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LoRaWAN Overview
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Abstract

Low Power Wide Area Networks (LPWAN) are wireless technologies covering different Internet of Things (IoT) applications. The common characteristics for LPWANs are large coverage, low bandwidth, small packet and application layer data sizes and long battery life operation. One of these technologies is LoRaWAN developed by the LoRa Alliance. LoRaWAN targets key requirements of the Internet of things such as secure bi-directional communication, mobility and localization services. This memo is an informational overview of LoRaWAN and gives the principal characteristics of this technology in order to help with the IETF work for providing IPv6 connectivity over LoRaWAN along with other LPWANs.

Status of This Memo

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This Internet-Draft will expire on May 1, 2017.

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1. Introduction

LoRaWAN is a wireless technology for long-range low-power low-data-rate applications developed by the LoRa Alliance, a membership consortium. <https://www.lora-alliance.org/> LoRaWAN networks are typically organized in a star-of-stars topology in which gateways relay messages between end-devices and a central "network server" in the backend. Gateways are connected to the network server via IP links while end-devices use single-hop LoRaWAN communication that can be received at one or more gateways. All communication is generally bi-directional, although uplink communication from end-devices to the network server are favoured in terms of overall bandwidth availability.

In LoRaWAN networks, end-device transmissions may be received at multiple gateways, so during nominal operation a network server may see multiple instances of the same uplink message from an end-device.

To maximize both battery life of end-devices and overall network capacity, the LoRaWAN network infrastructure manages the data rate and RF output power for each end-device individually by means of an adaptive data rate (ADR) scheme. End-devices may transmit on any channel allowed by local regulation at any time, using any of the currently available data rates.

This memo provides an overview of the LoRaWAN technology for the Internet community, but the definitive specification [LoRaSpec] is that produced by the LoRa Alliance. This draft is based on version 1.0.2 of the LoRa specification. (Note that version 1.0.2 is expected to be published in a few weeks. We will update this draft when that has happened. For now, version 1.0 is available at [LoRaSpec1.0])

2. Terminology

This section introduces some LoRaWAN terms. Figure 1 shows the entities involved in a LoRaWAN network.

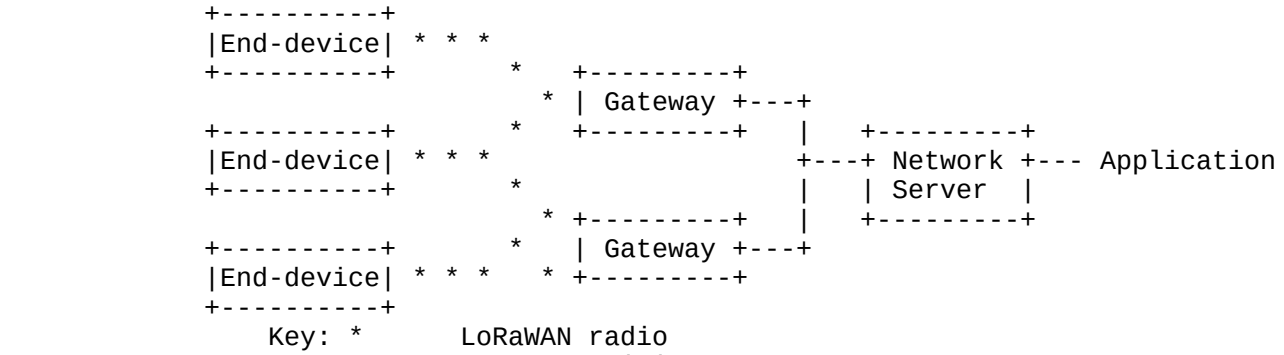

Figure 1: LoRaWAN architecture

- End-device: a LoRa client device, sometimes called a mote. Communicates with gateways.
- Gateway: a radio on the infrastructure-side, sometimes called a concentrator or base-station. Communicates with end-devices and, via IP, with a network server.
- Network Server: The Network Server (NS) terminates the LoRaWAN MAC layer for the end-devices connected to the network. It is the center of the star topology.
- Uplink message: refers to communications from end-device to network server or appliction via one or more gateways.
- Downlink message: refers to communications from network server or application via one gateway to a single end-device or a group of end-devices (considering multicasting).

- Application: refers to application layer code both on the end-device and running "behind" the network server. For LoRaWAN, there will generally only be one application running on most end-devices. Interfaces between the network server and application are not further described here.

- Classes A, B and C define different device capabilities and modes of operation for end-devices. End-devices can transmit uplink messages at any time in any mode of operation (so long as e.g., ISM band restrictions are honoured). An end-device in Class A can only receive downlink messages at predetermined timeslots after each uplink message transmission. Class B allows the end-device to receive downlink messages at periodically scheduled timeslots. Class C allows receipt of downlink messages at anytime. Class selection is based on the end-devices' application use case and its power supply. (While Classes B and C are not further described here, readers may have seen those terms elsewhere so we include them for clarity.)

3. Radio Spectrum

LoRaWAN radios make use of ISM bands, for example, 433MHz and 868MHz within the European Union and 915MHz in the Americas.

The end-device changes channel in a pseudo-random fashion for every transmission to help make the system more robust to interference and/or to conform to local regulations.

As with other LPWAN radio technologies, LoRaWAN end-devices respect the frequency, power and maximum transmit duty cycle requirements for the sub-band imposed by local regulators. In most cases, this means an end-device is only transmitting for 1% of the time, as specified by ISM band regulations. And in some cases the LoRaWAN specification calls for end-devices to transmit less often than is called for by the ISM band regulations in order to avoid congestion.

Figure 2 below shows that after a transmission slot a Class A device turns on its receiver for two short receive windows that are offset from the end of the transmission window. The frequencies and data rate chosen for the first of these receive windows match those used for the transmit window. The frequency and data-rate for the second receive window are configurable. If a downlink message preamble is detected during a receive window, then the end-device keeps the radio on in order to receive the frame.

End-devices can only transmit a subsequent uplink frame after the end of the associated receive windows. When a device joins a LoRaWAN

network (see Section 4 for details), there are similar timeouts on parts of that process.

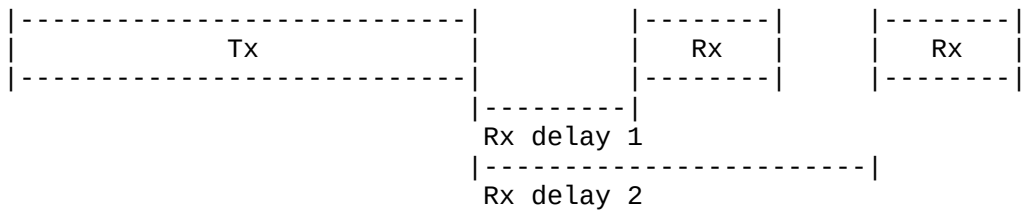

Figure 2: LoRaWAN Class A transmission and reception window

Given the different regional requirements the detailed specification for the LoRaWAN physical layer (taking up more than 30 pages of the specification) is not reproduced here. Instead and mainly to illustrate the kinds of issue encountered, in Table 1 we present some of the default settings for one ISM band (without fully explaining those here) and in Table 2 we describe maxima and minima for some parameters of interest to those defining ways to use IETF protocols over the LoRaWAN MAC layer.

Parameters	Default Value
Rx delay 1	1 s
Rx delay 2	2 s (must be RECEIVE_DELAY1 + 1s)
join delay 1	5 s
join delay 2	6 s
868MHz Default channels	3 (868.1,868.2,868.3), date rate: 0.3-5 kbps

Table 1: Default settings for EU868MHz band

Parameter/Notes	Min	Max
Duty Cycle: some but not all ISM bands impose a limit in terms of how often an end-device can transmit. In some cases LoRaWAN is more stringent in an attempt to avoid congestion.	1%	no-limit
EU 868MHz band data rate/frame-size	250 bits/s : 59 octets	50000 bits/s : 250 octets
US 915MHz band data rate/frame-size	980 bits/s : 19 octets	21900 bits/s : 250 octets

Table 2: Minima and Maxima for various LoRaWAN Parameters

Note that in the case of the smallest frame size (19 octets), 8 octets are required for LoRa MAC layer headers leaving only 11 octets for payload (including MAC layer options). However, those settings do not apply for the join procedure - end-devices are required to use a channel that can send the 23 byte Join-request message for the join procedure.

4. MAC Layer

Uplink and downlink higher layer data is carried in a MACPayload. There is a concept of "ports" (an optional 8 bit value) to handle different applications on an end-device. Port zero is reserved for LoRaWAN specific messaging, such as the join procedure.

The header also distinguishes the uplink/downlink directions and whether or not an acknowledgement ("confirmation") is required from the peer.

All payloads are encrypted and ciphertexts are protected with a cryptographic Message Integrity Check (MIC) - see Section 6 for details.

In addition to carrying higher layer PDUs there are Join-Request and Join-Response (aka Join-Accept) messages for handling network access. And so-called "MAC commands" (see below) up to 15 bytes long can be piggybacked in an options field ("FOpts").

LoRaWAN end-devices can choose various different data rates from a menu of available rates (dependent on the frequencies in use). It is however, recommended that end-devices set the Adaptive Data Rate ("ADR") bit in the MAC layer which is a signal that the network should control the data rate (via MAC commands to the end-device). The network can also assert the ADR bit and control data rates at it’s discretion. The goal is to ensure minimal on-time for radios whilst increasing throughput and reliability when possible. Other things being equal, the effect should be that end-devices closer to a gateway can successfully use higher data rates, whereas end-devices further from all gateways still receive connectivity though at a lower data rate.

Data rate changes can be validated via a scheme of acks from the network with a fall-back to lower rates in the event that downlink acks go missing.

There are 16 (or 32) bit frame counters maintained in each direction that are incremented on each transmission (but not re-transmissions) that are not re-used for a given key. When the device supports a 32 bit counter, then only the least significant 16 bits are sent in the MAC header, but all 32 bits are used in cryptographic operations. (If an end-device only supports a 16 bit counter internally, then the topmost 16 bits are set to zero.)

There are a number of MAC commands for: Link and device status checking, ADR and duty-cycle negotiation, managing the RX windows and radio channel settings. For example, the link check response message allows the network server (in response to a request from an end-device) to inform an end-device about the signal attenuation seen most recently at a gateway, and to also tell the end-device how many gateways received the corresponding link request MAC command.

Some MAC commands are initiated by the network server. For example, one command allows the network server to ask an end-device to reduce it’s duty-cycle to only use a proportion of the maximum allowed in a region. Another allows the network server to query the end-device’s power status with the response from the end-device specifying whether it has an external power source or is battery powered (in which case a relative battery level is also sent to the network server).

The network server can also inform an end-device about channel assignments (mid-point frequencies and data rates). Of course, these must also remain within the bands assigned by local regulation.

5. Names and Addressing

A LoRaWAN network has a short network identifier ("NwkID") which is a seven bit value. A private network (common for LoRaWAN) can use the value zero. If a network wishes to support "foreign" end-devices then the NwkID needs to be registered with the LoRA Alliance, in which case the NwkID is the seven least significant bits of a registered 24-bit NetID. (Note however, that the methods for "roaming" are currently being enhanced within the LoRA Alliance, so the situation here is somewhat fluid.)

In order to operate nominally on a LoRaWAN network, a device needs a 32-bit device address, which is the catentation of the NwkID and a 25-bit device-specific network address that is assigned when the device "joins" the network (see below for the join procedure) or that is pre-provisioned into the device.

End-devices are assumed to work with one or a quite limited number of applications, which matches most LoRaWAN use-cases. The applications are identified by a 64-bit AppEUI, which is assumed to be a registered IEEE EUI64 value.

In addition, a device needs to have two symmetric session keys, one for protecting network artefacts (port=0), the NwkSKey, and another for protecting appliction layer traffic, the AppSKey. Both keys are used for 128 bit AES cryptpgraphic operations. (See Section 6 for details.)

So, one option is for an end-device to have all of the above, plus channel information, somehow (pre-)provisioned, in which case the end-device can simply start transmitting. This is achievable in many cases via out-of-band means given the nature of LoRaWAN networks. Table 3 summarises these values.

Value	Description
DevAddr	DevAddr (32-bits) = NwkId (7-bits) + device-specific network address (25 bits)
AppEUI	IEEE EUI64 naming the application
NwkSKey	128 bit network session key for use with AES
AppSKey	128 bit application session key for use with AES

Table 3: Values required for nominal operation

As an alternative, end-devices can use the LoRaWAN join procedure in order to setup some of these values and dynamically gain access to the network.

To use the join procedure, an end-device must still know the AppEUI. In addition to the AppEUI, end-devices using the join procedure need to also know a different (long-term) symmetric key that is bound to the AppEUI - this is the application key (AppKey), and is distinct from the application session key (AppSKey). The AppKey is required to be specific to the device, that is, each end-device should have a different AppKey value. And finally the end-device also needs a long-term identifier for itself, syntactically also an EUI-64, and known as the device EUI or DevEUI. Table 4 summarises these values.

Value	Description
DevEUI	IEEE EUI64 naming the device
AppEUI	IEEE EUI64 naming the application
AppKey	128 bit long term application key for use with AES

Table 4: Values required for join procedure

The join procedure involves a special exchange where the end-device asserts the AppEUI and DevEUI (integrity protected with the long-term AppKey, but not encrypted) in a Join-request uplink message. This is then routed to the network server which interacts with an entity that knows that AppKey to verify the Join-request. All going well, a Join-accept downlink message is returned from the network server to the end-device that specifies the 24-bit NetID, 32-bit DevAddr and channel information and from which the AppSKey and NwkSKey can be derived based on knowledge of the AppKey. This provides the end-device with all the values listed in Table 3.

There is some special handling related to which channels to use and for multiple transmissions for the join-request which is intended to ensure a successful join in as many cases as possible. Join-request and Join-accept messages also include some random values (nonces) to both provide some replay protection and to help ensure the session keys are unique per run of the join procedure. If a Join-request fails validation, then no Join-accept message (indeed no message at all) is returned to the end-device. For example, if an end-device is factory-reset then it should end up in a state in which it can re-do the join procedure.

6. Security Considerations

In this section we describe the use of cryptography in LoRaWAN. This section is not intended as a full specification but to be sufficient so that future IETF specifications can encompass the required security considerations. The emphasis is on describing the externally visible characteristics of LoRaWAN.

6.1. Payload Encryption and Data Integrity

All payloads are encrypted and have data integrity. Frame options (used for MAC commands) when sent as a payload (port zero) are therefore protected. MAC commands piggy-backed as frame options ("FOpts") are however sent in clear. Since MAC commands may be sent as options and not only as payload, any values sent in that manner are visible to a passive attacker but are not malleable for an active attacker due to the use of the MIC.

For LoRaWAN version 1.0.x, the NWkSkey session key is used to provide data integrity between the end-device and the network server. The AppSKey is used to provide data confidentiality between the end-device and network server, or to the application "behind" the network server, depending on the implementation of the network.

All MAC layer messages have an outer 32-bit Message Integrity Code (MIC) calculated using AES-CMAC calculated over the ciphertext payload and other headers and using the NwkSkey.

Payloads are encrypted using AES-128, with a counter-mode derived from IEEE 802.15.4 using the AppSKey.

Gateways are not expected to be provided with the AppSKey or NwkSKey, all of the infrastructure-side cryptography happens in (or "behind") the network server.

6.2. Key Derivation

When session keys are derived from the AppKey as a result of the join procedure the Join-accept message payload is specially handled.

The long-term AppKey is directly used to protect the Join-accept message content, but the function used is not an aes-encrypt operation, but rather an aes-decrypt operation. The justification is that this means that the end-device only needs to implement the aes-encrypt operation. (The counter mode variant used for payload decryption means the end-device doesn’t need an aes-decrypt primitive.)

The Join-accept plaintext is always less than 16 bytes long, so electronic code book (ECB) mode is used for protecting Join-accept messages.

The Join-accept contains an AppNonce (a 24 bit value) that is recovered on the end-device along with the other Join-accept content (e.g. DevAddr) using the aes-encrypt operation.

Once the Join-accept payload is available to the end-device the session keys are derived from the AppKey, AppNonce and other values, again using an ECB mode aes-encrypt operation, with the plaintext input being a maximum of 16 octets.

7. IANA Considerations

There are no IANA considerations related to this memo.

8. Acknowledgements

The authors re-used some text from [I-D.vilajosana-lpwan-lora-hc]

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9. Contributors

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[LoRaSpec1.0]
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LPWAN Static Context Header Compression (SCHC) for CoAP
draft-ietf-lpwan-coap-static-context-hc-01

Abstract

This draft discusses the way SCHC header compression can be applied to CoAP headers in an LPWAN flow regarding the generated traffic. CoAP protocol differs from IPv6 and UDP protocols because the CoAP Header has a flexible header due to variable options. Another important difference is the asymmetric format in the header information used in the request and the response packets. This draft shows that the Client and the Server do not uses the same fields and how the SCHC header compression can be used.

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1. Introduction

[I-D.toutain-lpwan-ipv6-static-context-hc] defines a header compression mechanism for LPWAN network based on a static context. Where the context is said static since the element values composing the context are not learned during the packet exchanges but are previously defined. The context(s) is(are) known by both ends before transmission.

A context is composed of a set of rules (contexts) that are referenced by Rule IDs (identifiers). A rule describes the header fields with some associated Target Values (TV). A Matching Operator (MO) is associated to each header field description. The rule is selected if all the MOs fit the TVs. In that case, a Compression Decompression Function (CDF) associated to each field defines the link between the compressed and decompressed value for each of the header fields.

This draft discusses the way SCHC can be applied to CoAP headers, how to extend MOs to match a specific element when several fields of the same type are presented in the header. It also introduces the notion of bidirectional or unidirectional (upstream and downstream) fields.

2. CoAP Compressing

CoAP [RFC7252] is an implementation of the REST architecture for constrained devices. Gateway between CoAP and HTTP can be easily built since both protocols uses the same address space (URL), caching mechanisms and methods.

Nevertheless, if limited, the size of a CoAP header may be too large for LPWAN constraints and some compression may be needed to reduce the header size. CoAP compression is not straightforward. Some differences between IPv6/UDP and CoAP can be highlighted. CoAP differs from IPv6 and UDP protocols in the following aspects:

- IPv6 and UDP are symmetrical protocols. The same fields are found in the request and in the response, only position in the header may change (e.g. source and destination fields). A CoAP request is different from an response. For example, the URI-path option is mandatory in the request and is not found in the response.

- CoAP also obeys to the client/server paradigm and the compression rate can be different if the request is issued from a LPWAN node or from an non LPWAN device. For instance a Thing (ES) aware of LPWAN constraints can generate a 1 byte token, but a regular CoAP cleint will certainly send a larger token to the Thing.

- In IPv6 and UDP header fields have a fixed size. In CoAP, Token size may vary from 0 to 8 bytes, length is given by a field in the header. More systematically, the CoAP options are described using the Type-Length-Value. When applying SCHC header compression, the token size is not known at the rule creation, the sender and the receiver must agree on its compressed size.

- The options type in CoAP is not defined with the same value. The Delta TLV coding makes that the type is not independent of previous option and may vary regarding the options contained in the header.

2.1. CoAP behavior

A LPWAN node can either be a client or a server and sometimes both. In the client mode, the LPWAN node sends request to a server and expects an answer or acknowledgements. Acknowledgements can be at 2 different levels:

- In the transport level, a CON message is acknowledged by an ACK message. A NON confirmable message is not acknowledged at all.

- In REST level, a REST request is acknowledged by an "error" code. The [RFC7967] defines an option to limit the number of acknowledgements.

Note that acknowledgement can be optimized and a REST level acknowledgement can be used as a transport level acknowledgement.

2.2. CoAP protocol analysis

CoAP header format defines the following fields:

- version (2 bits): this field can be elided during the SCHC compresssion

- type (2 bits). It defines the type of the transport messages, 4 values are defined, regarding the type of exchange. If only NON messages are sent or CON/ACK messages, this field can be reduced to 0 or 1 bit.

- token length (4 bits). The standard allows up to 8 bytes for a token. If a fixed token size is chosen, then this field can be elided. If some variation in length are needed then 1 or 2 bits could be enough for most of LPWAN applications.

- code (8 bits). This field codes the request and the response values. In CoAP these values are represented in a more compact way then the coding used in HTTP, but the coding is not optimal.

- message id (16 bits). This value of this header field is used to acknowledge CON frames. The size of this field is computed to allow the anticipation (how many frames can be sent without acknowledgement). When a value is used, the [RFC7252] defines the time before it can be reused without ambiguities. This size defined may be too large for a LPWAN node sending or receiving few messages a day.

- Token (0 to 8 bytes). Token header field is used to identify active flows. Regarding the usage for LPWAN (stability in time and limited number), a short token (1 Byte or less) can be enough.

- options are coded using delta-TLV. The delta-T depends on previous values, length is encoded inside the option. The [RFC7252] distinguishes repeatable options that can appear several times in the header. Among them we can distinguish:

  * list options which appear several time in the header but are exclusive such as the Accept option.

  * cumulative options which appear several times in the header but are part of a more generic value such as Uri-Path and Uri-Query. In that case, some elements may not change during the Thing lifetime and other may change at each request. For instance CoMi [I-D.ietf-core-comi] defines the following path /c/X6?k="eth0", where the first path element "c" does not change, the second element can vary over time with a different length (it represents the base64 enconding of a SID) and the query string can also vary over time.

  For a given flow some value options are stable through time. Observe, ETag, If-Match, If-None-Match and Size varies in each message.

The CoAP protocol must not be altered by the compression/ decompression phase, but if no semantic is attributed to a value, it may be changed during this phase. For instance, the compression phase may reduce the size of a token but must maintain its unicity. The decompressor will not be able to restore the original value but

the behavior will remain the same. If no special semantic is assigned to the token, this will be transparent. If a special semantic is assigned to the token, its compression may not be possible.

3. SCHC rules for CoAP header compression

This draft refines the rules definition by adding the direction of the message, from the Thing point of view (uplink, downlink or bidirectional). It does not introduce new Machting Operator or new Compression Decompression Function, but add some possibility to check one particular element when several of them are present at the same time.

A rule can contain CoAP and IPv6/UDP entries. In that case, IPv6/UDP entries are tagged bidirectional.

3.1. Directional Rules

By default, an entry in a rule is bidirectional which means that it can be applied either on the uplink or downlink headers. By specifying the direction, the LC will take into account the specific field only if the direction match.

If the Thing is a client, the URI-Path option is only present on request and not on the response. Therefore, the exact matching principle to select a rule cannot apply.

Some options are marked unidirectional, the value (uplink or downlink) depends of the scenario. A Uri-Path option will be marked uplink if the Thing acts as a client and downlink if the Thing acts as a server. If the Thing acts both as client and server, two different rules will be defined.

3.2. Matching Operator

The Matching Operator behavior has not changed, but the value must take a position value, if the entry is repeated :

FID	TV	MO	CDF
URI-Path	foo	equal 1	not-sent
URI-Path	bar	equal 2	not-sent

Figure 1: Position entry.

For instance, the rule Figure 1 matches with /foo/bar, but not /bar/foo.

The position is added after the natural argument of the MO, for example MSB (4,3) indicates a most significant bit matching of 4 bits in a field located in position 3.

3.3. Compressed field length

When the length is not clearly indicated in the rule, the value length must be sent with the field data, which means for CoAP to send directly the CoAP option where the delta-T is set to 0.

For the CoMi path /c/X6?k="eth0" the rule can be set to:

FID	TV	MO	CDF
URI-Path	c	equal 1	not-sent
URI-Path		ignore 2	value-sent
URI-Query	k=	MSB (16, 1)	value-sent

Figure 2: CoMi URI compression

Figure 2 shows the parsing and the compression of the URI. where c is not sent. The second element is sent with the length (i.e. 0x02 X 6) followed by the query option (i.e. 0x08 k="eth0").

[[NOTE we don’t process URI with a multiple number of path element ??]].

4. Application to CoAP header fields

This section lists the different CoAP header fields and how they can be compressed.

4.1. CoAP version field

This field is bidirectional.

This field contains always the same value, therefore the TV may be 1, the MO is set to "equal" and the CDF is set to "not-sent"

4.2. CoAP type field

This field is bidirectional or undirectional.

Several strategies can be applied to this field regarding the values used:

- o if only one type is sent, for example NON message, its transmission can be avoided. TV is set to the value, MO is set to "equal" and CDF is set to "not-sent".

- o if two values are sent, for example CON and ACK and RST is not used, this field can be reduced to one bit. TV is set to a matching value {CON: 0, ACK: 1}, MO is set to match-mapping and CDF is set to mapping-sent.

- o It is also possible avoid transmission of this field by marking it unidirectional. In one direction, the TV is set to CON, MO is set to "equal" and CDF is set to "not-sent". On the other direction, the TV is set to ACK, the MO is set to "equal" and the CDF is set to "not-sent".

- o Otherwise TV is not set, MO is set to "ignore" and CDF is set to "value-sent".

4.3. CoAP token length field

This field is bi-directional.

Several strategies can be applied to this field regarding the values:

- o no token or a wellknown length, the transmission can be avoided. TV is set to the length, the MO is set to "equal" and CDF is set to "not-sent"

- o The length is variable from one message to another. TV is not set, MO is set to "ignore" and CDF is set to "value-sent". The size of the sent value must be known by ends. The size may be 4 bits. The receiver must take into account this value to retrieve the token. A CoAP proxy may be used before the compression to reduce the field size.

4.4. CoAP code field

This field is unidirectional. The client and the server do not use the same values.

The CoAP code field defines a tricky way to ensure compatibility with HTTP values. Nevertheless only 21 values are defined by [RFC7252] compared to the 255 possible values. So, it could efficiently be coded on 5 bits. The number of code may vary over time, some new codes may be introduced or some applications use a limited number of values.

Code	Description	Mapping
0.00		0x00
0.01	GET	0x01
0.02	POST	0x02
0.03	PUT	0x03
0.04	DELETE	0x04
0.05	FETCH	0x05
0.06	PATCH	0x06
0.07	iPATCH	0x07
2.01	Created	0x08
2.02	Deleted	0x09
2.03	Valid	0x0A
2.04	Changed	0x0B
2.05	Content	0x0C
4.00	Bad Request	0x0D
4.01	Unauthorized	0x0E
4.02	Bad Option	0x0F
4.03	Forbidden	0x10
4.04	Not Found	0x11
4.05	Method Not Allowed	0x12
4.06	Not Acceptable	0x13
4.12	Precondition Failed	0x14
4.13	Request Entity Too Large	0x15
4.15	Unsupported Content-Format	0x16
5.00	Internal Server Error	0x17
5.01	Not Implemented	0x18
5.02	Bad Gateway	0x19
5.03	Service Unavailable	0x1A
5.04	Gateway Timeout	0x1B
5.05	Proxying Not Supported	0x1C

Figure 3: Example of CoAP code mapping

Figure 3 gives a possible mapping, it can be changed to add new codes or reduced if some values are never used by both ends.

The field can be treated differently in upstream than in downstream. If the Thing is a client an entry can be set on the uplink message with a code matching for 0.0X values and another for downlink values for Y.ZZ codes. It is the opposite if the thing is a server.

4.5. CoAP Message ID field

This field is bidirectional.

Message ID is used for two purposes:

- To acknowledge a CON message with an ACK.
- To avoid duplicate messages.

In LPWAN, since a message can be received by several radio gateway, some LPWAN technologies include a sequence number in L2 to avoid duplicate frames. Therefore if the message does not need to be acknowledged (NON or RST message), the Message ID field can be avoided. In that case TV is not set, MO is set to ignore and CDF is set to "not-sent". The decompressor can generate a number.

[[Note; check id this field is not used by OSCOAP .]]

To optimize information sent on the LPWAN, shorter values may be used during the exchange, but Message ID values generated a common CoAP implementation will not take into account this limitation. Before the compression, a proxy may be needed to reduce the size. In that case, the TV is set to 0x0000, MO is set to "MSB(l)" and CDF is set to "LSB(16-l)", where "l" is the size of the compressed header.

Otherwise if no compression is needed the TV is not set, MO is set to ignore and CDF is set to "not-sent".

4.6. CoAP Token field

This field is bi-directional.

Token is used to identify transactions and varies from one transaction to another. Therefore, it is usually necessary to send the value of the token field on the LPWAN network. The optimization will occur by using small values.

Common CoAP implementations may generate large tokens, even if shorter tokens could be used regarding the LPWAN characteristics. A proxy may be needed to reduce the size of the token before compression.

Otherwise the TV is not set, the MO is set to ignore and CDF is set to "value-sent".

The decompression may know the length of the token field from the token length field.

4.7. CoAP option Content-format field.

This field is unidirectional and must not be set to bidirectional in a rule entry. It is used only by the server to inform the client about of the payload type and is never found in client requests.

If the value is known by both sides, the TV contains that value and MO is set to "equal" and the CDF is set to "not-sent".

Otherwise the TV is not set, MO is set to "ignore" and CDF is set to "value-sent"

A mapping list can also be used to reduce the size.

4.8. CoAP option Accept field

This field is unidirectional and must not be set to bidirectional in a rule entry. It is used only by the client to inform of the possible payload type and is never found in server response.

The number of accept options is not limited and can vary regarding the usage. To be selected a rule must contain the exact number about accept options with their positions.

if the accept value must be sent, the TV contains that value, MO is set to "ignore x" where "x" is the accept option’s position and CDF is set to value-sent. Since the value length is not known, it must be sent as a CoAP TLV with delta-T set to 0.

Otherwise the TV is not set, MO is set to "equal x" where x is the accept option’s position and CDF is set to "not-sent"

[[note: it could be more liberal and do not provide the same order after decompression]]

4.9. CoAP option Max-Age field

This field is unidirectional and must not be set to bidirectional in a rule entry. It is used only by the server to inform of the caching duration and is never found in client requests.

If the duration is known by both ends, the TV is set with this duration, the MO is set to "equal" and the CDF is set to "not-sent".

Otherwise the TV is not set, the MO is set to "ignore" and the CDF is set to "value-sent". Since the value length is not known, it must be sent as a CoAP TLV with delta-T set to 0.

[[note: we can reduce (or create a new option) the unit to minute, second is small for LPWAN]]

4.10. CoAP option Uri-Host and Uri-Port fields

This fields are unidirectional and must not be set to bidirectional in a rule entry. They are used only by the client to access to a specific server and are never found in server response.

For each option, if the value is known by both ends, the TV is set with this value, the MO is set to "equal" and the CDF is set to "not-sent".

Otherwise the TV is not set, the MO is set to "ignore" and the CDF is set to "value-sent". Since the value length is not known, it must be sent as a CoAP TLV with delta-T set to 0.

4.11. CoAP option Uri-Path and Uri-Query fields

This fields are unidirectional and must not be set to bidirectional in a rule entry. They are used only by the client to access to a specific resource and are never found in server response.

Path and Query option may have different formats. Section 3.2 gives some examples.

If the URI path as well as the query is composed of 2 or more elements, then the position must be set in the MO parameters.

If a Path or Query element is stable over the time, then TV is set with its value, MO is set to "equal x" where x is the position in the Path or the Query and CDF is set to "not-sent".

Otherwise if the value varies over time, TV is not set, MO is set to "ignore x" where x is the position in the Path or in the Query and CDF is set to "value-sent". Since the value length is not known, it must be sent as a CoAP TLV with deltaT set to 0.

A Mapping list can be used to reduce size of variable Paths or Queries. In that case, to optimize the compression, several elements can be regrouped into a single entry. Numbering of elements do not change, MO comparison is set with the first element of the matching.

For instance, the following Path /foo/bar/variable/stable can leads to the rule defined Figure 4.

FID	TV	MO	CDF
URI-Path	{"/foo/bar":1, "/bar/foo":2}	match-mapping 1	mapping-sent
URI-Path		ignore 3	value-sent
URI-Path	stable	equal 4	not-sent

Figure 4: complex path example

4.12. CoAP option Proxy-URI and Proxy-Scheme fields

These fields are unidirectional and must not be set to bidirectional in a rule entry. They are used only by the client to access to a specific resource and are never found in server response.

If the field value must be sent, TV is not set, MO is set to "ignore" and CDF is set to "value-sent. A mapping can also be used.

Otherwise the TV is set to the value, MO is set to "equal" and CDF is set to "not-sent"

4.13. CoAP option ETag, If-Match, If-None-Match, Location-Path and Location-Query fields

These fields are unidirectional.

These fields values cannot be stored in a rule entry. They must always be sent with the request.

[[Can include OSCOAP Object security in that category]]

5. Other RFCs

5.1. Block

Block option should be avoided in LPWAN. The minimum size of 16 bytes can be incompatible with some LPWAN technologies.

[[Note: do we recommand LPWAN fragmentation since the smallest value of 16 is too big?]]

5.2. Observe

[RFC7641] defines the Observe option. The TV is not set, MO is set to "ignore" and the CDF is set to "value-sent". SCHC does not limit the maximum size for this option (3 bytes). To reduce the transmission size either the Thing implementation should limit the value increase or a proxy can be used limit the increase.

Since RST message may be sent to inform a server that the client do not require Observe response, a rule must allow the transmission of this message.

5.3. No-Response

[RFC7967] defines an No-Response option limiting the responses made by a server to a request. If the value is not by both ends, then TV is set to this value, MO is set to "equal" and CDF is set to "not-sent".

Otherwise, if the value is changing over time, TV is not set, MO is set to "ignore" and CDF to "value-sent". A matching list can also be used to reduce the size.

6. Examples of CoAP header compression

6.1. Mandatory header with CON message

In this first scenario, the LPWAN compressor receives from outside client a POST message, which is immediately acknowledged by the Thing. For this simple scenario, the rules are described Figure 5.

rule id 1

Field	TV	MO	CDF	dir	Sent
CoAP version	01	equal	not-sent	bi	
CoAP Type		ignore	value-sent	bi	TT
CoAP TKL	0	equal	not-sent	bi	
CoAP Code	ML1	match-map	matching-sent	bi	CC CCC
CoAP MID	0000	MSB(7)	LSB(9)	bi	M-ID
CoAP Uri-Path	path	equal 1	not-sent	down	

Figure 5: CoAP Context to compress header without token

The version and Token Length fields are elided. Code has shrunk to 5 bits using the matching list (as the one given Figure 3: 0.01 is value 0x01 and 2.05 is value 0x0c) Message-ID has shrunk to 9 bits to preserve alignment on byte boundary. The most significant bit must be set to 0 through a CoAP proxy. Uri-Path contains a single element indicated in the matching operator.

Figure 6 shows the time diagram of the exchange. A LPWAN Application Server sends a CON message. Compression reduces the header sending only the Type, a mapped code and the least 9 significant bits of Message ID. The receiver decompresses the header. .

The CON message is a request, therefore the LC process to a dynamic mapping. When the ES receives the ACK message, this will not initiate locally a message ID mapping since it is a response. The LC receives the ACK and uncompressed it to restore the original value. Dynamic Mapping context lifetime follows the same rules as message ID duration.

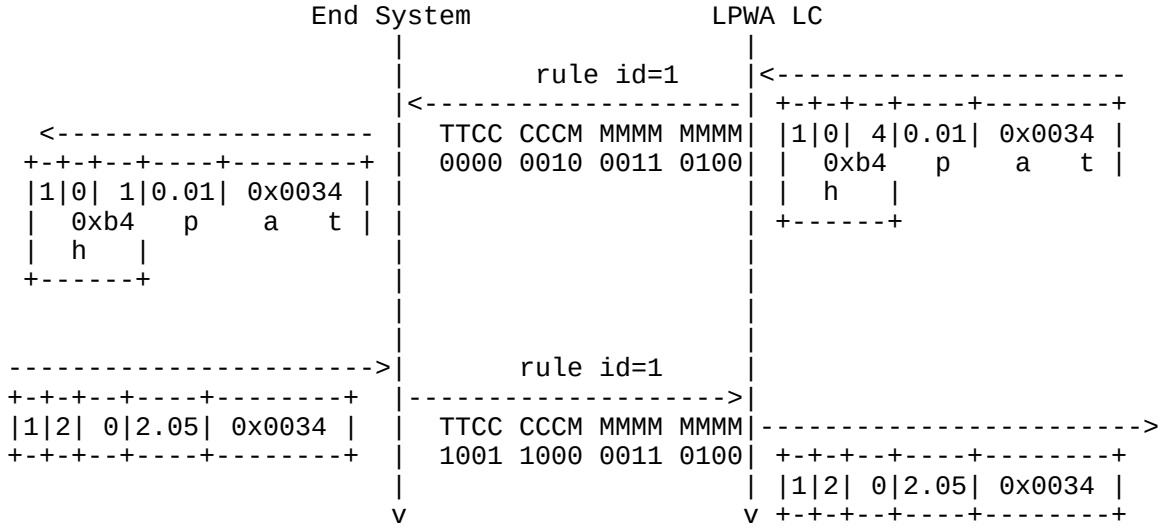


Figure 6: Compression with global addresses

The message can be further optimized by setting some fields unidirectional, as described in Figure 7. Note that Type is no more sent in the compressed format, Compressed Code size in not changed in that example (8 values are needed to code all the requests and 21 to code all the responses in the matching list Figure 3)

rule id 1

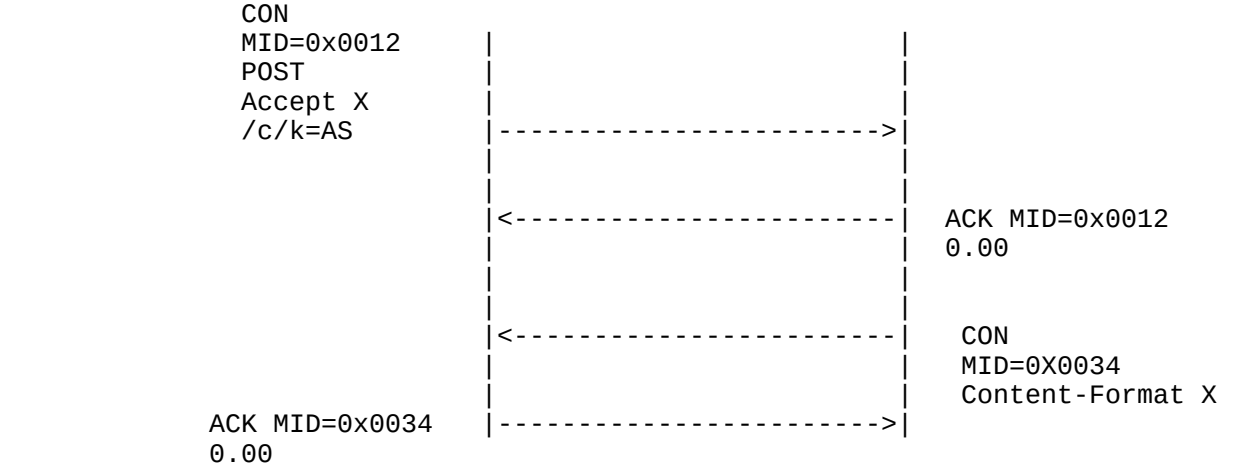
Field	TV	MO	CDF	dir	Sent
CoAP version	01	equal	not-sent	bi	
CoAP Type	CON	equal	not-sent	dw	
CoAP Type	ACK	equal	not-sent	up	
CoAP TKL	0	equal	not-sent	bi	
CoAP Code	ML2	match-map	matching-sent	dw	CCCC C
CoAP Code	ML3	match-map	matching-sent	up	CCCC C
CoAP MID	0000	MSB(5)	LSB(11)	bi	M-ID
CoAP Uri-Path	path	equal 1	not-sent	dw	

ML1 = {CON : 0, ACK:1} ML2 = {POST:0, 2.04:1, 0.00:3}

Figure 7: CoAP Context to compress header without token

6.2. Complete exchange

In that example, the Thing is using CoMi and sends queries for 2 SID.



rule id 3

Field	TV	MO	CDF	dir	Sent
CoAP version	01	equal	not-sent	bi	
CoAP Type	CON	equal	not-sent	up	
CoAP Type	ACK	equal	not-sent	dw	

```
|CoAP TKL      | 1    |equal    |not-sent     |bi |                |
|CoAP Code     | POST |equal    |not-sent     |up |                |
|CoAP Code     | 0.00 |equal    |not-sent     |dw |                |
|CoAP MID      | 0000 |MSB(8)   |LSB(8)       |bi |MMMMMMMM        |
|CoAP Token    |      |ignore   |send-value   |up |TTTTTTTT        |
|CoAP Uri-Path| /c    |equal 1  |not-sent     |dw |                |
|CoAP Uri-query ML4   |equal 1  |not-sent     |dw |P               |
|CoAP Content | X     |equal    |not-sent     |up |                |
+-------------+------+---------+-------------+---+----------------+
```

```
 rule id 4
+-------------+------+---------+-------------+---+----------------+
| Field       |TV    |MO       |CDF          |dir| Sent           |
+=============+======+=========+=============+===+================+
|CoAP version | 01   |equal    |not-sent     |bi |                |
|CoAP Type    | CON  |equal    |not-sent     |dw |                |
|CoAP Type    | ACK  |equal    |not-sent     |up |                |
|CoAP TKL     | 1    |equal    |not-sent     |bi |                |
|CoAP Code    | 2.05 |equal    |not-sent     |dw |                |
|CoAP Code    | 0.00 |equal    |not-sent     |up |                |
|CoAP MID     | 0000 |MSB(8)   |LSB(8)       |bi |MMMMMMMM        |
|CoAP Token   |      |ignore   |send-value   |dw |TTTTTTTT        |
|COAP Accept  | X    |equal    |not-sent     |dw |                |
+-------------+------+---------+-------------+---+----------------+
```

alternative rule:

```
 rule id 4
+-------------+------+---------+-------------+---+----------------+
| Field       |TV    |MO       |CDF          |dir| Sent           |
+=============+======+=========+=============+===+================+
|CoAP version | 01   |equal    |not-sent     |bi |                |
|CoAP Type    | ML1  |equal    |match-sent(1)|bi |t               |
|CoAP TKL     | 1    |equal    |not-sent     |bi |                |
|CoAP Code    | ML2  |equal    |match-sent(1)|up | cc             |
|CoAP Code    | ML3  |equal    |match-sent(2)|dw | cc             |
|CoAP MID     | 0000 |MSB(8)   |LSB(8)       |bi |MMMMMMMM        |
|CoAP Token   |      |ignore   |send-value   |dw |TTTTTTTT        |
|CoAP Uri-Path| /c   |equal 1  |not-sent     |dw |                |
|CoAP Uri-query ML4   |equal 1  |not-sent     |dw |P               |
|CoAP Content | X    |equal    |not-sent     |up |                |
|COAP Accept  | x    |equal    |not-sent     |dw |                |
+-------------+------+---------+-------------+---+----------------+
```

ML1 {CON:0, ACK:1} ML2 {POST:0, 0.00: 1} ML3 {2.05:0, 0.00:1}
ML4 {NULL:0, k=AS:1, K=AZE:2}

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LPWAN Static Context Header Compression (SCHC) and fragmentation for IPv6 and UDP
draft-ietf-lpwan-ipv6-static-context-hc-04

Abstract

This document describes a header compression scheme and fragmentation functionality for very low bandwidth networks. These techniques are especially tailored for LPWAN (Low Power Wide Area Network) networks.

The Static Context Header Compression (SCHC) offers a great level of flexibility when processing the header fields and must be used for this kind of networks. A common context stored in a LPWAN device and in the network is used. This context stores information that will not be transmitted in the constrained network. Static context means that information stored in the context which describes field values, does not change during packet transmission, avoiding complex resynchronization mechanisms, incompatible with LPWAN characteristics. In most of the cases, IPv6/UDP headers are reduced to a small identifier called Rule ID. But sometimes the SCHC header compression will not be enough to send the packet in one L2 PDU, so this document also describes a Fragmentation protocol that must be used when needed.

This document describes the generic compression/decompression mechanism and applies it to IPv6/UDP headers. Similar mechanisms for other protocols such as CoAP will be described in separate documents. Moreover, this document specifies fragmentation and reassembly mechanims for SCHC compressed packets exceeding the L2 PDU size and for the case where the SCHC compression is not possible then the IPv6/UDP packet is sent using the fragmentation protocol.

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 December 18, 2017.

Table of Contents

1. Introduction

Header compression is mandatory to efficiently bring Internet connectivity to the node within a LPWAN network. Some LPWAN networks properties can be exploited for an efficient header compression:

- Topology is star-oriented, therefore all the packets follow the same path. For the needs of this draft, the architecture can be summarized to Devices (Dev) exchanging information with LPWAN Application Server (App) through a Network Gateway (NGW).

- o Traffic flows are mostly known in advance, since devices embed built-in applications. Contrary to computers or smartphones, new applications cannot be easily installed.

The Static Context Header Compression (SCHC) is defined for this environment. SCHC uses a context where header information is kept in the header format order. This context is static (the values on the header fields do not change over time) avoiding complex resynchronization mechanisms, incompatible with LPWAN characteristics. In most of the cases, IPv6/UDP headers are reduced to a small context identifier.

The SCHC header compression mechanism is independent of the specific LPWAN technology over which it will be used.

LPWAN technologies are also characterized, among others, by a very reduced data unit and/or payload size [I-D.ietf-lpwan-overview]. However, some of these technologies do not support layer two fragmentation, therefore the only option for these to support the IPv6 MTU requirement of 1280 bytes [RFC2460] is the use of a fragmentation protocol at the adaptation layer below IPv6. This draft defines also a fragmentation functionality to support the IPv6 MTU requirements over LPWAN technologies. Such functionality has been designed under the assumption that data unit reordering will not happen between the entity performing fragmentation and the entity performing reassembly.

2. LPWAN Architecture

LPWAN technologies have similar architectures but different terminology. We can identify different types of entities in a typical LPWAN network, see Figure 1:

o Devices (Dev) are the end-devices or hosts (e.g. sensors, actuators, etc.). There can be a high density of devices per radio gateway.

o The Radio Gateway (RG), which is the end point of the constrained link.

o The Network Gateway (NGW) is the interconnection node between the Radio Gateway and the Internet.

o LPWAN-AAA Server, which controls the user authentication, the applications. We use the term LPWAN-AAA server because we are not assuming that this entity speaks RADIUS or Diameter as many/most AAA servers do, but equally we don’t want to rule that out, as the functionality will be similar.

o Application Server (App)

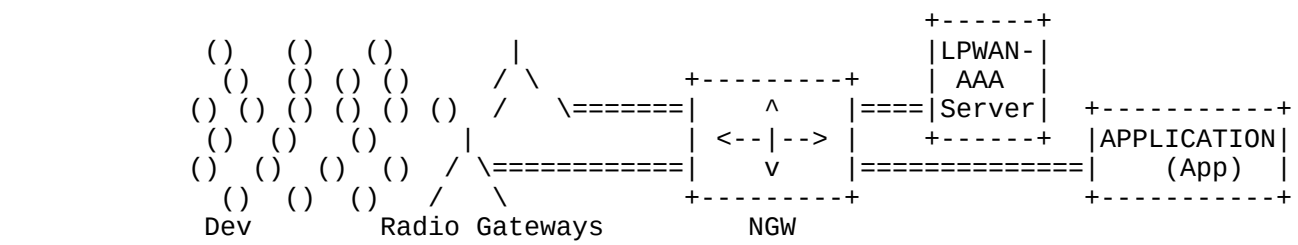


Figure 1: LPWAN Architecture

3. Terminology

This section defines the terminology and acronyms used in this document.

- CDA: Compression/Decompression Action. An action that is perfomed for both functionnalities to compress a header field or to recover its original value in the decompression phase.

- Context: A set of rules used to compress/decompress headers

- Dev: Device. Node connected to the LPWAN. A Dev may implement SCHC.

- App: LPWAN Application. An application sending/receiving IPv6 packets to/from the Device.

- SCHC C/D: LPWAN Compressor/Decompressor. A process in the network to achieve compression/decompressing headers. SCHC C/D uses SCHC rules to perform compression and decompression.

- MO: Matching Operator. An operator used to match a value contained in a header field with a value contained in a Rule.

- Rule: A set of header field values.

- Rule ID: An identifier for a rule, SCHC C/D and Dev share the same Rule ID for a specific flow.

- TV: Target value. A value contained in the Rule that will be matched with the value of a header field.

- FID: Field Indentifier is an index to describe the header fields in the Rule

- FP: Field Position is a list of possible correct values that a field may use

- DI: Direction Indicator is a differentiator for matching in order to be able to have different values for both sides.

- IID: Interface Identifier. See the IPv6 addressing architecture [RFC7136]

- Dev-IID: Device Interface Identifier. Second part of the IPv6 address to identify the device interface

- APP-IID: Application Interface Identifier. Second part of the IPv6 address to identify the application interface

- Dw: Down Link direction for compression, from SCHC C/D to Dev

- Up: Up Link direction for compression, from Dev to SCHC C/D

- Bi: Bidirectional, it can be used in both senses

4. Static Context Header Compression

Static Context Header Compression (SCHC) avoids context synchronization, which is the most bandwidth-consuming operation in other header compression mechanisms such as RoHC [RFC5795]. Based on the fact that the nature of data flows is highly predictable in LPWAN networks, a static context may be stored on the Device (Dev). The context must be stored in both ends, and it can either be learned by a provisioning protocol or by out of band means or it can be pre-provosioned, etc. The way the context is learned on both sides is out of the scope of this document.

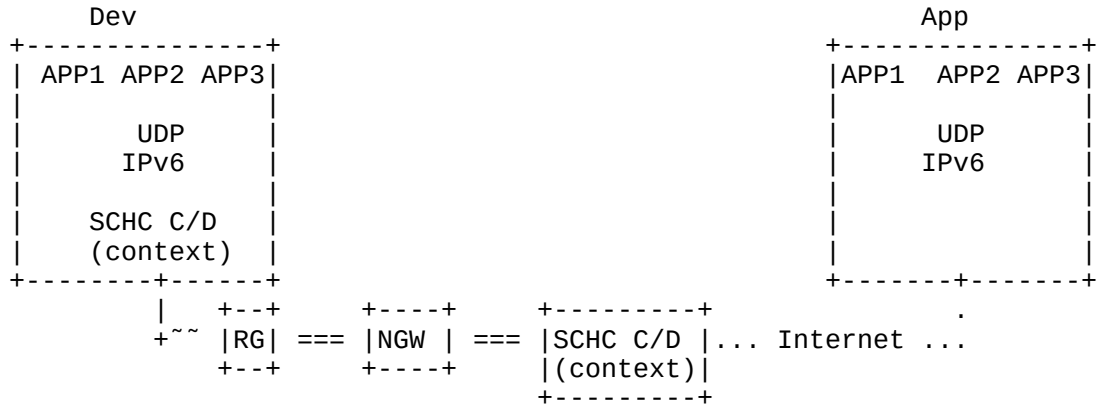


Figure 2: Architecture

Figure 2 based on [I-D.ietf-lpwan-overview] terminology represents the architecture for compression/decompression. The Device is sending applications flows using IPv6 or IPv6/UDP protocols. These flows are compressed by an Static Context Header Compression Compressor/Decompressor (SCHC C/D) to reduce headers size. Resulting information is sent on a layer two (L2) frame to the LPWAN Radio Network to a Radio Gateway (RG) which forwards the frame to a Network Gateway (NGW). The NGW sends the data to a SCHC C/D for decompression which shares the same rules with the Dev. The SCHC C/D can be located on the Network Gateway (NGW) or in another place as long as a tunnel is established between the NGW and the SCHC C/D. SCHC C/D in both sides must share the same set of Rules. After decompression, the packet can be sent on the Internet to one or several LPWAN Application Servers (App).

The SCHC C/D process is bidirectional, so the same principles can be applied in the other direction.

4.1. SCHC Rules

The main idea of the SCHC compression scheme is to send the Rule id to the other end that match as much as possible the original packet values instead of sending known field values. When a value is known by both ends, it is not necessary sent through the LPWAN network.

The context contains a list of rules (cf. Figure 3). Each Rule contains itself a list of fields descriptions composed of a field identifier (FID), a field position (FP), a direction indicator (DI), a target value (TV), a matching operator (MO) and a Compression/ Decompression Action (CDA).

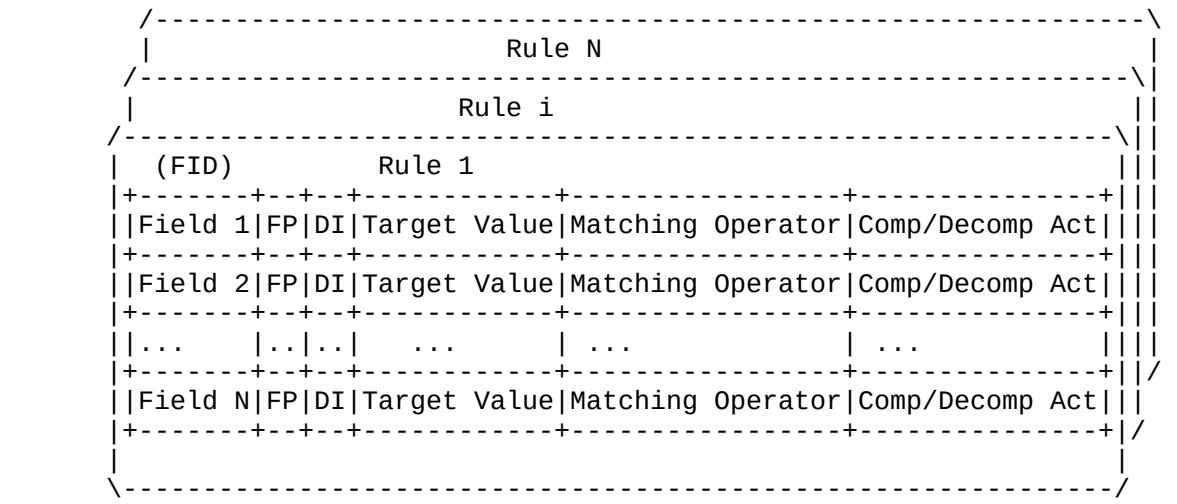


Figure 3: Compression/Decompression Context

The Rule does not describe the original packet format which must be known from the compressor/decompressor. The rule just describes the compression/decompression behavior for the header fields. In the rule, the description of the header field must be performed in the format packet order.

The Rule describes also the compressed header fields which are transmitted regarding their position in the rule which is used for data serialization on the compressor side and data deserialization on the decompressor side.

The Context describes the header fields and its values with the following entries:

- A Field ID (FID) is a unique value to define the header field.
- A Field Position (FP) indicating if several instances of the field exist in the headers which one is targeted. The default position is 1
- A direction indicator (DI) indicating the packet direction. Three values are possible:
  - UP LINK (Up) when the field or the value is only present in packets sent by the Dev to the App,
  - DOWN LINK (Dw) when the field or the value is only present in packet sent from the App to the Dev and

  * BIDIRECTIONAL (Bi) when the field or the value is present either upstream or downstream.

- o A Target Value (TV) is the value used to make the comparison with the packet header field. The Target Value can be of any type (integer, strings,...). For instance, it can be a single value or a more complex structure (array, list,...), such as a JSON or a CBOR structure.

- o A Matching Operator (MO) is the operator used to make the comparison between the Field Value and the Target Value. The Matching Operator may require some parameters. MO is only used during the compression phase.

- o A Compression Decompression Action (CDA) is used to describe the compression and the decompression process. The CDA may require some parameters, CDA are used in both compression and decompression phases.

4.2. Rule ID

Rule IDs are sent between both compression/decompression elements. The size of the Rule ID is not specified in this document, it is implementation-specific and can vary regarding the LPWAN technology, the number of flows, among others.

Some values in the Rule ID space may be reserved for goals other than header compression as fragmentation. (See Section 9).

Rule IDs are specific to a Dev. Two Devs may use the same Rule ID for different header compression. To identify the correct Rule ID, the SCHC C/D needs to combine the Rule ID with the Dev L2 identifier to find the appropriate Rule.

4.3. Packet processing

The compression/decompression process follows several steps:

- o compression Rule selection: The goal is to identify which Rule(s) will be used to compress the packet’s headers. When doing compression from Dw to Up the SCHC C/D needs to find the correct Rule to use by identifying its Dev-ID and the Rule-ID. In the Up situation only the Rule-ID is used. The next step is to choose the fields by their direction, using the direction indicator (DI), so the fields that does not correspond to the appropiated DI will be excluded. Next, then fields are identified according to their field identifier (FID) and field position (FP). If the field position does not correspond then the Rule is not use and the SCHC

take next Rule. Once the DI and the FP correspond to the header information, each field's value is then compared to the corresponding target value (TV) stored in the Rule for that specific field using the matching operator (MO). If all the fields in the packet's header satisfy all the matching operators (MOs) of a Rule (i.e. all results are True), the fields of the header are then processed according to the Compression/ Decompession Actions (CDAs) and a compressed header is obtained. Otherwise the next rule is tested. If no eligible rule is found, then the header must be sent without compression, in which case the fragmentation process must be required.

- o sending: The Rule ID is sent to the other end followed by information resulting from the compression of header fields. This information is sent in the order expressed in the Rule for the matching fields. The way the Rule ID is sent depends on the specific LPWAN layer two technology and will be specified in a specific document, and is out of the scope of this document. For example, it can be either included in a Layer 2 header or sent in the first byte of the L2 payload. (cf. Figure 4).

- o decompression: In both directions, The receiver identifies the sender through its device-id (e.g. MAC address) and selects the appropriate Rule through the Rule ID. This Rule gives the compressed header format and associates these values to header fields. It applies the CDA action to reconstruct the original header fields. The CDA application order can be different of the order given by the Rule. For instance Compute-* may be applied at end, after the other CDAs.

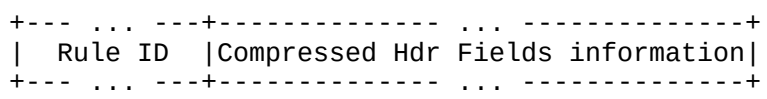


Figure 4: LPWAN Compressed Format Packet

5. Matching operators

Matching Operators (MOs) are functions used by both SCHC C/D endpoints involved in the header compression/decompression. They are not typed and can be applied indifferently to integer, string or any other data type. The result of the operation can either be True or False. MOs are defined as follows:

- o equal: A field value in a packet matches with a TV in a Rule if they are equal.

- o ignore: No check is done between a field value in a packet and a TV in the Rule. The result of the matching is always true.

- o MSB(length): A matching is obtained if the most significant bits of the length field value bits of the header are equal to the TV in the rule. The MSB Matching Operator needs a parameter, indicating the number of bits, to proceed to the matching.

- o match-mapping: The goal of mapping-sent is to reduce the size of a field by allocating a shorter value. The Target Value contains a list of values. Each value is idenfied by a short ID (or index). This operator matches if a field value is equal to one of those target values.

6. Compression Decompression Actions (CDA)

The Compression Decompression Actions (CDA) describes the action taken during the compression of headers fields, and inversely, the action taken by the decompressor to restore the original value.

Action	Compression	Decompression
not-sent	elided	use value stored in ctxt
value-sent	send	build from received value
mapping-sent	send index	value from index on a table
LSB(length)	send LSB	TV OR received value
compute-length	elided	compute length
compute-checksum	elided	compute UDP checksum
Deviid	elided	build IID from L2 Dev addr
Appiid	elided	build IID from L2 App addr

Figure 5: Compression and Decompression Functions

Figure 5 sumarizes the basics functions defined to compress and decompress a field. The first column gives the action’s name. The second and third columns outlines the compression/decompression behavior.

Compression is done in the rule order and compressed values are sent in that order in the compressed message. The receiver must be able to find the size of each compressed field which can be given by the rule or may be sent with the compressed header.

If the field is identified as variable, then its size must be sent first using the following coding:

- If the size is between 0 and 14 bytes it is sent using 4 bits.
- For values between 15 and 255, the first 4 bit sent are set to 1 and the size is sent using 8 bits.
- For higher value, the first 12 bytes are set to 1 and the size is sent on 2 bytes.

6.1. not-sent CDA

Not-sent function is generally used when the field value is specified in the rule and therefore known by the both Compressor and Decompressor. This action is generally used with the "equal" MO. If MO is "ignore", there is a risk to have a decompressed field value different from the compressed field.

The compressor does not send any value on the compressed header for the field on which compression is applied.

The decompressor restores the field value with the target value stored in the matched rule.

6.2. value-sent CDA

The value-sent action is generally used when the field value is not known by both Compressor and Decompressor. The value is sent in the compressed message header. Both Compressor and Decompressor must know the size of the field, either implicitly (the size is known by both sides) or explicitly in the compressed header field by indicating the length. This function is generally used with the "ignore" MO.

The compressor sends the Target Value stored on the rule in the compressed header message. The decompressor restores the field value with the one received from the LPWAN

6.3. mapping-sent

mapping-sent is used to send a smaller index associated to the list of values in the Target Value. This function is used together with the "match-mapping" MO.

The compressor looks in the TV to find the field value and send the corresponding index. The decompressor uses this index to restore the field value.

The number of bits sent is the minimal size to code all the possible indexes.

6.4. LSB CDA

LSB action is used to avoid sendind the known part of the packet field header to the other end. This action is used together with the "MSB" MO. A length can be specified in the rule to indicate how many bits have to be sent. If not length is specified, the number of bits sent are the field length minus the bits length specified in the MSB MO.

The compressor sends the "length" Least Significant Bits. The decompressor combines the value received with the Target Value.

If this action is made on a variable length field, the remaning size in byte has to be sent before.

6.5. DEViid, APPiid CDA

These functions are used to process respectively the Dev and the App Interface Identifiers (Deviid and Appiid) of the IPv6 addresses. Appiid CDA is less common, since current LPWAN technologies frames contain a single address.

The IID value can be computed from the Device ID present in the Layer 2 header. The computation is specific for each LPWAN technology and depends on the Device ID size.

In the downstream direction, these CDA are used to determine the L2 addresses used by the LPWAN.

6.6. Compute-*

Thes classes of functions are used by the decompressor to compute the compressed field value based on received information. Compressed fields are elided during compression and reconstructed during decompression.

- compute-length: compute the length assigned to this field. For instance, regarding the field ID, this CDA may be used to compute IPv6 length or UDP length.

- compute-checksum: compute a checksum from the information already received by the SCHC C/D. This field may be used to compute UDP checksum.

7. Application to IPv6 and UDP headers

This section lists the different IPv6 and UDP header fields and how they can be compressed.

7.1. IPv6 version field

This field always holds the same value, therefore the TV is 6, the MO is "equal" and the "CDA "not-sent"".

7.2. IPv6 Traffic class field

If the DiffServ field identified by the rest of the rule do not vary and is known by both sides, the TV should contain this well-known value, the MO should be "equal" and the CDA must be "not-sent.

If the DiffServ field identified by the rest of the rule varies over time or is not known by both sides, then there are two possibilities depending on the variability of the value, the first one is to do not compressed the field and sends the original value, or the second where the values can be computed by sending only the LSB bits:

- TV is not set to any value, MO is set to "ignore" and CDA is set to "value-sent"
- TV contains a stable value, MO is MSB(X) and CDA is set to LSB

7.3. Flow label field

If the Flow Label field identified by the rest of the rule does not vary and is known by both sides, the TV should contain this well-known value, the MO should be "equal" and the CDA should be "not-sent".

If the Flow Label field identified by the rest of the rule varies during time or is not known by both sides, there are two possibilities depending on the variability of the value, the first one is without compression and then the value is sent and the second where only part of the value is sent and the decompressor needs to compute the original value:

- TV is not set, MO is set to "ignore" and CDA is set to "value-sent"
- TV contains a stable value, MO is MSB(X) and CDA is set to LSB

7.4. Payload Length field

If the LPWAN technology does not add padding, this field can be elided for the transmission on the LPWAN network. The SCHC C/D recomputes the original payload length value. The TV is not set, the MO is set to "ignore" and the CDA is "compute-IPv6-length".

If the payload length needs to be sent and does not need to be coded in 16 bits, the TV can be set to 0x0000, the MO set to "MSB (16-s)" and the CDA to "LSB". The ’s’ parameter depends on the expected maximum packet length.

On other cases, the payload length field must be sent and the CDA is replaced by "value-sent".

7.5. Next Header field

If the Next Header field identified by the rest of the rule does not vary and is known by both sides, the TV should contain this Next Header value, the MO should be "equal" and the CDA should be "not-sent".

If the Next header field identified by the rest of the rule varies during time or is not known by both sides, then TV is not set, MO is set to "ignore" and CDA is set to "value-sent". A matching-list may also be used.

7.6. Hop Limit field

The End System is generally a device and does not forward packets, therefore the Hop Limit value is constant. So the TV is set with a default value, the MO is set to "equal" and the CDA is set to "not-sent".

Otherwise the value is sent on the LPWAN: TV is not set, MO is set to ignore and CDA is set to "value-sent".

Note that the field behavior differs in upstream and downstream. In upstream, since there is no IP forwarding between the Dev and the SCHC C/D, the value is relatively constant. On the other hand, the downstream value depends of Internet routing and may change more frequently. One solution could be to use the Direction Indicator (DI) to distinguish both directions to elide the field in the upstream direction and send the value in the downstream direction.

7.7. IPv6 addresses fields

As in 6LoWPAN [RFC4944], IPv6 addresses are split into two 64-bit long fields; one for the prefix and one for the Interface Identifier (IID). These fields should be compressed. To allow a single rule, these values are identified by their role (DEV or APP) and not by their position in the frame (source or destination). The SCHC C/D must be aware of the traffic direction (upstream, downstream) to select the appropriate field.

7.7.1. IPv6 source and destination prefixes

Both ends must be synchronized with the appropriate prefixes. For a specific flow, the source and destination prefix can be unique and stored in the context. It can be either a link-local prefix or a global prefix. In that case, the TV for the source and destination prefixes contains the values, the MO is set to "equal" and the CDA is set to "not-sent".

In case the rule allows several prefixes, mapping-list must be used. The different prefixes are listed in the TV associated with a short ID. The MO is set to "match-mapping" and the CDA is set to "mapping-sent".

Otherwise the TV contains the prefix, the MO is set to "equal" and the CDA is set to value-sent.

7.7.2. IPv6 source and destination IID

If the DEV or APP IID are based on an LPWAN address, then the IID can be reconstructed with information coming from the LPWAN header. In that case, the TV is not set, the MO is set to "ignore" and the CDA is set to "DEViid" or "APPiid". Note that the LPWAN technology is generally carrying a single device identifier corresponding to the DEV. The SCHC C/D may also not be aware of these values.

If the DEV address has a static value that is not derivated from the EUI-64, then TV contains the value, the MO operator is set to "equal" and the CDA is set to "not-sent".

If several IIDs are possible, then the TV contains the list of possible IIDs, the MO is set to "match-mapping" and the CDA is set to "mapping-sent".

Otherwise the value variation of the IID may be reduced to few bytes. In that case, the TV is set to the stable part of the IID, the MO is set to MSB and the CDA is set to LSB.

Finally, the IID can be sent on the LPWAN. In that case, the TV is not set, the MO is set to "ignore" and the CDA is set to "value-sent".

7.8. IPv6 extensions

No extension rules are currently defined. They can be based on the MOs and CDAs described above.

7.9. UDP source and destination port

To allow a single rule, the UDP port values are identified by their role (DEV or APP) and not by their position in the frame (source or destination). The SCHC C/D must be aware of the traffic direction (upstream, downstream) to select the appropriate field. The following rules apply for DEV and APP port numbers.

If both ends know the port number, it can be elided. The TV contains the port number, the MO is set to "equal" and the CDA is set to "not-sent".

If the port variation is on few bits, the TV contains the stable part of the port number, the MO is set to "MSB" and the CDA is set to "LSB".

If some well-known values are used, the TV can contain the list of this values, the MO is set to "match-mapping" and the CDA is set to "mapping-sent".

Otherwise the port numbers are sent on the LPWAN. The TV is not set, the MO is set to "ignore" and the CDA is set to "value-sent".

7.10. UDP length field

If the LPWAN technology does not introduce padding, the UDP length can be computed from the received data. In that case the TV is not set, the MO is set to "ignore" and the CDA is set to "compute-UDP-length".

If the payload is small, the TV can be set to 0x0000, the MO set to "MSB" and the CDA to "LSB".

On other cases, the length must be sent and the CDA is replaced by "value-sent".

7.11. UDP Checksum field

IPv6 mandates a checksum in the protocol above IP. Nevertheless, if a more efficient mechanism such as L2 CRC or MIC is carried by or over the L2 (such as in the LPWAN fragmentation process (see section Section 9)), the UDP checksum transmission can be avoided. In that case, the TV is not set, the MO is set to "ignore" and the CDA is set to "compute-UDP-checksum".

In other cases the checksum must be explicitly sent. The TV is not set, the MO is set to "ignore" and the CDF is set to "value-sent".

8. Examples

This section gives some scenarios of the compression mechanism for IPv6/UDP. The goal is to illustrate the SCHC behavior.

8.1. IPv6/UDP compression

The most common case using the mechanisms defined in this document will be a LPWAN Dev that embeds some applications running over CoAP. In this example, three flows are considered. The first flow is for the device management based on CoAP using Link Local IPv6 addresses and UDP ports 123 and 124 for Dev and App, respectively. The second flow will be a CoAP server for measurements done by the Device (using ports 5683) and Global IPv6 Address prefixes alpha::IID/64 to beta::1/64. The last flow is for legacy applications using different ports numbers, the destination IPv6 address prefix is gamma::1/64.

Figure 6 presents the protocol stack for this Device. IPv6 and UDP are represented with dotted lines since these protocols are compressed on the radio link.

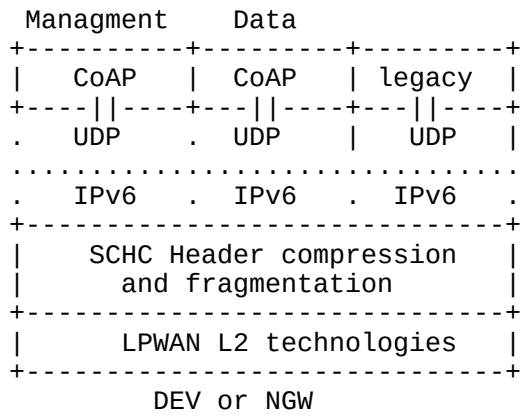


Figure 6: Simplified Protocol Stack for LP-WAN

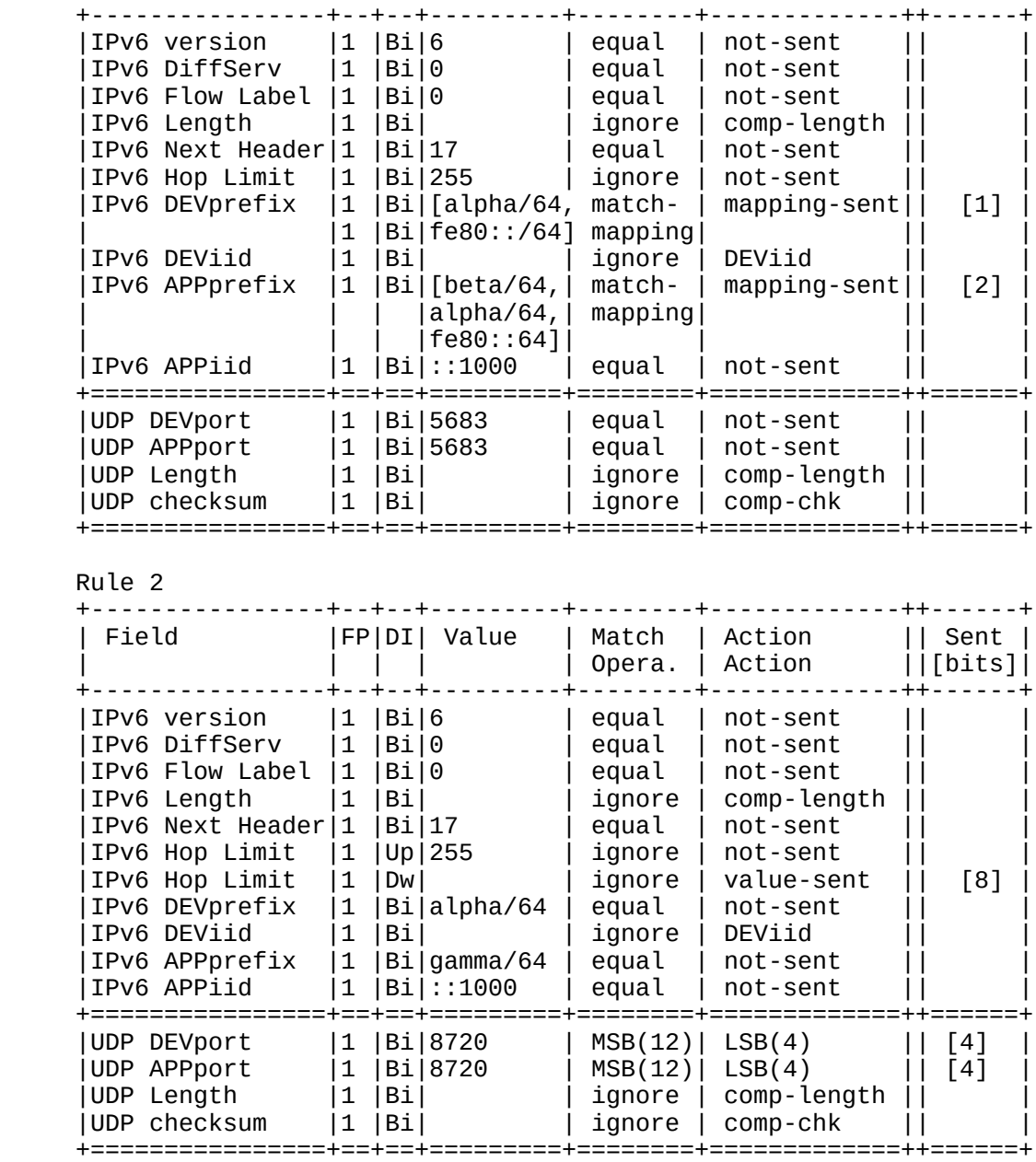
Note that in some LPWAN technologies, only the Devs have a device ID. Therefore, when such technologies are used, it is necessary to define statically an IID for the Link Local address for the SCHC C/D.

Rule 0

Field	FP	DI	Value	Match Opera.	Comp Decomp Action	Sent [bits]
IPv6 version	1	Bi	6	equal	not-sent	
IPv6 DiffServ	1	Bi	0	equal	not-sent	
IPv6 Flow Label	1	Bi	0	equal	not-sent	
IPv6 Length	1	Bi		ignore	comp-length	
IPv6 Next Header	1	Bi	17	equal	not-sent	
IPv6 Hop Limit	1	Bi	255	ignore	not-sent	
IPv6 DEVprefix	1	Bi	FE80::/64	equal	not-sent	
IPv6 DEViid	1	Bi		ignore	DEViid	
IPv6 APPprefix	1	Bi	FE80::/64	equal	not-sent	
IPv6 APPiid	1	Bi	::1	equal	not-sent	
UDP DEVport	1	Bi	123	equal	not-sent	
UDP APPport	1	Bi	124	equal	not-sent	
UDP Length	1	Bi		ignore	comp-length	
UDP checksum	1	Bi		ignore	comp-chk	

Rule 1

Field	FP	DI	Value	Match Opera.	Action Action	Sent [bits]



Field	FP	DI	Value	Match Opera.	Action Action	Sent [bits]
IPv6 version	1	Bi	6	equal	not-sent	
IPv6 DiffServ	1	Bi	0	equal	not-sent	
IPv6 Flow Label	1	Bi	0	equal	not-sent	
IPv6 Length	1	Bi		ignore	comp-length	
IPv6 Next Header	1	Bi	17	equal	not-sent	
IPv6 Hop Limit	1	Bi	255	ignore	not-sent	
IPv6 DEVprefix	1	Bi	[alpha/64, fe80::/64]	match-mapping	mapping-sent	[1]
IPv6 DEViid	1	Bi		ignore	DEViid	
IPv6 APPprefix	1	Bi	[beta/64, alpha/64, fe80::64]	match-mapping	mapping-sent	[2]
IPv6 APPiid	1	Bi	::1000	equal	not-sent	
UDP DEVport	1	Bi	5683	equal	not-sent	
UDP APPport	1	Bi	5683	equal	not-sent	
UDP Length	1	Bi		ignore	comp-length	
UDP checksum	1	Bi		ignore	comp-chk	

Rule 2

Field	FP	DI	Value	Match Opera.	Action Action	Sent [bits]
IPv6 version	1	Bi	6	equal	not-sent	
IPv6 DiffServ	1	Bi	0	equal	not-sent	
IPv6 Flow Label	1	Bi	0	equal	not-sent	
IPv6 Length	1	Bi		ignore	comp-length	
IPv6 Next Header	1	Bi	17	equal	not-sent	
IPv6 Hop Limit	1	Up	255	ignore	not-sent	
IPv6 Hop Limit	1	Dw		ignore	value-sent	[8]
IPv6 DEVprefix	1	Bi	alpha/64	equal	not-sent	
IPv6 DEViid	1	Bi		ignore	DEViid	
IPv6 APPprefix	1	Bi	gamma/64	equal	not-sent	
IPv6 APPiid	1	Bi	::1000	equal	not-sent	
UDP DEVport	1	Bi	8720	MSB(12)	LSB(4)	[4]
UDP APPport	1	Bi	8720	MSB(12)	LSB(4)	[4]
UDP Length	1	Bi		ignore	comp-length	
UDP checksum	1	Bi		ignore	comp-chk	

Figure 7: Context rules

All the fields described in the three rules depicted on Figure 7 are present in the IPv6 and UDP headers. The DEViid-DID value is found in the L2 header.

The second and third rules use global addresses. The way the Dev learns the prefix is not in the scope of the document.

The third rule compresses port numbers to 4 bits.

9. Fragmentation

9.1. Overview

Fragmentation support in LPWAN is mandatory when the underlying LPWAN technology is not capable of fulfilling the IPv6 MTU requirement. Fragmentation is used if, after SCHC header compression, the size of the resulting IPv6 packet is larger than the L2 data unit maximum payload. Fragmentation is also used if SCHC header compression has not been able to compress an IPv6 packet that is larger than the L2 data unit maximum payload. In LPWAN technologies, the L2 data unit size typically varies from tens to hundreds of bytes. If the entire IPv6 datagram fits within a single L2 data unit, the fragmentation mechanism is not used and the packet is sent unfragmented.
If the datagram does not fit within a single L2 data unit, it SHALL be broken into fragments.

Moreover, LPWAN technologies impose some strict limitations on traffic; therefore it is desirable to enable optional fragment retransmission, while a single fragment loss should not lead to retransmitting the full IPv6 datagram. On the other hand, in order to preserve energy, Devices are sleeping most of the time and may receive data during a short period of time after transmission. In order to adapt to the capabilities of various LPWAN technologies, this specification allows for a gradation of fragment delivery reliability. This document does not make any decision with regard to which fragment delivery reliability option is used over a specific LPWAN technology.

An important consideration is that LPWAN networks typically follow the star topology, and therefore data unit reordering is not expected in such networks. This specification assumes that reordering will not happen between the entity performing fragmentation and the entity performing reassembly. This assumption allows to reduce complexity and overhead of the fragmentation mechanism.

9.2. Reliability options: definition

This specification defines the following three fragment delivery reliability options:

- o No ACK
- o Window mode - ACK "always"
- o Window mode - ACK on error

The same reliability option MUST be used for all fragments of a packet. It is up to implementers and/or representatives of the underlying LPWAN technology to decide which reliability option to use and whether the same reliability option applies to all IPv6 packets or not. Note that the reliability option to be used is not necessarily tied to the particular characteristics of the underlying L2 LPWAN technology (e.g. the No ACK reliability option may be used on top of an L2 LPWAN technology with symmetric characteristics for uplink and downlink).

In the No ACK option, the receiver MUST NOT issue acknowledgments (ACK).

In Window mode - ACK "always", an ACK is transmitted by the fragment receiver after a window of fragments have been sent. A window of fragments is a subset of the full set of fragments needed to carry an IPv6 packet. In this mode, the ACK informs the sender about received and/or missing fragments from the window of fragments.

In Window mode - ACK on error, an ACK is transmitted by the fragment receiver after a window of fragments have been sent, only if at least one of the fragments in the window has been lost. In this mode, the ACK informs the sender about received and/or missing fragments from the window of fragments.

In Window mode, upon receipt of an ACK that informs about any lost fragments, the sender retransmits the lost fragments. The maximum number of ACKs to be sent by the receiver for a specific window, denoted MAX_ACKS_PER_WINDOW, is not stated in this document, and it is expected to be defined in other documents (e.g. technology-specific profiles).

This document does not make any decision as to which fragment delivery reliability option(s) need to be supported over a specific LPWAN technology.

Examples of the different reliability options described are provided in Appendix A.

9.3. Reliability options: discussion

This section discusses the properties of each fragment delivery reliability option defined in the previous section.

No ACK is the most simple fragment delivery reliability option. With this option, the receiver does not generate overhead in the form of ACKs. However, this option does not enhance delivery reliability beyond that offered by the underlying LPWAN technology.

The Window mode - ACK on error option is based on the optimistic expectation that the underlying links will offer relatively low L2 data unit loss probability. This option reduces the number of ACKs transmitted by the fragment receiver compared to the Window mode - ACK "always" option. This may be especially beneficial in asymmetric scenarios, e.g. where fragmented data are sent uplink and the underlying LPWAN technology downlink capacity or message rate is lower than the uplink one. However, if an ACK is lost, the sender assumes that all fragments covered by the ACK have been successfully delivered. In contrast, the Window mode - ACK "always" option does not suffer that issue, at the expense of an ACK overhead increase.

The Window mode - ACK "always" option provides flow control. In addition, it is able to handle long bursts of lost fragments, since detection of such events can be done before end of the IPv6 packet transmission, as long as the window size is short enough. However, such benefit comes at the expense of higher ACK overhead.

9.4. Tools

This subsection describes the different tools that are used to enable the described fragmentation functionality and the different reliability options supported. Each tool has a corresponding header field format that is defined in the next subsection. The list of tools follows:

o Rule ID. The Rule ID is used in fragments and in ACKs. The Rule ID in a fragment is set to a value that indicates that the data unit being carried is a fragment. This also allows to interleave non-fragmented IPv6 datagrams with fragments that carry a larger IPv6 datagram. Rule ID may also be used to signal which reliability option is in use for the IPv6 packet being carried. In an ACK, the Rule ID signals that the message this Rule ID is prepended to is an ACK.

o Compressed Fragment Number (CFN). The CFN is included in all fragments. This field can be understood as a truncated, efficient representation of a larger-sized fragment number, and does not necessarily carry an absolute fragment number. A special CFN value signals the last fragment that carries a fragmented IPv6 packet. In Window mode, the CFN is augmented with the W bit, which has the purpose of avoiding possible ambiguity for the receiver that might arise under certain conditions

o Datagram Tag (DTag). The DTag field, if present, is set to the same value for all fragments carrying the same IPv6 datagram, allows to interleave fragments that correspond to different IPv6 datagrams.

o Message Integrity Check (MIC). It is computed by the sender over the complete IPv6 packet before fragmentation by using the TBD algorithm. The MIC allows the receiver to check for errors in the reassembled IPv6 packet, while it also enables compressing the UDP checksum by use of SCHC.

o Bitmap. The bitmap is a sequence of bits included in the ACK for a given window, that provides feedback on whether each fragment of the current window has been received or not.

9.5. Formats

This section defines the fragment format, the fragmentation header formats, and the ACK format.

9.5.1. Fragment format

A fragment comprises a fragmentation header and a fragment payload, and conforms to the format shown in Figure 8. The fragment payload carries a subset of either the IPv6 packet after header compression or an IPv6 packet which could not be compressed. A fragment is the payload in the L2 protocol data unit (PDU).

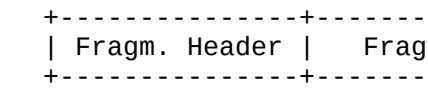


Figure 8: Fragment format.

9.5.2. Fragmentation header formats

In the No ACK option, fragments except the last one SHALL contain the fragmentation header as defined in Figure 9. The total size of this fragmentation header is R bits.

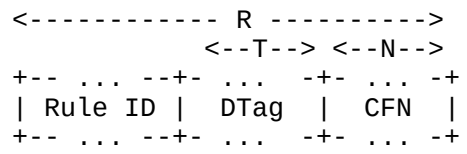


Figure 9: Fragmentation Header for Fragments except the Last One, No ACK option

In any of the Window mode options, fragments except the last one SHALL
contain the fragmentation header as defined in Figure 10. The total size of this fragmentation header is R bits.

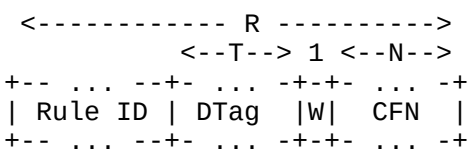


Figure 10: Fragmentation Header for Fragments except the Last One, Window mode

The last fragment of an IPv6 datagram SHALL contain a fragmentation header that conforms to the format shown in Figure 11. The total size of this fragmentation header is R+M bits.

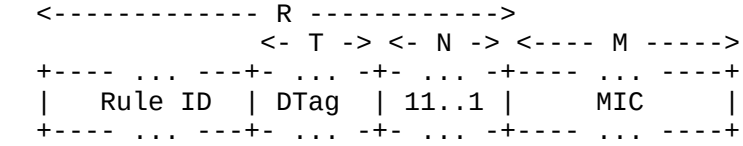


Figure 11: Fragmentation Header for the Last Fragment

- Rule ID: This field has a size of R - T - N - 1 bits in all fragments that are not the last one, when Window mode is used. In all other fragments, the Rule ID field has a size of R - T - N bits.

- DTag: The size of the DTag field is T bits, which may be set to a value greater than or equal to 0 bits. The DTag field in all fragments that carry the same IPv6 datagram MUST be set to the same value. DTag MUST be set sequentially increasing from 0 to 2^T - 1, and MUST wrap back from 2^T - 1 to 0.

- CFN: This field is an unsigned integer, with a size of N bits, that carries the CFN of the fragment. In the No ACK option, N=1. For the rest of options, N equal to or greater than 3 is recommended. The CFN MUST be set sequentially decreasing from the highest CFN in the window (which will be used for the first fragment), and MUST wrap from 0 back to the highest CFN in the window. The highest CFN in the window MUST be a value equal to or smaller than 2^N-2. (Example 1: for N=5, the highest CFN value may be configured to be 30, then subsequent CFNs are set sequentially and in decreasing order, and CFN will wrap from 0 back to 30. Example 2: for N=5, the highest CFN value may be set to 23, then subsequent CFNs are set sequentially and in decreasing order, and the CFN will wrap from 0 back to 23). The CFN for the last fragment has all bits set to 1. Note that, by this definition, the CFN value of 2^N - 1 is only used to identify a fragment as the last fragment carrying a subset of the IPv6 packet being transported, and thus the CFN does not strictly correspond to the N least significant bits of the actual absolute fragment number. It is also important to note that, for N=1, the last fragment of the packet will carry a CFN equal to 1, while all previous fragments will carry a CFN of 0.

- W: W is a 1-bit field. This field carries the same value for all fragments of a window, and it is complemented for the next window. The initial value for this field is 1.

- MIC: This field, which has a size of M bits, carries the MIC for the IPv6 packet.

The values for R, N, T and M are not specified in this document, and have to be determined in other documents (e.g. technology-specific profile documents).

9.5.3. ACK format

The format of an ACK is shown in Figure 12:

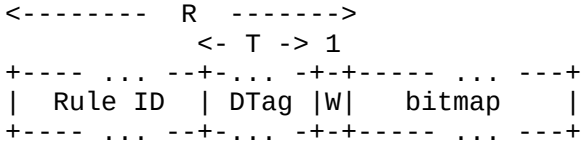


Figure 12: Format of an ACK

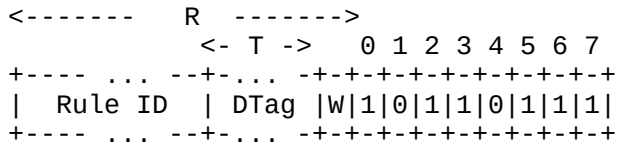
Rule ID: In all ACKs, Rule ID has a size of R - T - 1 bits.

DTag: DTag has a size of T bits. DTag carries the same value as the DTag field in the fragments carrying the IPv6 datagram for which this ACK is intended.

W: This field has a size of 1 bit. In all ACKs, the W bit carries the same value as the W bit carried by the fragments whose reception is being positively or negatively acknowledged by the ACK.

bitmap: This field carries the bitmap sent by the receiver to inform the sender about whether fragments in the current window have been received or not. Size of the bitmap field of an ACK can be equal to 0 or Ceiling(Number_of_Fragments/8) octets, where Number_of_Fragments denotes the number of fragments of a window. The bitmap is a sequence of bits, where the n-th bit signals whether the n-th fragment transmitted in the current window has been correctly received (n-th bit set to 1) or not (n-th bit set to 0). Remaining bits with bit order greater than the number of fragments sent (as determined by the receiver) are set to 0, except for the last bit in the bitmap, which is set to 1 if the last fragment of the window has been correctly received, and 0 otherwise. Feedback on reception of the fragment with CFN = 2^N - 1 (last fragment carrying an IPv6 packet) is only given by the last bit of the corresponding window. Absence of the bitmap in an ACK confirms correct reception of all fragments to be acknowledged by means of the ACK.

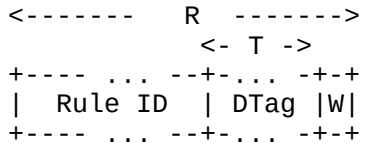
Figure 13 shows an example of an ACK (N=3), where the bitmap indicates that the second and the fifth fragments have not been correctly received.




```
            <- T ->   0 1 2 3 4 5 6 7
+---- ... --+-... -+-+-+-+-+-+-+-+-+
|  Rule ID  | DTag |W|1|0|1|1|0|1|1|1|
+---- ... --+-... -+-+-+-+-+-+-+-+-+
```

Figure 13: Example of the bitmap in an ACK (in Window mode, for N=3)

Figure 14 illustrates an ACK without a bitmap.




```
            <- T ->
+---- ... --+-... -+-+
|  Rule ID  | DTag |W|
+---- ... --+-... -+-+
```

Figure 14: Example of an ACK without a bitmap

Note that, in order to exploit the available L2 payload space to the fullest, a bitmap may have a size smaller than 2^N bits. In that case, the window in use will have a size lower than 2^N-1 fragments. For example, if the maximum available space for a bitmap is 56 bits, N can be set to 6, and the window size can be set to a maximum of 56 fragments.

9.6. Baseline mechanism

The receiver of link fragments SHALL use (1) the sender's L2 source address (if present), (2) the destination's L2 address (if present), (3) Rule ID and (4) DTag to identify all the fragments that belong to a given IPv6 datagram. The fragment receiver may determine the fragment delivery reliability option in use for the fragment based on the Rule ID field in that fragment.

Upon receipt of a link fragment, the receiver starts constructing the original unfragmented packet. It uses the CFN and the order of arrival of each fragment to determine the location of the individual fragments within the original unfragmented packet. For example, it may place the data payload of the fragments within a payload datagram reassembly buffer at the location determined from the CFN and order of arrival of the fragments, and the fragment payload sizes. In Window mode, the fragment receiver also uses the W bit in the received fragments. Note that the size of the original, unfragmented IPv6 packet cannot be determined from fragmentation headers.

When Window mode - ACK on error is used, the fragment receiver starts a timer (denoted "ACK on Error Timer") upon reception of the first fragment for an IPv6 datagram. The initial value for this timer is not provided by this specification, and is expected to be defined in additional documents. This timer is reset every time that a new fragment carrying data from the same IPv6 datagram is received. In Window mode - ACK on error, upon timer expiration, if neither the last fragment of the IPv6 datagram nor the last fragment of the current window (i.e. with CFN=0) have been received, an ACK MUST be transmitted by the fragment receiver to indicate received and not received fragments for the current window.

Note that, in Window mode, the first fragment of the window is the one sent with CFN=2^N-2. Also note that, in Window mode, the fragment with CFN=0 is considered the last fragment of its window, except for the last fragment of the whole packet (with all CFN bits set to 1), which is also the last fragment of the last window. Upon receipt of the last fragment of a window, if Window mode - ACK "Always" is used, the fragment receiver MUST send an ACK to the fragment sender. The ACK provides feedback on the fragments received and lost that correspond to the last window.

If the recipient receives the last fragment of an IPv6 datagram, it checks for the integrity of the reassembled IPv6 datagram, based on the MIC received. In No ACK mode, if the integrity check indicates that the reassembled IPv6 datagram does not match the original IPv6 datagram (prior to fragmentation), the reassembled IPv6 datagram MUST be discarded. If Window mode - ACK "Always" is used, the recipient MUST transmit an ACK to the fragment sender. The ACK provides feedback on the fragments that correspond to the last window. If Window mode - ACK on error is used, the recipient MUST NOT transmit an ACK to the sender if no losses have been detected for the last window. If losses have been detected, the recipient MUST then transmit an ACK to the sender to provide feedback on the last window.

When Window mode - ACK "Always" is used, the fragment sender starts a timer (denoted "ACK Always Timer") after transmitting the last fragment of a fragmented IPv6 datagram. The fragment sender also starts the ACK Always Timer after transmitting the last fragment of a window. The initial value for this timer is not provided by this specification, and is expected to be defined in additional documents. Upon expiration of the timer, if no ACK has been received for the current window, the sender retransmits the last fragment, and it reinitializes and restarts the timer. Note that retransmitting the last fragment of a window as described serves as an ACK request. The maximum number of requests for a specific ACK, denoted MAX_ACK_REQUESTS, is not stated in this document, and it is expected to be defined in other documents (e.g. technology-specific profiles).

In all Window mode options, the fragment sender retransmits any lost fragments reported in an ACK.

If a fragment recipient disassociates from its L2 network, the recipient MUST discard all link fragments of all partially reassembled payload datagrams, and fragment senders MUST discard all not yet transmitted link fragments of all partially transmitted payload (e.g., IPv6) datagrams. Similarly, when a node first receives a fragment of a packet, it starts a reassembly timer. When this time expires, if the entire packet has not been reassembled, the existing fragments MUST be discarded and the reassembly state MUST be flushed. The value for this timer is not provided by this specification, and is expected to be defined in technology-specific profile documents.

9.7. Supporting multiple window sizes

For Window mode operation, implementers may opt to support a single window size or multiple window sizes. The latter, when feasible, may provide performance optimizations. For example, a large window size may be used for IPv6 packets that need to be carried by a large

number of fragments. However, when the number of fragments required to carry an IPv6 packet is low, a smaller window size, and thus a shorter bitmap, may be sufficient to provide feedback on all fragments. If multiple window sizes are supported, the Rule ID may be used to signal the window size in use for a specific IPv6 packet transmission.

9.8. Aborting fragmented IPv6 datagram transmissions

For several reasons, a fragment sender or a fragment receiver may want to abort the on-going transmission of one or several fragmented IPv6 datagrams. The entity (either the fragment sender or the fragment receiver) that triggers abortion transmits to the other endpoint a format that only comprises a Rule ID (of size R bits), which signals abortion of all on-going fragmented IPv6 packet transmissions. The specific value to be used for the Rule ID of this abortion signal is not defined in this document, and is expected to be defined in future documents.

Upon transmission or reception of the abortion signal, both entities MUST release any resources allocated for the fragmented IPv6 datagram transmissions being aborted.

9.9. Downlink fragment transmission

In some LPWAN technologies, as part of energy-saving techniques, downlink transmission is only possible immediately after an uplink transmission. In order to avoid potentially high delay for fragmented IPv6 datagram transmission in the downlink, the fragment receiver MAY perform an uplink transmission as soon as possible after reception of a fragment that is not the last one. Such uplink transmission may be triggered by the L2 (e.g. an L2 ACK sent in response to a fragment encapsulated in a L2 frame that requires an L2 ACK) or it may be triggered from an upper layer.

10. Security considerations

10.1. Security considerations for header compression

A malicious header compression could cause the reconstruction of a wrong packet that does not match with the original one, such corruption may be detected with end-to-end authentication and integrity mechanisms. Denial of Service may be produced but its arise other security problems that may be solved with or without header compression.

10.2. Security considerations for fragmentation

This subsection describes potential attacks to LPWAN fragmentation and suggests possible countermeasures.

A node can perform a buffer reservation attack by sending a first fragment to a target. Then, the receiver will reserve buffer space for the IPv6 packet. Other incoming fragmented packets will be dropped while the reassembly buffer is occupied during the reassembly timeout. Once that timeout expires, the attacker can repeat the same procedure, and iterate, thus creating a denial of service attack. The (low) cost to mount this attack is linear with the number of buffers at the target node. However, the cost for an attacker can be increased if individual fragments of multiple packets can be stored in the reassembly buffer. To further increase the attack cost, the reassembly buffer can be split into fragment-sized buffer slots. Once a packet is complete, it is processed normally. If buffer overload occurs, a receiver can discard packets based on the sender behavior, which may help identify which fragments have been sent by an attacker.

In another type of attack, the malicious node is required to have overhearing capabilities. If an attacker can overhear a fragment, it can send a spoofed duplicate (e.g. with random payload) to the destination. A receiver cannot distinguish legitimate from spoofed fragments. Therefore, the original IPv6 packet will be considered corrupt and will be dropped. To protect resource-constrained nodes from this attack, it has been proposed to establish a binding among the fragments to be transmitted by a node, by applying content-chaining to the different fragments, based on cryptographic hash functionality. The aim of this technique is to allow a receiver to identify illegitimate fragments.

Further attacks may involve sending overlapped fragments (i.e. comprising some overlapping parts of the original IPv6 datagram). Implementers should make sure that correct operation is not affected by such event.

11. Acknowledgements

Thanks to Dominique Barthel, Carsten Bormann, Philippe Clavier, Arunprabhu Kandasamy, Antony Markovski, Alexander Pelov, Pascal Thubert, Juan Carlos Zuniga and Diego Dujovne for useful design consideration and comments.

12. References

12.1. Normative References

[RFC2460] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, DOI 10.17487/RFC2460, December 1998, <http://www.rfc-editor.org/info/rfc2460>.

[RFC4944] Montenegro, G., Kushalnagar, N., Hui, J., and D. Culler, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks", RFC 4944, DOI 10.17487/RFC4944, September 2007, <http://www.rfc-editor.org/info/rfc4944>.

[RFC5795] Sandlund, K., Pelletier, G., and L-E. Jonsson, "The RObust Header Compression (ROHC) Framework", RFC 5795, DOI 10.17487/RFC5795, March 2010, <http://www.rfc-editor.org/info/rfc5795>.

[RFC7136] Carpenter, B. and S. Jiang, "Significance of IPv6 Interface Identifiers", RFC 7136, DOI 10.17487/RFC7136, February 2014, <http://www.rfc-editor.org/info/rfc7136>.

12.2. Informative References

[I-D.ietf-lpwan-overview] Farrell, S., "LPWAN Overview", draft-ietf-lpwan-overview-04 (work in progress), June 2017.

Appendix A. Fragmentation examples

This section provides examples of different fragment delivery reliability options possible on the basis of this specification.

Figure 15 illustrates the transmission of an IPv6 packet that needs 11 fragments in the No ACK option.

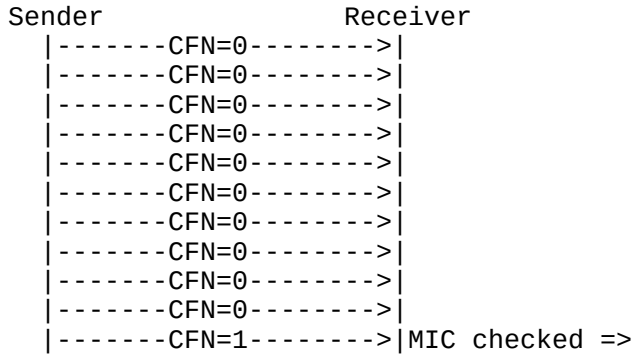


Figure 15: Transmission of an IPv6 packet carried by 11 fragments in the No ACK option

Figure 16 illustrates the transmission of an IPv6 packet that needs 11 fragments in Window mode - ACK on error, for N=3, without losses.

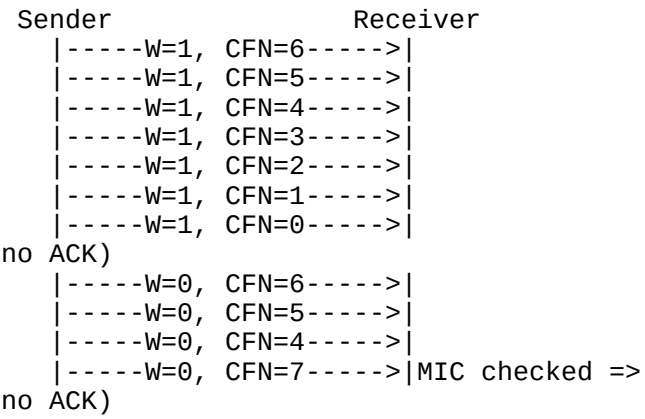


Figure 16: Transmission of an IPv6 packet carried by 11 fragments in Window mode - ACK on error, for N=3, without losses.

Figure 17 illustrates the transmission of an IPv6 packet that needs 11 fragments in Window mode - ACK on error, for N=3, with three losses.

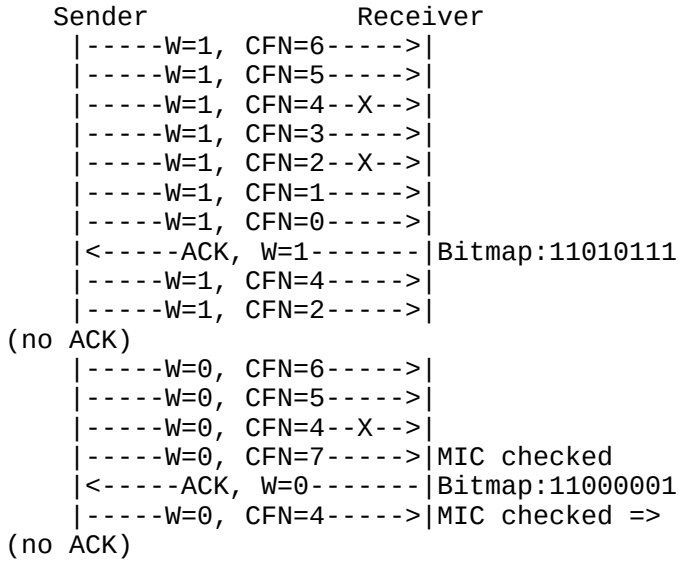


Figure 17: Transmission of an IPv6 packet carried by 11 fragments in Window mode - ACK on error, for N=3, three losses.

Figure 18 illustrates the transmission of an IPv6 packet that needs 11 fragments in Window mode - ACK "always", for N=3, without losses. Note: in Window mode, an additional bit will be needed to number windows.

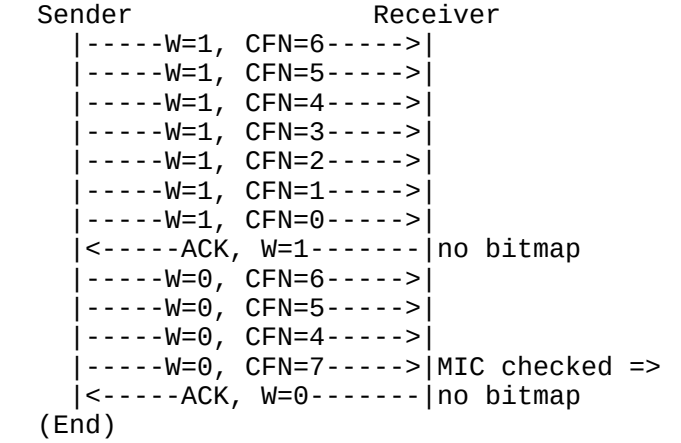


Figure 18: Transmission of an IPv6 packet carried by 11 fragments in Window mode - ACK "always", for N=3, no losses.

Figure 19 illustrates the transmission of an IPv6 packet that needs 11 fragments in Window mode - ACK "always", for N=3, with three losses.

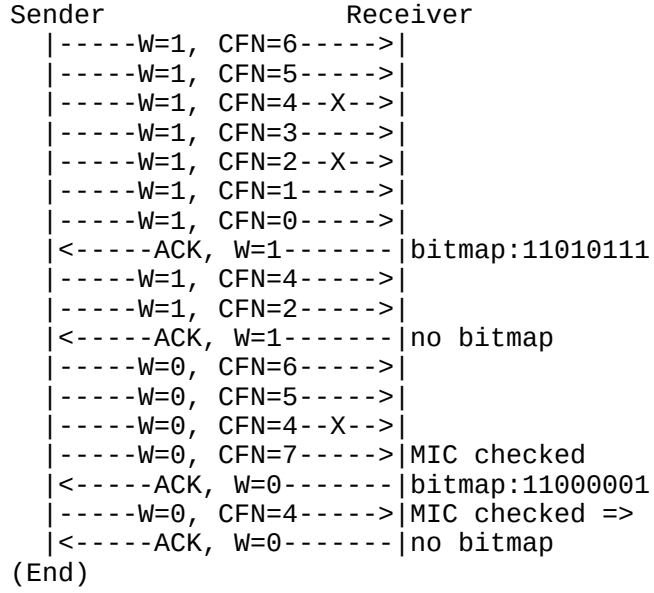


Figure 19: Transmission of an IPv6 packet carried by 11 fragments in Window mode - ACK "Always", for N=3, with three losses.

Appendix B. Rule IDs for fragmentation

Different Rule IDs may be used for different aspects of fragmentation functionality as per this document. A summary of such Rule IDs follows:

- A fragment, and the reliability option in use for the IPv6 datagram being carried: i) No ACK, ii) Window mode - ACK on error, iii) Window mode - ACK "always". In Window mode, a specific Rule ID may be used for each supported window size.

- An ACK message.

- A message to abort all on-going transmissions.

Appendix C. Note

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June 13, 2017

LPWAN Overview
draft-ietf-lpwan-overview-04

Abstract

Low Power Wide Area Networks (LPWAN) are wireless technologies with characteristics such as large coverage areas, low bandwidth, possibly very small packet and application layer data sizes and long battery life operation. This memo is an informational overview of the set of LPWAN technologies being considered in the IETF and of the gaps that exist between the needs of those technologies and the goal of running IP in LPWANs.

Status of This Memo

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

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at http://datatracker.ietf.org/drafts/current/.

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This Internet-Draft will expire on December 15, 2017.

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Table of Contents

1. Introduction

This document provides background material and an overview of the technologies being considered in the IETF's Low Power Wide-Area Networking (LPWAN) working group. We also provide a gap analysis between the needs of these technologies and currently available IETF specifications.

Most technologies in this space aim for similar goals of supporting large numbers of very low-cost, low-throughput devices with very-low power consumption, so that even battery-powered devices can be deployed for years. LPWAN devices also tend to be constrained in their use of bandwidth, for example with limited frequencies being allowed to be used within limited duty-cycles (usually expressed as a percentage of time per-hour that the device is allowed to transmit.) And as the name implies, coverage of large areas is also a common goal. So, by and large, the different technologies aim for deployment in very similar circumstances.

Existing pilot deployments have shown huge potential and created much industrial interest in these technologies. As of today, essentially no LPWAN devices have IP capabilities. Connecting LPWANs to the Internet would provide significant benefits to these networks in terms of interoperability, application deployment, and management, among others. The goal of the IETF LPWAN working group is to, where necessary, adapt IETF-defined protocols, addressing schemes and naming to this particular constrained environment.

This document is largely the work of the people listed in Section 7.

2. LPWAN Technologies

This section provides an overview of the set of LPWAN technologies that are being considered in the LPWAN working group. The text for each was mainly contributed by proponents of each technology.

Note that this text is not intended to be normative in any sense, but simply to help the reader in finding the relevant layer 2 specifications and in understanding how those integrate with IETF-defined technologies. Similarly, there is no attempt here to set out the pros and cons of the relevant technologies.

Note that some of the technology-specific drafts referenced below may have been updated since publication of this document.

2.1. LoRaWAN

Text here is largely from [I-D.farrell-lpwan-lora-overview]

2.1.1. Provenance and Documents

LoRaWAN is a wireless technology for long-range low-power low-data-rate applications developed by the LoRa Alliance, a membership consortium. <https://www.lora-alliance.org/> This draft is based on version 1.0.2 [LoRaSpec] of the LoRa specification. Version 1.0, which has also seen some deployment, is available at [LoRaSpec1.0].

2.1.2. Characteristics

LoRaWAN networks are typically organized in a star-of-stars topology in which gateways relay messages between end-devices and a central "network server" in the backend. Gateways are connected to the network server via IP links while end-devices use single-hop LoRaWAN communication that can be received at one or more gateways. All communication is generally bi-directional, although uplink communication from end-devices to the network server are favored in terms of overall bandwidth availability.

Figure 1 shows the entities involved in a LoRaWAN network.

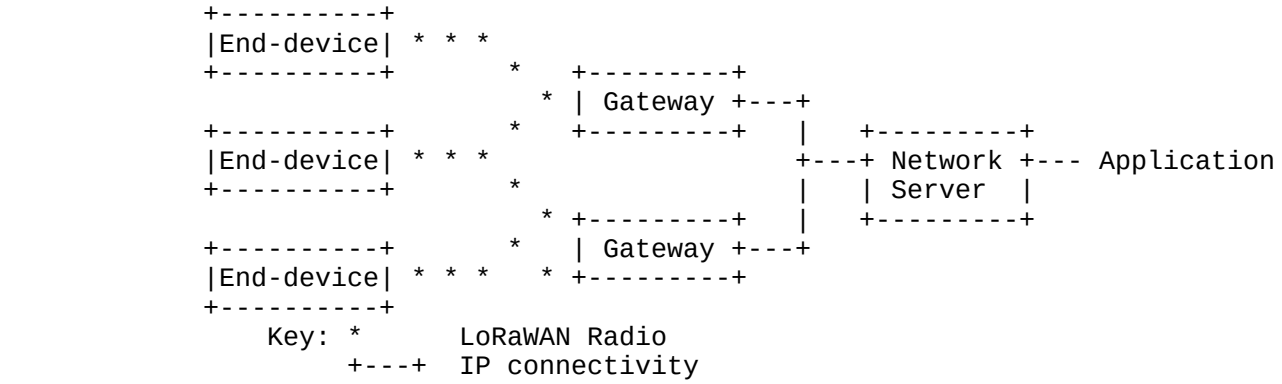

Figure 1: LoRaWAN architecture

- End-device: a LoRa client device, sometimes called a mote. Communicates with gateways.

- Gateway: a radio on the infrastructure-side, sometimes called a concentrator or base-station. Communicates with end-devices and, via IP, with a network server.

- Network Server: The Network Server (NS) terminates the LoRaWAN MAC layer for the end-devices connected to the network. It is the center of the star topology.

- Uplink message: refers to communications from end-device to network server or application via one or more gateways.

- Downlink message: refers to communications from network server or application via one gateway to a single end-device or a group of end-devices (considering multicasting).

- Application: refers to application layer code both on the end-device and running "behind" the network server. For LoRaWAN, there will generally only be one application running on most end-devices. Interfaces between the network server and application are not further described here.

In LoRaWAN networks, end-device transmissions may be received at multiple gateways, so during nominal operation a network server may see multiple instances of the same uplink message from an end-device.

The LoRaWAN network infrastructure manages the data rate and RF output power for each end-device individually by means of an adaptive data rate (ADR) scheme. End-devices may transmit on any channel allowed by local regulation at any time.

LoRaWAN radios make use of industrial, scientific and medical (ISM) bands, for example, 433MHz and 868MHz within the European Union and 915MHz in the Americas.

The end-device changes channel in a pseudo-random fashion for every transmission to help make the system more robust to interference and/or to conform to local regulations.

Figure 2 below shows that after a transmission slot a Class A device turns on its receiver for two short receive windows that are offset from the end of the transmission window. End-devices can only transmit a subsequent uplink frame after the end of the associated receive windows. When a device joins a LoRaWAN network, there are similar timeouts on parts of that process.

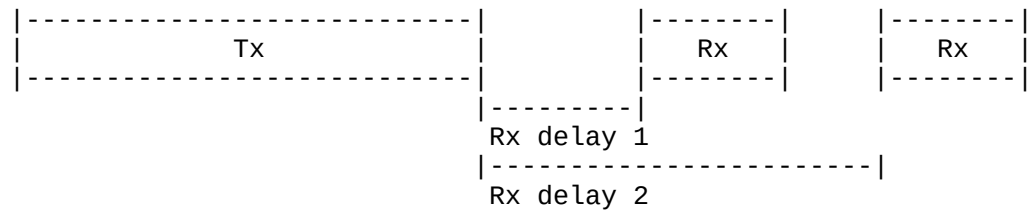

Figure 2: LoRaWAN Class A transmission and reception window

Given the different regional requirements the detailed specification for the LoRaWAN physical layer (taking up more than 30 pages of the specification) is not reproduced here. Instead and mainly to illustrate the kinds of issue encountered, in Table 1 we present some of the default settings for one ISM band (without fully explaining those here) and in Table 2 we describe maxima and minima for some parameters of interest to those defining ways to use IETF protocols over the LoRaWAN MAC layer.

Parameters	Default Value
Rx delay 1	1 s
Rx delay 2	2 s (must be RECEIVE_DELAY1 + 1s)
join delay 1	5 s
join delay 2	6 s
868MHz Default channels	3 (868.1,868.2,868.3), data rate: 0.3-5 kbps

Table 1: Default settings for EU868MHz band

Parameter/Notes	Min	Max
Duty Cycle: some but not all ISM bands impose a limit in terms of how often an end-device can transmit. In some cases LoRaWAN is more stringent in an attempt to avoid congestion.	1%	no-limit
EU 868MHz band data rate/frame-size	250 bits/s : 59 octets	50000 bits/s : 250 octets
US 915MHz band data rate/frame-size	980 bits/s : 19 octets	21900 bits/s : 250 octets

Table 2: Minima and Maxima for various LoRaWAN Parameters

Note that in the case of the smallest frame size (19 octets), 8 octets are required for LoRa MAC layer headers leaving only 11 octets for payload (including MAC layer options). However, those settings do not apply for the join procedure - end-devices are required to use a channel and data rate that can send the 23-byte Join-request message for the join procedure.

Uplink and downlink higher layer data is carried in a MACPayload. There is a concept of "ports" (an optional 8-bit value) to handle different applications on an end-device. Port zero is reserved for LoRaWAN specific messaging, such as the configuration of the end device’s network parameters (available channels, data rates, ADR parameters, RX1/2 delay, etc.).

In addition to carrying higher layer PDUs there are Join-Request and Join-Response (aka Join-Accept) messages for handling network access. And so-called "MAC commands" (see below) up to 15 bytes long can be piggybacked in an options field ("FOpts").

There are a number of MAC commands for link and device status checking, ADR and duty-cycle negotiation, managing the RX windows and radio channel settings. For example, the link check response message allows the network server (in response to a request from an end-device) to inform an end-device about the signal attenuation seen most recently at a gateway, and to also tell the end-device how many gateways received the corresponding link request MAC command.

Some MAC commands are initiated by the network server. For example, one command allows the network server to ask an end-device to reduce its duty-cycle to only use a proportion of the maximum allowed in a region. Another allows the network server to query the end-device's power status with the response from the end-device specifying whether it has an external power source or is battery powered (in which case a relative battery level is also sent to the network server).

A LoRaWAN network has a network identifier ("NwkID"), currently a seven-bit value. A private network (common for LoRaWAN) can use the value zero or one. If a network wishes to support "foreign" end-devices then the NwkID needs to be registered with the LoRA Alliance, in which case the NwkID is the seven least significant bits of a registered 24-bit NetID. (Note however, that the methods for "roaming" are defined in the upcoming LoRaWAN 1.1 specification.)

In order to operate nominally on a LoRaWAN network, a device needs a 32-bit device address, which is the catenation of the NwkID and a 25-bit device-specific network address that is assigned when the device "joins" the network (see below for the join procedure) or that is pre-provisioned into the device.

End-devices are assumed to work with one or a quite limited number of applications, identified by a 64-bit AppEUI, which is assumed to be a registered IEEE EUI64 value. In addition, a device needs to have two symmetric session keys, one for protecting network artifacts (port=0), the NwkSKey, and another for protecting application layer traffic, the AppSKey. Both keys are used for 128-bit AES cryptographic operations. So, one option is for an end-device to have all of the above, plus channel information, somehow (pre-)provisioned, in which case the end-device can simply start transmitting. This is achievable in many cases via out-of-band means given the nature of LoRaWAN networks. Table 3 summarizes these values.

Value	Description
DevAddr	DevAddr (32-bits) = device-specific network address generated from the NwkID
AppEUI	IEEE EUI64 naming the application
NwkSKey	128-bit network session key for use with AES
AppSKey	128-bit application session key for use with AES

Table 3: Values required for nominal operation

As an alternative, end-devices can use the LoRaWAN join procedure in order to setup some of these values and dynamically gain access to the network. To use the join procedure, an end-device must still know the AppEUI, and in addition, a different (long-term) symmetric key that is bound to the AppEUI - this is the application key (AppKey), and is distinct from the application session key (AppSKey). The AppKey is required to be specific to the device, that is, each end-device should have a different AppKey value. And finally, the end-device also needs a long-term identifier for itself, syntactically also an EUI-64, and known as the device EUI or DevEUI. Table 4 summarizes these values.

Value	Description
DevEUI	IEEE EUI64 naming the device
AppEUI	IEEE EUI64 naming the application
AppKey	128-bit long term application key for use with AES

Table 4: Values required for join procedure

The join procedure involves a special exchange where the end-device asserts the AppEUI and DevEUI (integrity protected with the long-term AppKey, but not encrypted) in a Join-request uplink message. This is then routed to the network server which interacts with an entity that knows that AppKey to verify the Join-request. All going well, a Join-accept downlink message is returned from the network server to the end-device that specifies the 24-bit NetID, 32-bit DevAddr and channel information and from which the AppSKey and NwkSKey can be

derived based on knowledge of the AppKey. This provides the end-device with all the values listed in Table 3.

All payloads are encrypted and have data integrity. MAC commands, when sent as a payload (port zero), are therefore protected. MAC commands piggy-backed as frame options ("FOpts") are however sent in clear. Any MAC commands sent as frame options and not only as payload, are visible to a passive attacker but are not malleable for an active attacker due to the use of the Message Integrity Check (MIC) described below..

For LoRaWAN version 1.0.x, the NWkSkey session key is used to provide data integrity between the end-device and the network server. The AppSKey is used to provide data confidentiality between the end-device and network server, or to the application "behind" the network server, depending on the implementation of the network.

All MAC layer messages have an outer 32-bit MIC calculated using AES-CMAC calculated over the ciphertext payload and other headers and using the NwkSkey. Payloads are encrypted using AES-128, with a counter-mode derived from IEEE 802.15.4 using the AppSKey. Gateways are not expected to be provided with the AppSKey or NwkSKey, all of the infrastructure-side cryptography happens in (or "behind") the network server. When session keys are derived from the AppKey as a result of the join procedure the Join-accept message payload is specially handled.

The long-term AppKey is directly used to protect the Join-accept message content, but the function used is not an AES-encrypt operation, but rather an AES-decrypt operation. The justification is that this means that the end-device only needs to implement the AES-encrypt operation. (The counter mode variant used for payload decryption means the end-device doesn’t need an AES-decrypt primitive.)

The Join-accept plaintext is always less than 16 bytes long, so electronic code book (ECB) mode is used for protecting Join-accept messages. The Join-accept contains an AppNonce (a 24 bit value) that is recovered on the end-device along with the other Join-accept content (e.g. DevAddr) using the AEs-encrypt operation. Once the Join-accept payload is available to the end-device the session keys are derived from the AppKey, AppNonce and other values, again using an ECB mode AES-encrypt operation, with the plaintext input being a maximum of 16 octets.

2.2. Narrowband IoT (NB-IoT)

Text here is largely from [I-D.ratilainen-lpwan-nb-iot]

2.2.1. Provenance and Documents

Narrowband Internet of Things (NB-IoT) is developed and standardized by 3GPP. The standardization of NB-IoT was finalized with 3GPP Release 13 in June 2016, and further enhancements for NB-IoT are specified in 3GPP Release 14 in 2017, for example in the form of multicast support. Further features and improvements will be developed in the following releases, but NB-IoT has been ready to be deployed since 2016, and is rather simple to deploy especially in the existing LTE networks with a software upgrade in the operator's base stations. For more information of what has been specified for NB-IoT, 3GPP specification 36.300 [TGPP36300] provides an overview and overall description of the E-UTRAN radio interface protocol architecture, while specifications 36.321 [TGPP36321], 36.322 [TGPP36322], 36.323 [TGPP36323] and 36.331 [TGPP36331] give more detailed description of MAC, RLC, PDCP and RRC protocol layers, respectively. Note that the description below assumes familiarity with numerous 3GPP terms.

2.2.2. Characteristics

Specific targets for NB-IoT include: Less than US$5 module cost, extended coverage of 164 dB maximum coupling loss, battery life of over 10 years, ~55000 devices per cell and uplink reporting latency of less than 10 seconds.

NB-IoT supports Half Duplex FDD operation mode with 60 kbps peak rate in uplink and 30 kbps peak rate in downlink, and a maximum transmission unit (MTU) size of 1600 bytes limited by PDCP layer (see Figure 4 for the protocol structure), which is the highest layer in the user plane, as explained later. Any packet size up to the said MTU size can be passed to the NB-IoT stack from higher layers, segmentation of the packet is performed in the RLC layer, which can segment the data to transmission blocks with size as small as 16 bits. As the name suggests, NB-IoT uses narrowbands with the bandwidth of 180 kHz in both downlink and uplink. The multiple access scheme used in the downlink is OFDMA with 15 kHz sub-carrier spacing. In uplink SC-FDMA single tone with either 15kHz or 3.75 kHz tone spacing is used, or optionally multi-tone SC- FDMA can be used with 15 kHz tone spacing.

NB-IoT can be deployed in three ways. In-band deployment means that the narrowband is deployed inside the LTE band and radio resources are flexibly shared between NB-IoT and normal LTE carrier. In Guard-

band deployment the narrowband uses the unused resource blocks between two adjacent LTE carriers. Standalone deployment is also supported, where the narrowband can be located alone in dedicated spectrum, which makes it possible for example to reframe a GSM carrier at 850/900 MHz for NB-IoT. All three deployment modes are used in licensed frequency bands. The maximum transmission power is either 20 or 23 dBm for uplink transmissions, while for downlink transmission the eNodeB may use higher transmission power, up to 46 dBm depending on the deployment.

A maximum coupling loss (MCL) target for NB-IoT coverage enhancements defined by 3GPP is 164 dB. With this MCL, the performance of NB-IoT in downlink varies between 200 bps and 2-3 kbps, depending on the deployment mode. Stand-alone operation may achieve the highest data rates, up to few kbps, while in-band and guard-band operations may reach several hundreds of bps. NB-IoT may even operate with MCL higher than 170 dB with very low bit rates.

For signaling optimization, two options are introduced in addition to legacy LTE RRC connection setup; mandatory Data-over-NAS (Control Plane optimization, solution 2 in [TGPP23720]) and optional RRC Suspend/Resume (User Plane optimization, solution 18 in [TGPP23720]). In the control plane optimization the data is sent over Non-Access Stratum, directly to/from Mobility Management Entity (MME) (see Figure 3 for the network architecture) in the core network to the User Equipment (UE) without interaction from the base station. This means there are no Access Stratum security or header compression provided by the PDCP layer in the eNodeB, as the Access Stratum is bypassed, and only limited RRC procedures. RoHC based header compression may still optionally be provided and terminated in MME.

The RRC Suspend/Resume procedures reduce the signaling overhead required for UE state transition from RRC Idle to RRC Connected mode compared to legacy LTE operation in order to have quicker user plane transaction with the network and return to RRC Idle mode faster.

In order to prolong device battery life, both power-saving mode (PSM) and extended DRX (eDRX) are available to NB-IoT. With eDRX the RRC Connected mode DRX cycle is up to 10.24 seconds and in RRC Idle the eDRX cycle can be up to 3 hours. In PSM the device is in a deep sleep state and only wakes up for uplink reporting, after which there is a window, configured by the network, during which the device receiver is open for downlink connectivity, of for periodical "keep-alive" signaling (PSM uses periodic TAU signaling with additional reception window for downlink reachability).

Since NB-IoT operates in licensed spectrum, it has no channel access restrictions allowing up to a 100% duty-cycle.

3GPP access security is specified in [TGPP33203].

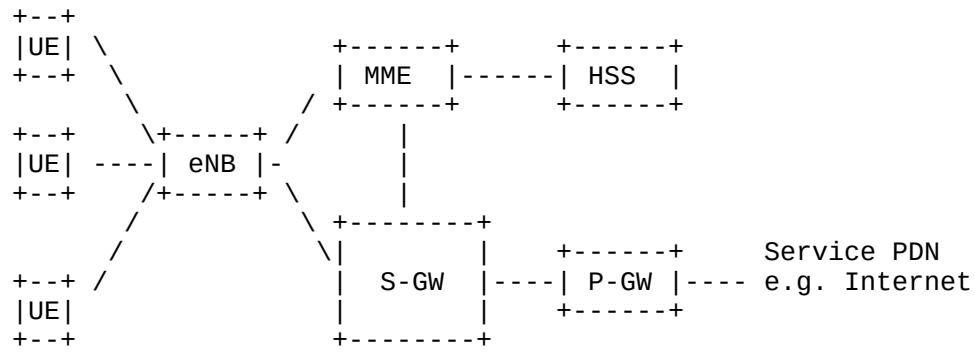

Figure 3: 3GPP network architecture

Figure 3 shows the 3GPP network architecture, which applies to NB-IoT. Mobility Management Entity (MME) is responsible for handling the mobility of the UE. MME tasks include tracking and paging UEs, session management, choosing the Serving gateway for the UE during initial attachment and authenticating the user. At MME, the Non-Access Stratum (NAS) signaling from the UE is terminated.

Serving Gateway (S-GW) routes and forwards the user data packets through the access network and acts as a mobility anchor for UEs during handover between base stations known as eNodeBs and also during handovers between NB-IoT and other 3GPP technologies.

Packet Data Node Gateway (P-GW) works as an interface between 3GPP network and external networks.

The Home Subscriber Server (HSS) contains user-related and subscription- related information. It is a database, which performs mobility management, session establishment support, user authentication and access authorization.

E-UTRAN consists of components of a single type, eNodeB. eNodeB is a base station, which controls the UEs in one or several cells.

The illustration of 3GPP radio protocol architecture can be seen from Figure 4.

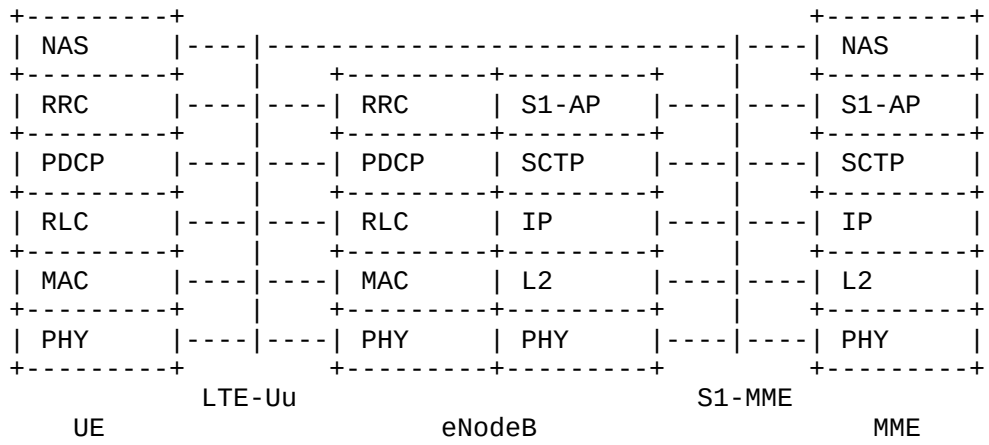

Figure 4: 3GPP radio protocol architecture for control plane

Control plane protocol stack

The radio protocol architecture of NB-IoT (and LTE) is separated into control plane and user plane. The control plane consists of protocols which control the radio access bearers and the connection between the UE and the network. The highest layer of control plane is called Non-Access Stratum (NAS), which conveys the radio signaling between the UE and the EPC, passing transparently through the radio network. It is responsible for authentication, security control, mobility management and bearer management.

Access Stratum (AS) is the functional layer below NAS, and in control plane it consists of Radio Resource Control protocol (RRC) [TGPP36331], which handles connection establishment and release functions, broadcast of system information, radio bearer establishment, reconfiguration and release. RRC configures the user and control planes according to the network status. There exists two RRC states, RRC_Idle or RRC_Connected, and RRC entity controls the switching between these states. In RRC_Idle, the network knows that the UE is present in the network and the UE can be reached in case of incoming call/downlink data. In this state, the UE monitors paging, performs cell measurements and cell selection and acquires system information. Also the UE can receive broadcast and multicast data, but it is not expected to transmit or receive unicast data. In RRC_Connected the UE has a connection to the eNodeB, the network knows the UE location on the cell level and the UE may receive and transmit unicast data. An RRC connection is established when the UE is expected to be active in the network, to transmit or receive data. The RRC connection is released, switching back to RRC_Idle, when there is no more traffic in order to preserve UE battery life and

radio resources. However, a new feature was introduced for NB-IoT, as mentioned earlier, which allows data to be transmitted from the MME directly to the UE transparently to the eNodeB, thus bypassing AS functions.

Packet Data Convergence Protocol's (PDCP) [TGPP36323] main services in control plane are transfer of control plane data, ciphering and integrity protection.

Radio Link Control protocol (RLC) [TGPP36322] performs transfer of upper layer PDUs and optionally error correction with Automatic Repeat reQuest (ARQ), concatenation, segmentation, and reassembly of RLC SDUs, in-sequence delivery of upper layer PDUs, duplicate detection, RLC SDU discard, RLC-re-establishment and protocol error detection and recovery.

Medium Access Control protocol (MAC) [TGPP36321] provides mapping between logical channels and transport channels, multiplexing of MAC SDUs, scheduling information reporting, error correction with HARQ, priority handling and transport format selection.

Physical layer [TGPP36201] provides data transport services to higher layers. These include error detection and indication to higher layers, FEC encoding, HARQ soft-combining. Rate matching and mapping of the transport channels onto physical channels, power weighting and modulation of physical channels, frequency and time synchronization and radio characteristics measurements.

User plane protocol stack

User plane is responsible for transferring the user data through the Access Stratum. It interfaces with IP and the highest layer of user plane is PDCP, which in user plane performs header compression using Robust Header Compression (RoHC), transfer of user plane data between eNodeB and UE, ciphering and integrity protection. Similar to control plane, lower layers in user plane include RLC, MAC and physical layer performing the same tasks as in control plane.

2.3. SIGFOX

Text here is largely from [I-D.zuniga-lpwan-sigfox-system-description] which may have been updated since this was published.

2.3.1. Provenance and Documents

The SIGFOX LPWAN is in line with the terminology and specifications being defined by ETSI [etsi_unb]. As of today, SIGFOX's network has been fully deployed in 12 countries, with ongoing deployments on 26 other countries, giving in total a geography of 2 million square kilometers, containing 512 million people.

2.3.2. Characteristics

SIGFOX LPWAN autonomous battery-operated devices send only a few bytes per day, week or month, in principle allowing them to remain on a single battery for up to 10-15 years. Hence, the system is designed as to allow devices to last several years, sometimes even buried underground.

Since the radio protocol is connection-less and optimized for uplink communications, the capacity of a SIGFOX base station depends on the number of messages generated by devices, and not on the actual number of devices. Likewise, the battery life of devices depends on the number of messages generated by the device. Depending on the use case, devices can vary from sending less than one message per device per day, to dozens of messages per device per day.

The coverage of the cell depends on the link budget and on the type of deployment (urban, rural, etc.). The radio interface is compliant with the following regulations:

Spectrum allocation in the USA [fcc_ref]

Spectrum allocation in Europe [etsi_ref]

Spectrum allocation in Japan [arib_ref]

The SIGFOX radio interface is also compliant with the local regulations of the following countries: Australia, Brazil, Canada, Kenya, Lebanon, Mauritius, Mexico, New Zealand, Oman, Peru, Singapore, South Africa, South Korea, and Thailand.

The radio interface is based on Ultra Narrow Band (UNB) communications, which allow an increased transmission range by spending a limited amount of energy at the device. Moreover, UNB allows a large number of devices to coexist in a given cell without significantly increasing the spectrum interference.

Both uplink and downlink are supported, although the system is optimized for uplink communications. Due to spectrum optimizations,

different uplink and downlink frames and time synchronization methods are needed.

The main radio characteristics of the UNB uplink transmission are:

- Channelization mask: 100 Hz / 600 Hz (depending on the region)
- Uplink baud rate: 100 baud / 600 baud (depending on the region)
- Modulation scheme: DBPSK
- Uplink transmission power: compliant with local regulation
- Link budget: 155 dB (or better)
- Central frequency accuracy: not relevant, provided there is no significant frequency drift within an uplink packet transmission

For example, in Europe the UNB uplink frequency band is limited to 868.00 to 868.60 MHz, with a maximum output power of 25 mW and a duty cycle of 1%.

The format of the uplink frame is the following:

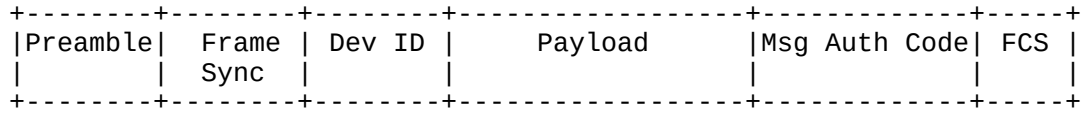

Figure 5: Uplink Frame Format

The uplink frame is composed of the following fields:

- Preamble: 19 bits
- Frame sync and header: 29 bits
- Device ID: 32 bits
- Payload: 0-96 bits
- Authentication: 16-40 bits
- Frame check sequence: 16 bits (CRC)

The main radio characteristics of the UNB downlink transmission are:

- Channelization mask: 1.5 kHz
- Downlink baud rate: 600 baud
- Modulation scheme: GFSK
- Downlink transmission power: 500 mW / 4W (depending on the region)
- Link budget: 153 dB (or better)
- Central frequency accuracy: Centre frequency of downlink transmission are set by the network according to the corresponding uplink transmission

For example, in Europe the UNB downlink frequency band is limited to 869.40 to 869.65 MHz, with a maximum output power of 500 mW with 10% duty cycle.

The format of the downlink frame is the following:

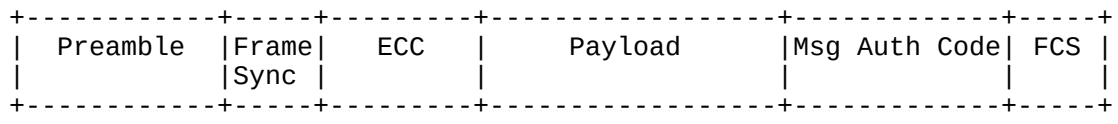

Figure 6: Downlink Frame Format

The downlink frame is composed of the following fields:

- Preamble: 91 bits
- Frame sync and header: 13 bits
- Error Correcting Code (ECC): 32 bits
- Payload: 0-64 bits
- Authentication: 16 bits
- Frame check sequence: 8 bits (CRC)

The radio interface is optimized for uplink transmissions, which are asynchronous. Downlink communications are achieved by devices querying the network for available data.

A device willing to receive downlink messages opens a fixed window for reception after sending an uplink transmission. The delay and

duration of this window have fixed values. The network transmits the downlink message for a given device during the reception window, and the network also selects the base station (BS) for transmitting the corresponding downlink message.

Uplink and downlink transmissions are unbalanced due to the regulatory constraints on ISM bands. Under the strictest regulations, the system can allow a maximum of 140 uplink messages and 4 downlink messages per device per day. These restrictions can be slightly relaxed depending on system conditions and the specific regulatory domain of operation.

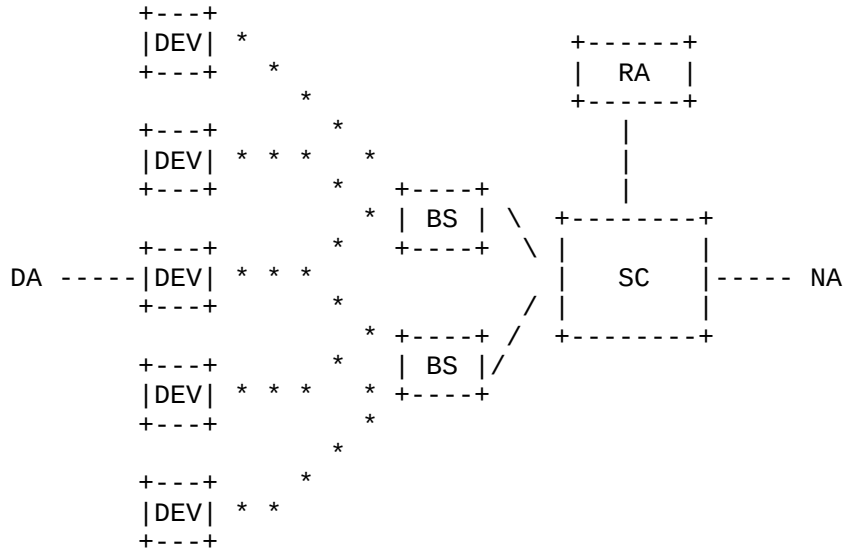

Figure 7: SIGFOX network architecture

Figure 7 depicts the different elements of the SIGFOX network architecture.

SIGFOX has a "one-contract one-network" model allowing devices to connect in any country, without any need or notion of either roaming or handover.

The architecture consists of a single cloud-based core network, which allows global connectivity with minimal impact on the end device and radio access network. The core network elements are the Service Center (SC) and the Registration Authority (RA). The SC is in charge of the data connectivity between the Base Station (BS) and the Internet, as well as the control and management of the BSs and End

Points. The RA is in charge of the End Point network access authorization.

The radio access network is comprised of several BSs connected directly to the SC. Each BS performs complex L1/L2 functions, leaving some L2 and L3 functionalities to the SC.

The Devices (DEVs) or End Points (EPs) are the objects that communicate application data between local device applications (DAs) and network applications (NAs).

Devices (or EPs) can be static or nomadic, as they associate with the SC and they do not attach to any specific BS. Hence, they can communicate with the SC through one or multiple BSs.

Due to constraints in the complexity of the Device, it is assumed that Devices host only one or very few device applications, which most of the time communicate each to a single network application at a time.

The radio protocol provides mechanisms to authenticate and ensure integrity of the message. This is achieved by using a unique device ID and a message authentication code, which allow ensuring that the message has been generated and sent by the device with the ID claimed in the message.

Security keys are independent for each device. These keys are associated with the device ID and they are pre-provisioned. Application data can be encrypted at the application level or not, depending on the criticality of the use case, allowing hence to balance cost and effort vs. risk.

2.4. Wi-SUN Alliance Field Area Network (FAN)

Text here is via personal communication from Bob Heile (bheile@ieee.org) and was authored by Bob and Sum Chin Sean. Duffy (paduffy@cisco.com) also provided additional comments/input on this section.

2.4.1. Provenance and Documents

The Wi-SUN Alliance <https://www.wi-sun.org/> is an industry alliance for smart city, smart grid, smart utility, and a broad set of general IoT applications. The Wi-SUN Alliance Field Area Network (FAN) profile is open standards based (primarily on IETF and IEEE802 standards) and was developed to address applications like smart municipality/city infrastructure monitoring and management, electric vehicle (EV) infrastructure, advanced metering infrastructure (AMI),

distribution automation (DA), supervisory control and data acquisition (SCADA) protection/management, distributed generation monitoring and management, and many more IoT applications. Additionally, the Alliance has created a certification program to promote global multi-vendor interoperability.

The FAN profile is currently being specified within ANSI/TIA as an extension of work previously done on Smart Utility Networks. [ANSI-4957-000]. Updates to those specifications intended to be published in 2017 will contain details of the FAN profile. A current snapshot of the work to produce that profile is presented in [wisun-pressie1] [wisun-pressie2] .

2.4.2. Characteristics

The FAN profile is an IPv6 frequency hopping wireless mesh network with support for enterprise level security. The frequency hopping wireless mesh topology aims to offer superior network robustness, reliability due to high redundancy, good scalability due to the flexible mesh configuration and good resilience to interference. Very low power modes are in development permitting long term battery operation of network nodes.

The core architecture of Wi-SUN FAN is a mesh network. A FAN contains one or more networks. Within a network, nodes assume one of three operational roles. First, each network contains a Border Router providing Wide Area Network (WAN) connectivity to the network. The Border Router maintains source routing tables for all nodes within its network, provides node authentication and key management services, and disseminates network-wide information such as broadcast schedules. Secondly, Router nodes, which provide upward and downward packet forwarding (within a network). A Router also provides services for relaying security and address management protocols. Lastly, Leaf nodes provide minimum capabilities: discovering and joining a network, send/receive IPv6 packets, etc. A low power network may contain a mesh topology with Routers at the edges that construct a star topology with Leaf nodes.

The FAN profile is based on various open standards developed by the IETF (including [RFC0768], [RFC2460], [RFC4443] and [RFC6282]), IEEE802 (including [IEEE-802-15-4] and [IEEE-802-15-9]) and ANSI/TIA [ANSI-4957-210] for low power and lossy networks.

The FAN profile specification provides an application-independent IPv6-based transport service for both connectionless (i.e. UDP) and connection-oriented (i.e. TCP) services. There are two possible methods for establishing the IPv6 packet routing: mandatory Routing Protocol for Low-Power and Lossy Networks (RPL) at the Network layer

or optional Multi-Hop Delivery Service (MHDS) at the Data Link layer. Table 5 provides an overview of the FAN network stack.

The Transport service is based on User Datagram Protocol (UDP) defined in RFC768 or Transmission Control Protocol (TCP) defined in RFC793.

The Network service is provided by IPv6 defined in RFC2460 with 6LoWPAN adaptation as defined in RC4944 and RFC6282. Additionally, ICMPv6, as defined in RFC4443, is used for control plane in information exchange.

The Data Link service provides both control/management of the Physical layer and data transfer/management services to the Network layer. These services are divided into Media Access Control (MAC) and Logical Link Control (LLC) sub-layers. The LLC sub-layer provides a protocol dispatch service which supports 6LoWPAN and an optional MAC sub-layer mesh service. The MAC sub-layer is constructed using data structures defined in IEEE802.15.4-2015. Multiple modes of frequency hopping are defined. The entire MAC payload is encapsulated in an IEEE802.15.9 Information Element to enable LLC protocol dispatch between upper layer 6LoWPAN processing, MAC sublayer mesh processing, etc. These areas will be expanded once IEEE802.15.12 is completed

The PHY service is derived from a sub-set of the SUN FSK specification in IEEE802.15.4-2015. The 2-FSK modulation schemes, with channel spacing range from 200 to 600 kHz, are defined to provide data rates from 50 to 300 kbps, with Forward Error Coding (FEC) as an optional feature. Towards enabling ultra-low-power applications, the PHY layer design is also extendable to low energy and critical infrastructure monitoring networks.

Layer	Description
IPv6 protocol suite	TCP/UDP
	6LoWPAN Adaptation + Header Compression
	DHCPv6 for IP address management.
	Routing using RPL.
	ICMPv6.
	Unicast and Multicast forwarding.
MAC based on IEEE 802.15.4e + IE extensions	Frequency hopping
	Discovery and Join
	Protocol Dispatch (IEEE 802.15.9)
	Several Frame Exchange patterns
	Optional Mesh Under routing (ANSI 4957.210).
PHY based on 802.15.4g	Various data rates and regions
Security	802.1X/EAP-TLS/PKI Authentication.
	802.11i Group Key Management
	Optional ETSI-TS-102-887-2 Node 2 Node Key Management

Table 5: Wi-SUN Stack Overview

The FAN security supports Data Link layer network access control, mutual authentication, and establishment of a secure pairwise link between a FAN node and its Border Router, which is implemented with an adaptation of IEEE802.1X and EAP-TLS as described in [RFC5216] using secure device identity as described in IEEE802.1AR. Certificate formats are based upon [RFC5280]. A secure group link between a Border Router and a set of FAN nodes is established using

an adaptation of the IEEE802.11 Four-Way Handshake. A set of 4 group keys are maintained within the network, one of which is the current transmit key. Secure node to node links are supported between one-hop FAN neighbors using an adaptation of ETSI-TS-102-887-2. FAN nodes implement Frame Security as specified in IEEE802.15.4-2015.

3. Generic Terminology

LPWAN technologies, such as those discussed above, have similar architectures but different terminology. We can identify different types of entities in a typical LPWAN network:

- End-Devices are the devices or the "things" (e.g. sensors, actuators, etc.), they are named differently in each technology (End Device, User Equipment or End Point). There can be a high density of end devices per radio gateway.

- The Radio Gateway, which is the end point of the constrained link. It is known as: Gateway, Evolved Node B or Base station.

- The Network Gateway or Router is the interconnection node between the Radio Gateway and the Internet. It is known as: Network Server, Serving GW or Service Center.

- LPWAN-AAA Server, which controls the user authentication, the applications. It is known as: Join-Server, Home Subscriber Server or Registration Authority. (We use the term LPWAN-AAA server because we’re not assuming that this entity speaks RADIUS or Diameter as many/most AAA servers do, but equally we don’t want to rule that out, as the functionality will be similar.

- At last we have the Application Server, known also as Packet Data Node Gateway or Network Application.

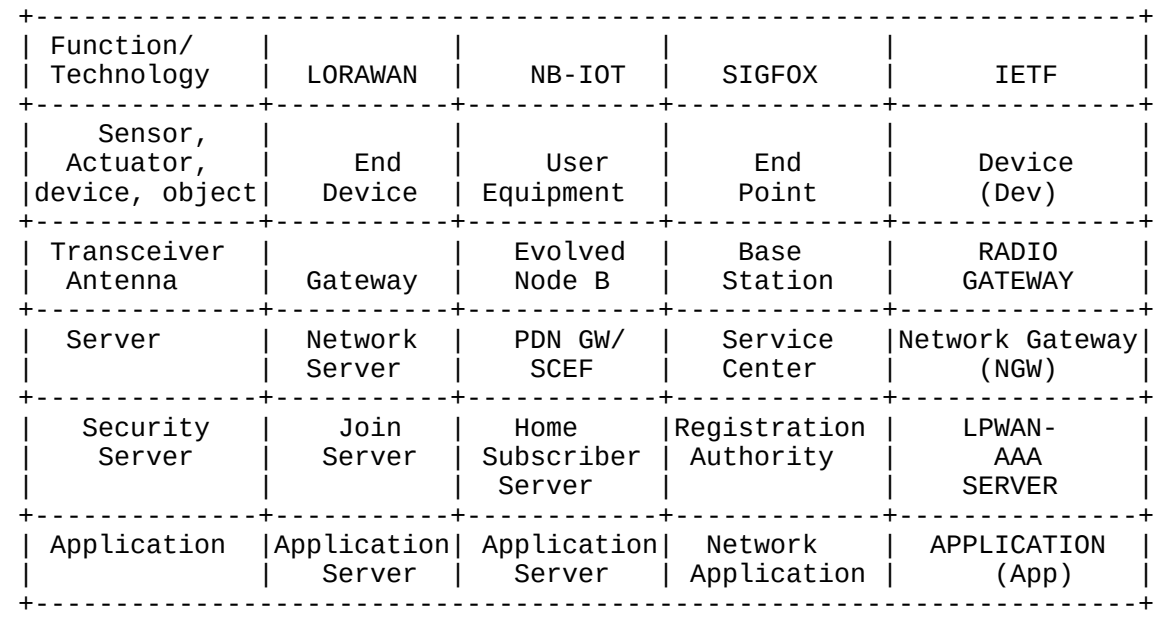

Figure 8: LPWAN Architecture Terminology

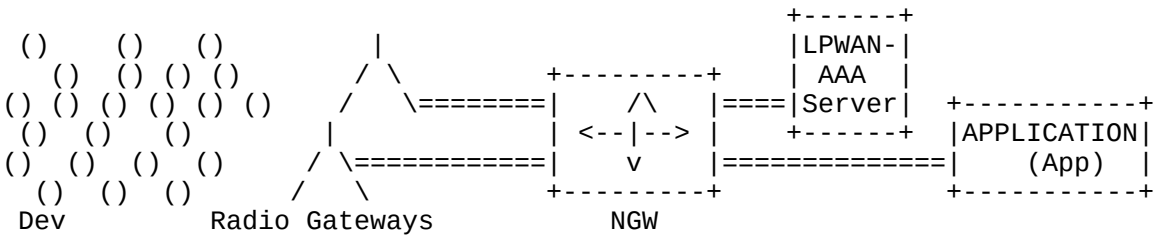

Figure 9: LPWAN Architecture

In addition to the names of entities, LPWANs are also subject to possibly regional frequency band regulations. Those may include restrictions on the duty-cycle, for example requiring that hosts only transmit for a certain percentage of each hour.

4. Gap Analysis

4.1. Naive application of IPv6

IPv6 [RFC2460] has been designed to allocate addresses to all the nodes connected to the Internet. Nevertheless, the header overhead of at least 40 bytes introduced by the protocol is incompatible with LPWAN constraints. If IPv6 with no further optimization were used,

several LPWAN frames could be needed just to carry the IP header. Another problem arises from IPv6 MTU requirements, which require the layer below to support at least 1280 byte packets [RFC2460].

IPv6 has a configuration protocol - neighbor discovery protocol, (NDP) [RFC4861]). For a node to learn network parameters NDP generates regular traffic with a relatively large message size that does not fit LPWAN constraints.

In some LPWAN technologies, layer two multicast is not supported. In that case, if the network topology is a star, the solution and considerations of section 3.2.5 of [RFC7668] may be applied.

Other key protocols such as DHCPv6 [RFC3315], IPsec [RFC4301] and TLS [RFC5246] have similarly problematic properties in this context. Each of those require relatively frequent round-trips between the host and some other host on the network. In the case of cryptographic protocols such as IPsec and TLS, in addition to the round-trips required for secure session establishment, cryptographic operations can require padding and addition of authenticators that are problematic when considering LPWAN lower layers.

4.2. 6LoWPAN

Several technologies that exhibit significant constraints in various dimensions have exploited the 6LoWPAN suite of specifications [RFC4944], [RFC6282], [RFC6775] to support IPv6 [I-D.hong-6lo-use-cases]. However, the constraints of LPWANs, often more extreme than those typical of technologies that have (re)used 6LoWPAN, constitute a challenge for the 6LoWPAN suite in order to enable IPv6 over LPWAN. LPWANs are characterized by device constraints (in terms of processing capacity, memory, and energy availability), and specially, link constraints, such as:

- very low layer two payload size (from ~10 to ~100 bytes),
- very low bit rate (from ~10 bit/s to ~100 kbit/s), and
- in some specific technologies, further message rate constraints (e.g. between ~0.1 message/minute and ~1 message/minute) due to regional regulations that limit the duty cycle.

4.2.1. Header Compression

6LoWPAN header compression reduces IPv6 (and UDP) header overhead by eliding header fields when they can be derived from the link layer, and by assuming that some of the header fields will frequently carry expected values. 6LoWPAN provides both stateless and stateful header

compression. In the latter, all nodes of a 6LoWPAN are assumed to share compression context. In the best case, the IPv6 header for link-local communication can be reduced to only 2 bytes. For global communication, the IPv6 header may be compressed down to 3 bytes in the most extreme case. However, in more practical situations, the smallest IPv6 header size may be 11 bytes (one address prefix compressed) or 19 bytes (both source and destination prefixes compressed). These headers are large considering the link layer payload size of LPWAN technologies, and in some cases are even bigger than the LPWAN PDUs. 6LoWPAN has been initially designed for IEEE 802.15.4 networks with a frame size up to 127 bytes and a throughput of up to 250 kb/s, which may or may not be duty-cycled.

4.2.2. Address Autoconfiguration

Traditionally, Interface Identifiers (IIDs) have been derived from link layer identifiers [RFC4944] . This allows optimizations such as header compression. Nevertheless, recent guidance has given advice on the fact that, due to privacy concerns, 6LoWPAN devices should not be configured to embed their link layer addresses in the IID by default.

4.2.3. Fragmentation

As stated above, IPv6 requires the layer below to support an MTU of 1280 bytes [RFC2460]. Therefore, given the low maximum payload size of LPWAN technologies, fragmentation is needed.

If a layer of an LPWAN technology supports fragmentation, proper analysis has to be carried out to decide whether the fragmentation functionality provided by the lower layer or fragmentation at the adaptation layer should be used. Otherwise, fragmentation functionality shall be used at the adaptation layer.

6LoWPAN defined a fragmentation mechanism and a fragmentation header to support the transmission of IPv6 packets over IEEE 802.15.4 networks [RFC4944]. While the 6LoWPAN fragmentation header is appropriate for IEEE 802.15.4-2003 (which has a frame payload size of 81-102 bytes), it is not suitable for several LPWAN technologies, many of which have a maximum payload size that is one order of magnitude below that of IEEE 802.15.4-2003. The overhead of the 6LoWPAN fragmentation header is high, considering the reduced payload size of LPWAN technologies and the limited energy availability of the devices using such technologies. Furthermore, its datagram offset field is expressed in increments of eight octets. In some LPWAN technologies, the 6LoWPAN fragmentation header plus eight octets from the original datagram exceeds the available space in the layer two

payload. In addition, the MTU in the LPWAN networks could be variable which implies a variable fragmentation solution.

4.2.4. Neighbor Discovery

6LoWPAN Neighbor Discovery [RFC6775] defined optimizations to IPv6 Neighbor Discovery [RFC4861], in order to adapt functionality of the latter for networks of devices using IEEE 802.15.4 or similar technologies. The optimizations comprise host-initiated interactions to allow for sleeping hosts, replacement of multicast-based address resolution for hosts by an address registration mechanism, multihop extensions for prefix distribution and duplicate address detection (note that these are not needed in a star topology network), and support for 6LoWPAN header compression.

6LoWPAN Neighbor Discovery may be used in not so severely constrained LPWAN networks. The relative overhead incurred will depend on the LPWAN technology used (and on its configuration, if appropriate). In certain LPWAN setups (with a maximum payload size above ~60 bytes, and duty-cycle-free or equivalent operation), an RS/RA/NS/NA exchange may be completed in a few seconds, without incurring packet fragmentation.

In other LPWANs (with a maximum payload size of ~10 bytes, and a message rate of ~0.1 message/minute), the same exchange may take hours or even days, leading to severe fragmentation and consuming a significant amount of the available network resources. 6LoWPAN Neighbor Discovery behavior may be tuned through the use of appropriate values for the default Router Lifetime, the Valid Lifetime in the PIOs, and the Valid Lifetime in the 6CO, as well as the address Registration Lifetime. However, for the latter LPWANs mentioned above, 6LoWPAN Neighbor Discovery is not suitable.

4.3. 6lo

The 6lo WG has been reusing and adapting 6LoWPAN to enable IPv6 support over link layer technologies such as Bluetooth Low Energy (BTLE), ITU-T G.9959, DECT-ULE, MS/TP-RS485, NFC IEEE 802.11ah. (See <https://tools.ietf.org/wg/6lo> for details.) These technologies are similar in several aspects to IEEE 802.15.4, which was the original 6LoWPAN target technology.

6lo has mostly used the subset of 6LoWPAN techniques best suited for each lower layer technology, and has provided additional optimizations for technologies where the star topology is used, such as BTLE or DECT-ULE.

The main constraint in these networks comes from the nature of the devices (constrained devices), whereas in LPWANs it is the network itself that imposes the most stringent constraints.

4.4. 6tisch

The 6tisch solution is dedicated to mesh networks that operate using 802.15.4e MAC with a deterministic slotted channel. The time slot channel (TSCH) can help to reduce collisions and to enable a better balance over the channels. It improves the battery life by avoiding the idle listening time for the return channel.

A key element of 6tisch is the use of synchronization to enable determinism. TSCH and 6TiSCH may provide a standard scheduling function. The LPWAN networks probably will not support synchronization like the one used in 6tisch.

4.5. RoHC

Robust header compression (RoHC) is a header compression mechanism [RFC3095] developed for multimedia flows in a point to point channel. RoHC uses 3 levels of compression, each level having its own header format. In the first level, RoHC sends 52 bytes of header, in the second level the header could be from 34 to 15 bytes and in the third level header size could be from 7 to 2 bytes. The level of compression is managed by a sequence number, which varies in size from 2 bytes to 4 bits in the minimal compression. SN compression is done with an algorithm called W-LSB (Window- Least Significant Bits). This window has a 4-bit size representing 15 packets, so every 15 packets RoHC needs to slide the window in order to receive the correct sequence number, and sliding the window implies a reduction of the level of compression. When packets are lost or errored, the decompressor loses context and drops packets until a bigger header is sent with more complete information. To estimate the performance of RoHC, an average header size is used. This average depends on the transmission conditions, but most of the time is between 3 and 4 bytes.

RoHC has not been adapted specifically to the constrained hosts and networks of LPWANs: it does not take into account energy limitations nor the transmission rate, and RoHC context is synchronised during transmission, which does not allow better compression.

4.6. ROLL

Most technologies considered by the lpwan WG are based on a star topology, which eliminates the need for routing at that layer. Future work may address additional use-cases that may require

adaptation of existing routing protocols or the definition of new ones. As of the time of writing, work similar to that done in the ROLL WG and other routing protocols are out of scope of the LPWAN WG.

4.7. CoAP

CoAP [RFC7252] provides a RESTful framework for applications intended to run on constrained IP networks. It may be necessary to adapt CoAP or related protocols to take into account for the extreme duty cycles and the potentially extremely limited throughput of LPWANs.

For example, some of the timers in CoAP may need to be redefined. Taking into account CoAP acknowledgments may allow the reduction of L2 acknowledgments. On the other hand, the current work in progress in the CoRE WG where the COMI/CoOL network management interface which, uses Structured Identifiers (SID) to reduce payload size over CoAP may prove to be a good solution for the LPWAN technologies. The overhead is reduced by adding a dictionary which matches a URI to a small identifier and a compact mapping of the YANG model into the CBOR binary representation.

4.8. Mobility

LPWANs nodes can be mobile. However, LPWAN mobility is different from the one specified for Mobile IP. LPWAN implies sporadic traffic and will rarely be used for high-frequency, real-time communications. The applications do not generate a flow, they need to save energy and most of the time the node will be down.

In addition, LPWAN mobility may mostly apply to groups of devices, that represent a network in which case mobility is more a concern for the gateway than the devices. NEMO [RFC3963] Mobility solutions may be used in the case where some end-devices belonging to the same network gateway move from one point to another such that they are not aware of being mobile.

4.9. DNS and LPWAN

The Domain Name System (DNS) DNS [RFC1035], enables applications to name things with a globally resolvable name. Many protocols use the DNS to identify hosts, for example applications using CoAP.

The DNS query/answer protocol as a pre-cursor to other communication within the time-to-live (TTL) of a DNS answer is clearly problematic in an LPWAN, say where only one round-trip per hour can be used, and with a TTL that is less than 3600. It is currently unclear whether and how DNS-like functionality might be provided in LPWANs.

5. Security Considerations

Most LPWAN technologies integrate some authentication or encryption mechanisms that were defined outside the IETF. The working group may need to do work to integrate these mechanisms to unify management. A standardized Authentication, Accounting, and Authorization (AAA) infrastructure [RFC2904] may offer a scalable solution for some of the security and management issues for LPWANs. AAA offers centralized management that may be of use in LPWANs, for example [I-D.garcia-dime-diameter-lorawan] and [I-D.garcia-radext-radius-lorawan] suggest possible security processes for a LoRaWAN network. Similar mechanisms may be useful to explore for other LPWAN technologies.

Some applications using LPWANs may raise few or no privacy considerations. For example, temperature sensors in a large office building may not raise privacy issues. However, the same sensors, if deployed in a home environment and especially if triggered due to human presence, can raise significant privacy issues - if an end-device emits (an encrypted) packet every time someone enters a room in a home, then that traffic is privacy sensitive. And the more that the existence of that traffic is visible to network entities, the more privacy sensitivities arise. At this point, it is not clear whether there are workable mitigations for problems like this - in a more typical network, one would consider defining padding mechanisms and allowing for cover traffic. In some LPWANs, those mechanisms may not be feasible. Nonetheless, the privacy challenges do exist and can be real and so some solutions will be needed. Note that many aspects of solutions in this space may not be visible in IETF specifications, but can be e.g. implementation or deployment specific.

Another challenge for LPWANs will be how to handle key management and associated protocols. In a more traditional network (e.g. the web), servers can "staple" OCSP responses in order to allow browsers to check revocation status for presented certificates. [RFC6961] While the stapling approach is likely something that would help in an LPWAN, as it avoids an RTT, certificates and OCSP responses are bulky items and will prove challenging to handle in LPWANs with bounded bandwidth.

6. IANA Considerations

There are no IANA considerations related to this memo.

7. Contributors

As stated above this document is mainly a collection of content developed by the full set of contributors listed below. The main input documents and their authors were:

- Text for Section 2.1 was provided by Alper Yegin and Stephen Farrell in [I-D.farrell-lpwan-lora-overview].
- Text for Section 2.2 was provided by Antti Ratilainen in [I-D.ratilainen-lpwan-nb-iot].
- Text for Section 2.3 was provided by Juan Carlos Zuniga and Benoit Ponsard in [I-D.zuniga-lpwan-sigfox-system-description].
- Text for Section 2.4 was provided via personal communication from Bob Heile (bheile@ieee.org) and was authored by Bob and Sum Chin Sean. There is no Internet draft for that at present.
- Text for Section 4 was provided by Ana Minabiru, Carles Gomez, Laurent Toutain, Josep Paradells and Jon Crowcroft in [I-D.minaburo-lpwan-gap-analysis]. Additional text from that draft is also used elsewhere above.

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[[Ed: If I omitted anyone, sorry and just let me know and I’ll add you here.]]

Alexander Pelov and Pascal Thubert were the LPWAN WG chairs while this document was developed.

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Appendix A. Changes

A.1. From -00 to -01

- WG have stated they want this to be an RFC.
- WG clearly want to keep the RF details.
- Various changes made to remove/resolve a number of editorial notes from -00 (in some cases as per suggestions from Ana Minaburo)
- Merged PR's: #1...
- Rejected PR's: #2 (change was made to .txt not .xml but was replicated manually by editor)
- Github repo is at: https://github.com/sftcd/lpwan-ov

A.2. From -01 to -02

- WG seem to agree with editor suggestions in slides 13-24 of the presentation on this topic given at IETF98 (See: https://www.ietf.org/proceedings/98/slides/slides-98-lpwan-aggregated-slides-07.pdf)
- Got new text wrt Wi-SUN via email from Paul Duffy and merged that in
- Reflected list discussion wrt terminology and "end-device"
- Merged PR's: #3...

A.3. From -02 to -03

- Editorial changes and typo fixes thanks to Fred Baker running something called Grammerly and sending me it's report.
- Merged PR's: #4, #6, #7...
- Editor did an editing pass on the lot.

A.4. From -03 to -04

- Picked up a PR that had been wrongly applied that expands UE
- Editorial changes wrt LoRa suggested by Alper
- Editorial changes wrt SIGFOX provided by Juan-Carlos

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