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Abstract

The Constrained Application Protocol (CoAP) is designed for resource-constrained nodes and networks such as sensor nodes in a low-power lossy network (LLN). Yet to implement this Internet protocol on Class 1 devices (as per RFC 7228, ~ 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. In particular, it provides guidance on correct implementation of the CoAP specification RFC 7252, memory optimizations, and customized protocol parameters.

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1. Introduction

The Constrained Application Protocol [RFC7252] has been designed specifically for machine-to-machine communication in networks with very constrained nodes. Typical application scenarios therefore include building automation, process optimization, 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 [RFC7230].

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 on the other. For constrained nodes of Class 1 or even Class 2 [RFC7228], the most limiting factors usually are dynamic memory needs, static code size, and energy. Most implementations

therefore need to optimize internal buffer usage, omit idle protocol features, and maximize sleeping cycles.

The present document gives possible strategies to solve this tradeoff for very constrained nodes (i.e., Class 1). For this, it provides guidance on correct implementation of the CoAP specification [RFC7252], memory optimizations, and customized protocol parameters.

2. Protocol Implementation

In the programming styles supported by very simple operating systems as found on constrained nodes, 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 parallel observe notifications [RFC7641]). Note that implementations on constrained platforms often not even support the full MTU. Larger messages must then use blockwise transfers [RFC7959], 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 (blockwise) payload plus an estimate of the maximum header size for the worst case option setting.

2.1. Client/Server Model

In general, CoAP servers can be implemented more efficiently than clients. REST allows them to keep the communication stateless and piggy-backed responses are not stored for retransmission, saving buffer space. The use of idempotent requests also allows to relax deduplication, which further decreases memory usage. It is also easy to estimate the required maximum size of message buffers, since URI paths, supported options, and maximum payload sizes of the application are known at compile time. Hence, when the application is distributed over constrained and unconstrained nodes, the constrained ones should preferably have the server role.

HTTP-based applications have established an inverse model because of the need for simple push notifications: A constrained client uses POST requests to update resources on an unconstrained server whenever an event (e.g., a new sensor reading) is triggered. This requirement is solved by the Observe option [RFC7641] of CoAP. It allows servers

to initiate communication and send push notifications to interested client nodes. This allows a more efficient and also more natural model for CoAP-based applications, where the information source is an origin server, which can also benefit from caching. Publish-subscribe brokers [I-D.ietf-core-coap-pubsub] may be deployed to act in the server role on behalf of constrained clients.

2.2. Message Processing

Apart from the required buffers, message processing is symmetric for clients and servers. First the base header has to be parsed and thereby checked if it is a valid CoAP message. For UDP datagrams, the version identifier or a size smaller than four bytes identify non-CoAP data. These datagrams need to be silently ignored. Other message format errors, such as an incomplete datagram or the usage of reserved values, may need to be rejected with a Reset (RST) message (see Section 4.2 and 4.3 of [RFC7252] for details).

As CoAP over TCP has a different base header, the Length field must be parsed to determine the message size. As this field may have up to five bytes, it may be extend over TCP segment boundaries. For CoAP over WebSockets the actual message length is given by the WebSocket frame hence the Length field is always zero.

Next, the token length is read based on the TKL field which is for all transports contained in the four least significant bits of the first byte. The (possibly empty) Token itself is located immediately after the four-byte base header for UDP, while for TCP and WebSockets, it follows the variable Length field and Code byte.

For the options following the Token, there are two alternatives: either process them 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 no additional memory needs to be allocated to store the option values, which are stored efficiently inline in the buffer for incoming messages. 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 (a direct pointer) can be added to a sparse list (e.g., a one-dimensional array) for fast retrieval.

This particularly enables efficient handling of options that might occur more than once such as Uri-Path. In this implementation strategy, the delta is zero for any subsequent path segment, hence the stored byte index for this option (e.g., 11 for Uri-Path) would be overwritten to hold a pointer to only the last occurrence of that option. The Uri-Path can be resolved on the fly, though, and a pointer to the targeted resource stored directly in the sparse list.

Once the option list has been processed, all known critical option and all elective options can be masked out in the bit-vector 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 full processing must only be done up to the highest supported option number. Beyond that, only the least significant bit (Critical or Elective) needs to be checked. Otherwise, if all critical options are supported, the sparse list of option pointers is used for further handling of the message.

2.2.2. Internal Data Structure

Using an internal data structure for all parsed options has an advantage when working on the option values, as they are already in a variable of corresponding type (e.g., an integer in host byte order). The incoming payload and byte strings of the header can be accessed directly in the buffer for incoming messages using pointers (similar to on-the-fly processing). 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).

Many of the byte strings (e.g., the URI) are usually not required when generating the response. When all important values are copied (e.g., the Token, which needs to be mirrored), the internal data structure facilitates using the buffer for incoming messages also for the assembly of outgoing messages - which can be the shared IP buffer provided by the operating system.

Setting options for outgoing messages is also easier with an internal data structure. Application developers can set options independent from the option number and do not need to care about the order for the delta encoding. The CoAP encoding is applied in a serialization step before sending. In contrast, assembling outgoing messages with on-the-fly processing requires either extensive memmove operations to

insert new options, or restrictions for developers to set options in their correct order.

2.3. Message ID Usage

Many applications of CoAP use unreliable transports, in particular UDP, which can lose, reorder, and duplicate messages. Although DTLS's replay protection deals with duplication by the network, losses are addressed with DTLS retransmissions only for the handshake protocol and not for the application data protocol. Furthermore, CoAP implementations usually send CON retransmissions in new DTLS records, which are not considered duplicates at the DTLS layer.

2.3.1. Duplicate Rejection

CoAP's messaging sub-layer has been designed with protocol functionality such that rejection of duplicate messages is always possible. It is realized through the Message IDs (MIDs) and their lifetimes with regard to the message type.

Duplicate detection is under the discretion of the recipient (see Section 4.5 of [RFC7252], Section 2.3.3, Section 2.3.4). Where it is desired, the receiver needs to keep track of MIDs to filter the duplicates for at least `NON_LIFETIME` (145 s). This time also holds for CON messages, since it equals the possible reception window of `MAX_TRANSMIT_SPAN + MAX_LATENCY`.

On the sender side, MIDs of CON messages must not be re-used within the `EXCHANGE_LIFETIME`; MIDs of NONs respectively within the `NON_LIFETIME`. In typical scenarios, however, senders will re-use MIDs with intervals far larger than these lifetimes: with sequential assignment of MIDs, coming close to them would require 250 messages per second, much more than the bandwidth of constrained networks would usually allow for.

In cases where senders might come closer to the maximum message rate, it is recommended to use more conservative timings for the re-use of MIDs. Otherwise, opposite inaccuracies in the clocks of sender and recipient may lead to obscure message loss. If needed, higher rates can be achieved by using multiple endpoints for sending requests and managing the local MID per remote endpoint instead of a single counter per system (essentially extending the 16-bit message ID by a 16-bit port number and/or an 128-bit IP address). In controlled scenarios, such as real-time applications over industrial Ethernet, the protocol parameters can also be tweaked to achieve higher message rates (Section 4.1).

2.3.2. MID Namespaces

MIDs are assigned under the control of the originator of CON and NON messages, and they do not mix with the MIDs assigned by the peer for CON and NON in the opposite direction. Hence, CoAP implementors need to make sure to manage different namespaces for the MIDs used for deduplication. MIDs of outgoing CONs and NONs belong to the local endpoint; so do the MIDs of incoming ACKs and RSTs. Accordingly, MIDs of incoming CONs and NONs and outgoing ACKs and RSTs belong to the corresponding remote endpoint. Figure 1 depicts a scenario where mixing the namespaces would cause erroneous filtering.

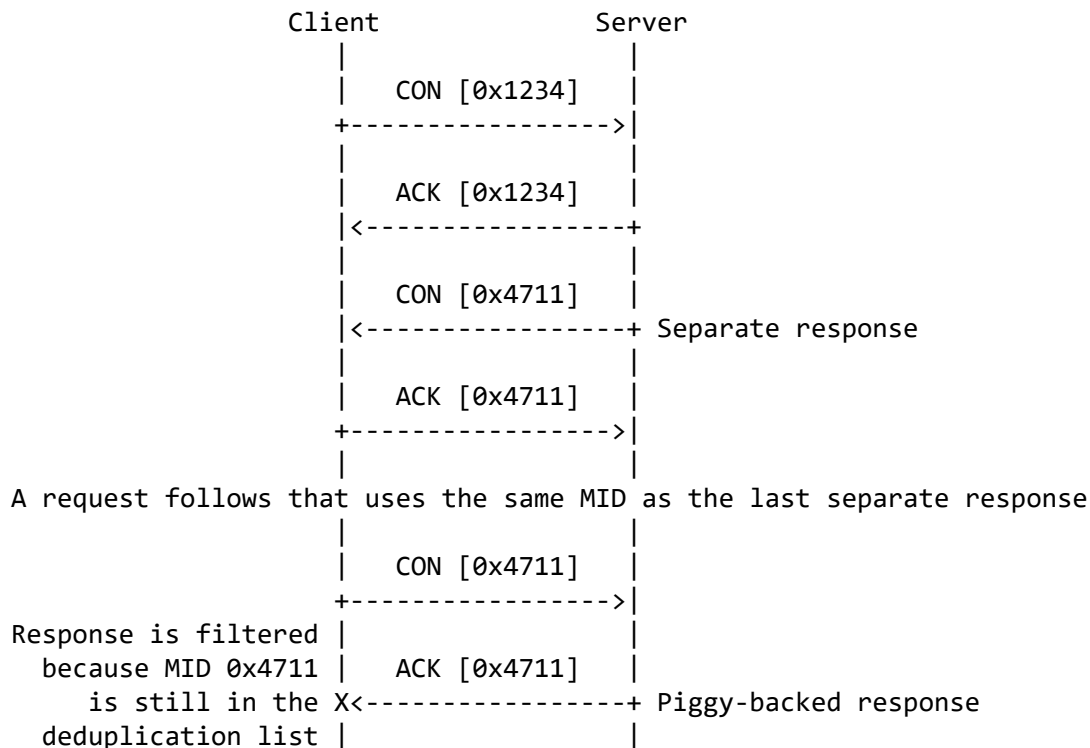


Figure 1: Deduplication must manage the MIDs in different namespace corresponding to their origin endpoints.

2.3.3. Relaxation on the Server

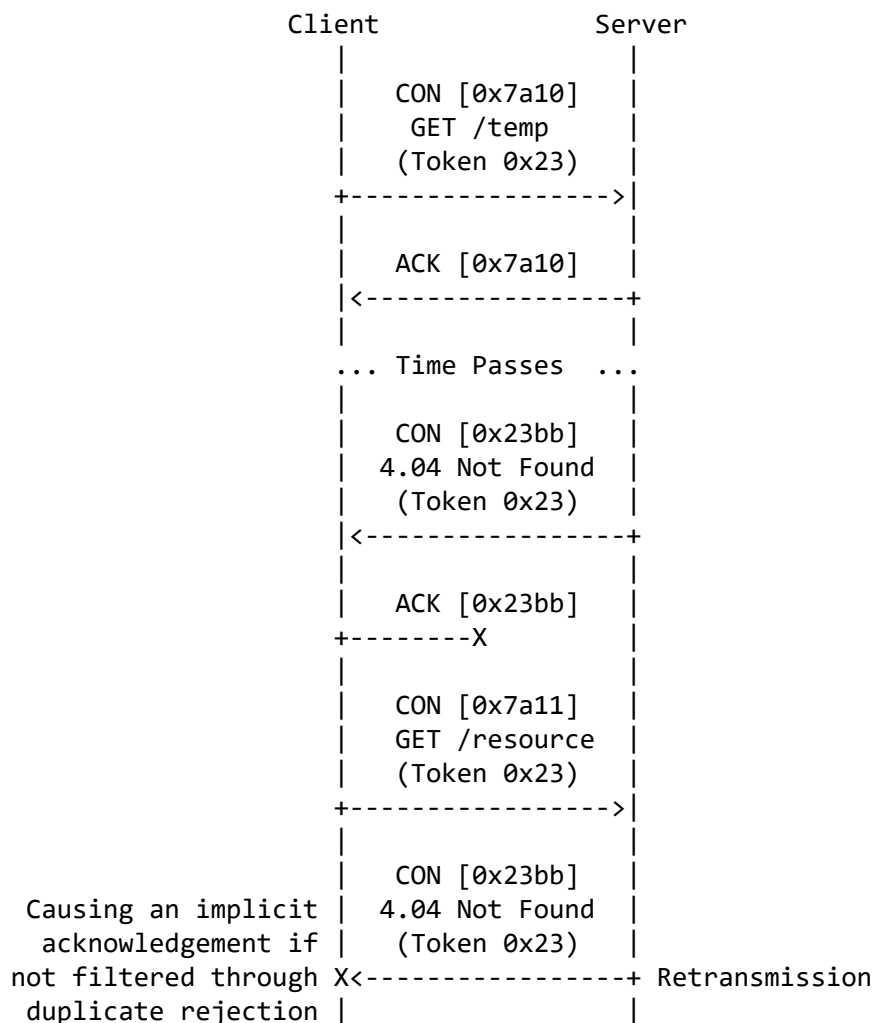
Using the de-duplication functionality is at the discretion of the receiver: Processing of duplicate messages comes at a cost, but so does the management of the state associated with duplicate rejection. The number of remote endpoints that need to be managed might be vast. This can be costly in particular for less constrained nodes that have throughput in the order of hundreds of thousands requests per second (which needs about 16 GiB of RAM just for duplicate rejection). Deduplication is also heavy for servers on Class 1 devices, as also

piggy-backed responses need to be stored for the case that the ACK message is lost. Hence, a receiver may have good reasons to decide not to perform deduplication. This behavior is possible when the application is designed with idempotent operations only and makes good use of the If-Match/If-None-Match options.

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. It can be reduced, for instance, by deduplication at resource level: Knowledge of the application and supported representations can minimize the amount of state that needs to be kept.

2.3.4. Relaxation on the Client

Duplicate rejection on the client side can be simplified by choosing clever Tokens that are virtually not re-used (e.g., through an obfuscated sequence number in the Token value) and only filter based on the list of open Tokens. If a client wants to re-use Tokens (e.g., the empty Token for optimizations), it requires strict duplicate rejection based on MIDs to avoid the scenario outlined in Figure 2.



2.4. Token Usage

As already mentioned, a clever assignment of Tokens can help to simplify duplicate rejection. Yet this is also important for coping with client crashes. When a client restarts during an open request

and (unknowingly) re-uses the same Token, it might match the response from the previous request to the current one. Hence, when only the Token is used for matching, which is always the case for separate responses, randomized Tokens with enough entropy should be used. The 8-byte range for Tokens can even allow for one-time usage throughout the lifetime of a client node. When DTLS is used, client crashes/restarts will lead to a new security handshake, thereby solving the problem of mismatching responses and/or notifications.

2.4.1. Tokens for Observe

In the case of Observe [RFC7641], a request will be answered with multiple notifications and it is important to continue keeping track of the Token that was used for the request - its lifetime will end much later. Upon establishing an Observe relationship, the Token is registered at the server. Hence, the client's use of that specific Token is now limited to controlling the Observation relationship. A client can use it to cancel the relationship, which frees the Token upon success (i.e., the message with an Observe Option with the value set to 'deregister' (1) is confirmed with a response; see [RFC7641] section 3.6). However, the client might never receive the response due to a temporary network outage or worse, a server crash. Although a network outage will also affect notifications so that the Observe garbage collection could apply, the server might simply happen not to send CON notifications during that time. Alternative Observe lifetime models such as Stubbornness(tm) might also keep relationships alive for longer periods.

Thus, it is best to carefully choose the Token value used with Observe requests. (The empty value will rarely be applicable.) One option is to assign and re-use dedicated Tokens for each Observe relationship the client will establish. The choice of Token values also is critical in NoSec mode, to limit the effectiveness of spoofing attacks. Here, the recommendation is to use randomized Tokens with a length of at least four bytes (see Section 5.3.1 of [RFC7252]). Thus, dedicated ranges within the 8-byte Token space should be used when in NoSec mode. This also solves the problem of mismatching notifications after a client crash/restart.

When the client wishes to reinforce its interest in a resource, maybe not really being sure whether the server has forgotten it or not, the Token value allocated to the Observe relationship is used to re-register that observation (see Section 3.3.1 of [RFC7641] for details): If the server is still aware of the relationship (an entry with a matching endpoint and token is already present in its list of observers for the resource), it will not add a new relationship but will replace or update the existing one (Section 4.1 of [RFC7641]).

If not, it will simply establish a new registration which of course also uses the Token value.

If the client sends an Observe request for the same resource with a new Token, this is not a protocol violation, because the specification allows the client to observe the same resource in a different Observe relationship if the cache-key is different (e.g., requesting a different Content-Format). If the cache-key is not different, though, an additional Observe relationship just wastes the server's resources, and is therefore not allowed; the server might rely on this for its housekeeping.

2.4.2. Tokens for Blockwise Transfers

In general, blockwise transfers are independent from the Token and are correlated through client endpoint address and server address and resource path (destination URI). Thus, each block may be transferred using a different Token. Still it can be beneficial to use the same Token (it is freed upon reception of a response block) for all blocks, e.g., to easily route received blocks to the same response handler.

When Block2 is combined with Observe, notifications only carry the first block and it is up to the client to retrieve the remaining ones. These GET requests do not carry the Observe option and need to use a different Token, since the Token from the notification is still in use.

2.5. Transmission States

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 `RR_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).

2.5.1. Request/Response Layer

Figure 3 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.

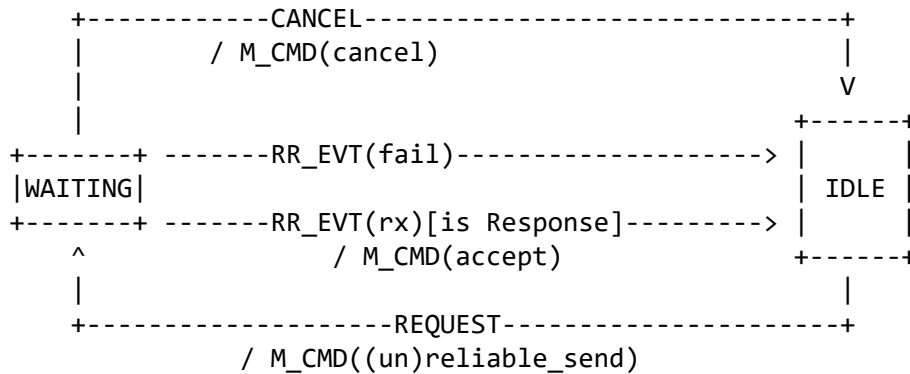


Figure 3: CoAP Client Request/Response Layer FSM

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 4, SERVING and SEPARATE. An incoming receive event with a NON request directly triggers the transition to the SEPARATE state.

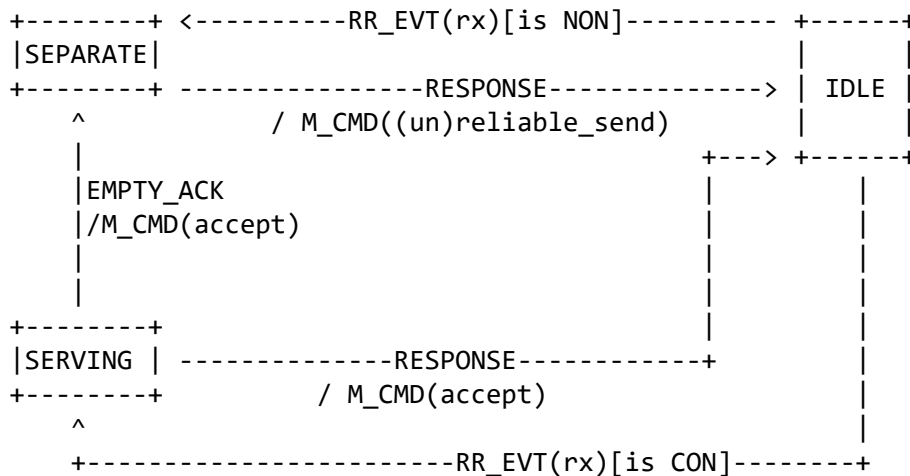


Figure 4: CoAP Server Request/Response Layer FSM

2.5.2. Message Layer

Figure 5 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

```

+-----+ <-----M_CMD(reliable_send)-----+
|                                     | \
|                                     +-----+
| RELIABLE_TX | ---TIMEOUT(RETX_WINDOW)-----> |
|               / RR_EVT(fail)                |
|             -----RX_RST-->                 | <-----+
|                   / RR_EVT(fail)              |
+-----+ ---M_CMD(cancel)-----> | CLOSED      |
^   |   ^   |   ^   |   ^   |   ^   |   ^   |
+*1+ \   \   \   \   \   \   \   \   \   \   \   \
+-----RX_ACK-----> |                     |
          / RR_EVT(rx)    +-----+
+---RX_NON-----> +-----+
          / RR_EVT(rx)    ^ ^ ^ ^ | | | |
                        | | | | +*2+ | | | |
                        | | | | +-*3--+ | | | |
                        | | | | +----*4----+ | | | |
                        +-----*5-----+
                                +-----+
                                | ACK_PENDING | <--RX_CON-----+
                                +-----+       / RR_EVT(rx)
+---RX_CON-----> |         |
          / RR_EVT(rx) +-----+ -----M_CMD(accept)-----+
                                   / TX(ack)

```

- Figure 5: CoAP Message Layer FSM

2.6. Out-of-band Information

[Page 14]

pause or cancel ongoing transmission to conserve energy. Providing ICMP information to the CoAP implementation is easier in constrained environments, where developers usually can adapt the underlying OS (or firmware). This is not the case on general purpose platforms that have full-fledged OSes and make use of high-level programming frameworks.

The most important ICMP messages are host, network, port, or protocol unreachable errors. After appropriate vetting (cf. [RFC5927]), they should cause the cancellation of ongoing CON transmissions and clearing (or deferral) of Observe relationships. Requests to this destination should be paused for a sensible interval. In addition, the device could indicate of this error through a notification to a management endpoint or external status indicator, since the cause could be a misconfiguration or general unavailability of the required service. Problems reported through the Parameter Problem message are usually caused through a similar fundamental problem.

The CoAP specification recommends to ignore Source Quench and Time Exceeded ICMP messages, though. Source Quench messages were originally intended to inform the sender to reduce the rate of packets. However, this mechanism is deprecated through [RFC6633]. CoAP also comes with its own congestion control mechanism, which is already designed conservatively. One advanced mechanism that can be employed for better network utilization is CoCoA, [I-D.ietf-core-cocoa]. Time Exceeded messages often occur during transient routing loops (unless they are caused by a too small initial Hop Limit value).

2.7. Programming Model

The event-driven approach, which is common in event-loop-based firmware, has also proven very efficient for embedded operating systems [TinyOS], [Contiki]. Note that an OS is not necessarily required and a traditional firmware approach can suffice for Class 1 devices. Event-driven systems use split-phase operations (i.e., there are no blocking functions, but functions return and an event handler is called once a long-lasting operation completes) to enable cooperative multi-threading with a single stack.

Bringing a Web transfer protocol to constrained environments does not only change the networking of the corresponding systems, but also the programming model. The complexity of event-driven systems can be hidden through APIs that resemble classic RESTful Web service implementations.

2.7.1. Client

An API for asynchronous requests with response handler functions goes hand-in-hand with the event-driven approach. Synchronous requests with a blocking send function can facilitate applications that require strictly ordered, sequential request execution (e.g., to control a physical process) or other checkpointing (e.g., starting operation only after registration with the resource directory was successful). However, this can also be solved by triggering the next operation in the response handlers. Furthermore, as mentioned in Section 2.1, it is more like that complex control flow is done by more powerful devices and Class 1 devices predominantly run a CoAP server (which might include a minimal client to communicate with a resource directory).

2.7.2. Server

On CoAP servers, the event-driven nature can be hidden through resource handler abstractions as known from traditional REST frameworks. The following types of RESTful resources have proven useful to provide an intuitive API on constrained event-driven systems:

NORMAL A normal resource defined by a static Uri-Path and an associated 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 under a given base path by programmatically evaluating the Uri-Path. Defining a URI template (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-specific interval. It can be used to sample a sensor or perform similar periodic updates of its state. Usually, a periodic resource is observable and sends the notifications by triggering its normal resource handler from the periodic handler. 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.

SEPARATE Separate responses are usually used when handling a request takes more time, e.g., due to a slow sensor or UART-based subsystems. To not fully block the system during this time, the handler should also employ split-phase execution: The resource handler returns as soon as possible and an event handler resumes responding when the result is ready. The separate resource type can abstract from the split-phase operation and take care of temporarily storing the request information that is required later in the result handler to send the response (e.g., source address and Token).

3. Optimizations

3.1. Message Buffers

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 or firmware.

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.

3.2. 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 [RFC7641]. 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.

3.3. Observable Resources

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.

3.4. Blockwise Transfers

Blockwise 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 [RFC7959] also anticipates atomic handling of blocks, i.e., only fully received CoAP messages, this is not possible on Class 1 devices.

When receiving a blockwise transfer, each block 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 [RFC7959], 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 blockwise transfer out of dynamically generated information, 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. For instance, if the CoRE Link Format at /.well-known/core is dynamically generated, 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.

3.4.1. Generic Proxying of Block Messages

Proxies cannot ignore the Block options by specification, because the options Block1 and Block2 are not safe-to-forward. The rationale behind this design decision is that servers might not be able to distinguish blocks originating from different senders once they have been forwarded by a CoAP proxy. For atomic operations where all blocks are assembled before actually executing the desired operation, this could lead to inconsistent state on the server side.

To ensure that this does not happen, a proxy can add the Request-Tag option (see [I-D.ietf-core-echo-request-tag]) containing data that uniquely identifies the originating endpoint in the proxy namespace.

3.4.2. Atomic Blockwise Operations

When an implementation needs to assemble blocks from block-wise transfers, applications need to create an identifier to group messages that belong together. This "Block Key" at least contains:

- o The source endpoint (e.g., IP address and port in the UDP case),
- o the destination endpoint,
- o the Cache-Key (as updated in [RFC7252]), and
- o all options that are proxy unsafe and not explicitly described as safe for block-wise assembly.

The only known options safe for block-wise assembly are the options Block1 and Block2 [RFC7959].

For the Block1 phase, the request payload is excluded from the identifier generation as it is just being assembled.

If a message is received that is not the start of a block-wise operation has a Block Key that is not known, and the implementation needs to act atomically on a request body, it must answer 4.08 (Request Entity Incomplete).

Conversely, clients should be aware that requests whose Block Key matches can be interpreted by the server atomically. This especially affects proxies (see Section 3.4.1).

3.5. Deduplication with Sequential MIDs

CoAP's duplicate rejection functionality can be straightforwardly implemented in a CoAP endpoint by storing, for each remote CoAP endpoint ("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_` ([RFC7252] section "Reliable Messages") and the time packets can stay alive in the network.

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

- o many clients are making periodic, non-idempotent requests to a single CoAP server;
- o 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 using a Message ID variable [RFC7252] 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 endpoint 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 endpoints, 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 endpoints it communicates with, which partly breaks sequentiality from the receiving CoAP endpoint'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 endpoint 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 endpoint 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 endpoint uses sequential MIDs and in response improve efficiency by switching its mode to the bitfield based storage.

4. Alternative Configurations

4.1. Transmission Parameters

When a constrained network of CoAP nodes is not communicating over the Internet, for instance because it is shielded by a proxy or a closed deployment, alternative transmission parameters can be used. Consequently, the derived time values provided in [RFC7252] section 4.8.2 will also need to be adjusted, since most implementations will encode their absolute values.

Static adjustments require a fixed deployment with a constant number or upper bound for the number of nodes, number of hops, and expected concurrent transmissions. Furthermore, the stability of the wireless links should be evaluated. `ACK_TIMEOUT` should be chosen above the `xx%` percentile of the round-trip time distribution.

`ACK_RANDOM_FACTOR` depends on the number of nodes on the network. `MAX_RETRANSMIT` should be chosen suitable for the targeted application. A lower bound for `LEISURE` can be calculated as

$$lb_Leisure = S * G / R$$

where `S` is the estimated response size, `G` the group size, and `R` the target data transfer rate (see [RFC7252] section 8.2). `NSTART` and `PROBING_RATE` depend on estimated network utilization. If the main cause for loss are weak links, higher values can be chosen.

Dynamic adjustments will be performed by advanced congestion control mechanisms such as [I-D.ietf-core-cocoa]. They are required if the

main cause for message loss is network or endpoint congestion. Semi-dynamic adjustments could be implemented by disseminating new static transmission parameters to all nodes when the network configuration changes (e.g., new nodes are added or long-lasting interference is detected).

4.2. CoAP over IPv4

CoAP was designed for the properties of IPv6, which is dominating in constrained environments because of the 6LoWPAN adaption layer [RFC6282]. In particular, the size limitations of CoAP are tailored to the minimal MTU of 1280 bytes. Until the transition towards IPv6 converges, CoAP nodes might also communicate over IPv4, though. Sections 4.2 and 4.6 of the base specification [RFC7252] already provide guidance and implementation notes to handle the smaller minimal MTUs of IPv4.

Another deployment issue in legacy IPv4 deployments is caused by Network Address Translators (NATs). The session timeouts are unpredictable and NATs may close UDP sessions with timeout as short as 60 seconds. This makes CoAP endpoints behind NATs practically unreachable, even when they contact the remote endpoint with a public IP address first. Incorrect behavior may also arise when the NAT session heuristic changes the external port between two successive CoAP messages. For the remote endpoint, this will look like two different CoAP endpoints on the same IP address. Such behavior can be fatal for the resource directory registration interface.

5. Binding to specific lower-layer APIs

Implementing CoAP on specific lower-layer APIs appears to consistently bring up certain less-known aspects of these APIs. This section is intended to alert implementers to such aspects.

5.1. Berkeley Socket Interface

5.1.1. Responding from the right address

In order for a client to recognize a reply (response or acknowledgement) as coming from the endpoint to which the initiating packet was addressed, the source IPv6 address of the reply needs to match the destination address of the initiating packet.

Implementers that have previously written TCP-based applications are used to binding their server sockets to `INADDR_ANY`. Any TCP connection received over such a socket is then more specifically bound to the source address from which the TCP connection setup was received; no programmer action is needed for this.

For stateless UDP sockets, more manual work is required. Simply receiving a packet from a UDP socket bound to `INADDR_ANY` loses the information about the destination address; replying to it through the same socket will use the default address established by the kernel. Two strategies are available:

- o Only use sockets bound to a specific address (not `INADDR_ANY`). A system with multiple interfaces (or addresses) will thus need to bind multiple sockets and send replies back on the same socket the initiating packet was received on.
- o Use `IPV6_RECVPKTINFO` [RFC3542] to configure the socket, and mirror back the `IPV6_PKTINFO` information for the reply (see also Section 5.1.1.1).

5.1.1.1. Managing interfaces

For some applications, it may further be relevant what interface is chosen to send to an endpoint, beyond the kernel choosing one that has a routing table entry for the destination address. E.g., it may be natural to send out a response or acknowledgment on the same interface that the packet prompting it was received. The end of the introduction to section 6 of [RFC3542] describes a simple technique for this, where that RFC's API (`IPV6_PKTINFO`) is available. The same data structure can be used for indicating an interface to send a packet that is initiating an exchange. (Choosing that interface is too application-specific to be in scope for the present document.)

5.1.2. Handling ICMP errors

Sockets that use the connect and send functions usually receive ICMP errors in the form of error codes, sockets that use `sendto` or `sendmsg` do not receive them at all.

Neither is sufficient to implement the guidance in Section 2.6, as the vetting of the message requires access to the CoAP headers in the ICMP error. The necessary information can be obtained by using the `IPV6_RECVERR` option.

5.2. Java

Java provides a wildcard address (`0.0.0.0`) to bind a socket to all network interface. This is useful when a server is supposed to listen on any available interface including the loopback address. For UDP, and hence CoAP this poses a problem, however, because the `DatagramPacket` class does not provide the information to which address it was sent. When replying through the wildcard socket, the JVM will pick the default address, which can break the correlation of

messages when the remote endpoint did not send the message to the default address. This is in particular precarious for IPv6 where it is common to have multiple IP addresses per network interface. Thus, it is recommended to bind to all addresses explicitly and manage the destination address of incoming messages within the CoAP implementation.

5.3. Multicast detection

Similar to the considerations above, Section 8 of [RFC7252] requires a node to detect whether a packet that it is going to reply to was sent to a unicast or to a multicast address. On most platforms, binding a UDP socket to a unicast address ensures that it only receives packets addressed to that address. Programmers relying on this property should ensure that it indeed applies to the platform they are using. If it does not, IPV6_PKTINFO may, again, help for Berkeley Socket Interfaces. For Java, explicit management of different sockets (in this case a MulticastSocket) is required.

5.4. DTLS

CoAPS implementations require access to the authenticated user/device principal to realize access control for resources. How this information can be accessed heavily depends on the DTLS implementation used. Generic and portable CoAP implementations might want to provide an abstraction layer that can be used by application developers that implement resource handlers. It is recommended to keep the API of such an application layer close to popular HTTPS solutions that are available for the targeted platform, for instance, `mod_ssl` or the Java Servlet API.

6. CoAP on various transports

As specified in [RFC7252], CoAP is defined for two underlying transports: UDP and DTLS. These transports are relatively similar in terms of the properties they expose to their users. (The main difference, apart from the increased security, is that DTLS provides an abstraction of a connection, into which the endpoint abstraction is placed; in contrast, the UDP endpoint abstraction is based on four-tuples of IP addresses and ports.)

Recently, the need to carry CoAP over other transports [I-D.silverajan-core-coap-alternative-transports] has led to specifications such as CoAP over TLS or TCP or WebSockets[RFC8323], or even over non-IP transports such as SMS [I-D.becker-core-coap-sms-gprs]. This section discusses considerations that arise when handling these different transports in an implementation.

6.1. CoAP over reliable transports

To cope with transports without reliable delivery (such as UDP and DTLS), CoAP defines its own message layer, with acknowledgments, timers, and retransmission. When CoAP is run over a transport that provides its own reliability (such as TCP or TLS), running this machinery would be redundant. Worse, keeping the machinery in place is likely to lead to interoperability problems as it is unlikely to be tested as well as on unreliable transports. Therefore, [I-D.silverajan-core-coap-alternative-transports] was defined by removing the message layer from CoAP and just running the request/response layer directly on top of the reliable transport. This also leads to a reduced (from the UDP/DTLS 4-byte header) header format.

Conversely, where reliable transports provide a byte stream abstraction, some form of message delimiting had to be added, which now needs to be handled in the CoAP implementation. The use of reliable transports may reduce the disincentive for using messages larger than optimal link layer packet sizes. Where different message sizes are chosen by an application for reliable and for unreliable transports, this can pose additional challenges for translators (Section 6.2).

Where existing CoAP APIs expose details of the the message layer (e.g., CON vs. NON, or assigning application layer semantics to ACKs), using a reliable transport may require additional adjustments.

6.2. Translating between transports

One obvious way to convey CoAP exchanges between different transports is to run a CoAP proxy that supports both transports. The usual considerations for proxies apply. Section 6.2.1 discusses some additional considerations.

Where not much of the functionality of CoAP proxies (such as caching) is required, a simpler 1:1 translation may be possible, as discussed in Section 6.2.2.

6.2.1. Transport translation by proxies

(TBD. In particular, point out the obvious: fan-in/fan-out means that separate message ID and token spaces need to be maintained at the ends of the proxy.)

One more CoAP specific function of a transport translator proxy may be to convert between different block sizes, e.g. between a TCP connection that can tolerate large blocks and UDP over a constrained node network.

6.2.2. One-to-one Transport translation

A translator with reduced requirements for state maintenance can be constructed when no fan-in or fan-out is required, and when the namespace lifetimes of the two sides can be made to coincide. For this one-to-one translation, there is no need to manage message-ID and Token value spaces for both sides separately. So, a simple UDP-to-UDP one-to-one translator could simply copy the messages (among other applications, this might be useful for translation between IPv4 and IPv6 spaces). Similarly, a DTLS-to-TCP translator could be built that executes the message layer (deduplication, retransmission) on the DTLS side, and repackages the CoAP header (add/remove the length information, and remove/add the message ID and message type) between the DTLS and the TCP side.

By definition, such a simple one-to-one translator needs to shut down the connection on one side when the connection on the other side terminates. However, a UDP-to-TCP one-to-one translator cannot simply shut down the UDP endpoint when the TCP endpoint vanishes because the TCP connection closes, so some additional management of state will be necessary.

7. IANA considerations

This document has no actions for IANA.

8. Security considerations

TBD

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