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Guidance on RESTful Design for Internet of Things Systems

Abstract

This document gives guidance for designing Internet of Things (IoT) systems that follow the principles of the Representational State Transfer (REST) architectural style. This document is a product of the IRTF Thing-to-Thing Research Group (T2TRG).

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on 15 July 2023.

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1. Introduction

The Representational State Transfer (REST) architectural style [REST] is a set of guidelines and best practices for building distributed hypermedia systems. At its core is a set of constraints,

which when fulfilled enable desirable properties for distributed software systems such as scalability and modifiability. When REST principles are applied to the design of a system, the result is often called RESTful and in particular an API following these principles is called a RESTful API.

Different protocols can be used with RESTful systems, but at the time of writing the most common protocols are HTTP [RFC9110] and CoAP [RFC7252]. Since RESTful APIs are often lightweight and enable loose coupling of system components, they are a good fit for various Internet of Things (IoT) applications, which in general aim at interconnecting the physical world with the virtual world. The goal of this document is to give basic guidance for designing RESTful systems and APIs for IoT applications and give pointers for more information.

Designing a good RESTful IoT system naturally has many commonalities with other Web systems. Compared to others, the key characteristics of many RESTful IoT systems include:

* accommodating for constrained devices [RFC7228], so with IoT, REST is not only used for scaling out (large number of clients on a Web server), but also for scaling down (efficient server on constrained node, e.g., in energy consumption or implementation complexity)

* facilitating efficient transfer over (often) constrained networks and lightweight processing in constrained nodes through compact and simple data formats

* avoiding (or at least minimizing) the need for human interaction through machine-understandable data formats and interaction patterns

* enabling the system to evolve gradually in the field, as the usually large number of endpoints can not be updated simultaneously

* having endpoints that are both clients and servers

2. Terminology

This section explains selected terminology that is commonly used in the context of RESTful design for IoT systems. For terminology of constrained nodes and networks, see [RFC7228]. Terminology on modeling of Things and their affordances (Properties, Actions, and Events) was taken from [I-D.ietf-asdf-sdf].

Action: An affordance that can potentially be used to perform a named operation on a Thing.

Action Result:
A representation sent as a response by a server that does not represent resource state, but the result of the interaction with the originally addressed resource.

Affordance: An element of an interface offered for interaction, defining its possible uses or making clear how it can or should be used. The term is used here for the digital interfaces of a Thing only; the Thing might also have physical affordances such as buttons, dials, and displays.

Cache: A local store of response messages and the subsystem that controls storage, retrieval, and deletion of messages in it.

Client: A node that sends requests to servers and receives responses; it therefore has the initiative to interact. In RESTful IoT systems it is common for nodes to have more than one role (i.e., to be both server and client; see Section 3.1).

Client State: The state kept by a client between requests. This typically includes the currently processed representation, the set of active requests, the history of requests, bookmarks (URIs stored for later retrieval), and application-specific state (e.g., local variables). (Note that this is called "Application State" in [REST], which has some ambiguity in modern (IoT) systems where resources are highly dynamic and the overall state of the distributed application (i.e., application state) is reflected in the union of all Client States and Resource States of all clients and servers involved.)

Content Type: A string that carries the media type plus potential parameters for the representation format such as "text/plain;charset=UTF-8".

Content Negotiation: The practice of determining the "best" representation for a client when examining the current state of a resource. The most common forms of content negotiation are Proactive Content Negotiation and Reactive Content Negotiation.

Dereference: To use an access mechanism (e.g., HTTP or CoAP) to interact with the resource of a URI.

Dereferenceable URI: A URI that can be dereferenced, i.e., interaction with the identified resource is possible. Not all HTTP or CoAP URIs are dereferenceable, e.g., when the target resource does not exist.

Event: An affordance that can potentially be used to (recurrently) obtain information about what happened to a Thing, e.g., through server push.

Form:
A hypermedia control that enables a client to construct more complex requests, e.g., to change the state of a resource or perform specific queries.

Forward Proxy: An intermediary that is selected by a client, usually via local configuration rules, and that can be tasked to make requests on behalf of the client. This may be useful, for example, when the client lacks the capability to make the request itself or to service the response from a cache in order to reduce response time, network bandwidth, and energy consumption.

Gateway: A reverse proxy that provides an interface to a non-RESTful system such as legacy systems or alternative technologies such as Bluetooth Attribute Profile (ATT) or Generic Attribute Profile (GATT). See also "Reverse Proxy".

Hypermedia Control: Information provided by a server on how to use its RESTful API; usually a URI and instructions on how to dereference it for a specific interaction. Hypermedia Controls are the serialized/encoded affordances of hypermedia systems.

Idempotent Method: A method where multiple identical requests with that method lead to the same visible resource state as a single such request.

Intermediary: System component in both server and client role. See "Forward Proxy", "Gateway", and "Reverse Proxy".

Link: A hypermedia control that enables a client to navigate between resources and thereby change the client state.

Link Relation Type: An identifier that describes how the link target resource relates to the current resource (see [RFC8288]).

Media Type: An IANA-registered string such as "text/html" or "application/json" that is used to label representations so that it is known how the representation should be interpreted and how it is encoded.

Method: An operation associated with a resource. Common methods include GET, PUT, POST, and DELETE (see Section 3.5 for details).

Origin Server: A server that is the definitive source for representations of its resources and the ultimate recipient of any request that intends to modify its resources. In contrast, intermediaries (such as proxies caching a representation) can assume the role of a server, but are not the source for representations as these are acquired from the origin server.

Proactive Content Negotiation: A content negotiation mechanism where the server selects a representation based on the expressed preference of the client. For example, an IoT application could send a request that prefers to accept the media type "application/senml+json".

Property: An affordance that can potentially be used to read, write, and/or observe state on a Thing.

Reactive Content Negotiation: A content negotiation mechanism where the client selects a representation from a list of available representations. The list may, for example, be included by a server in an initial response. If the user agent is not satisfied by the initial response representation, it can request one or more of the alternative representations, selected based on metadata (e.g., available media types) included in the response.

Representation: A serialization that represents the current or intended state of a resource and that can be transferred between client and server. REST requires representations to be self-describing, meaning that there must be metadata that allows peers to understand which representation format is used. Depending on the protocol needs and capabilities, there can be additional metadata that is transmitted along with the representation.

Representation Format: A set of rules for serializing resource state. On the Web, the most prevalent representation format is HTML. Other common formats include plain text and formats based on JSON [RFC8259], XML, or RDF. Within IoT systems, often compact formats based on JSON, CBOR [RFC8949], and EXI [W3C.REC-exi-20110310] are used.

Representational State Transfer (REST): An architectural style for Internet-scale distributed hypermedia systems.

Resource: An item of interest identified by a URI. Anything that can be named can be a resource. A resource often encapsulates a piece of state in a system. Typical resources in an IoT system can be, e.g., a sensor, the current value of a sensor, the location of a device, or the current state of an actuator.

Resource State: A model of the possible states of a resource that is expressed in supported representation formats. Resources can change state because of REST interactions with them, or they can change state for reasons outside of the REST model, e.g.,

business logic implemented on the server side such as sampling a sensor.

Resource Type: An identifier that annotates the application-semantics of a resource (see Section 3.1 of [RFC6690]).

Reverse Proxy: An intermediary that appears as a server towards the client, but satisfies the requests by making its own request toward the origin server (possibly via one or more other intermediaries) and replying accordingly. A reverse proxy is often used to encapsulate legacy services, to improve server performance through caching, or to enable load balancing across multiple machines.

Safe Method: A method that does not result in any state change on the origin server when applied to a resource.

Server: A node that listens for requests, performs the requested operation, and sends responses back to the clients. In RESTful IoT systems it is common for nodes to have more than one role (i.e., to be both server and client; see Section 3.1).

Thing: A physical item that is made available in the Internet of Things, thereby enabling digital interaction with the physical world for humans, services, and/or other Things.

Transfer protocols: In particular in the IoT domain, protocols above the transport layer that are used to transfer data objects and provide semantics for operations on the data.

Transfer layer: Re-usable part of the application layer used to transfer the application specific data items using a standard set of methods that can fulfill application-specific operations.

Uniform Resource Identifier (URI): A global identifier for resources. See Section 3.3 for more details.

3. Basics

3.1. Architecture

Components of a RESTful system assume one of two roles when interacting: client or server. Classic user agents (e.g., Web browsers) are always in the client role and have the initiative to interact with other components. Origin servers govern over the resources they host and always have the server role, in which they wait for requests.

Simple IoT devices, such as connected sensors and actuators, are commonly acting as servers to expose their physical world

interaction capabilities (e.g., temperature measurement or door lock control capability) as resources. A typical example of an IoT system client is a cloud service that retrieves data from the sensors and commands the actuators based on the sensor information. Alternatively an IoT data storage system could work as a server where IoT sensor devices send their data in client role.

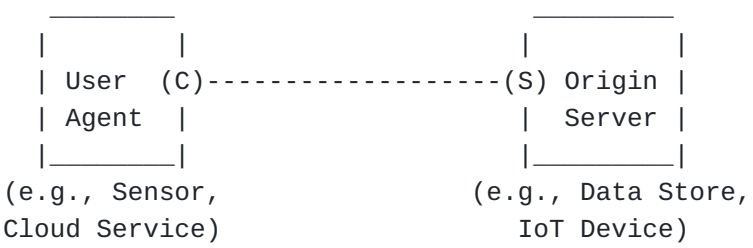


Figure 1: Client-Server Communication

Intermediaries implement both roles, as they receive requests in server role and satisfy them by issuing their own requests in client role. They do not, however, have initiative to issue requests on their own. They often provide a cache to improve the overall system performance or, in the case of IoT, shield constrained devices from too many requests. They can also translate requests to different RESTful protocols, for instance, as CoAP-HTTP cross-proxies [RFC8075].

A forward proxy is an intermediary selected by the user agent because of local application or system configuration. It then forwards the request on behalf of the user agent, for instance, when the user agent is restricted by firewall rules or otherwise lacks the capability itself (e.g., a CoAP device contacting an HTTP origin server).

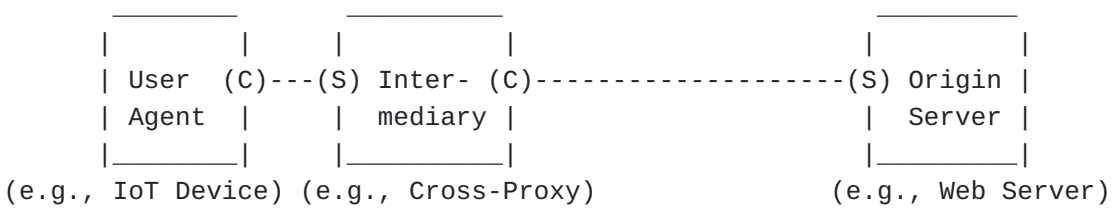


Figure 2: Communication with Forward Proxy

A reverse proxy is usually imposed by the origin server to transparently implement new features such as load balancing or interfaces to non-RESTful services such as legacy systems or alternative technologies such as Bluetooth ATT/GATT [BTCorev5.3]. In the latter case, reverse proxies are usually called gateways. Because of the Layered System constraint of REST, which says that a

client cannot see beyond the server it is connected to, the user agent is not and does not need to be aware of the changes introduced through reverse proxies.

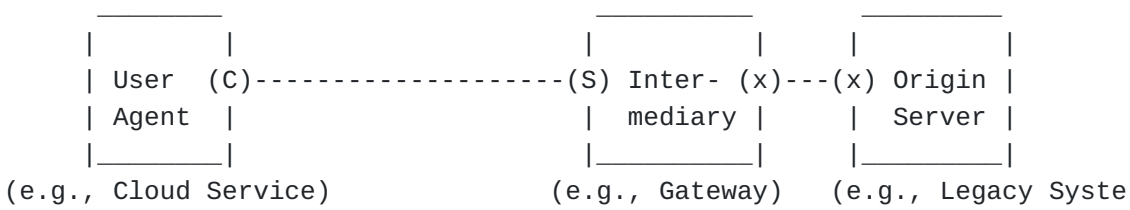


Figure 3: Communication with Reverse Proxy

Components in IoT systems often implement both roles. Unlike intermediaries, however, they can take the initiative as a client (e.g., to register with a directory, such as CoRE Resource Directory [RFC9176], or to interact with another IoT device) and act as origin server at the same time (e.g., to serve sensor values or provide an actuator interface).

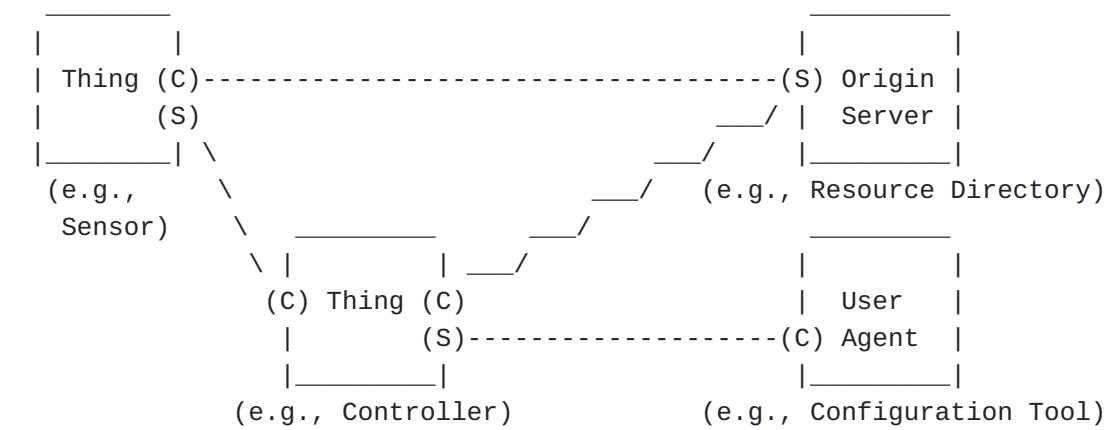


Figure 4: Communication with Things

3.2. System Design

When designing a RESTful system, the primary effort goes into modeling the application as distributed state and assigning it to the different components (i.e., clients and servers). The secondary effort is then selecting or designing the necessary representation formats to exchange information and enable interaction between the components through resources.

Which resources exist and how they can be used is expressed by the server in so-called affordances, a concept adopted in the field of human-computer interaction [HCI]. Affordances can be described in responses (e.g., the initial response from a well-known resource) or

out of band (e.g., through a W3C Thing Description document [W3C-TD] from a directory). In RESTful systems, affordances are encoded as hypermedia controls (links and forms): links allow to navigate between resources and forms enable clients to formulate more complex requests (e.g., to modify a resource or perform a query).

A physical door may have a door knob as affordance, indicating that the door can be opened by twisting the knob; a keyhole may indicate that it can be locked. For Things in the IoT, these affordances may be serialized as two hypermedia forms, which include semantic identifiers from a controlled vocabulary (e.g., schema.org) and the instructions on how to formulate the requests for opening and locking, respectively. Overall, this allows to realize a Uniform Interface (see Section 4.4), which enables loose coupling between clients and servers.

Hypermedia controls span a kind of state machine, where the nodes are resources or action results and the transitions are links or forms. Clients run this distributed state machine (i.e., the application) by retrieving representations, processing the data, and following the included links and/or submitting forms to trigger the corresponding transition. This is usually done by retrieving the current state, modifying the copy of the state on the client side, and transferring the new state to the server in the form of new representations -- rather than calling a service and modifying the state on the server side.

Client state encompasses the current state of the described state machine and the possible next transitions derived from the hypermedia controls within the currently processed representation. Furthermore, clients can have part of the state of the distributed application in local variables.

Resource state includes the more persistent data of an application (i.e., data that exists independent of individual clients). This can be static data such as device descriptions, persistent data such as system configurations, but also dynamic data such as the current value of a sensor on a Thing.

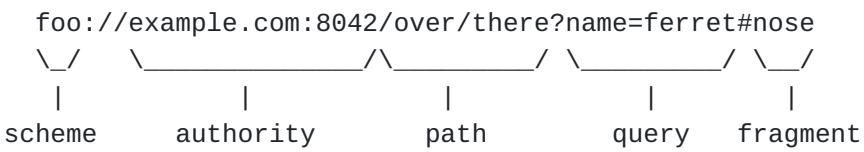
In the design, it is important to distinguish between "client state" and "resource state", and keep them separate. Following the Stateless constraint, the client state must be kept only on clients. That is, there is no establishment of shared information about past and future interactions between client and server (usually called a session). On the one hand, this makes requests a bit more verbose since every request must contain all the information necessary to process it. On the other hand, this makes servers efficient and scalable, since they do not have to keep any state about their clients. Requests can easily be distributed over multiple worker

threads or server instances (cf. load balancing). For IoT systems, this constraint lowers the memory requirements for server implementations, which is particularly important for constrained servers (e.g., sensor nodes) and servers serving large amount of clients (e.g., Resource Directory).

3.3. Uniform Resource Identifiers (URIs)

An important aspect of RESTful API design is to model the system as a set of resources, which potentially can be created and/or deleted dynamically and whose state can be retrieved and/or modified.

Uniform Resource Identifiers (URIs) are used to indicate resources for interaction, to reference a resource from another resource, to advertise or bookmark a resource, or to index a resource by search engines.



A URI is a sequence of characters that matches the syntax defined in [RFC3986]. It consists of a hierarchical sequence of five components: scheme, authority, path, query, and fragment identifier (from most significant to least significant), while not all components are necessary to form a valid URI. A scheme creates a namespace for resources and defines how the following components identify a resource within that namespace. The authority identifies an entity that governs part of the namespace, such as the server "www.example.org" in the "https" scheme. A hostname (e.g., a fully qualified domain name) or an IP address literal, optionally followed by a transport layer port number, are usually used for the authority component. The path and optional query contain data to identify a resource within the scope of the scheme-dependent naming authority (i.e., "http://www.example.org" is a different authority than "https://www.example.org"); if no path is given, the root resource is addressed. The fragment identifier allows referring to some portion of the resource, such as a Record in a SenML Pack (Section 9 of [RFC8428]). However, fragment identifiers are processed only at client side and not sent on the wire. [RFC8820] provides more details on URI design and ownership with best current practices for establishing URI structures, conventions, and formats.

For RESTful IoT applications, typical schemes include "https", "coaps", "http", and "coap". These refer to HTTP and CoAP, with and without Transport Layer Security (TLS, [RFC5246] for TLS 1.2 and [RFC8446] for TLS 1.3). (CoAP uses Datagram TLS (DTLS) [RFC6347] [RFC9147], the variant of TLS for UDP.) These four schemes also

provide means for locating the resource; using the protocols HTTP for "http" and "https" and CoAP for "coap" and "coaps". If the scheme is different for two URIs (e.g., "coap" vs. "coaps"), it is important to note that even if the remainder of the URI is identical, these are two different resources, in two distinct namespaces.

Some schemes are for URIs with the main purpose as identifiers, and hence are not dereferenceable, e.g., the "urn" scheme can be used to construct unique names in registered namespaces. In particular the "urn:dev" URI [RFC9039] details multiple ways for generating and representing endpoint identifiers of IoT devices.

The query parameters can be used to parameterize the resource. For example, a GET request may use query parameters to request the server to send only certain kind data of the resource (i.e., filtering the response). Query parameters in PUT and POST requests do not have such established semantics and are not used consistently. Whether the order of the query parameters matters in URIs is up to the server implementation; they might even be re-ordered, for instance by intermediaries. Therefore, applications should not rely on their order; see Section 3.3.4 of [RFC6943] for more details.

Due to the relatively complex processing rules and text representation format, URI handling can be difficult to implement correctly in constrained devices. Constrained Resource Identifiers [I-D.ietf-core-href] provide a CBOR-based format of URIs that is better suited for resource constrained devices.

3.4. Representations

Clients can retrieve the resource state from a server or manipulate resource state on the (origin) server by transferring resource representations. Resource representations must have metadata that identifies the representation format used, so the representations can be interpreted correctly. This is usually a simple string such as the IANA-registered Internet Media Types. Typical media types for IoT systems include:

* "text/plain" for simple text (more precisely "text/plain;charset=UTF-8" for UTF-8 encoding)

* "application/octet-stream" for arbitrary binary data

* "application/json" for the JSON format [RFC8259]

* "application/cbor" for CBOR [RFC8949]

* "application/exi" for EXI [W3C.REC-exi-20110310]

* "application/link-format" for CoRE Link Format [RFC6690]

* "application/senml+json" and "application/senml+cbor" for Sensor Measurement Lists (SenML) data [RFC8428]

A full list of registered Internet Media Types is available at the IANA registry [IANA-media-types]. Numerical identifiers for media types, parameters, and content codings registered for use with CoAP are listed at CoAP Content-Formats IANA registry [IANA-CoAP-media].

The terms "media type", "content type" (media type plus potential parameters), and "content format" (short identifier of content type and content coding, abbreviated for historical reasons "ct") are often used when referring to representation formats used with CoAP. The differences between these terms are discussed in more detail in Section 2 of [RFC9193].

3.5. HTTP/CoAP Methods

Section 9.3 of [RFC9110] defines the set of methods in HTTP; Section 5.8 of [RFC7252] defines the set of methods in CoAP. As part of the Uniform Interface constraint, each method can have certain properties that give guarantees to clients.

Safe methods do not cause any state change on the origin server when applied to a resource. For example, the GET method only returns a representation of the resource state but does not change the resource. Thus, it is always safe for a client to retrieve a representation without affecting server-side state.

Idempotent methods can be applied multiple times to the same resource while causing the same eventual resource state as a single such request (unless something else caused the resource state to change). For example, the PUT method replaces the state of a resource with a new state; replacing the state multiple times with the same new state still results in the same state for the resource. However, responses from the server can be different when the same idempotent method is used multiple times. For example when DELETE is used twice on an existing resource, the first request would remove the association and return a success acknowledgement, whereas the second request would likely result in an error response due to non-existing resource (note that neither response is a representation of the resource).

The following lists the most relevant methods and gives a short explanation of their semantics.

3.5.1. GET

The GET method requests a current representation for the target resource, while the origin server must ensure that there are no side effects on the resource state. Only the origin server needs to know how each of its resource identifiers corresponds to an implementation and how each implementation manages to select and send a current representation of the target resource in a response to GET.

A payload within a GET request message has no defined semantics.

The GET method is safe and idempotent.

3.5.2. POST

The POST method requests that the target resource process the representation enclosed in the request according to the resource's own specific semantics.

If one or more resources has been created on the origin server as a result of successfully processing a POST request, the origin server sends a 201 (Created) response containing a Location header field (with HTTP) or Location-Path and/or Location-Query Options (with CoAP) that provide an identifier for the resource created. The server also includes a representation that describes the status of the request while referring to the new resource(s).

The POST method is not safe nor idempotent.

3.5.3. PUT

The PUT method requests that the state of the target resource be created or replaced with the state defined by the representation enclosed in the request message payload. A successful PUT of a given representation would suggest that a subsequent GET on that same target resource will result in an equivalent representation being sent. A PUT request applied to the target resource can have side effects on other resources.

The fundamental difference between the POST and PUT methods is highlighted by the different intent for the enclosed representation. The target resource in a POST request is intended to handle the enclosed representation according to the resource's own semantics, whereas the enclosed representation in a PUT request is defined as replacing the state of the target resource. Hence, the intent of PUT is idempotent and visible to intermediaries, even though the exact effect is only known by the origin server.

The PUT method is not safe, but is idempotent.

3.5.4. DELETE

The DELETE method requests that the origin server remove the association between the target resource and its current functionality.

If the target resource has one or more current representations, they might or might not be destroyed by the origin server, and the associated storage might or might not be reclaimed, depending entirely on the nature of the resource and its implementation by the origin server.

The DELETE method is not safe, but is idempotent.

3.5.5. FETCH

The CoAP-specific FETCH method [RFC8132] requests a representation of a resource parameterized by a representation enclosed in the request.

The fundamental difference between the GET and FETCH methods is that the request parameters are included as the payload of a FETCH request, while in a GET request they are typically part of the query string of the request URI.

The FETCH method is safe and idempotent.

3.5.6. PATCH

The PATCH method [RFC5789] [RFC8132] requests that a set of changes described in the request entity be applied to the target resource.

The PATCH method is not safe nor idempotent.

The CoAP-specific iPATCH method is a variant of the PATCH method that is not safe, but is idempotent.

3.6. HTTP/CoAP Status/Response Codes

Section 15 of [RFC9110] defines a set of Status Codes in HTTP that are assigned by the server to indicate whether a request was understood and satisfied, and how to interpret the answer. Similarly, Section 5.9 of [RFC7252] defines the set of Response Codes in CoAP.

The codes consist of three digits (e.g., "404" with HTTP or "4.04" with CoAP) where the first digit expresses the class of the code. Implementations do not need to understand all codes, but the class of the code must be understood. Codes starting with 1 are informational; the request was received and being processed (not

available in CoAP). Codes starting with 2 indicate a successful request. Codes starting with 3 indicate redirection; further action is needed to complete the request (not available in CoAP). Codes stating with 4 and 5 indicate errors. The codes starting with 4 mean client error (e.g., bad syntax in the request) whereas codes starting with 5 mean server error; there was no apparent problem with the request, but the server was not able to fulfill the request.

Responses may be stored in a cache to satisfy future, equivalent requests. HTTP and CoAP use two different patterns to decide what responses are cacheable. In HTTP, the cacheability of a response depends on the request method (e.g., responses returned in reply to a GET request are cacheable). In CoAP, the cacheability of a response depends on the response code (e.g., responses with code 2.04 are cacheable). This difference also leads to slightly different codes starting with 2; for example, CoAP does not have a 2.00 response code whereas 200 ("OK") is commonly used with HTTP.

4. REST Constraints

The REST architectural style defines a set of constraints for the system design. When all constraints are applied correctly, REST enables architectural properties of key interest [REST]:

*Performance

*Scalability

*Reliability

*Simplicity

*Modifiability

*Visibility

*Portability

The following subsections briefly summarize the REST constraints and explain how they enable the listed properties.

4.1. Client-Server

As explained in the Architecture section, RESTful system components have clear roles in every interaction. Clients have the initiative to issue requests, intermediaries can only forward requests, and servers respond to requests, while origin servers are the ultimate recipient of requests that intend to modify resource state.

This improves simplicity and visibility (also for digital forensics), as it is clear which component started an interaction. Furthermore, it improves modifiability through a clear separation of concerns.

In IoT systems, endpoints often assume both roles of client and (origin) server simultaneously. When an IoT device has initiative (because there is a user, e.g., pressing a button, or installed rules/policies), it acts as a client. When a device offers a service, it is in server role.

4.2. Stateless

The Stateless constraint requires messages to be self-contained. They must contain all the information to process it, independent from previous messages. This allows to strictly separate the client state from the resource state.

This improves scalability and reliability, since servers or worker threads can be replicated. It also improves visibility because message traces contain all the information to understand the logged interactions. Furthermore, the Stateless constraint enables caching.

For IoT, the scaling properties of REST become particularly important. Note that being self-contained does not necessarily mean that all information has to be inlined. Constrained IoT devices may choose to externalize metadata and hypermedia controls using Web linking, so that only the dynamic content needs to be sent and the static content such as schemas or controls can be cached.

4.3. Cache

This constraint requires responses to have implicit or explicit cache-control metadata. This enables clients and intermediaries to store responses and re-use them to locally answer future requests. The cache-control metadata is necessary to decide whether the information in the cached response is still fresh or stale and needs to be discarded.

A cache improves performance, as less data needs to be transferred and response times can be reduced significantly. Needing fewer transfers also improves scalability, as origin servers can be protected from too many requests. Local caches furthermore improve reliability, since requests can be answered even if the origin server is temporarily not available.

Introducing additional components to perform caching only makes sense when the data is used by multiple participants (otherwise client-side caching would be enough). In IoT systems, however, it might make sense to cache also individual data to protect

constrained devices and networks from frequent requests of data that does not change often. Security often hinders the ability to cache responses. For IoT systems, object security [RFC8613] may be preferable over transport layer security, as it enables intermediaries to cache responses while preserving security.

4.4. Uniform Interface

All RESTful APIs use the same, uniform interface independent of the application. This simple interaction model is enabled by exchanging representations and modifying state locally, which simplifies the interface between clients and servers to a small set of methods to retrieve, update, and delete state. This small set can apply to many different applications.

In contrast, in a service-oriented RPC approach, state is modified remotely, directly by the server, and only the instruction what to modify is exchanged. Also retrieving state for local use is usually solved through specific instructions depending on the individual information. This requires to model all the necessary instructions beforehand and assign them to named procedures. This results in a application-specific interface with a large set of methods/ procedures. Moreover, it is also likely that different parties come up with different ways how to modify state, including the naming of the procedures. Hence, even very similar applications are likely not interoperable.

A REST interface is fully defined by:

- URIs to identify resources
- representation formats to represent and manipulate resource state
- self-descriptive messages with a standard set of methods (e.g., GET, POST, PUT, DELETE with their guaranteed properties)
- hypermedia controls within representations

The concept of hypermedia controls is also known as HATEOAS: Hypermedia As The Engine Of Application State [HATEOAS]. The origin server embeds controls for the interface into its representations and thereby informs the client about possible next requests. The most used control for RESTful systems today is Web Linking [RFC8288]. Hypermedia forms are more powerful controls that describe how to construct more complex requests, including representations to modify resource state.

While this is the most complex constraint (in particular the hypermedia controls), it improves many key properties. It improves simplicity, as uniform interfaces are easier to understand. The

self-descriptive messages improve visibility. The limitation to a known set of representation formats fosters portability. Most of all, however, this constraint is the key to modifiability, as hypermedia-driven, uniform interfaces allow clients and servers to evolve independently, and hence enable a system to evolve.

For a large number of IoT applications, the hypermedia controls are mainly used for the discovery of resources, as they often serve sensor data. Such resources are "dead ends", as they usually do not link any further and only have one form of interaction: fetching the sensor value. For IoT, the critical parts of the Uniform Interface constraint are the descriptions of messages and representation formats used. Simply using, for instance, "application/json" does not help machine clients to understand the semantics of the representation. Yet defining very precise media types limits the re-usability and interoperability. Representation formats such as SenML [RFC8428] try to find a good trade-off between precision and re-usability. Another approach is to combine a generic format such as JSON with syntactic as well as semantic annotations (see [I-D.handrews-json-schema-validation] and [W3C-TD], resp.).

4.5. Layered System

This constraint enforces that a client cannot see beyond the server with which it is interacting.

A layered system is easier to modify, as topology changes become transparent (i.e., remain unnoticed by previous layers). This in turn helps scalability, as reverse proxies such as load balancers can be introduced without changing the client side. The clean separation of concerns in layers helps with simplicity.

IoT systems greatly benefit from this constraint, as it allows to effectively shield constrained devices behind intermediaries. It is also the basis for gateways, which are used to integrate other (IoT) ecosystems.

4.6. Code-on-Demand

This principle enables origin servers to ship code to clients.

Code-on-Demand improves modifiability, since new features can be deployed during runtime (e.g., support for a new representation format). It also improves performance, as the server can provide code for local pre-processing before transferring the data.

As of today, code-on-demand has not been explored much in IoT systems. Aspects to consider are that either one or both nodes are constrained and might not have the resources to host or dynamically fetch and execute such code. Moreover, the origin server often has

no understanding of the actual application a mashup client realizes. Still, code-on-demand can be useful for small polyfills [POLYFILLS], e.g., to decode payloads, and potentially other features in the future.

5. Hypermedia-driven Applications

Hypermedia-driven applications take advantage of hypermedia controls, i.e., links and forms, which are embedded in representations or response message headers. A hypermedia client is a client that is capable of processing these hypermedia controls. Hypermedia links can be used to give additional information about a resource representation (e.g., the source URI of the representation) or pointing to other resources. The forms can be used to describe the structure of the data that can be sent (e.g., with a POST or PUT method) to a server, or how a data retrieval (e.g., GET) request for a resource should be formed. In a hypermedia-driven application the client interacts with the server using only the hypermedia controls, instead of selecting methods and/or constructing URIs based on out-of-band information, such as API documentation. The Constrained RESTful Application Language (CoRAL) [I-D.ietf-core-coral] provides a hypermedia-format that is suitable for constrained IoT environments.

5.1. Motivation

The advantage of this approach is increased evolvability and extensibility. This is important in scenarios where servers exhibit a range of feature variations, where it's expensive to keep evolving client knowledge and server knowledge in sync all the time, or where there are many different client and server implementations. Hypermedia controls serve as indicators in capability negotiation. In particular, they describe available resources and possible operations on these resources using links and forms, respectively.

There are multiple reasons why a server might introduce new links or forms:

* The server implements a newer version of the application. Older clients ignore the new links and forms, while newer clients are able to take advantage of the new features by following the new links and submitting the new forms.

* The server offers links and forms depending on the current state. The server can tell the client which operations are currently valid and thus help the client navigate the application state machine. The client does not have to have knowledge which operations are allowed in the current state or make a request just to find out that the operation is not valid.

* The server offers links and forms depending on the client's access control rights. If the client is unauthorized to perform a certain operation, then the server can simply omit the links and forms for that operation.

5.2. Knowledge

A client needs to have knowledge of a couple of things for successful interaction with a server. This includes what resources are available, what representations of resource states are available, what each representation describes, how to retrieve a representation, what state changing operations on a resource are possible, how to perform these operations, and so on.

Some part of this knowledge, such as how to retrieve the representation of a resource state, is typically hard-coded in the client software. For other parts, a choice can often be made between hard-coding the knowledge or acquiring it on-demand. The key to success in either case is the use of in-band information for identifying the knowledge that is required. This enables the client to verify that it has all the required knowledge or to acquire missing knowledge on-demand.

A hypermedia-driven application typically uses the following identifiers:

* URI schemes that identify communication protocols,
* Internet Media Types that identify representation formats,
* link relation types or resource types that identify link semantics,
* form relation types that identify form semantics,
* variable names that identify the semantics of variables in templated links, and
* form field names that identify the semantics of form fields in forms.

The knowledge about these identifiers as well as matching implementations have to be shared a priori in a RESTful system.

5.3. Interaction

A client begins interacting with an application through a GET request on an entry point URI. The entry point URI is the only URI a client is expected to know before interacting with an application. From there, the client is expected to make all requests by following

links and submitting forms that are provided in previous responses. The entry point URI can be obtained, for example, by manual configuration or some discovery process (e.g., DNS-SD [RFC6763] or Resource Directory [RFC9176]). For Constrained RESTful environments "/.well-known/core", a relative URI is defined as a default entry point for requesting the links hosted by servers with known or discovered addresses [RFC6690].

5.4. Hypermedia-driven Design Guidance

Assuming self-describing representation formats (i.e., human-readable with carefully chosen terms or processable by a formatting tool) and a client supporting the URI scheme used, a good rule of thumb for a good hypermedia-driven design is the following: A developer should only need an entry point URI to drive the application. All further information how to navigate through the application (links) and how to construct more complex requests (forms) are published by the server(s). There must be no need for additional, out-of-band information (e.g., an API specification).

For machines, a well-chosen set of information needs to be shared a priori to agree on machine-understandable semantics. Agreeing on the exact semantics of terms for relation types and data elements will of course also help the developer. [I-D.hartke-core-apps] proposes a convention for specifying the set of information in a structured way.

6. Design Patterns

Certain kinds of design problems are often recurring in a variety of domains, and often re-usable design patterns can be applied to them. Also, some interactions with a RESTful IoT system are straightforward to design; a classic example of reading a temperature from a thermometer device is almost always implemented as a GET request to a resource that represents the current value of the thermometer. However, certain interactions, for example data conversions or event handling, do not have as straightforward and well established ways to represent the logic with resources and REST methods.

The following sections describe how common design problems such as different interactions can be modeled with REST and what are the benefits of different approaches.

6.1. Collections

A common pattern in RESTful systems across different domains is the collection. A collection can be used to combine multiple resources together by providing resources that consist of set of (often partial) representations of resources, called items, and links to

resources. The collection resource also defines hypermedia controls for managing and searching the items in the collection.

Examples of the collection pattern in RESTful IoT systems include the CoRE Resource Directory [RFC9176], CoAP pub/sub broker [I-D.ietf-core-coap-pubsub], and resource discovery via ".well-known/core". Collection+JSON [CollectionJSON] is an example of a generic collection Media Type.

6.2. Calling a Procedure

To modify resource state, clients usually use GET to retrieve a representation from the server, modify that locally, and transfer the resulting state back to the server with a PUT (see Section 4.4). Sometimes, however, the state can only be modified on the server side, for instance, because representations would be too large to transfer or part of the required information shall not be accessible to clients. In this case, resource state is modified by calling a procedure (or "function"). This is usually modeled with a POST request, as this method leaves the behavior semantics completely to the server. Procedure calls can be divided into two different classes based on how long they are expected to execute: "instantly" returning and long-running.

6.2.1. Instantly Returning Procedures

When the procedure can return within the expected response time of the system, the result can be directly returned in the response. The result can either be actual content or just a confirmation that the call was successful. In either case, the response does not contain a representation of the resource, but a so-called action result. Action results can still have hypermedia controls to provide the possible transitions in the application state machine.

6.2.2. Long-running Procedures

When the procedure takes longer than the expected response time of the system, or even longer than the response timeout, it is a good pattern to create a new resource to track the "task" execution. The server would respond instantly with a "Created" status (HTTP code 201 or CoAP 2.01) and indicate the location of the task resource in the corresponding header field (or CoAP option) or as a link in the action result. The created resource can be used to monitor the progress, to potentially modify queued tasks or cancel tasks, and to eventually retrieve the result.

Monitoring information would be modeled as state of the task resource, and hence be retrievable as representation. CoAP Observe can help to be notified efficiently about completion or other changes to this information. The result -- when available -- can be

embedded in the representation or given as a link to another sub-resource. Modifying tasks can be modeled with forms that either update sub-resources via PUT or do a partial write using PATCH or POST. Canceling a task would be modeled with a form that uses DELETE to remove the task resource.

6.2.3. Conversion

A conversion service is a good example where REST resources need to behave more like a procedure call. The knowledge of converting from one representation to another is located only at the server to relieve clients from high processing or storing lots of data. There are different approaches that all depend on the particular conversion problem.

As mentioned in the previous sections, POST requests are a good way to model functionality that does not necessarily affect resource state. When the input data for the conversion is small and the conversion result is deterministic, however, it can be better to use a GET request with the input data in the URI query part. The query is parameterizing the conversion resource, so that it acts like a look-up table. The benefit is that results can be cached also for HTTP (where responses to POST are not cacheable). In CoAP, cacheability depends on the response code, so that also a response to a POST request can be made cacheable through a 2.05 Content code.

When the input data is large or has a binary encoding, it is better to use POST requests with a proper Media Type for the input representation. A POST request is also more suitable, when the result is time-dependent and the latest result is expected (e.g., exchange rates).

6.2.4. Events as State

In event-centric paradigms such as Publish-Subscribe (pub/sub), events are usually represented by an incoming message that might even be identical for each occurrence. Since the messages are queued, the receiver is aware of each occurrence of the event and can react accordingly. For instance, in an event-centric system, ringing a doorbell would result in a message being sent that represents the event that it was rung.

In resource-oriented paradigms such as REST, messages usually carry the current state of the remote resource, independent from the changes (i.e., events) that have lead to that state. In a naive yet natural design, a doorbell could be modeled as a resource that can have the states unpressed and pressed. There are, however, a few issues with this approach. Polling (i.e., periodically retrieving) the doorbell resource state is not a good option, as the client is

highly unlikely to be able to observe all the changes in the pressed state with any realistic polling interval. When using CoAP Observe with Confirmable notifications, the server will usually send two notifications for the event that the doorbell was pressed: notification for changing from unpressed to pressed and another one for changing back to unpressed. If the time between the state changes is very short, the server might drop the first notification, as Observe guarantees eventual consistency only (see Section 1.3 of [RFC7641]).

The solution is to pick a state model that fits better to the application. In the case of the doorbell -- and many other event-driven resources -- the solution could be a counter that counts how often the bell was pressed. The corresponding action is taken each time the client observes a change in the received representation. In the case of a network outage, this could lead to a ringing sound long after the bell was rung. Also including a timestamp of the last counter increment in the state can help to suppress ringing a sound when the event has become obsolete. Another solution would be to change the client/server roles of the doorbell button and the ringer, as described in Section 6.3.

6.3. Server Push

Overall, a universal mechanism for server push, that is, change-of-state notifications and stand-alone event notifications, is still an open issue that is being discussed in the Thing-to-Thing Research Group. It is connected to the state-event duality problem and custody transfer, that is, the transfer of the responsibility that a message (e.g., event) is delivered successfully.

A proficient mechanism for change-of-state notifications is currently only available for CoAP: Observing resources [RFC7641]. The CoAP Observe mechanism offers eventual consistency, which guarantees "that if the resource does not undergo a new change in state, eventually all registered observers will have a current representation of the latest resource state". It intrinsically deals with the challenges of lossy networks, where notifications might be lost, and constrained networks, where there might not be enough bandwidth to propagate all changes.

For stand-alone event notifications, that is, where every single notification contains an identifiable event that must not be lost, observing resources is not a good fit. A better strategy is to model each event as a new resource, whose existence is notified through change-of-state notifications of an index resource [I-D.bormann-t2trg-stp]. Large numbers of events will cause the notification to grow large, as it needs to contain a large number of Web links. Block-wise transfers [RFC7959] or pagination can help

here. When the links are ordered by freshness of the events, the first block or page can already contain all links to new events. Then, observers do not need to retrieve the remaining blocks or pages from the server, but only the representations of the new event resources.

An alternative pattern is to exploit the dual roles of IoT devices, in particular when using CoAP: they are usually client and server at the same time. An endpoint interested in observing the events would subscribe to them by registering a callback URI at the origin server, e.g., using a POST request with the URI or a hypermedia document in the payload, and receiving the location of a temporary "subscription resource" as handle in the response. The origin server would then publish events by sending requests containing the event data to the observer's callback URI; here POST can be used to add events to a collection located at the callback URI or PUT can be used when the event data is a new state that shall replace the outdated state at the callback URI. The cancellation can be modeled through deleting the subscription resource. This pattern makes the origin server responsible for delivering the event notifications. This goes beyond retransmissions of messages; the origin server is usually supposed to queue all undelivered events and to retry until successful delivery or explicit cancellation. In HTTP, this pattern is known as REST Hooks.

Methods for configuring server push and notification conditions with CoAP are provided by the CoRE Dynamic Resource Linking specification [I-D.ietf-core-dynlink].

In HTTP, there exist a number of workarounds to enable server push, e.g., long polling and streaming [RFC6202] or server-sent events [W3C.REC-html5-20141028]. In IoT systems, long polling can introduce a considerable overhead, as the request has to be repeated for each notification. Streaming and server-sent events (the latter is actually an evolution of the former) are more efficient, as only one request is sent. However, there is only one response header and subsequent notifications can only have content. Individual status and metadata needs to be included in the content message. This reduces HTTP again to a pure transport, as its status signaling and metadata capabilities cannot be used.

7. Security Considerations

This document does not define new functionality and therefore does not introduce new security concerns. We assume that system designers apply classic Web security on top of the basic RESTful guidance given in this document. Thus, security protocols and considerations

from related specifications apply to RESTful IoT design. These include:

- *Transport Layer Security (TLS): [RFC8446], [RFC5246], and [RFC6347]
- *Internet X.509 Public Key Infrastructure: [RFC5280]
- *HTTP security: Section 11 of [RFC9112], Section 17 of [RFC9110], etc.
- *CoAP security: Section 11 of [RFC7252]
- *URI security: Section 7 of [RFC3986]

IoT-specific security is an active area of standardization at the time of writing. First finalized specifications include:

- *(D)TLS Profiles for the Internet of Things: [RFC7925]
- *CBOR Object Signing and Encryption (COSE) [RFC8152]
- *CBOR Web Token [RFC8392]
- *Proof-of-Possession Key Semantics for CBOR Web Tokens (CWTs) [RFC8747]
- *Object Security for Constrained RESTful Environments (OSCORE) [RFC8613]
- *Authentication and Authorization for Constrained Environments (ACE) using the OAuth 2.0 Framework [RFC9200]
- *ACE profiles for DTLS [RFC9202] and OSCORE [RFC9203]

Further IoT security considerations are available in [RFC8576].

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