Redes de sensores inalámbricos (RSI)

IEEE802.15.4 & 6lowpan (capa de adaptación a IPv6)

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Objetivos

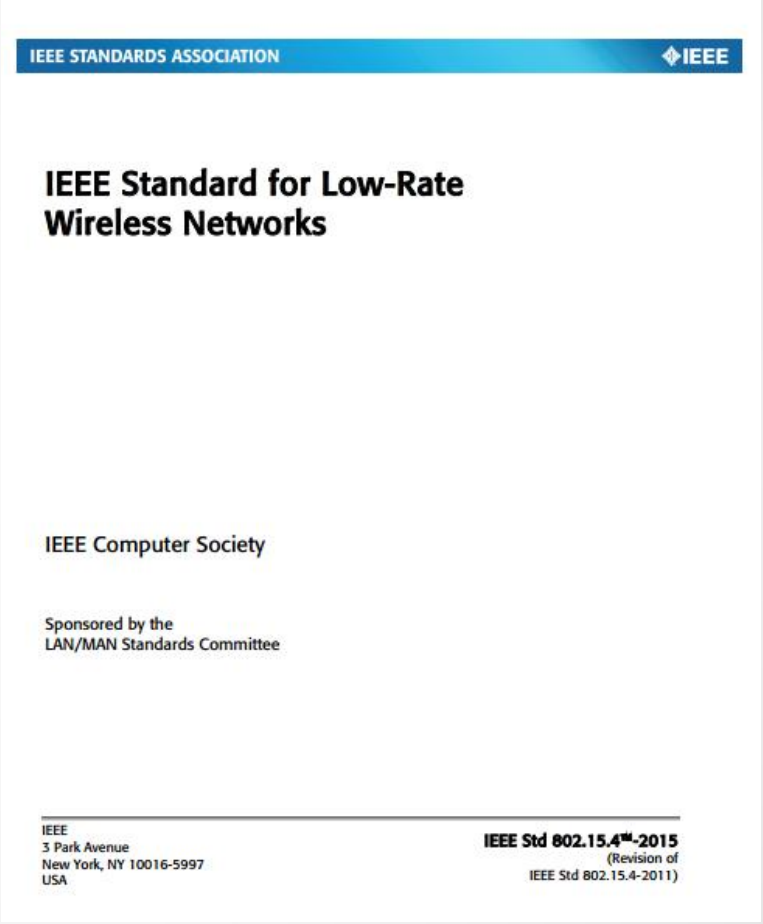
- Describir los diferentes tramas IEEE 802.15.4.
- Comprender las limitaciones de IEEE 802.15.4 para contener paquetes IPv6.
- Describir los conceptos aplicados por 6LoWPAN para fragmentación de paquetes y compresión de encabezados.

Agenda

- IEEE 802.15.4 PHY/MAC
  - funciones y tramas (*data units*)
  - tipos y direccionamiento
- 6LoWPAN
  - motivación & desafíos
  - funciones

IEEE Std 802.15.4™-2015

- LR-WAN (Low Rate WPAN), define:
  - PHY: capa física
  - MAC: subcapa de acc. al medio
- versiones:
  - 2003, 2006, 2011, 2015, **2020**
- Enmiendas:
  - incorp. versión 2015, ejemplos:
    - 802.15.4e-2012
    - 802.15.4g-2012
  - vigentes (a incluir en prox. ver.):
    - 802.15.4z-2020 (Enhanced UWB)



IEEE GET Program

IEEE 802.15.4 PHY & MAC: funciones

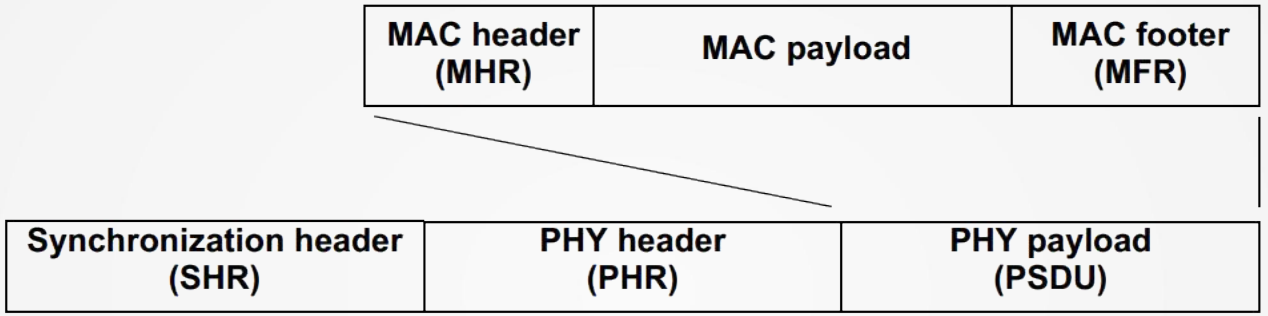
- PHY
  - Tx & Rx datos
  - ED: energy detection
  - LQI: link quality indication
  - channel selection
  - CCA: clear channel assesment
- MAC
  - channel access
  - frame validation
  - acknowledged frame delivery
  - beacon management
  - GTS management
  - etc.

IEEE 802.15.4 PHY

- Canales y bandas
- Antes: únificado
  - frec. de los canales identificados por num.
  - limitado a 27 canales
  - no había PHY opcionales.
- Ahora: channel page
  - a partir de IEEE 802.15.4-2006
  - distinguir capas físicas soportadas
- Channel pages:
  - 0: definido en 2003 (1)
  - 1: definido como opcionales 2006 (2)

Page	Num.	Description
0 (1)	0	868 MHz band (BPSK)
	1–10	915 MHz band (BPSK)
	11–26	2.4 GHz band (O-QPSK)
1 (2)	0	868 MHz band (ASK)
	1–10	915 MHz band (ASK)
	11–26	Reserved
2	0	868 MHz band (O-QPSK)
	1–10	915 MHz band (O-QPSK)
	11–26	Reserved
3	0-13	2450 MHz (CSS)
4	0	sub-GHz band for UWB
	1-4	low band for UWB PHY
	5-15	high band for UWB PHY
5	0-3	780 MHz band (O-QPSK)
	4-7	780 MHz band (MPSK)
6	0-9	950 MHz band (BPSK)
	10-21	950 MHz band (GFSK)
7-31	Reser.	Reserved

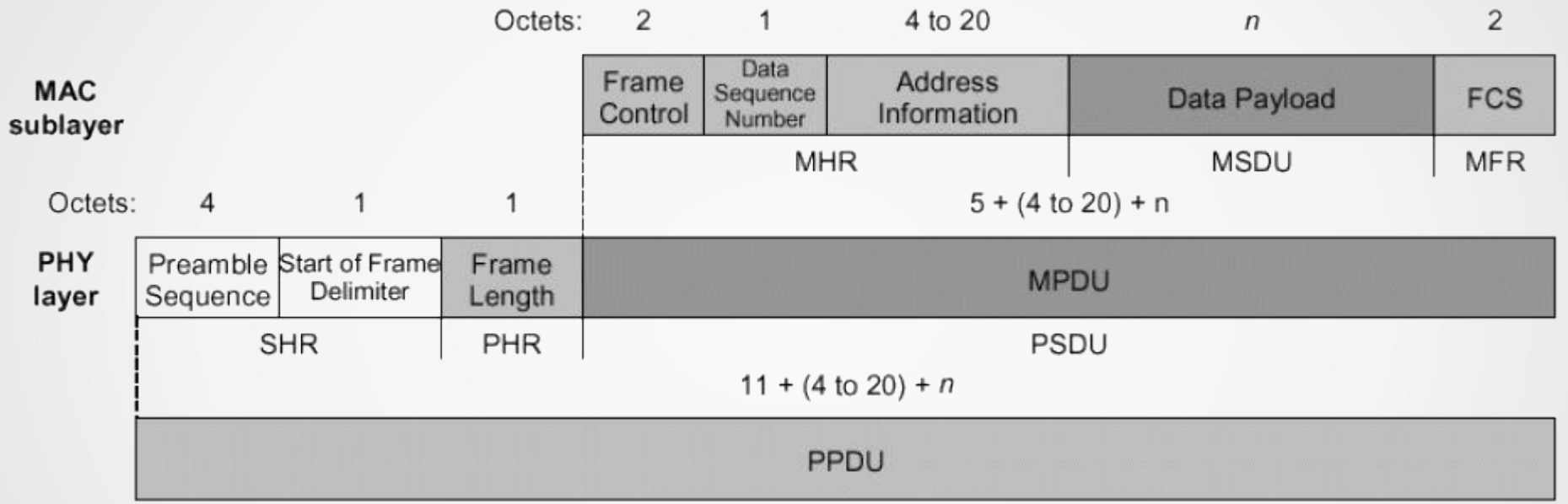
IEEE 802.15.4 PHY & MAC: tramas



"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2015, pp. 53, Apr. 2016.

- PHY service data unit (PSDU) <=> MAC frame
- Capa física: modulación próxima clase.

IEEE 802.15.4: formato de trama



M: MAC
P: PHY

X

PDU: **protocol** data unit
SDU: **service** data unit

=

MSDU: MAC service data unit
MPDU: MAC protocol data unit
PSDU: PHY service data unit
PPDU: PHY protocol data units

Formato de trama (versión 1, 2003+)

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	Ack. Request	PAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2006, Sept. 2006.

Tipos de trama (versión 1, 2003)

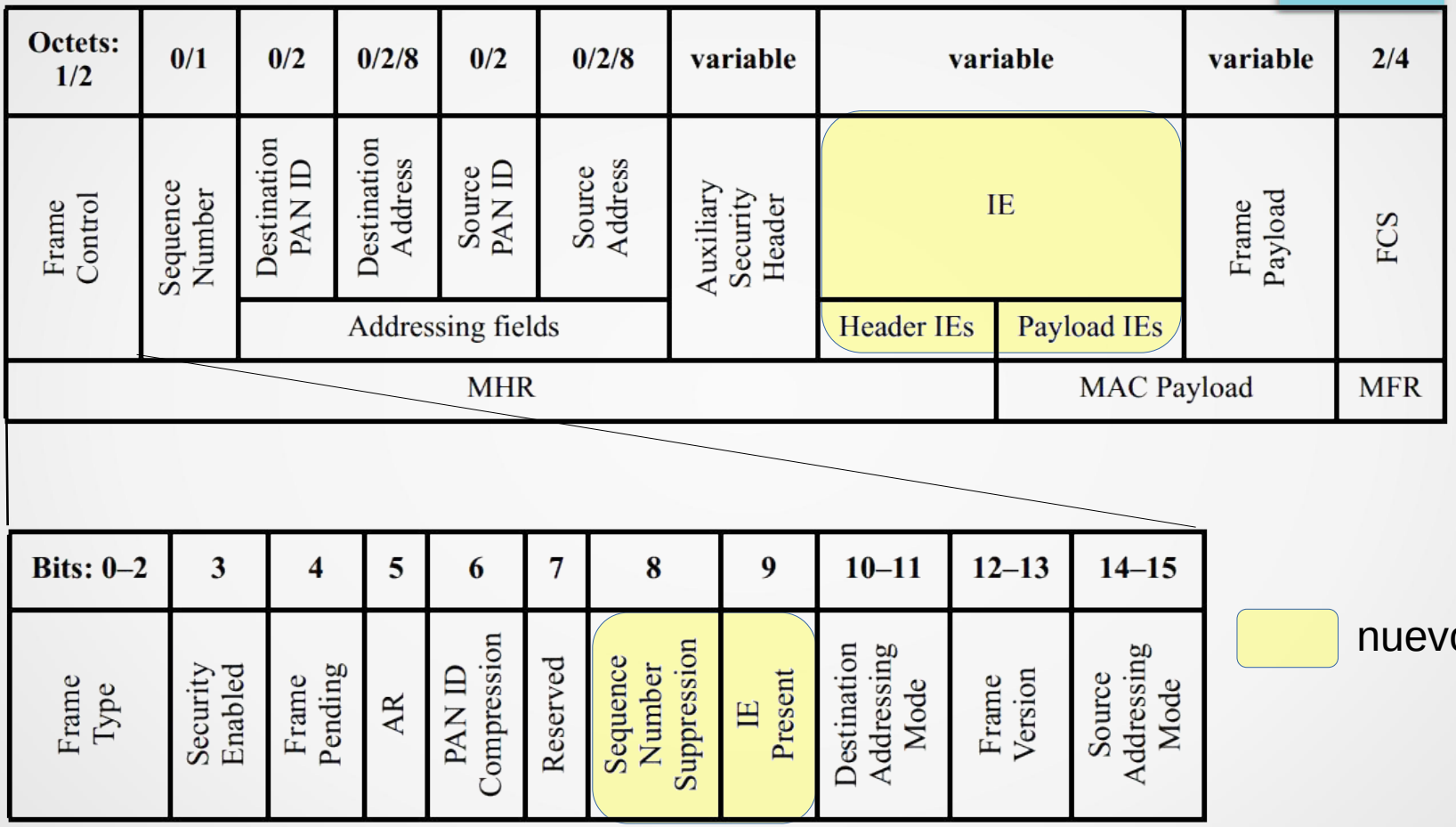
Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	AR	PAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

Frame type value $b_2\ b_1\ b_0$	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100–111	Reserved

"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2006, Sept. 2006.

Formato de trama (versión 2, 2015)



"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2015, Apr. 2015.

Tipos de trama (versión 2, 2015)

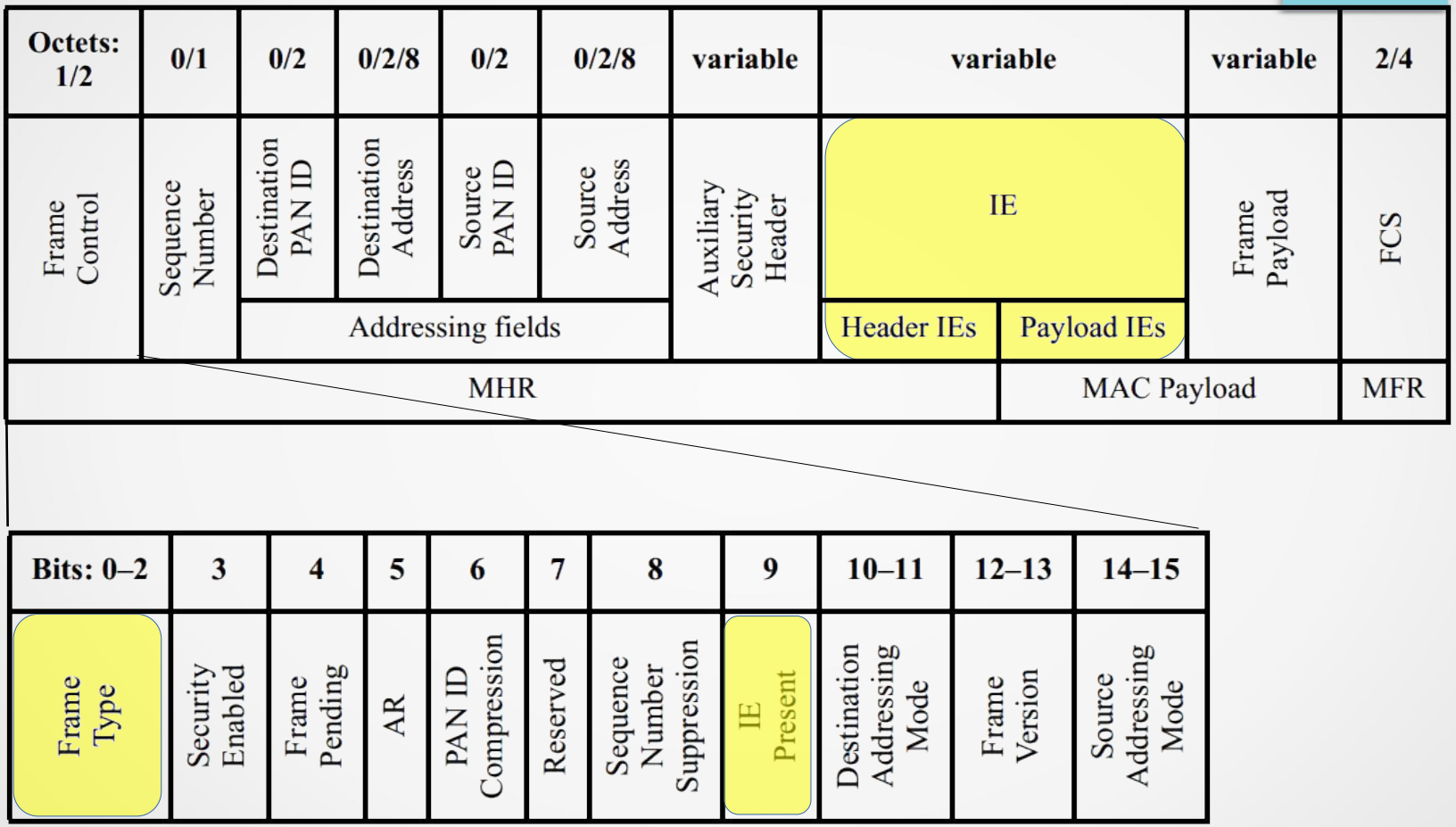
Table 7-1—Values of the Frame Type field

Frame type value b2 b1 b0	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100	Reserved
101	Multipurpose
110	Fragment or Frak[a]
111	Extended

nuevo

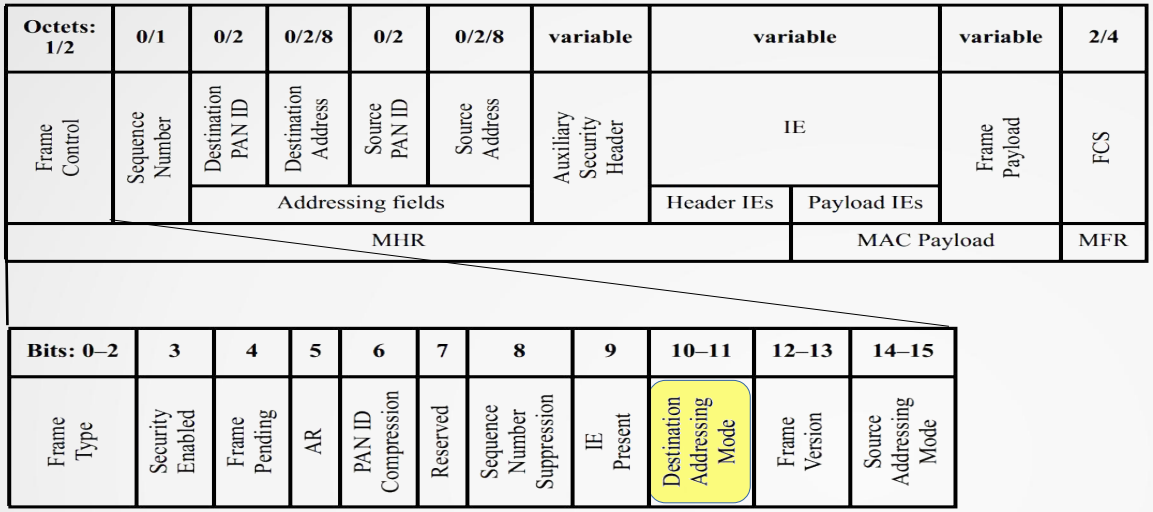
"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2015, Apr. 2015.

IEEE 802.15.4: Information Elements



"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2015, Apr. 2015.

Direccionamiento



Addressing mode value b1 b0	Description
00	PAN ID and address fields are not present.
01	Reserved
10	Address field contains a short address (16 bit).
11	Address field contains an extended address (64 bit).

Tipos de trama: Data & ACK

Data Frame Format

Octets:2	1	4 to 20	variable	2
Frame control	Data sequence number	Address information	Data payload	Frame check sequence
MAC header			**MAC Payload**	**MAC footer**

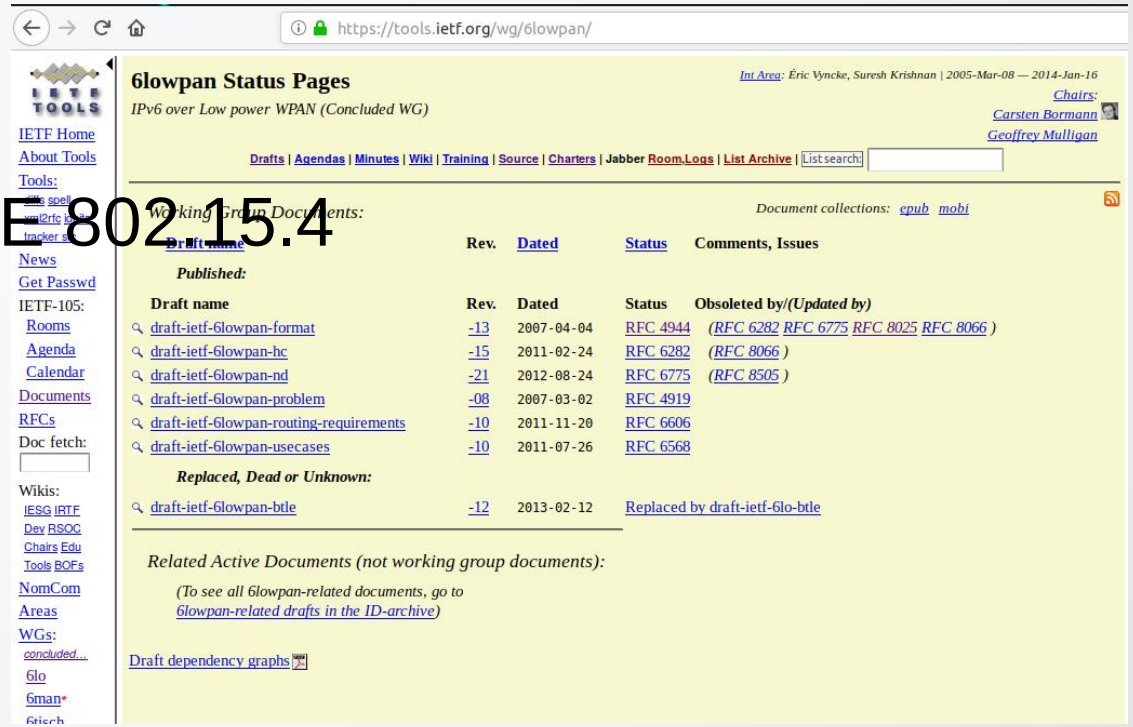
Acknowledgement Frame Format

Octets:2	1	2
Frame control	Data sequence number	Frame check sequence
MAC header		**MAC footer**

IPv6 over Low power WPAN

- **6lowpan**: IETF Working Group (finalizado)

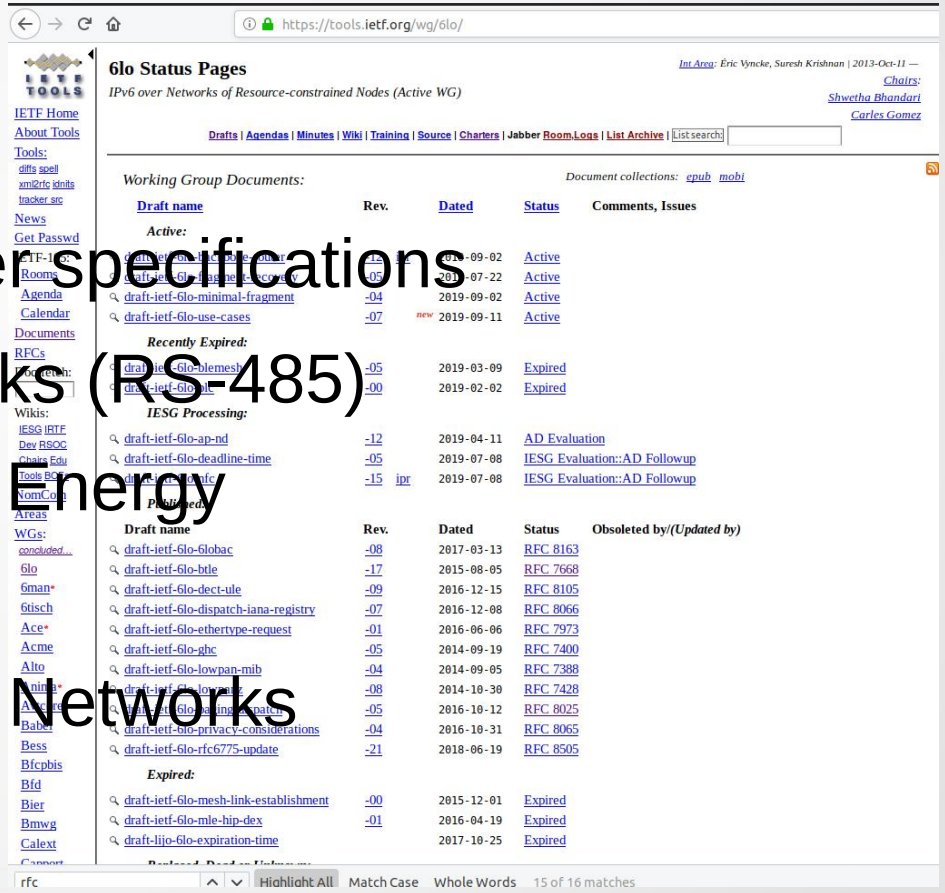
- IPv6 Packets over IEEE 802.15.4
  - RFC 4944: bases
  - RFC 6282: NHC
  - RFC 6775: ND



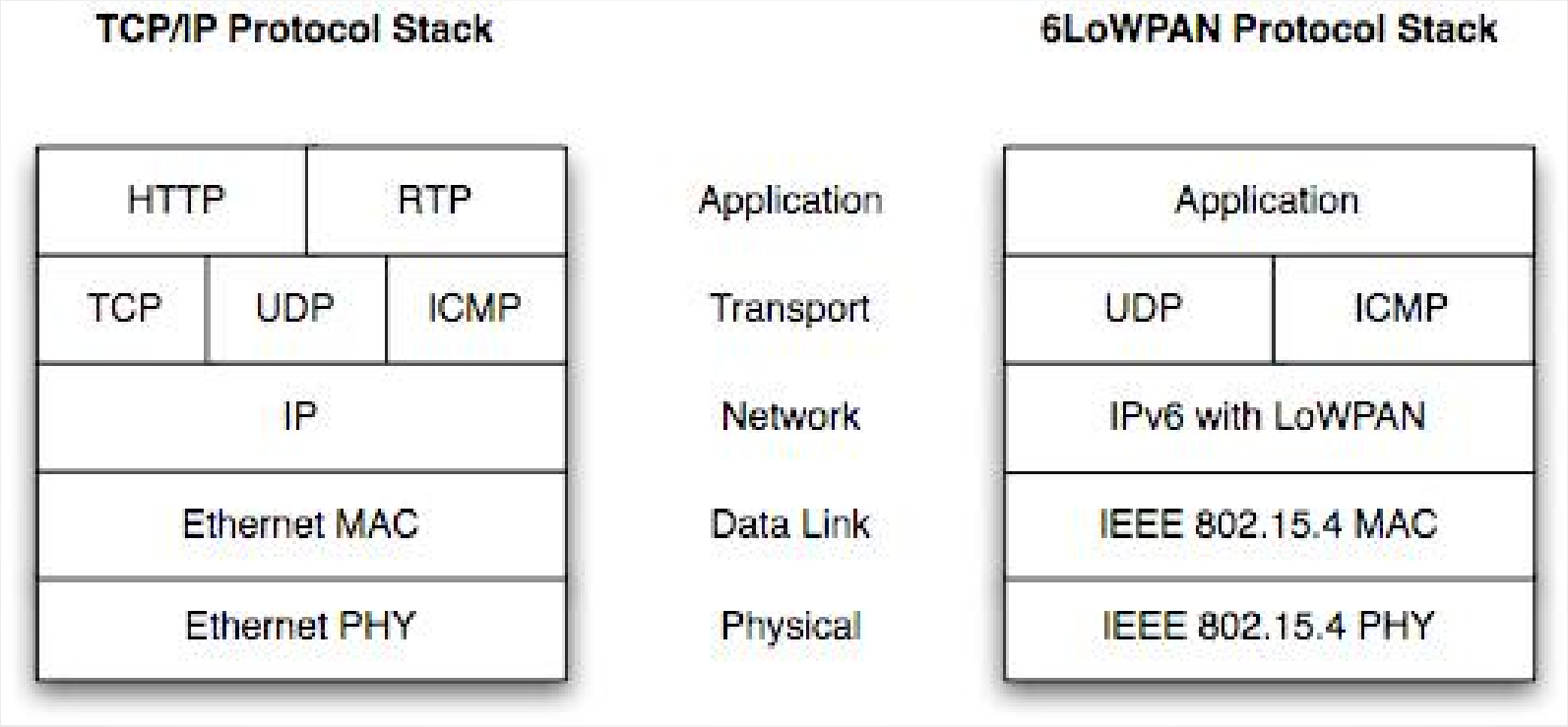
IPv6 over Netw. of Resource-constrained Nodes

- **6lo**: IETF Working Group (activo)
  - generaliza **6lowpan**

- IPv6-over-foo adaptation layer specifications
  - RFC 8163: MS/TP Networks (RS-485)
  - RFC 7668: Bluetooth Low Energy
  - RFC 8105: DECT – ULE
  - RFC 7428: ITU-T G.9959 Networks

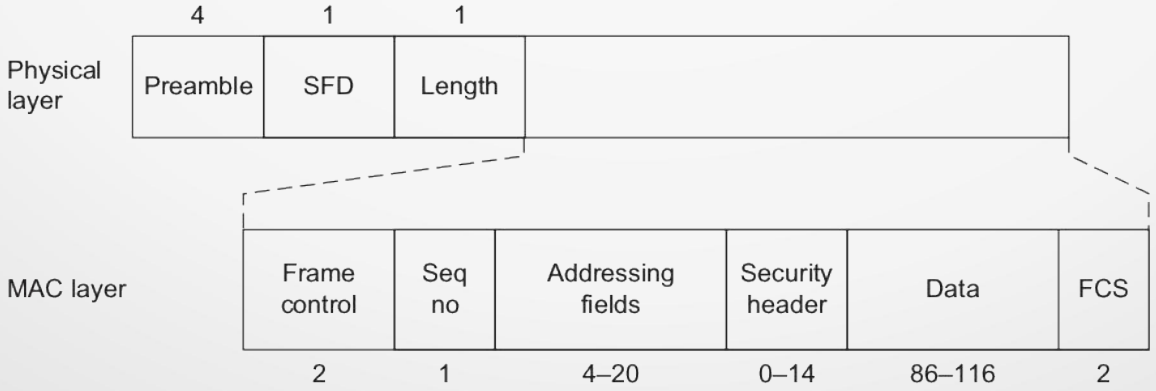


6lowpan: capa de adaptación



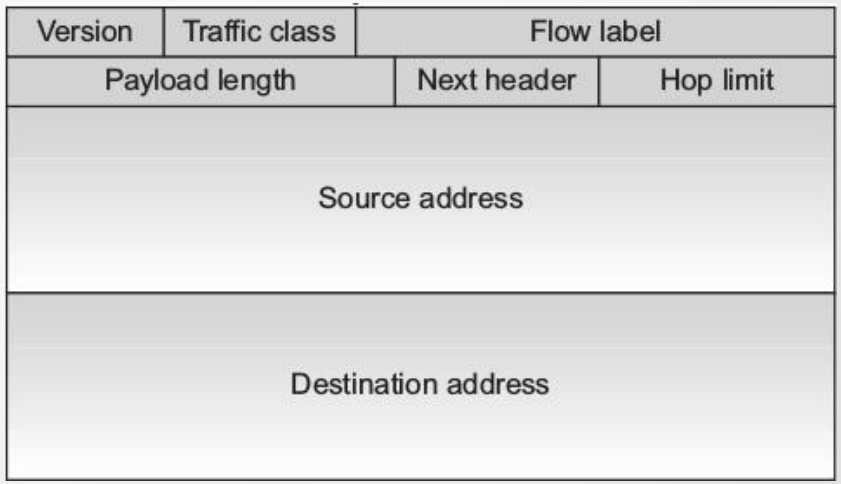
IEEE 802.15.4: algunas características

- Frame pequeño: 127 bytes
  - PER razonablemente bajos para BER no despreciables
- Direcciones
  - 16-bit short / IEEE 64-bit extended MAC.
- Low data rates
  - De 20 kbps (868 MHz) a 250 kbps (2.45 GHz).



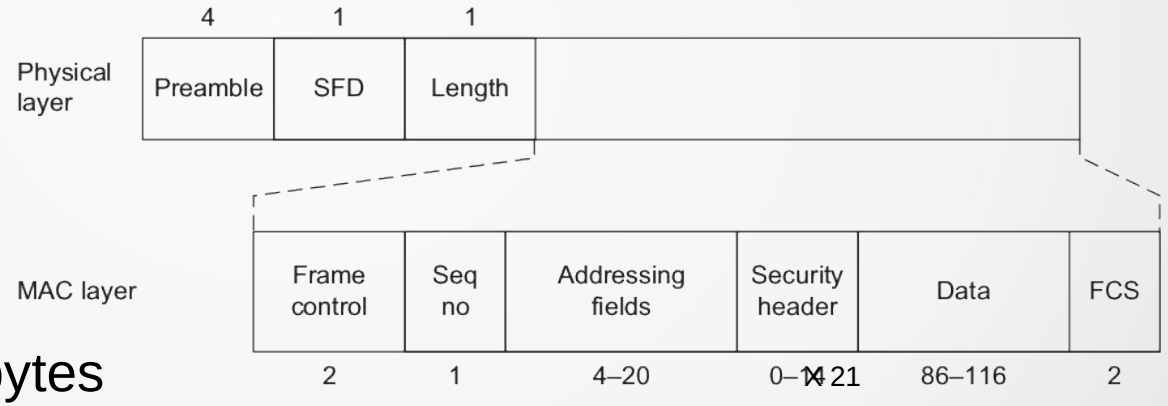
IPv6: algunas características

- Paquete relativamente grande: 1280 bytes.
- Direcciones: 128 bits.
- Stateless address autoconfiguration (SAA)
  - Simplifica configuración y gestión
- IPv6 incluye multicast como parte integral de su arquitectura,
  - Neighbor Discovery (ND) usa link-local multicast para
    - address resolution
    - duplicate address detection
    - router discovery.



IPv6 over LoWPAN: desafíos

- Paquetes IPv6 en LoWPANs.
  - Bajo throughput
  - Buffers limitados
  - **Frames ~10 veces menores que MTU mínimo requerido por IPv6**
- Necesidad
  - Fragmentación
  - Compresión
- Ejemplo:
  - Payload efectivo 81 bytes
  - IPv6 header: 40 bytes
  - UDP/TCP header: 8 / 20 bytes,
  - Queda: ....



127−(2+1+20+2) = 102 bytes
AES-CCM-128: 21 bytes extra

6LoWPAN: capa de adaptación

- RFC 4944 (September 2007):
  - Transmission of IPv6 Packets over IEEE 802.15.4 Networks
    - técnicas de compresión de encabezados
- RFC 6282 (September 2011):
  - Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks
    - mejoras a RFC 4944
- RFC 6775 (November 2012):
  - Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)

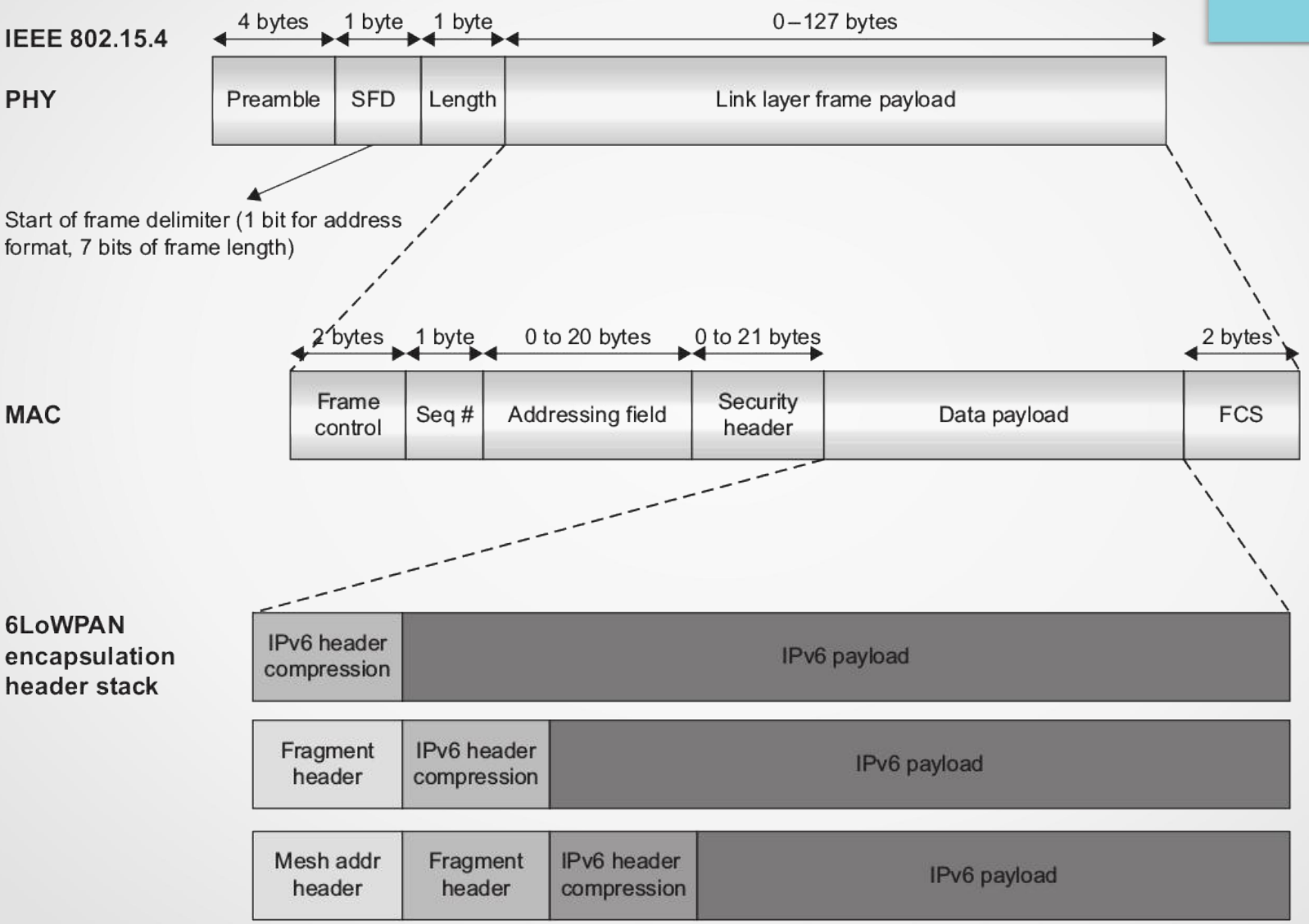
6LoWPAN: funciones

- Provee tres servicios:
  - Fragmentado y reensamblado de paquetes
  - Compresión de encabezados
  - Enrutamiento en capa 2 “mesh-under”

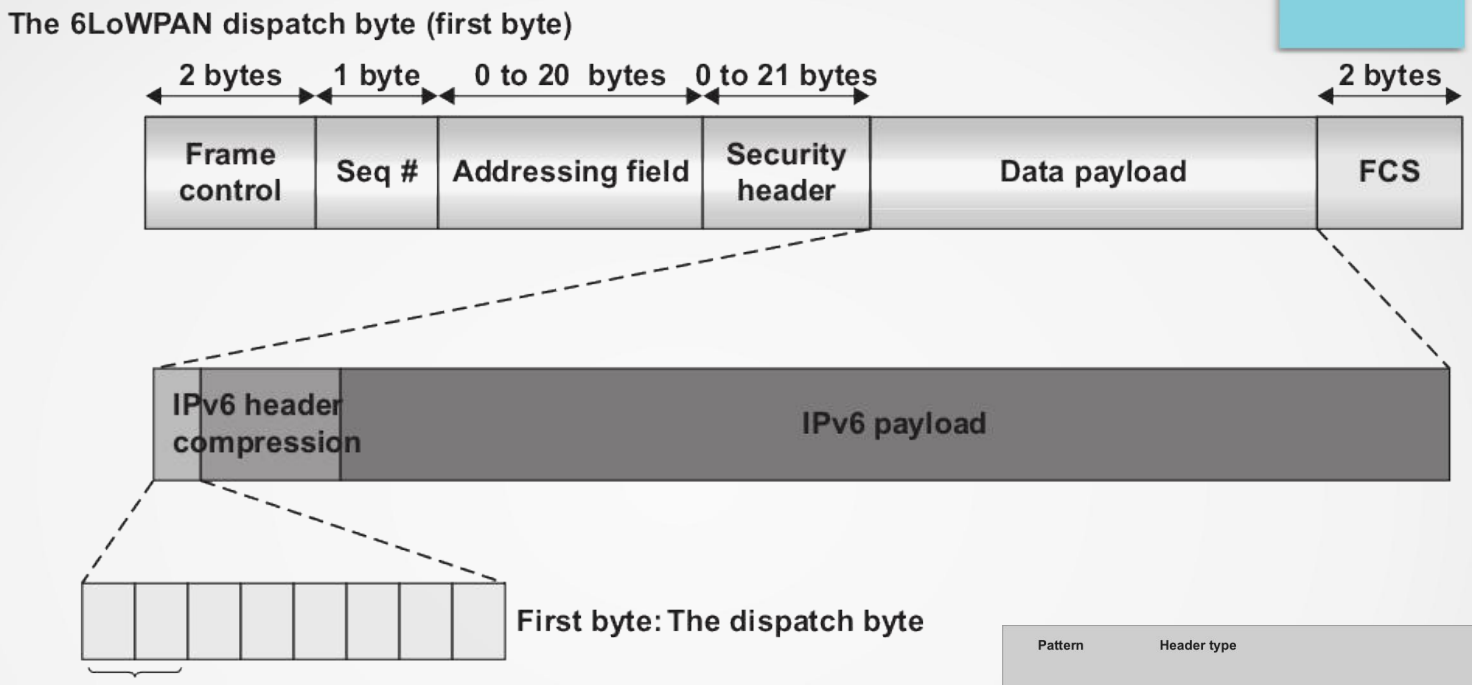
6loWPAN: pila de encabezados

- IEEE 802.15.4 encapsula paquete IPv6
  - “encapsulation header stack” antes de cada paquete IPv6
  - cada encabezado se agrega si se necesita
  - dispach byte (primer byte): identifica el *next header* de la pila.
- Tres encabezados:
  - mesh addressing header
  - fragment header
  - IPv6 header compression header
- Nota: deben aparecer en ese orden si están presentes

6loWPAN: encapsulado de IPv6



6loWPAN: dispach byte (header)



00	**Not a 6LoWPAN frame**
01	IPv6 addressing header
10	Mesh header
11	Fragmentation header (6 lower bits are 100xxx)

Pattern	Header type
00 xxxxxx	NALP - not a LoWPAN frame
01 000001	IPv6 - uncompressed IPv6 addresses
01 000010	LOWPAN_HC1-LOWPAN_HC1 compressed IPv6
01 000011	reserved - reserved for future use
...	reserved - reserved for future use
01 001111	reserved - reserved for future use
01 010000	LOWPAN_BCO - LOWPAN_BCO broadcast
01 010001	reserved - reserved for future use
...	reserved - reserved for future use
01 111110	reserved - reserved for future use
01 111111	ESC - additional dispatch byte follows
10 xxxxxx	MESH - Mesh header
11 000xxx	FRAG1 - fragmentation header (first)
11 001000	reserved - reserved for future use
...	reserved - reserved for future use
11 011111	reserved - reserved for future use
11 100xxx	FRAGN - fragmentation header (subsequent)
11 101000	reserved - reserved for future use
...	reserved - reserved for future use
11 111111	reserved - reserved for future use

6loWPAN: dispach byte (detalle)

00	**Not a 6LoWPAN frame**
01	IPv6 addressing header
10	Mesh header
11	Fragmentation header (6 lower bits are 100xxx)

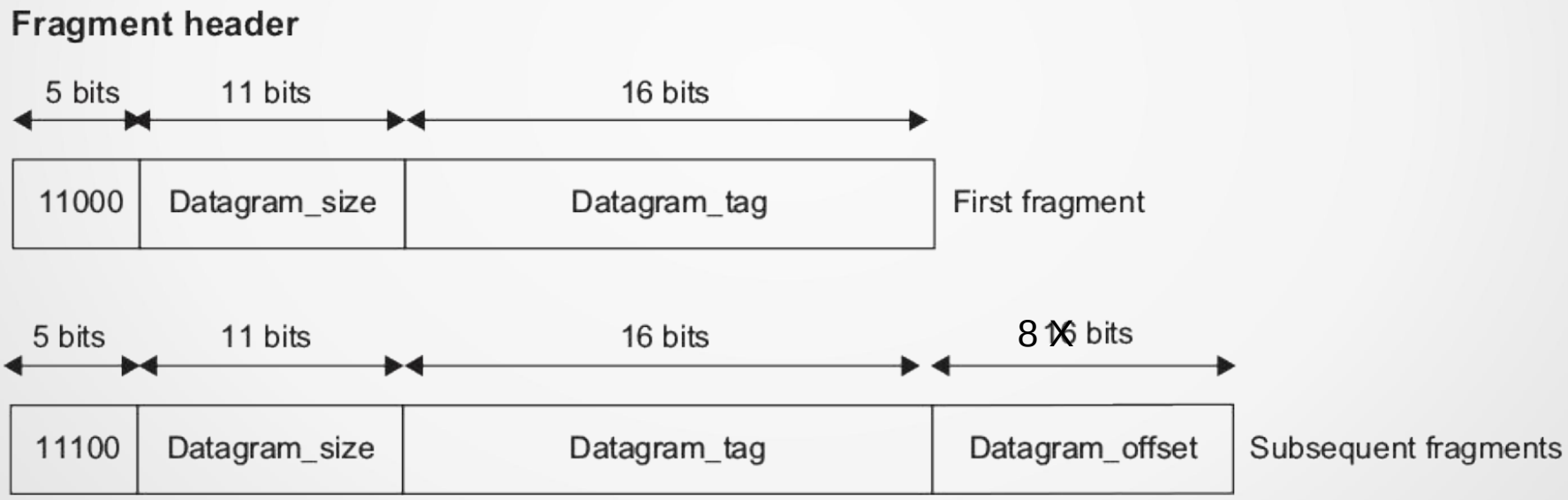
Pattern	Header type
00 xxxxxx	NALP - not a LoWPAN frame
01 000001	IPv6 - uncompressed IPv6 addresses
01 000010	LOWPAN_HC1-LOWPAN_HC1 compressed IPv6
01 000011	reserved - reserved for future use
...	reserved - reserved for future use
01 001111	reserved - reserved for future use
01 010000	LOWPAN_BCO - LOWPAN_BCO broadcast
01 010001	reserved - reserved for future use
...	reserved - reserved for future use
01 111110	reserved - reserved for future use
01 111111	ESC - additional dispatch byte follows
10 xxxxxx	MESH - Mesh header
11 000xxx	FRAG1 - fragmentation header (first)
11 001000	reserved - reserved for future use
...	reserved - reserved for future use
11 011111	reserved - reserved for future use
11 100xxx	FRAGN - fragmentation header (subsequent)
11 101000	reserved - reserved for future use
...	reserved - reserved for future use
11 111111	reserved - reserved for future use

Mesh addressing header (dispach: 10)

- Estrategia mesh-under “routing”
  - nodos rutean en capa 2 (link layer) usando direcciones de capa 2
  - solo FFD (full function devices, según IEEE 802.15.4), reduced function devices (RFDs) mandan a FFD

Fragmentation header (dispach 11)

- FRAG1: primero 11 000 XXX
- FRAGN: siguientes 11 100 XXX



Fragmentation

- FRAG1
  - datagram_size (11 bits)
    - Suficiente para 1280 bytes?
  - datagram_tag (16 bits)
    - identificador único, igual en todos los fragmentos
    - se recomienda incrementar con cada nuevo *frame* fragmentado
- FRAGN
  - datagram_offset (8 bit)
  - indica offset (en unidades de 8 bytes)
- RFC4944 especifica usar un timer de 60 s para recibir todos los fragmentos

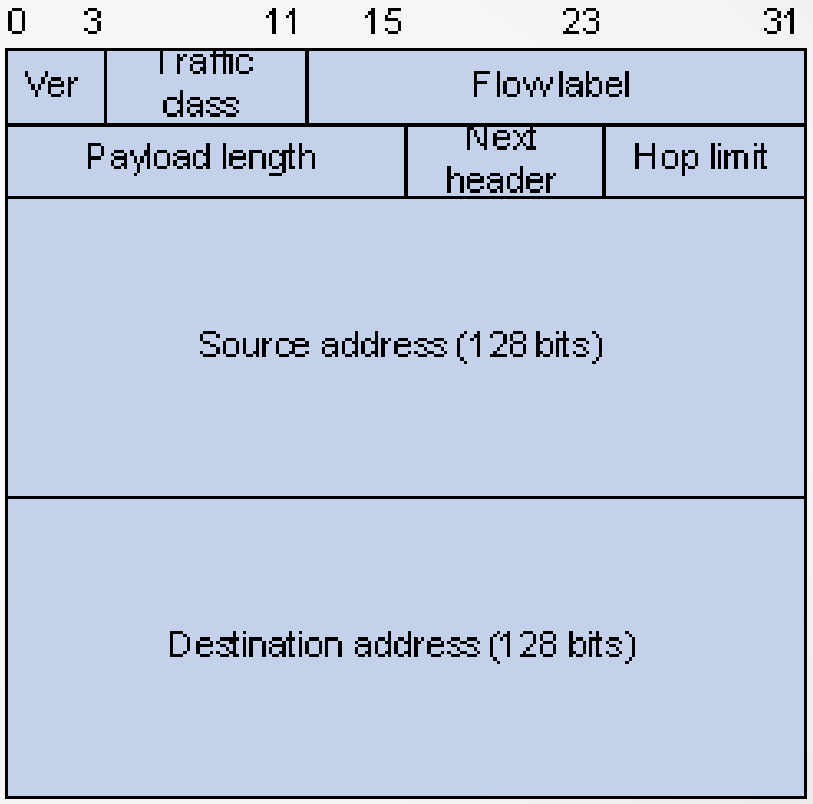
6LoWPAN Header Compression

- RFC 4944:
  - LOWPAN_HC1 / LOWPAN_HC2
- RFC 6282:
  - LOWPAN_IPHC (IPHC)
  - LOWPAN_NHC (NHC).
- Nota: IPHC seguramente sea la técnica usada, HC1 y HC2 serán declaradas obsoletas (deprecated).

HC1 Compression Technique

- ¿Qué podemos hacer?

  Ideas....



Basic IPv6 header

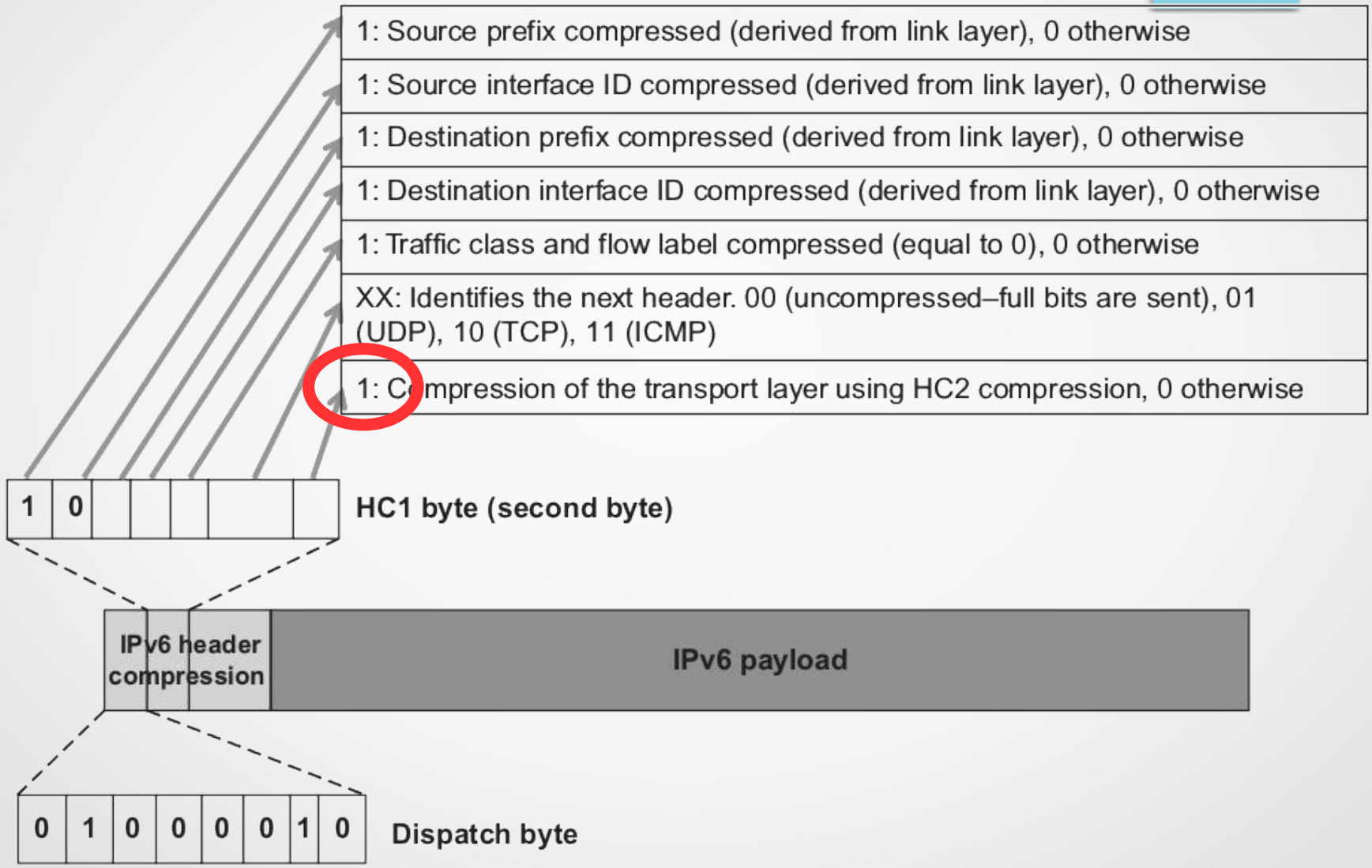
HC1 Compression Technique

- Se basa en:
  - IP version es siempre 6.
  - Packet length puede inferirse del *frame length* (IEEE 802.15.4 frame).
  - Traffic Class y Flow label comúnmente vale 0
  - Next header es: UDP, TCP, or ICMP.
  - IPv6 interface ID (últimos 64 bits de la dirección IPv6) puede inferirse de la dirección link layer MAC (si se usó para asignarla)

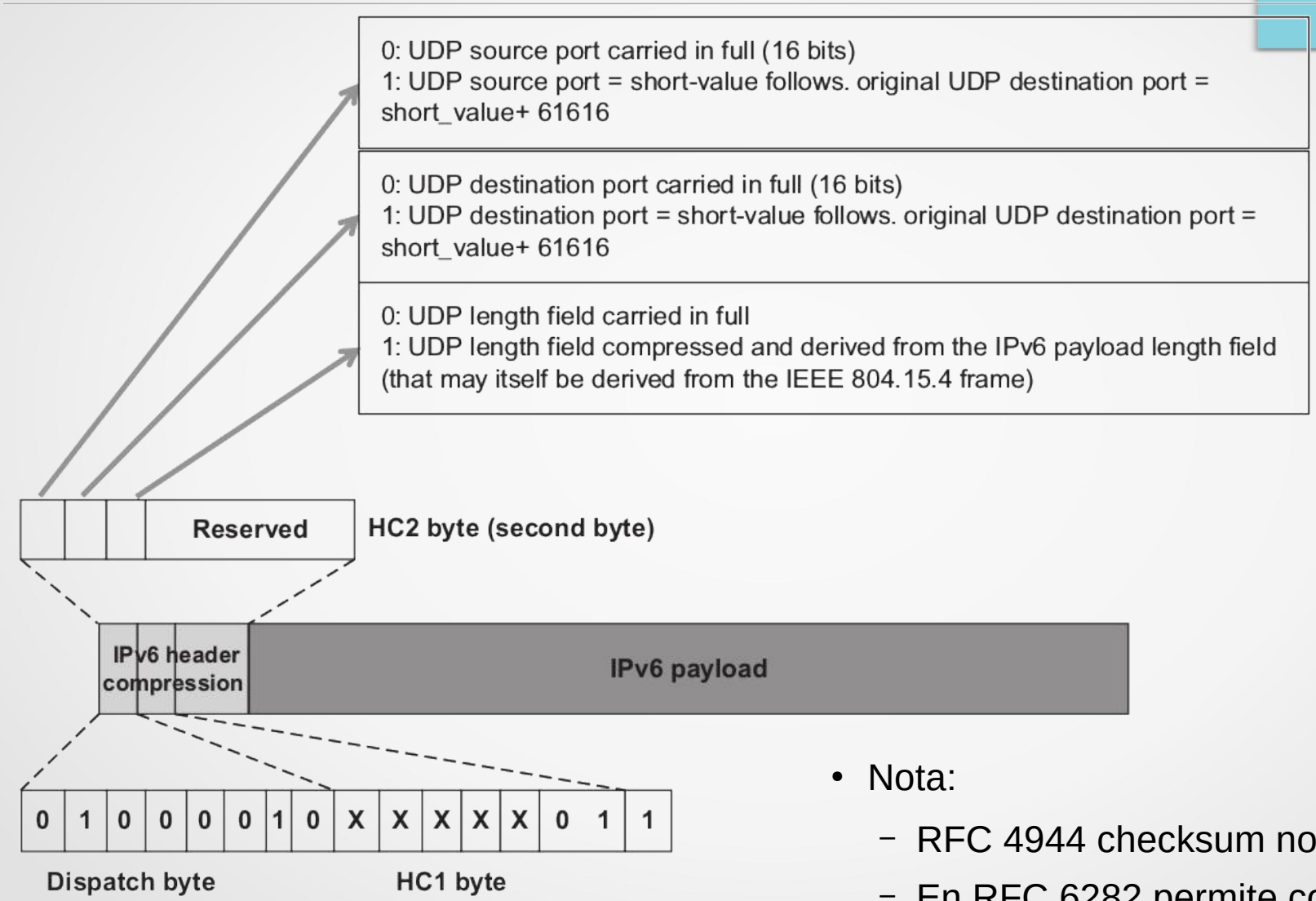
HC1 Compression Technique (dispach: 01)

- IPv6 header: 40 bytes => 3 bytes (mejor caso)
  - dispatch byte (equal to 01000010)
  - HC1 byte
  - Hop limit field (1 byte)
- Si existen campos sin comprimir, van en el sig. orden:
  - source address prefix (64 bits) y/o interface ID (64 bits),
  - destination address prefix (64 bits) y/o interface ID (64 bits)
  - TC (8 bits), flow label (20 bits)
  - next header (8 bits)

HC1 byte

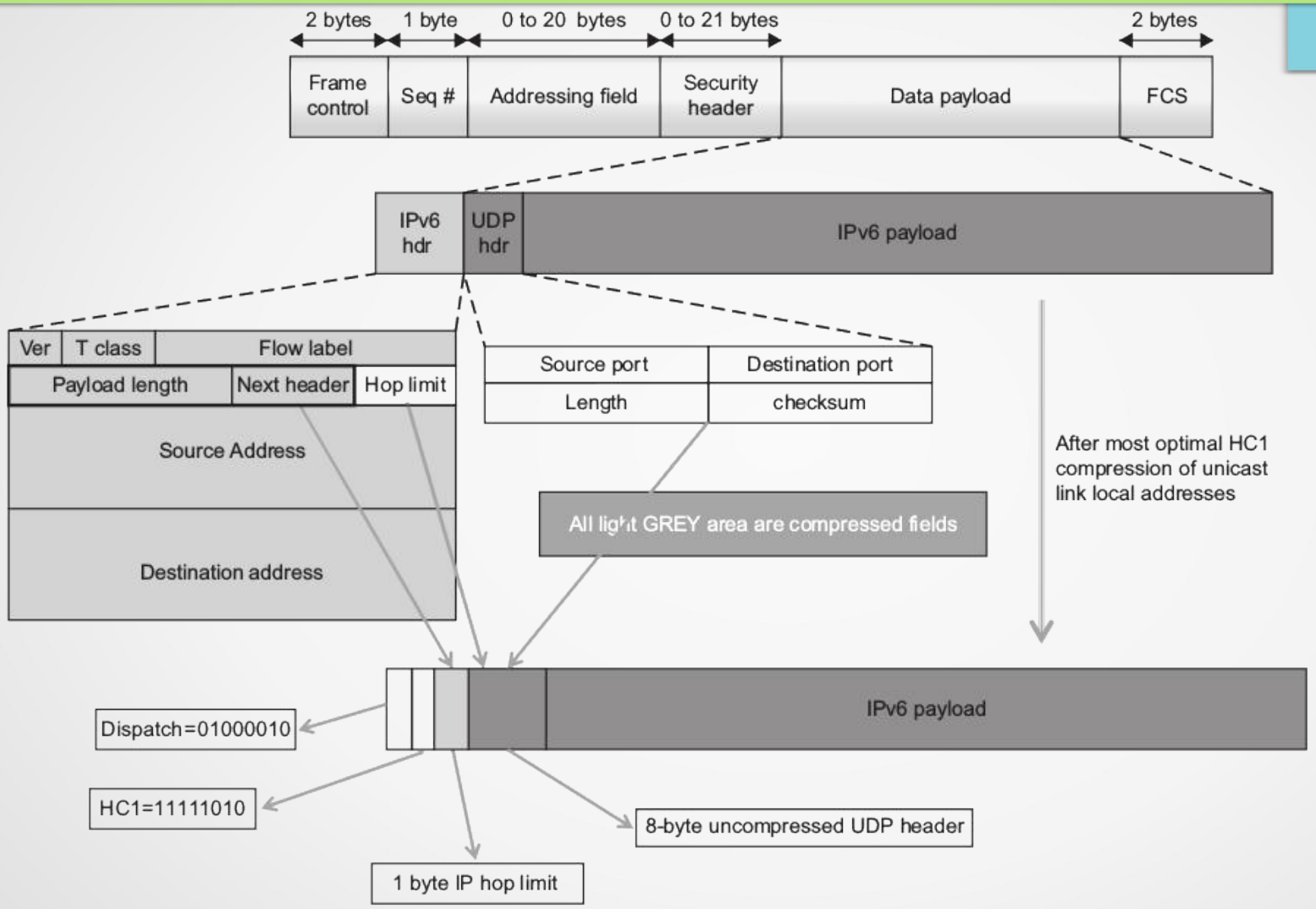

1: Source prefix compressed (derived from link layer), 0 otherwise
1: Source interface ID compressed (derived from link layer), 0 otherwise
1: Destination prefix compressed (derived from link layer), 0 otherwise
1: Destination interface ID compressed (derived from link layer), 0 otherwise
1: Traffic class and flow label compressed (equal to 0), 0 otherwise
XX: Identifies the next header. 00 (uncompressed–full bits are sent), 01 (UDP), 10 (TCP), 11 (ICMP)
1: Compression of the transport layer using HC2 compression, 0 otherwise
1 0
HC1 byte (second byte)
IPv6 header compression
IPv6 payload
0 1 0 0 0 0 1 0
Dispatch byte

HC2 byte: HC UDP



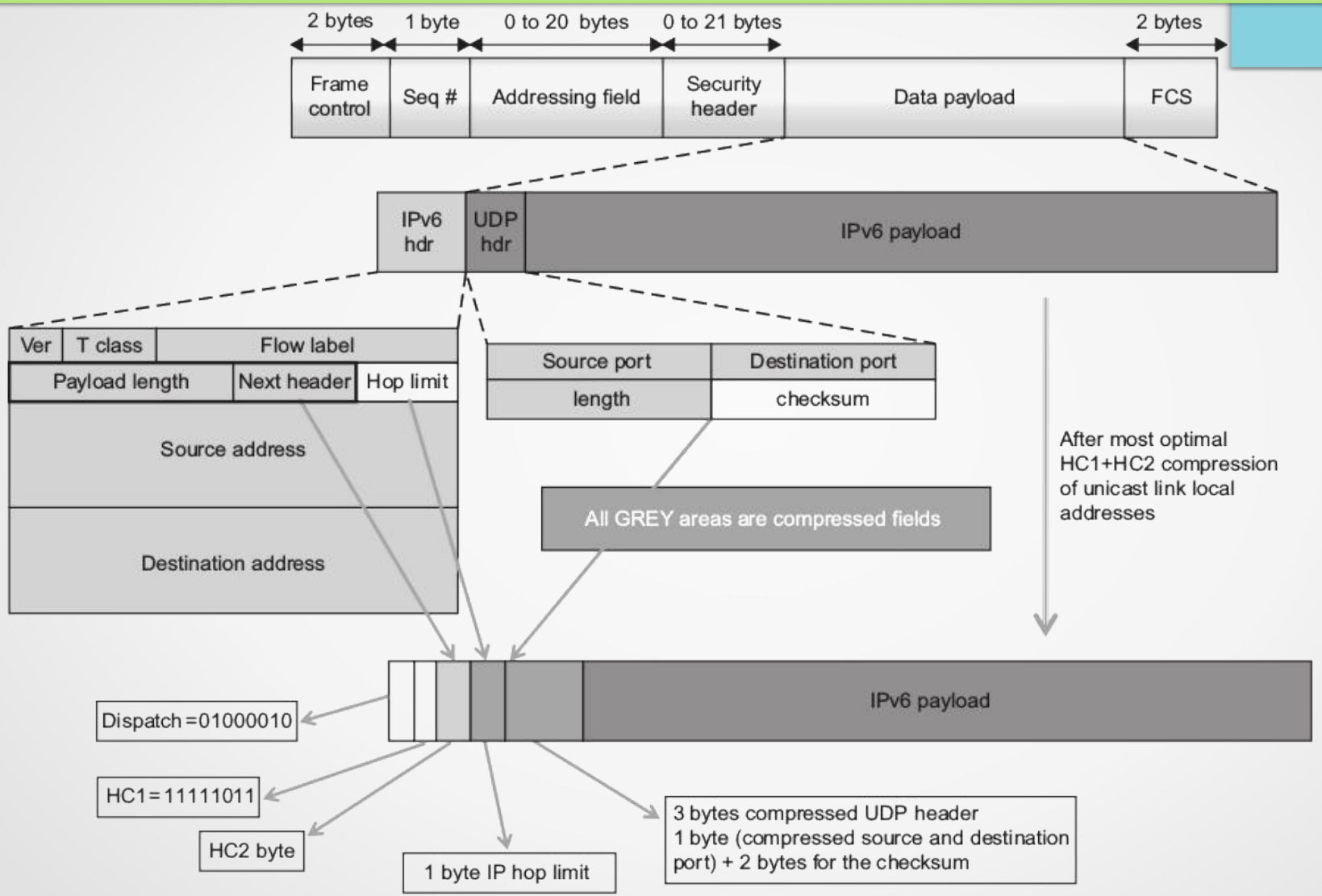
- Nota:
  - RFC 4944 checksum no comprimido
  - En RFC 6282 permite compresión.

Resultados I



HC1 link-local IPv6 addresses sin compresión UDP header

Resultados II

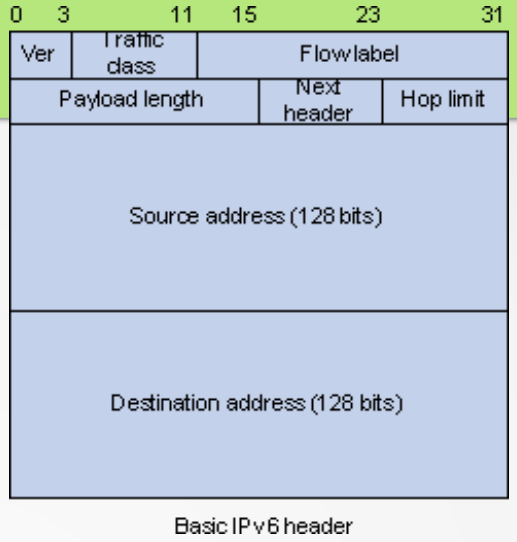


IPv6 y UDP headers usando HC1 y HC2 con direcciones link-local IPv6

Evaluación

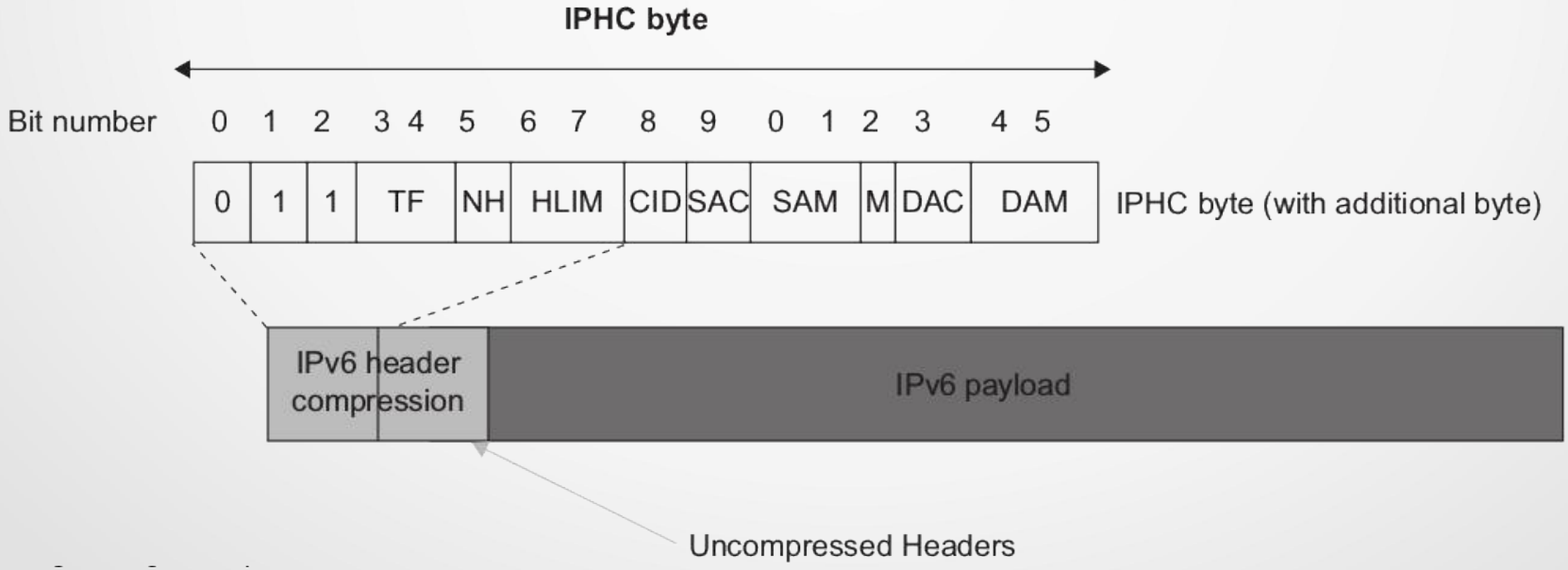
- RFC 4944
  - Define esquema general de encapsulado
  - HC1 / HC2
    - bastante eficiente para direcciones unicast link-local (usadas por protocolos ND, DHCP, y otros)
    - efecto limitado en direcciones globales y multicast
    - Estrategia: todo o nada.
- RFC 6282: nuevas técnicas de compresión
  - LOWPAN_IPHC (IPHC)
  - LOWPAN_NHC (NHC)

IPHC (dispach 011)

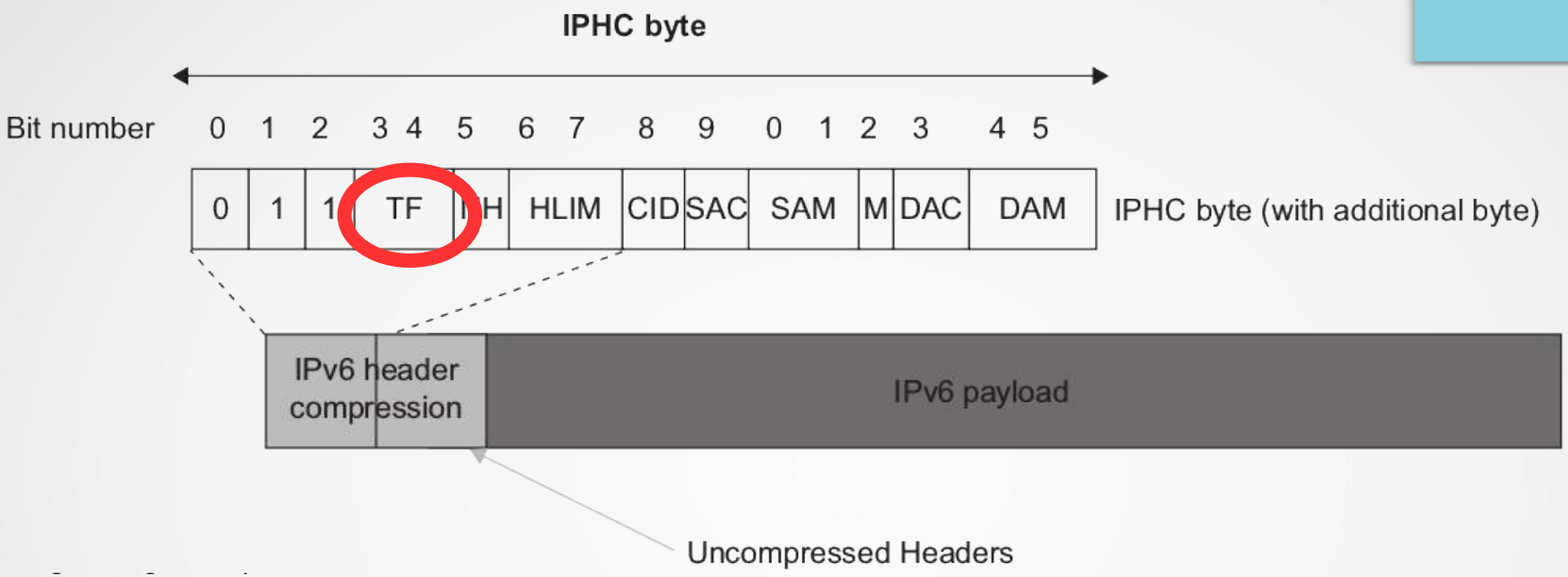


Basic IPv6 header

- IPHC: 13 bits
  - 5 bits del dispatch byte
  - 1 byte adicional opcional
- Campos de encabezado sin comprimir en orden

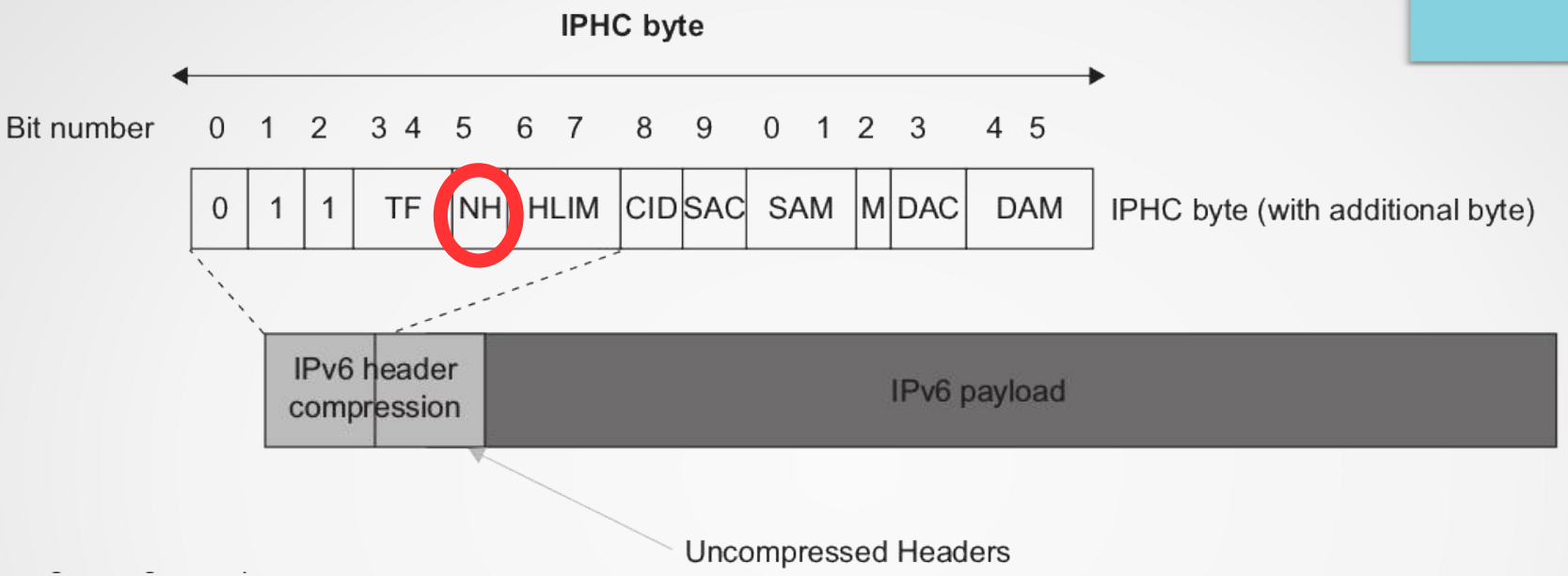


IPHC



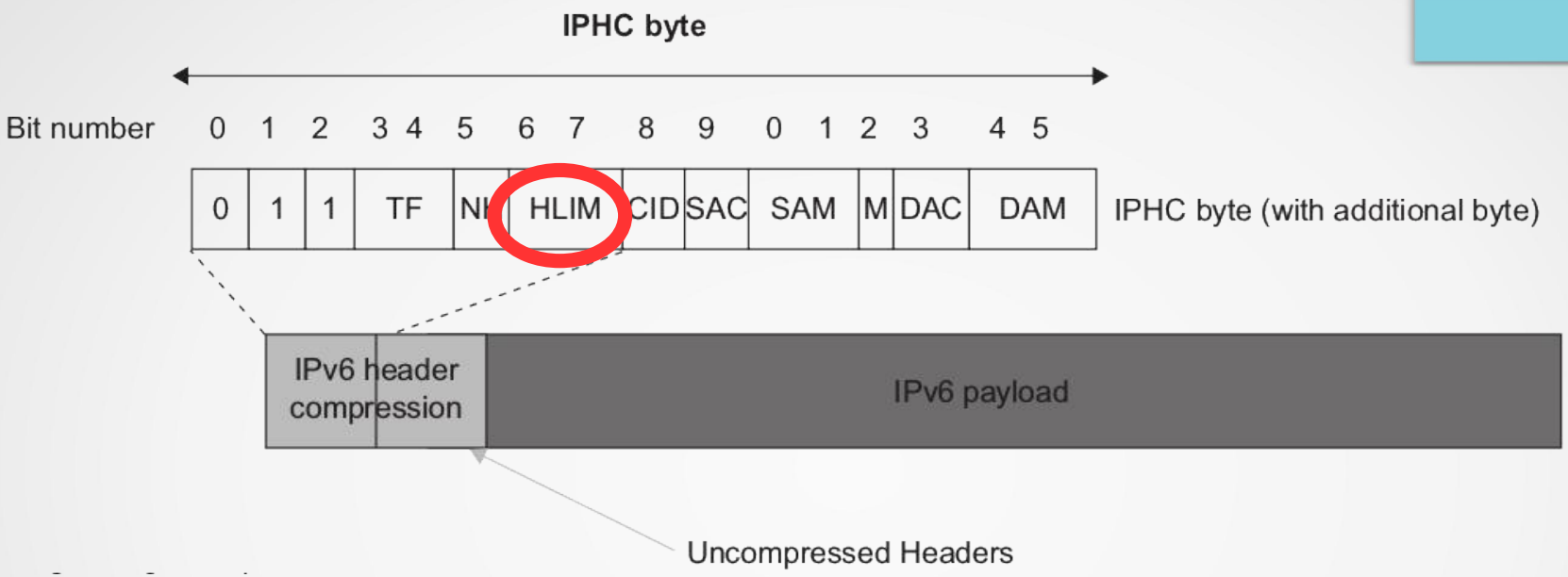
- TF: Traffic class (8 bits), Flow label (20 bits)
  - 00: in-line (Nota: + 4 bits para alineado)
  - 01: TC comprimido a 2 bits (ECN), y flow label sin comprimir
  - 10: TC in-line, y flow label field comprimido
  - 11: TC y flow label comprimidos.

IPHC



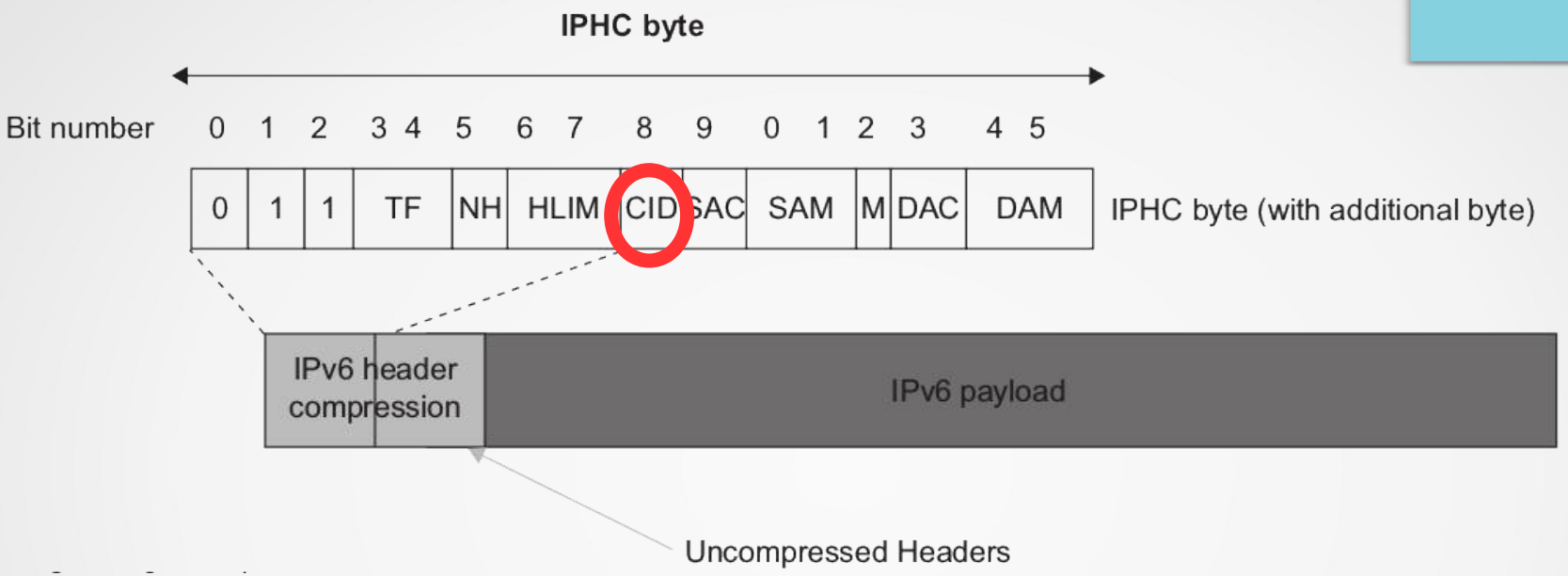
- NH (next header)
  - 0: in-line.
  - 1: next header codificado usando NHC (next header coding)

IPHC



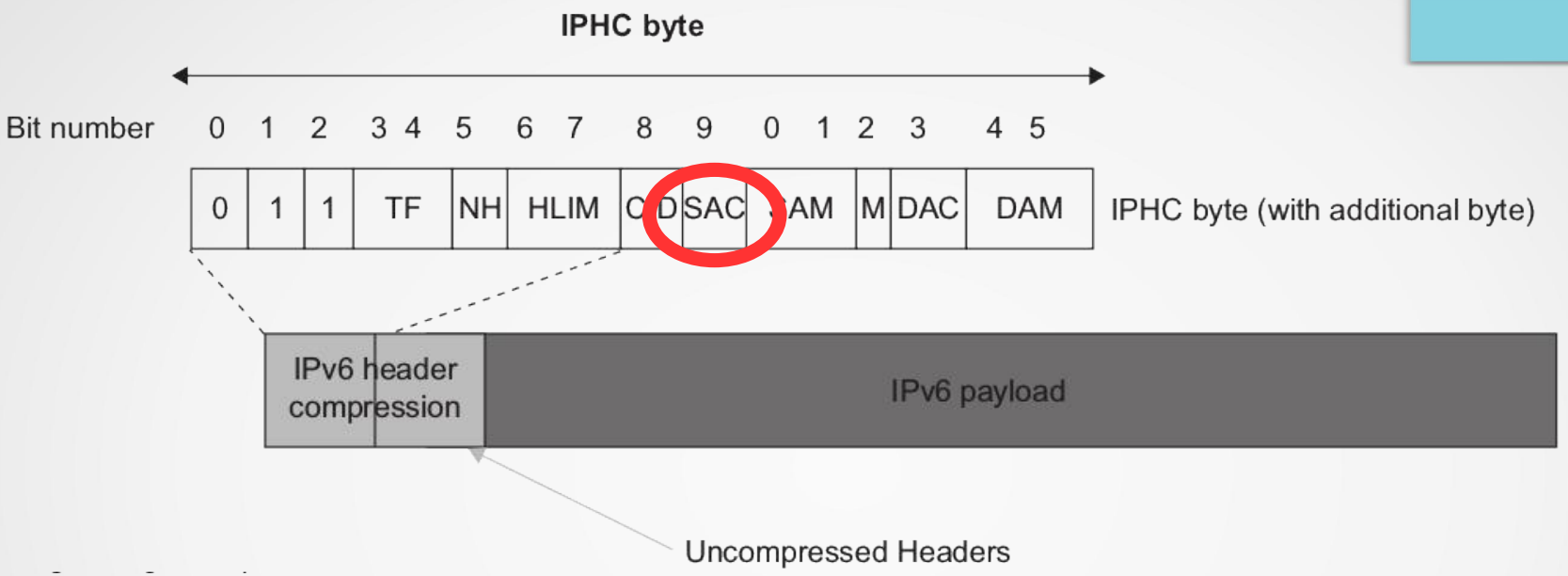
- HLIM (hop limit)
  - 00: in-line.
  - 01: hop limit = 1
  - 10: hop limit = 64
  - 11: hop limit = 255
- Nota: HC1 no comprimía.

IPHC



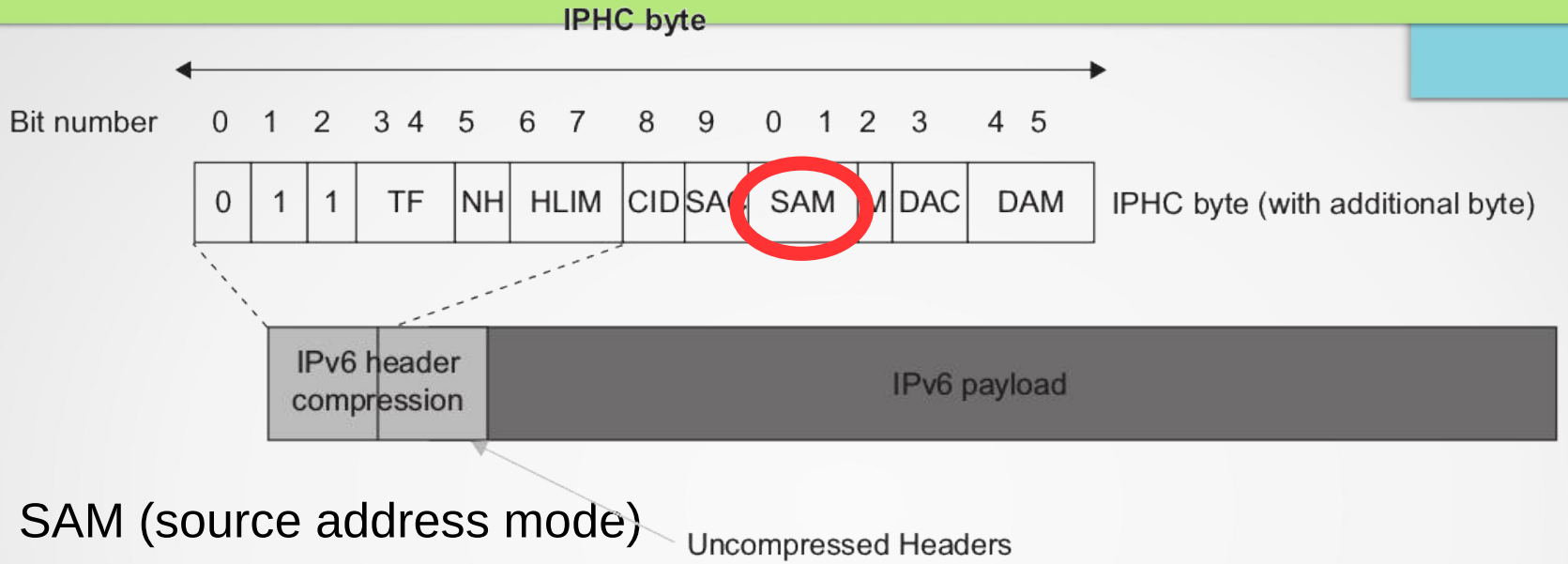
- CID (context identifier extension)
  - 0: no se usa info de contexto adicional
  - 1: se agrega 1 byte de CID luego de DAM.

IPHC



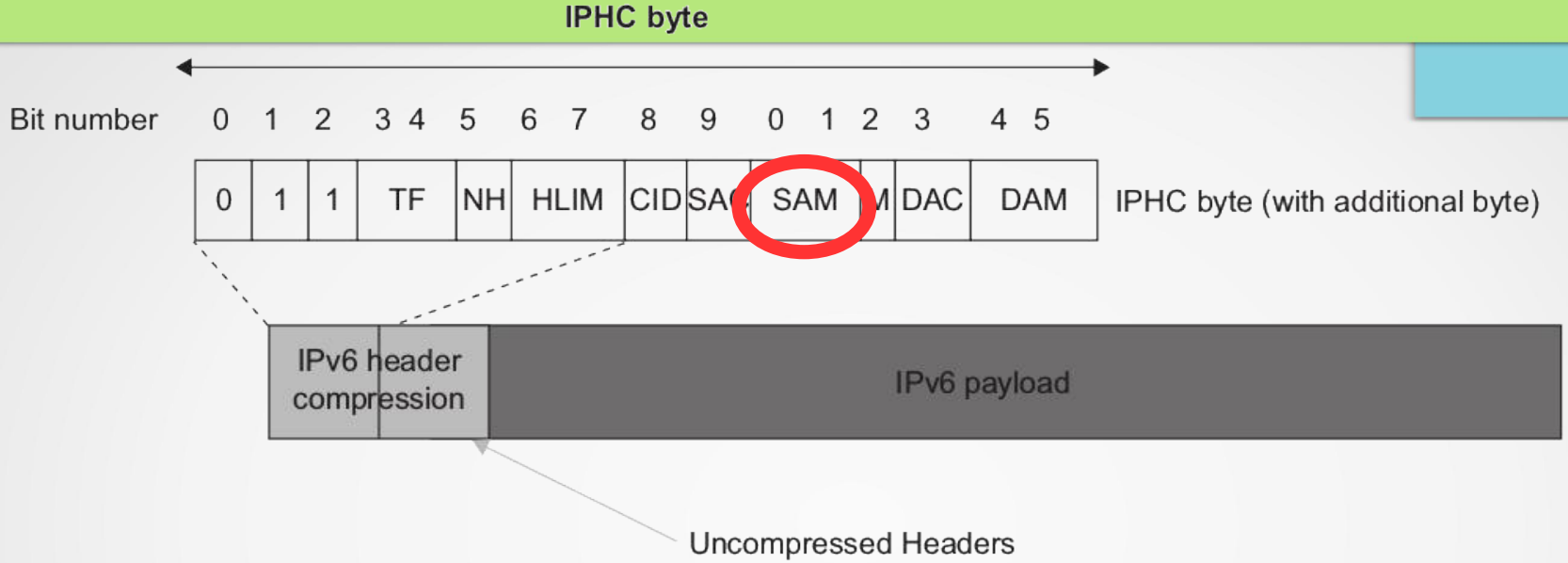
- SAC (source address compression)
  - 0: stateless.
  - 1: stateful basada en contexto.

IPHC



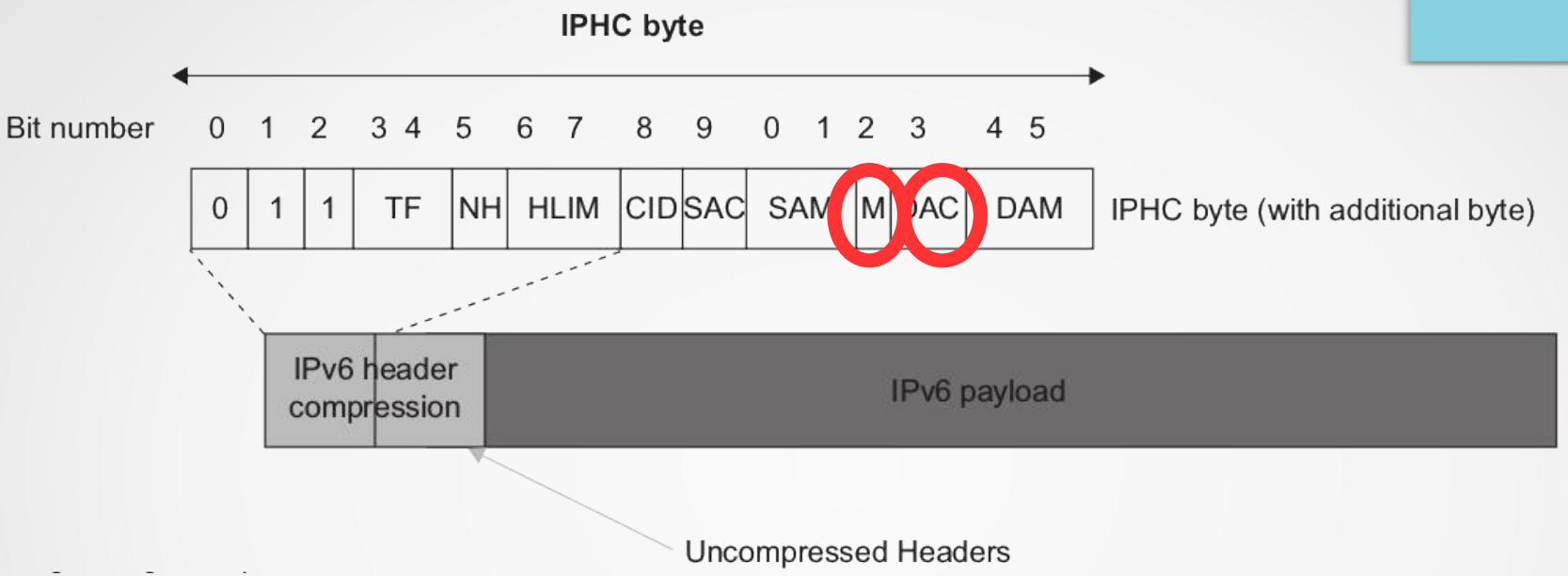
- SAM (source address mode)
- If SAC = 0 (stateless)
  - 00: 128-bit, in-line.
  - 01: 64 bits, primeros 64 bits link-local prefix rellenado con ceros, 64 bits restantes in-line
  - 10: 16 bits, primeros 64 bits link-local prefix rellenado con ceros, 64 bits restantes son 0000:00ff:fe00:XXXX, donde XXXX son los 16 bits in-line.
  - 11: 0 bits, primeros 64 bits link-local prefix rellenado con ceros, 64 bits restantes inferidos de IEEE 802.15.4 frame.

IPHC



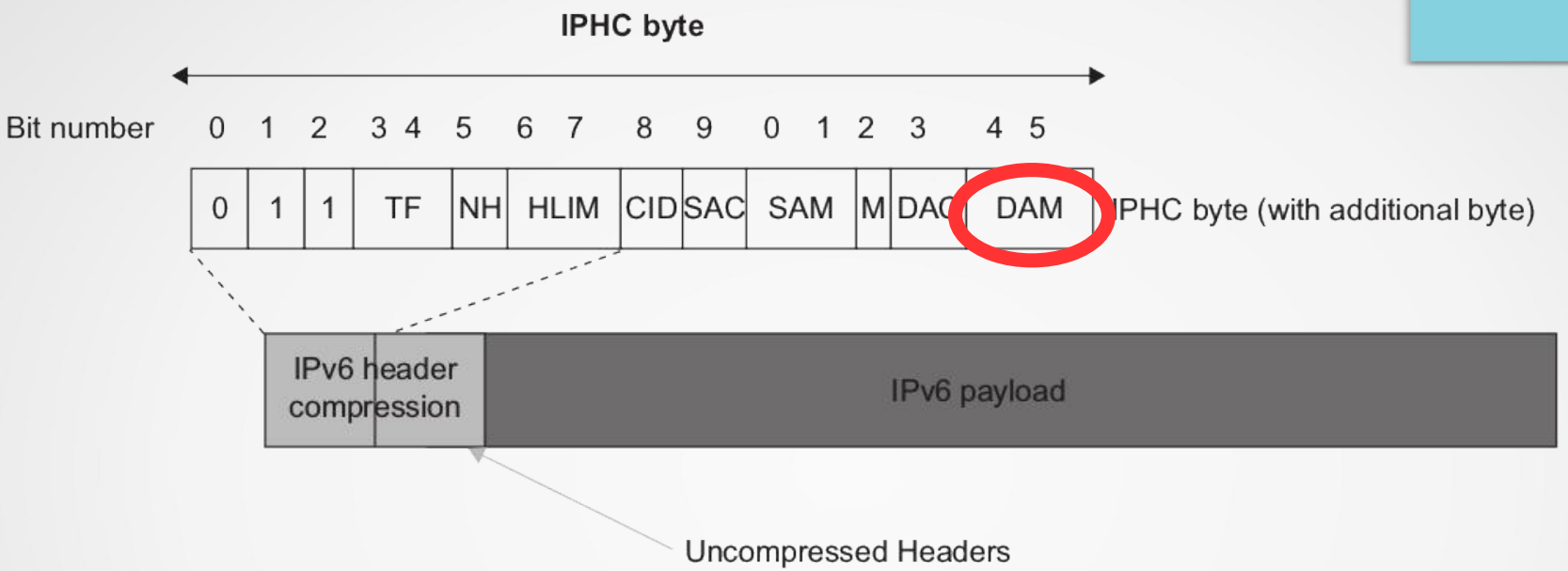
- SAM (source address mode)
- If SAC = 1 (stateful basada en contexto)
  - 01: 64 bits. 64-bit prefix inferida de la info de contexto, 64 bits restantes in-line.
  - 10: 16-bits. 64-bit prefix inferida de info de contexto, 16 bits restantes in-line.
  - 11: 0 bits. Dirección inferida de contexto y posiblemente de link layer.

IPHC



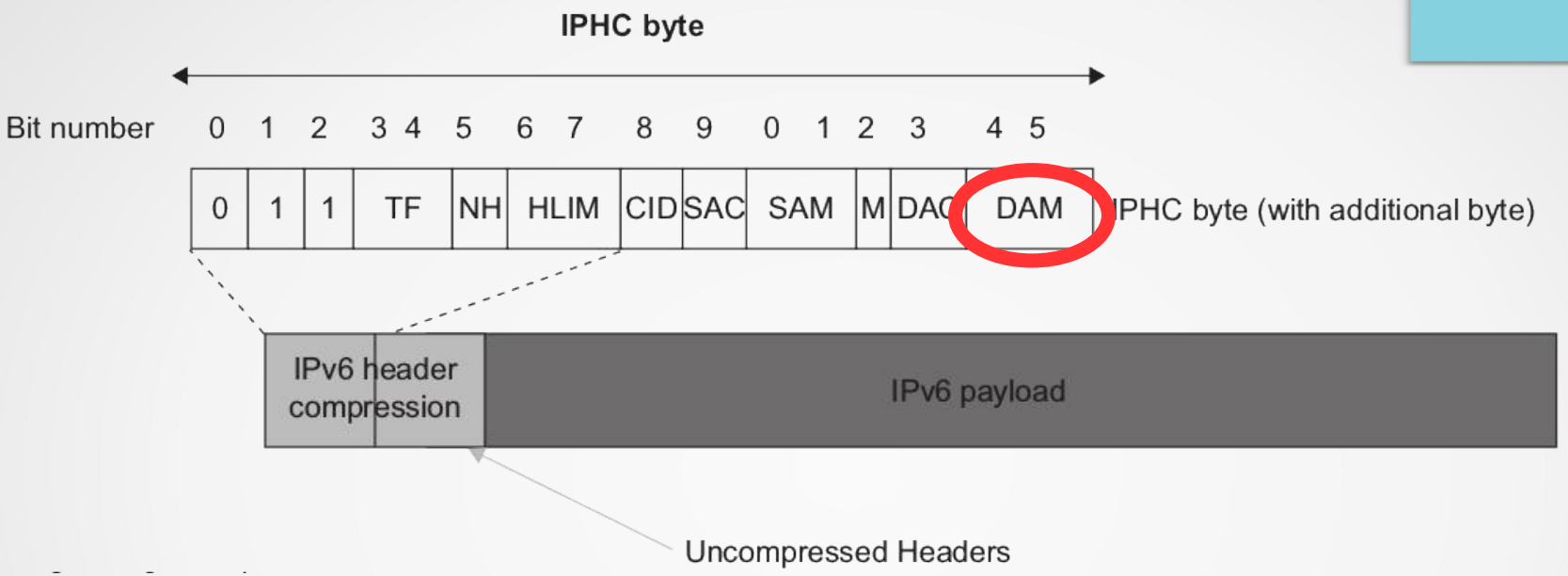
- M (multicast compression)
  - 0: destino no es multicast address.
  - 1: destino es multicast address.
- DAC (destination address compression)
  - 0: stateless.
  - 1: stateful basada en contexto.

IPHC



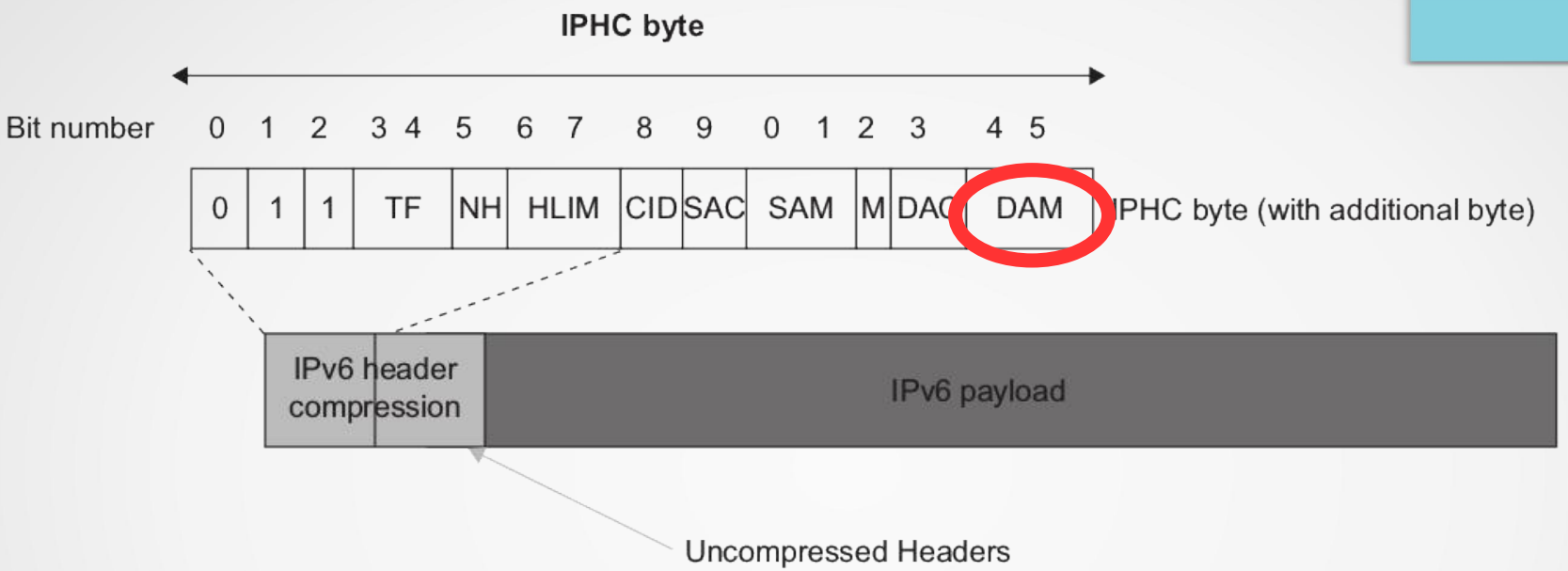
- DAM (destination address mode)
- Si M=0 & DAC=0 (no multicast y stateless) => igual a SAC = 0
  - 00: 128 bits.
  - 01: 64 bits.
  - 10: 16 bits.
  - 11: 0 bits.

IPHC



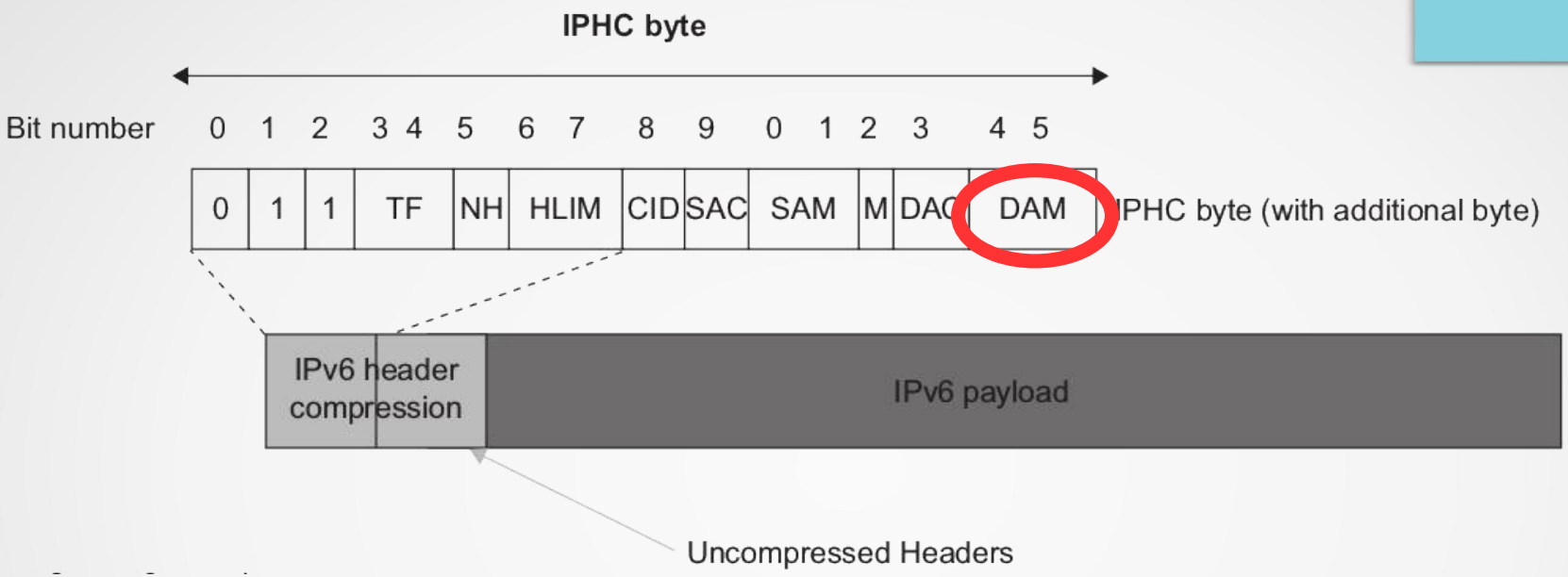
- DAM (destination address mode)
- Si M=0 & DAC=1 (no multicast y stateful basada en contexto)
  - 00: Reserved.
  - 01: 64 bits. Dirección inferida de contexto y de los 64 bits in-line.
  - 10: 16 bits. Similar a anterior.
  - 11: 0 bits.

IPHC



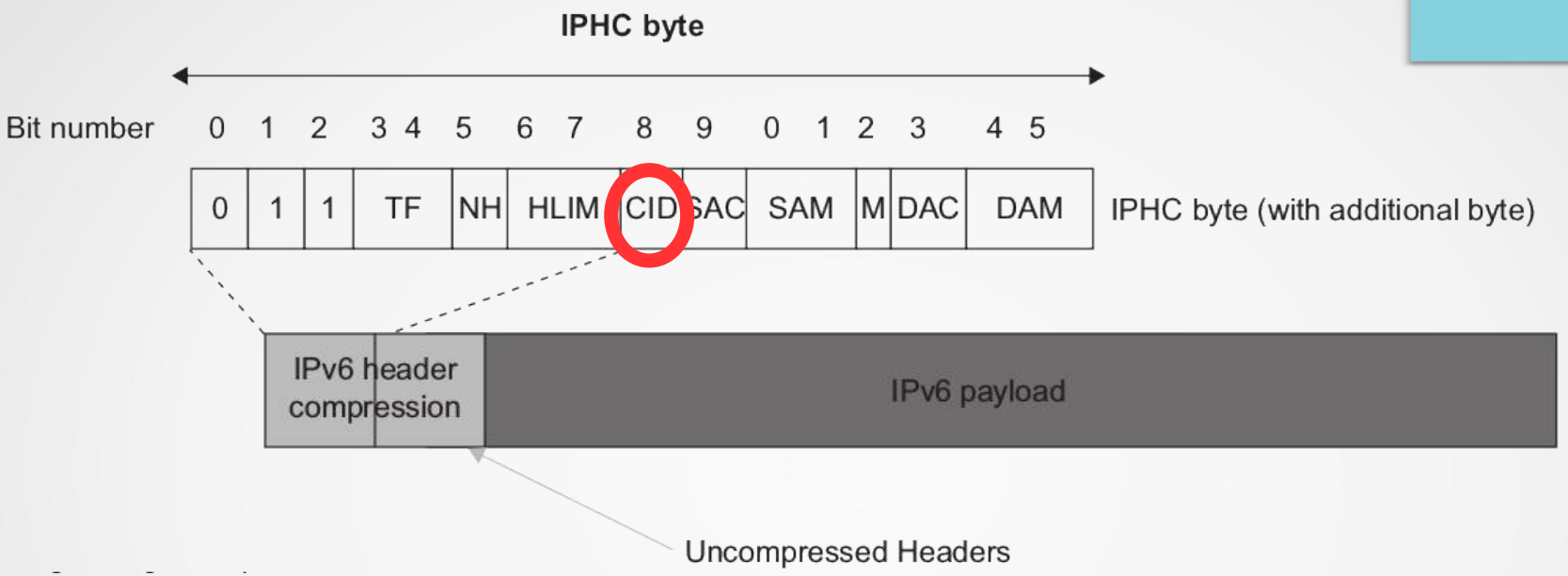
- DAM (destination address mode)
- Si M=1 & DAC=0 (multicast y stateless)
  - 00: 128 bits, in-line
  - 01: 48 bits, ffXX::00XX:XXXX:XXXX
  - 10: 32 bits. ffXX::00XX:XXXX.
  - 11: 8 bits. ff02::00XX

IPHC



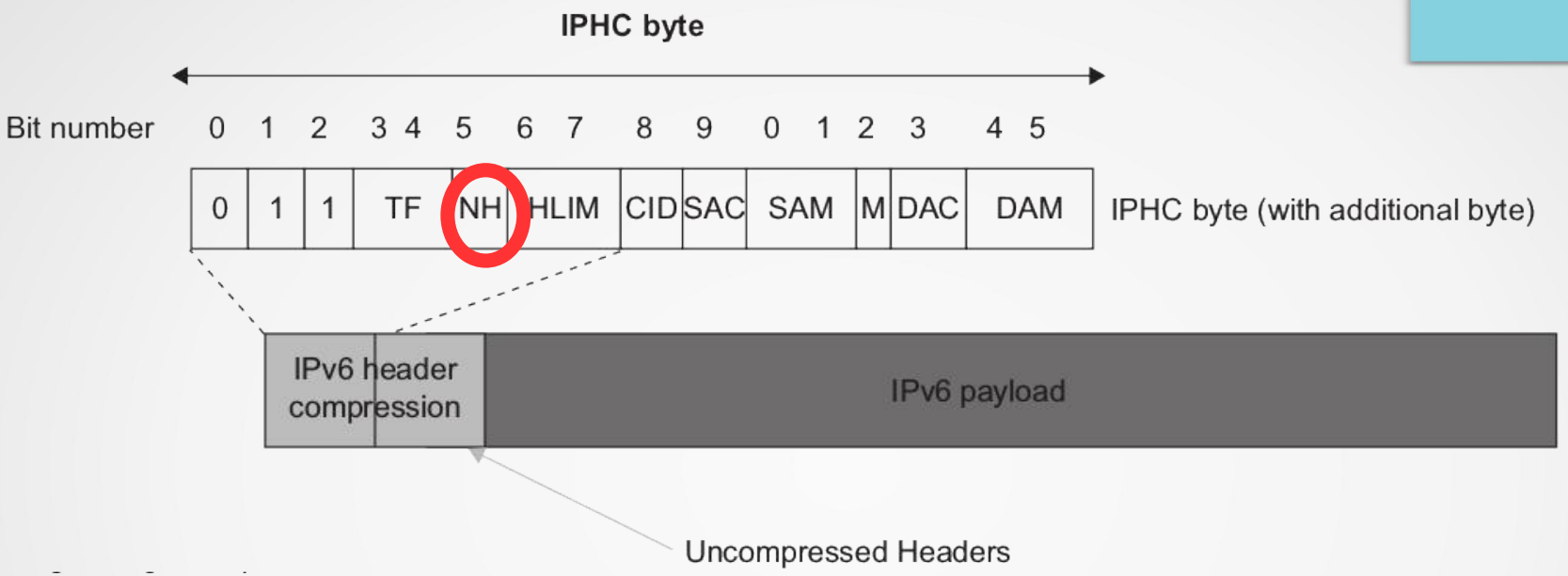
- DAM (destination address mode)
- Si M=1 & DAC=1 (multicast y stateful basada en contexto)
  - 00: 48 bits. ffXX:XXLL:PPPP:PPPP:PPPP:PPPP:XXXX:XXXX donde: X nibbles in-line, P and L se obtiene de contexto
  - 01: reserved
  - 10: reserved
  - 11: reserved

IPHC



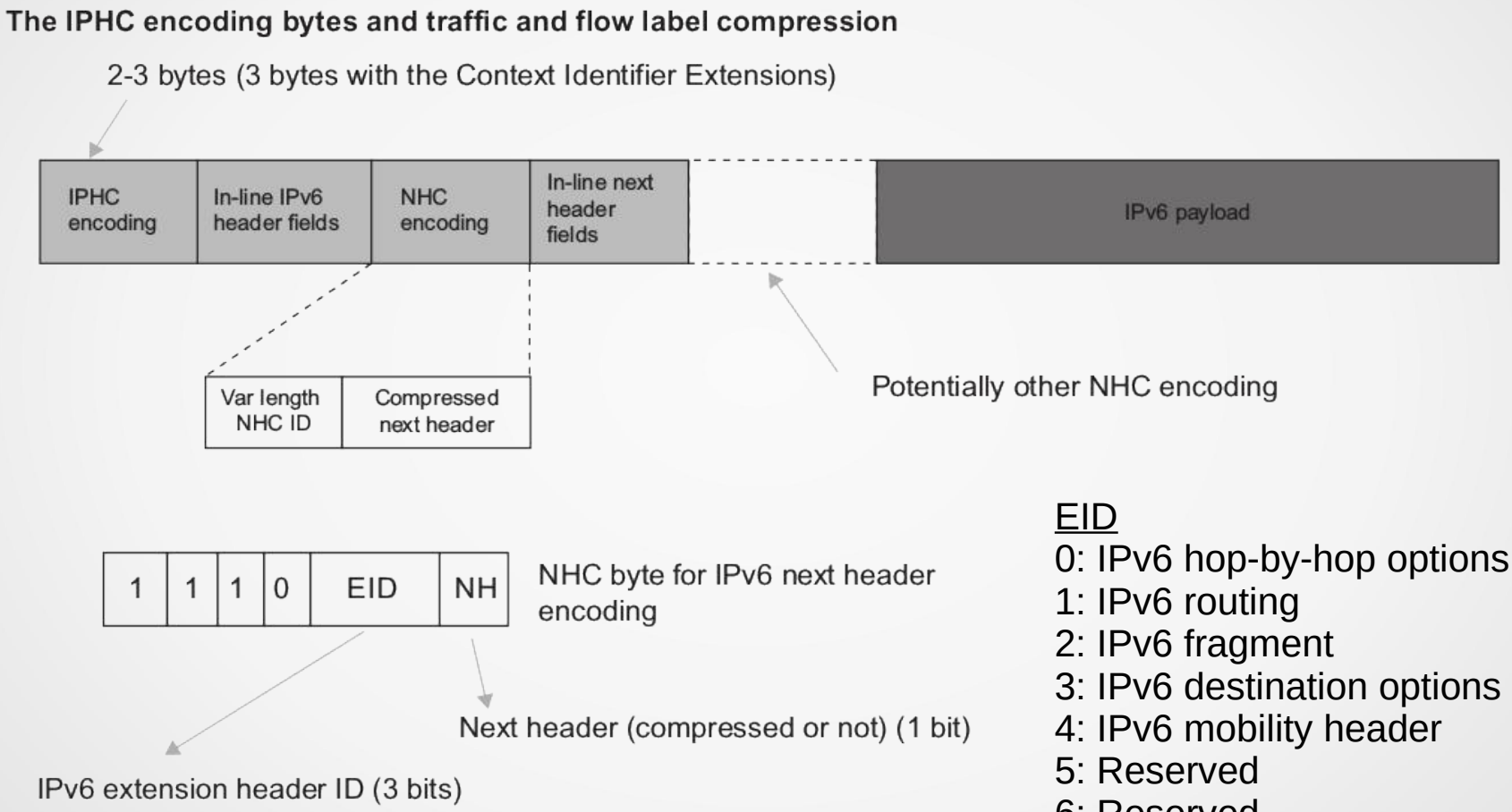
- Si CID = 1 => 1 byte adicional
  - SCI (source context identifier)
  - DCI (destination context identifier)
- 16 contextos

IPHC



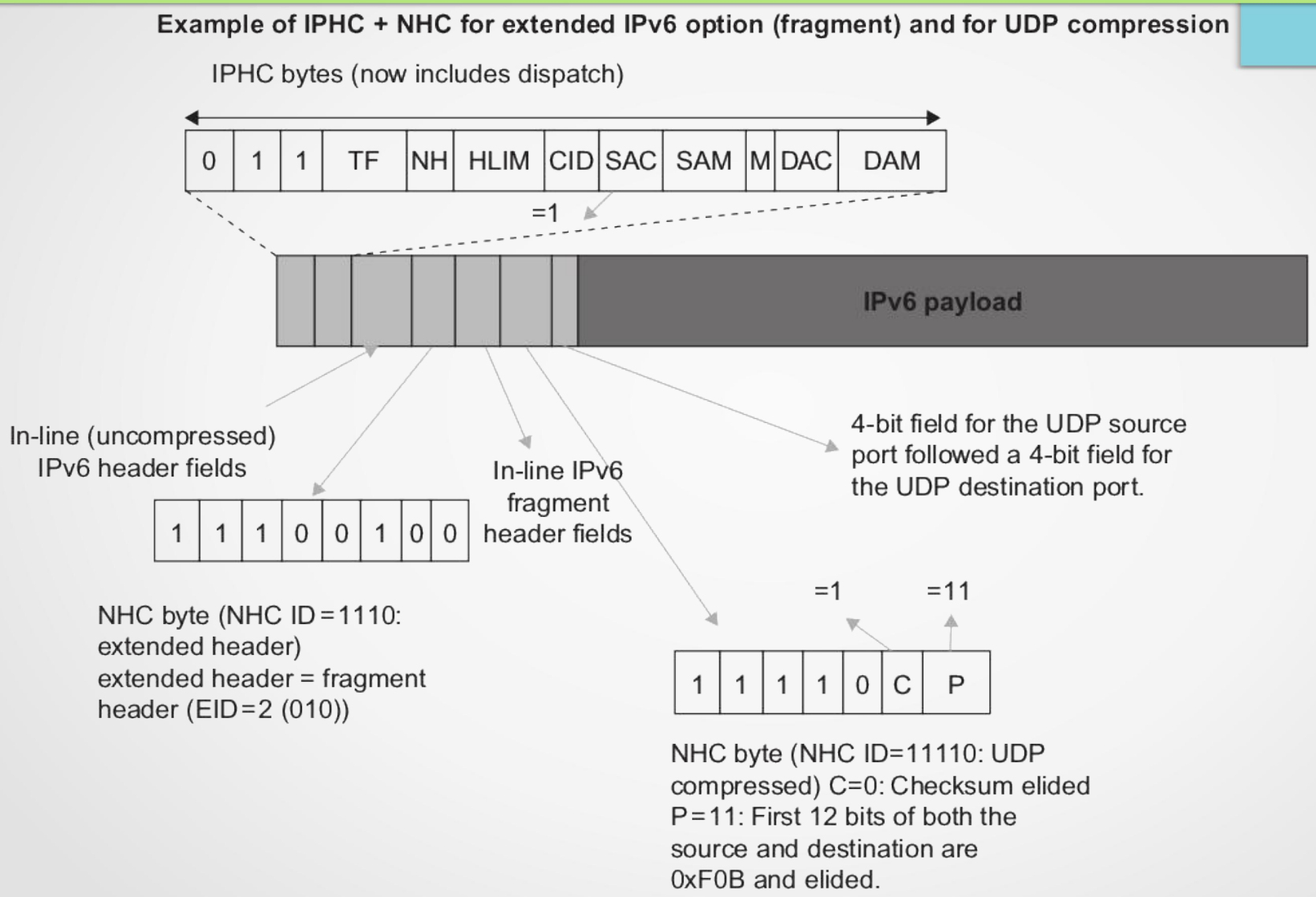
- Si NH = 1 => 1 byte adicional
  - LOWPAN_NHC (Next Header Compression)

NHC: next header compression



EID
0: IPv6 hop-by-hop options
1: IPv6 routing
2: IPv6 fragment
3: IPv6 destination options
4: IPv6 mobility header
5: Reserved
6: Reserved
7: IPv6 header

Resultado


Example of IPHC + NHC for extended IPv6 option (fragment) and for UDP compression
IPHC bytes (now includes dispatch)
0 1 1 TF NH HLIM CID SAC SAM M DAC DAM
=1
IPv6 payload
In-line (uncompressed) IPv6 header fields
In-line IPv6 fragment header fields
4-bit field for the UDP source port followed a 4-bit field for the UDP destination port.
1 1 1 0 0 1 0 0
NHC byte (NHC ID=1110: extended header) extended header = fragment header (EID=2 (010))
=1
=11
1 1 1 1 0 C P
NHC byte (NHC ID=11110: UDP compressed) C=0: Checksum elided P=11: First 12 bits of both the source and destination are 0xF0B and elided.

6lowpan en ContikiOS

- contiki/core/net/ipv6
  - sicslowpan.h
  - sicslowpan.c

Conclusiones

- 6LowPAN permite mandar paquetes IPv6:
  - Fragmentado y reensamblado de paquetes
  - Compresión de encabezados

Normalización

- IETF groups:
  - 6lowpan: IPv6 over Low power WPAN (concluded)
  - 6lo: IPv6 over Networks of Resource-constrained Nodes
  - 6tisch: IPv6 over the TSCH mode of IEEE 802.15.4e
  - RoLL: Routing over Low-power and Lossy networks (ROLL)

Referencias

- G. Montenegro, J. Hui, D. Culler, and N. Kushalnagar, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks," **RFC 4944**, Sept. 2007.
- P. Thubert and J. Hui, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks," **RFC 6282**, Sept. 2011.
- J. P. Vasseur and A. Dunkels, Interconnecting Smart Objects with IP: The Next Internet. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2010.
  - **Nota**: las figuras casi en su totalidad fueron tomadas de este libro.

Planificación clases

- 1. Introducción RSI
- 2. IPv6
- 3. Plataforma de hardware
- 4. Plataforma de software: Contiki OS I
- 5. Plataforma de software: Contiki OS II
- 6. Capa de aplicación: CoAP
- 7. Capa de red: RPL
- 8. Subcapa MAC
- **9. IEEE 802.15.4 / 6lowpan**
- 10. Capa Fisica & antenas
- 11. IoT y las RSI

FIN... ¿preguntas?