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M. Kovatsch
ETH Zurich
O. Bergmann
Universitaet Bremen TZI
E. Dijk
Philips Research
X. He
Hitachi (China) R&D Corp.
C. Bormann, Ed.
Universitaet Bremen TZI
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CoAP Implementation Guidance
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Abstract

The Constrained Application Protocol (CoAP) is designed for resource-constrained nodes and networks, e.g., sensor nodes in a low-power lossy network (LLN). Yet to implement this Internet protocol on Class 1 devices (i.e., ~ 10 KiB of RAM and ~ 100 KiB of ROM) also lightweight implementation techniques are necessary. This document provides lessons learned from implementing CoAP for tiny, battery-operated networked embedded systems. The guidelines for transmission state management and developer APIs can also help with the implementation of CoAP for less constrained nodes.

Table of Contents

1. Introduction

The Constrained Application Protocol [I-D.ietf-core-coap] has been designed specifically for machine-to-machine communication in networks with very constrained nodes. Typical application scenarios therefore include building automation and the Internet of Things. The major design objectives have been set on small protocol overhead, robustness against packet loss, and against high latency induced by small bandwidth shares or slow request processing in end nodes. To leverage integration of constrained nodes with the world-wide Internet, the protocol design was led by the REST architectural style that accounts for the scalability and robustness of the Hypertext Transfer Protocol [RFC2616].

Lightweight implementations benefit from this design in many respects: First, the use of Uniform Resource Identifiers (URIs) for naming resources and the transparent forwarding of their representations in a server-stateless request/response protocol make protocol translation to HTTP a straightforward task. Second, the set of protocol elements that are unavoidable for the core protocol and thus must be implemented on every node has been kept very small, minimizing the unnecessary accumulation of "optional" features. Options that - when present - are critical for message processing are explicitly marked as such to force immediate rejection of messages with unknown critical options. Third, the syntax of protocol data units is easy to parse and is carefully defined to avoid creation of state in servers where possible.

Although these features enable lightweight implementations of the Constrained Application Protocol, there is still a tradeoff between robustness and latency of constrained nodes on one hand and resource demands (such as battery consumption, dynamic memory needs, and static code size) on the other. The present document gives some guidance on possible strategies to solve this tradeoff for very constrained nodes (Class 1 in [I-D.ietf-lwig-terminology]). The main focus is on servers as this is deemed the predominant case where CoAP applications are faced with tight resource constraints.

Additional considerations for the implementation of CoAP on tiny sensors are given in [I-D.arkko-core-sleepy-sensors].

2. Message Processing

For constrained nodes of Class 1 or even Class 2, the most limiting factors for (wireless) network communication usually are memory size and battery lifetime. Most applications therefore try to minimize internal buffer space for both transmit and receive operations, and to maximize sleeping cycles.

In the programming styles supported by very simple operating systems, preemptive multi-threading is not an option. Instead, all operations are triggered by an event loop system, e.g., in a send-receive-dispatch cycle. It is also common practice to allocate memory statically to ensure stable behavior, as no memory management unit (MMU) or other abstractions are available. For a CoAP node, the two key parameters for memory usage are the number of (re)transmission buffers and the maximum message size that must be supported by each buffer. Often the maximum message size is set far below the 1280-byte MTU of 6LoWPAN to allow more than one open Confirmable transmission at a time (in particular for observe notifications). Note that implementations on constrained platforms often not even support the full MTU. Larger messages must then use block-wise transfers [I-D.ietf-core-block], while a good tradeoff between 6LoWPAN fragmentation and CoAP header overhead must be found. Usually the amount of available free RAM dominates this decision. For Class 1 devices, the maximum message size is typically 128 or 256 bytes plus an estimate of the maximum header size with a worst case option setting.

2.1. Message Buffer Usage

The cooperative multi-threading of an event loop system allows to optimize memory usage through in-place processing and reuse of buffers, in particular the IP buffer provided by the OS.

CoAP servers can significantly benefit from in-place processing, as they can create responses directly in the incoming IP buffer. Note that an embedded OS usually only has a single buffer for incoming and outgoing IP packets. The first few bytes of the basic header are usually parsed into an internal data structure and can be overwritten without harm. Thus, empty ACKs and RST messages can promptly be assembled and sent using the IP buffer. Also when a CoAP server only sends piggy-backed or Non-confirmable responses, no additional buffer is required at the application layer. This, however, requires careful timing so that no incoming data is overwritten before it was processed. Because of cooperative multi-threading, this requirement is relaxed, though. Once the message is sent, the IP buffer can accept new messages again. This does not work for Confirmable messages, however. They need to be stored for retransmission and would block any further IP communication.

Depending on the number of requests that can be handled in parallel, an implementation might create a stub response filled with any option that has to be copied from the original request to the separate response, especially the Token option. The drawback of this technique is that the server must be prepared to receive retransmissions of the previous (Confirmable) request to which a new

acknowledgement must be generated. If memory is an issue, a single buffer can be used for both tasks: Only the message type and code must be updated, changing the message id is optional. Once the resource representation is known, it is added as new payload at the end of the stub response. Acknowledgements still can be sent as described before as long as no additional options are required to describe the payload.

2.2. Header Option Parsing and Management

There are two alternatives to handle the header: Either process the header on the fly when an option is accessed or initially parse all values into an internal data structure.

2.2.1. On-the-fly Processing

The advantage of on-the-fly processing is that the compact encoding saves memory and fully reuses the buffer for incoming messages. The basic message header information should always be copied into an internal data structure, as Message ID and/or Token are required for request/response matching and generating the response. Once the message is accepted for further processing, the set of options contained in the received message must be decoded to check for unknown critical options. To avoid multiple passes through the option list, the option parser might maintain a bit-vector where each bit represents an option number that is present in the received request. With the wide and sparse range of option numbers, the number itself cannot be used to indicate the number of left-shift operations to mask the corresponding bit. Hence, an implementation-specific enum of supported options should be used to mask the present options of a message in the bitmap. In addition, the byte index of every option can be added to a sparse list (e.g., a one-dimensional array) for fast retrieval.

Once the option list has been processed at least up to the highest option number that is supported by the application, any known critical option and all elective options can be masked out to determine if any unknown critical option was present. If this is the case, this information can be used to create a 4.02 response accordingly. (Note that the remaining options also must be processed to add further critical options included in the original request.)

2.2.2. Internal Data Structure

Using an internal data structure for all parsed options has advantages when processing the values, as they are already in a variable of corresponding type and integers in host byte order. The incoming payload and byte strings of the header can be accessed

directly in its IP buffer using pointers. This approach also benefits from a bitmap. Otherwise special values must be reserved to encode an unset option, which might require a larger type than required for the actual value range (e.g., a 32-bit integer instead of 16-bit).

The byte strings (e.g., the URI) are usually not required when generating the response. Thus, this alternative also facilitates the usage of the IP buffer for message assembly - all important values are copied from the shared incoming/outgoing buffer.

Setting options for outgoing messages is also easier with an internal data structure. Application developers can set options independent from the option number order required for the delta encoding. The CoAP encoding is then applied in a serialization step before sending. On-the-fly processing might require extensive memmove operations to insert new header options or needs to restrict developers to set options in order.

2.3. Retransmissions

CoAP's reliable transmissions require the before-mentioned retransmission buffers. Messages, such as the requests of a client, should be stored in serialized form. For servers, retransmissions apply for Confirmable separate responses and Confirmable notifications [I-D.ietf-core-observe]. As separate responses stem from long-lasting resource handlers, the response should be stored for retransmission instead of re-dispatching a stored request (which would allow for updating the representation). For Confirmable notifications, please see Section 2.6, as simply storing the response can break the concept of eventual consistency.

String payloads such as JSON require a buffer to print to. By splitting the retransmission buffer into header and payload part, it can be reused. First to generate the payload and then storing the CoAP message by serializing into the same memory. Thus, providing a retransmission for any message type can save the need for a separate application buffer. This, however, requires an estimation about the maximum expected header size to split the buffer and a memmove to concatenate the two parts.

For platforms that disable clock tick interrupts in sleep states, the application must take into consideration the clock deviation that occurs during sleep (or ensure to remain in idle state until the message has been acknowledged or the maximum number of retransmissions is reached). Since CoAP allows up to four retransmissions with a binary exponential back-off it could take up to 45 seconds until the send operation is complete. Even in idle

state, this means substantial energy consumption for low-power nodes. Implementers therefore might choose a two-step strategy: First, do one or two retransmissions and then, in the later phases of back-off, go to sleep until the next retransmission is due. In the meantime, the node could check for new messages including the acknowledgement for any Confirmable message to send.

2.4. Deduplication

If CoAP is used directly on top of UDP (i.e., in NoSec mode), it needs to cope with the fact that the UDP datagram transport can reorder and duplicate messages. (In contrast to UDP, DTLS has its own duplicate detection.) CoAP has been designed with protocol functionality such that rejection of duplicate messages is always possible. It is at the discretion of the receiver if it actually wants to make use of this functionality. Processing of duplicate messages comes at a cost, but so does the management of the state associated with duplicate rejection. Hence, a receiver may have good reasons to decide not to do the duplicate rejection. If duplicate rejection is indeed necessary, e.g., for non-idempotent requests, it is important to control the amount of state that needs to be stored.

2.4.1. Managing Peer MIDs

CoAP's duplicate rejection functionality can be straightforwardly implemented in a CoAP end-point by storing, for each remote CoAP end-point ("peer") that it communicates with, a list of recently received CoAP Message IDs (MIDs) along with some timing information. A CoAP message from a peer with a MID that is in the list for that peer can simply be discarded.

The timing information in the list can then be used to time out entries that are older than the _expected extent of the re-ordering_, an upper bound for which can be estimated by adding the _potential retransmission window_ ([I-D.ietf-core-coap] section "Reliable Messages") and the time packets can stay alive in the network.

Such a straightforward implementation is suitable in case other CoAP end-points generate random MIDs. However, this storage method may consume substantial RAM in specific cases, such as:

- many clients are making periodic, non-idempotent requests to a single CoAP server;

- one client makes periodic requests to a large number of CoAP servers and/or requests a large number of resources; where servers happen to mostly generate separate CoAP responses (not piggy-backed);

For example, consider the first case where the expected extent of re-ordering is 50 seconds, and N clients are sending periodic POST requests to a single CoAP server during a period of high system activity, each on average sending one client request per second. The server would need 100 * N bytes of RAM to store the MIDs only. This amount of RAM may be significant on a RAM-constrained platform. On a number of platforms, it may be easier to allocate some extra program memory (e.g. Flash or ROM) to the CoAP protocol handler process than to allocate extra RAM. Therefore, one may try to reduce RAM usage of a CoAP implementation at the cost of some additional program memory usage and implementation complexity.

Some CoAP clients generate MID values by a using a Message ID variable [I-D.ietf-core-coap] that is incremented by one each time a new MID needs to be generated. (After the maximum value 65535 it wraps back to 0.) We call this behavior "sequential" MIDs. One approach to reduce RAM use exploits the redundancy in sequential MIDs for a more efficient MID storage in CoAP servers.

Naturally such an approach requires, in order to actually reduce RAM usage in an implementation, that a large part of the peers follow the sequential MID behavior. To realize this optimization, the authors therefore RECOMMEND that CoAP end-point implementers employ the "sequential MID" scheme if there are no reasons to prefer another scheme, such as randomly generated MID values.

Security considerations might call for a choice for (pseudo)randomized MIDs. Note however that with truly randomly generated MIDs the probability of MID collision is rather high in use cases as mentioned before, following from the Birthday Paradox. For example, in a sequence of 52 randomly drawn 16-bit values the probability of finding at least two identical values is about 2 percent.

From here on we consider efficient storage implementations for MIDs in CoAP end-points, that are optimized to store "sequential" MIDs. Because CoAP messages may be lost or arrive out-of-order, a solution has to take into account that received MIDs of CoAP messages are not actually arriving in a sequential fashion, due to lost or reordered messages. Also a peer might reset and lose its MID counter(s) state. In addition, a peer may have a single Message ID variable used in messages to many CoAP end-points it communicates with, which partly breaks sequentiality from the receiving CoAP end-point’s perspective. Finally, some peers might use a randomly generated MID values approach. Due to these specific conditions, existing sliding window bitfield implementations for storing received sequence numbers are typically not directly suitable for efficiently storing MIDs.

Table 1 shows one example for a per-peer MID storage design: a table with a bitfield of a defined length _K_ per entry to store received MIDs (one per bit) that have a value in the range [MID_i + 1 , MID_i + K].

MID base	K-bit bitfield	base time value
MID_0	010010101001	t_0
MID_1	111101110111	t_1
... etc.		

Table 1: A per-peer table for storing MIDs based on MID_i

The presence of a table row with base MID_i (regardless of the bitfield values) indicates that a value MID_i has been received at a time t_i. Subsequently, each bitfield bit k (0...K-1) in a row i corresponds to a received MID value of MID_i + k + 1. If a bit k is 0, it means a message with corresponding MID has not yet been received. A bit 1 indicates such a message has been received already at approximately time t_i. This storage structure allows e.g. with k=64 to store in best case up to 130 MID values using 20 bytes, as opposed to 260 bytes that would be needed for a non-sequential storage scheme.

The time values t_i are used for removing rows from the table after a preset timeout period, to keep the MID store small in size and enable these MIDs to be safely re-used in future communications. (Note that the table only stores one time value per row, which therefore needs to be updated on receipt of another MID that is stored as a single bit in this row. As a consequence of only storing one time value per row, older MID entries typically time out later than with a simple per-MID time value storage scheme. The end-point therefore needs to ensure that this additional delay before MID entries are removed from the table is much smaller than the time period after which a peer starts to re-use MID values due to wrap-around of a peer’s MID variable. One solution is to check that a value t_i in a table row is still recent enough, before using the row and updating the value t_i to current time. If not recent enough, e.g. older than N seconds, a new row with an empty bitfield is created.) [Clearly, these optimizations would benefit if the peer were much more conservative about re-using MIDs than currently required in the protocol specification.]

The optimization described is less efficient for storing randomized MIDs that a CoAP end-point may encounter from certain peers. To solve this, a storage algorithm may start in a simple MID storage mode, first assuming that the peer produces non-sequential MIDs. While storing MIDs, a heuristic is then applied based on monitoring some "hit rate", for example, the number of MIDs received that have a Most Significant Byte equal to that of the previous MID divided by the total number of MIDs received. If the hit rate tends towards 1 over a period of time, the MID store may decide that this particular CoAP end-point uses sequential MIDs and in response improve efficiency by switching its mode to the bitfield based storage.

2.4.2. Resource-specific Deduplication

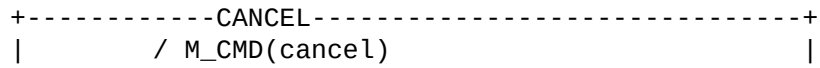
Deduplication is heavy for Class 1 devices, as the number of peer addresses can be vast. Servers should be kept stateless, i.e., the REST API should be designed idempotent whenever possible. When this is not the case, the resource handler could perform an optimized deduplication by exploiting knowledge about the application. Another, server-wide strategy is to only keep track of non-idempotent requests.

3. Transmission State Management

CoAP endpoints must keep transmission state to manage open requests, to handle the different response modes, and to implement reliable delivery at the message layer. The following finite state machines (FSMs) model the transmissions of a CoAP exchange at the request/response layer and the message layer. These layers are linked through actions. The M_CMD() action triggers a corresponding transition at the message layer and the FF_EVT() action triggers a transition at the request/response layer. The FSMs also use guard conditions to distinguish between information that is only available through the other layer (e.g., whether a request was sent using a CON or NON message).

3.1. Request/Response Layer

Figure 1 depicts the two states at the request/response layer of a CoAP client. When a request is issued, a "reliable_send" or "unreliable_send" is triggered at the message layer. The WAITING state can be left through three transitions: Either the client cancels the request and triggers cancellation of a CON transmission at the message layer, the client receives a failure event from the message layer, or a receive event containing a response.



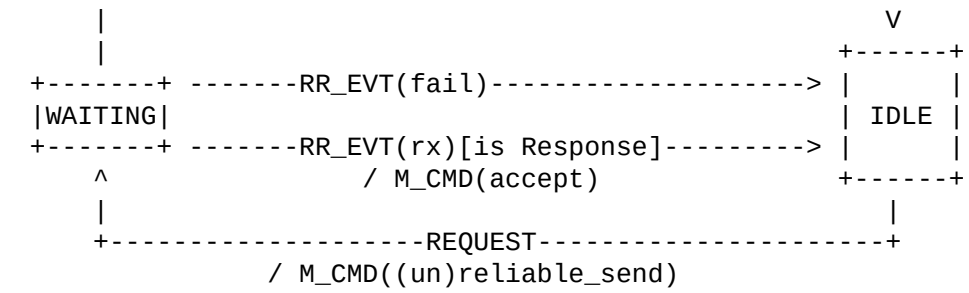


Figure 1: CoAP Client Request/Response Layer FSM

A server resource can decide at the request/response layer whether to respond with a piggy-backed or a separate response. Thus, there are two busy states in Figure 2, SERVING and SEPARATE. An incoming receive event with a NON request directly triggers the transition to the SEPARATE state.

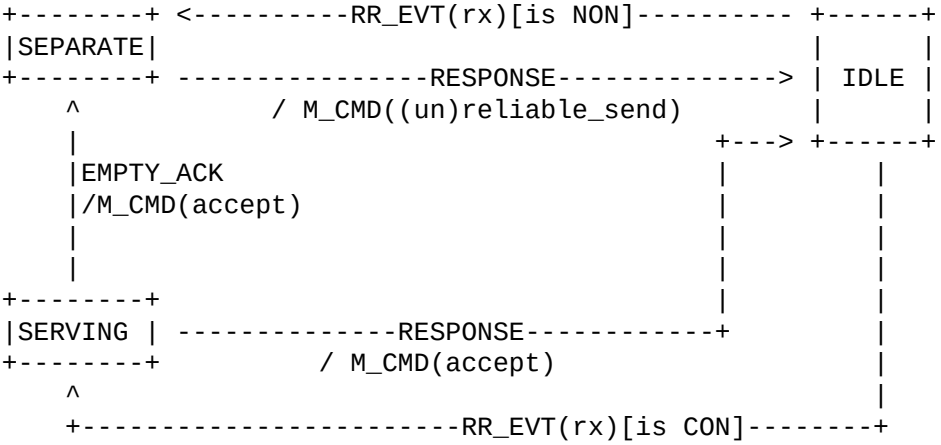
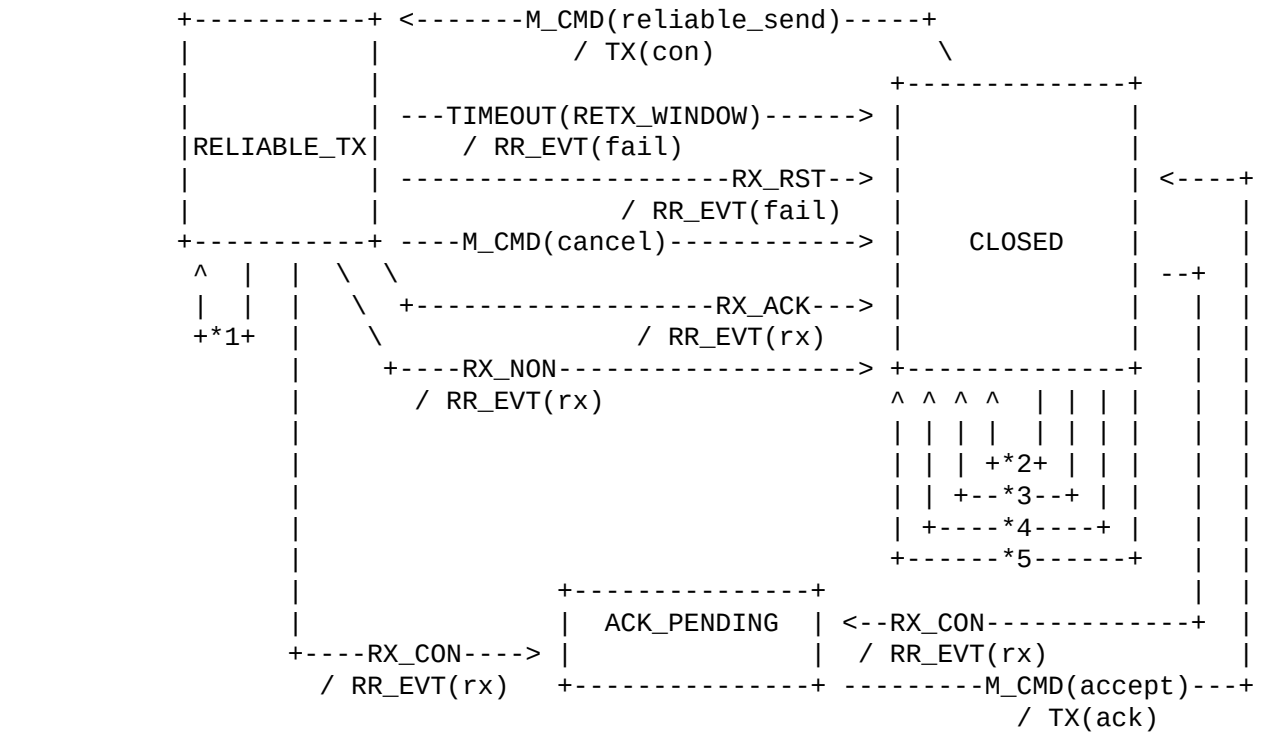


Figure 2: CoAP Server Request/Response Layer FSM

3.2. Message Layer

Figure 3 shows the different states of a CoAP endpoint per message exchange. Besides the linking action RR_EVT(), the message layer has a TX action to send a message. For sending and receiving NONs, the endpoint remains in its CLOSED state. When sending a CON, the endpoint remains in RELIABLE_TX and keeps retransmitting until the transmission times out, it receives a matching RST, the request/response layer cancels the transmission, or the endpoint receives an implicit acknowledgement through a matching NON or CON. Whenever the endpoint receives a CON, it transitions into the ACK_PENDING state, which can be left by sending the corresponding ACK.



*1: TIMEOUT(RETX_TIMEOUT) / TX(con)
*2: M_CMD(unreliable_send) / TX(non)
*3: RX_NON / RR_EVT(rx)
*4: RX_RST / REMOVE_OBSERVER
*5: RX_ACK

Figure 3: CoAP Message Layer FSM

T.B.D.: (i) Rejecting messages (can be triggered at message and request/response layer). (ii) ACKs can also be triggered at both layers.

4. Observing

For each observer, the server needs to store at least address, port, token, and the last outgoing message ID. The latter is needed to match incoming RST messages and cancel the observe relationship.

It is favorable to have one retransmission buffer per observable resource that is shared among all observers. Each notification is serialized once into this buffer and only address, port, and token are changed when iterating over the observer list (note that different token lengths might require realignment). The advantage becomes clear for Confirmable notifications: Instead of one

retransmission buffer per observer, only one buffer and only individual retransmission counters and timers in the list entry need to be stored. When the notifications can be sent fast enough, even a single timer would suffice. Furthermore, per-resource buffers simplify the update with a new resource state during open deliveries.

5. Block-wise Transfers

Block-wise transfers have the main purpose of providing fragmentation at the application layer, where partial information can be processed. This is not possible at lower layers such as 6LoWPAN, as only assembled packets can be passed up the stack. While [I-D.ietf-core-block] also anticipates atomic handling of blocks, i.e., only fully received CoAP messages, this is not possible on Class 1 devices.

When receiving a block-wise transfer, each blocks is usually passed to a handler function that for instance performs stream processing or writes the blocks to external memory such as flash. Although there are no restrictions in [I-D.ietf-core-block], it is beneficial for Class 1 devices to only allow ordered transmission of blocks. Otherwise on-the-fly processing would not be possible.

When sending a block-wise transfer, Class 1 devices usually do not have sufficient memory to print the full message into a buffer, and slice and send it in a second step. When transferring the CoRE Link Format from /.well-known/core for instance, a generator function is required that generates slices of a large string with a specific offset length (a 'sonprintf()'). This functionality is required recurrently and should be included in a library.

6. Application Developer API

Bringing a Web transfer protocol to constrained environments does not only change the networking of the corresponding systems, but also the way they should be programmed. A CoAP implementation should provide a developer API similar to REST frameworks in traditional computing. A server should not be created around an event loop with several function calls, but rather by implementing handlers following the resource abstraction.

So far, the following types of RESTful resources were identified:

NORMAL A normal resource defined by a static Uri-Path that is associated with a resource handler function. Allowed methods could already be filtered by the implementation based on flags. This is the basis for all other resource types.

PARENT A parent resource manages several sub-resources by programmatically evaluating the Uri-Path, which may be longer than that of the parent resource. Defining a URI templates (see [RFC6570]) would be a convenient way to pre-parse arguments given in the Uri-Path.

PERIODIC A resource that has an additional handler function that is triggered periodically by the CoAP implementation with a resource-defined interval. It can be used to sample a sensor or perform similar periodic updates. Usually, a periodic resource is observable and sends the notifications in the periodic handler function. These periodic tasks are quite common for sensor nodes, thus it makes sense to provide this functionality in the CoAP implementation and avoid redundant code in every resource.

EVENT An event resource is similar to an periodic resource, only that the second handler is called by an irregular event such as a button.

7. References

7.1. Normative References

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Authors' Addresses

Matthias Kovatsch
ETH Zurich
Universitaetstrasse 6
CH-8092 Zurich
Switzerland

Email: kovatsch@inf.ethz.ch

Olaf Bergmann
Universitaet Bremen TZI
Postfach 330440
D-28359 Bremen
Germany

Email: bergmann@tzi.org

Esko Dijk
Philips Research

Email: esko.dijk@philips.com

Xuan He
Hitachi (China) R&D Corp.
301, Tower C North, Raycom, 2 Kexuyuan Nanlu
Beijing, 100190
P.R.China

Email: xhe@hitachi.cn

Carsten Bormann (editor)
Universitaet Bremen TZI
Postfach 330440
D-28359 Bremen
Germany

Phone: +49-421-218-63921
Email: cabo@tzi.org