which is 63% of devices. Ren et al. also attempted to measure encryption adoption with slightly different results: no device had more than 75% unencrypted traffic [14]. The key difference in our results is we are focusing solely on extractable HTTP objects, whereas Ren et al. attempted to guess if certain UDP traffic was encrypted or not by measuring byte entropy, which only concludes if certain packets are likely encrypted [14].

In the following sections, we describe our results for identifying software update keywords, characterizing software updates based on device interaction, and our TLS results. These results are summarized as follows:

- **III-A** Out of the 35 devices that did not encrypt all traffic, 9 (25%) checked for available software updates in a transparent way.
- **III-B** Update-related traffic is heavily correlated to device power-cycle events, but a small percentage of devices checked periodically (some as often as once per hour).
- **III-C** Update endpoints (where software update files are hosted) for devices in our set exist primarily in 3rd party cloud service platforms, or on content delivery networks (CDNs), which makes DNS-based identification difficult.
- **III-D** TLS is pervasively used in IoT communications, possibly including update-related traffic. Devices that only use TLS for communication could be vulnerable to key compromise if there are no additional protections in place [16].

A. Update Keywords Results

We successfully extracted several HTTP interactions between IoT devices and web services related to software

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[3] Ren et al.’s original study had 81 devices with 26 common devices between regions, thus 55 unique devices.
updates. Our most prominent keyword is `update` with 1,351 occurrences among extracted HTTP objects, `firmware` with 639 occurrences, `software` with 89, and `download` appearing only 8 times.

The specific devices and the corresponding keywords they matched are shown in Figure 2. The heatmap shows the number of occurrences of the keywords in the rows for the devices in the columns, where a darker blue indicates more occurrences. We observed that certain devices exchange update-related information much more often than others, such as the Wemo plug and Phillips hub. The Wemo plug device had the most occurrences of keywords, which means the Wemo plug was polling the most frequently for updates; however, this does not imply there may be a software update in progress. For example, the Wemo Plug exchanges firmware information in nearly every request which contributes to the high amount of keyword detection; however, we did not find any proof that the Wemo plug performed an update during the capture period. There is an update web service offered by the WeMo plug, which we discuss in detail in Section IV-C. By contrast, the Apple TV only has a single occurrence of exchanging update-related keywords, and we found that the Apple TV downloaded system firmware over HTTP, which would imply that the Apple TV installed the aforementioned firmware, which we discuss in Section IV-B. This contrast shows that our heuristic does not guarantee a device is performing an update, but it is enough to detect traffic that might be update related.

Aside from being able to detect firmware downloads in real-time, an unexpected result from our heuristic was it picks up current update and firmware versions in 7 of the 9 devices. This is because these 7 devices report their firmware version as a HTTP request, or as part of a service discovery response. This is valuable information for both defensive and offensive applications. A potential application for this in defensive security is an active firewall appliance can scan IoT devices and fetch firmware versions from them, if a CVE is released for that particular firmware the firewall can automatically quarantine the affected devices. This assumes that the firmware version is accurately reported, which may not be the case for malicious devices. For offensive security applications, an attacker could perform reconnaissance by identifying vulnerable firmware versions of devices that actively advertise these versions.

B. Update Events Results

Our results for event-related update activity are compiled in Figure 3. The heatmap shows the number of update keyword occurrences in the rows for the interaction event in the columns, where a lighter color indicates more occurrences. Due to the granularity of the experiments in Ren et al.’s study, Android-related events (e.g., taking a photo, controlling device from an app, etc) and Alexa interactions (e.g., invoking Alexa, changing color, etc.) were merged into two respective categories. Aside from these events, all 9 of the IoT devices in Figure 2 exchange update related keywords on power events, and even moreso on idle events. Examples of update traffic include devices reporting their `firmware` version to a update service, then receiving an `update` response in return. We noticed a large amount of update-related traffic on idle events being issued between devices. This seemed out of the ordinary, as independent IoT devices should not be issuing or exchanging update commands to one another when idle – these communications should only occur between the device and the vendor’s update platform. We investigated these inter-device occurrences and found that as part of service discovery protocols (e.g., SSDP, UPnP, etc) the devices exchange firmware information, and certain devices even advertise endpoints for invoking update behavior manually, see Section IV-C for more information regarding these endpoints.

Other than power and idle events, Alexa interaction events contribute the most to our heatmap. Alexa devices did not exchange detectable update-related traffic; however, the Philips hub exchanged update-related information when being controlled by Alexa. Additionally, the Roku TV, Samsung TV, and Wemo plug exchanged update-related data when controlled remotely by Android interaction events. We believe there is no correlation between these interactions and update traffic: these devices exchange the same information when not being controlled by Alexa or Android.

C. Observed Design Patterns

We analyzed the extracted HTTP interactions flagged as being update-related to attempt characterizing common designs or behaviors between device vendors. Unfortunately, no common architecture or strategy was used between the 9 devices we identified. The heterogeneity of the designs and schemas involved provide great motivation for standardized update system designs, such as RFC 9019 and RFC 9124 [18], [19]. While there is no common schema among different device vendors, we noticed some common patterns among certain device manufacturers.
### No Security

The D-Link movement sensor, Amcrest camera, and WeMo fetch firmware update metadata from a web service that returns a complete URL for downloading the firmware image. What is concerning about this is there is no tamper-protection in place for any of these devices. To make matters worse, both of these devices fetch data from public S3 bucket endpoints over HTTP\(^3\). We examined firmware images served through these endpoints and found no forms of tamper-protection such as checksums, digital signatures, etc., built into the firmware.

### Out-of-band Security

While insecure device update schemes are certainly concerning, there are update techniques that allow authentication and integrity verification even over HTTP. The Apple TV exchanged all update-related traffic over HTTP, including web service interactions for downloading the firmware and related metadata. What sets the Apple TV apart is it exchanges digital signatures and certificates over HTTP to validate the responses. Apple’s design provides a happy medium of ensuring the integrity (assuming the signatures and certificates are validated) of the update through cryptographic means while giving us insight into specific details that can be leveraged by a network appliance, such as specific firmware and information assuming that the network appliance can parse the XML schema Apple uses.

### Full TLS

The remaining devices encrypted all cloud-destined communications using TLS. It is reasonable to expect that, if implemented, a software update mechanism would also use one of the available TLS channels. While communication encryption is advantageous for security and privacy, we believe transparency in software update implementations (perhaps implemented with an out-of-band scheme as described above) can be beneficial in many scenarios as described in Section VI.

3AWS S3 buckets do not support HTTPS unless the S3 bucket is proxied through Cloud Gateway, which would require an entirely different URL than the default S3 URL [20].

### Cipher Suite Results

We see a larger amount of devices with extractable TLS cipher suites, which is expected as many IoT devices use TLS as a means of interacting with the web services they depend on. In Figure 4 we observe there were a total of 16 insecure cipher suites used between IoT devices. All 16 cipher suites have significant vulnerabilities that when combined with a downgrade attack could allow an attacker to perform a MITM attack; however, among the 24 devices that advertise insecure cipher suites, we estimate 4 of them would be vulnerable to a downgrade attack. This is because the secure and recommended cipher suites would take precedence over the weak and insecure cipher suites, and the cipher suites contained in secure and recommended classes contain measures to prevent downgrade attacks.

We have only discussed the TLS cipher suites in the context of IoT devices. To see these results in perspective to other applications that require secure communication, we searched for a dataset of TLS cipher suite support in web browsers. While we did not find a comprehensive dataset that summarized recent browsers, we did find a service that provides us with what our browser supports [21]. Using this service, we found modern browsers (Firefox 94, Chromium 96) support far fewer cipher suites with none of them being insecure – although roughly half of the cipher suites supported were deemed to be “weak”. This can be used to offset the large amount of IoT devices that also offer large amounts of “weak” cipher suites, as these may only be present for backward compatibility. In this context, the weak cipher suites used by IoT devices do not strictly increase the attack surface as...
compared to modern web browsers; however, insecure cipher suites when not using TLS 1.3 do increase the attack surface.

E. Limitations of our Analysis

In total, we found 11 devices that did not have extractable HTTP data or extractable TLS data. For these devices, we inspected packet captures and found a large portion that stream data over UDP, which is a consistent finding with the Ren et al. study [14]. The data was not meaningful and was either encoded using some vendor-specific encoding or a stream of application-specific data (e.g., a video stream) that can not easily be deciphered. While these edge cases are technically possible to extract, it is challenging to do so at scale given the wide breadth of devices and a large amount of packet captures.

A potential workaround for TLS-encrypted edge cases is an alternative heuristic. For example, instead of flagging traffic as update-related through detected plaintext keywords, another approach that is agnostic to the protocol in use is to look at response sizes. If a device exchanges a large amount of data in a short burst, assuming that this burst of traffic is abnormal for the device based on regular usage, we can assume that the traffic is update-related. This approach is not ideal, as there is no way to verify that it correctly identifies update-related traffic – it only identifies large bursts of abnormal traffic. Furthermore, even if we could somehow deduce that the traffic is a device update, there is no meaningful extractable information from an encrypted payload such as firmware version, which is crucial to our motivation for detecting IoT software updates in real-time.

Another potential heuristic is to analyze traffic patterns temporally. O’Connor et al. developed a simple yet effective methodology for classifying various IoT subsystems without any form of decrypting or inspecting packet payloads, instead opting to analyze traffic frequency and size over a long period of time [22]. This temporal approach proved effective for identifying IoT device telemetry, and in an active measurements context, O’Connor et al. were able to derive various attacks based on a temporal analysis of IoT device traffic. While this approach is novel, it is not ideal for a large-scale passive analysis of traffic.

In regards to our keyword analysis, our heuristic which associates terms such as “firmware” and “software” to update-related events can produce false positives. For example, some devices report a current firmware version to a web service contained as an HTTP payload. While this is not an update request, our pipeline will flag it as such and require manual removal. Future work will investigate the use of additional heuristics to improve the accuracy of identification of updates without requiring manual verification. Adding checks for outbound traffic, inbound traffic, and schema verification would greatly assist in avoiding false positives.

Our analysis only scratched the surface of characterizing IoT update systems as we only covered 15% of traffic (total of 33 devices) that was extractable. Of the 33 devices, we characterized update system design patterns and interactions for 9. The observed behaviors in this small set may not hold true for all IoT devices.

IV. Case Studies

In this section, we discuss our findings by analyzing specific update practices and firmware files that we extracted through our methodology. First, we look at the firmware update interactions from the D-Link Camera, which we use to illustrate several harmful practices. We then contrast this approach with the firmware update interactions we observed against the Apple TV, which combines several distinct tamper-resistant mechanisms with update transparency. Finally, we conclude our case studies with a vulnerable WeMo update service, that allows for unsigned code to be uploaded from an arbitrary source.

A. D-Link Camera Firmware

The D-Link camera exchanged firmware update information through HTTP, which allowed us to extract the firmware update endpoint and also download a firmware image. The firmware update endpoint is simply a web service that accepts a device model and returns an XML response containing firmware metadata information along with a URL to the latest firmware download. We were able to download the latest firmware image as it is being hosted by a static file store which does not require any prior authorization. The firmware update endpoint does not return any form of checksum or signature to validate that the firmware image was not tampered with. Using the binwalk utility [23] we successfully analyzed the firmware image and found the following:

1) A µImage header, indicating that the OS is Linux built for a MIPS CPU. This is likely a boot loader for the next item
2) LZMA compressed data, likely the kernel image to be executed by (1)
3) A SquashFS filesystem, which is likely the root filesystem

Using binwalk, we extracted each of these items and performed an analysis on them. The image header indicates that the OS is a Linux Kernel from roughly 2014 (6 years old at the time of writing). Looking at the kernel image (2) we extracted the image version, which is Kernel version 2.6.31 released in 2009 [24]. While we did not find any notable CVEs for this particular version (2.6.31) of the kernel [25], we did find CVEs for the parent minor version (2.6) which allow for arbitrary code execution through multiple buffer overflows [26]. In any case, it is debatable whether these CVEs apply to this build of the kernel as it was released in 2014, it is likely that D-Link camera maintainers kept the kernel patched as vulnerabilities were found. It is likely after 2014 the device reached the end of its “service life”, thus D-Link stopped updating it. This is unfortunately a fairly common occurrence amongst IoT devices [27].

Theoretically speaking, the D-Link camera is vulnerable to MITM attacks as shown in Figure 5; (1) the communication with the update service is unauthenticated and does not have
integrity protection; and (2) the communication with the image repository is unauthenticated and does not have integrity protection. For (1), an on-path attacker can intercept traffic between the IoT device and the vendor’s cloud. In this case, the message responded by the vendor’s cloud contains the full URL to the firmware image being hosted on an S3 bucket (also on HTTP). A second MITM attack (2) could occur if an attacker intercepts HTTP traffic between the IoT device and the S3 bucket. With this in mind, it is highly likely an attacker can leverage (1) to give the D-Link camera the URL of a different S3 bucket hosted on the “malicious cloud instance” which would then serve the modified firmware. An attacker could build and distribute modified firmware trivially, as the original firmware file is not signed, nor does it have any other protection mechanisms in place for the file.

B. Apple TV Firmware

In contrast to the D-Link camera, the Apple TV combines transparency in updates with security. The complete update flow of the Apple TV is shown in Figure 6. Similar to the D-Link Camera update metadata is exchanged over HTTP; however, there are several additional measures to harden communications against attackers.

The Apple TV first connects to an updates repository over HTTP which returns an XML response containing available updates for that particular device, which is similar behavior to the D-Link camera. Although the connection for update metadata happens over HTTP, we found the API response contains a certificate and signature field, which is used to validate the response [28]. Parsing the certificate using the openssl utility [29] we found the following: the certificate was issued by the “Apple iPhone Certification Authority”, with a common name of “Asset Manifest Signing”. This suggests that the certificate is purpose-made specifically for signing these update manifest responses. Additionally, the signature included in the response can be used to validate the integrity of the response. Unfortunately, the certificate expired in 2018, and the API response indicated updates from as recently as 2020.

When it comes to downloading the update, this communication also takes place over HTTP using a similar design to the D-Link camera. The Apple TV firmware repository contains a field that points to a content delivery network (CDN) that hosts the firmware image. One significant difference is there is a field that contains a measurement related to the update. Unfortunately, we could not identify how this measurement is derived; however, we are assuming that if the update file is downloaded and does not match the measurement, the update is invalid. This is consistent with Apple’s platform security documentation which details the measures taken to secure device updates [28].

Using the Apple Repository response, we reconstructed the firmware download URL and acquired the firmware image for the AppleTV by downloading it over HTTP. The firmware image is distributed as a ZIP file, which when unpacked reveals a file tree for distributing software updates. Without having the source code to the software responsible for performing updates on Apple devices, we are unable to determine how exactly the
update is performed; however, combining an analysis of the directory tree with prior reverse engineering efforts [30] along with Apple’s platform security documentation [28] gives us a relatively good understanding of how the update is performed.

After the AppleTV has validated the update payload, assuming the device-side verification of the update has no errors, the AppleTV must then perform remote attestation with the Apple Updates Authorization server to perform the update. According to our packet captures, this communication takes place over HTTPS, so we do not have concrete knowledge of what exactly is being sent. According to Apple’s platform security documentation, cryptographic measurements of the bootloader (iBoot), kernel, operating system image, and exclusive chip ID (ECID) are sent to the update authorization server [28]. The server validates all the measurements sent by the device, and if they are valid, the update server returns the signature for the software, an anti-replay value, and the device’s ECID [28].

C. WeMo Update Service

The Belkin WeMo plug largely communicates using Simple Service Discovery Protocol (SSDP), which is a protocol used to advertise services and consume them in a standardized way [31]. SSDP uses HTTP as its underlying communication protocol, therefore all SSDP activity was captured by our passive analysis. We observed among the various device management services listed is one for firmware updates. The firmware update service advertised two actions: “GetFirmwareVersion” and “UpdateFirmware”. The “GetFirmwareVersion” endpoint takes no arguments and returns a firmware version string. The “UpdateFirmware” endpoint takes several arguments including “NewFirmwareVersion”, “ReleaseDate”, “URL”, “Signature”, “DownloadStartTime”, and “WithUnsignedImage”. Particular arguments of interest to an attacker would be the “URL” and “WithUnsignedImage” fields, which indicate that the endpoint accepts arbitrary URLs along with being able to accept unsigned firmware images.

We, unfortunately, cannot test the viability of uploading arbitrary firmware to the WeMo update service as we are only passively analyzing packet captures; however, our research into the aforementioned update service shows previous efforts have proven to be successful in exploiting the WeMo device [32]. An attacker could have a local (or remote) firmware repository, and upload a modified firmware image to the WeMo device. The WeMo device would then attempt to download the modified firmware image and install it, similar to what we show in Figure 5. The only difference between the exploit used in the D-Link camera and the WeMo plug is the attacker has the ability to trigger device update behavior by interacting with an endpoint, whereas the D-Link camera has no such functionality.

V. RELATED WORK

As we have demonstrated, the methods employed by IoT vendors for software updates show a large amount of heterogeneity. Due to the previously discussed challenges, the “walled garden” of IoT devices has a lot of potential opportunities to explore and innovate. Related work in this space consists of several proposed designs for IoT update systems relating to firmware updates and library management. Zandberg et al. present a prototype for a firmware update system on IoT devices by leveraging various open-source libraries and standards [5]. An aspect of Zandberg et al.’s approach is how they leverage SUIT, a new IETF standard that provides encrypted firmware update files with encryption keys provided by hybrid public-key encryption [33]. The SUIT standard appears as if it may not work on resource-constrained IoT devices, but Zandberg et al. have their reference implementation built on IoT devices with less than 32 KB of RAM and 128 KB of storage [5].

A unique approach to IoT firmware update systems was designed by Boudguiga et al. in 2017, which is a conceptual design for better accountability and availability for IoT firmware updates by leveraging blockchain technology [10]. Later in 2019, He et al. presented a similar implementation that secures IoT firmware updates using blockchain smart contracts [11]. While using a blockchain is a novel approach, the large-scale feasibility of these designs is questionable due to the various scalability issues blockchain is facing [34].

Zhang et al. present a novel design that offloads expensive update operations onto a third party, a “hub” of sorts that acts as an update management system for heterogeneous IoT devices [7]. The core methodology behind the design is the computationally expensive aspects of package management can be handled by the hub, which can securely receive update packages from some sort of central IoT update repository. The hubs would then handle the “last mile” of delivery to the end IoT devices.

On the topic of TLS usage in IoT devices, Alrawi et al. provide an excellent SoK of the overall security of home IoT devices by systematizing the current state (as of 2019) of IoT vulnerability literature and then evaluating 45 devices, a subset of the security evaluation involves looking at various encryption qualities that would make the device vulnerable [35]. More recently in 2021, Paracha et al. performed a deep dive of IoT TLS usage patterns which ultimately found 11/32 IoT devices are vulnerable to interception attacks [36].

Related to centralized vendored solutions is the managed IoT platforms that are offered by various cloud providers. Google Cloud Platform offers Google Cloud IoT [2], Amazon Web Services offers AWS IoT [1], and Microsoft Azure offers Azure IoT [3]. All of these are turn-key platforms that give vendors a pre-made solution for IoT devices. These platforms are locked down compared to a from-scratch implementation; however, they offer IoT vendors a full hardware and software solution for new IoT devices. Many are skeptical of these managed IoT solutions, Yu et al. performed a survey of these various IoT solutions to find various issues revolving around vendor-specific designs, such as different vendor designs having different vulnerabilities [4]. In the context of Yu et al.’s work, there is a need for an open standard generic IoT platforms which would avoid vendor-specific vulnerabilities.
Our analysis of preliminary IoT update-related data has highlighted concerning trends among vendors and devices; there is a lack of consistency in implementations and standards, minimal transparency to users, and sometimes complete disregard for software update (and sometimes general security) best practices. Moreover, the research literature on software updates has not evolved quickly enough to consider the unique challenges of IoT devices (i.e., deployment scale, lifespan, unique UX, etc.). We conclude this paper with a research agenda as a call-to-action to improve the state of IoT software update security. The list below is not intended to be exhaustive but rather aims to highlight research gaps and elicit discussion among researchers and practitioners.

**Standards and Toolkit Availability.** Initial work on standardization of software updates for IoT is underway by the IETF as the SUIT framework in RFC 9019 [18]. This document considers update dissemination and data transmission authentication and integrity, device architecture issues, and trust requirements. RFC 9019 serves as a technical blueprint for vendors to implement an update infrastructure, but as described in Section [III-C], we see no widespread adoption of this or any other standard. We expect the availability of software toolkits or libraries[4] that implement the standard to facilitate adoption by vendors, but more work is needed in creating and maintaining these libraries.

**Transparency of Updates.** We identified pervasive use of TLS, which precludes the identification of update-related traffic without additional data analysis. In many cases, users cannot tell whether their devices are running up-to-date software, the last time they were updated, or whether the vendor will continue supporting the device via updates. This lack of transparency toward users over time will cause networks to be composed of up-to-date desktop and servers, and blatantly out-of-date/vulnerable IoT devices. The security implications of this mean that all networks with IoT devices will be effectively untrusted. Thus, we urge researchers, vendors, and regulators to improve the detection, notification, and requirements of updates for devices moving forward.

**Network-level Detection Improvements.** If the points above do not materialize, networks will require some way to better detect/classify update-related traffic (in order to provide transparency, for example). The plaintext heuristics used in this paper will be insufficient to accurately classify encrypted traffic at scale, so we expect novel approaches to make improvements in this space. Machine learning and deep learning [37] could work in this context, where the data in question is not inherently adversarial.

**Post-support Considerations.** It is unreasonable to expect vendors to support devices indefinitely. An open research question then is what should happen with devices that are no longer supported, and, more specifically, what happens if a vulnerability is found after the support period has concluded. Billions of devices becoming unsupported will likely result in untenable amounts of e-waste [38], so it is imperative to design update architectures that consider IoT vendors going out of business and ending support. Researchers and practitioners should focus on designing viable transition paths to community-supported software and such paths should be required for future devices.

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