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IEEE 802.15.4 TSCH MAC Protocol and Channel Hopping Sequence algorithm

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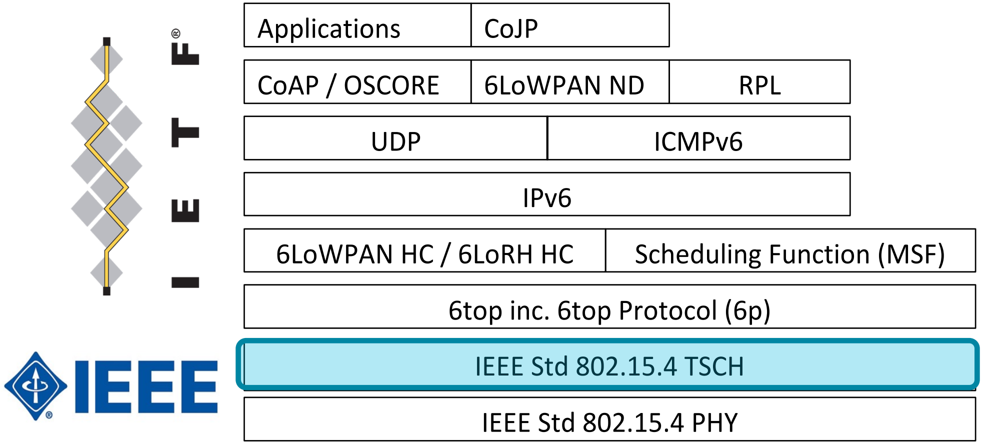
Overview



The **6TiSCH** Protocol Stack

- ✓ **TS**CH: Time-Slotted (synchronized), allows both distributed and centralized implementations.
- ✓ TS**CH**: Channel Hopping, to give resilience to interference and multi-path fadings.

Timeline

- 2006: TSCH approach emerges in the proprietary *Time Synchronized Mesh Protocol* (TSMP)
- 2008: TSMP is standardized in ISA100.11a
  - The IEEE 802.15.4e Working group is created:

    Issue: IEEE 802.15.4-2006 MAC is ill-suited for low-power multi-hop network because of

    (i) high energy consumption due to relay/router nodes

    (ii) use of a single channel that implies interference and multi-path fading

    Final aim: to redesign the existing IEEE 802.15.4-2006 MAC Std. and make it suitable for low-power multi-hop networks in industrial applications

- 2009: TSMP is standardized in WirelessHART
- 2010: Part of IEEE 802.15.4e draft
- 2011: IEEE802.15.4e draft in Sponsor Ballot (opened on 27 July 2011 and closed on 28 August with 96% of votes being affirmative)
- 2012: IEEE802.15.4e TSCH published
- 2016: IEEE802.15.4-2015-TSCH published

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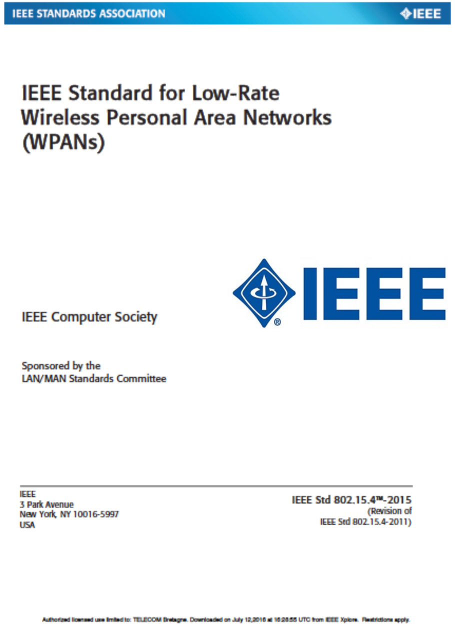

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IEEE Std 802.15.4™-2015
(Revision of
IEEE Std 802.15.4-2011)

IEEE 802.15.4-2015 TSCH:

- Targets low-**power**, low-**data-rate**, and low-**cost** **wireless meshes**.

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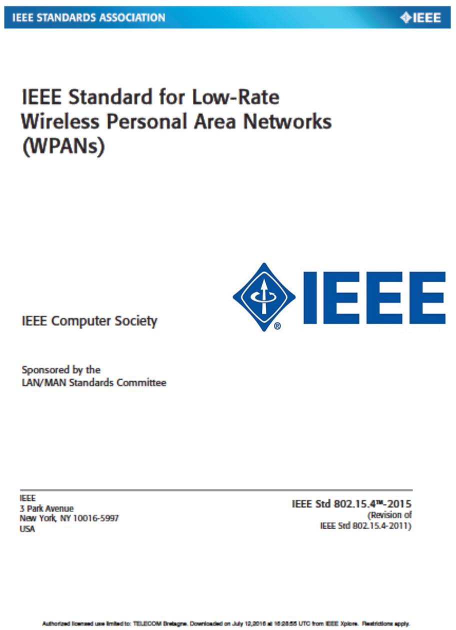
- Time-Slotted Channel Hopping (**TSCH**) **was added** in the **2015 revision** of the IEEE 802.15.4 standard.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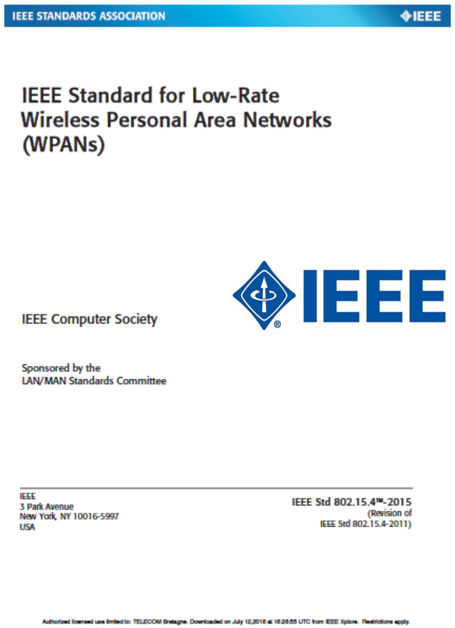
- TSCH is designed for ***reliable and deterministic communication***.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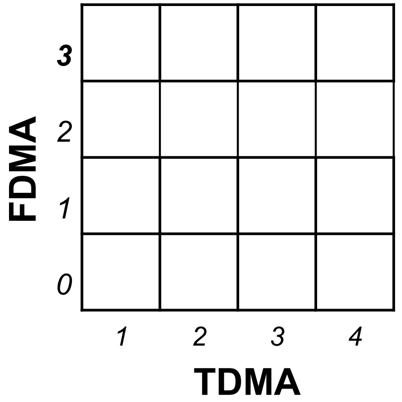
- Time-Slotted Channel Hopping (TSCH) was added in the 2015 revision of the IEEE 802.15.4 standard.
- TSCH is designed for ***reliable and deterministic communication***, and for ***low-power operation***.

By enabling long radio sleep intervals, the low-power operation is to guaranteed.

It is a combination of **time-division** and **frequency-division multiple access**

IEEE 802.15.4-2015 TSCH:

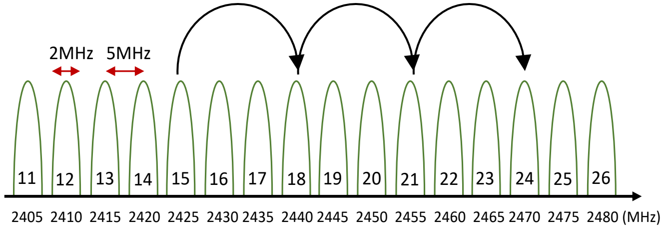
- Time Division Multiple Access (TDMA)
- Frequency Division Multiple Access (FDMA)



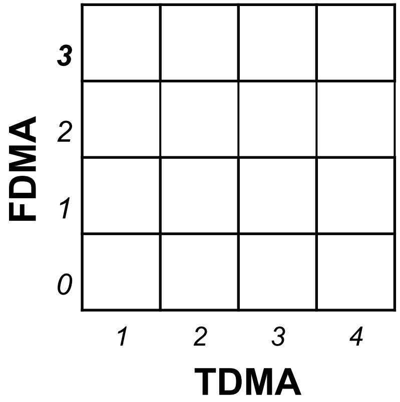
IEEE 802.15.4-2015 TSCH:

It is a combination of **time-division** and **frequency-division multiple access** in conjunction with a **radio channel hopping** technique.

- ► Time Division Multiple Access (TDMA)
- ► Frequency Division Multiple Access (FDMA)
- ► Radio Channel Hopping technique



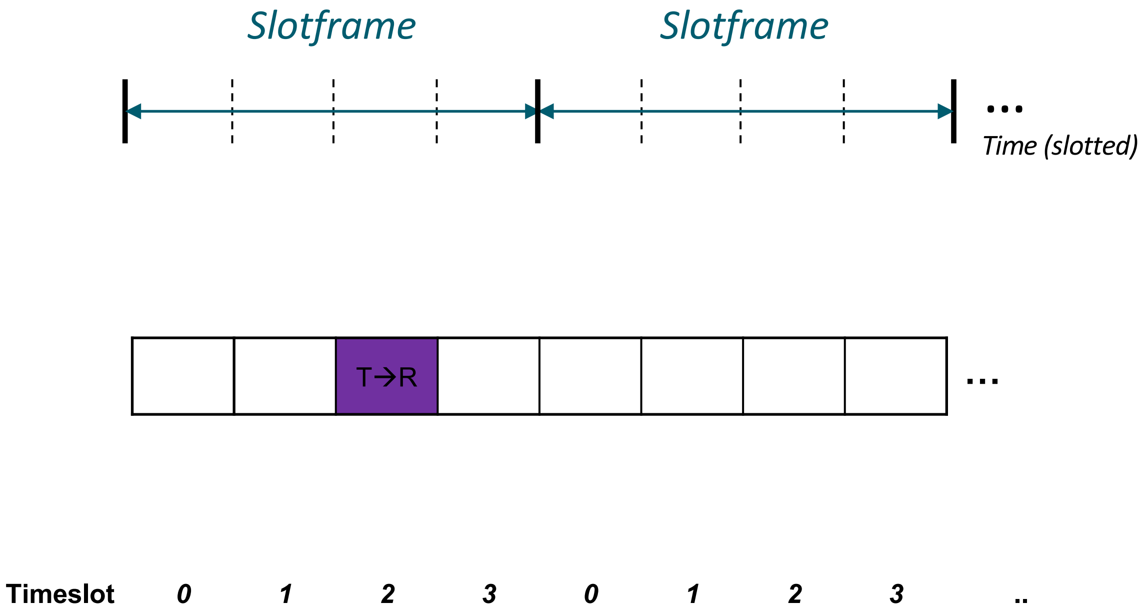
The 16 radio channels in 2.4 GHz band.



A Timeslot and a Slotframe

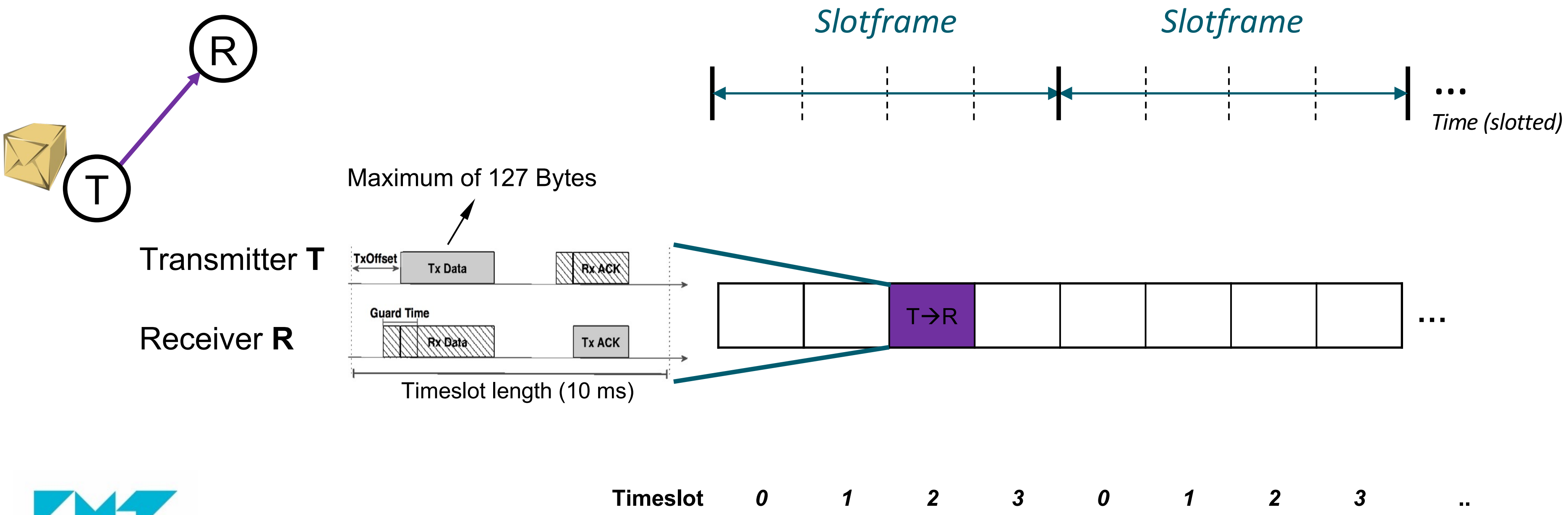
In a TSCH network, the continuous time is divided into timeslots of equal length.

A Timeslot and a Slotframe



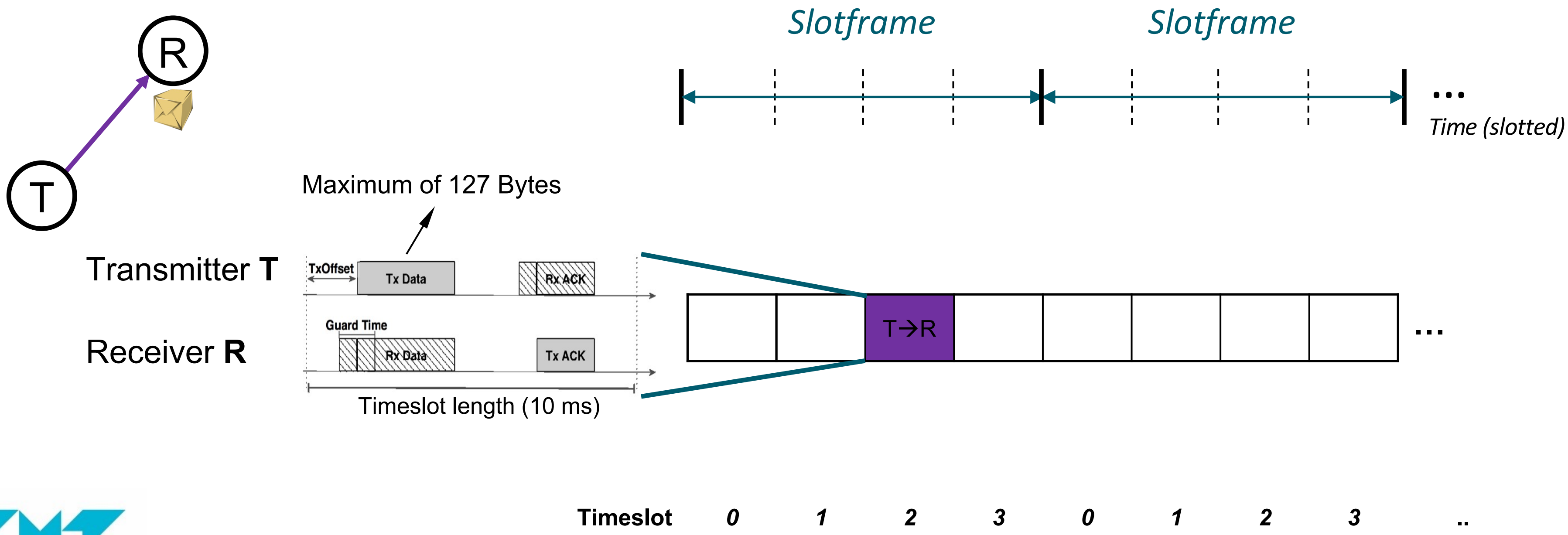
Then, a set of timeslots are grouped into a Slotframe structure that repeats in time for the whole duration of the network.

A Timeslot and a Slotframe



A timeslot is long enough (typically 10 ms) for a node in the network to send a maximum sized 127 Byte frame to its radio neighbor

A Timeslot and a Slotframe



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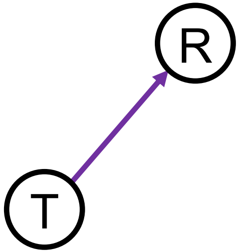
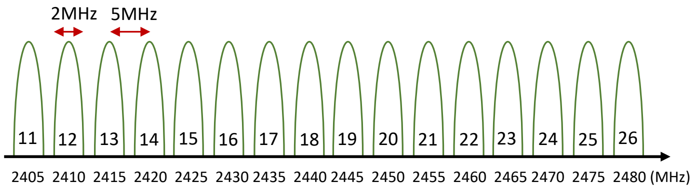
A timeslot is long enough (typically 10 ms) for a node in the network to send a maximum sized 127 Byte frame to its radio neighbour and for that neighbour to send back a link-layer acknowledgment.

A Timeslot and a Slotframe





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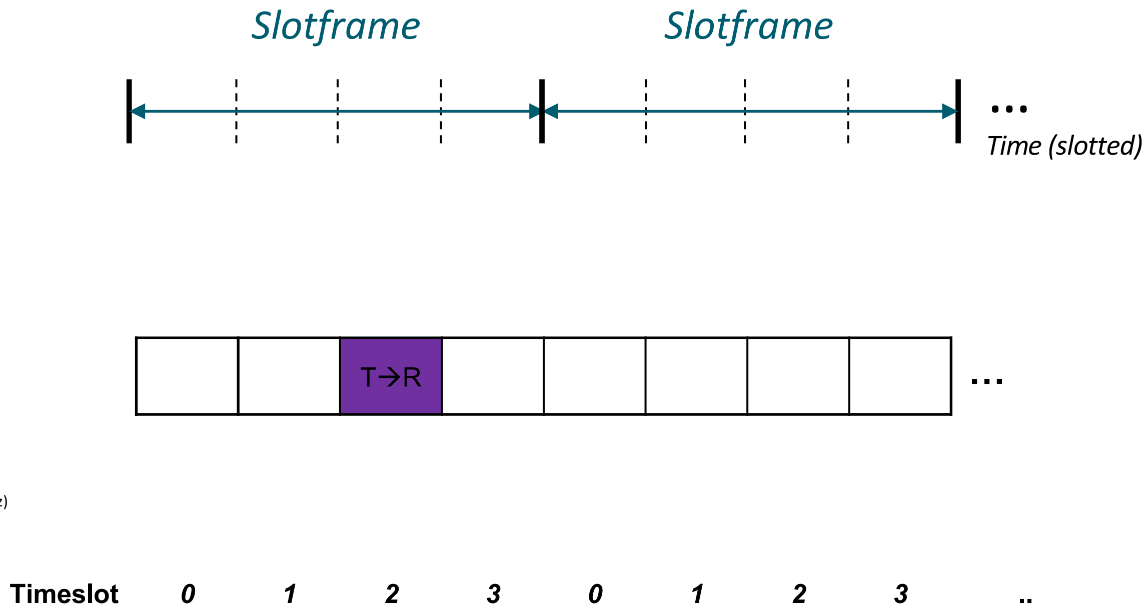

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For each timeslot, there are 16 radio channels available to be employed, where each radio channel has a bandwidth of 2MHz and a channel separation of 5MHz.

A Schedule

"A schedule orchestrates all the possible communications of a node with its neighbors, and it is managed by a Scheduling Function. Indeed, the actions of a node on each timeslot within a Slotframe are determined by the schedule of that node."

Note that a Schedule can be built either in a ***centralized*** *manner, by a Path Computation Element (PCE), or in a* ***distributed*** *fashion (6P and MSF) where nodes decide locally which and how many cells, they will use for communicating with their neighbors.*

A Schedule

At each timeslot, each node knows (i.e., actions) if:

- it has the “right” to transmit a frame and to whom,
- it must stay “awake” to receive a frame,
- it can “sleep”, to save energy.

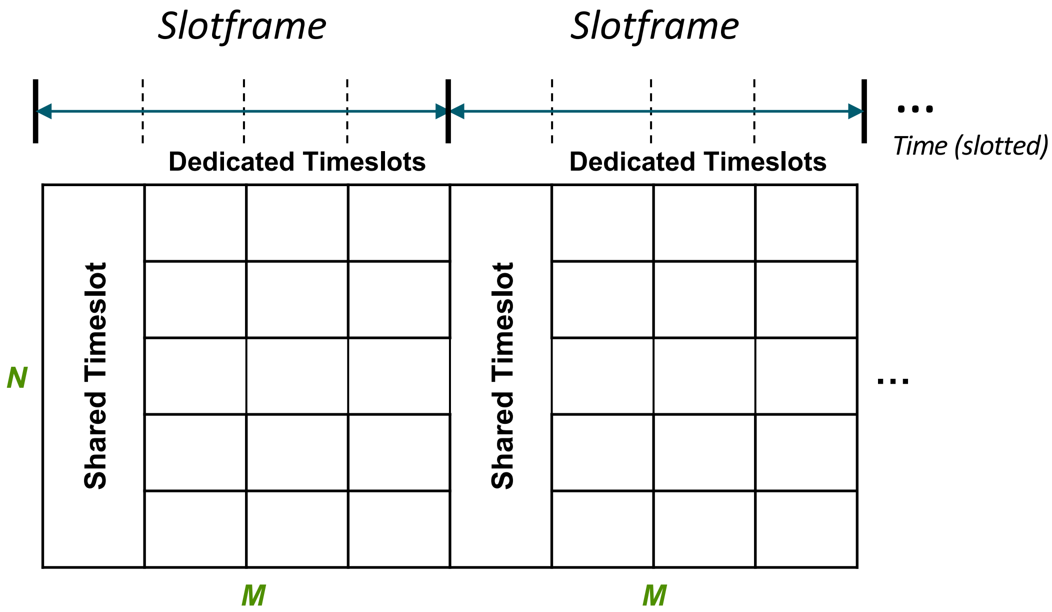
A schedule provides tunable trade-off:

- Network capacity.
- Bounded latency.
- Network reliability.
- Energy consumption.

A typical industrial trade-off scenario:

to target *network reliability* and *bounded latency* at the cost of *network capacity* and *energy*.

A Schedule



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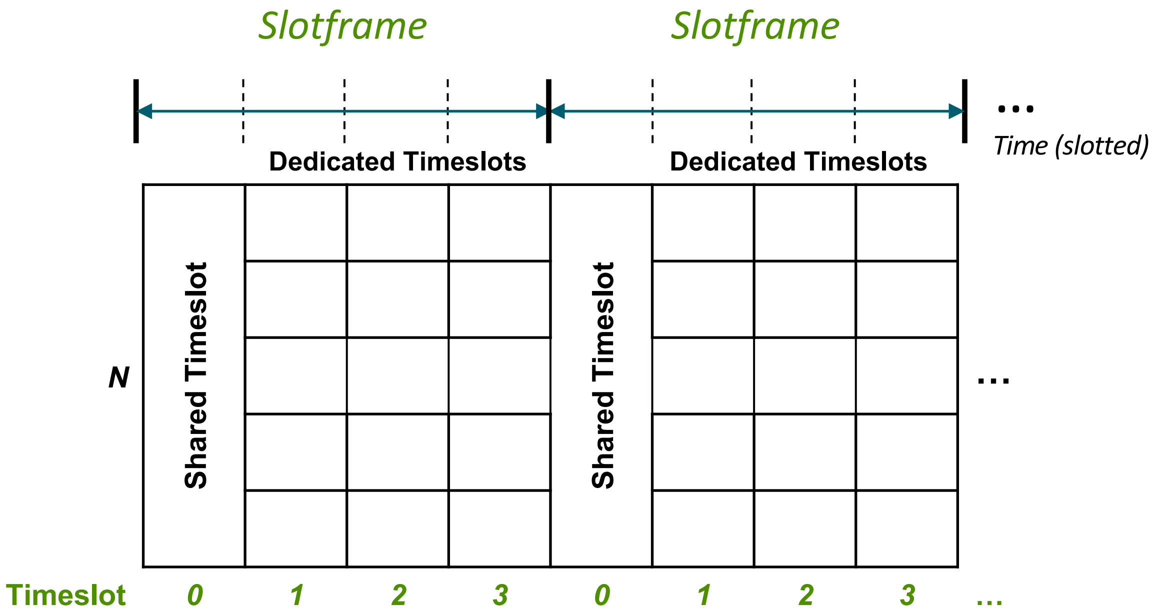
The schedule can be represented as an M multiplied by N matrix,

A Schedule



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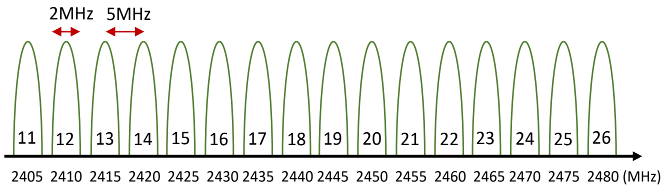
The schedule can be represented as an M multiplied by N matrix, **where M is the length of the slotframe in timeslots**,

A Schedule



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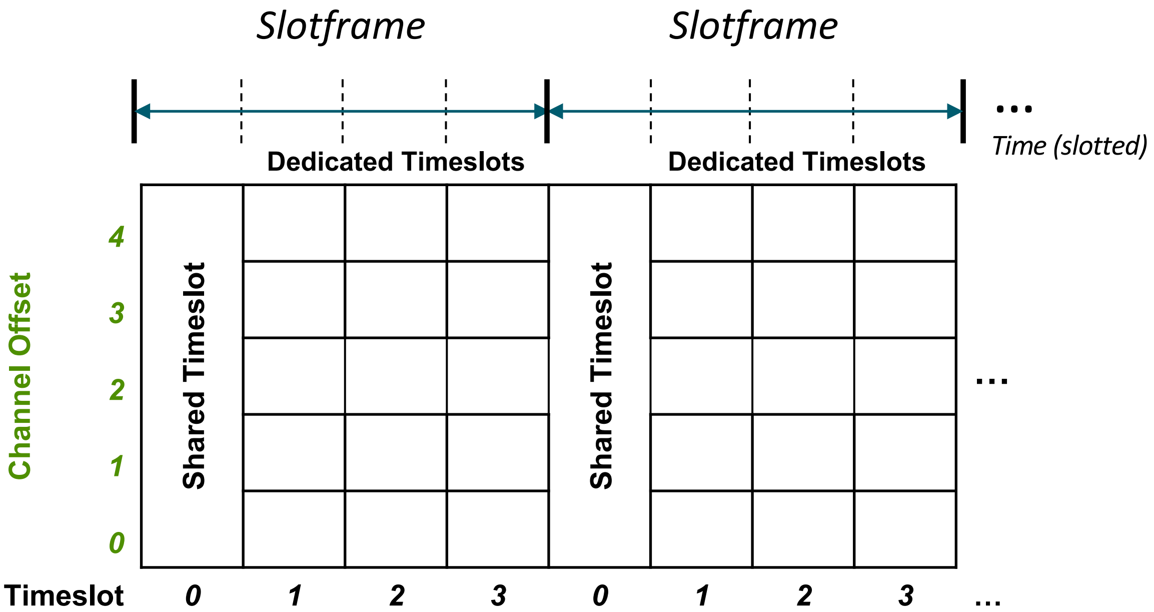
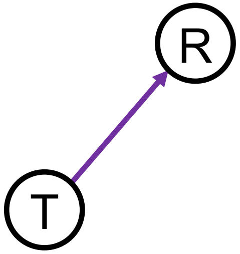
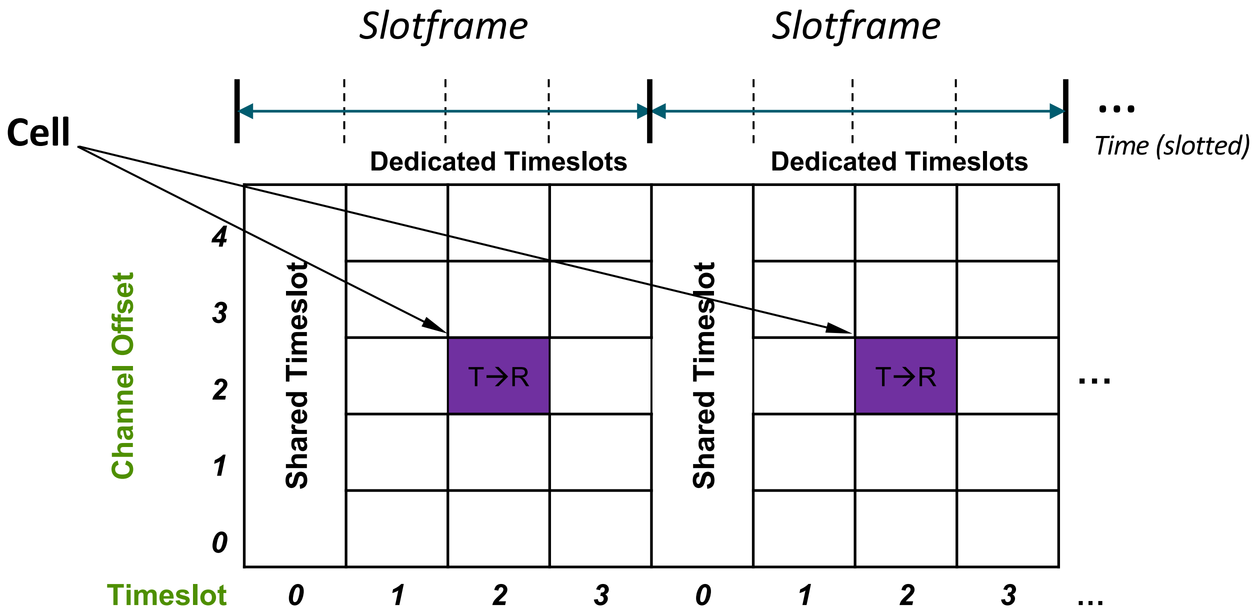


The schedule can be represented as an M multiplied by N matrix, where M is the length of the slotframe in timeslots, **and N is the number of available radio channels to hop, as you can see here**.

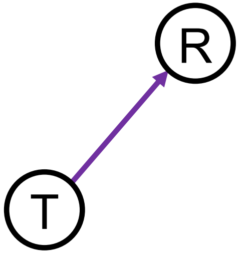
A Schedule

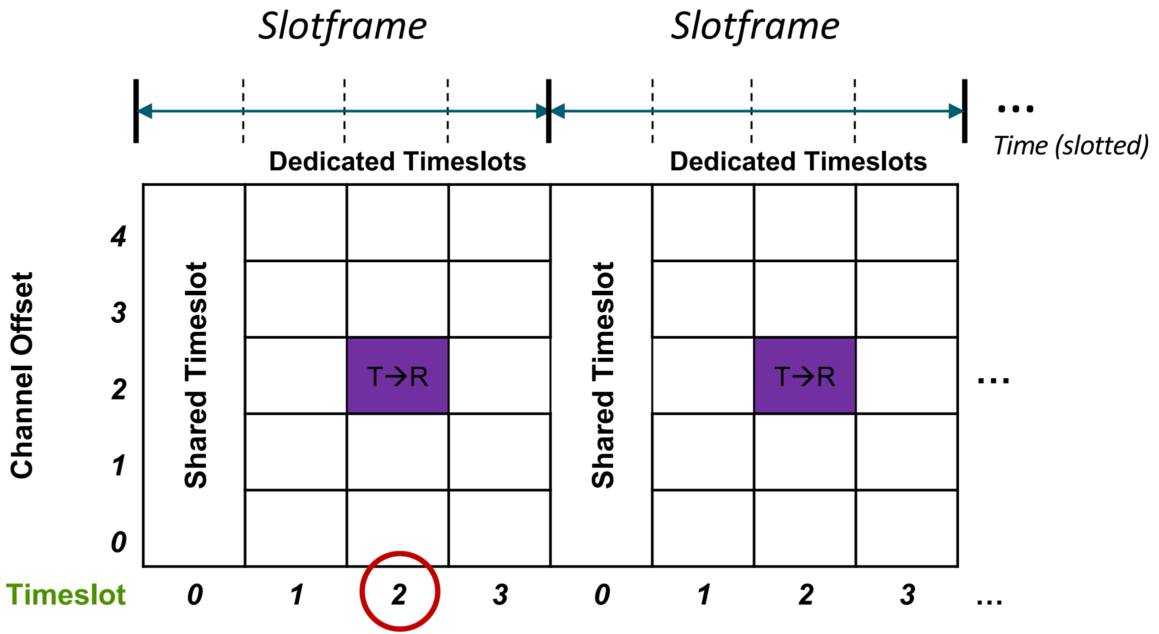




An element in the schedule matrix is called a ***cell***, which is identified by the (timeslot offset, channel offset) pair.

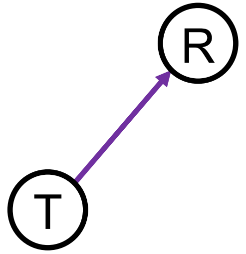
A Schedule

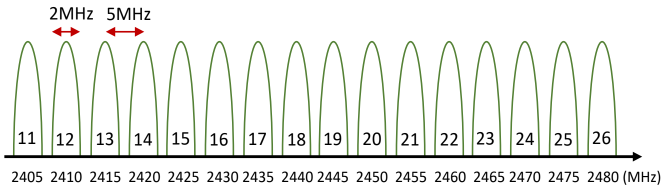




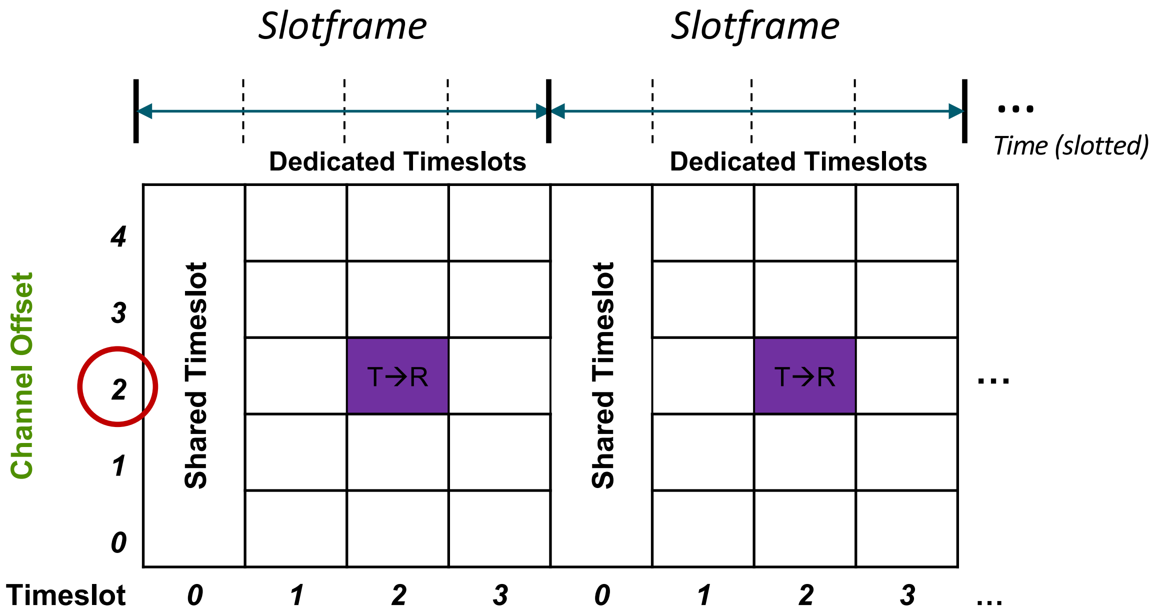
A cell's **timeslotoffset** indicates its position in time, relative to the beginning of the slotframe.

A Schedule



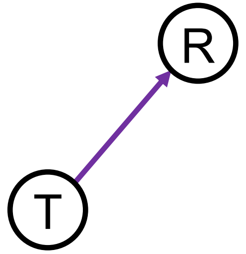


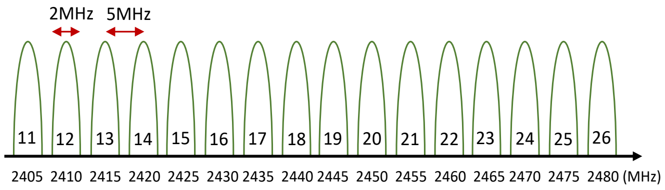
The 16 radio channels in 2.4 GHz band.



A cell's **channeloffset** is an index which maps to a frequency (or radio channel) that a node should tune its radio transceiver to.

A Schedule





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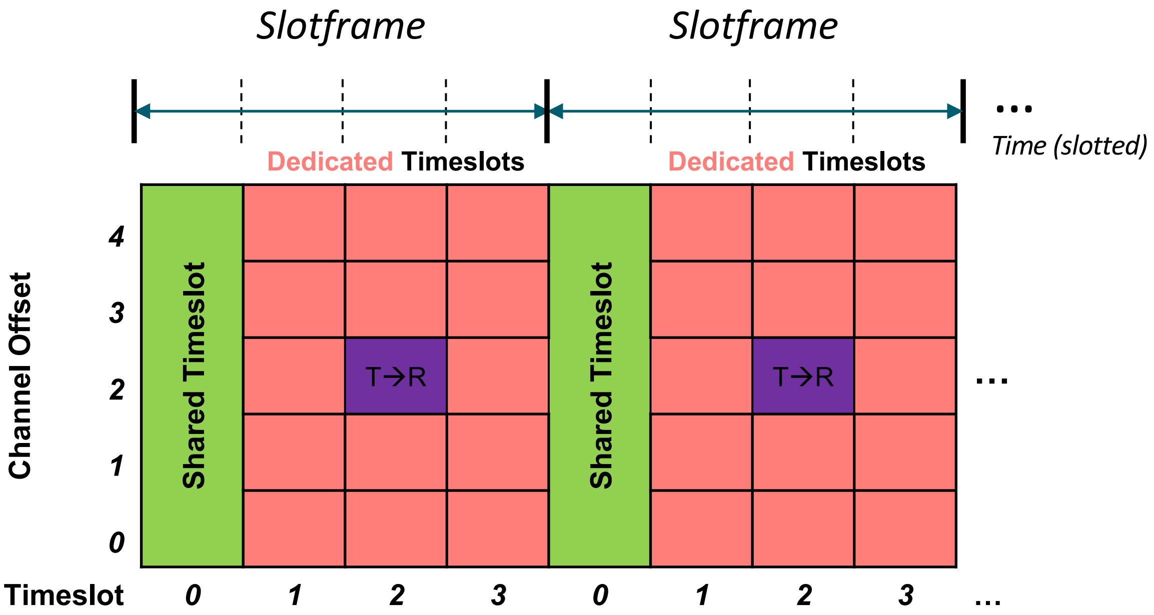


There are **shared** (i.e., contention-based) cells and/or **dedicated** (contention-free) cells. For the shared cells, a MAC protocol based on random access method is applied, i.e., CSMA/CA!

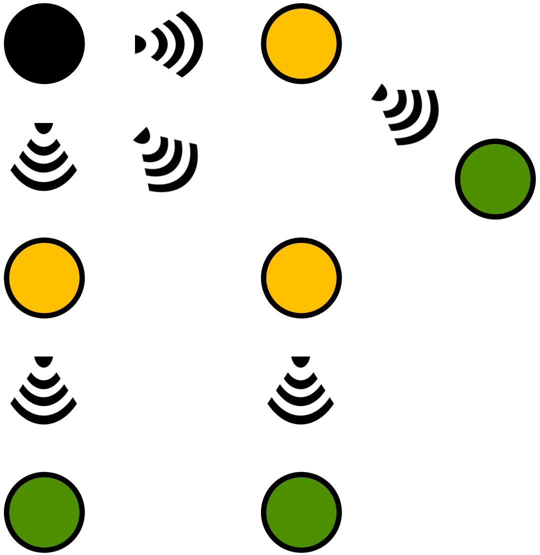
Enhanced Beacons (EBs) (1/2)

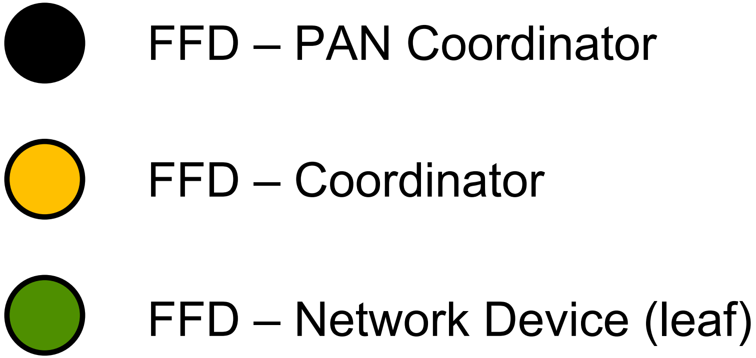
- EBs are transmitted in broadcast from the Personal Area Network (PAN) Coordinator to advertise the network.
- An EB may contain the following information ASN and Join Metric, Channel Hopping Sequence IDentifier, TSCH slotframe size.
- EB are transmitted from the Full Function Devices (FFD) once they are synchronized in the network in order to extend the network.
- The EB may also be used as a means for a node already part of the network to re-synchronize.
- There are a limited number of timeslots designated as a broadcast timeslot. These timeslots are rare, and with a Slotframe length of 100, there may be only 1 timeslot/slotframe for an EB.

Enhanced Beacons (EBs) (2/2)

- TX EB → the transmitter can send EB only in the first Timeslot of each Slotframe. Each EB is transmitted over a different radio channel.
- RX EB → The Joining node will be listening in one of the 16 radio channels.
- A joining node should wait to receive an EB. When it receives the EB, it extracts the ASN and synchronizes to the Slotframe of the network.

IEEE Terminologies: FFD and RFD | PAN, Coordinator, Network Device (1/3)





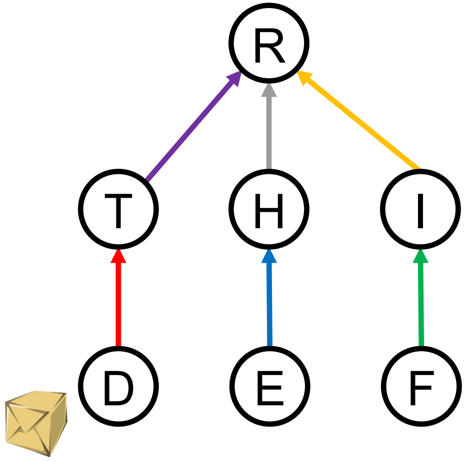
IEEE Terminologies: FFD and RFD | PAN, Coordinator, Network Device (2/3)

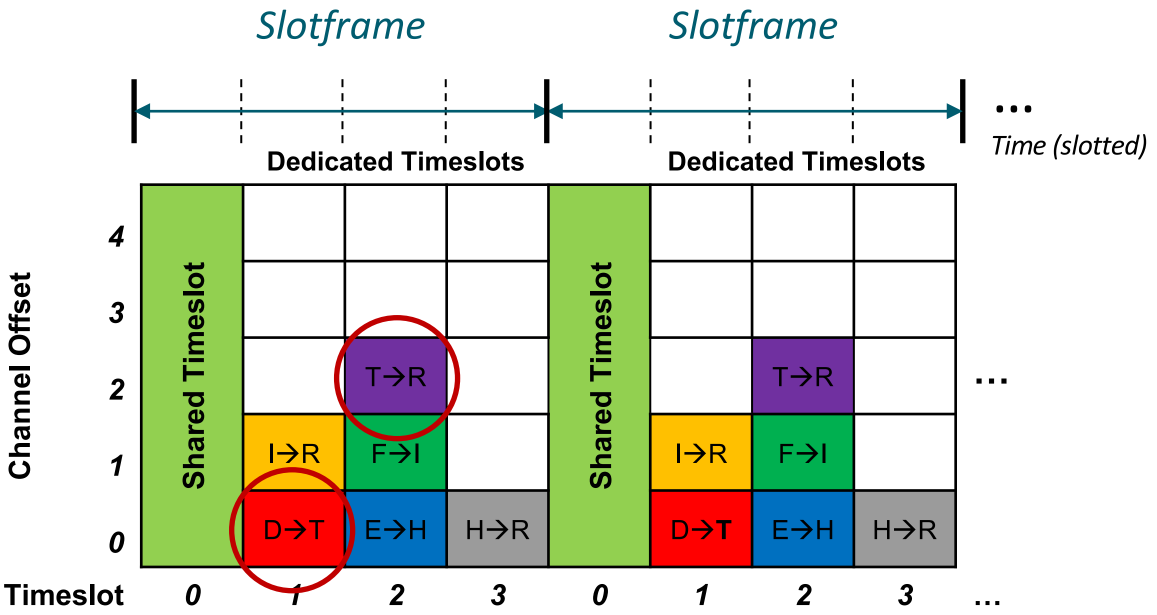
- 2 types of nodes
  - Full Function Device (FFD)
    - Any topology
    - PAN coordinator capable
    - Talks to any other device (**routing**)
    - Implements complete protocol set
  - Reduced Function Device (RFD – leaf nodes)
    - Limited to star topology or end-device in a peer-to-peer network.
    - Cannot become a PAN coordinator
    - Reduced (Very simple implementation) protocol set (sensing node)

IEEE Terminologies: FFD and RFD | PAN, Coordinator, Network Device (3/3)

- 3 possible roles
  - Personal Area Network (PAN) Coordinator
    - A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.
  - Coordinator
    - A device that provides coordination and other services to the network (extension of the network of the PAN coordinator (FFD))
  - Network Device (leaf)
    - An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium (end device of a network (FFD or RFD))

Summary



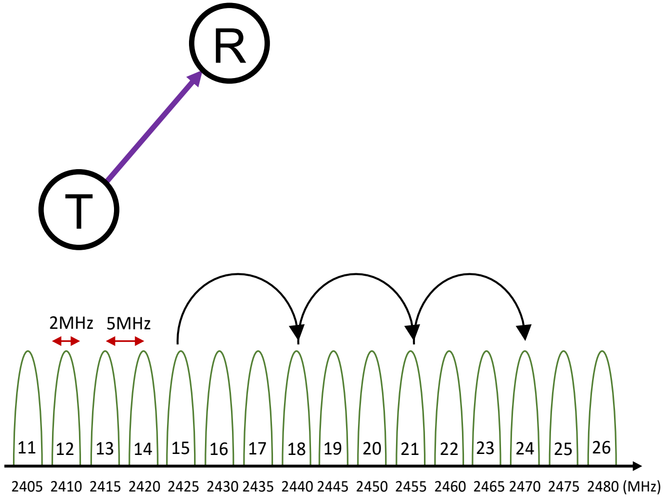


Each packet exchanged between neighbors happens within one cell.

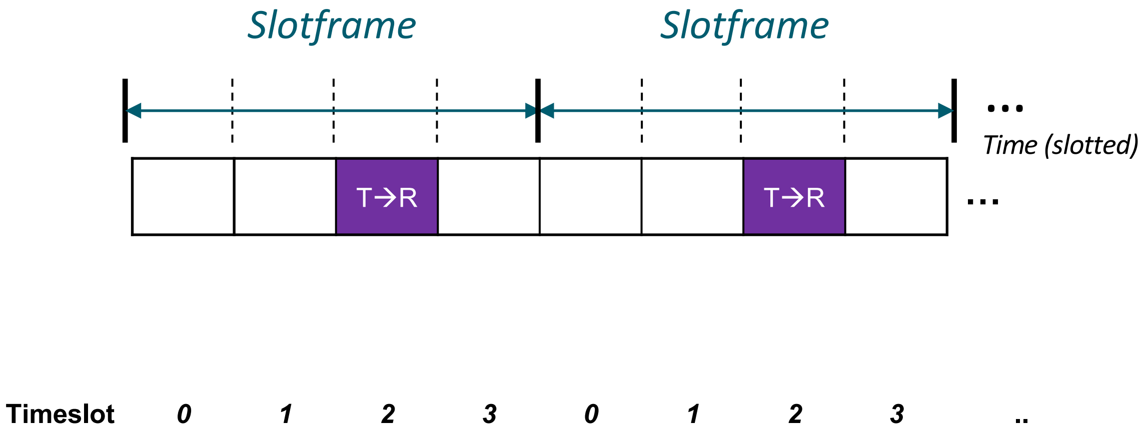
Channel Hopping Sequence (CHS)

Channel Hopping

- The Channel Hopping mechanism of TSCH, allows a node to transmit its subsequent frames over different radio channels.

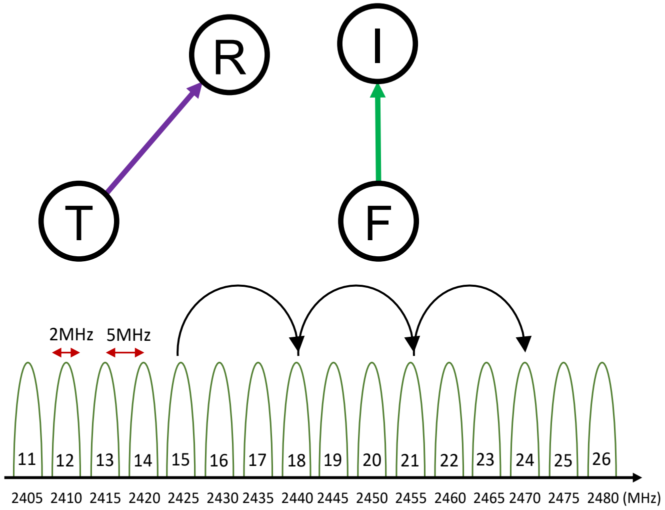


The 16 radio channels in 2.4 GHz band.



Channel Hopping

- It also allows for two distinct sources to send their frames at the same time over different radio channels to two different destinations, ***which increases the network capacity***.



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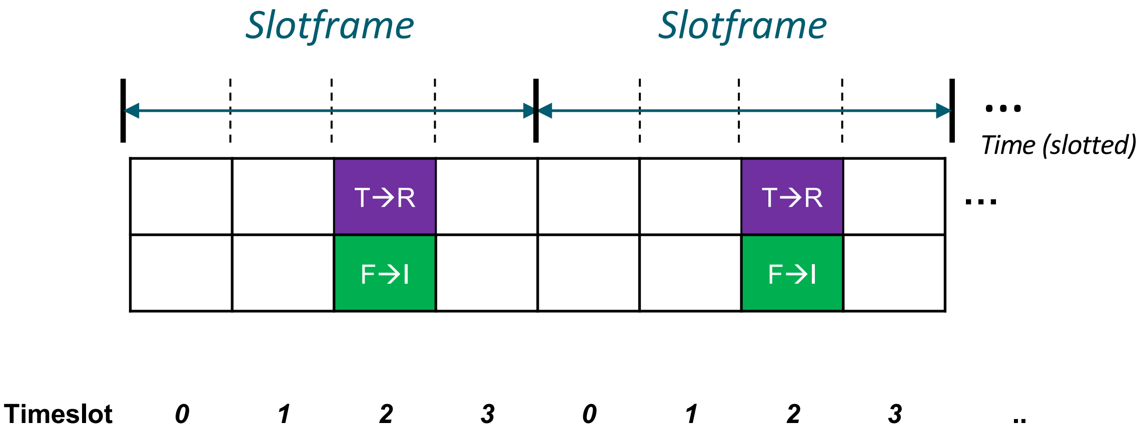

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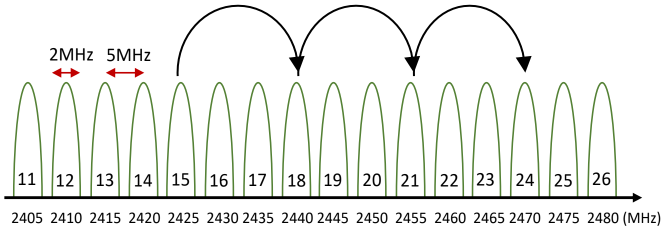
Channel Hopping Sequence (CHS)



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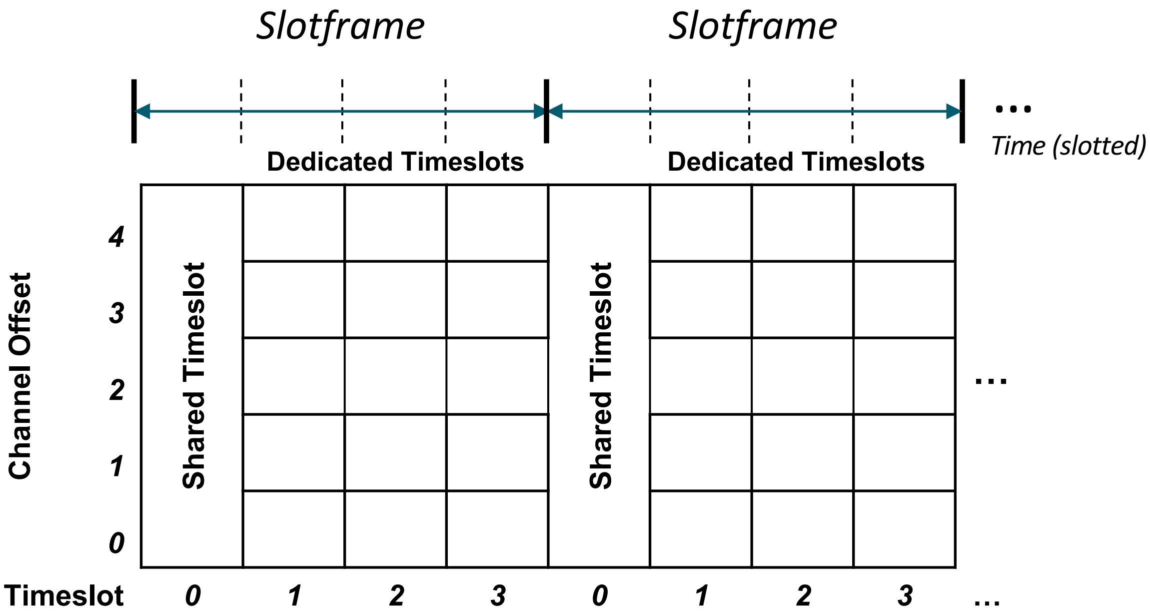

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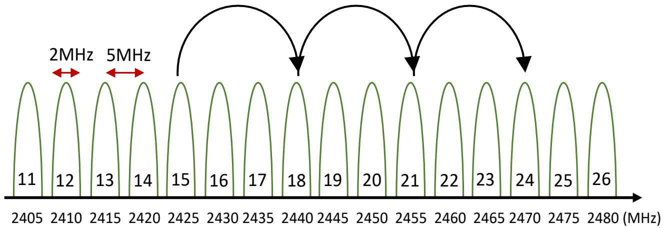
CHS is handled by TSCH through a channel hopping sequence,

Channel Hopping Sequence (CHS)



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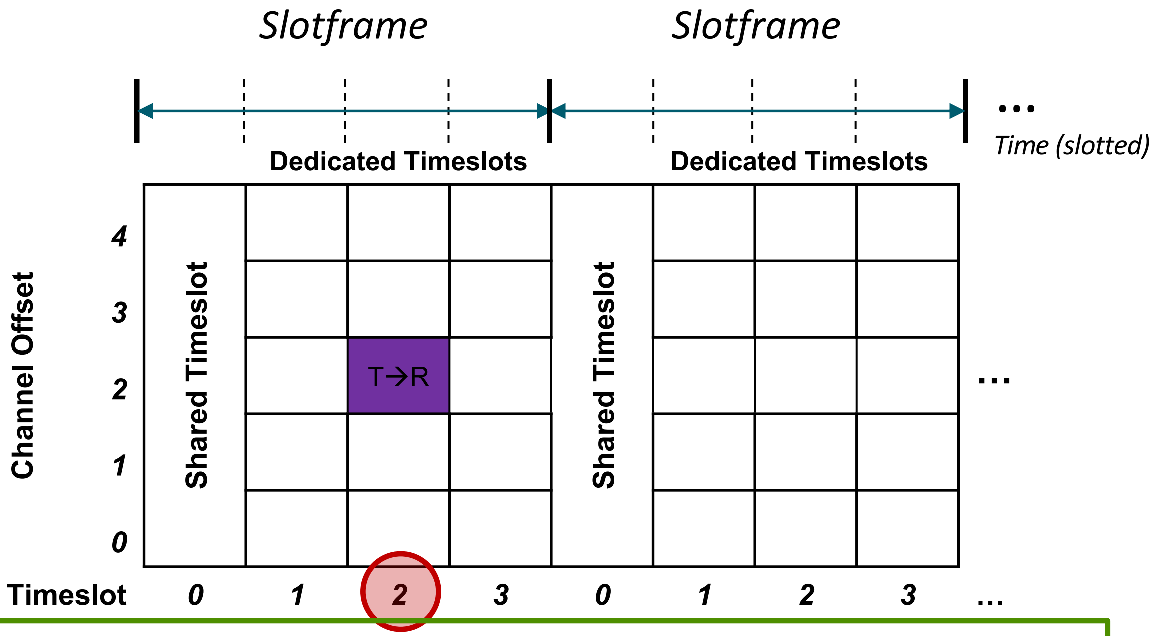
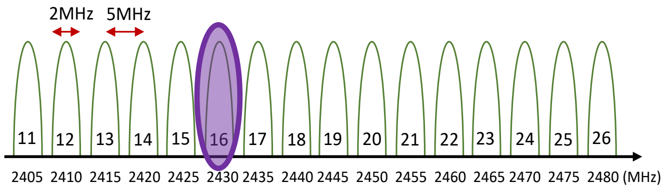


CHS is handled by TSCH through a channel hopping sequence, where at each timeslot,

Channel Hopping Sequence (CHS)

$$Radio\ Channel = F[(ASN + chOffset)\%nFreq]$$



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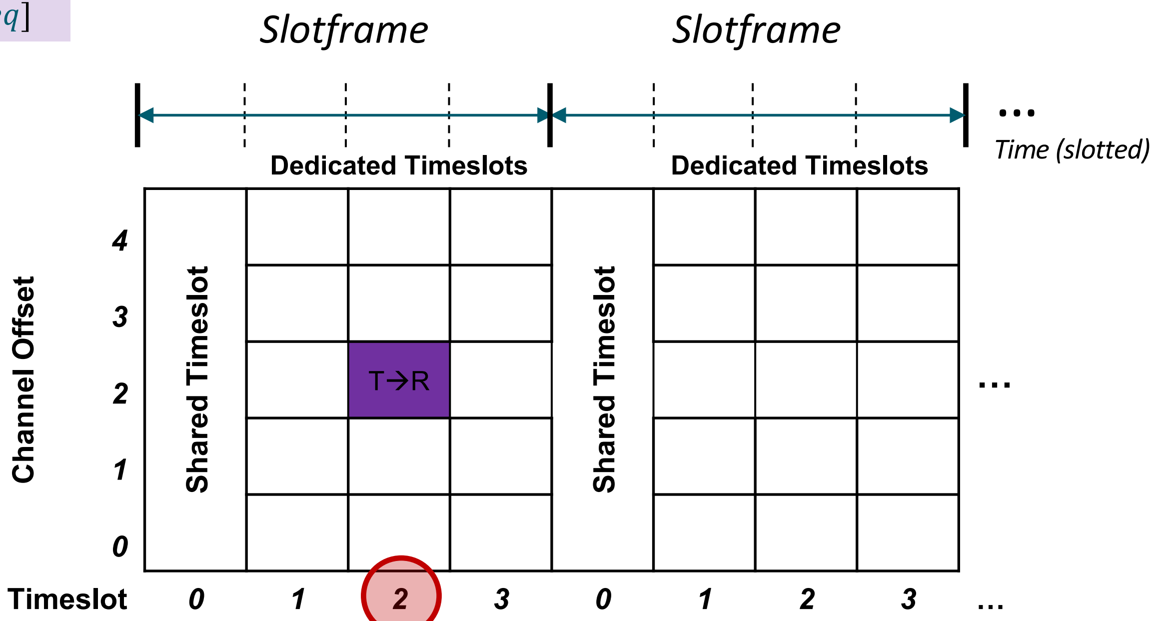
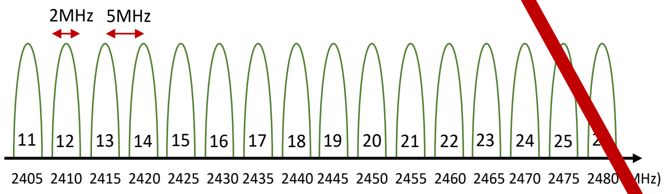


CHS is handled by TSCH through a channel hopping sequence, where at each timeslot, the physical radio channel to be used by the radio is computed by the following equation:

Channel Hopping Sequence (CHS)

Absolute Slot Number (**ASN**) indicates the number of timeslots elapsed since the network started.

$$Radio\ Channel = F[(ASN + chOffset)\%nFreq]$$



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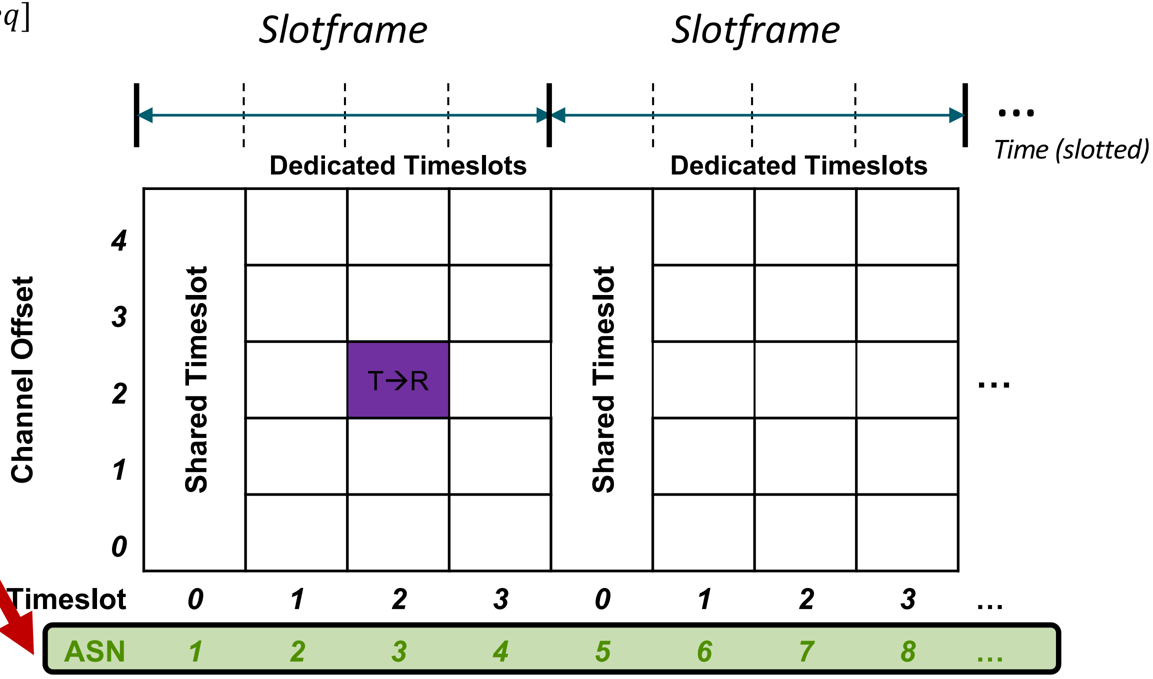
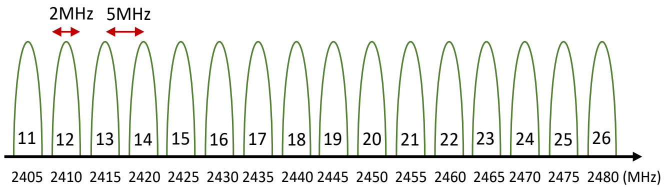


Channel Hopping Sequence (CHS)

ChannelOffset, we have previously explained.

$$Radio\ Channel = F[(ASN + \mathbf{chOffset})\%nFreq]$$



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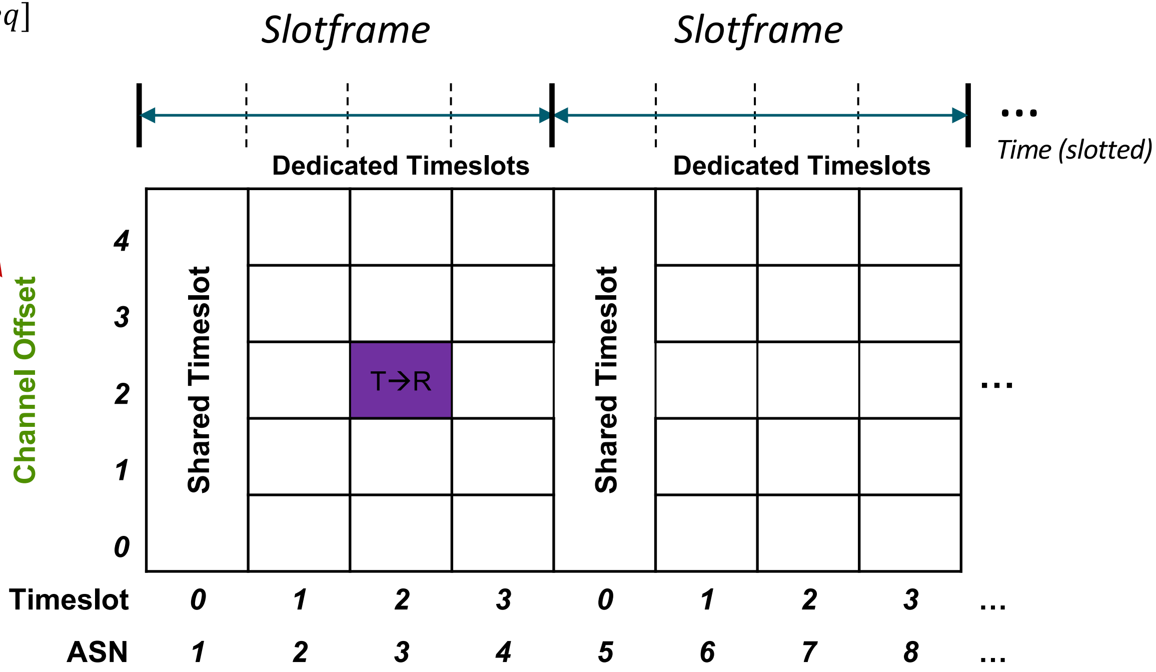
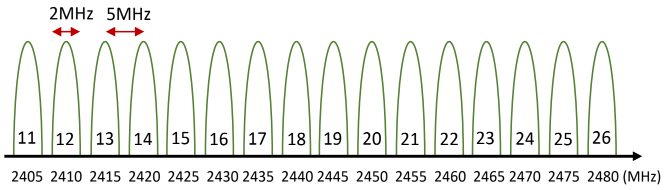


Channel Hopping Sequence (CHS)

nFreq is the number of available physical radio channels. There are 16 radio channels when using IEEE 802.15.4-compliant radios at 2.4 GHz.

$$Radio\ Channel = F[(ASN + chOffset)\%\mathbf{nFreq}]$$



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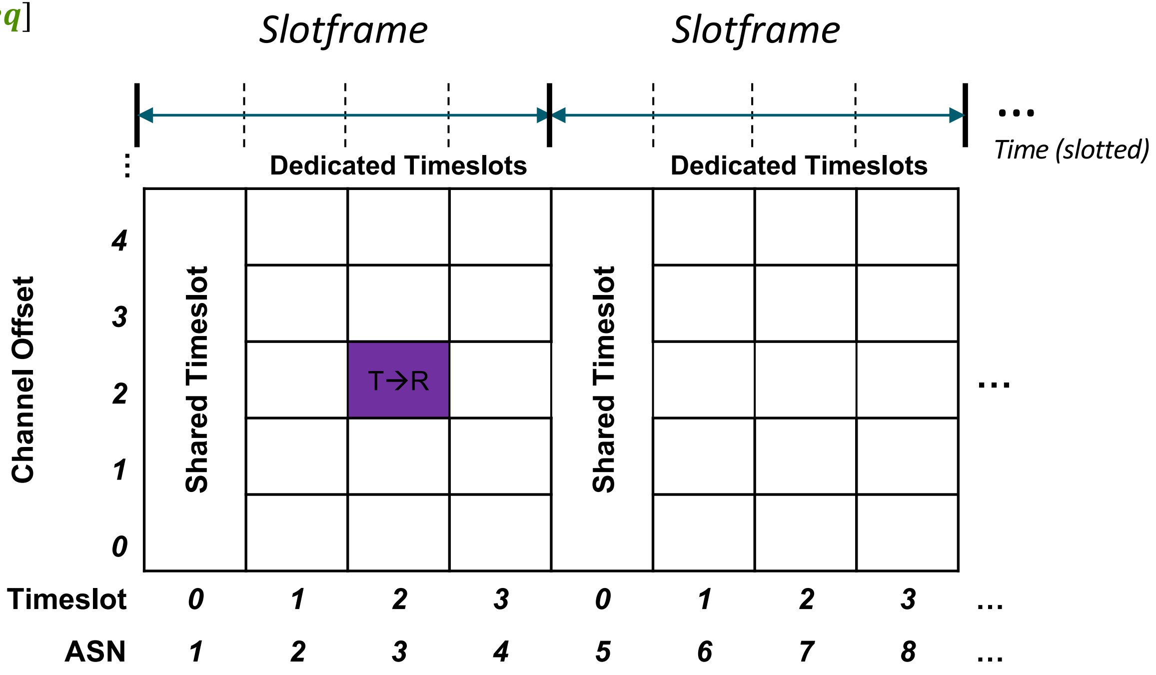

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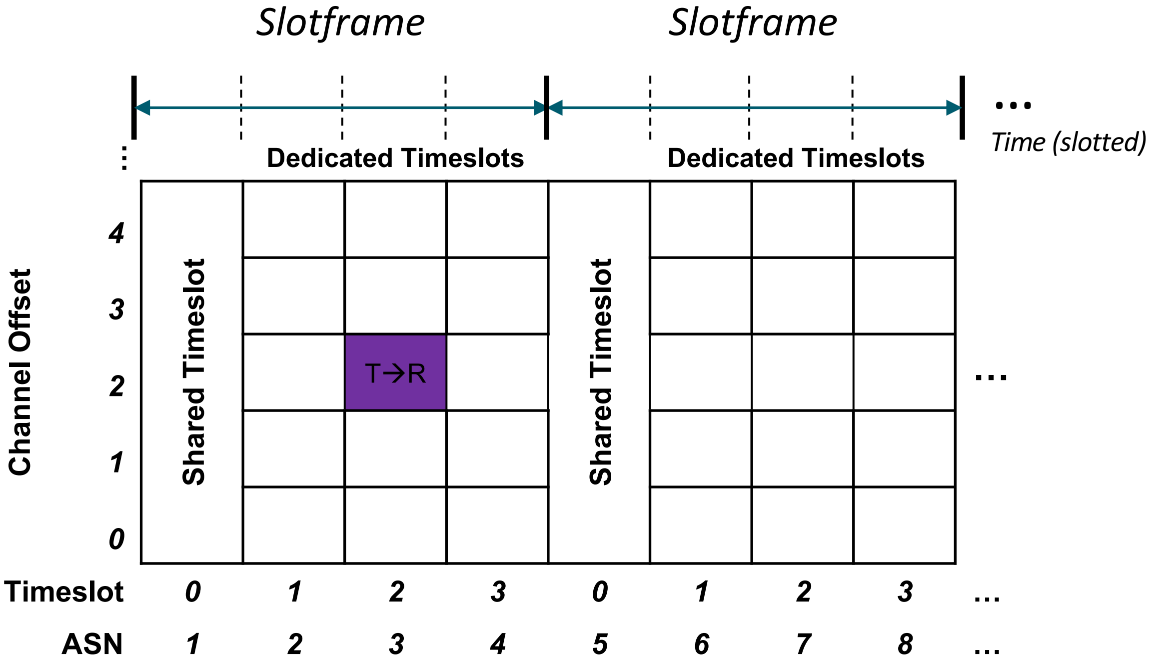
Channel Hopping Sequence (CHS)

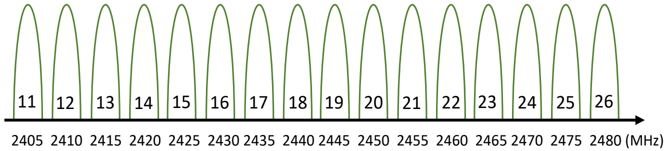
Lookup Table

Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*

$$Radio\ Channel = \boldsymbol{F}[(ASN + chOffset)\%nFreq]$$

F is a **Look-up Table function** that translates the result from the operation to actual radio channel (i.e., from channel 11th to 26th in 2.4 GHz band).





The 16 radio channels in 2.4 GHz band.

An Example of the CHS Operation

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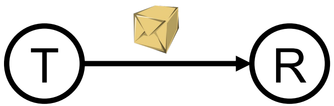
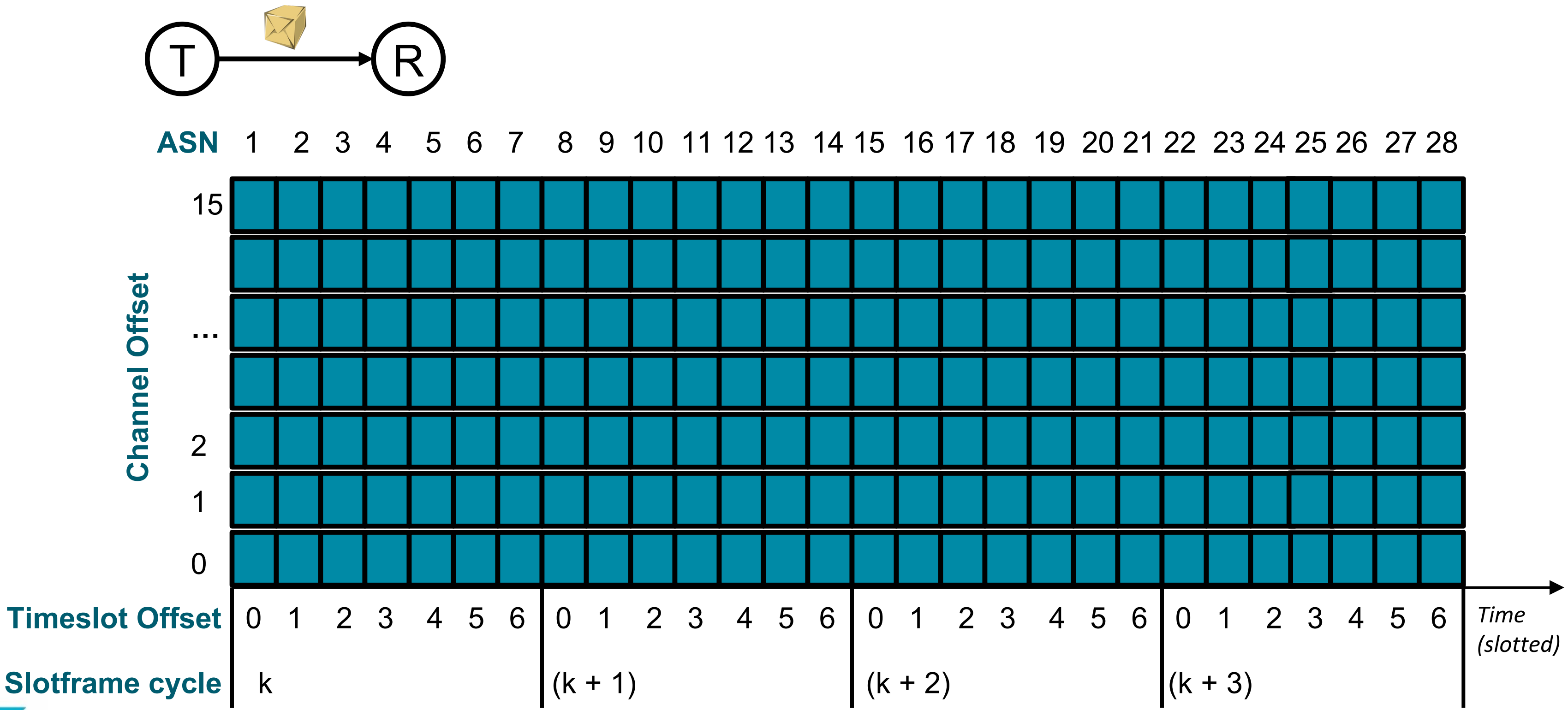
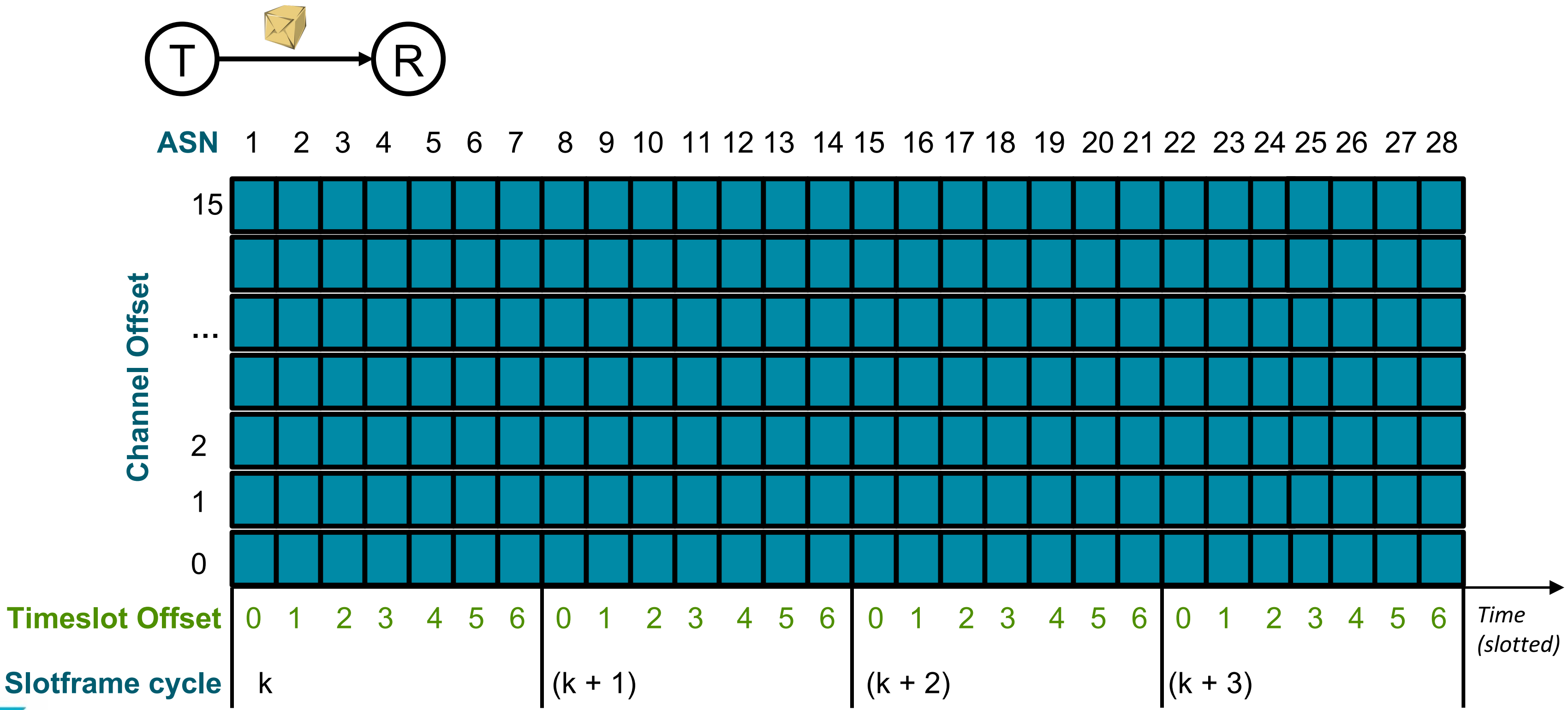
An Example of the CHS Operation



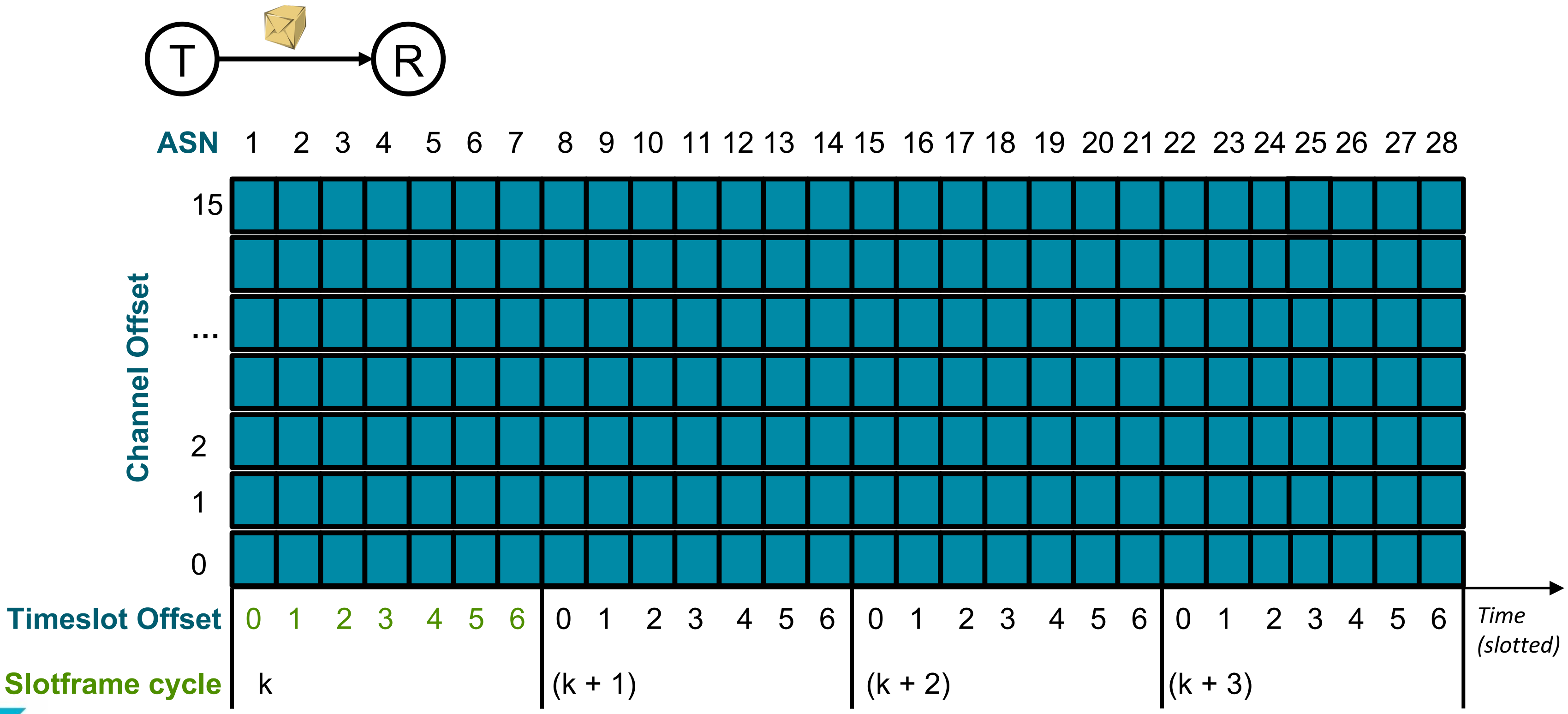
An Example of the CHS Operation



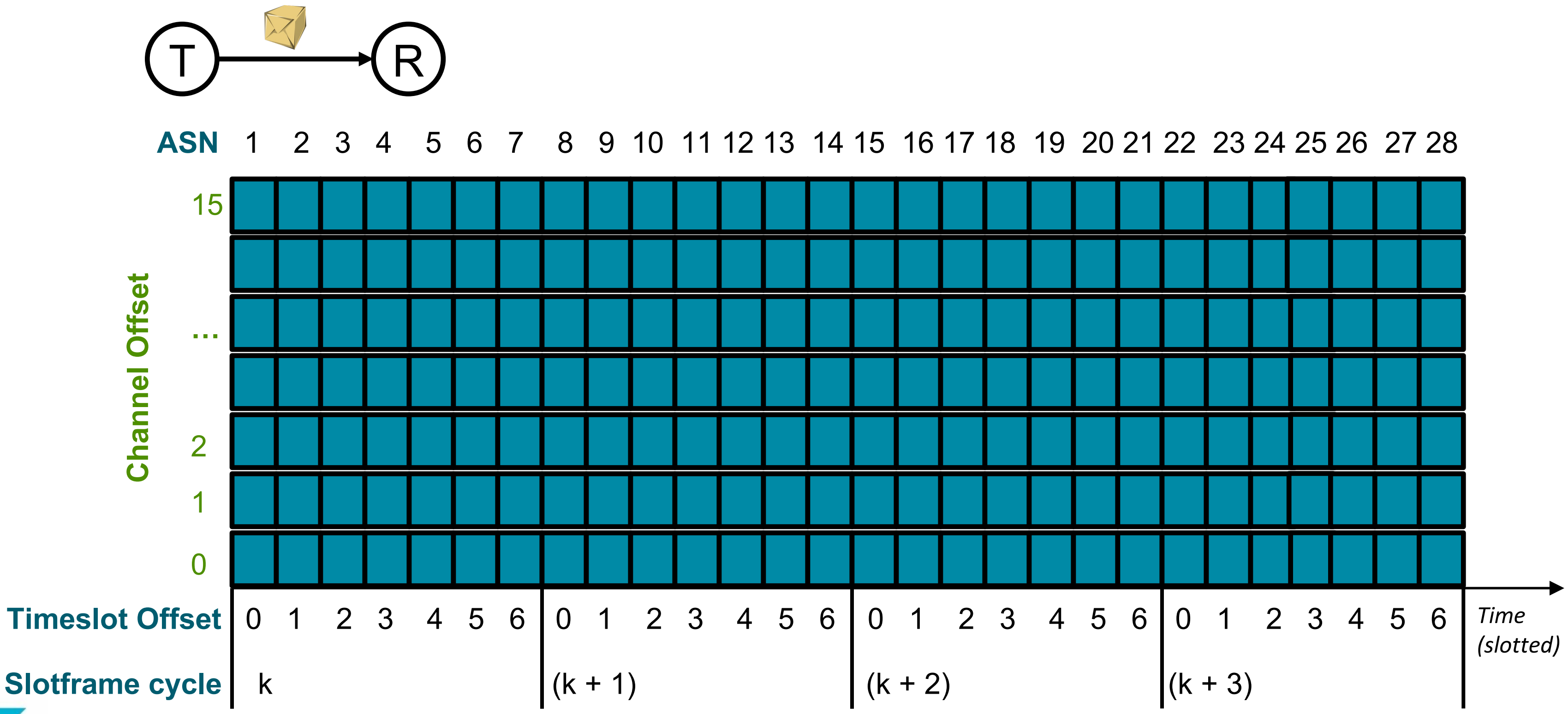
An Example of the CHS Operation



An Example of the CHS Operation

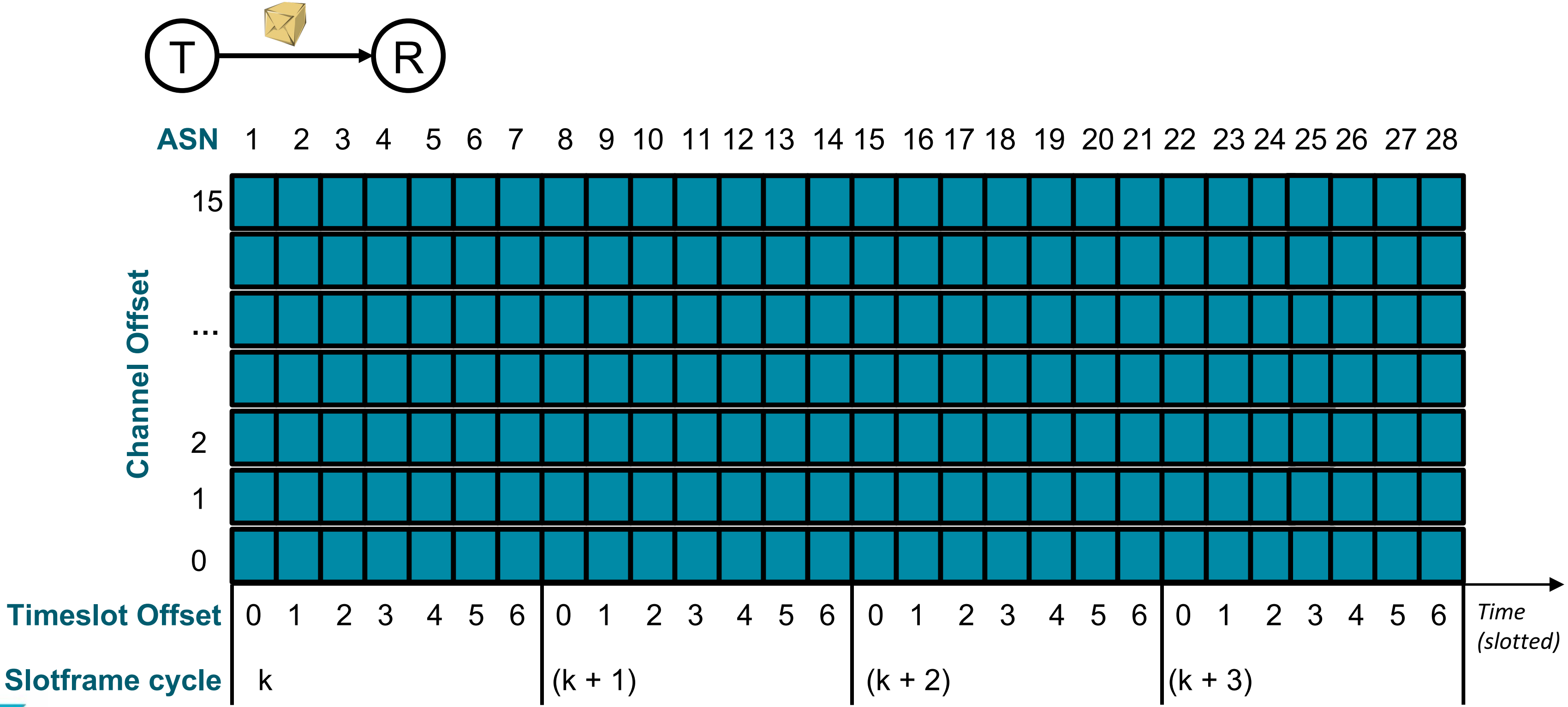


An Example of the CHS Operation



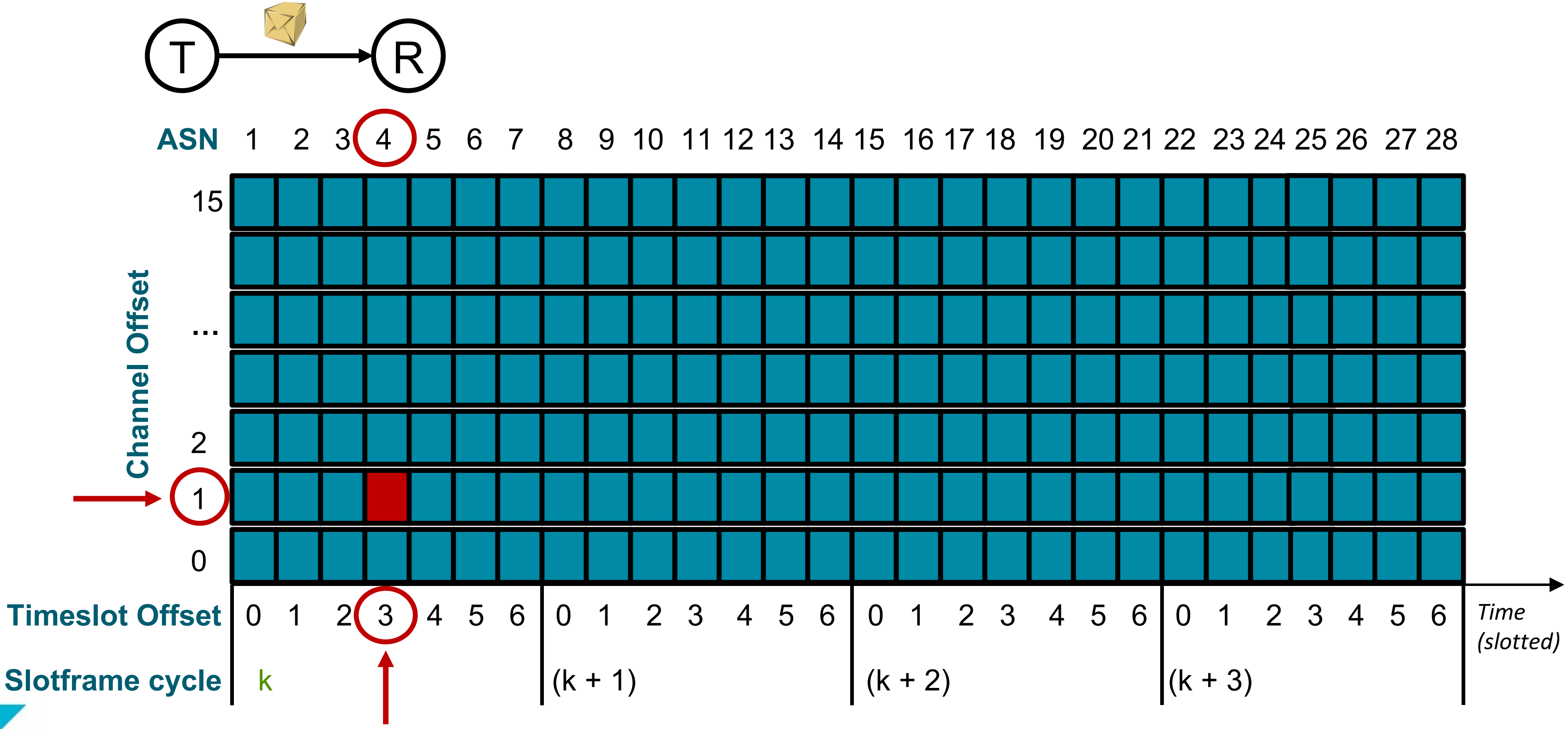
An Example of the CHS Operation

Lookup Table	
Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



An Example of the CHS Operation

Lookup Table	
Index	Radio Channel
0	11
1	12
2	13
3	14
4	15
5	16
6	17
7	18
8	19
9	20
10	21
11	22
12	23
13	24
14	25
15	26



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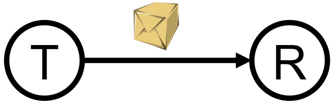
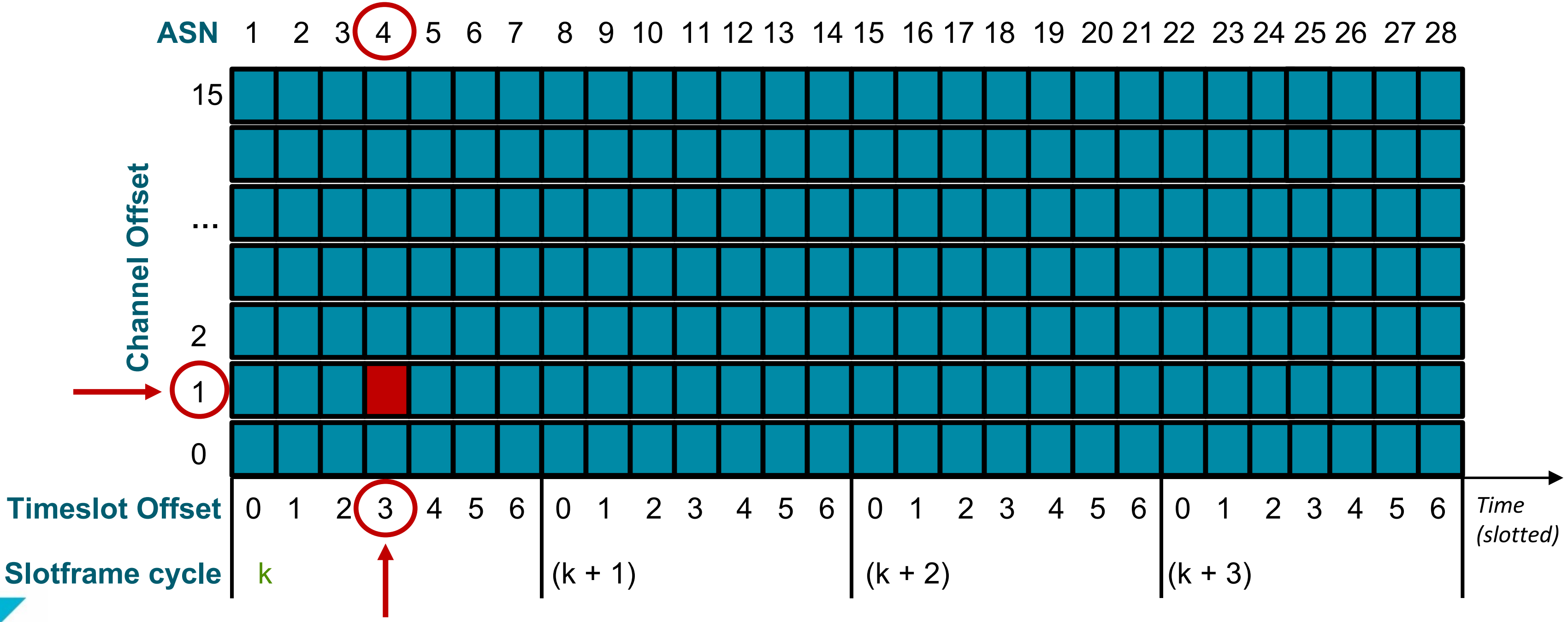
An Example of the CHS Operation

Lookup Table	
Index	Radio Channel
0	11
1	12
2	13
3	14
4	15
5	16
6	17
7	18
8	19
9	20
10	21
11	22
12	23
13	24
14	25
15	26

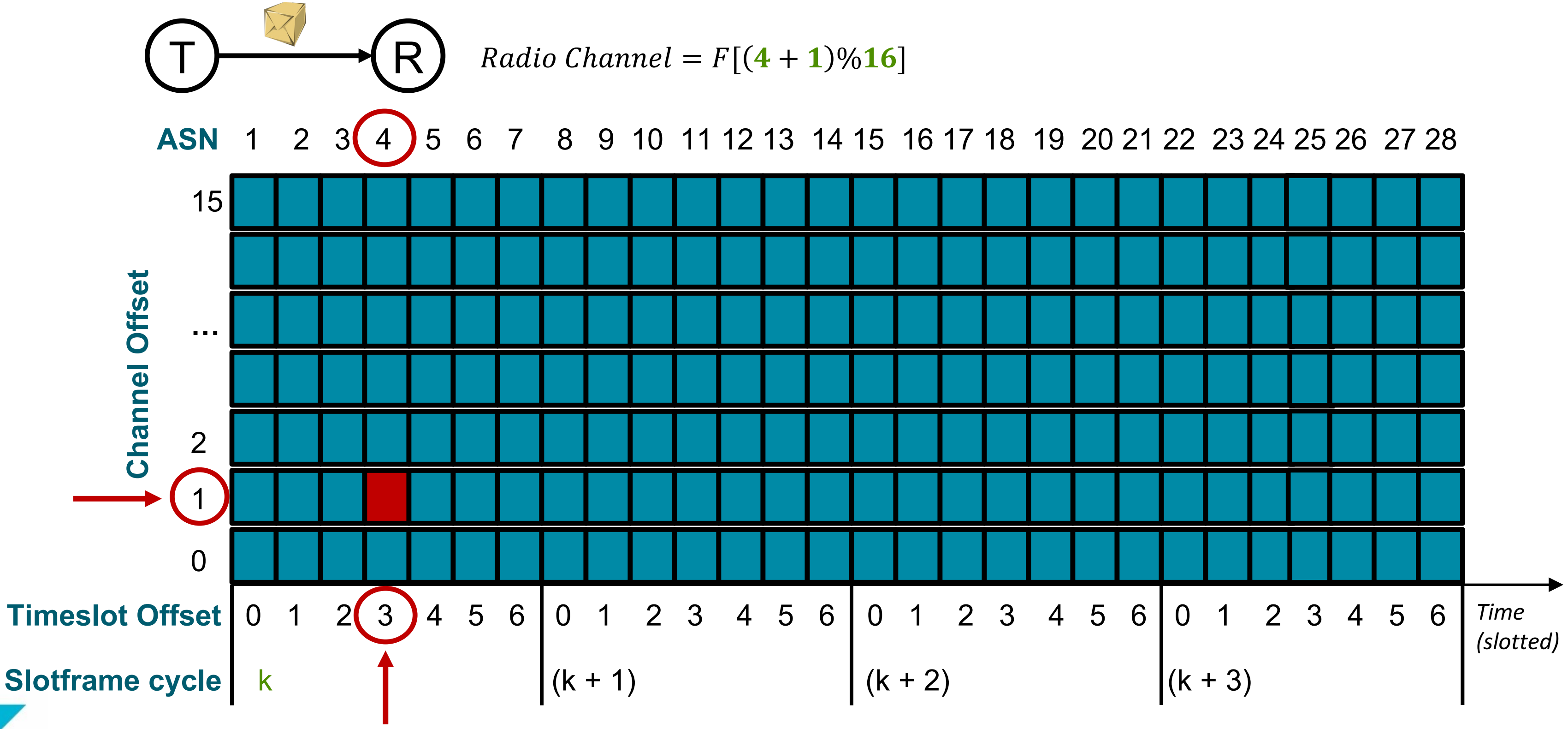


$$Radio\ Channel = F[(ASN + chOffset)\%nFreq]$$



An Example of the CHS Operation

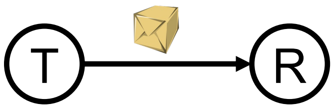
Lookup Table	
Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



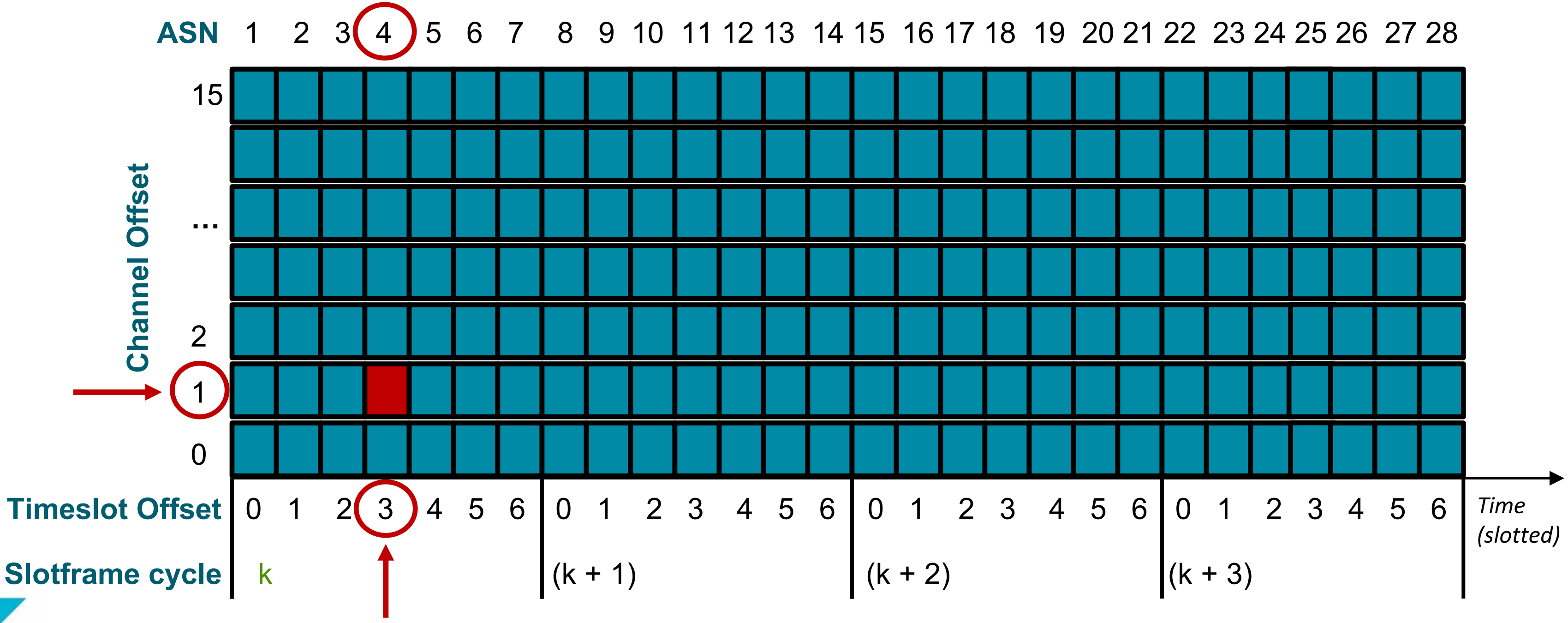
An Example of the CHS Operation

Lookup Table

Index	Radio Channel
0	11
1	12
2	13
3	14
4	15
5	16
6	17
7	18
8	19
9	20
10	21
11	22
12	23
13	24
14	25
15	26



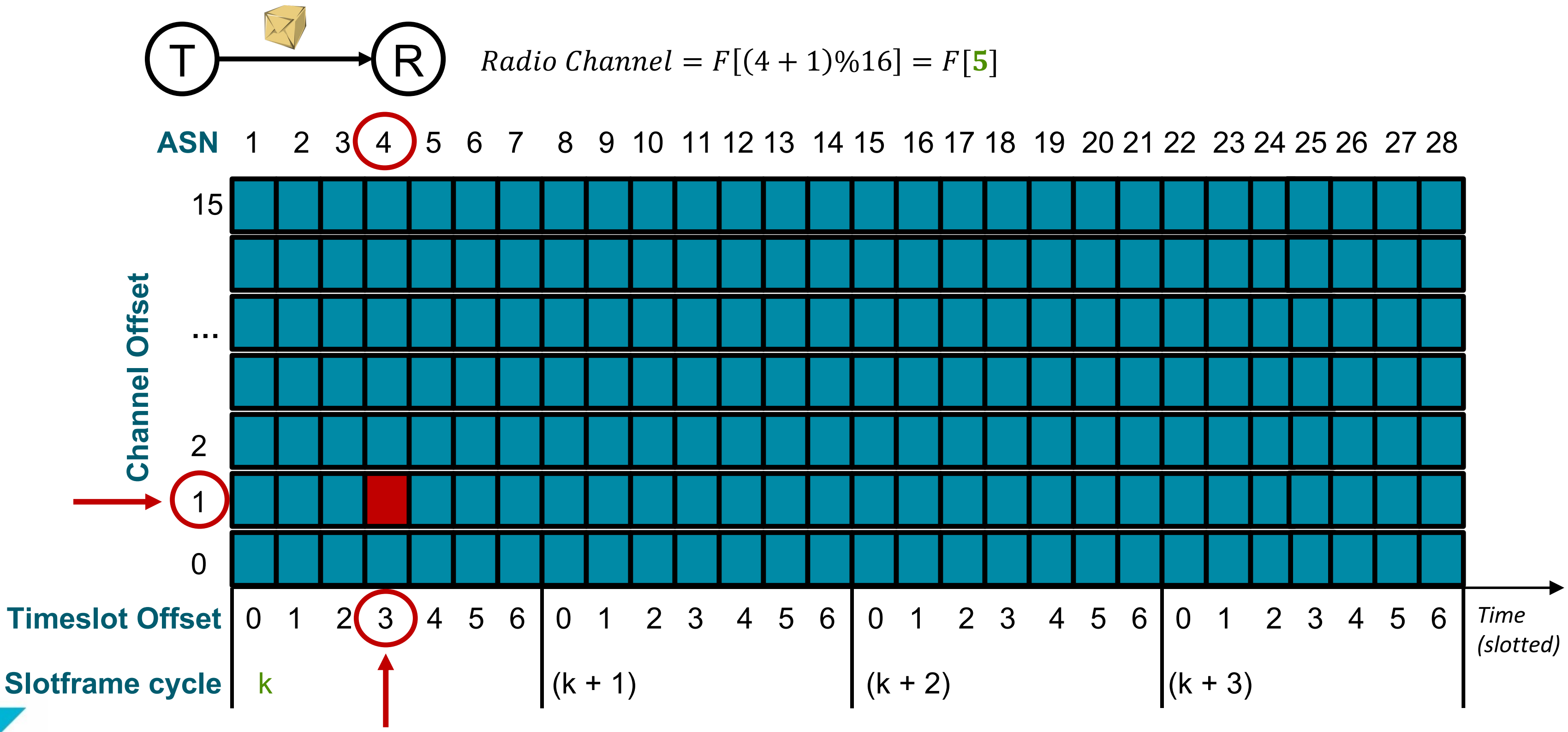
$$Radio\ Channel = F[(4+1)\%16] = F[5]$$



An Example of the CHS Operation

Lookup Table

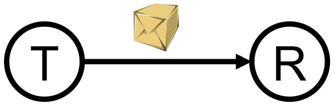
Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



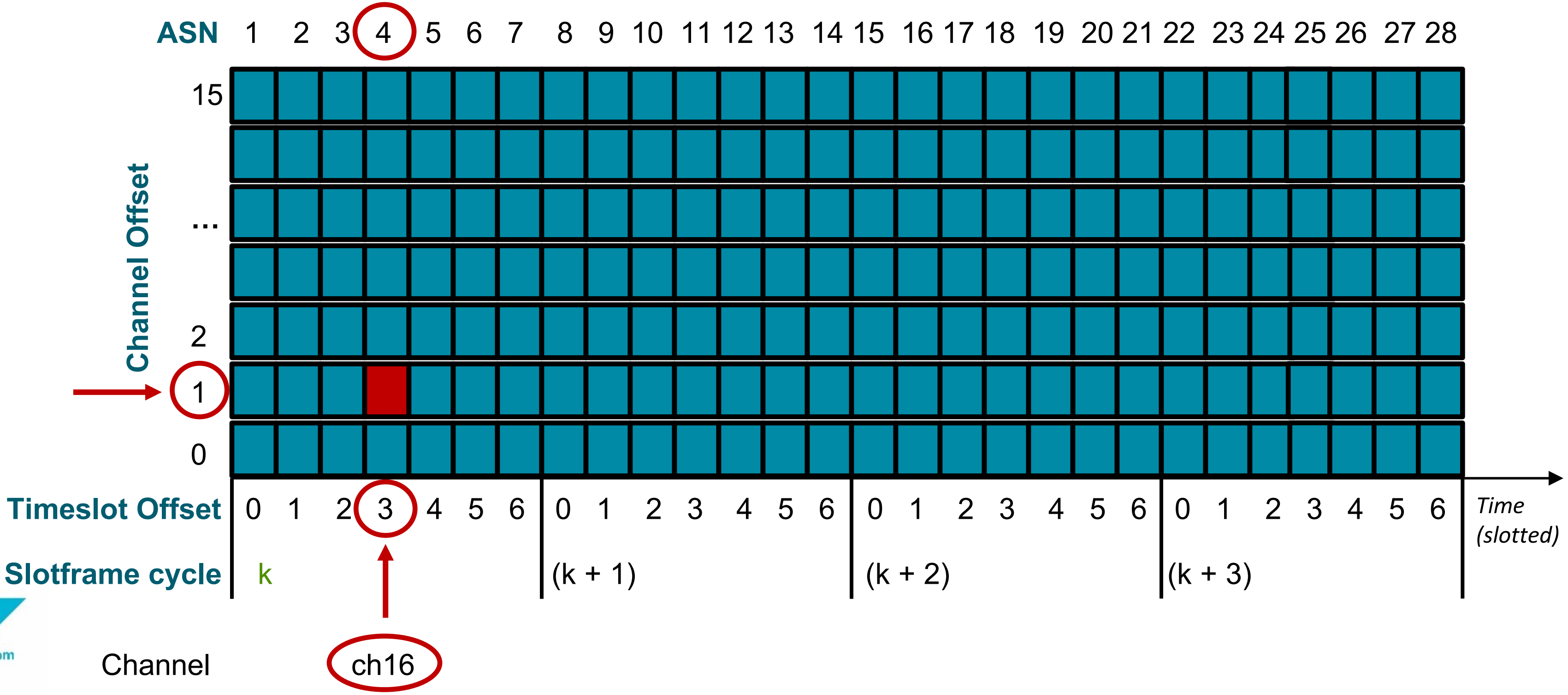
An Example of the CHS Operation

Lookup Table

Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



$$Radio\ Channel = F[(4+1)\%16] = F[5]$$



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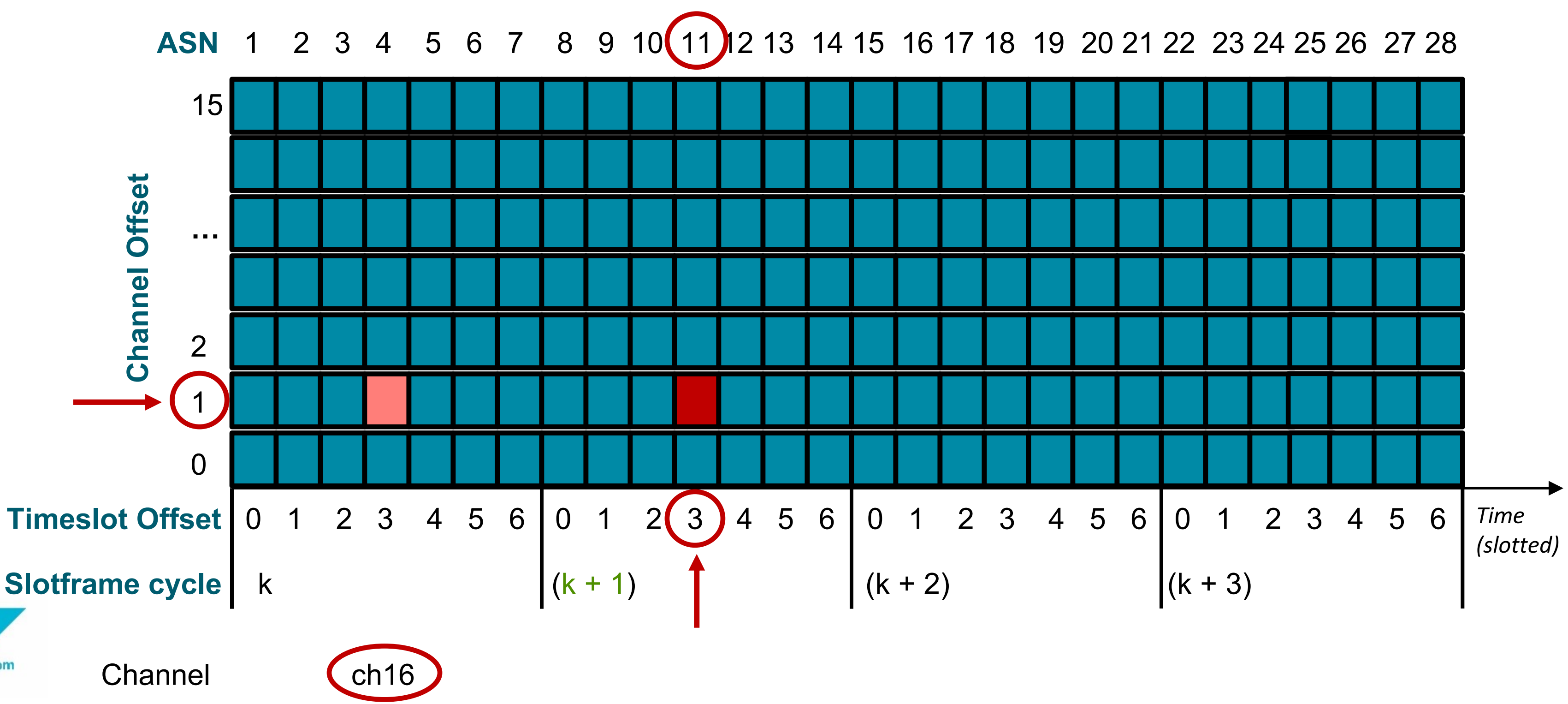
An Example of the CHS Operation

Lookup Table	
Index	**Radio Channel**
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*

$$Radio\ Channel = F[(ASN + chOffset)\%nFreq]$$



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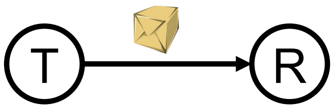
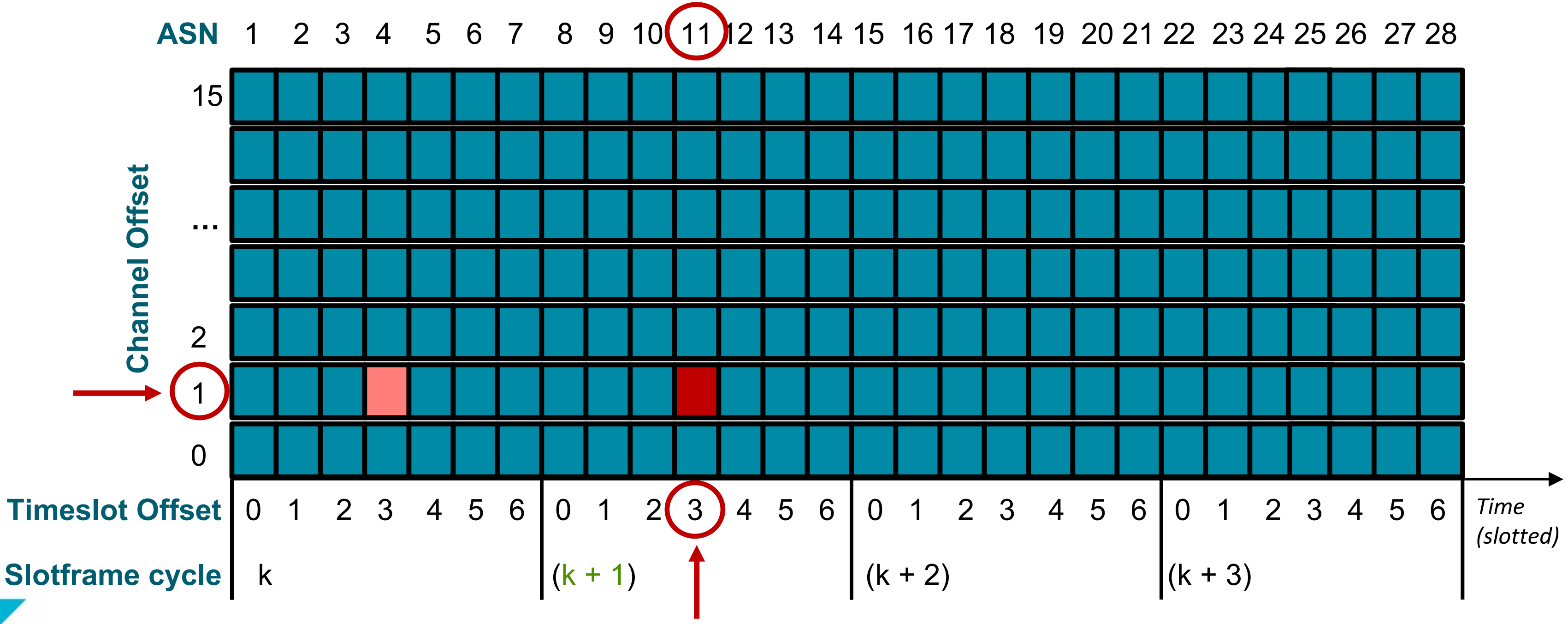
An Example of the CHS Operation

Lookup Table

Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



$$Radio\ Channel = F[(11 + 1)\%16]$$

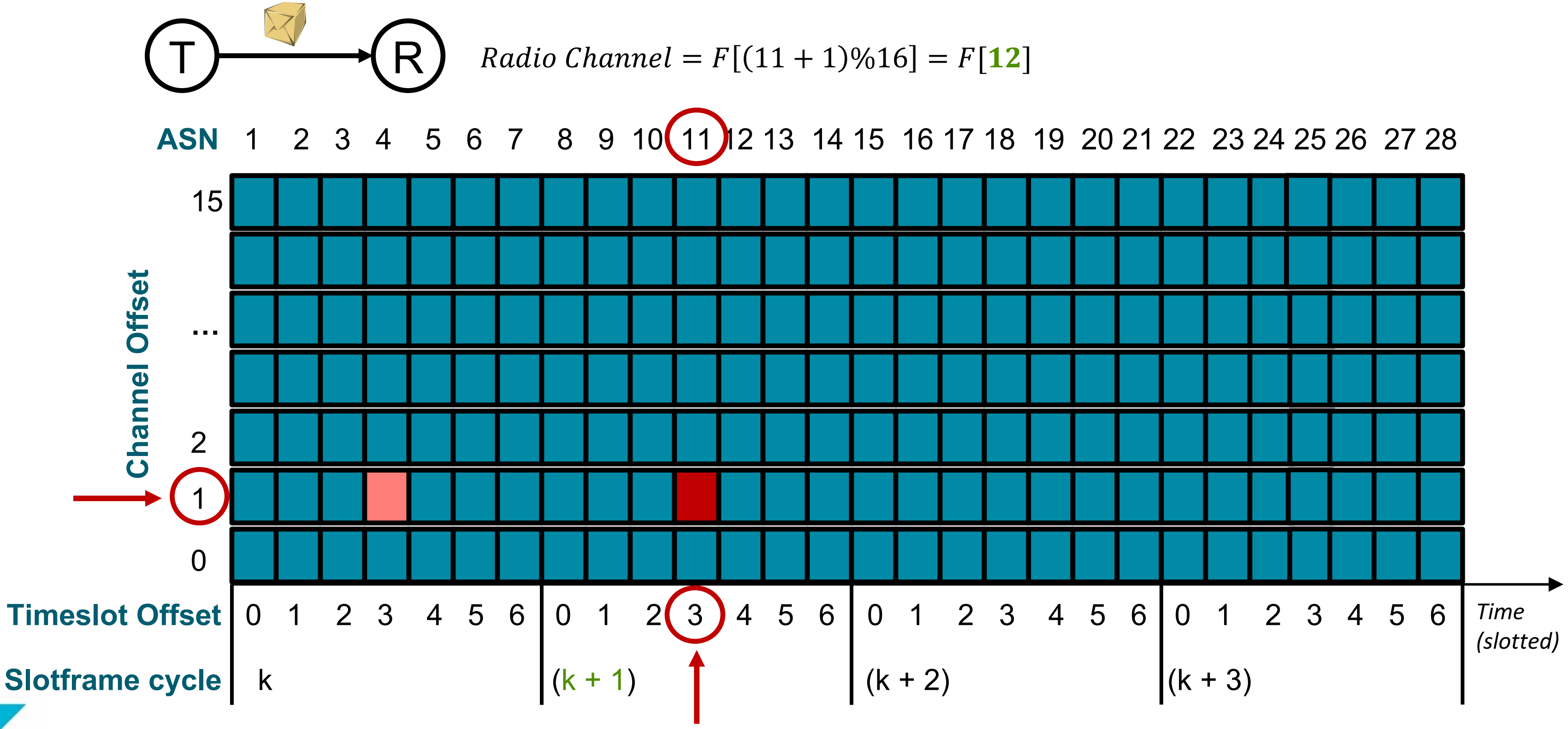


Channel ch16

An Example of the CHS Operation

Lookup Table	
Index	Radio Channel
0	11
1	12
2	13
3	14
4	15
5	16
6	17
7	18
8	19
9	20
10	21
11	22
12	23
13	24
14	25
15	26

$$Radio\ Channel = F[(11+1)\%16] = F[\mathbf{12}]$$

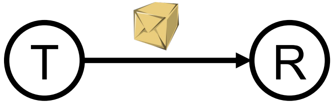


Channel ch16

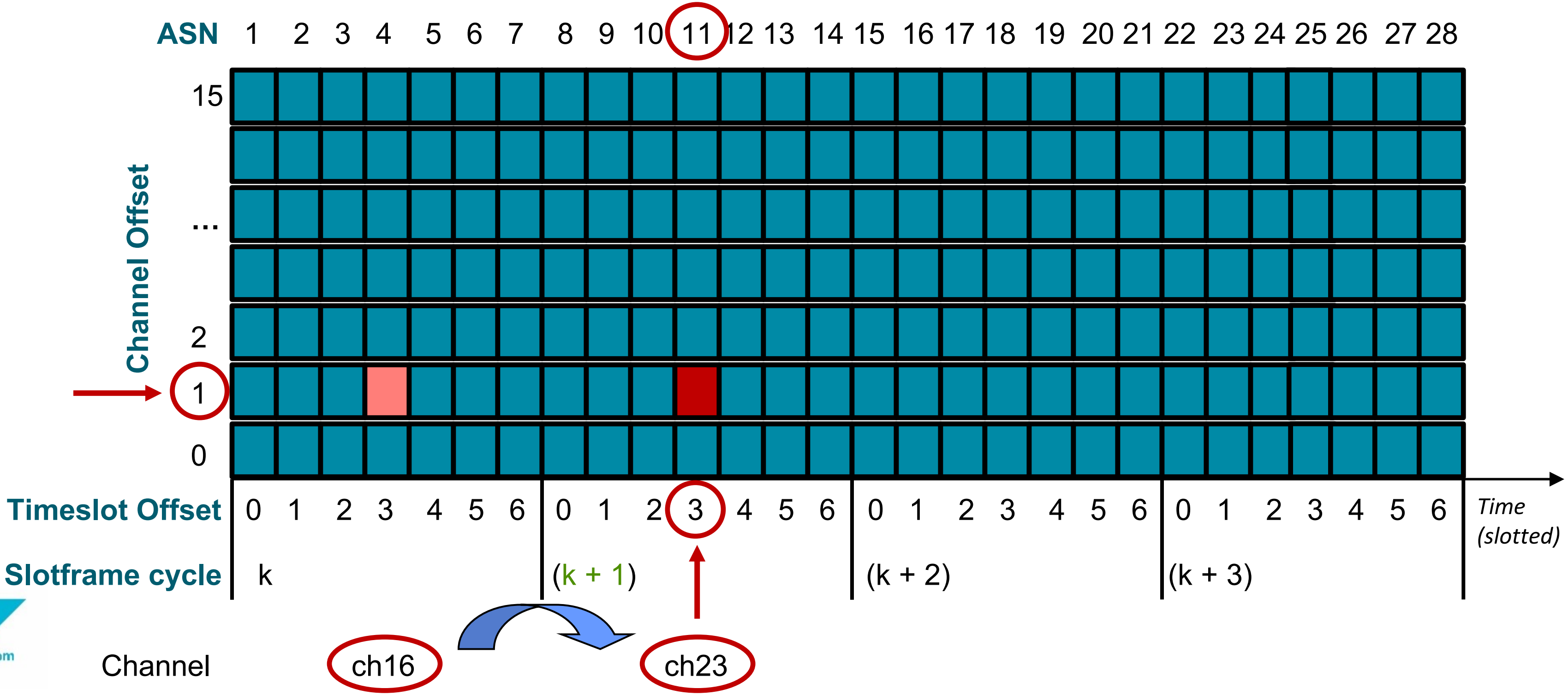
An Example of the CHS Operation

Lookup Table

Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*



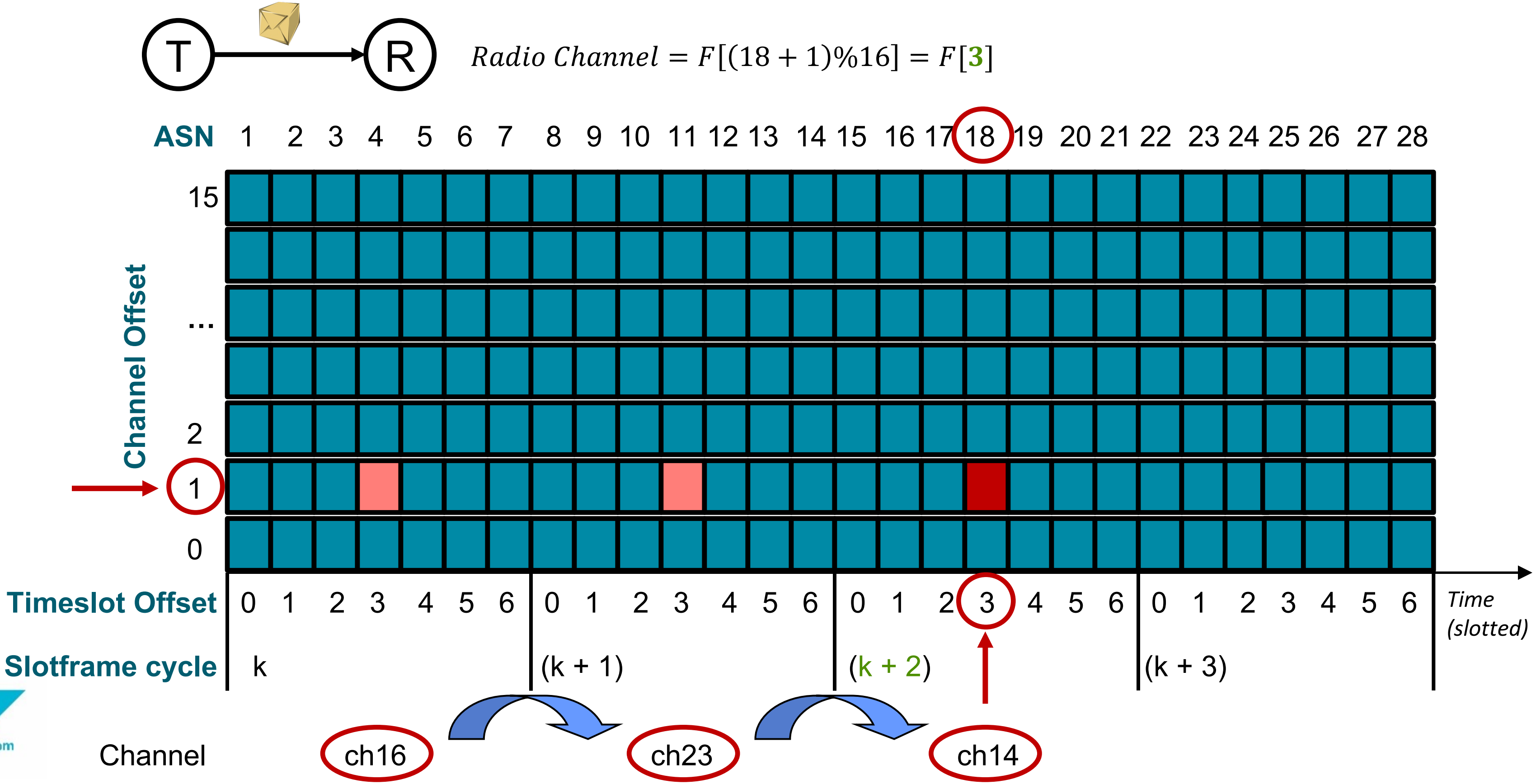
$$Radio\ Channel = F[(11+1)\%16] = F[12]$$



An Example of the CHS Operation

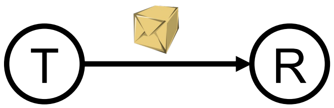
Lookup Table

Index	Radio Channel
0	*11*
1	*12*
2	*13*
3	*14*
4	*15*
5	*16*
6	*17*
7	*18*
8	*19*
9	*20*
10	*21*
11	*22*
12	*23*
13	*24*
14	*25*
15	*26*

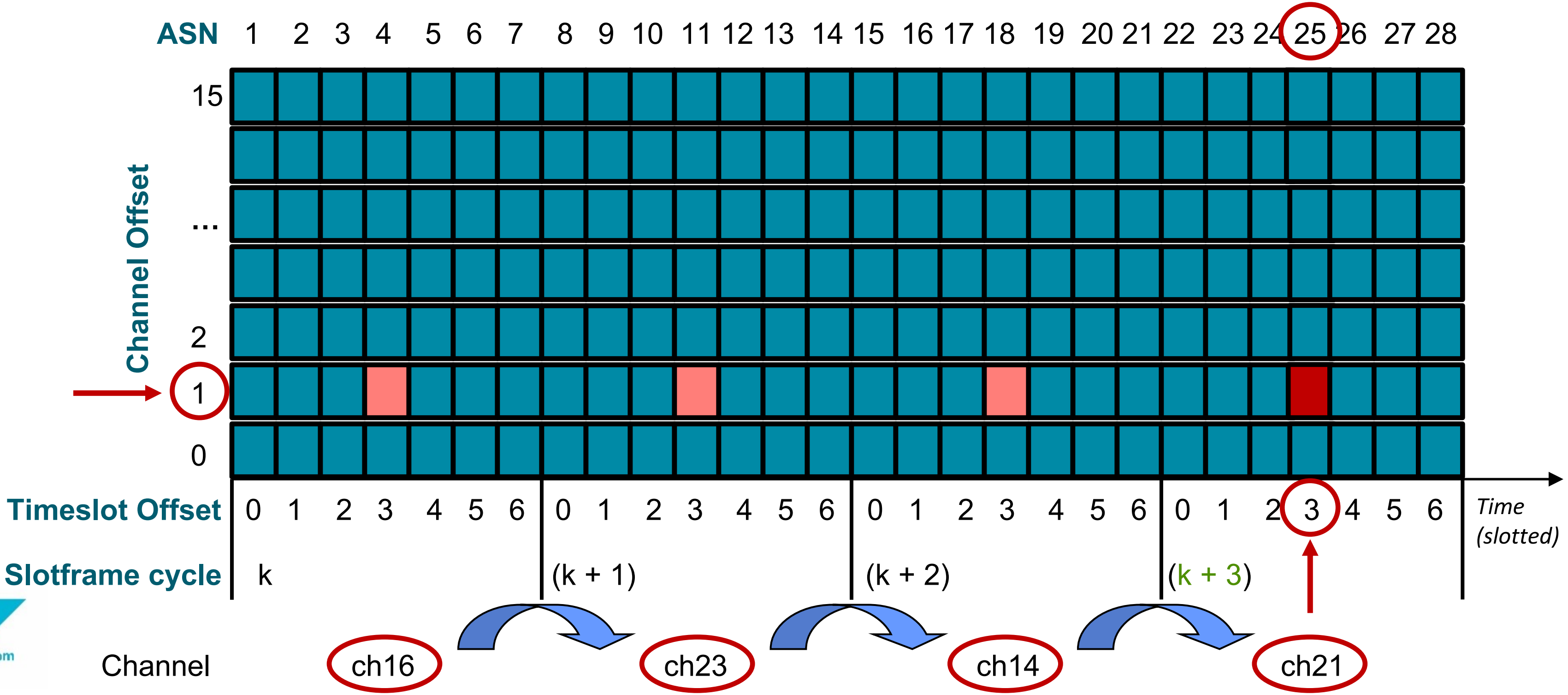


An Example of the CHS Operation

Lookup Table	
Index	Radio Channel
0	11
1	12
2	13
3	14
4	15
5	16
6	17
7	18
8	19
9	20
10	21
11	22
12	23
13	24
14	25
15	26



$$Radio\ Channel = F[(25+1)\%16] = F[10]$$



IEEE 802.15.4 TSCH MAC Protocol and Channel Hopping Sequence algorithm

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