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Internet of Things (IoT) Security: State of the Art and Challenges

Abstract

The Internet of Things (IoT) concept refers to the usage of standard Internet protocols to allow for human-to-thing and thing-to-thing communication. The security needs for IoT systems are well recognized, and many standardization steps to provide security have been taken -- for example, the specification of the Constrained Application Protocol (CoAP) secured with Datagram Transport Layer Security (DTLS). However, security challenges still exist, not only because there are some use cases that lack a suitable solution, but also because many IoT devices and systems have been designed and deployed with very limited security capabilities. In this document, we first discuss the various stages in the lifecycle of a thing. Next, we document the security threats to a thing and the challenges that one might face to protect against these threats. Lastly, we discuss the next steps needed to facilitate the deployment of secure IoT systems. This document can be used by implementers and authors of IoT specifications as a reference for details about security considerations while documenting their specific security challenges, threat models, and mitigations.

This document is a product of the IRTF Thing-to-Thing Research Group (T2TRG).

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1. Introduction

The Internet of Things (IoT) denotes the interconnection of highly heterogeneous networked entities and networks that follow a number of different communication patterns, such as: human-to-human (H2H), human-to-thing (H2T), thing-to-thing (T2T), or thing-to-things (T2Ts). The term "IoT" was first coined in 1999 by the Auto-ID center [AUTO-ID], which had envisioned a world where every physical object has a radio-frequency identification (RFID) tag with a globally unique identifier. This would not only allow tracking of objects in real time but also allow querying of data about them over the Internet. However, since then, the meaning of the Internet of Things has expanded and now encompasses a wide variety of technologies, objects, and protocols. It is not surprising that the IoT has received significant attention from the research community to (re)design, apply, and use standard Internet technology and protocols for the IoT.

The things that are part of the Internet of Things are computing devices that understand and react to the environment they reside in. These things are also often referred to as smart objects or smart devices. The introduction of IPv6 [RFC6568] and CoAP [RFC7252] as fundamental building blocks for IoT applications allows connecting IoT hosts to the Internet. This brings several advantages, including: (i) a homogeneous protocol ecosystem that allows simple integration with other Internet hosts; (ii) simplified development for devices that significantly vary in their capabilities; (iii) a unified interface for applications, removing the need for application-level proxies. These building blocks greatly simplify the deployment of the envisioned scenarios, which range from building automation to production environments and personal area networks.

This document presents an overview of important security aspects for the Internet of Things. We begin by discussing the lifecycle of a thing in Section 2. In Section 3, we discuss security threats for the IoT and methodologies for managing these threats when designing a secure system. Section 4 reviews existing IP-based (security) protocols for the IoT and briefly summarizes existing guidelines and regulations. Section 5 identifies remaining challenges for a secure IoT and discusses potential solutions. Section 6 includes final remarks and conclusions. This document can be used by IoT standards specifications as a reference for details about security considerations that apply to the specified system or protocol.

The first draft version of this document was submitted in March 2011. Initial draft versions of this document were presented and discussed during the meetings of the Constrained RESTful Environments (CORE) Working Group at IETF 80 and later. Discussions on security

lifecycle at IETF 92 (March 2015) evolved into more general security considerations. Thus, the draft was selected to address the T2TRG work item on the security considerations and challenges for the Internet of Things. Further updates of the draft were presented and discussed during the T2TRG meetings at IETF 96 (July 2016) and IETF 97 (November 2016) and at the joint interim meeting in Amsterdam (March 2017). This document has been reviewed by, commented on, and discussed extensively for a period of nearly six years by a vast majority of the T2TRG and related group members, the number of which certainly exceeds 100 individuals. It is the consensus of T2TRG that the security considerations described in this document should be published in the IRTF Stream of the RFC series. This document does not constitute a standard.

2. The Thing Lifecycle

The lifecycle of a thing refers to the operational phases of a thing in the context of a given application or use case. Figure 1 shows the generic phases of the lifecycle of a thing. This generic lifecycle is applicable to very different IoT applications and scenarios. For instance, [RFC7744] provides an overview of relevant IoT use cases.

In this document, we consider a Building Automation and Control (BAC) system to illustrate the lifecycle and the meaning of these different phases. A BAC system consists of a network of interconnected nodes that performs various functions in the domains of Heating, Ventilating, and Air Conditioning (HVAC), lighting, safety, etc. The nodes vary in functionality, and a large majority of them represent resource-constrained devices such as sensors and luminaries. Some devices may be battery operated or may rely on energy harvesting. This requires us to also consider devices that sleep during their operation to save energy. In our BAC scenario, the life of a thing starts when it is manufactured. Due to the different application areas (i.e., HVAC, lighting, or safety), nodes/things are tailored to a specific task. It is therefore unlikely that one single manufacturer will create all nodes in a building. Hence, interoperability as well as trust bootstrapping between nodes of different vendors is important.

The thing is later installed and commissioned within a network by an installer during the bootstrapping phase. Specifically, the device identity and the secret keys used during normal operation may be provided to the device during this phase. Different subcontractors may install different IoT devices for different purposes. Furthermore, the installation and bootstrapping procedures may not be a discrete event and may stretch over an extended period. After being bootstrapped, the device and the system of things are in

operational mode and execute the functions of the BAC system. During this operational phase, the device is under the control of the system owner and used by multiple system users. For devices with lifetimes spanning several years, occasional maintenance cycles may be required. During each maintenance phase, the software on the device can be upgraded, or applications running on the device can be reconfigured. The maintenance tasks can be performed either locally or from a backend system. Depending on the operational changes to the device, it may be required to rebootstrap at the end of a maintenance cycle. The device continues to loop through the operational phase and the eventual maintenance phases until the device is decommissioned at the end of its lifecycle. However, the end-of-life of a device does not necessarily mean that it is defective; rather, it denotes a need to replace and upgrade the network to next-generation devices for additional functionality. Therefore, the device can be removed and recommissioned to be used in a different system under a different owner, thereby starting the lifecycle all over again.

We note that the presented lifecycle represents to some extent a simplified model. For instance, it is possible to argue that the lifecycle does not start when a tangible device is manufactured but rather when the oldest bit of code that ends up in the device -- maybe from an open-source project or the operating system -- was written. Similarly, the lifecycle could also include an on-the-shelf phase where the device is in the supply chain before an owner/user purchases and installs it. Another phase could involve the device being rebadged by some vendor who is not the original manufacturer. Such phases can significantly complicate other phases such as maintenance and bootstrapping. Finally, other potential end states can be, e.g., a vendor that no longer supports a device type because it is at the end of its life or a situation in which a device is simply forgotten but remains functional.

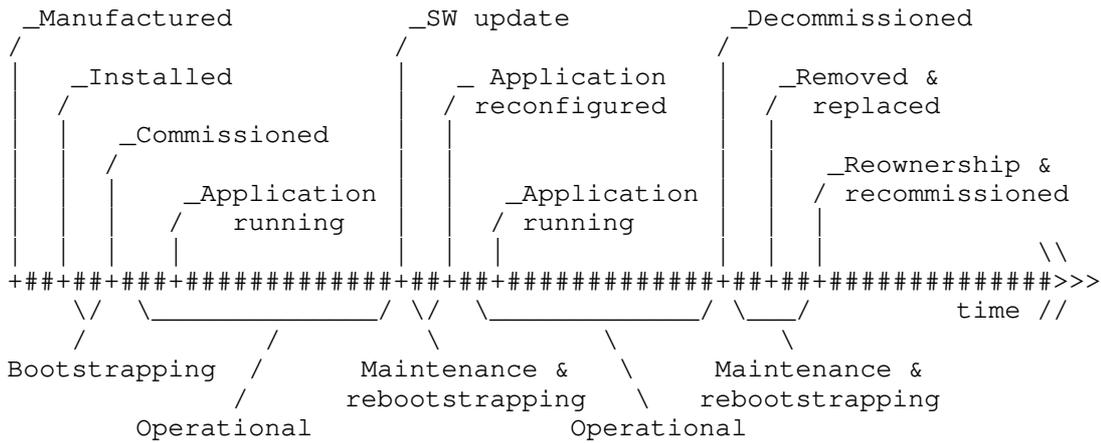


Figure 1: The Lifecycle of a Thing in the Internet of Things

Security is a key requirement in any communication system. However, security is an even more critical requirement in real-world IoT deployments for several reasons. First, compromised IoT systems can not only endanger the privacy and security of a user but can also cause physical harm. This is because IoT systems often comprise sensors, actuators, and other connected devices in the physical environment of the user that could adversely affect the user if they are compromised. Second, a vulnerable IoT system means that an attacker can alter the functionality of a device from a given manufacturer. This not only affects the manufacturer’s brand image but can also leak information that is very valuable for the manufacturer (such as proprietary algorithms). Third, the impact of attacking an IoT system goes beyond a specific device or an isolated system, since compromised IoT systems can be misused at scale. For example, they may be used to perform a Distributed Denial of Service (DDoS) attack that limits the availability of other networks and services. The fact that many IoT systems rely on standard IP protocols allows for easier system integration, but this also makes attacks on standard IP protocols widely applicable in other environments. This results in new requirements regarding the implementation of security.

The term "security" subsumes a wide range of primitives, protocols, and procedures. For instance, it includes services such as confidentiality, authentication, integrity, authorization, source authentication, and availability. It often also includes augmented services such as duplicate detection and detection of stale packets (timeliness). These security services can be implemented through a combination of cryptographic mechanisms such as block ciphers, hash functions, and signature algorithms, as well as noncryptographic

mechanisms that implement authorization and other aspects of security-policy enforcement. For ensuring security in IoT networks, one should not only focus on the required security services but also pay special attention to how the services are realized in the overall system.

3. Security Threats and Managing Risk

Security threats in related IP protocols have been analyzed in multiple documents, including Hypertext Transfer Protocol (HTTP) over Transport Layer Security (TLS) (HTTPS) [RFC2818], Constrained Application Protocol (CoAP) [RFC7252], IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) [RFC4919], Access Node Control Protocol (ANCP) [RFC5713], Domain Name System (DNS) [RFC3833], IPv6 Neighbor Discovery (ND) [RFC3756], and Protocol for Carrying Authentication and Network Access (PANA) [RFC4016]. In this section, we specifically discuss the threats that could compromise an individual thing or the network as a whole. Some of these threats might go beyond the scope of Internet protocols, but we gather them here for the sake of completeness. The threats in the following list are not in any particular order, and some threats might be more critical than others, depending on the deployment scenario under consideration:

1. **Vulnerable software/code:** Things in the Internet of Things rely on software that might contain severe bugs and/or bad design choices. This makes the things vulnerable to many different types of attacks, depending on the criticality of the bugs, e.g., buffer overflows or lack of authentication. This can be considered one of the most important security threats. The large-scale Distributed Denial of Service (DDoS) attack, popularly known as the Mirai botnet [Mirai], was caused by things that had well-known or easy-to-guess passwords for configuration.
2. **Privacy threat:** The tracking of a thing's location and usage may pose a privacy risk to people around it. For instance, an attacker can infer privacy-sensitive information from the data gathered and communicated by individual things. Such information may subsequently be sold to interested parties for marketing purposes and targeted advertising. In extreme cases, such information might be used to track dissidents in oppressive regimes. Unlawful surveillance and interception of traffic to/from a thing by intelligence agencies is also a privacy threat.
3. **Cloning of things:** During the manufacturing process of a thing, an untrusted factory can easily clone the physical characteristics, firmware/software, or security configuration of

the thing. Deployed things might also be compromised and their software reverse engineered, allowing for cloning or software modifications. Such a cloned thing may be sold at a cheaper price in the market and yet can function normally as a genuine thing. For example, two cloned devices can still be associated and work with each other. In the worst-case scenario, a cloned device can be used to control a genuine device or perform an attack. One should note here that an untrusted factory may also change functionality of the cloned thing, resulting in degraded functionality with respect to the genuine thing (thereby inflicting potential damage to the reputation of the original thing manufacturer). Moreover, additional functionality can be introduced in the cloned thing. An example of such functionality is a backdoor.

4. Malicious substitution of things: During the installation of a thing, a genuine thing may be replaced by a similar variant (of lower quality) without being detected. The main motivation may be cost savings, where the installation of lower-quality things (for example, noncertified products) may significantly reduce the installation and operational costs. The installers can subsequently resell the genuine things to gain further financial benefits. Another motivation may be to inflict damage to the reputation of a competitor's offerings.
5. Eavesdropping attack: During the commissioning of a thing into a network, it may be susceptible to eavesdropping, especially if operational keying materials, security parameters, or configuration settings are exchanged in the clear using a wireless medium or if used cryptographic algorithms are not suitable for the envisioned lifetime of the device and the system. After obtaining the keying material, the attacker might be able to recover the secret keys established between the communicating entities, thereby compromising the authenticity and confidentiality of the communication channel, as well as the authenticity of commands and other traffic exchanged over this communication channel. When the network is in operation, T2T communication can be eavesdropped if the communication channel is not sufficiently protected or if a session key is compromised due to protocol weaknesses. An adversary may also be able to eavesdrop if keys are not renewed or updated appropriately. Lastly, messages can also be recorded and decrypted offline at a later point of time. The VENONA project [venona-project] is one such example where messages were recorded for offline decryption.

6. **Man-in-the-middle attack:** Both the commissioning and operational phases may be vulnerable to man-in-the-middle attacks. For example, when keying material between communicating entities is exchanged in the clear, the security of the key establishment protocol depends on the tacit assumption that no third party can eavesdrop during the execution of this protocol. Additionally, device authentication or device authorization may be nontrivial or need the support of a human decision process, since things usually do not have a priori knowledge about each other and cannot always differentiate friends and foes via completely automated mechanisms.
7. **Firmware attacks:** When a thing is in operation or maintenance phase, its firmware or software may be updated to allow for new functionality or new features. An attacker may be able to exploit such a firmware upgrade by maliciously replacing the thing's firmware, thereby influencing its operational behavior. For example, an attacker could add a piece of malicious code to the firmware that will cause it to periodically report the energy usage of the thing to a data repository for analysis. The attacker can then use this information to determine when a home or enterprise (where the thing is installed) is unoccupied and break in. Similarly, devices whose software has not been properly maintained and updated might contain vulnerabilities that might be exploited by attackers to replace the firmware on the device.
8. **Extraction of private information:** IoT devices (such as sensors, actuators, etc.) are often physically unprotected in their ambient environment, and they could easily be captured by an attacker. An attacker with physical access may then attempt to extract private information such as keys (for example, a group key or the device's private key), data from sensors (for example, healthcare status of a user), configuration parameters (for example, the Wi-Fi key), or proprietary algorithms (for example, the algorithm performing some data analytics task). Even when the data originating from a thing is encrypted, attackers can perform traffic analysis to deduce meaningful information, which might compromise the privacy of the thing's owner and/or user.

9. Routing attack: As highlighted in [Daniel], routing information in IoT networks can be spoofed, altered, or replayed, in order to create routing loops, attract/repel network traffic, extend/shorten source routes, etc. A nonexhaustive list of routing attacks includes:
 - a. Sinkhole attack (or blackhole attack), where an attacker declares himself to have a high-quality route/path to the base station, thus allowing him to do manipulate all packets passing through it.
 - b. Selective forwarding, where an attacker may selectively forward packets or simply drop a packet.
 - c. Wormhole attack, where an attacker may record packets at one location in the network and tunnel them to another location, thereby influencing perceived network behavior and potentially distorting statistics, thus greatly impacting the functionality of routing.
 - d. Sybil attack, whereby an attacker presents multiple identities to other things in the network. We refer to [Daniel] for further router attacks and a more detailed description.
10. Elevation of privilege: An attacker with low privileges can misuse additional flaws in the implemented authentication and authorization mechanisms of a thing to gain more privileged access to the thing and its data.
11. Denial of Service (DoS) attack: Often things have very limited memory and computation capabilities. Therefore, they are vulnerable to resource-exhaustion attack. Attackers can continuously send requests to specific things so as to deplete their resources. This is especially dangerous in the Internet of Things since an attacker might be located in the backend and target resource-constrained devices that are part of a constrained-node network [RFC7228]. A DoS attack can also be launched by physically jamming the communication channel. Network availability can also be disrupted by flooding the network with a large number of packets. On the other hand, things compromised by attackers can be used to disrupt the operation of other networks or systems by means of a Distributed DoS (DDoS) attack.

To deal with the above threats, it is required to find and apply suitable security mitigations. However, new threats and exploits appear on a daily basis, and products are deployed in different environments prone to different types of threats. Thus, ensuring a proper level of security in an IoT system at any point of time is challenging. To address this challenge, some of the following methodologies can be used:

1. A Business Impact Analysis (BIA) assesses the consequences of the loss of basic security attributes: confidentiality, integrity, and availability in an IoT system. These consequences might include the impact from lost data, reduced sales, increased expenses, regulatory fines, customer dissatisfaction, etc. Performing a business impact analysis allows a business to determine the relevance of having a proper security design.
2. A Risk Assessment (RA) analyzes security threats to an IoT system while considering their likelihood and impact. It also includes categorizing each of them with a risk level. Risks classified as moderate or high must be mitigated, i.e., the security architecture should be able to deal with those threats.
3. A Privacy Impact Assessment (PIA) aims at assessing the Personally Identifiable Information (PII) that is collected, processed, or used in an IoT system. By doing so, the goal is to fulfill applicable legal requirements and determine the risks and effects of manipulation and loss of PII.
4. Procedures for incident reporting and mitigation refer to the methodologies that allow becoming aware of any security issues that affect an IoT system. Furthermore, this includes steps towards the actual deployment of patches that mitigate the identified vulnerabilities.

BIA, RA, and PIA should generally be realized during the creation of a new IoT system or when deploying significant system/feature upgrades. In general, it is recommended to reassess them on a regular basis, taking into account new use cases and/or threats. The way a BIA, RA, or PIA is performed depends on the environment and the industry. More information can be found in NIST documents such as [NISTSP800-34r1], [NISTSP800-30r1], and [NISTSP800-122].

4. State of the Art

This section is organized as follows. Section 4.1 summarizes the state of the art on IP-based IoT systems, within both the IETF and other standardization bodies. Section 4.2 summarizes the state of the art on IP-based security protocols and their usage. Section 4.3 discusses guidelines and regulations for securing IoT as proposed by other bodies. Note that the references included in this section are a representative of the state of the art at the point of writing, and they are by no means exhaustive. The references are also at varying levels of maturity; thus, it is advisable to review their specific status.

4.1. IP-Based IoT Protocols and Standards

Nowadays, there exists a multitude of control protocols for IoT. For BAC systems, the ZigBee standard [ZB], BACNet [BACNET], and DALI [DALI] play key roles. Recent trends, however, focus on an all-IP approach for system control.

In this setting, a number of IETF working groups are designing new protocols for resource-constrained networks of smart things. The 6LoWPAN Working Group [WG-6LoWPAN], for example, has defined methods and protocols for the efficient transmission and adaptation of IPv6 packets over IEEE 802.15.4 networks [RFC4944].

The CoRE Working Group [WG-CoRE] has specified the Constrained Application Protocol (CoAP) [RFC7252]. CoAP is a RESTful protocol for constrained devices that is modeled after HTTP and typically runs over UDP to enable efficient application-level communication for things. ("RESTful" refers to the Representational State Transfer (REST) architecture.)

In many smart-object networks, the smart objects are dispersed and have intermittent reachability either because of network outages or because they sleep during their operational phase to save energy. In such scenarios, direct discovery of resources hosted on the constrained server might not be possible. To overcome this barrier, the CoRE Working Group is specifying the concept of a Resource Directory (RD) [RD]. The Resource Directory hosts descriptions of resources that are located on other nodes. These resource descriptions are specified as CoRE link format [RFC6690].

While CoAP defines a standard communication protocol, a format for representing sensor measurements and parameters over CoAP is required. "Sensor Measurement Lists (SenML)" [RFC8428] is a specification that defines media types for simple sensor measurements and parameters. It has a minimalistic design so that constrained

devices with limited computational capabilities can easily encode their measurements and, at the same time, servers can efficiently collect a large number of measurements.

In many IoT deployments, the resource-constrained smart objects are connected to the Internet via a gateway that is directly reachable. For example, an IEEE 802.11 Access Point (AP) typically connects the client devices to the Internet over just one wireless hop. However, some deployments of smart-object networks require routing between the smart objects themselves. The IETF has therefore defined the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [RFC6550]. RPL provides support for multipoint-to-point traffic from resource-constrained smart objects towards a more resourceful central control point, as well as point-to-multipoint traffic in the reverse direction. It also supports point-to-point traffic between the resource-constrained devices. A set of routing metrics and constraints for path calculation in RPL are also specified [RFC6551].

The IPv6 over Networks of Resource-constrained Nodes (6lo) Working Group of the IETF [WG-6lo] has specified how IPv6 packets can be transmitted over various link-layer protocols that are commonly employed for resource-constrained smart-object networks. There is also ongoing work to specify IPv6 connectivity for a Non-Broadcast Multi-Access (NBMA) mesh network that is formed by IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH) links [ARCH-6TiSCH]. Other link-layer protocols for which the IETF has specified or is currently specifying IPv6 support include Bluetooth [RFC7668], Digital Enhanced Cordless Telecommunications (DECT) Ultra Low Energy (ULE) air interface [RFC8105], and Near Field Communication (NFC) [IPv6-over-NFC].

Baker and Meyer [RFC6272] identify which IP protocols can be used in smart-grid environments. They give advice to smart-grid network designers on how they can decide on a profile of the Internet protocol suite for smart-grid networks.

The Low Power Wide-Area Network (LPWAN) Working Group [WG-LPWAN] is analyzing features, requirements, and solutions to adapt IP-based protocols to networks such as LoRa [LoRa], Sigfox [sigfox], NB-IoT [NB-IoT], etc. These networking technologies enable a smart thing to run for years on a single coin-cell by relying on a star network topology and using optimized radio modulation with frame sizes in the order of tens of bytes. Such networks bring new security challenges, since most existing security mechanism do not work well with such resource constraints.

JavaScript Object Notation (JSON) is a lightweight text-representation format for structured data [RFC8259]. It is often used for transmitting serialized structured data over the network. The IETF has defined specifications for encoding cryptographic keys, encrypted content, signed content, and claims to be transferred between two parties as JSON objects. They are referred to as JSON Web Keys (JWKs) [RFC7517], JSON Web Encryption (JWE) [RFC7516], JSON Web Signatures (JWSs) [RFC7515], and JSON Web Token (JWT) [RFC7519].

An alternative to JSON, Concise Binary Object Representation (CBOR) [RFC7049], is a concise binary data format that is used for serialization of structured data. It is designed for resource-constrained nodes, and therefore it aims to provide a fairly small message size with minimal implementation code and extensibility without the need for version negotiation. CBOR Object Signing and Encryption (COSE) [RFC8152] specifies how to encode cryptographic keys, message authentication codes, encrypted content, and signatures with CBOR.

The Light-Weight Implementation Guidance (LWIG) Working Group [WG-LWIG] is collecting experiences from implementers of IP stacks in constrained devices. The working group has already produced documents such as [RFC7815], which defines how a minimal Internet Key Exchange Version 2 (IKEv2) initiator can be implemented.

The Thing-2-Thing Research Group (T2TRG) [RG-T2TRG] is investigating the remaining research issues that need to be addressed to quickly turn the vision of IoT into a reality where resource-constrained nodes can communicate with each other and with other more capable nodes on the Internet.

Additionally, industry alliances and other standardization bodies are creating constrained IP protocol stacks based on the IETF work. Some important examples of this include:

1. Thread [Thread]: Specifies the Thread protocol that is intended for a variety of IoT devices. It is an IPv6-based network protocol that runs over IEEE 802.15.4.
2. Industrial Internet Consortium [IIoT]: The consortium defines reference architectures and security frameworks for development, adoption, and widespread use of Industrial Internet technologies based on existing IETF standards.
3. IPSO Alliance (which subsequently merged with OMA SpecWorks [OMASpecWorks]): The alliance specifies a common object model that enables application software on any device to interoperate with other conforming devices.

4. OneM2M [OneM2M]: The standards body defines technical and API specifications for IoT devices. It aims to create a service layer that can run on any IoT device hardware and software.
5. Open Connectivity Foundation (OCF) [OCF]: The foundation develops standards and certifications primarily for IoT devices that use Constrained Application Protocol (CoAP) as the application-layer protocol.
6. Fairhair Alliance [Fairhair]: Specifies an IoT middleware to enable a common IP network infrastructure between different application standards used in building automation and lighting systems such as BACnet, KNX, and ZigBee.
7. OMA Lwm2m [LWM2M]: OMA Lightweight M2M is a standard from the OMA SpecWorks for M2M and IoT device management. Lwm2m relies on CoAP as the application-layer protocol and uses a RESTful architecture for remote management of IoT devices.

4.2. Existing IP-Based Security Protocols and Solutions

There are three main security objectives for IoT networks:

1. protecting the IoT network from attackers
2. protecting IoT applications and thus the things and users
3. protecting the rest of the Internet and other things from attacks that use compromised things as an attack platform

In the context of the IP-based IoT deployments, consideration of existing Internet security protocols is important. There are a wide range of specialized as well as general-purpose security solutions for the Internet domain, such as IKEv2/IPsec [RFC7296], Transport Layer Security (TLS) [RFC8446], Datagram Transport Layer Security (DTLS) [RFC6347], Host Identity Protocol (HIP) [RFC7401], PANA [RFC5191], Kerberos [RFC4120], Simple Authentication and Security Layer (SASL) [RFC4422], and Extensible Authentication Protocol (EAP) [RFC3748].

TLS provides security for TCP and requires a reliable transport. DTLS secures and uses datagram-oriented protocols such as UDP. Both protocols are intentionally kept similar and share the same ideology and cipher suites. The CoAP base specification [RFC7252] provides a description of how DTLS can be used for securing CoAP. It proposes three different modes for using DTLS: the PreSharedKey mode, where nodes have pre-provisioned keys for initiating a DTLS session with another node, RawPublicKey mode, where nodes have asymmetric-key

pairs but no certificates to verify the ownership, and Certificate mode, where public keys are certified by a certification authority. An IoT implementation profile is defined for TLS version 1.2 and DTLS version 1.2 that offers communication security for resource-constrained nodes [RFC7925].

There is ongoing work to define an authorization and access-control framework for resource-constrained nodes. The Authentication and Authorization for Constrained Environments (ACE) Working Group [WG-ACE] is defining a solution to allow only authorized access to resources that are hosted on a smart-object server and identified by a URI. The current proposal [ACE-OAuth] is based on the OAuth 2.0 framework [RFC6749], and it comes with profiles intended for different communication scenarios, e.g., "Datagram Transport Layer Security (DTLS) Profile for Authentication and Authorization for Constrained Environments (ACE)" [ACE-DTLS].

Object Security for Constrained RESTful Environments (OSCORE) [OSCORE] is a proposal that protects CoAP messages by wrapping them in the COSE format [RFC8152]. Thus, OSCORE falls in the category of object security, and it can be applied wherever CoAP can be used. The advantage of OSCORE over DTLS is that it provides some more flexibility when dealing with end-to-end security. Section 5.1.3 discusses this further.

The Automated Certificate Management Environment (ACME) Working Group [WG-ACME] is specifying conventions for automated X.509 certificate management. This includes automatic validation of certificate issuance, certificate renewal, and certificate revocation. While the initial focus of the working group is on domain-name certificates (as used by web servers), other uses in some IoT deployments are possible.

The Internet Key Exchange (IKEv2)/IPsec -- as well as the less used Host Identity protocol (HIP) -- reside at or above the network layer in the OSI model. Both protocols are able to perform an authenticated key exchange and set up the IPsec for secure payload delivery. Currently, there are also ongoing efforts to create a HIP variant coined Diet HIP [HIP-DEX] that takes constrained networks and nodes into account at the authentication and key-exchange level.

Migault et al. [Diet-ESP] are working on a compressed version of IPsec so that it can easily be used by resource-constrained IoT devices. They rely on the Internet Key Exchange Protocol Version 2 (IKEv2) for negotiating the compression format.

The Extensible Authentication Protocol (EAP) [RFC3748] is an authentication framework supporting multiple authentication methods.

EAP runs directly over the data link layer and thus does not require the deployment of IP. It supports duplicate detection and retransmission but does not allow for packet fragmentation. PANA is a network-layer transport for EAP that enables network access authentication between clients and the network infrastructure. In EAP terms, PANA is a UDP-based EAP lower layer that runs between the EAP peer and the EAP authenticator.

4.3. IoT Security Guidelines

Attacks on and from IoT devices have become common in recent years -- for instance, large-scale DoS attacks on the Internet Infrastructure from compromised IoT devices. This fact has prompted many different standards bodies and consortia to provide guidelines for developers and the Internet community at large to build secure IoT devices and services. The following is a subset of the different guidelines and ongoing projects:

1. Global System for Mobile Communications Association (GSMA) IoT security guidelines [GSMAsecurity]: GSMA has published a set of security guidelines for the benefit of new IoT product and service providers. The guidelines are aimed at device manufacturers, service providers, developers, and network operators. An enterprise can complete an IoT Security Self-Assessment to demonstrate that its products and services are aligned with the security guidelines of the GSMA.
2. Broadband Internet Technical Advisory Group (BITAG) IoT Security and Privacy Recommendations [BITAG]: BITAG has published recommendations for ensuring the security and privacy of IoT device users. BITAG observes that many IoT devices are shipped from the factory with software that is already outdated and vulnerable. The report also states that many devices with vulnerabilities will not be fixed, either because the manufacturer does not provide updates or because the user does not apply them. The recommendations include that IoT devices should function without cloud and Internet connectivity and that all IoT devices should have methods for automatic secure software updates.
3. United Kingdom Department for Digital, Culture, Media and Sport (DCMS) [DCMS]: UK DCMS has released a report that includes a list of 13 steps for improving IoT security. These steps, for example, highlight the need for implementing a vulnerability disclosure policy and keeping software updated. The report is aimed at device manufacturers, IoT service providers, mobile application developers, and retailers.

4. Cloud Security Alliance (CSA) New Security Guidance for Early Adopters of the IoT [CSA]: CSA recommendations for early adopters of IoT encourage enterprises to implement security at different layers of the protocol stack. It also recommends implementation of an authentication/authorization framework for IoT deployments. A complete list of recommendations is available in the report [CSA].
5. United States Department of Homeland Security (DHS) [DHS]: DHS has put forth six strategic principles that would enable IoT developers, manufacturers, service providers, and consumers to maintain security as they develop, manufacture, implement, or use network-connected IoT devices.
6. National Institute of Standards and Technology (NIST) [NIST-Guide]: The NIST special publication urges enterprise and US federal agencies to address security throughout the systems engineering process. The publication builds upon the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 15288 standard and augments each process in the system lifecycle with security enhancements.
7. National Institute of Standards and Technology (NIST) [NIST-LW-PROJECT] [NIST-LW-2016]: NIST is running a project on lightweight cryptography with the purpose of: (i) identifying application areas for which standard cryptographic algorithms are too heavy, classifying them according to some application profiles to be determined; (ii) determining limitations in those existing cryptographic standards; and (iii) standardizing lightweight algorithms that can be used in specific application profiles.
8. Open Web Application Security Project (OWASP) [OWASP]: OWASP provides security guidance for IoT manufacturers, developers, and consumers. OWASP also includes guidelines for those who intend to test and analyze IoT devices and applications.
9. IoT Security Foundation [IoTSecFoundation]: The IoT Security Foundation has published a document that enlists various considerations that need to be taken into account when developing IoT applications. For example, the document states that IoT devices could use a hardware root of trust to ensure that only authorized software runs on the devices.
10. National Highway Traffic Safety Administration (NHTSA) [NHTSA]: The US NHTSA provides guidance to the automotive industry for improving the cyber security of vehicles. While some of the

guidelines are general, the document provides specific recommendations for the automotive industry, such as how various automotive manufacturers can share cybersecurity vulnerabilities discovered.

11. "Best Current Practices for Securing Internet of Things (IoT) Devices" [Moore]: This document provides a list of minimum requirements that vendors of IoT devices should take into account while developing applications, services, and firmware updates in order to reduce the frequency and severity of security incidents that arise from compromised IoT devices.
12. European Union Agency for Network and Information Security (ENISA) [ENISA-ICS]: ENISA published a document on communication-network dependencies for Industrial Control Systems (ICS)/Supervisory Control And Data Acquisition (SCADA) systems in which security vulnerabilities, guidelines, and general recommendations are summarized.
13. Internet Society Online Trust Alliance [ISOC-OTA]: The Internet Society's IoT Trust Framework identifies the core requirements that manufacturers, service providers, distributors, purchasers, and policymakers need to understand, assess, and embrace for effective security and privacy as part of the Internet of Things.

Other guideline and recommendation documents may exist or may later be published. This list should be considered nonexhaustive. Despite the acknowledgment that security in the Internet is needed and the existence of multiple guidelines, the fact is that many IoT devices and systems have very limited security. There are multiple reasons for this. For instance, some manufacturers focus on delivering a product without paying enough attention to security. This may be because of lack of expertise or limited budget. However, the deployment of such insecure devices poses a severe threat to the privacy and safety of users. The vast number of devices and their inherently mobile nature also imply that an initially secure system can become insecure if a compromised device gains access to the system at some point in time. Even if all other devices in a given environment are secure, this does not prevent external attacks caused by insecure devices. Recently, the US Federal Communications Commission (FCC) has stated the need for additional regulation of IoT systems [FCC]. It is possible that we may see other such regional regulations in the future.

5. Challenges for a Secure IoT

In this section, we take a closer look at the various security challenges in the operational and technical features of IoT and then discuss how existing Internet security protocols cope with these technical and conceptual challenges through the lifecycle of a thing. This discussion should not be understood as a comprehensive evaluation of all protocols, nor can it cover all possible aspects of IoT security. Yet, it aims at showing concrete limitations and challenges in some IoT design areas rather than giving an abstract discussion. In this regard, the discussion handles issues that are most important from the authors' perspectives.

5.1. Constraints and Heterogeneous Communication

Coupling resource-constrained networks and the powerful Internet is a challenge, because the resulting heterogeneity of both networks complicates protocol design and system operation. In the following subsections, we briefly discuss the resource constraints of IoT devices and the consequences for the use of Internet protocols in the IoT domain.

5.1.1. Resource Constraints

IoT deployments are often characterized by lossy and low-bandwidth communication channels. IoT devices are also often constrained in terms of the CPU, memory, and energy budget available [RFC7228]. These characteristics directly impact the design of protocols for the IoT domain. For instance, small packet-size limits at the physical layer (127 Bytes in IEEE 802.15.4) can lead to (i) hop-by-hop fragmentation and reassembly or (ii) small IP-layer maximum transmission unit (MTU). In the first case, excessive fragmentation of large packets that are often required by security protocols may open new attack vectors for state-exhaustion attacks. The second case might lead to more fragmentation at the IP layer, which commonly downgrades the overall system performance due to packet loss and the need for retransmission.

The size and number of messages should be minimized to reduce memory requirements and optimize bandwidth usage. In this context, layered approaches involving a number of protocols might lead to worse performance in resource-constrained devices since they combine the headers of the different protocols. In some settings, protocol negotiation can increase the number of exchanged messages. To improve performance during basic procedures such as, for example, bootstrapping, it might be a good strategy to perform those procedures at a lower layer.

Small CPUs and scarce memory limit the usage of resource-expensive cryptographic primitives such as public key cryptography as used in most Internet security standards. This is especially true if the basic cryptographic blocks need to be frequently used or the underlying application demands low delay.

There are ongoing efforts to reduce the resource consumption of security protocols by using more efficient underlying cryptographic primitives such as Elliptic Curve Cryptography (ECC) [RFC8446]. The specification of elliptic curve X25519 [ecc25519], stream ciphers such as ChaCha [ChaCha], Diet HIP [HIP-DEX], and ECC groups for IKEv2 [RFC5903] are all examples of efforts to make security protocols more resource efficient. Additionally, most modern security protocols have been revised in the last few years to enable cryptographic agility, making cryptographic primitives interchangeable. However, these improvements are only a first step in reducing the computation and communication overhead of Internet protocols. The question remains if other approaches can be applied to leverage key agreement in these heavily resource-constrained environments.

A further fundamental need refers to the limited energy budget available to IoT nodes. Careful protocol (re)design and usage are required to reduce not only the energy consumption during normal operation but also under DoS attacks. Since the energy consumption of IoT devices differs from other device classes, judgments on the energy consumption of a particular protocol cannot be made without tailor-made IoT implementations.

5.1.2. Denial-of-Service Resistance

The tight memory and processing constraints of things naturally alleviate resource-exhaustion attacks. Especially in unattended T2T communication, such attacks are difficult to notice before the service becomes unavailable (for example, because of battery or memory exhaustion). As a DoS countermeasure, DTLS, IKEv2, HIP, and Diet HIP implement return routability checks based on a cookie mechanism to delay the establishment of state at the responding host until the address of the initiating host is verified. The effectiveness of these defenses strongly depends on the routing topology of the network. Return routability checks are particularly effective if hosts cannot receive packets addressed to other hosts and if IP addresses present meaningful information as is the case in today's Internet. However, they are less effective in broadcast media or when attackers can influence the routing and addressing of hosts (for example, if hosts contribute to the routing infrastructure in ad hoc networks and meshes).

In addition, HIP implements a puzzle mechanism that can force the initiator of a connection (and potential attacker) to solve cryptographic puzzles with variable difficulties. Puzzle-based defense mechanisms are less dependent on the network topology but perform poorly if CPU resources in the network are heterogeneous (for example, if a powerful Internet host attacks a thing). Increasing the puzzle difficulty under attack conditions can easily lead to situations where a powerful attacker can still solve the puzzle while weak IoT clients cannot and are excluded from communicating with the victim. Still, puzzle-based approaches are a viable option for sheltering IoT devices against unintended overload caused by misconfiguration or malfunctioning things.

5.1.3. End-to-End Security, Protocol Translation, and the Role of Middleboxes

The term "end-to-end security" often has multiple interpretations. Here, we consider end-to-end security in the context of end-to-end IP connectivity from a sender to a receiver. Services such as confidentiality and integrity protection on packet data, message authentication codes, or encryption are typically used to provide end-to-end security. These protection methods render the protected parts of the packets immutable as rewriting is either not possible because (i) the relevant information is encrypted and inaccessible to the gateway or (ii) rewriting integrity-protected parts of the packet would invalidate the end-to-end integrity protection.

Protocols for constrained IoT networks are not exactly identical to their larger Internet counterparts, for efficiency and performance reasons. Hence, more or less subtle differences between protocols for constrained IoT networks and Internet protocols will remain. While these differences can be bridged with protocol translators at middleboxes, they may become major obstacles if end-to-end security measures between IoT devices and Internet hosts are needed.

If access to data or messages by the middleboxes is required or acceptable, then a diverse set of approaches for handling such a scenario is available. Note that some of these approaches affect the meaning of end-to-end security in terms of integrity and confidentiality, since the middleboxes will be able to either decrypt or partially modify the exchanged messages:

1. Sharing credentials with middleboxes enables them to transform (for example, decompress, convert, etc.) packets and reapply the security measures after transformation. This method abandons end-to-end security and is only applicable to simple scenarios with a rudimentary security model.

2. Reusing the Internet wire format for IoT makes conversion between IoT and Internet protocols unnecessary. However, it can lead to poor performance in some use cases because IoT-specific optimizations (for example, stateful or stateless compression) are not possible.
3. Selectively protecting vital and immutable packet parts with a message authentication code or encryption requires a careful balance between performance and security. Otherwise, this approach might either result in poor performance or poor security, depending on which parts are selected for protection, where they are located in the original packet, and how they are processed. [OSCORE] proposes a solution in this direction by encrypting and integrity protecting most of the message fields except those parts that a middlebox needs to read or change.
4. Homomorphic encryption techniques can be used in the middlebox to perform certain operations. However, this is limited to data processing involving arithmetic operations. Furthermore, the performance of existing libraries -- for example, Microsoft SEAL [SEAL] -- is still too limited, and homomorphic encryption techniques are not widely applicable yet.
5. Message authentication codes that sustain transformation can be realized by considering the order of transformation and protection (for example, by creating a signature before compression so that the gateway can decompress the packet without recalculating the signature). Such an approach enables IoT-specific optimizations but is more complex and may require application-specific transformations before security is applied. Moreover, the usage of encrypted or integrity-protected data prevents middleboxes from transforming packets.
6. Mechanisms based on object security can bridge the protocol worlds but still require that the two worlds use the same object-security formats. Currently, the object-security format based on COSE [RFC8152] is different from JSON Object Signing and Encryption (JOSE) [RFC7520] or Cryptographic Message Syntax (CMS) [RFC5652]. Legacy devices relying on traditional Internet protocols will need to update to the newer protocols for constrained environments to enable real end-to-end security. Furthermore, middleboxes do not have any access to the data, and this approach does not prevent an attacker who is capable of modifying relevant message header fields that are not protected.

To the best of our knowledge, none of the mentioned security approaches that focus on the confidentiality and integrity of the communication exchange between two IP endpoints provide the perfect solution in this problem space.

5.1.4. New Network Architectures and Paradigm

There is a multitude of new link-layer protocols that aim to address the resource-constrained nature of IoT devices. For example, IEEE 802.11ah [IEEE802ah] has been specified for extended range and lower energy consumption to support IoT devices. Similarly, LPWAN protocols such as LoRa [LoRa], Sigfox [sigfox], and NarrowBand IoT (NB-IoT) [NB-IoT] are all designed for resource-constrained devices that require long range and low bit rates. [RFC8376] provides an informational overview of the set of LPWAN technologies being considered by the IETF. It also identifies the potential gaps that exist between the needs of those technologies and the goal of running IP in such networks. While these protocols allow IoT devices to conserve energy and operate efficiently, they also add additional security challenges. For example, the relatively small MTU can make security handshakes with large X509 certificates a significant overhead. At the same time, new communication paradigms also allow IoT devices to communicate directly amongst themselves with or without support from the network. This communication paradigm is also referred to as Device-to-Device (D2D), Machine-to-Machine (M2M), or Thing-to-Thing (T2T) communication, and it is motivated by a number of features such as improved network performance, lower latency, and lower energy requirements.

5.2. Bootstrapping of a Security Domain

Creating a security domain from a set of previously unassociated IoT devices is a key operation in the lifecycle of a thing in an IoT network. This aspect is further elaborated and discussed in the T2TRG draft on bootstrapping [BOOTSTRAP].

5.3. Operational Challenges

After the bootstrapping phase, the system enters the operational phase. During the operational phase, things can use the state information created during the bootstrapping phase in order to exchange information securely. In this section, we discuss the security challenges during the operational phase. Note that many of the challenges discussed in Section 5.1 apply during the operational phase.

5.3.1. Group Membership and Security

Group-key negotiation is an important security service for IoT communication patterns in which a thing sends some data to multiple things or data flows from multiple things towards a thing. All discussed protocols only cover unicast communication and therefore do not focus on group-key establishment. This applies in particular to (D)TLS and IKEv2. Thus, a solution is required in this area. A potential solution might be to use the Diffie-Hellman keys -- which are used in IKEv2 and HIP to set up a secure unicast link -- for group Diffie-Hellman key negotiations. However, Diffie-Hellman is a relatively heavy solution, especially if the group is large.

Symmetric and asymmetric keys can be used in group communication. Asymmetric keys have the advantage that they can provide source authentication. However, doing broadcast encryption with a single public/private key pair is also not feasible. Although a single symmetric key can be used to encrypt the communication or compute a message authentication code, it has inherent risks since the capture of a single node can compromise the key shared throughout the network. The usage of symmetric keys also does not provide source authentication. Another factor to consider is that asymmetric cryptography is more resource-intensive than symmetric key solutions. Thus, the security risks and performance trade-offs of applying either symmetric or asymmetric keys to a given IoT use case need to be well analyzed according to risk and usability assessments [RFC8387]. [MULTICAST] is looking at a combination of confidentiality using a group key and source authentication using public keys in the same packet.

Conceptually, solutions that provide secure group communication at the network layer (IPsec/IKEv2, HIP/Diet HIP) may have an advantage in terms of the cryptographic overhead when compared to application-focused security solutions (TLS/DTLS). This is due to the fact that application-focused solutions require cryptographic operations per group application, whereas network-layer approaches may allow sharing secure group associations between multiple applications (for example, for neighbor discovery and routing or service discovery). Hence, implementing shared features lower in the communication stack can avoid redundant security measures. However, it is important to note that sharing security contexts among different applications involves potential security threats, e.g., if one of the applications is malicious and monitors exchanged messages or injects fake messages. In the case of OSCORE, it provides security for CoAP group communication as defined in RFC 7390, i.e., based on multicast IP. If the same security association is reused for each application, then this solution does not seem to have more cryptographic overhead compared to IPsec.

Several group-key solutions have been developed by the MSEC Working Group of the IETF [WG-MSEC]. The MIKEY architecture [RFC4738] is one example. While these solutions are specifically tailored for multicast and group-broadcast applications in the Internet, they should also be considered as candidate solutions for group-key agreement in IoT. The MIKEY architecture, for example, describes a coordinator entity that disseminates symmetric keys over pair-wise end-to-end secured channels. However, such a centralized approach may not be applicable in a distributed IoT environment, where the choice of one or several coordinators and the management of the group key is not trivial.

5.3.2. Mobility and IP Network Dynamics

It is expected that many things (for example, user devices and wearable sensors) will be mobile in the sense that they are attached to different networks during the lifetime of a security association. Built-in mobility signaling can greatly reduce the overhead of the cryptographic protocols because unnecessary and costly re-establishments of the session (possibly including handshake and key agreement) can be avoided. IKEv2 supports host mobility with the MOBIKE extension [RFC4555] [RFC4621]. MOBIKE refrains from applying heavyweight cryptographic extensions for mobility. However, MOBIKE mandates the use of IPsec tunnel mode, which requires the transmission of an additional IP header in each packet.

HIP offers simple yet effective mobility management by allowing hosts to signal changes to their associations [RFC8046]. However, slight adjustments might be necessary to reduce the cryptographic costs -- for example, by making the public key signatures in the mobility messages optional. Diet HIP does not define mobility yet, but it is sufficiently similar to HIP and can use the same mechanisms. DTLS provides some mobility support by relying on a connection ID (CID). The use of connection IDs can provide all the mobility functionality described in [Williams] except sending the updated location. The specific need for IP-layer mobility mainly depends on the scenario in which the nodes operate. In many cases, mobility supported by means of a mobile gateway may suffice to enable mobile IoT networks, such as body-sensor networks. Using message-based application-layer security solutions such as OSCORE [OSCORE] can also alleviate the problem of re-establishing lower-layer sessions for mobile nodes.

5.4. Secure Software Update and Cryptographic Agility

IoT devices are often expected to stay functional for several years or decades, even though they might operate unattended with direct Internet connectivity. Software updates for IoT devices are therefore required not only for new functionality but also to

eliminate security vulnerabilities due to software bugs, design flaws, or deprecated algorithms. Software bugs might remain even after careful code review. Implementations of security protocols might contain (design) flaws. Cryptographic algorithms can also become insecure due to advances in cryptanalysis. Therefore, it is necessary that devices that are incapable of verifying a cryptographic signature are not exposed to the Internet, even indirectly.

In his essay, Schneier highlights several challenges that hinder mechanisms for secure software update of IoT devices [SchneierSecurity]. First, there is a lack of incentives for manufacturers, vendors, and others on the supply chain to issue updates for their devices. Second, parts of the software running on IoT devices is simply a binary blob without any source code available. Since the complete source code is not available, no patches can be written for that piece of code. Lastly, Schneier points out that even when updates are available, users generally have to manually download and install them. However, users are never alerted about security updates, and many times do not have the necessary expertise to manually administer the required updates.

The US Federal Trade Commission (FTC) staff report on "Internet of Things - Privacy & Security in a Connected World" [FTCreport] and the Article 29 Working Party's "Opinion 8/2014 on the Recent Developments on the Internet of Things" [Article29] also document the challenges for secure remote software update of IoT devices. They note that even providing such a software-update capability may add new vulnerabilities for constrained devices. For example, a buffer overflow vulnerability in the implementation of a software update protocol (TR69) [TR69] and an expired certificate in a hub device [wink] demonstrate how the software-update process itself can introduce vulnerabilities.

Powerful IoT devices that run general-purpose operating systems can make use of sophisticated software-update mechanisms known from the desktop world. However, resource-constrained devices typically do not have any operating system and are often not equipped with a memory management unit or similar tools. Therefore, they might require more specialized solutions.

An important requirement for secure software and firmware updates is source authentication. Source authentication requires the resource-constrained things to implement public key signature verification algorithms. As stated in Section 5.1.1, resource-constrained things have limited computational capabilities and energy supply available, which can hinder the amount and frequency of cryptographic processing that they can perform. In addition to source authentication,

software updates might require confidential delivery over a secure (encrypted) channel. The complexity of broadcast encryption can force the usage of point-to-point secure links; however, this increases the duration of a software update in a large system. Alternatively, it may force the usage of solutions in which the software update is delivered to a gateway and then distributed to the rest of the system with a network key. Sending large amounts of data that later needs to be assembled and verified over a secure channel can consume a lot of energy and computational resources. Correct scheduling of the software updates is also a crucial design challenge. For example, a user of connected light bulbs would not want them to update and restart at night. More importantly, the user would not want all the lights to update at the same time.

Software updates in IoT systems are also needed to update old and insecure cryptographic primitives. However, many IoT systems, some of which are already deployed, are not designed with provisions for cryptographic agility. For example, many devices come with a wireless radio that has an AES128 hardware coprocessor. These devices solely rely on the coprocessor for encrypting and authenticating messages. A software update adding support for new cryptographic algorithms implemented solely in software might not fit on these devices due to limited memory, or might drastically hinder its operational performance. This can lead to the use of old and insecure software. Therefore, it is important to account for the fact that cryptographic algorithms would need to be updated and consider the following when planning for cryptographic agility:

1. Would it be secure to use the existing cryptographic algorithms available on the device for updating with new cryptographic algorithms that are more secure?
2. Will the new software-based implementation fit on the device given the limited resources?
3. Would the normal operation of existing IoT applications on the device be severely hindered by the update?

Finally, we would like to highlight the previous and ongoing work in the area of secure software and firmware updates at the IETF. [RFC4108] describes how Cryptographic Message Syntax (CMS) [RFC5652] can be used to protect firmware packages. The IAB has also organized a workshop to understand the challenges for secure software update of IoT devices. A summary of the recommendations to the standards community derived from the discussions during that workshop have been documented [RFC8240]. A working group called Software Updates for Internet of Things (SUIT) [WG-SUIT] is currently working on a new specification to reflect the best current practices for firmware

update based on experience from IoT deployments. It is specifically working on describing an IoT firmware update architecture and specifying a manifest format that contains metadata about the firmware update package. Finally, the Trusted Execution Environment Provisioning Working Group [WG-TEEP] aims at developing a protocol for lifecycle management of trusted applications running on the secure area of a processor (Trusted Execution Environment (TEE)).

5.5. End-of-Life

Like all commercial devices, IoT devices have a given useful lifetime. The term "end-of-life" (EOL) is used by vendors or network operators to indicate the point of time at which they limit or end support for the IoT device. This may be planned or unplanned (for example, when the manufacturer goes bankrupt, the vendor just decides to abandon a product, or a network operator moves to a different type of networking technology). A user should still be able to use and perhaps even update the device. This requires for some form of authorization handover.

Although this may seem far-fetched given the commercial interests and market dynamics, we have examples from the mobile world where the devices have been functional and up to date long after the original vendor stopped supporting the device. CyanogenMod for Android devices and OpenWrt for home routers are two such instances where users have been able to use and update their devices even after the official EOL. Admittedly, it is not easy for an average user to install and configure their devices on their own. With the deployment of millions of IoT devices, simpler mechanisms are needed to allow users to add new trust anchors [RFC6024] and install software and firmware from other sources once the device is EOL.

5.6. Verifying Device Behavior

Users using new IoT appliances such as Internet-connected smart televisions, speakers, and cameras are often unaware that these devices can undermine their privacy. Recent revelations have shown that many IoT device vendors have been collecting sensitive private data through these connected appliances with or without appropriate user warnings [cctv].

An IoT device's user/owner would like to monitor and verify its operational behavior. For instance, the user might want to know if the device is connecting to the server of the manufacturer for any reason. This feature -- connecting to the manufacturer's server -- may be necessary in some scenarios, such as during the initial configuration of the device. However, the user should be kept aware

of the data that the device is sending back to the vendor. For example, the user might want to know if his/her TV is sending data when he/she inserts a new USB stick.

Providing such information to the users in an understandable fashion is challenging. This is because IoT devices are not only resource constrained in terms of their computational capability but also in terms of the user interface available. Also, the network infrastructure where these devices are deployed will vary significantly from one user environment to another. Therefore, where and how this monitoring feature is implemented still remains an open question.

Manufacturer Usage Description (MUD) files [RFC8520] are perhaps a first step towards implementation of such a monitoring service. The idea behind MUD files is relatively simple: IoT devices would disclose the location of their MUD file to the network during installation. The network can then retrieve those files and learn about the intended behavior of the devices stated by the device manufacturer. A network-monitoring service could then warn the user/owner of devices if they don't behave as expected.

Many devices and software services that automatically learn and monitor the behavior of different IoT devices in a given network are commercially available. Such monitoring devices/services can be configured by the user to limit network traffic and trigger alarms when unexpected operation of IoT devices is detected.

5.7. Testing: Bug Hunting and Vulnerabilities

Given that IoT devices often have inadvertent vulnerabilities, both users and developers would want to perform extensive testing on their IoT devices, networks, and systems. Nonetheless, since the devices are resource constrained and manufactured by multiple vendors, some of them very small, devices might be shipped with very limited testing, so that bugs can remain and can be exploited at a later stage. This leads to two main types of challenges:

1. It remains to be seen how the software-testing and quality-assurance mechanisms used from the desktop and mobile world will be applied to IoT devices to give end users the confidence that the purchased devices are robust. Bodies such as the European Cyber Security Organization (ECSO) [ECSO] are working on processes for security certification of IoT devices.
2. It is also an open question how the combination of devices from multiple vendors might actually lead to dangerous network configurations -- for example, if the combination of specific

devices can trigger unexpected behavior. It is needless to say that the security of the whole system is limited by its weakest point.

5.8. Quantum-Resistance

Many IoT systems that are being deployed today will remain operational for many years. With the advancements made in the field of quantum computers, it is possible that large-scale quantum computers will be available in the future for performing cryptanalysis on existing cryptographic algorithms and cipher suites. If this happens, it will have two consequences. First, functionalities enabled by means of primitives such as RSA or ECC -- namely, key exchange, public key encryption, and signature -- would not be secure anymore due to Shor's algorithm. Second, the security level of symmetric algorithms will decrease, for example, the security of a block cipher with a key size of b bits will only offer $b/2$ bits of security due to Grover's algorithm.

The above scenario becomes more urgent when we consider the so-called "harvest and decrypt" attack in which an attacker can start to harvest (store) encrypted data today, before a quantum computer is available, and decrypt it years later, once a quantum computer is available. Such "harvest and decrypt" attacks are not new and were used in the VENONA project [venona-project]. Many IoT devices that are being deployed today will remain operational for a decade or even longer. During this time, digital signatures used to sign software updates might become obsolete, making the secure update of IoT devices challenging.

This situation would require us to move to quantum-resistant alternatives -- in particular, for those functionalities involving key exchange, public key encryption, and signatures. [C2PQ] describes when quantum computers may become widely available and what steps are necessary for transitioning to cryptographic algorithms that provide security even in the presence of quantum computers. While future planning is hard, it may be a necessity in certain critical IoT deployments that are expected to last decades or more. Although increasing the key size of the different algorithms is definitely an option, it would also incur additional computational overhead and network traffic. This would be undesirable in most scenarios. There have been recent advancements in quantum-resistant cryptography. We refer to [ETSI-GR-QSC-001] for an extensive overview of existing quantum-resistant cryptography, and [RFC7696] provides guidelines for cryptographic algorithm agility.

5.9. Privacy Protection

People will eventually be surrounded by hundreds of connected IoT devices. Even if the communication links are encrypted and protected, information about people might still be collected or processed for different purposes. The fact that IoT devices in the vicinity of people might enable more pervasive monitoring can negatively impact their privacy. For instance, imagine the scenario where a static presence sensor emits a packet due to the presence or absence of people in its vicinity. In such a scenario, anyone who can observe the packet can gather critical privacy-sensitive information.

Such information about people is referred to as personal data in the European Union (EU) or Personally identifiable information (PII) in the US. In particular, the General Data Protection Regulation (GDPR) [GDPR] defines personal data as: "any information relating to an identified or identifiable natural person ('data subject'); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person".

Ziegeldorf [Ziegeldorf] defines privacy in IoT as a threefold guarantee:

1. Awareness of the privacy risks imposed by IoT devices and services. This awareness is achieved by means of transparent practices by the data controller, i.e., the entity that is providing IoT devices and/or services.
2. Individual control over the collection and processing of personal information by IoT devices and services.
3. Awareness and control of the subsequent use and dissemination of personal information by data controllers to any entity outside the subject's personal control sphere. This point implies that the data controller must be accountable for its actions on the personal information.

Based on this definition, several threats to the privacy of users have been documented [Ziegeldorf] [RFC6973], in particular considering the IoT environment and its lifecycle:

1. Identification - refers to the identification of the users, their IoT devices, and generated data.

2. Localization - relates to the capability of locating a user and even tracking them, e.g., by tracking MAC addresses in Wi-Fi or Bluetooth.
3. Profiling - is about creating a profile of the user and their preferences.
4. Interaction - occurs when a user has been profiled and a given interaction is preferred, presenting (for example, visually) some information that discloses private information.
5. Lifecycle transitions - take place when devices are, for example, sold without properly removing private data.
6. Inventory attacks - happen if specific information about IoT devices in possession of a user is disclosed.
7. Linkage - is about when information of two or more IoT systems (or other data sets) is combined so that a broader view of the personal data captured can be created.

When IoT systems are deployed, the above issues should be considered to ensure that private data remains private. These issues are particularly challenging in environments in which multiple users with different privacy preferences interact with the same IoT devices. For example, an IoT device controlled by user A (low privacy settings) might leak private information about another user B (high privacy settings). How to deal with these threats in practice is an area of ongoing research.

5.10. Reverse-Engineering Considerations

Many IoT devices are resource constrained and often deployed in unattended environments. Some of these devices can also be purchased off the shelf or online without any credential-provisioning process. Therefore, an attacker can have direct access to the device and apply advanced techniques to retrieve information that a traditional black-box model does not consider. Examples of those techniques are side-channel attacks or code disassembly. By doing this, the attacker can try to retrieve data such as:

1. Long-term keys. These long-term keys can be extracted by means of a side-channel attack or reverse engineering. If these keys are exposed, then they might be used to perform attacks on devices deployed in other locations.

2. Source code. Extraction of source code might allow the attacker to determine bugs or find exploits to perform other types of attacks. The attacker might also just sell the source code.
3. Proprietary algorithms. The attacker can analyze these algorithms gaining valuable know-how. The attacker can also create copies of the product (based on those proprietary algorithms) or modify the algorithms to perform more advanced attacks.
4. Configuration or personal data. The attacker might be able to read personal data, e.g., healthcare data, that has been stored on a device.

One existing solution to prevent such data leaks is the use of a secure element, a tamper-resistant device that is capable of securely hosting applications and their confidential data. Another potential solution is the usage of a Physical Unclonable Function (PUF) that serves as unique digital fingerprint of a hardware device. PUFs can also enable other functionalities such as secure key storage. Protection against such data leakage patterns is not trivial since devices are inherently resource-constrained. An open question is whether there are any viable techniques to protect IoT devices and the data in the devices in such an adversarial model.

5.11. Trustworthy IoT Operation

Flaws in the design and implementation of IoT devices and networks can lead to security vulnerabilities. A common flaw is the use of well-known or easy-to-guess passwords for configuration of IoT devices. Many such compromised IoT devices can be found on the Internet by means of tools such as Shodan [shodan]. Once discovered, these compromised devices can be exploited at scale -- for example, to launch DDoS attacks. Dyn, a major DNS service provider, was attacked by means of a DDoS attack originating from a large IoT botnet composed of thousands of compromised IP cameras [Dyn-Attack]. There are several open research questions in this area:

1. How to avoid vulnerabilities in IoT devices that can lead to large-scale attacks?
2. How to detect sophisticated attacks against IoT devices?
3. How to prevent attackers from exploiting known vulnerabilities at a large scale?

Some ideas are being explored to address this issue. One of the approaches relies on the use of Manufacturer Usage Description (MUD) files [RFC8520]. As explained earlier, this proposal requires IoT devices to disclose the location of their MUD file to the network during installation. The network can then (i) retrieve those files, (ii) learn from the manufacturers the intended usage of the devices (for example, which services they need to access), and then (iii) create suitable filters and firewall rules.

6. Conclusions and Next Steps

This document provides IoT security researchers, system designers, and implementers with an overview of security requirements in the IP-based Internet of Things. We discuss the security threats, state of the art, and challenges.

Although plenty of steps have been realized during the last few years (summarized in Section 4.1) and many organizations are publishing general recommendations describing how IoT should be secured (Section 4.3), there are many challenges ahead that require further attention. Challenges of particular importance are bootstrapping of security, group security, secure software updates, long-term security and quantum-resistance, privacy protection, data leakage prevention -- where data could be cryptographic keys, personal data, or even algorithms -- and ensuring trustworthy IoT operation.

Authors of new IoT specifications and implementers need to consider how all the security challenges discussed in this document (and those that emerge later) affect their work. The authors of IoT specifications need to put in a real effort towards not only addressing the security challenges but also clearly documenting how the security challenges are addressed. This would reduce the chances of security vulnerabilities in the code written by implementers of those specifications.

7. Security Considerations

This entire memo deals with security issues.

8. IANA Considerations

This document has no IANA actions.

9. Informative References

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