



Tecnologías de Comunicación para IoT (cont.)

Leonardo Steinfeld





Agenda



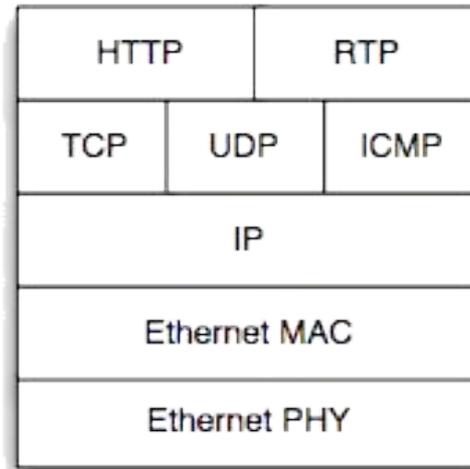
- Introducción
- Tecnologías LPWAN
 - SigFox
 - LoRa
 - Weightless/Telensa
 - RPMA/Ingenu
- Tecnologías “Celulares”
 - NB-IoT
 - LTE-M
- **Tecnologías WPAN**
 - 802.15.4/Zigbee



Introducción

■ Previos

TCP/IP Protocol Stack

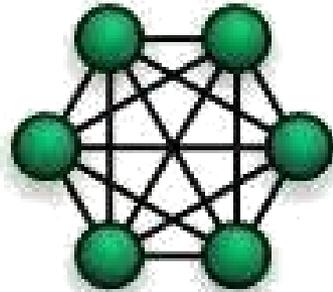




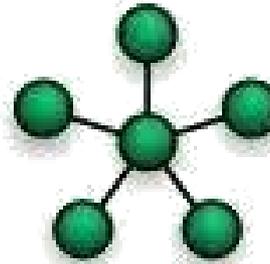
Introducción

■ Estrella (star) vs. Malla (mesh)

Mesh Topology



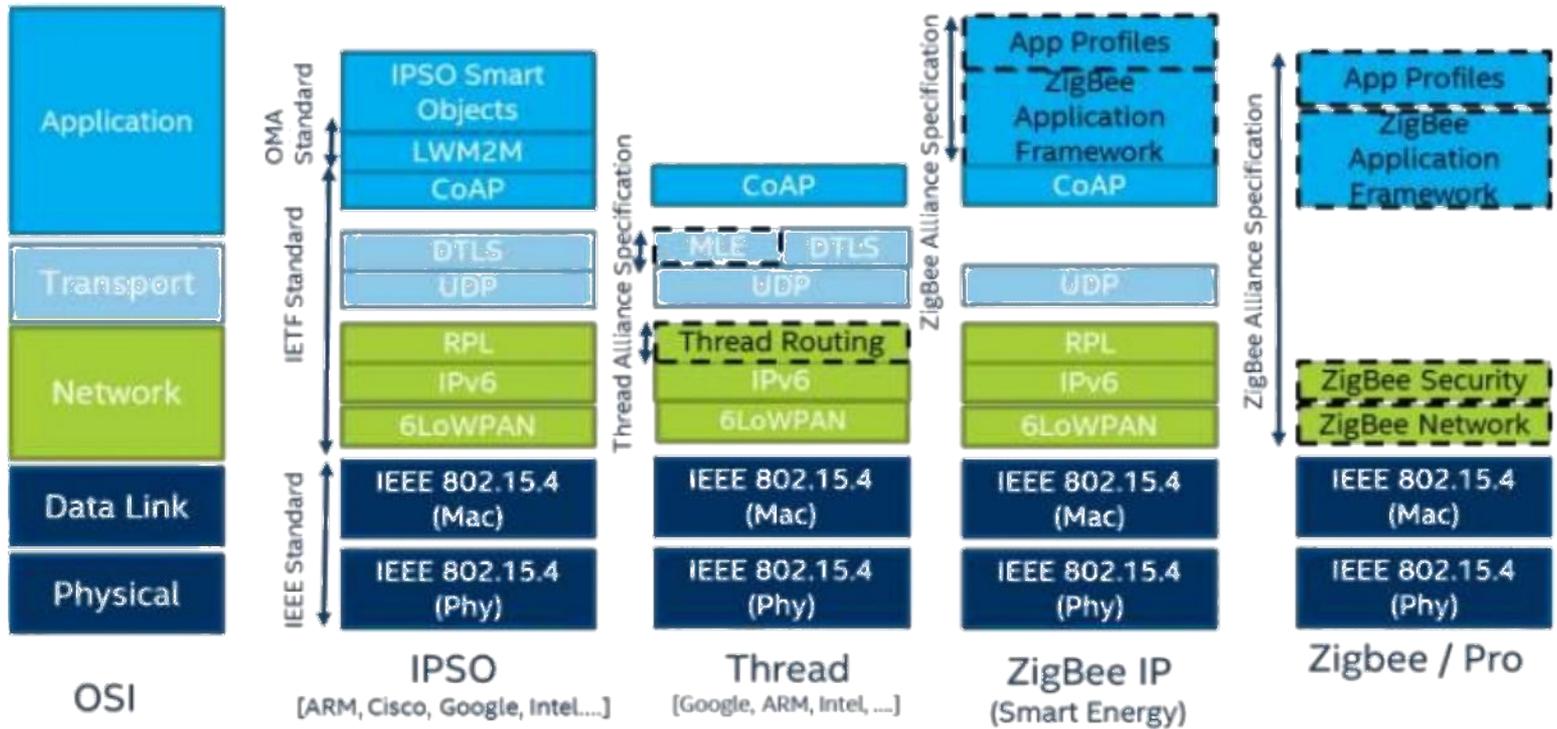
Star Topology



■ Ventajas & desventajas

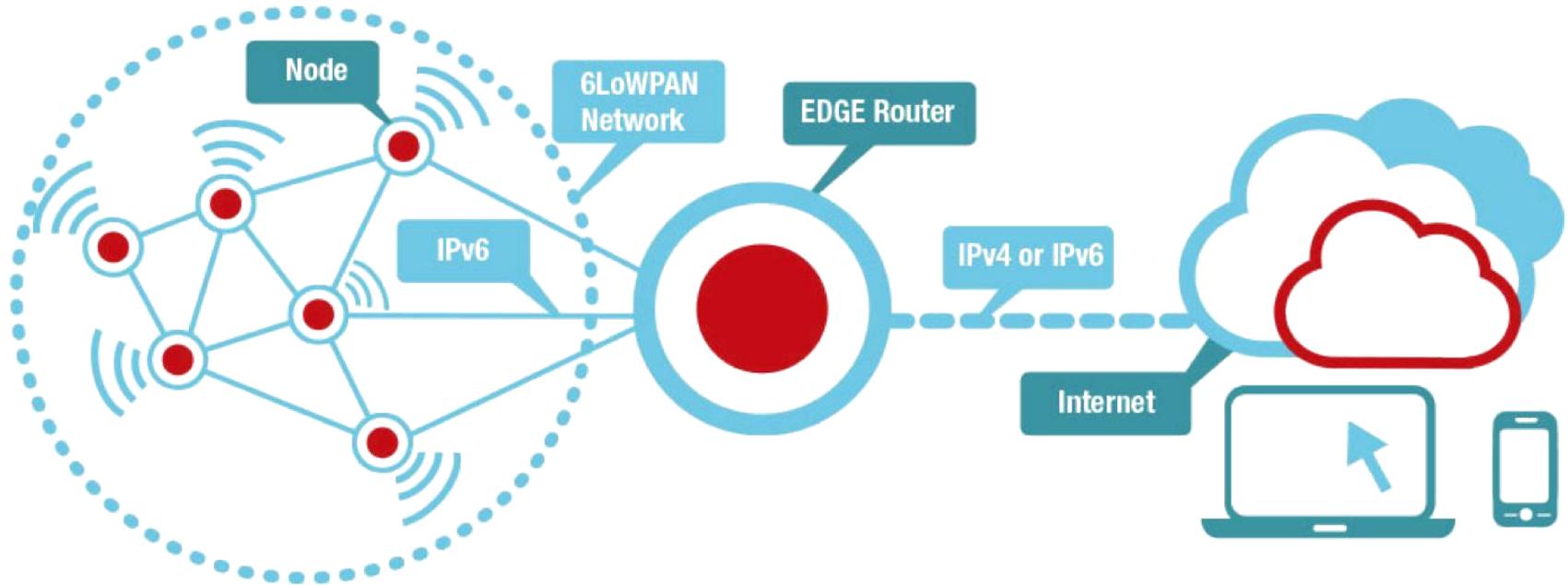


Introducción





Introducción





Agenda



- Introducción
- **IEEE 802.15.4**
 - PHY: capa física
 - MAC: acceso al medio
- 6LoWPAN
- RPL: capa de ruteo
- Conclusiones



IEEE Std 802.15.4™-2015



■ LR-WPAN (Low Rate WPAN) define:

- PHY: capa física
- MAC: subcapa de acceso al medio

■ versiones:

- 2003, 2006, 2011, 2015

■ Enmiendas:

- 802.15.4e-2012
- 802.15.4g-2012

■ vigentes:

- 802.15.4q-2016 (ULP PHY)

IEEE STANDARDS ASSOCIATION



**IEEE Standard for Low-Rate
Wireless Networks**

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 802.15.4™-2015
(Revision of
IEEE Std 802.15.4-2011)

IEEE GET Program





IEEE 802.15.4: 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.

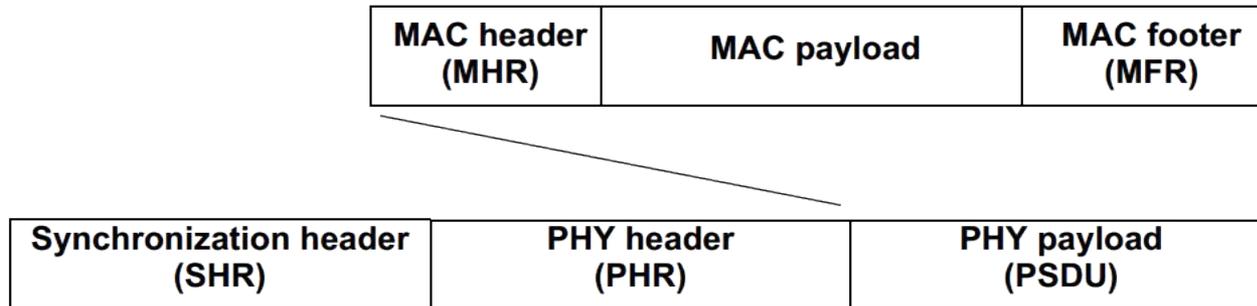


IEEE 802.15.4

- Canales y bandas
- Originalmente
 - frec. de los canales
 - num.
- limitado a 27 canales
- no había PHY o
- Ahora: channel pages
 - a partir de IEEE 802.15.4-2011
 - distinguir capas
- Channel pages:
 - 0: definido en 2006
 - 1: definido com

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) \Leftrightarrow MAC frame



MAC: caract. & desafíos



- Características del medio inalámbrico
 - Medio compartido:
 - NO Rx y Tx simultáneas
 - Interferencias:
 - Tx no sabe si el Rx recibió bien
 - Pérdida de paquetes:
 - dificultan la señalización
- Requerimientos
 - Usuales:
 - high throughput, low overhead, low error rates, ...
 - Se agrega:
 - energy-efficient → apagado de radio





MAC: clasificación clásica



- Protocolos basados en
 - Reserva
 - Contienda / disputa (contention)



Protocolos basados en reserva



- Idea básica
 - Cada nodo es asignado a un slot
 - Existe un *schedule* para acceder y comunicarse
- Ejemplos:
 - TDMA (Time-division multiple access)
- Ventajas
 - Evita colisiones
 - Latencia predecible
 - Throughput alto para tráfico alto (limitado indiv.)
 - Justo
- Desventajas
 - Necesidad de sincronización



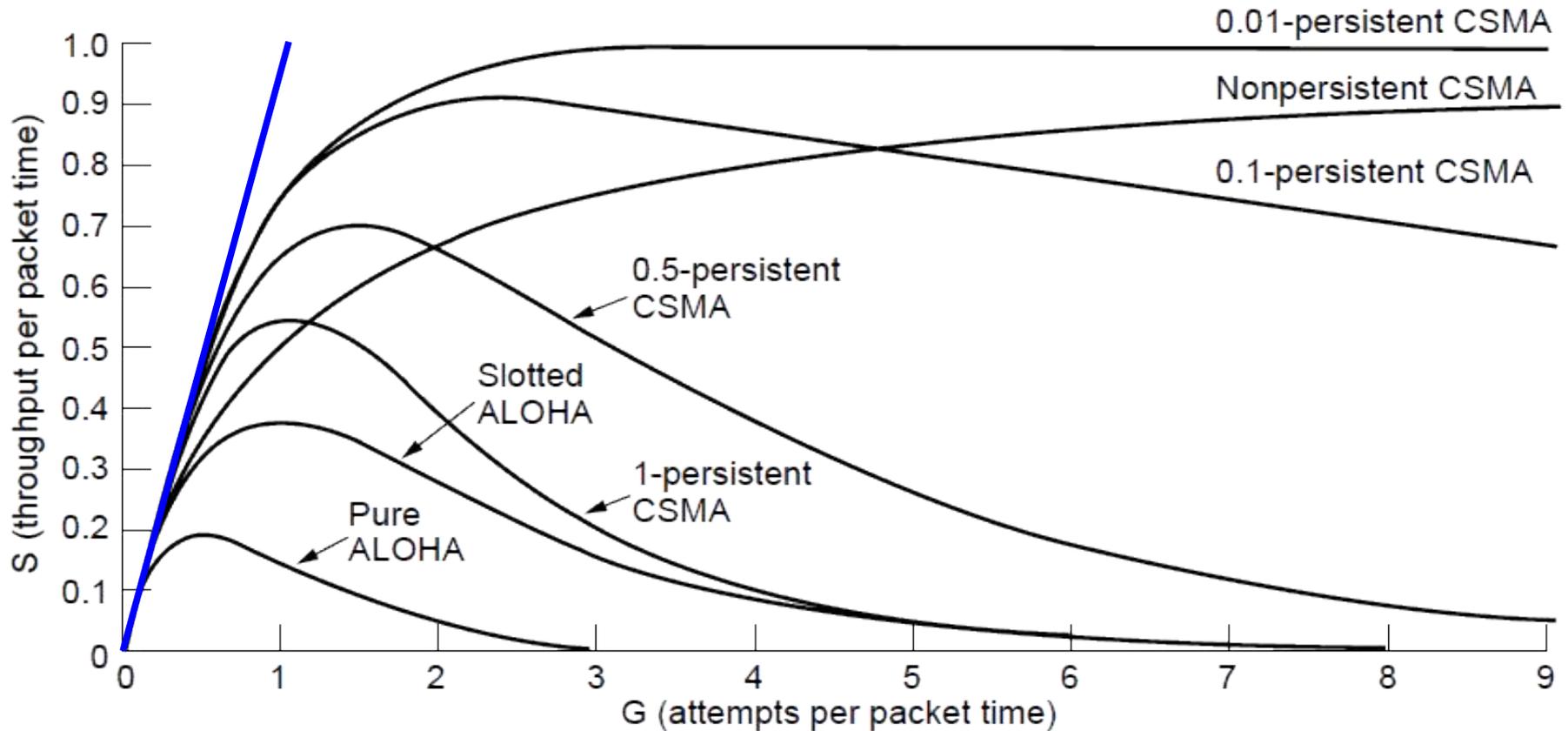
Protocolos basados en contienda



- Idea básica
 - Nodos compiten por el canal, ganador usa el canal para transmitir
- Ejemplos:
 - ALOHA, CSMA (slotted vs unslotted, 1 o p - persistente)
- Ventajas
 - Simple (no requiere sincronización)
 - Descentralizado
- Desventajas
 - Propenso a colisiones
 - Throughput decae si tráfico aumenta
 - Eficiencia (capacidad de canal)



Protocolos basados en contienda



Computer Networks, Fifth Edition by Andrew Tanenbaum and David Wetherall, © Pearson Education-Prentice Hall, 2011





MAC: consideraciones para IoT

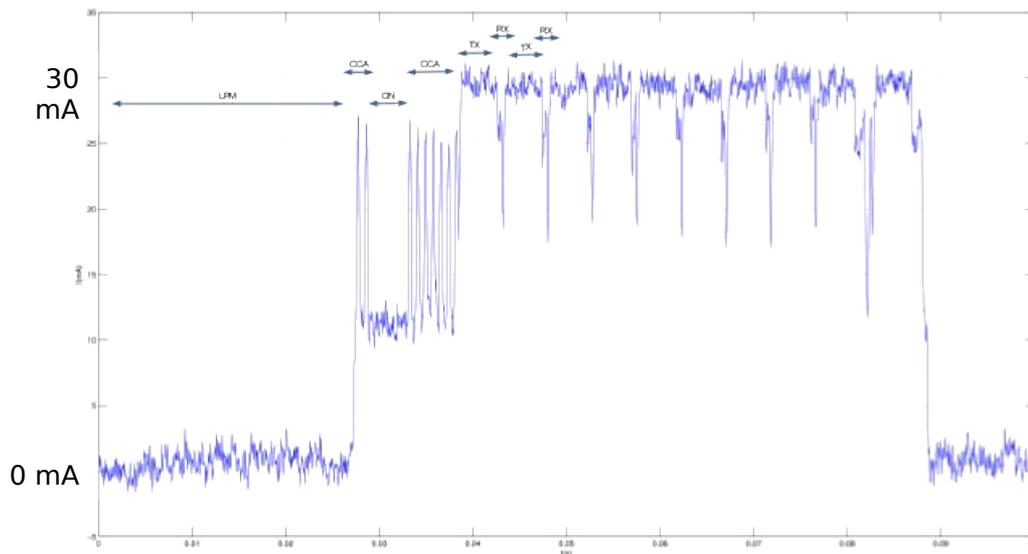
- Limitaciones
 - Energía
 - Memoria y capacidad de cómputo
- Requerimientos
 - Confiabilidad
 - Bajo tiempo de acceso (latencia)
 - Throughput
- En general:
 - foco en energía cuidando el resto



MAC: consumo de potencia



- Característica: nodos homogéneos
- Consumo de energía
 - Tx son “caras”
 - RX también
 - Escuchar menos, pero importante (CCA)



Ejemplo: 802.15.4, 2.4 GHz

State	$I_{avg}(mA)$
ON	11.23
TX	29.64
RX	24.17
CCA	21.64



MAC: consumo de energía



- Afectado por:
 - Colisiones
 - Overhearing (escuchar sin querer)
 - Idle listening (inútil, improductiva)
 - Protocol overhead
- Siempre es mejor:
 - solución sencilla



IEEE 802.15.4 MAC: opciones



- Estructuras de “super” frames
 - Beacon superframe (Zigbee)
 - Slotframes (6tisch/WirelessHART/ISA100.11a)
 - DSME multi-superframe (Wi-SUN)
 - Sin beacon/superframe
- Modos de acceso
 - CSL
 - TSCH



MAC: Estuctura super frames



■ Beacon superframe

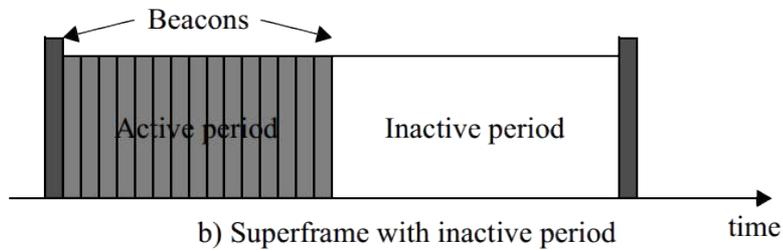
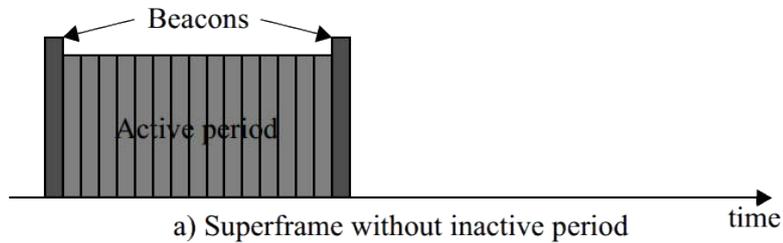


Figure 5-5—Superframe structure

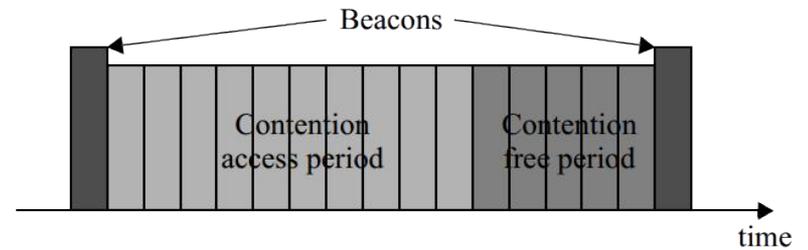


Figure 5-6—Structure of the active periods with GTSs



MAC: Estructura super frames



■ Slotframes

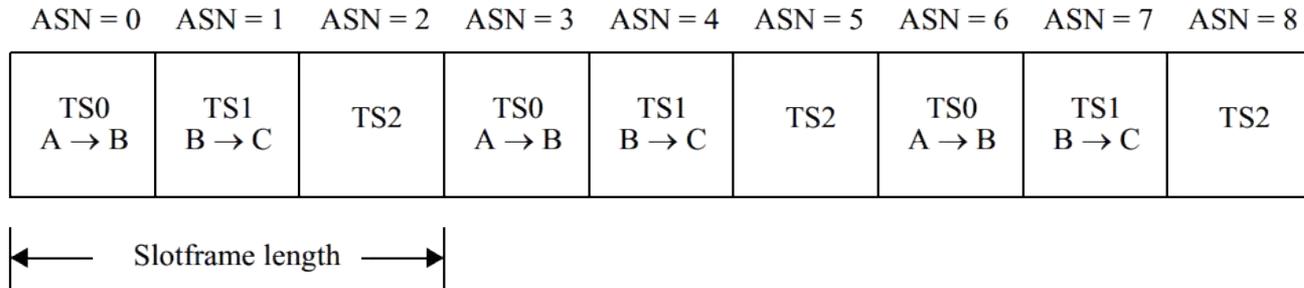


Figure 6-9—Example of a three time-slot slotframe



MAC: Estructura super frames



■ DSME multi-superframe

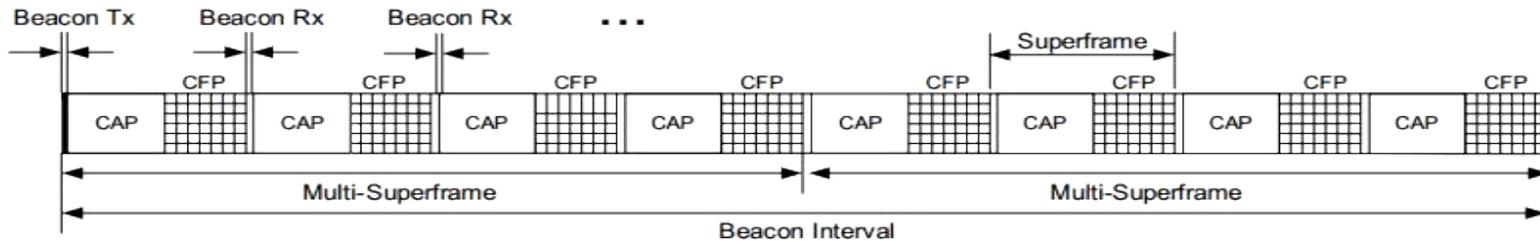
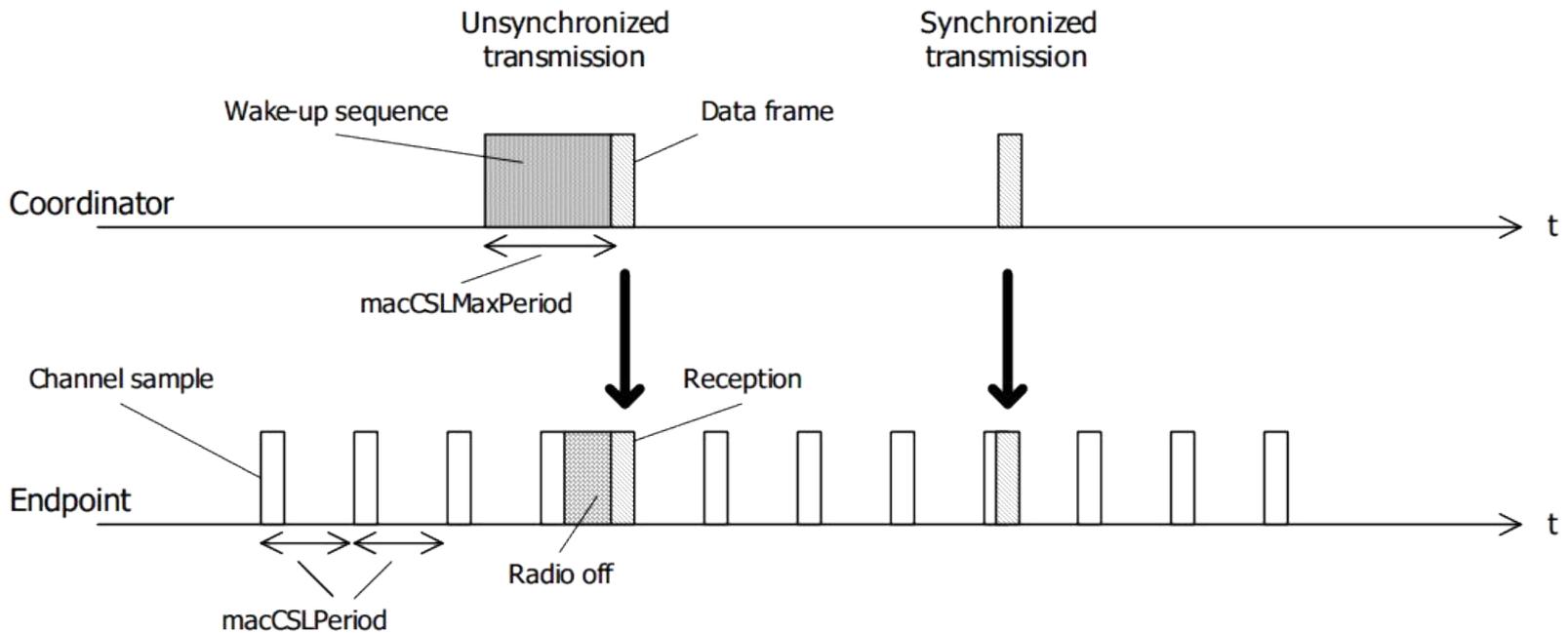


Figure 5-7—General DSME Multi-superframe Structure

■ Sin beacon/superframe

IEEE 802.15.4e- 2012

- Nuevos modos de acceso:
 - Coordinated Sampled Listing (CSL)





IEEE 802.15.4e- 2012



- Nuevos modos de acceso:
 - TSCH
- ¿Qué es?
 - Técnica de acceso al medio que usa:
 - TS (Time-Slotted): sincronización
 - CH (Channel Hopping): saltos de canal
- Objetivo
 - Bajo consumo (apagado de radio)
 - Mayor confiabilidad (diversidad de canales)



TSCH: motivación

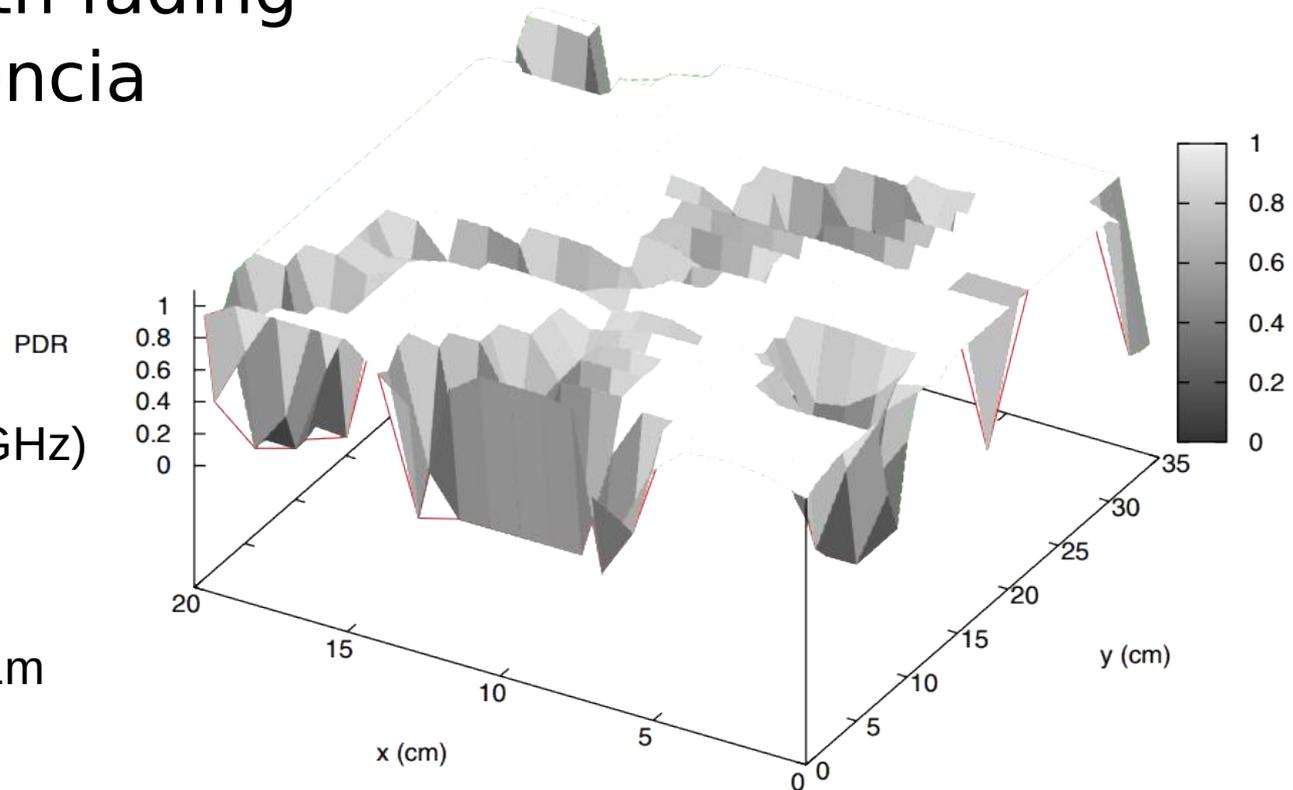


■ Problema

- Multi-path fading
- Interferencia

Experimento

- IEEE 802.15.4 (2.4 GHz)
- canal 20
- $P_{TX} = -16\text{dBm}$
- Tx y RX separados 1m



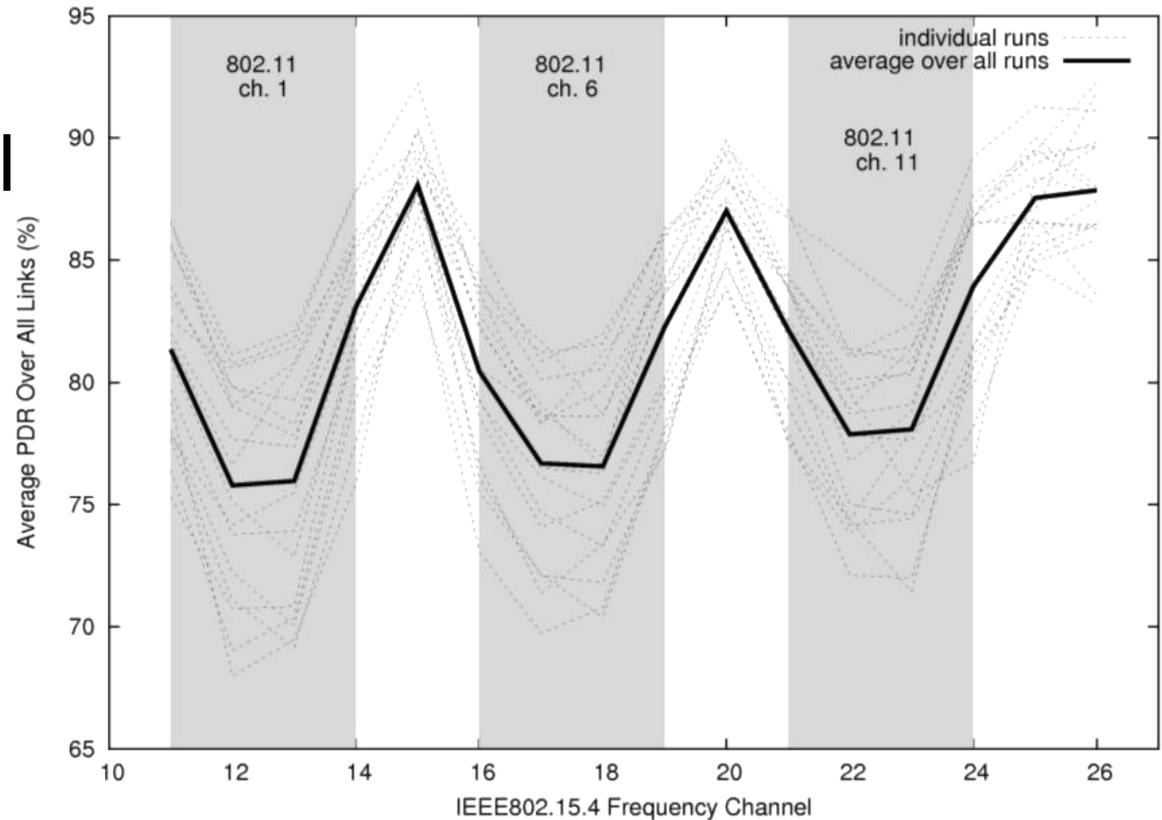
T. Watteyne, S. Lanzisera, A. Mehta, and K. S. J. Pister, "Mitigating multipath fading through channel hopping in wireless sensor networks," in 2010 IEEE International Conference on Communications, May 2010, pp. 1-5.



TSCH: motivación



- Solución:
salto de canal



- Soluciones previas:
 - WirelesHART / ISA100.11



TSCH: observaciones



- Define
 - Mecanismo MAC
 - NO altera capa física (sirven “viejas radios”)
- No define
 - Política para crear y mantener agenda de comunicación (schedule)
 - Cómo se asignan time slots y canales
- Logical Link Control (LLC)
 - Entidad funcional que define “schedule”
 - Tipos:
 - Protocolo distribuido
 - Servidor centralizado



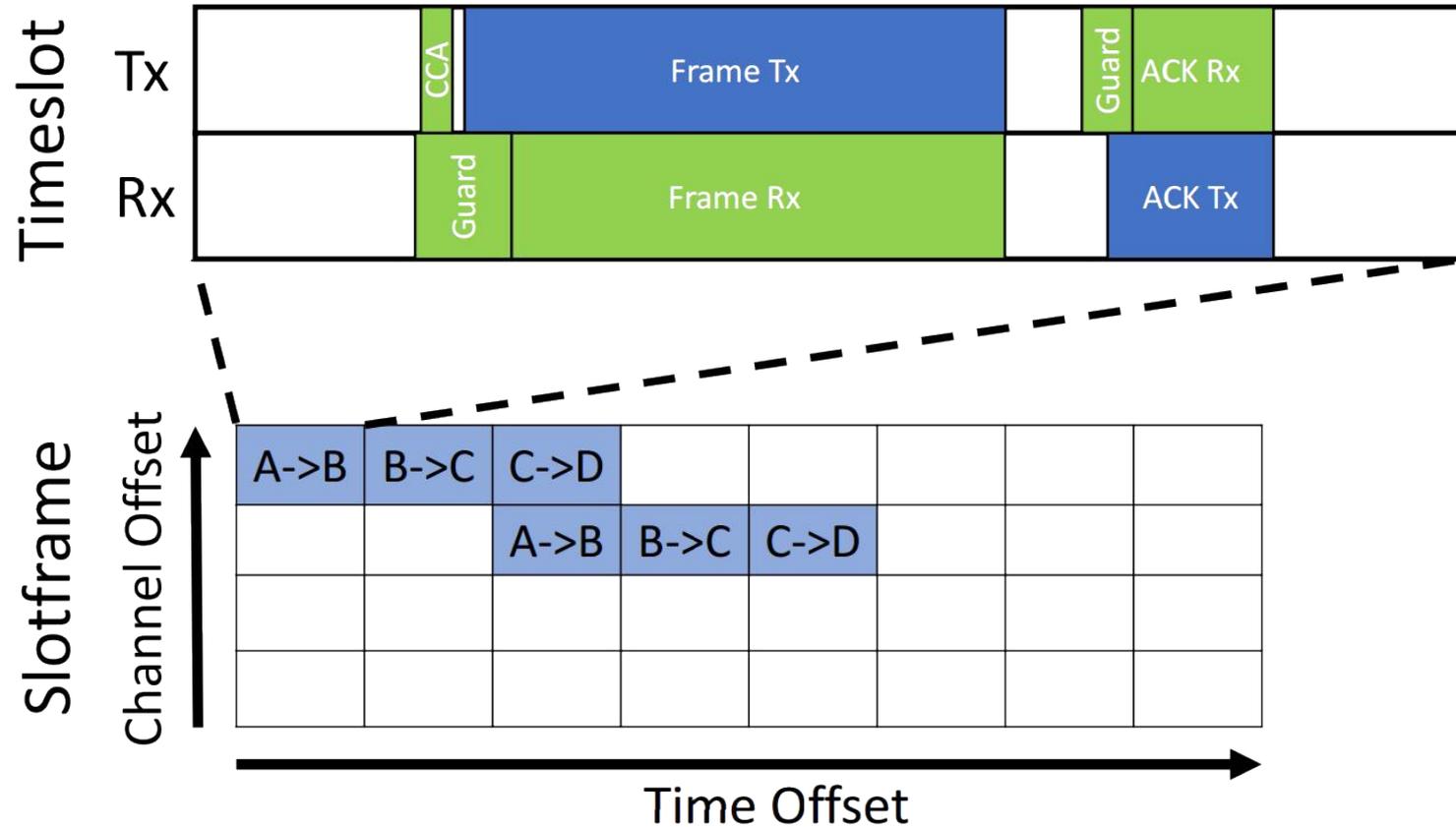
TSCH: conceptos



- Time Slots: tiempo se divide en time slots
 - Duración suficiente para enviar un marco MAC y recibir ACK
 - Típica: 10 ms slot
- Noción común del tiempo
 - ASN (Absolute Slot Number)
- Slotframes: grupos de uno o más time slots
 - Se repite a través del tiempo



TSCH: conceptos

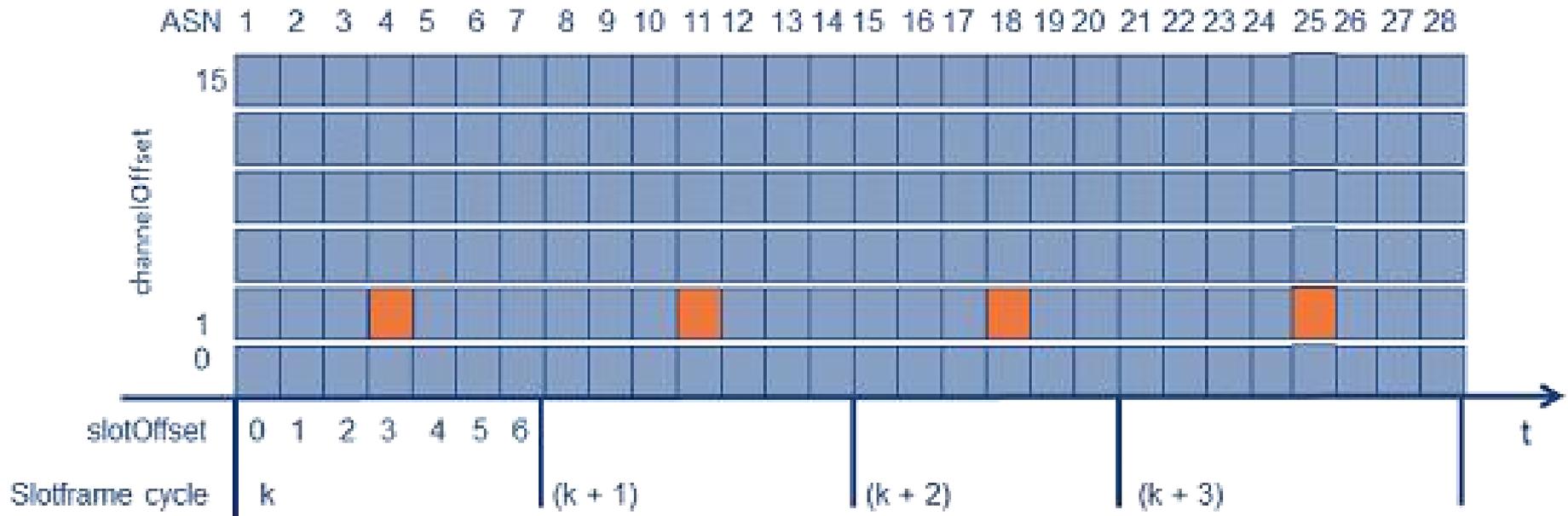


S. Duquennoy, A. Elsts, B. Al Nahas, and G. Oikonomou, "TSCH and 6TiSCH for contiki: Challenges, design and evaluation," in International Conference on Distributed Computing in Sensor Systems (IEEE DCOSS), 2017.





TSCH: conceptos



$$F(x)=x+11$$

$$\begin{aligned} f_{ch} &= F([4 + 1] \text{ mod } 16) \\ f_{ch} &= F(5) = 11 + 5 = 16 \\ f_{ch} &= 16 \end{aligned}$$

C. M. García Algora, V. Alfonso Reguera, and K. Steenhaut, "Evaluación experimental del protocolo IEEE 802.15.4 TSCH en una red 6TiSCH," Ingeniería Electrónica, Automática y Comunicaciones, vol. 39, pp. 70-78, 2018.



TSCH: schedule



■ Minimal configuration

- IETF RFC 8180

Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration



■ Orchestra

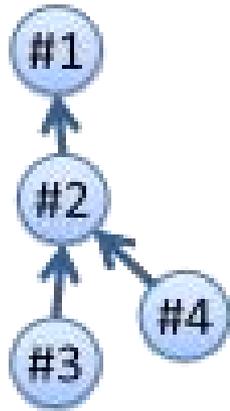
- S. Duquennoy, et al. "Orchestra: Robust mesh networks through autonomously scheduled TSCH," in ACM SenSys 2015), vol. 93.

- IETF draft

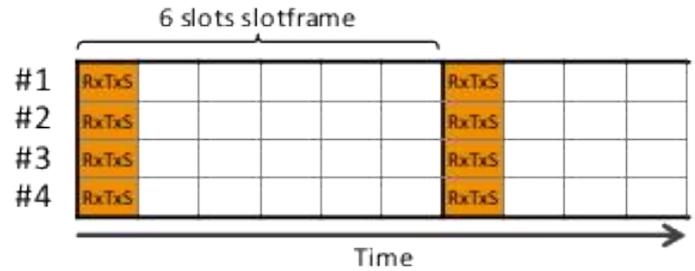
6TiSCH Autonomous Scheduling Function (ASF)



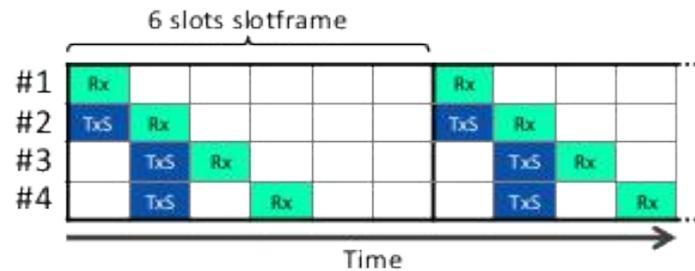
TSCH: Orchestra



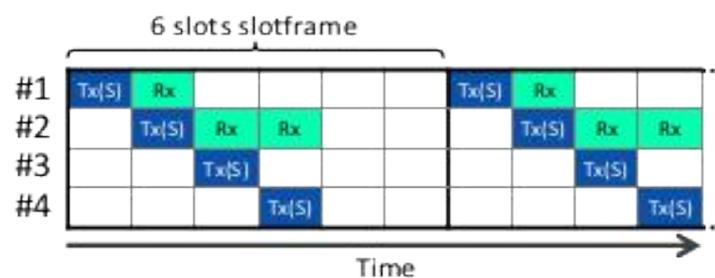
(a) Topology



(b) Common Shared Slot



(c) Receiver-based Shared Slot

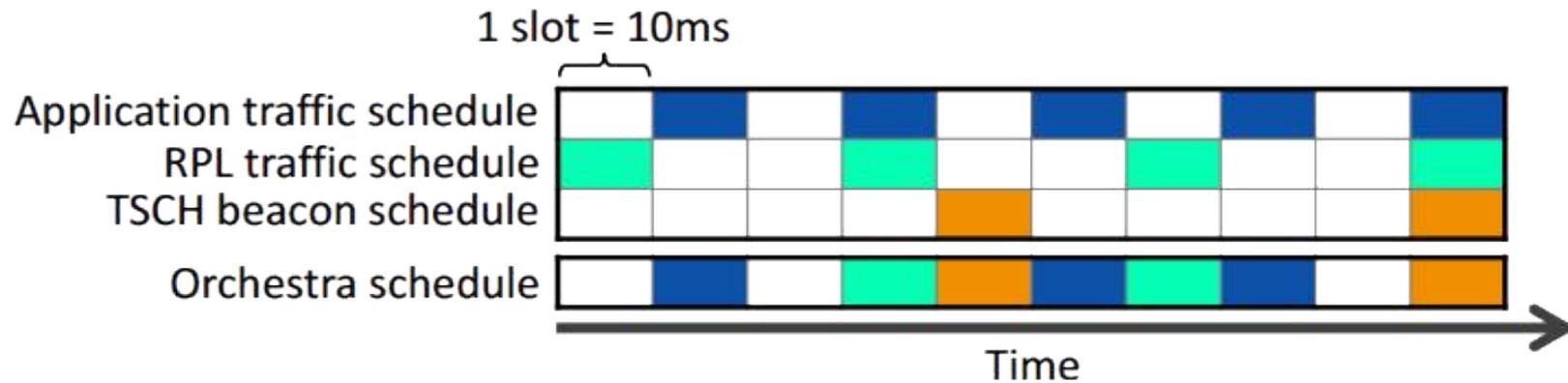


(d) Sender-based (Shared) Slot





TSCH: Orchestra





Agenda



- Introducción
- IEEE 802.15.4
 - PHY: capa física
 - MAC: acceso al medio
- **6LoWPAN**
- RPL: capa de ruteo
- Conclusiones



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



← → ↻ 🏠 <https://tools.ietf.org/wg/6lowpan/>

6lowpan Status Pages *Int Area:* [Éric Vyncke](#), [Suresh Krishnan](#) | 2005-Mar-08 — 2014-Jan-16

IPv6 over Low power WPAN (Concluded WG) *Chairs:* [Carsten Bormann](#) [Geoffrey Mulligan](#)

[Drafts](#) | [Agendas](#) | [Minutes](#) | [Wiki](#) | [Training](#) | [Source](#) | [Charters](#) | [Jabber](#) | [Room Logs](#) | [List Archive](#) |

Working Group Documents: Document collections: [cpub](#) [mobi](#)

<u>Draft name</u>	<u>Rev.</u>	<u>Dated</u>	<u>Status</u>	<u>Comments, Issues</u>
Published:				
Draft name	Rev.	Dated	Status	Obsoleted by/(Updated by)
draft-ietf-6lowpan-format	-13	2007-04-04	RFC 4944	(RFC 6282 RFC 6775 RFC 8025 RFC 8066)
draft-ietf-6lowpan-hc	-15	2011-02-24	RFC 6282	(RFC 8066)
draft-ietf-6lowpan-nd	-21	2012-08-24	RFC 6775	(RFC 8505)
draft-ietf-6lowpan-problem	-08	2007-03-02	RFC 4919	
draft-ietf-6lowpan-routing-requirements	-10	2011-11-20	RFC 6606	
draft-ietf-6lowpan-usecases	-10	2011-07-26	RFC 6568	
Replaced, Dead or Unknown:				
draft-ietf-6lowpan-btle	-12	2013-02-12	Replaced by draft-ietf-6lo-btle	

Related Active Documents (not working group documents):

(To see all 6lowpan-related documents, go to [6lowpan-related drafts in the ID-archive](#))

[Draft dependency graphs](#)

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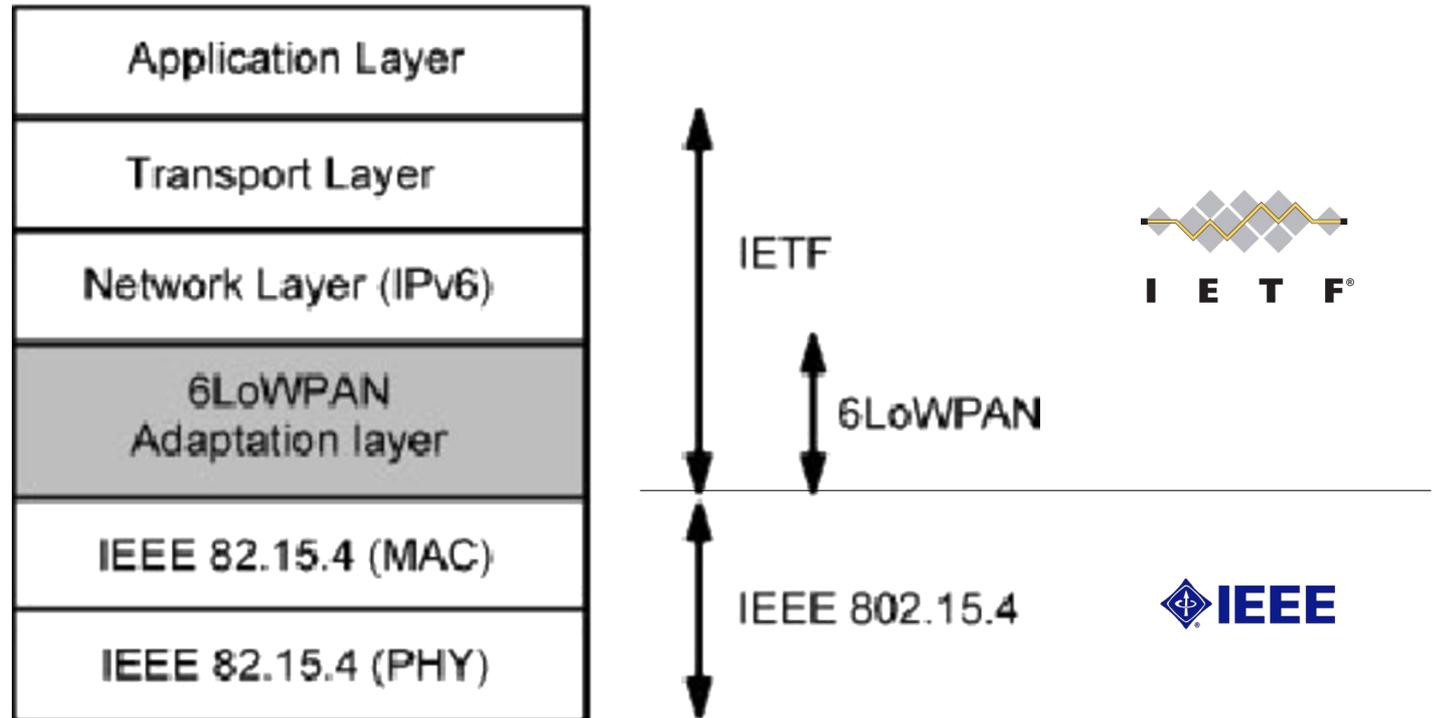
Areas

WGs:
[concluded...](#)
[6lo](#)
[6man*](#)
[6tisch](#)





6lowpan





IPv6 over Network of Resource-constrained Nodes



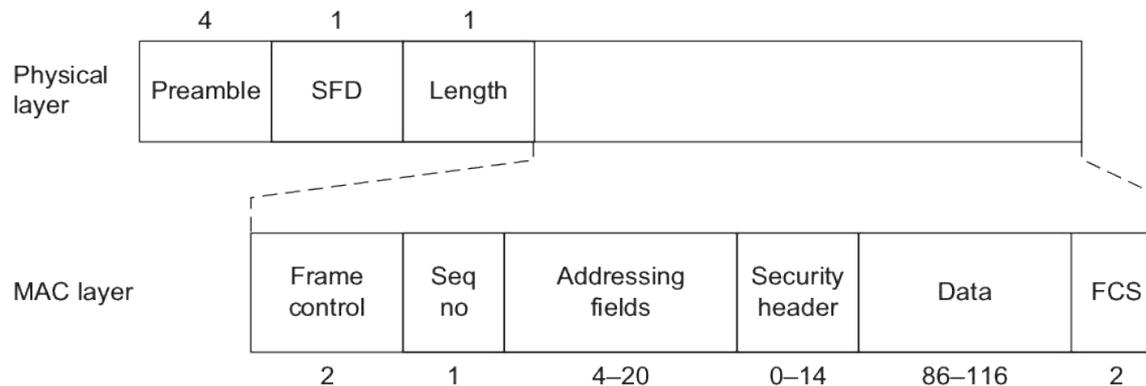
- 6lo: IETF Working Group (activo)
 - generaliza 6lowpan
- IPv6-over-foo adaptation layer specifications
 - RFC 8163: MS/TP Networks (RS-485)
 - RFC 7668: Bluetooth Low Energy
 - RFC 8105: DECT - ULE
 - RFC 7428: ITU-T G.9959 Networks



IEEE 802.15.4: características



- Frame pequeño: 127 bytes
 - PER razonablemente bajos para BER no despreciables
- Direcciones
 - 16-bit short / IEEE 64-bit extended MAC.
- Low data rates
 - Ej.: de 40 Kbps (915 MHz) a 250 Kbps (2.4 GHz)

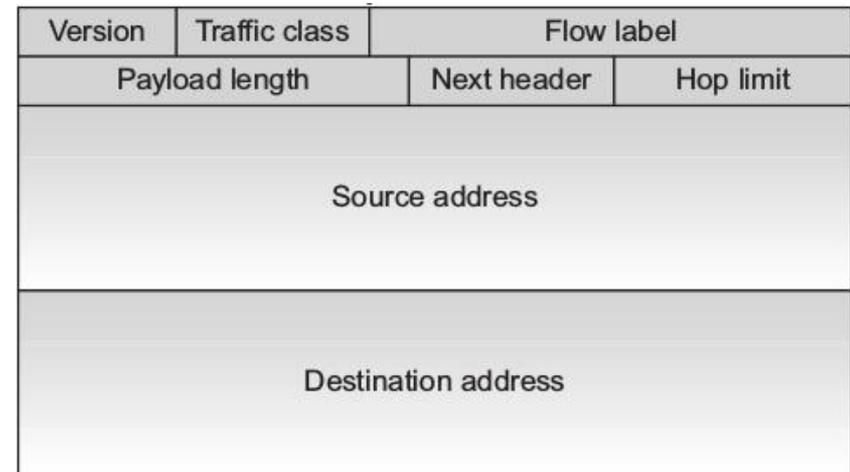




IPv6: características



- Paquete relativamente grande: 1280 bytes.
- Direcciones: 128 bits.
- IPv6 incluye multicast
 - Neighbor Discovery
 - link-local multicast para address resolution



duplicate address detection
router discovery.



IPv6 over LoWPAN: desafíos



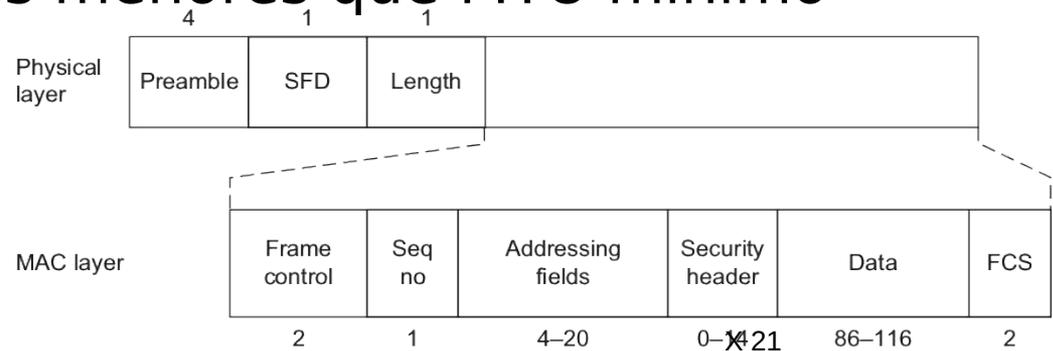
- Paquetes IPv6 en LoWPANs.
 - Bajo throughput
 - Buffers limitados
 - Frames ~10 veces menores que MTU mínimo

- Necesidad

- Fragmentación
- Compresión

- Ejemplo:

- Payload efectivo 81 bytes
- IPv6 header: 40 bytes
- UDP/TCP header: 8 / 20 bytes



$$127 - (2 + 1 + 20 + 2) = 102 \text{ bytes}$$

AES-CCM-128: 21 bytes extra



6LoWPAN: funciones



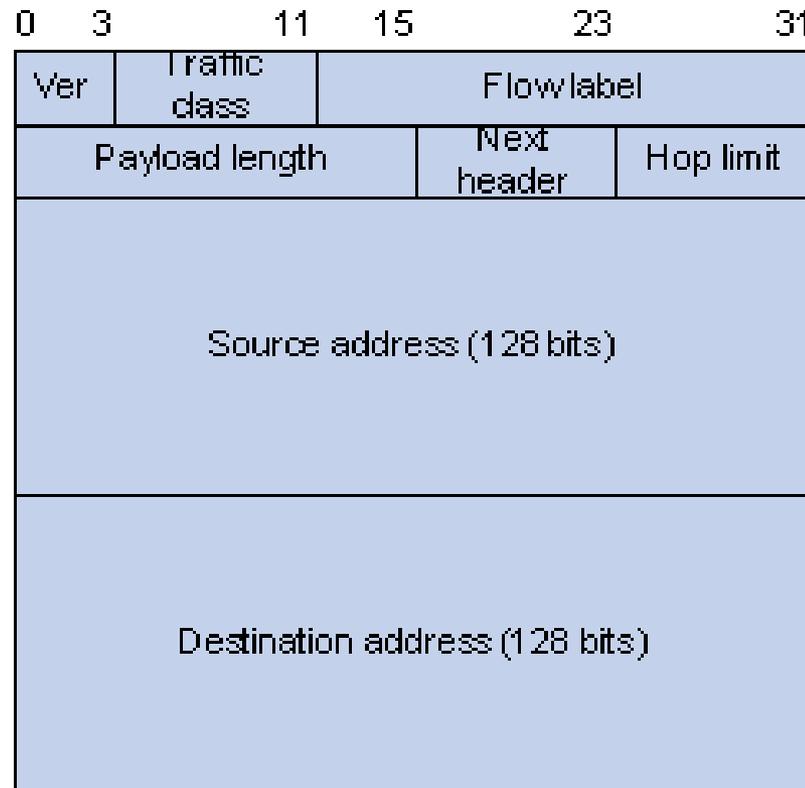
- Provee tres servicios:
 - Fragmentado y reensamblado de paquetes
 - Compresión de encabezados
 - Enrutamiento en capa 2 “mesh-under”
- IEEE 802.15.4 encapsula paquete IPv6
 - “encapsulation header stack” antes de cada paquete IPv6
 - cada encabezado se agrega si se necesita
 - dispatch byte (primer byte): identifica el next header de la pila.



6LoWPAN: técnicas



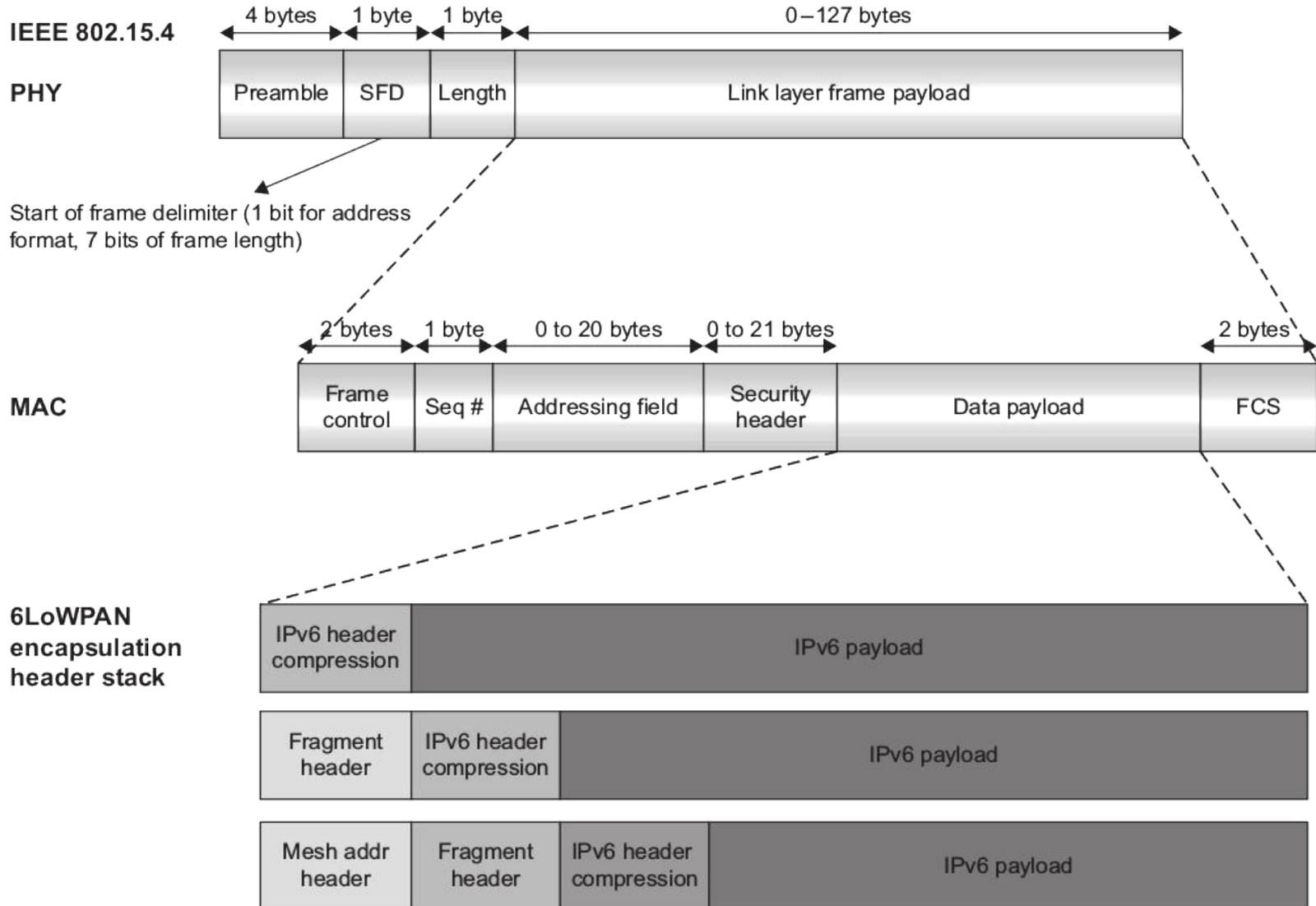
■ Ideas



Basic IPv6 header



6LoWPAN: encapsulado de IPv6

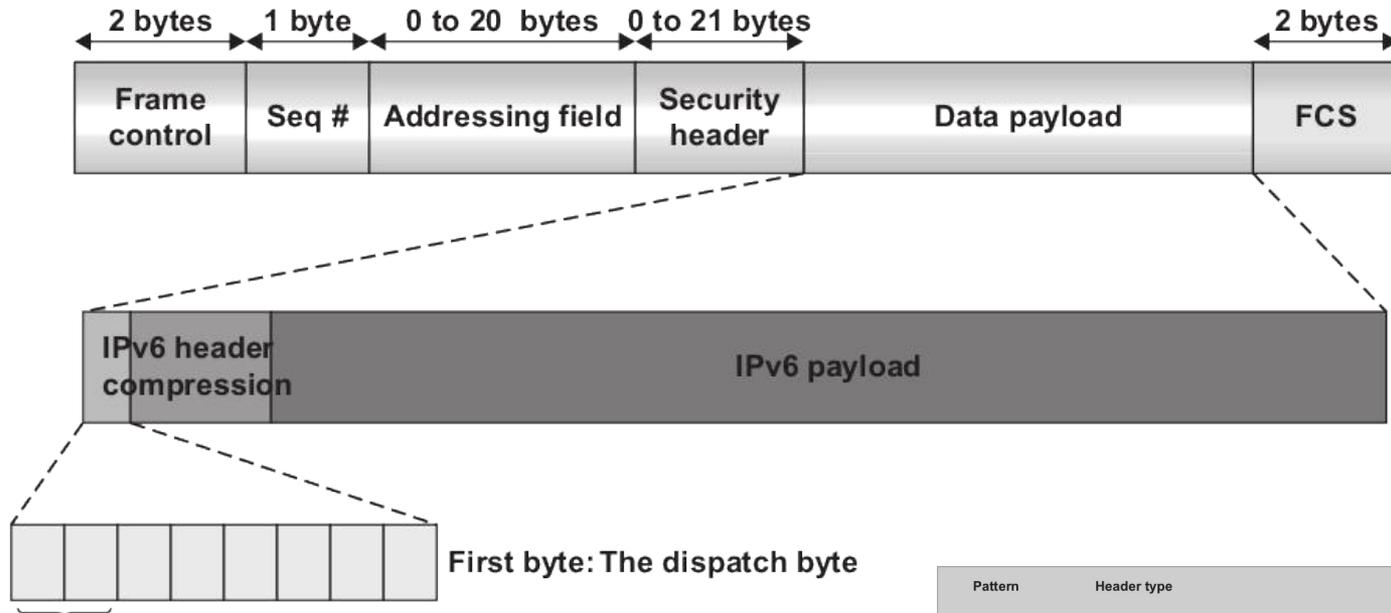




6LoWPAN: encapsulado de IPv6



The 6LoWPAN dispatch byte (first byte)



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: wireshark



File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help

Apply a display filter ... <Ctrl-/> Expression... +

No.	Time	Source	Destination	Length	Info	Protocol
1102	16:22:01.515068			5	Ack	IEEE 802.15.4
1103	16:22:01.518940	::212:7408:8:4	::212:7408:8:2	47	Payload Unk: 6, Bad FCS	SKYPE
1104	16:22:01.520857			5	Ack, Bad FCS	IEEE 802.15.4
1105	16:22:01.538668	00:12:74:08:00:00:03	00:12:74:08:00:00:02	120	Data, Dst: NitLab_08:00:08:00:02, Src: NitLab_08:00:08:00:03, Bad FCS	6LoWPAN
1106	16:22:01.544497	00:12:74:08:00:00:03	00:12:74:08:00:00:02	120	Data, Dst: NitLab_08:00:08:00:02, Src: NitLab_08:00:08:00:03, Bad FCS	6LoWPAN
1107	16:22:01.549318	00:12:74:08:00:00:03	00:12:74:08:00:00:02	120	Data, Dst: NitLab_08:00:08:00:02, Src: NitLab_08:00:08:00:03, Bad FCS	6LoWPAN

Frame 1105: 120 bytes on wire (960 bits), 120 bytes captured (960 bits)

IEEE 802.15.4 Data, Dst: NitLab_08:00:08:00:02, Src: NitLab_08:00:08:00:03, Bad FCS

6LoWPAN

- Fragmentation Header
 - 1100 0... = Pattern: First fragment (0x18)
 - Datagram size: 147
 - Datagram tag: 0x0000
- IPHC Header
 - 011 = Pattern: IP header compression (0x03)
 - ...1 1... .. = Traffic class and flow label: Version, traffic class, and flow label compressed (0x3)
 -0. = Next header: Inline
 -00 = Hop limit: Inline (0x0)
 -1. = Context identifier extension: True
 -1. = Source address compression: Stateful
 -01 = Source address mode: 64-bits inline (0x0001)
 -0. = Multicast address compression: False
 -1. = Destination address compression: Stateful
 -11 = Destination address mode: Compressed (0x0003)
 - 0000 = Source context identifier: 0x0
 - ...0000 = Destination context identifier: 0x0
 - Next header: IPv6 Hop-by-Hop Option (0x00)
 - Hop limit: 63
 - Source: ::212:7408:8:4
 - Destination: ::212:7408:8:2
 - Reassembled in: 1119
- Data (120 bytes)
 - Data: 60000000006b003f0000000000000000212740800080004...
 - [Length: 120]

```

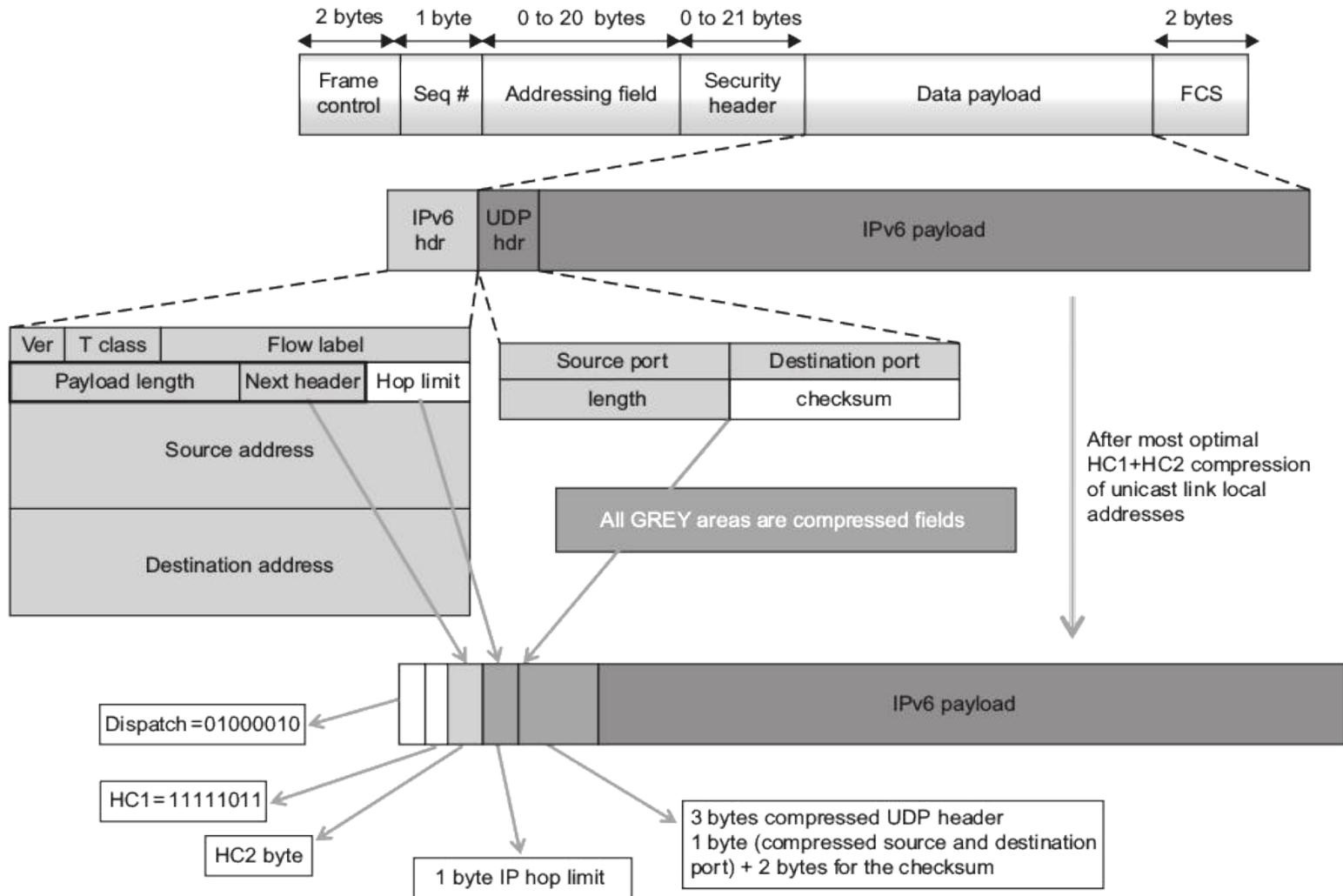
0000 71 dc b6 cd ab 02 00 08 00 08 74 12 00 03 00 08 q.....t....
0010 00 08 74 12 00 03 00 00 78 d7 00 00 3f 02 12 .t...x...?..
0020 74 08 00 08 00 04 11 00 63 04 00 1e 02 50 04 57 t.....c...Y.W
0030 04 57 00 63 2f ce 4c 61 62 20 52 53 49 20 32 30 W.c/La b RSI 20
0040 31 36 2e 2e 2e 2e 2e 2e 2e 33 30 31 32 33 34 35 16.....3012345
0050 36 37 38 39 34 31 32 33 34 35 36 37 38 39 35 31 67894123 45678951
0060 32 33 34 35 36 37 38 39 36 31 32 33 34 35 36 37 23456789 61234567
0070 38 39 37 31 32 33 bc 07 897123 ..

```





6LoWPAN: compesión



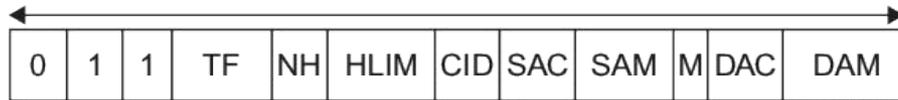


6LoWPAN: compesión



Example of IPHC + NHC for extended IPv6 option (fragment) and for UDP compression

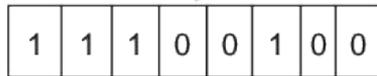
IPHC bytes (now includes dispatch)



=1



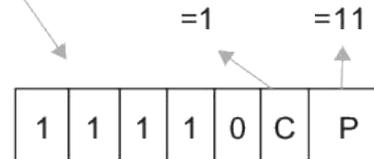
In-line (uncompressed) IPv6 header fields



In-line IPv6 fragment header fields

4-bit field for the UDP source port followed a 4-bit field for the UDP destination port.

NHC byte (NHC ID = 1110: extended header) extended header = fragment header (EID=2 (010))



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.

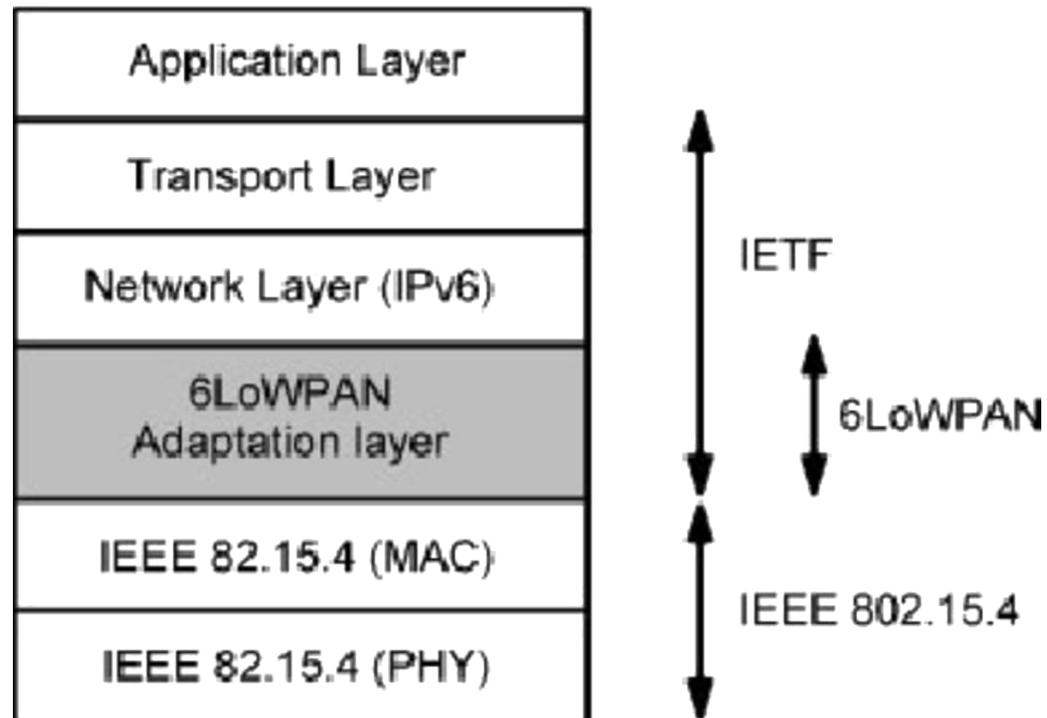




6LoWPAN



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





Agenda



- Introducción
- IEEE 802.15.4
 - PHY: capa física
 - MAC: acceso al medio
- 6LoWPAN
- RPL: capa de ruteo
- Conclusiones



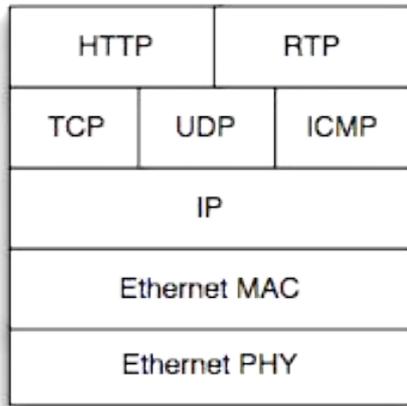
Capa de red



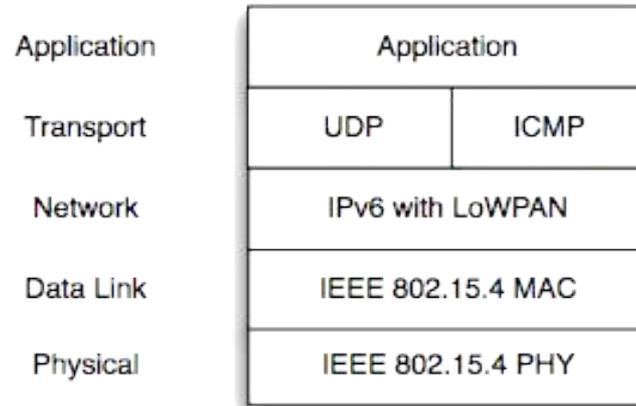
■ Funciones:

- responsable de reenvío de paquetes de otros

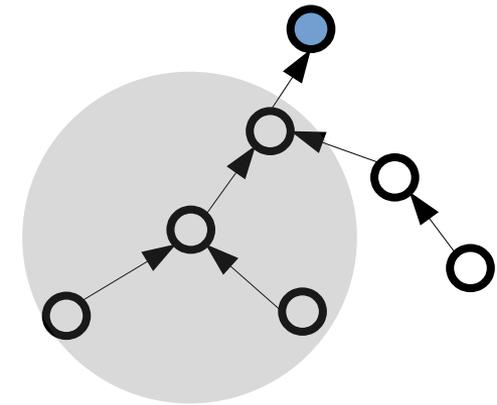
TCP/IP Protocol Stack



6LoWPAN Protocol Stack



MESH





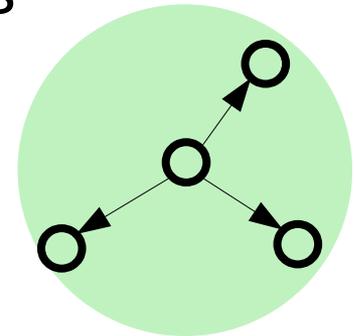
Capa de red



- Premisas: tipo frames (enlace de datos)

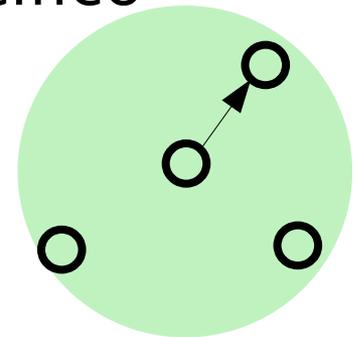
- broadcast:

- recibidos por todos nodos vecinos



- unicast

- mensaje dirigido a un nodo específico





Capa de red: tipos de ruteo

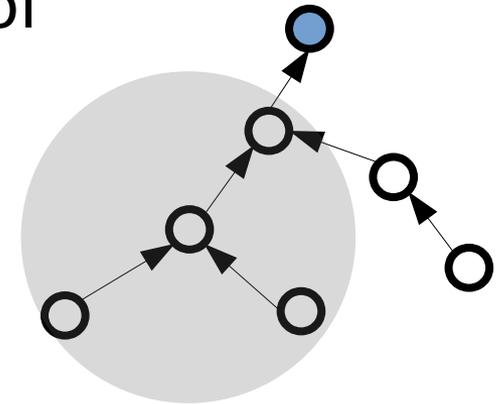


■ Reactivo:

- busca rutas cuando se necesitan
- Ejemplos:
 - AODV: Ad hoc On Demand Distance Vector
 - DSR: Dynamic Source Routing
 - FCP: Flexible Control Protocol

■ Proactivo:

- rutas disponibles al momento de mandar datos

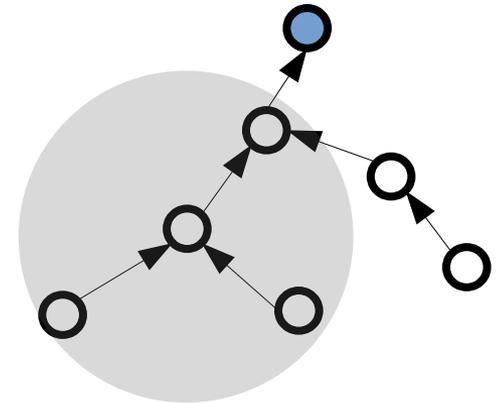




Capa de red: RPL



- RPL: Routing Protocol for Low power and lossy networks
 - Protocolo de ruteo para LLN sobre IPv6
 - Medio físico: 802.15.4 u otros
 - Proactivo:
 - basado en vector distancia
 - Topología tipo "árbol":
 - construye grafo (distribuidamente)
 - Trafico en direcciones "up" y "down"
 - Selección de padres basado en función objetivo





Capa de red: RPL



- IP separa (arquitectura)
 - procesado y reenvío de paquetes
 - encaminar paquetes en base a la tabla de ruteo
 - objetivo de optimización de ruteo
 - completar y mantener tabla de ruteo
- RPL: protocolo por vector distancia genérico
 - Función objetivo (OF)
 - combinación de métricas y restricciones para computar el "mejor camino".
 - permite adaptarlo a variedad de tipos de red

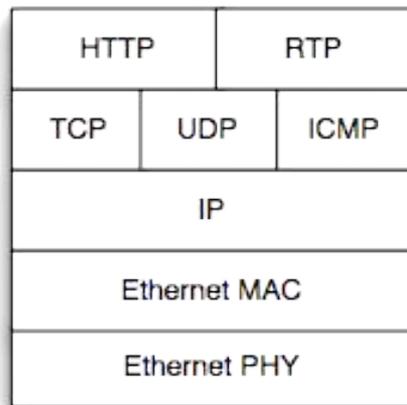


Capa de transporte



- Servicios disponibles
 - UDP datagrama a {dirección, puerto}
 - TCP conexión a {dirección, puerto}
- Diferencias entre UDP y TCP

TCP/IP Protocol Stack



Application

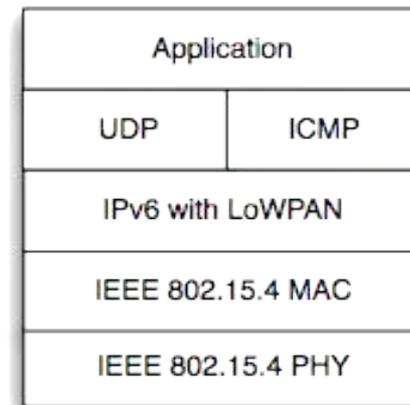
Transport

Network

Data Link

Physical

6LoWPAN Protocol Stack





Capa de aplicación



- clase más adelante



Gracias!