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Security Considerations in the IP-based Internet of Things
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Abstract

A direct interpretation of the Internet of Things concept refers to the usage of standard Internet protocols to allow for human-to-thing or thing-to-thing communication. Although the security needs are well-recognized, it is still not fully clear how existing IP-based security protocols can be applied to this new setting. This Internet-Draft first provides an overview of security architecture, its deployment model and general security needs in the context of the lifecycle of a thing. Then, it presents challenges and requirements for the successful roll-out of new applications and usage of standard IP-based security protocols when applied to get a functional Internet of Things.

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1. Conventions and Terminology Used in this Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in "Key words for use in RFCs to Indicate Requirement Levels" [RFC2119].

2. Introduction

The Internet of Things (IoT) denotes the interconnection of highly heterogeneous networked entities and networks following a number of 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 by the Auto-ID center [AUTO-ID] in 1999. Since then, the development of the underlying concepts has ever increased its pace. Nowadays, the IoT presents a strong focus of research with various initiatives working on the (re)design, application, and usage of standard Internet technology in the IoT.

The introduction of IPv6 and web services as fundamental building blocks for IoT applications [RFC6568] promises to bring a number of basic advantages including: (i) a homogeneous protocol ecosystem that allows simple integration with Internet hosts; (ii) simplified development of very different appliances; (iii) an unified interface for applications, removing the need for application-level proxies. Such features greatly simplify the deployment of the envisioned scenarios ranging from building automation to production environments to personal area networks, in which very different things such as a temperature sensor, a luminaire, or an RFID tag might interact with each other, with a human carrying a smart phone, or with backend services.

This Internet Draft presents an overview of the security aspects of the envisioned all-IP architecture as well as of the lifecycle of an IoT device, a thing, within this architecture. In particular, we review the most pressing aspects and functionalities that are required for a secure all-IP solution.

With this, this Internet-Draft pursues several goals. First, we aim at presenting a comprehensive view of the interactions and relationships between an IoT application and security. Second, we aim at describing challenges for a secure IoT in the specific context of the lifecycle of a resource-constrained device. The final goal of

this draft is to discuss the security considerations that need to be taken into consideration towards a secure IoT.

The rest of the Internet-Draft is organized as follows. Section 3 depicts the lifecycle of a thing and gives general definitions for the main security aspects within the IoT domain. In Section 4, we review existing protocols and work done in the area of security for wireless sensor networks. Section 5 identifies general challenges and needs for an IoT security protocol design and discusses existing protocols and protocol proposals against the identified requirements. Section 6 proposes a number of illustrative security suites describing how different applications involve distinct security needs. Section 7 includes final remarks and conclusions.

3. The Thing Lifecycle and Architectural Considerations

We consider the installation of a Building Automation and Control (BAC) system to illustrate the lifecycle of a thing but can be similarly extended to other scenarios. A BAC system consists of a network of interconnected nodes that perform various functions in the domains of HVAC (Heating, Ventilating, and Air Conditioning), lighting, safety etc. The nodes vary in functionality and a majority of them represent resource constrained devices such as sensors and luminaries. Some devices may also be battery operated or battery-less nodes, demanding for a focus on low energy consumption and on sleeping devices.

In our example, the life of a thing starts when it is manufactured. Due to the different application areas (i.e., HVAC, lighting, safety) nodes 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 are 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 defined event but may stretch over an extended period of time. After being bootstrapped, the device and the system of things are in operational mode and run the functions of the BAC system. During this operational phase, the device is under the control of the system owner. 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 thereby be performed either locally or from a backend system. Depending on the operational

changes of the device, it may be required to re-bootstrap at the end of a maintenance cycle. The device continues to loop through the operational phase and the eventual maintenance phase 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 but rather denotes a need to replace and upgrade the network to next-generation devices in order to provide additional functionality. Therefore the device can be removed and re-commissioned to be used in a different network under a different owner by starting the lifecycle over again. Figure 1 shows the generic lifecycle of a thing. This generic lifecycle is also applicable for various IoT scenarios other than BAC systems.

More recently building control networks employ IP-based standards allowing seamless control over the various nodes with a single management system. While allowing for easier integration, this shift towards IP-based standards results in new requirements regarding the implementation of IP security protocols on constrained devices and the bootstrapping of security keys for devices across multiple manufacturers.

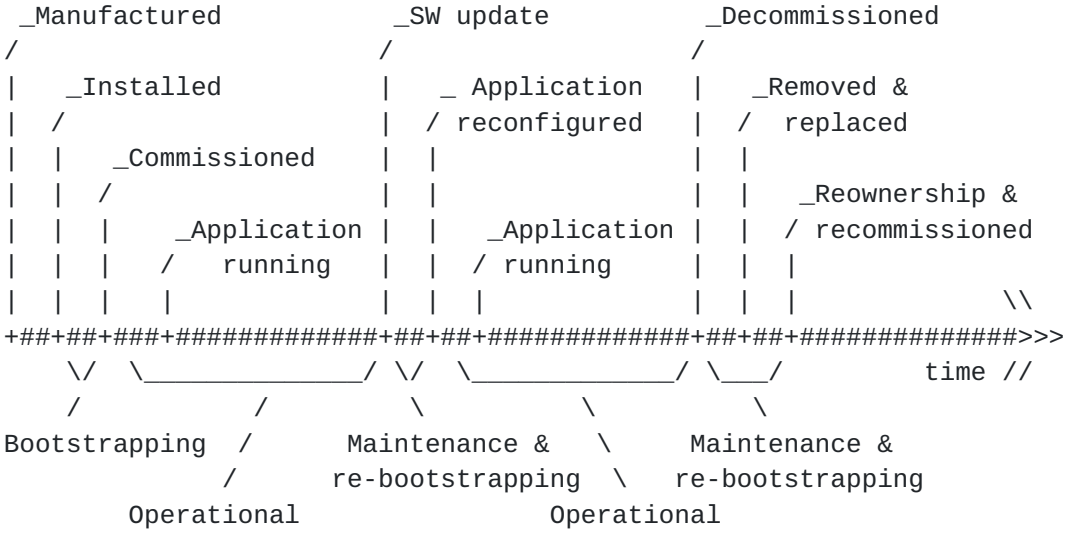


Figure 1: The lifecycle of a thing in the Internet of Things.

3.1. Threat Analysis

This section explores the security threats and vulnerabilities of a network of things in the IoTs. Security threats have been analyzed in related IP protocols including HTTPS [RFC2818], COAP[RFC7252] 6LoWPAN [RFC4919], ANCP [RFC5713], DNS security threats [RFC3833], SIP [RFC3261], IPv6 ND [RFC3756], and PANA [RFC4016]. Nonetheless, the challenge is about their impacts on scenarios of the IoTs. In this section, we specifically discuss the threats that could

compromise an individual thing, or network as a whole, with regard to different phases in the thing's lifecycle. Note that these set of threats might go beyond the scope of Internet protocols but we gather them here for the sake of completeness.

1. Cloning of things: During the manufacturing process of a thing, an untrusted manufacturer can easily clone the physical characteristics, firmware/software, or security configuration of the thing. Subsequently, such a cloned thing may be sold at a cheaper price in the market, and yet be still able to 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. One should note here, that an untrusted manufacturer may also change functionality of the cloned thing, resulting in degraded functionality with respect to the genuine thing (thereby, inflicting potential reputational risk to the original thing manufacturer). Moreover, it can implement additional functionality with the cloned thing, such as a backdoor.

2. Malicious substitution of things: During the installation of a thing, a genuine thing may be substituted with a similar variant of lower quality without being detected. The main motivation may be cost savings, where the installation of lower-quality things (e.g., non-certified products) may significantly reduce the installation and operational costs. The installers can subsequently resell the genuine things in order to gain further financial benefits. Another motivation may be to inflict reputational damage on a competitor's offerings.

3. 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 clear using a wireless medium. After obtaining the keying material, the attacker might be able to recover the secret keys established between the communicating entities (e.g., H2T, T2Ts, or Thing to the backend management system), 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 may be eavesdropped upon if the communication channel is not sufficiently protected or in the event of session key compromise due to a long period of usage without key renewal or updates.

4. Man-in-the-middle attack: Both the commissioning phase and operational phases may also be vulnerable to man-in-the-middle

attacks, e.g., when keying material between communicating entities is exchanged in the clear and the security of the key establishment protocol depends on the tacit assumption that no third party is able to eavesdrop on or sit in between the two communicating entities during the execution of this protocol. Additionally, device authentication or device authorization may be nontrivial, or may need support of a human decision process, since things usually do not have a priori knowledge about each other and can, therefore, not always be able to differentiate friends and foes via completely automated mechanisms. Thus, even if the key establishment protocol provides cryptographic device authentication, this knowledge on device identities may still need complementing with a human-assisted authorization step (thereby, presenting a weak link and offering the potential of man-in-the-middle attacks this way).

5. Firmware Replacement attack: 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 replacing the thing's with malicious software, thereby influencing the operational behavior of the thing. 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 lamp to a data repository for analysis.

6. Extraction of security parameters: A thing deployed in the ambient environment (such as sensors, actuators, etc.) is usually physically unprotected and could easily be captured by an attacker. Such an attacker may then attempt to extract security information such as keys (e.g., device's key, private-key, group key) from this thing or try and re-program it to serve his needs. If a group key is used and compromised this way, the whole network may be compromised as well. Compromise of a thing's unique key has less security impact, since only the communication channels of this particular thing in question are compromised. Here, one should caution that compromise of the communication channel may also compromise all data communicated over this channel. In particular, one has to be weary of, e.g., compromise of group keys communicated over this channel (thus, leading to transitive exposure ripple effects).

7. Routing attack: As highlighted in [ID-Daniel], routing information in IoT can be spoofed, altered, or replayed, in order to create routing loops, attract/repel network traffic, extend/ shorten source routes, etc. Other relevant routing attacks include 1) 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 anything to all packets passing through it. 2) Selective forwarding, where an attacker may selectively forward packets or simply drop a packet. 3) 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. 4) Sybil attack, whereby an attacker presents multiple identities to other things in the network.

8. Privacy threat: The tracking of a thing's location and usage may pose a privacy risk to its users. An attacker can infer information based on the information gathered about individual things, thus deducing behavioral patterns of the user of interest to him. Such information can subsequently be sold to interested parties for marketing purposes and targeted advertising.

9. Denial-of-Service attack: Typically, things have tight memory and limited computation, they are thus vulnerable to resource exhaustion attack. Attackers can continuously send requests to be processed by specific things so as to deplete their resources. This is especially dangerous in the IoTs since an attacker might be located in the backend and target resource-constrained devices in an LLN. Additionally, DoS attack can be launched by physically jamming the communication channel, thus breaking down the T2T communication channel. Network availability can also be disrupted by flooding the network with a large number of packets.

The following table summarizes the security threats we identified above and the potential point of vulnerabilities at different layers of the communication stack. We also include related RFCs that include a threat model that might apply to the IoTs.

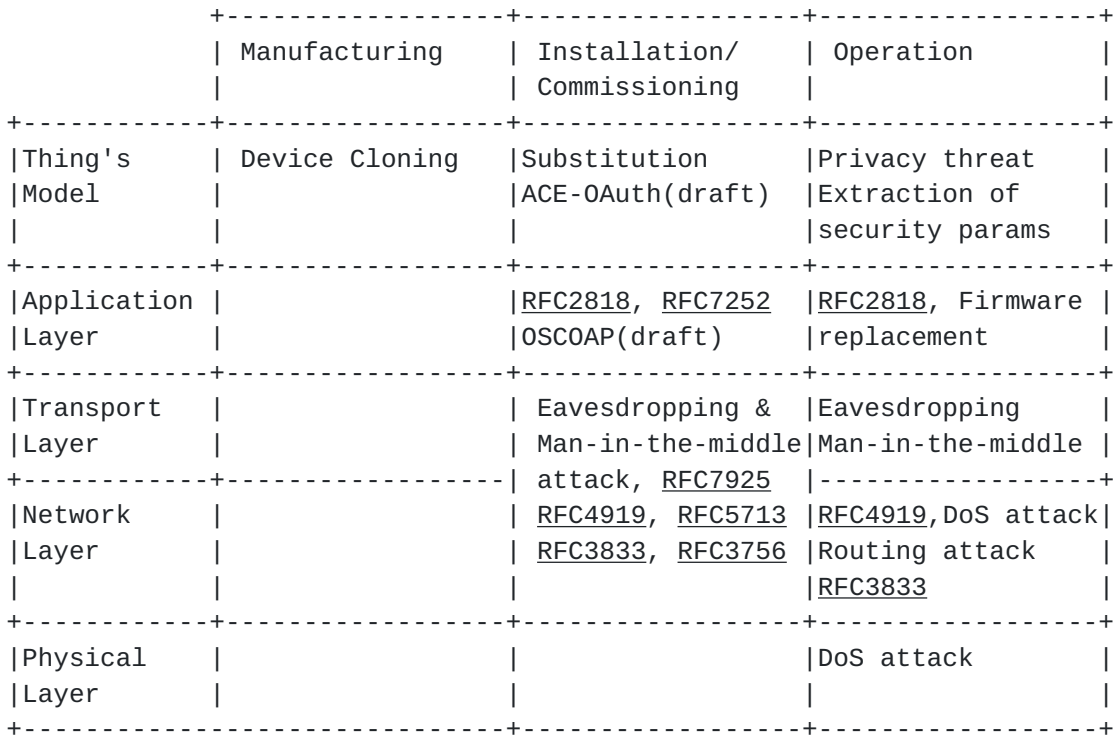


Figure 2: The security threat analysis

3.2. Security Aspects

The term security subsumes a wide range of different concepts. In the first place, it refers to the basic provision of security services including confidentiality, authentication, integrity, authorization, non-repudiation, and availability, and some augmented services, such as duplicate detection and detection of stale packets (timeliness). These security services can be implemented by a combination of cryptographic mechanisms, such as block ciphers, hash functions, or signature algorithms, and non-cryptographic mechanisms, which implement authorization and other security policy enforcement aspects. For each of the cryptographic mechanisms, a solid key management infrastructure is fundamental to handling the required cryptographic keys, whereas for security policy enforcement, one needs to properly codify authorizations as a function of device roles and a security policy engine that implements these authorization checks and that can implement changes hereto throughout the system's lifecycle.

In the context of the IoT, however, the security must not only focus on the required security services, but also how these are realized in the overall system and how the security functionalities are executed. To this end, we use the following terminology to analyze and classify security aspects in the IoT:

1. The security architecture refers to the system elements involved in the management of the security relationships between things and the way these security interactions are handled (e.g., centralized or distributed) during the lifecycle of a thing.

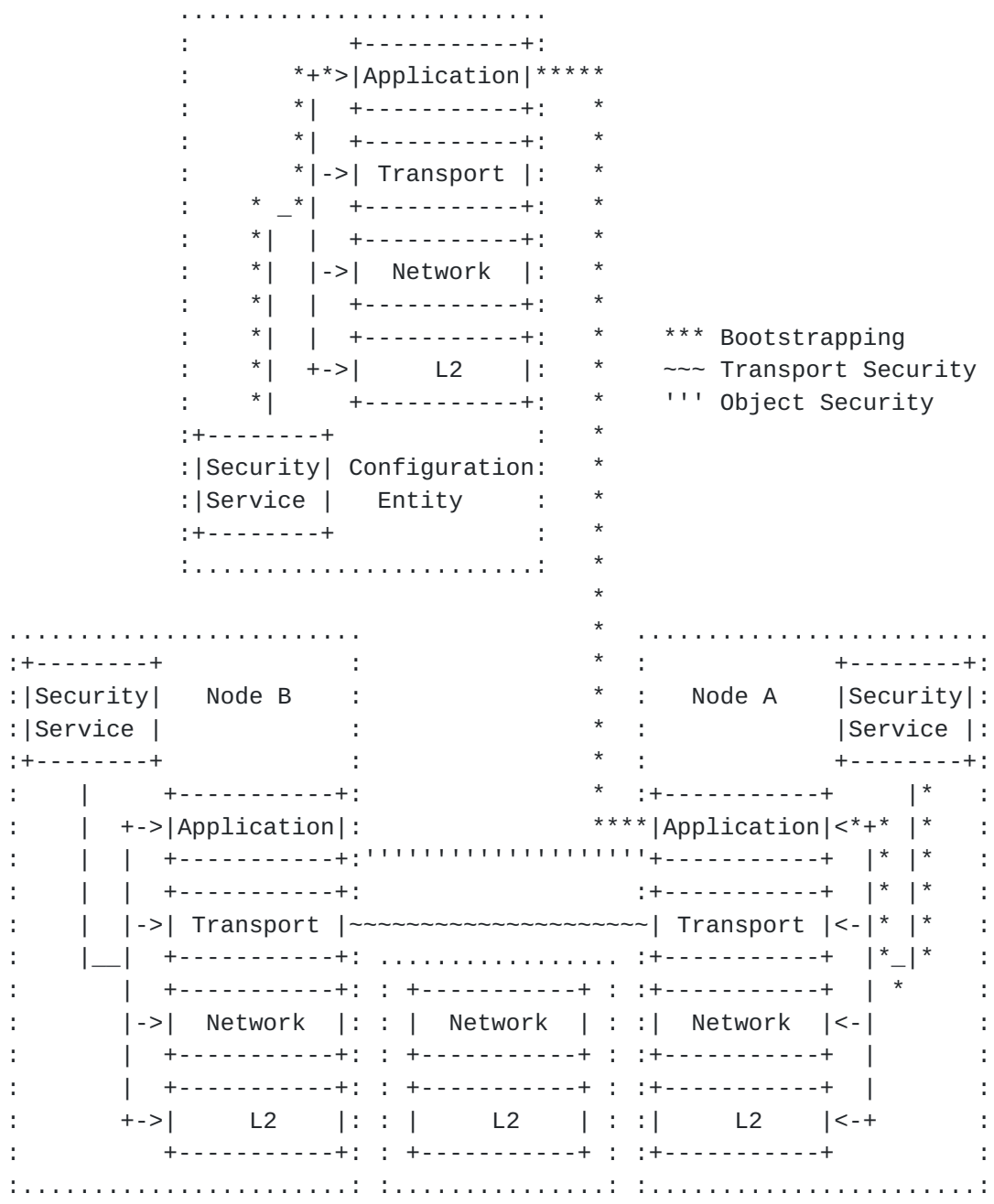
2. The security model of a node describes how the security parameters, processes, and applications are managed in a thing. This includes aspects such as process separation, secure storage of keying materials, etc.

3. Security bootstrapping denotes the process by which a thing securely joins the IoT at a given location and point in time. Bootstrapping includes the authentication and authorization of a device as well as the transfer of security parameters allowing for its trusted operation in a given network.

4. Network security describes the mechanisms applied within a network to ensure trusted operation of the IoT. Specifically, it prevents attackers from endangering or modifying the expected operation of networked things. Network security can include a number of mechanisms ranging from secure routing to data link layer and network layer security.

5. Object security describes mechanisms to allow transfer of secured blocks of data with end-to-end assurances independent of communication pattern, for e.g through proxies or other store-and-forward mechanisms.

6. Application security guarantees that only trusted instances of an application running in the IoT can communicate with each other, while illegitimate instances cannot interfere.



Overview of Security Mechanisms.

Figure 3

We now discuss an exemplary security architecture relying on a configuration entity for the management of the system with regard to the introduced security aspects (see Figure 2). Inspired by the security framework for routing over low power and lossy network [ID-Tsao], we show an example of security model and illustrates how different security concepts and the lifecycle phases map to the Internet communication stack. Assume a centralized architecture in

which a configuration entity stores and manages the identities of the things associated with the system along with their cryptographic keys. During the bootstrapping phase, each thing executes the bootstrapping protocol with the configuration entity, thus obtaining the required device identities and the keying material. The security service on a thing in turn stores the received keying material for the network layer and application security mechanisms for secure communication. Things can then securely communicate with each other during their operational phase by means of the employed network and application security mechanisms.

4. State of the Art

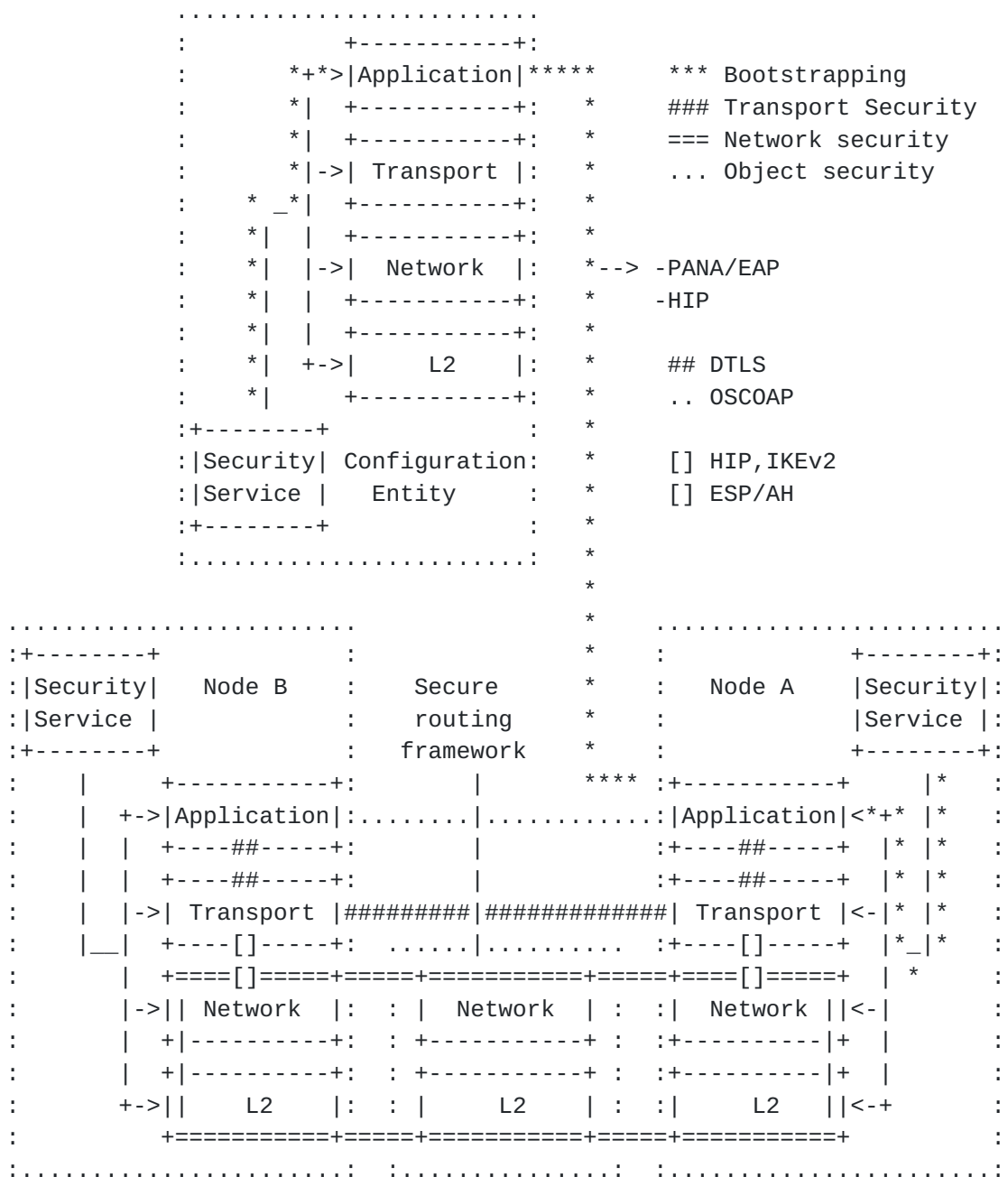
Nowadays, there exists a multitude of control protocols for the IoT. For BAC systems, the ZigBee standard [ZB], BACNet [BACNET], or DALI [DALI] play key roles. Recent trends, however, focus on an all-IP approach for system control.

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] concentrates on the definition of 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] provides a framework for resource-oriented applications intended to run on constrained IP network (6LoWPAN). One of its main tasks is the definition of a lightweight version of the HTTP protocol, the Constrained Application Protocol (CoAP) [RFC7252], that runs over UDP and enables efficient application-level communication for things. Also IRTF groups are actively contributing to improve IoT security.

Additionally industry alliances like Thread [Thread] are creating constrained IP protocol stacks based on the IETF work.

4.1. IP-based Security Solutions

In the context of the IP-based IoT solutions, consideration of TCP/IP security protocols is important as these protocols are designed to fit the IP network ideology and technology. There are a wide range of specialized as well as general-purpose key exchange and security solutions exist for the Internet domain such as IKEv2/IPsec [RFC7296], TLS/SSL [RFC5246], DTLS [RFC5238], HIP [RFC7401], PANA [RFC5191], and EAP [RFC3748]. Some of these solutions are also been investigated now, such as, e.g., OSCOAP. Figure 3 depicts the relationships between the discussed protocols in the context of the security terminology introduced in Section 3.1.



Relationships between IP-based security protocols.

Figure 4

The Internet Key Exchange (IKEv2)/IPsec and the 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 transforms for secure payload delivery. Currently, there are also ongoing efforts to create a HIP variant coined Diet HIP [ID-HIP] that takes lossy low-power networks into account at the authentication and key exchange level.

Transport Layer Security (TLS) and its datagram-oriented variant DTLS secure transport-layer connections. TLS provides security for TCP and requires a reliable transport, while 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 Extensible Authentication Protocol (EAP) 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. The Protocol for Carrying Authentication for Network Access (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.

In addition, there is also new activities in IETF and W3C to define security protocols better tailored to IoT or for specific deployment situations. The ACE WG is designing an authorization mechanism based on OAuth for constrained devices. There is work on Object Security based CoAP protection mechanism being defined in OSCOAP. <<similar work in W3C - Oliver?>>

5. Security Levels for the IP-based Internet of Things

Different applications have different security requirements and needs and, depending on various factors, such as device capability, availability of network infrastructure, security services needed, usage, etc., the required security protection may vary from "simple security" to "full-blown security". For example, applications may have different needs regarding authentication and confidentiality. While some application might not require any authentication at all, others might require strong end-to-end authentication. In terms of secure bootstrapping of keys, some applications might assume the existence and online availability of a central key-distribution-center (KDC) within the 6LoWPAN network to distribute and manage keys; while other applications cannot rely on such a central party or their availability.

Thus, it is essential to define security profiles to better tailor security solutions for different applications with the same characteristics and requirements. This provides a means of grouping applications into profiles and then defines the minimal required security primitives to enable and support the security needs of the profile. The security elements in a security profile can be classified according to Section 3.1, namely:

1 Security architecture,

2 Security model,

3 Security bootstrapping,

4 Network security, and

5 Application security.

In order to (i) guide the design process by identifying open gaps; (ii) allow for later interoperability; and (iii) prevent possible security misconfigurations, this section defines a number of generic security profiles with different security needs. Each security profile is identified by:

1. a short description,

2. an exemplary application that might use/require such a security policy,

3. the security requirements for each of the above security aspects according to our classification in Section 3.1.

These security profiles can serve to guide the standardization process, since these explicitly describe the basic functionalities and protocols required to get different use cases up and running. It can allow for later interoperability since different manufacturers can describe the implemented security profile in their products. Finally, the security profiles can avoid possible security misconfigurations, since each security profile can be bound to a different application area so that it can be clearly defined which security protocols and approaches can be applied where and under which circumstances.

Note that each of these security profiles aim at summarizing the required security requirements for different applications and at providing a set of initial security features. In other words, these profiles reflect the need for different security configurations, depending on the threat and trust models of the underlying applications. In this sense, this section does not provide an overview of existing protocols as done in previous sections of the Internet Draft, but it rather explicitly describes what should be in place to ensure secure system operation. Observe also that this list of security profiles is not exhaustive and that it should be considered just as an example not related to existing legal regulations for any existing application. These security profiles are summarized in the table below:

Exemnplary Application	Description
SecProf_1 Home usage	Enables operation between home things without interaction with central device
SecProf_2 Managed Home usage	Enables operation between home things. Interaction with a central and local device is possible
SecProf_3 Industrial usage	Enables operation between things. Relies on central (local or backend) device for security
SecProf_4 Advanced Industrial usage	Enables ad-hoc operation between things and relies on central device or on a collection of control devices

Figure 5: Security profiles and application areas.

The classification in the table considers different potential applications and situations in which their security needs change due to different operational features (network size, existence of a central device, connectivity to the Internet, importance of the exchanged information, etc) or threat model (what are the assets that an attacker looks for). As already pointed out, this set of scenarios is exemplary and they should be further discussed based on a broader consensus.

The security suite (SecProf_1) is catered for environments in which IP protocols (e.g., 6LoWPAN/CoAP) can be used to enable communication between things in an ad-hoc manner and the security requirements are minimal. An example, is a home application in which two devices should exchange information and no further connection with other devices (local or with a backend) is required. In this scenario, value of the exchanged information is low and that it usually happen in a confined room, thus, it is possible to have a short period of time during which initial secrets can be exchanged in the clear. Due to this fact, there is no requirement to enable devices from different manufacturers to interoperate in a secure way (keys are just exchanged). The expected network size of applications using this profile is expected to be small such that the provision of network security, e.g., secure routing, is of low importance.

The next security suite (SecProf_2) represents an evolution of SecProf_1 in which, e.g., home devices, can be managed locally. A

first possibility for the securing domain management refers to the creation of a centrally managed security domain without any connectivity to the Internet. The central device used for management can serve as, e.g., a key distribution center including policies for key update, storage, etc. The presence of a central device can help in the management of larger networks. Network security becomes more relevant in this scenario since the IP network (e.g., 6LoWPAN/CoAP network) can be prone to Denial of Service attacks (e.g., flooding if L2 is not protected) or routing attacks.

SecProf_3 considers that a central device is always required for network management. Example applications of this profile include building control and automation, sensor networks for industrial use, environmental monitoring, etc. As before, the network manager can be located in the IP network (e.g., 6LoWPAN/CoAP network) and handle key management. In this case, the first association of devices to the network is required to be done in a secure way. In other words, the threat model requires measurements to protect against any vulnerable period of time. This step can involve the secure transmission of keying materials used for network security at different layers. The information exchanged in the network is considered to be valuable and it should be protected in the sense of pairwise links. Commands should be secured and broadcast should be secured with entity authentication [RFC7390]. Network should be protected from attacks. A further extension to this use case is to allow for remote management. A "backend manager" is in charge of managing SW or information exchanged or collected within the IP network, e.g., a 6LoWPAN/CoAP network. This requires connection of devices to the Internet over a 6LBR involving a number of new threats that were not present before. A list of potential attacks include: resource-exhaustion attacks from the Internet; amplification attacks; trust issues related a HTTP-CoAP proxy [ID-proHTTPCoAP], etc. This use case requires protecting the communication from a device in the backend to a device in the IP network, e.g., a 6LoWPAN/CoAP network, end-to-end. This use case also requires measures to provide the 6LBR with the capability of dropping fake requests coming from the Internet. This becomes especially challenging when the 6LBR is not trusted and access to the exchanged information is limited; and even more in the case of a HTTP-CoAP proxy since protocol translation is required. This use case should take care of protecting information accessed from the backend due to privacy issues (e.g., information such as type of devices, location, usage, type and amount of exchanged information, or mobility patterns can be gathered at the backend threatening the privacy sphere of users) so that only required information is disclosed.

The last security suite (SecProf_4) essentially represents interoperability of all the security profiles defined previously. It

considers applications with some additional requirements regarding operation such as: (i) ad-hoc establishment of security relationships between things (potentially from different manufacturers) in non-secure environments or (ii) dynamic roaming of things between different IP network security domains. Such operational requirements pose additional security requirements, e.g., in addition to secure bootstrapping of a device within an IP, e.g., 6LowPan/CoAP, security domain and the secure transfer of network operational key, there is a need to enable inter-domains secure communication to facilitate data sharing.

The above description illustrates how different applications of IP networks, e.g., 6LoWPAN/CoAP networks, involve different security needs. In the following sections, we summarize the expected security features or capabilities for each the security profile with regards to "Security Architecture", "Security Model", "Security Bootstrapping", "Network Security", and "Application Security".

5.1. Security Architecture

Most things might be required to support both centralized and distributed operation patterns. Distributed thing-to-thing communication might happen on demand, for instance, when two things form an ad-hoc security domain to cooperatively fulfill a certain task. Likewise, nodes may communicate with a backend service located in the Internet without a central security manager. The same nodes may also be part of a centralized architecture with a dedicated node being responsible for the security management for group communication between things in the IoT domain. In today's IoT, most common architectures are fully centralized in the sense that all the security relationships within a segment are handled by a central party. In the ZigBee standard, this entity is the trust center. Current proposals for 6LoWPAN/CoRE identify the 6LoWPAN Border Router (6LBR) as such a device.

A centralized architecture allows for central management of devices and keying materials as well as for the backup of cryptographic keys. However, it also imposes some limitations. First, it represents a single point of failure. This is a major drawback, e.g., when key agreement between two devices requires online connectivity to the central node. Second, it limits the possibility to create ad-hoc security domains without dedicated security infrastructure. Third, it codifies a more static world view, where device roles are cast in stone, rather than a more dynamic world view that recognizes that networks and devices, and their roles and ownership, may change over time (e.g., due to device replacement and hand-over of control).

Decentralized architectures, on the other hand, allow creating ad-hoc security domains that might not require a single online management entity and are operative in a much more stand-alone manner. The ad-hoc security domains can be added to a centralized architecture at a later point in time, allowing for central or remote management.

The choice of security architecture has many implications regarding key management, access control, or security scope. A distributed (or ad-hoc) architecture means that security relationships between things are setup on the fly between a number of objects and kept in a decentralized fashion. A locally centralized security architecture means that a central device, e.g., the 6LBR, handles the keys for all the devices in the security domain. Alternatively, a central security architecture could also refer to the fact that smart objects are managed from the backend. The security architecture for the different security profiles is classified as follows.

	Description
SecProf_1	Distributed
SecProf_2	Distributed able to move centralized (local)
SecProf_3	Centralized (local &/or backend)
SecProf_4	Distributed & centralized (local &/or backend)

Figure 6: Security architectures in different security profiles.

In "SecProf_1", management mechanisms for the distributed assignment and management of keying materials is required. Since this is a very simple use case, access control to the security domain can be enabled by means of a common secret known to all devices. In the next security suite (SecProf_2), a central device can assume key management responsibilities and handle the access to the network. The last two security suites (SecProf_3 and SecProf_4) further allow for the management of devices or some keying materials from the backend.

5.2. Security Model

While some applications might involve very resource-constrained things such as, e.g., a humidity, pollution sensor, other applications might target more powerful devices aimed at more exposed applications. Security parameters such as keying materials, certificates, etc must be protected in the thing, for example by

means of tamper-resistant hardware. Keys may be shared across a thing's networking stack to provide authenticity and confidentiality in each networking layer. This would minimize the number of key establishment/agreement handshake and incurs less overhead for constrained thing. While more advance applications may require key separation at different networking layers, and possibly process separation and sandboxing to isolate one application from another. In this sense, this section reflects the fact that different applications require different sets of security mechanisms.

	Description
SecProf_1	No tamper resistant Sharing keys between layers
SecProf_2	No tamper resistant Sharing keys between layers
SecProf_3	Tamper resistant Key and process separation
SecProf_4	(no) Tamper resistant Sharing keys between layers/Key and process separation Sandbox

Figure 7: Thing security models in different security profiles.

5.3. Security Bootstrapping and Management

Bootstrapping refers to the process by which a thing initiates its life within a security domain and includes the initialization of secure and/or authentic parameters bound to the thing and at least one other device in the network. Here, different mechanisms may be used to achieve confidentiality and/or authenticity of these parameters, depending on deployment scenario assumptions and the communication channel(s) used for passing these parameters. The simplest mechanism for initial set-up of secure and authentic parameters is via communication in the clear using a physical interface (USB, wire, chip contact, etc.). Here, one commonly assumes this communication channel is secure, since eavesdropping and/or manipulation of this interface would generally require access to the physical medium and, thereby, to one or both of the devices themselves. This mechanism was used with the so-called original "resurrecting duckling" model, as introduced in [PROC-Stajano-99]. This technique may also be used securely in wireless, rather than wired, set-ups, if the prospect of eavesdropping and/or manipulating

this channel are dim (a so-called "location-limited" channel [PROC-Smetters-04][PROC-Smetters-02]). Examples hereof include the communication of secret keys in the clear using near field communication (NFC) - where the physical channel is purported to have very limited range (roughly 10cm), thereby thwarting eavesdropping by far-away adversarial devices, and in-the-clear communication during a small time window (triggered by, e.g., a button-push) - where eavesdropping is presumed absent during this small time window. With the use of public-key based techniques, assumptions on the communication channel can be relaxed even further, since then the cryptographic technique itself provides for confidentiality of the channel set-up and the location-limited channel - or use of certificates - rules out man-in-the-middle attacks, thereby providing authenticity [PROC-Smetters-02]. The same result can be obtained using password-based public-key protocols [SPEKE], where authenticity depends on the (weak) password not being guessed during execution of the protocol.

It should be noted that while most of these techniques realize a secure and authentic channel for passing parameters, these generally do not provide for explicit authorization. As an example, with use of certificate-based public-key based techniques, one may obtain hard evidence on whom one shares secret and/or authentic parameters with, but this does not answer the question as to whether one wishes to share this information at all with this specifically identified device (the latter usually involves a human-decision element). Thus, the bootstrapping mechanisms above should generally be complemented by mechanisms that regulate (security policies for) authorization. Furthermore, the type of bootstrapping is very related to the required type of security architecture. Distributed bootstrapping means that a pair of devices can setup a security relationship on the fly, without interaction with a central device elsewhere within the system. In many cases, it is handy to have a distributed bootstrapping protocol based on existing security protocols (e.g., DTLS in CoAP) required for other purposes: this reduces the amount of required software. A centralized bootstrapping protocol is one in which a central device manages the security relationships within a network. This can happen locally, e.g., handled by the 6LBR, or remotely, e.g., from a server connected via the Internet. The security bootstrapping for the different security profiles is as follows.

	Description
SecProf_1	* Distributed, (e.g., Resurrecting duckling) * First key distribution happens in the clear
SecProf_2	* Distributed, (e.g., Resurrecting duckling) * Centralized (local), 6LBR acts as KDC * First key distribution occurs in the clear, if the KDC is available, the KDC can manage network access
SecProf_3	* 6LBR acts as KDC. It handles node joining, provides them with keying material from L2 to application layers * Bootstrapping occurs in a secure way - either in secure environment or the security mechanisms ensure that eavesdropping is not possible. * KDC and backend can implement secure methods for network access
SecProf_4	* As in SecProf_3.

Figure 8: Security bootstrapping methods in different security profiles

5.4. Network Security

Network security refers to the mechanisms used to ensure the secure transport of 6LoWPAN frames. This involves a multitude of issues ranging from secure discovery, frame authentication, routing security, detection of replay, secure group communication, etc. Network security is important to thwart potential attacks such as denial-of-service (e.g., through message flooding) or routing attacks.

The Internet Draft [ID-Tsao] presents a very good overview of attacks and security needs classified according to the confidentiality, integrity, and availability needs. A potential limitation is that there exist no differentiation in security between different use cases and the framework is limited to L3. The security suites gathered in the present ID aim at solving this by allowing for a more flexible selection of security needs at L2 and L3.

	Description
SecProf_1	* Network key creating a home security domain at L2 ensuring authentication and freshness of exchanged data * Secure multicast does not ensure origin authentication * No need for secure routing at L3
SecProf_2	* Network key creating a home security domain at L2 ensuring authentication and freshness of exchanged data * Secure multicast does not ensure origin authentication * No need for secure routing at L3
SecProf_3	* Network key creating an industry security domain at L2 ensuring authentication and freshness of exchanged data * Secure routing needed (integrity & availability) at L3 within 6LoWPAN/CoAP * Secure multicast requires origin authentication
SecProf_4	* Network key creating an industry security domain at L2 ensuring authentication and freshness of exchanged data * Inter-domain authentication/secure handoff * Secure routing needed at L3 * Secure multicast requires origin authentication * 6LBR (HTTP-CoAP proxy) requires verification of forwarded messages and messages leaving or entering the 6LoWPAN/CoAP network.

Figure 9: Network security needs in different security profiles

5.5. Application Security

In the context of 6LoWPAN/CoAP networks, application security refers firstly to the configuration of DTLS used to protect the exchanged information. It further refers to the measures required in potential translation points (e.g., a (HTTP-CoAP) proxy) where information can be collected and the privacy sphere of users in a given security domain is endangered. Application security for the different security profiles is as follows.

	Description
SecProf_1	-
SecProf_2	* DTLS is used for end-to-end application security between management device and things and between things * DTLS ciphersuites configurable to provide confidentiality and/or authentication and/or freshness * Key transport and policies for generation of session keys are required
SecProf_3	* Requirements as in SecProf_2 and * DTLS is used for end-to-end application security between management device and things and between things * Communication between KDC and each thing secured by pairwise keys * Group keys for communication in a group distributed by KDC * Privacy protection should be provided in translation points
SecProf_4	* Requirements as in SecProf_3 and * TLS or DTLS can be used to send commands from the backend to the 6LBR or things in a 6LoWPAN/CoAP network * End-to-end secure connectivity from backend required * Secure broadcast in a network from backend required

Figure 10: Application security methods in different security profiles

The first two security profiles do not include any security at the application layer. The reason is that, in the first case, security is not provided and, in the second case, it seems reasonable to provide basic security at L2. In the third security profile (SecProf_2), DTLS becomes the way of protecting messages at application layer between things and with the KDC running on a 6LBR. A key option refers to the capability of easily configuring DTLS to provide a subset of security services (e.g., some applications do not require confidentiality) to reduce the impact of security in the system operation of resource-constrained things. In addition to basic key management mechanisms running within the KDC, communication protocols for key transport or key update are required. These protocols could be based on DTLS. The next security suite (SecProf_3) requires pairwise keys for communication between things within the security domain. Furthermore, it can involve the usage of group keys for group communication. If secure multicast is

implemented, it should provide origin authentication. Finally, privacy protection should be taken into account to limit access to valuable information -- such as identifiers, type of collected data, traffic patterns -- in potential translation points (proxies) or in the backend. The last security suite (SecProf_4) further extends the previous set of requirements considering security mechanisms to deal with translations between TLS and DTLS or for the provision of secure multicast within a 6LoWPAN/CoAP network from the backend.

6. Challenges and Security Considerations for a Secure Internet of Things

<<Oliver and Mohit add stuff in this section>>

In this section, we take a closer look at the various security challenges in the operational and technical features of the IoT and then discuss how existing Internet security protocols cope with these technical and conceptual challenges through the lifecycle of a thing. Figure 2 summarizes which requirements need to be met in the lifecycle phases as well as some of the considered protocols. This discussion should neither 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 of existing Internet security protocols in some areas rather than giving an abstract discussion about general properties of the protocols. In this regard, the discussion handles issues that are most important from the authors' perspectives.

6.1. 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 we briefly discuss the resource constraints of IoT devices and the consequences for the use of Internet Protocols in the IoT domain.

6.1.1. Tight Resource Constraints

The IoT is a resource-constrained network that relies on lossy and low-bandwidth channels for communication between small nodes, regarding CPU, memory, and energy budget. These characteristics directly impact the threats to and the design of security protocols for the IoT domain. First, the use of small packets, e.g., IEEE 802.15.4 supports 127-byte sized packets at the physical layer, may result in fragmentation of larger packets of security protocols. This may open new attack vectors for state exhaustion DoS attacks, which is especially tragic, e.g., if the fragmentation is caused by large key exchange messages of security protocols. Moreover, packet

fragmentation commonly downgrades the overall system performance due to fragment losses and the need for retransmissions. For instance, fate-sharing packet flight as implemented by DTLS might aggravate the resulting performance loss.

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, e.g., 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 cryptoprimitives such as public-key cryptography as used in most Internet security standards. This is especially true, if the basic cryptoblocks need to be frequently used or the underlying application demands a low delay.

Independently from the development in the IoT domain, all discussed security protocols show efforts to reduce the cryptographic cost of the required public-key-based key exchanges and signatures with ECC[RFC5246][RFC5903][RFC7401][ID-HIP]. Moreover, all protocols have been revised in the last years to enable crypto 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 is 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.

6.1.2. 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 (e.g., 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 (e.g., 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 (e.g., 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 misconfigured or malfunctioning things.

6.1.3. Protocol Translation and End-to-End Security

Even though 6LoWPAN and CoAP progress towards reducing the gap between Internet protocols and the IoT, they do not target protocol specifications that are identical to their Internet counterparts due to performance reasons. Hence, more or less subtle differences between IoT protocols and Internet protocols will remain. While these differences can easily be bridged with protocol translators at gateways, they become major obstacles if end-to-end security measures between IoT devices and Internet hosts are used.

Cryptographic payload processing applies message authentication codes or encryption to packets. These protection methods render the protected parts of the packets immutable as rewriting is either not possible because a) the relevant information is encrypted and inaccessible to the gateway or b) rewriting integrity-protected parts of the packet would invalidate the end-to-end integrity protection.

There are essentially four solutions for this problem:

1. Sharing credentials with gateways enables gateways to transform (e.g., de-compress, convert, etc.) packets and re-apply 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 in the IoT makes conversion between IoT and Internet protocols unnecessary. However, it leads to poor performance because IoT specific optimizations (e.g., stateful or stateless compression) are not possible.

3. Selectively protecting vital and immutable packet parts with a MAC or with encryption requires a careful balance between performance and security. Otherwise, this approach will either result in poor performance (protect as much as possible) or poor security (compress and transform as much as possible).

4. Message authentication codes that sustain transformation can be realized by considering the order of transformation and protection (e.g., by creating a signature before compression so that the gateway can decompress the packet without recalculating the signature). This enables IoT specific optimizations but is more complex and may require application-specific transformations before security is applied. Moreover, it cannot be used with encrypted data because the lack of cleartext prevents gateways from transforming packets.

5. Object security based mechanisms can bridge the protocol worlds, but still requires that the two worlds use the same object security formats. Currently the IoT based object security format based on COSE is different from the Internet based JOSE or CMS. Legacy devices on the Internet side will need to update to the newer IoT protocols to enable real end-to-end security.

To the best of our knowledge, none of the mentioned security protocols provides a fully customizable solution in this problem space.

6.2. 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 and in the IoT network. This aspect is further elaborated and discussed in the T2TRG draft on bootstrapping [ID-bootstrap].

6.3. Operation

After the bootstrapping phase, the system enters the operational phase. During the operational phase, things can relate to the state information created during the bootstrapping phase in order to exchange information securely and in an authenticated fashion. In

this section, we discuss aspects of communication patterns and network dynamics during this phase.

6.3.1. End-to-End Security

Providing end-to-end security is of great importance to address and secure individual T2T or H2T communication within one IoT domain. Moreover, end-to-end security associations are an important measure to bridge the gap between the IoT and the Internet. IKEv2 and HIP, TLS and DTLS provide end-to-end security services including peer entity authentication, end-to-end encryption and integrity protection above the network layer and the transport layer respectively. Once bootstrapped, these functions can be carried out without online connections to third parties, making the protocols applicable for decentralized use in the IoT. However, protocol translation by intermediary nodes may invalidate end-to-end protection measures (see Section 5.1). Also these protocols require end-to-end connectivity between the devices and do not support store-and-forward scenarios. Object security is an option for such scenarios and the work on OSCOAP [ID-OSCOAP] is a potential solution in this space, in particular, in the context of forwarding proxies.

6.3.2. Group Membership and Security

In addition to end-to-end security, group key negotiation is an important security service for the T2Ts and Ts2T communication patterns in the IoT as efficient local broadcast and multicast relies on symmetric group keys.

All discussed protocols only cover unicast communication and therefore do not focus on group-key establishment. However, the Diffie-Hellman keys that are used in IKEv2 and HIP could be used for group Diffie-Hellman key-negotiations. Conceptually, solutions that provide secure group communication at the network layer (IPsec/IKEv2, HIP/Diet HIP) may have an advantage regarding the cryptographic overhead compared to application-focused security solutions (TLS/ DTLS or OSCOAP). This is due to the fact that application-focused solutions require cryptographic operations per group application, whereas network layer approaches may allow to share secure group associations between multiple applications (e.g., for neighbor discovery and routing or service discovery). Hence, implementing shared features lower in the communication stack can avoid redundant security measures.

A number of group key solutions have been developed in the context of the IETF working group MSEC in the context of the MIKEY architecture [WG-MSEC][RFC4738]. These are specifically tailored for multicast and group broadcast applications in the Internet and should also be

considered as candidate solutions for group key agreement in the IoT. The MIKEY architecture 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 environment, where the choice of one or several coordinators and the management of the group key is not trivial.

6.3.3. Mobility and IP Network Dynamics

It is expected that many things (e.g., wearable sensors, and user devices) 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 [RFC4555][RFC4621] extension. MOBIKE refrains from applying heavyweight cryptographic extensions for mobility. However, MOBIKE mandates the use of IPsec tunnel mode which requires to transmit an additional IP header in each packet. This additional overhead could be alleviated by using header compression methods or the Bound End-to-End Tunnel (BEET) mode [ID-Nikander], a hybrid of tunnel and transport mode with smaller packet headers.

HIP offers a simple yet effective mobility management by allowing hosts to signal changes to their associations [RFC5206]. 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 to employ the same mechanisms. TLS and DTLS do not have standards for mobility support, however, work on DTLS mobility exists in the form of an Internet draft [ID-Williams]. The specific need for IP-layer mobility mainly depends on the scenario in which nodes operate. In many cases, mobility support by means of a mobile gateway may suffice to enable mobile IoT networks, such as body sensor networks. However, if individual things change their point of network attachment while communicating, mobility support may gain importance.

6.4. Software update

IoT devices have a reputation for being insecure at the time of manufacture. Yet they are often expected to stay functional in live deployments for years and even decades. Additionally, these devices typically operate unattended with direct Internet connectivity. Therefore, a remote software update mechanism to fix vulnerabilities, to update configuration settings, and for adding new functionality is needed.

Schneier [SchneierSecurity] in his essay expresses concerns about the status of software and firmware update mechanisms for Internet of Things (IoT) devices. He highlights several challenges that hinder mechanisms for secure software update of IoT devices. First, there is a lack of incentives for manufactures, vendors and others on the supply chain to issue updates for their devices. Second, parts of the software running on the IoT devices is simply a binary blob without any source code available. Since the complete source code isn't available, no patches can be written for that piece of code. Third, even when updates are available, users generally have to manually download and install those updates. However, users are never alerted about security updates and many times don't have the necessary expertise to manually administer the required updates.

The FTC staff report on Internet of Things - Privacy & Security in a Connected World [FTCreport] and the Article 29 Working Party Opinion 8/2014 on the on 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.

While powerful IoT devices that run general purpose operating systems can make use of sophisticated software update mechanisms known from the desktop world, a more considerate effort is needed for resource-constrained devices that don't have any operating system and are typically not equipped with a memory management unit or similar tools. The IAB also organized a workshop to understand the challenges for secure software update of IoT devices. A summary of the workshop and the proposed next steps have been documented [iotsu].

6.5. Verifying device behavior

Users often have a false sense of privacy when using new Internet of Things (IoT) appliances such as Internet-connected smart televisions, speakers and cameras. Recent revelations have shown that this user belief is often unfounded. Many IoT device vendors have been caught collecting sensitive private data through these connected appliances with or without appropriate user warnings [cctv].

An IoT device user/owner would like to monitor and know if the device is calling home (i.e. verify its operational behavior). The calling home feature 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 should be ensured that his/her TV is not 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 the IoT device 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.

6.6. End-of-life

Like all commercial devices, most IoT devices will be end-of-lifed by vendors. This may be planned or unplanned (for example when the vendor or manufacturer goes bankrupt). 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 they were end-of-lifed. Admittedly these are not easy for an average users to install and configure on their devices. With the deployment of millions of IoT devices, simpler mechanisms are needed to allow users to add new root-of-trusts and install software and firmware from other sources once the device has been end-of-lifed.

6.7. Penetration testing

Given that the IoT devices often have inadvertent vulnerabilities, both users and developers would want to perform penetration testing on their IoT devices. Nonetheless, since the devices are resource-constrained they often barf of crash even when minimal tests are performed. 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.

6.8. 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 are available in the future for performing cryptanalysis on existing cryptographic algorithms and cipher suites. If this happened, it would have two consequences. First, functionalities enabled by means of RSA/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, e.g., 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.

This would require to update to quantum-resistant alternatives, in particular, for those functionalities involving key exchange, public-key encryption and signatures. While such future planning is hard, it may be a necessity in certain critical IoT deployments which 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 computation 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. RFC7696 provides guidelines for cryptographic algorithm agility.

7. Next Steps towards a Flexible and Secure Internet of Things

This Internet Draft included an overview of both operational and security requirements of things in the Internet of Things, discussed a general threat model and security issues, and introduced a number of potential security suites fitting different types of IoT deployments.

We conclude this document by giving our assessment of the current status of IoT security with respect to addressing the IP security challenges. <<TBD>>

8. Security Considerations

This document reflects upon the requirements and challenges of the security architectural framework for Internet of Things.

9. IANA Considerations

This document contains no request to IANA.

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