# REALIZATION OF AN 802.15.4-LIKE MAC LAYER WITH MOTE RUNNER

DISIM - Università degli Studi dell'Aquila

Students:
Andrea Salini - 231413
Lorenzo Di Giuseppe - 227515
Matteo Gentile - 230997

Professors:
Fortunato Santucci
Luigi Pomante

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# INTRODUCTION

- Object of this project is the exploration of Mote Runner, an IBM's infrastructure platform for WSN
- For a deep understanding of MR the focus of this works was the design and develop of a 802.15.4-like MAC layer
- Oscilloscope is an applications developed to test the MAC layer
- The application was tested on IRIS mote

# INDEX


- Introduction to Mote Runner
- Testing Mote Runner
- A MAC Layer in Mote Runner
- 6LoWPAN implementation in Mote Runner
- Conclusion

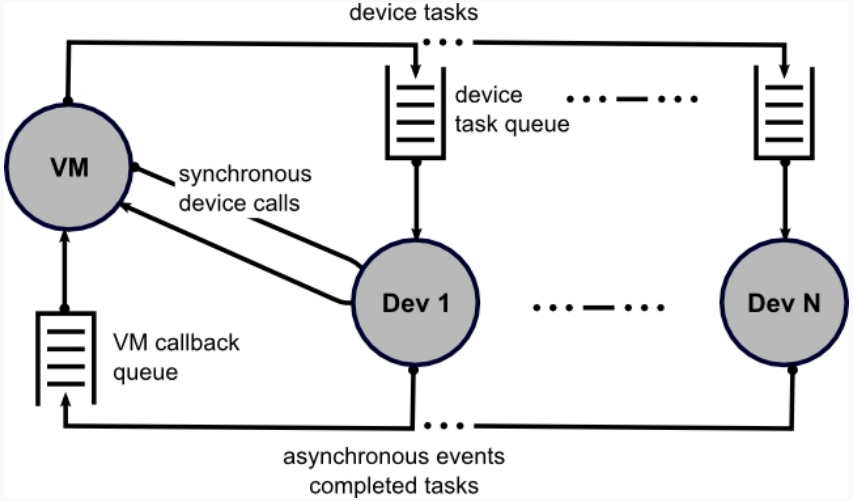
# INTRODUCTION TO MOTE RUNNER

# MOTE RUNNER

- An OS and a runtime and development environment for WSN
- Key features:
  - Support for RT constraints & energy awareness
  - Portability thanks to a VM that abstracts the HW
  - Event oriented programming paradigm
  - High level coding (Java - C#)
  - Debugging & simulation environments
- It’s still in beta and is evolving towards IoT

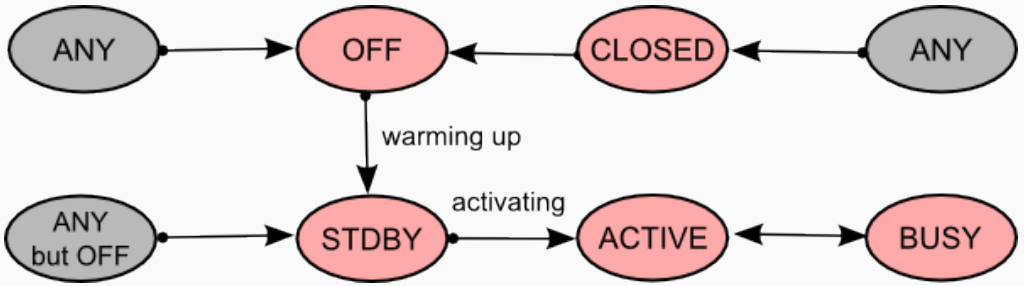
# MOTE RUNNER OPERATING SYSTEM

- Mote Runner system provides:
  - A Virtual Machine for executing byte codes
  - An Operating System for:
    - organizing access to different devices
    - scheduling the various activities



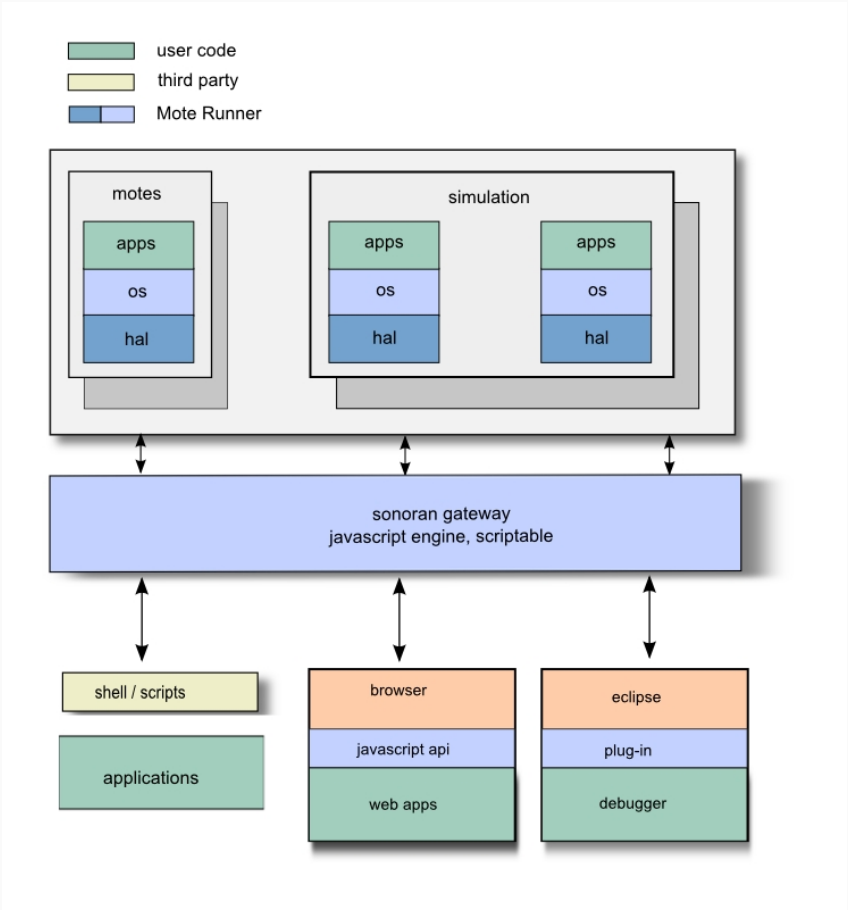
# DEVICE MODEL

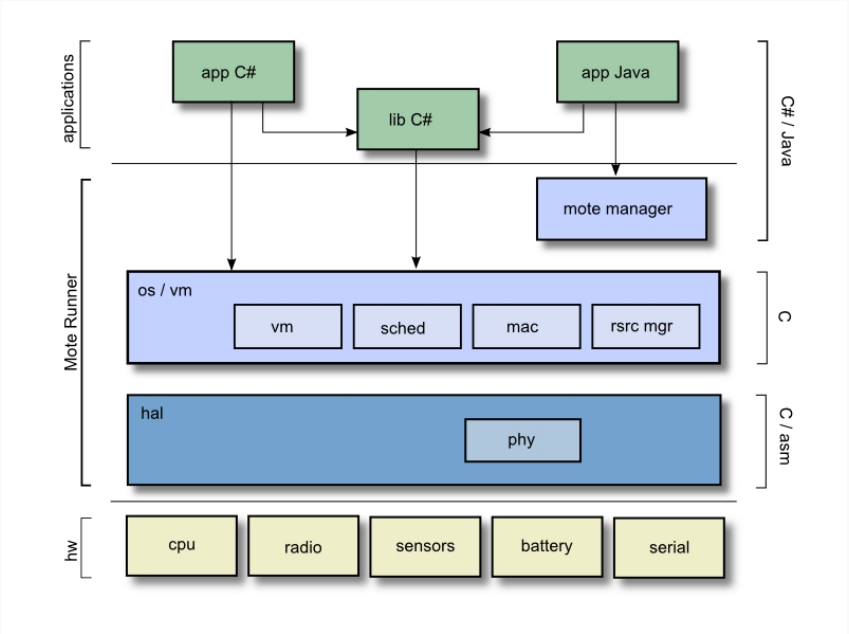
- The OS assumes that all devices have the following states




- The OS manage implicitely most of the state changes:
  - Makes sure that the device ramp up happens before the requested time
  - Keeps device in states with the lowest energy consumption
  - Application, however, can put devices into the states CLOSED, OFF and STDBY

# MOTE RUNNER


user code
third party
Mote Runner
motes
apps
os
hal
simulation
apps
os
hal
apps
os
hal
sonoran gateway
javascript engine, scriptable
shell / scripts
applications
browser
javascript api
web apps
eclipse
plug-in
debugger


applications
app C#
app Java
lib C#
mote manager
C# / Java
Mote Runner
os / vm
vm
sched
mac
rsrc mgr
C
hal
phy
C / asm
hw
cpu
radio
sensors
battery
serial

# Mote runner - v.11, v.13 beta

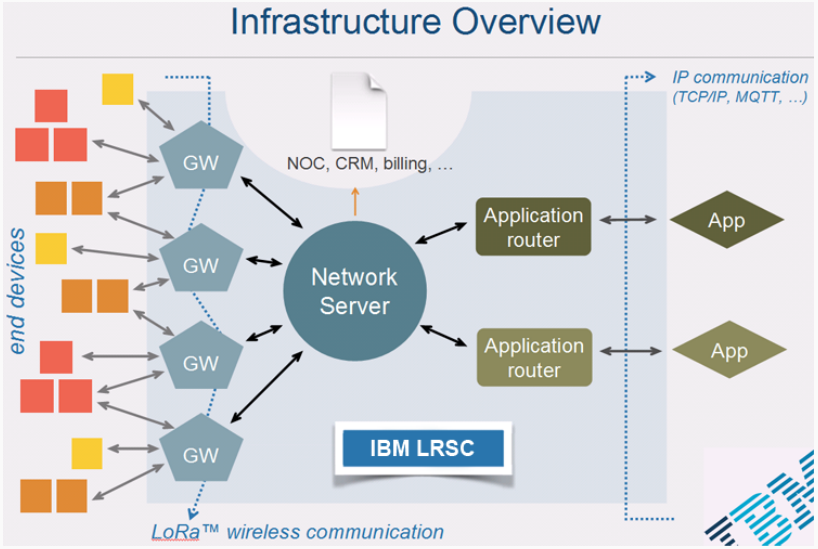
- They support IEEE 802.15.4
  - exposing a low radio level API that can be used to implement custom MAC layer
  - dropping messages with header structure not 802.15.4 compliant in the radio stack
- Offer Hopi
  - A multi-hop data gathering protocol
  - Used to collect data from motes setting automatically a tree network

# MOTE RUNNER - V.17.1.8C (LATEST)

- Supports only two platforms: IMST & Blipper
- It's based on a different radio layer: LoRa™
- It offers a build-in MAC layer: LRSC - Low Range Signaling & Control
  - It supports only a network topology: the LRSC one
  - The offered API is poor since the radio is hidden in the firmware (not compatible with previous versions)

# LRSC - ARCHITECTURE

- Gateways (GW) are connected to server on IP
- Motes comunicate with server in tunneling TCP/UDP over IP
- Motes comunicate with GW with LoRa single-hop



# IBM LRSC

- The Long Range Signaling and Control (LRSC) system is a network infrastructure which relies on LoRa™, modulation technology developed by Semtech for wireless bidirectional communication over distances of up to 15 km in semi-rural environments and up to five km in dense urban environments.
- All communication is generally bi-directional, although uplink communication from end devices to the network server is strongly favored, and is based on LoRa.

# LRSC NETWORK SIMULATION

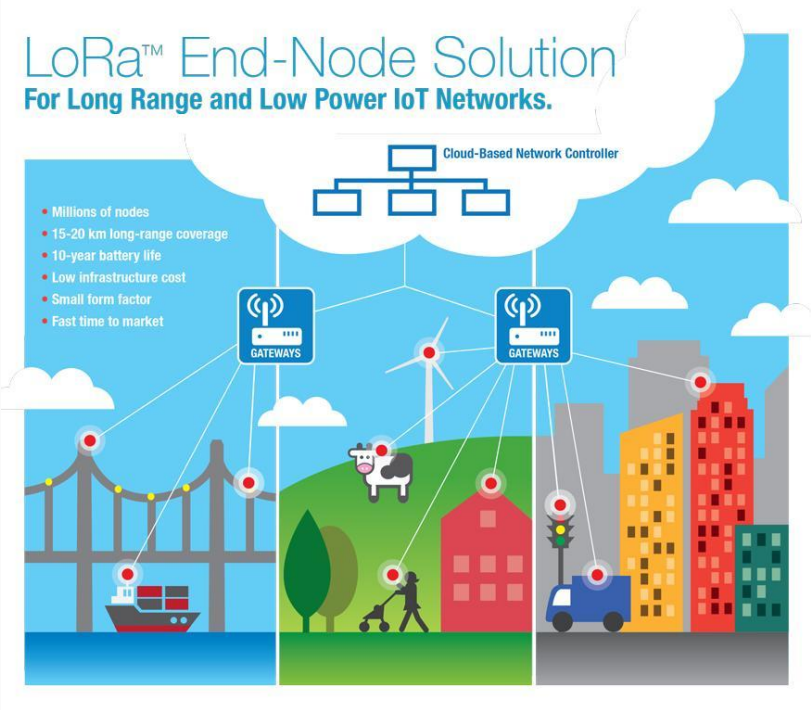
The Mote Runner SDK ships with:

- LoRa Mac library providing an API for accessing a LRSC network.
- LIP shell interface to control the Mac from the Mote Runner shell MRSH.

The main constraint for our intial purpose depends on the fact that the end devices cannot communicate directly. Any message should be sent over the LRSC network.

# LORA™

- LoRa™Alliance
  - Target: IoT, machine-to-machine (M2M), smart city, and industrial applications
  - Intiated to standardize Low Power Wide Area Networks (LPWAN)



# LORA™

- LoRa™Technology
  - LoRaWAN pledeges to extend the radio range by 10x while using only one third of the power used by competing solutions
  - Star (of stars) topology
  - Gateways relay messages between end-devices and a central network server
  - Communication between end-devices and gateways is spread out on different frequency channels and data rates.
  - Data rates: 0.3 - 50 kbps

# LORA™

- ...and more
  - adaptive data rate (ADR)
  - secure communication (on network and application layers and end-point device key)
  - three classes of end-point devices.
  - More info on http://lora-alliance.org/

# MOTE RUNNER - CONCLUSION

- For the purpose of this work:
  - MR allows dynamic reprogramming of motes with a control server using WLIP
  - v.17.1.8c is not suitable
    - LoRa is available only for a limited number of platforms (until now!)
    - LRSC doesn't permit to customize the MAC behaviour
    - The radio is not exposed
  - v.11, v.13 are better choices:
    - radio interface could be used to implement an 802.15.4 MAC
    - this MAC could be possibly used to build upper layer with WIDS
- This does not exclude a future integration with LoRa-LRSC

# LORAWAN

# A DEEPER LOOK AT LORA

- LoRaWAN is a Low Power Wide Area Network (LPWAN) specification intended for wireless battery operated Things in regional, national or global network.
- LoRaWAN target key requirements of internet of things:
  - secure bi-directional communication
  - mobility
  - localization services

# LORA DEVICES SYNC

For time synchronization gateways periodically broadcast so-called beacons. Each beacon minimally contains:

- available channels (ChMask)
- current GPS time (Time)

The broadcasting of beacons (in implicit mode) is done time-synchronously (BEACON_INTERVAL) by all gateways of a network with no interference.

| | **PHY** | Preamble | BCNPayload | | | | |
|---|---|---|---|---|---|---|---|
| **Octets** | 4 | 3 | 2 | 4 | 2 | 7 | 2 |
| **BCNPayload** | RFU | NetID | ChMask | Time | CRC | GwID | CRC |

# LORA MAC PAYLOAD FRAME

LoRa MAC message types:

- join request
- join accept
- unconfirmed data messages
- confirmed data messages

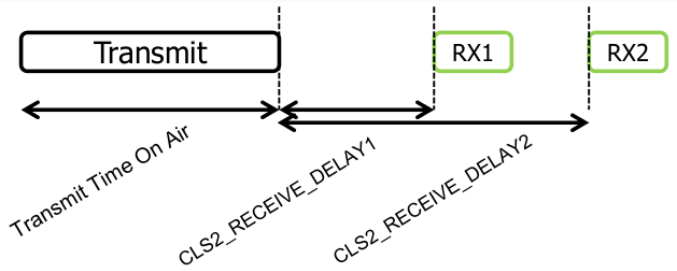
| Octets | 1 | 1..59 | 4 |
|---|---|---|---|
| PHYPayload | MHDR | MACPayload | MIC |

| Bit# | 7..5 | 4..2 | 1..0 |
|---|---|---|---|
| MHDR | MType | RFU | Major |

| MType | Description |
|---|---|
| 000 | Join Request |
| 001 | Join Accept |
| 010 | Data Unconfirmed |
| 011 | Data Confirmed |
| 100..110 | RFU |
| 111 | Proprietary |

# LORA END-DEVICES

- Release v1.0 allows at MAC and Application layers, Bi-directional communications:
  - Class A: after send operation two tiny time windows are opened in order to allow reception
  - Class B: send and receive operations may be scheduled based on the time information contained in the beacons
- subsequent releases:
  - Class C: nearly continuously open receive windows, only closed when transmitting.



# LORA SECURE COMMUNICATIONS - 1

In order to partecipate in a LoRa network an end device first has to be personalized and the activated. Activation of an end device can be achieved in two ways:

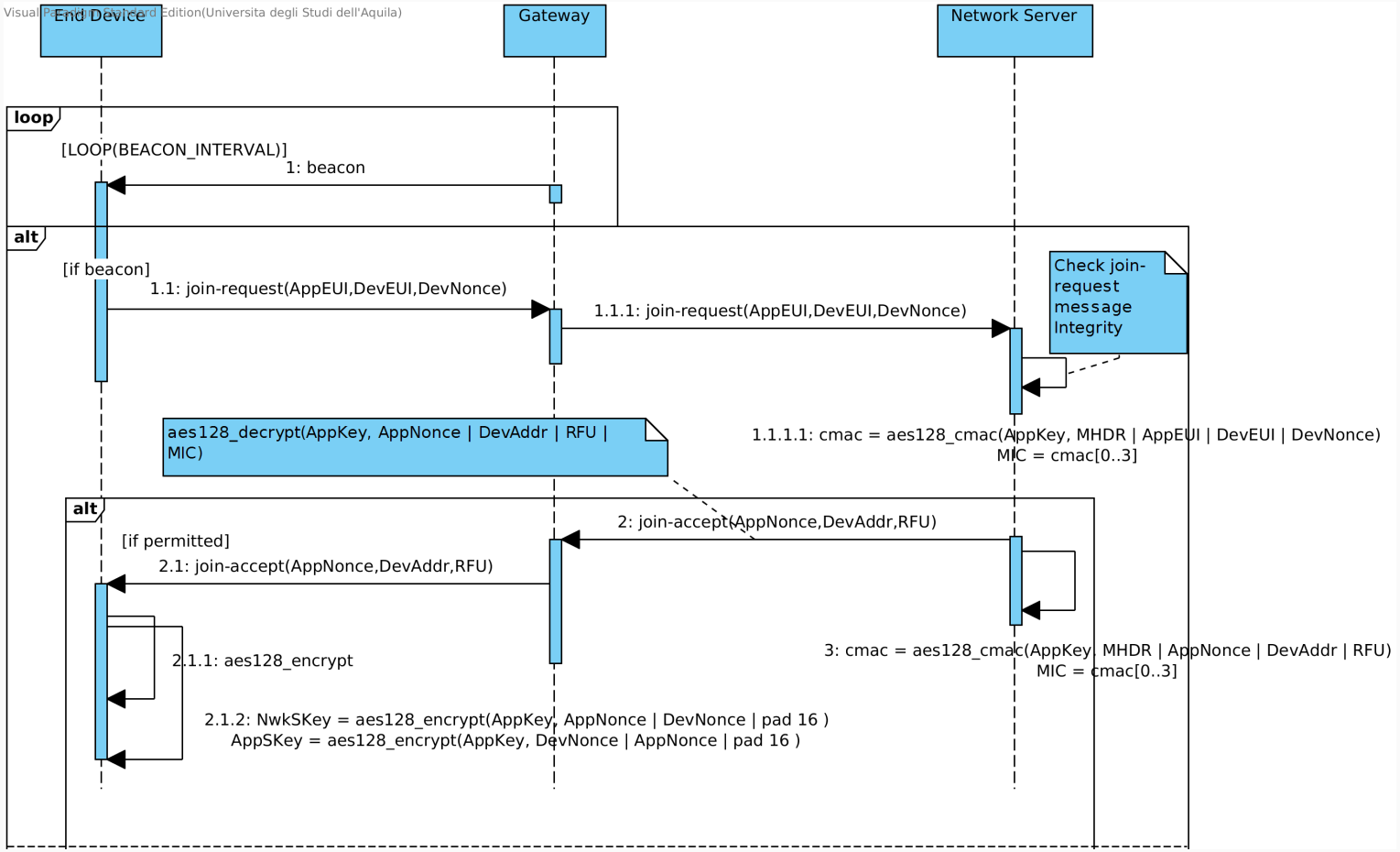
- OTAA (over-the-air activation) when an end device is deployed or reset;
- APB (activation by personalization) one-step personalization and activation.

# LORA SECURE COMMUNICATIONS - 2

During activation the end device holds the following informations:

- **DevAddr:** device ID of 32 bits that uniquely identifies the end device.
- **AppEUI:** globally unique application ID that uniquely identifies the application provider of the end device.
- **NwkSKey:** device-specific network session key, ensures data integrity and os used to encrypt/decrypt MAC data messages payload
- **AppSKey:** device-specific application session key, used to encrypt and decrypt the payload field of application-specific data messages.

# LORA SECURE COMMUNICATIONS - OTAA



# LORA MOBILITY

LoRa network data rates are:

- Network controlled for fixed devices by means of using ADR bit in the PHY payload of data messages:
  - If is set, the network will control the data rate of the end device through the appropriate MAC commands
  - If is cleared, the network will not attempt to control the data rate of the end device independently of the received signal quality
- default for mobile end-devices.

| Octets | 4 | 1 | 2 | 0..15 |
|---|---|---|---|---|
| FHDR | DevAddr | FCtrl | FCnt | FOpts |

| Bit# | 7 | 6 | 5 | 4 | 3..0 |
|---|---|---|---|---|---|
| FCtrl | ADR | ADRACKReq | ACK | FPending | FOptsLen |

LoRa modes (868Mhz band):

| Mode | BW | CR | SF | Sensitivity (dB) | Transmission time (ms) for a 100-byte packet sent | Transmission time (ms) for a 100-byte packet sent and ACK received | Comments |
|---|---|---|---|---|---|---|---|
| 1 | 125 | 4/5 | 12 | -134 | 4245 | 5781 | max range, slow data rate |
| 2 | 250 | 4/5 | 12 | -131 | 2193 | 3287 | - |
| 3 | 125 | 4/5 | 10 | -129 | 1208 | 2120 | - |
| 4 | 500 | 4/5 | 12 | -128 | 1167 | 2040 | - |
| 5 | 250 | 4/5 | 10 | -126 | 674 | 1457 | - |
| 6 | 500 | 4/5 | 11 | -125,5 | 715 | 1499 | - |
| 7 | 250 | 4/5 | 9 | -123 | 428 | 1145 | - |
| 8 | 500 | 4/5 | 9 | -120 | 284 | 970 | - |
| 9 | 500 | 4/5 | 8 | -117 | 220 | 890 | - |
| 10 | 500 | 4/5 | 7 | -114 | 186 | 848 | min range, fast data rate, minimum battery impact |

**Figure 1:** SX1272 module modes

All gateways send their beacon at exactly the same point in time:

- on first 15 bytes there are no visible on-air collisions
- wrt the optional part , device within the proximity of more than one gateway will still be able to decode the strongest beacon with high probability

| Bits | 4 | 4 | 24 | 24 |
|---|---|---|---|---|
| GwID | InfoDesc | Info | Lat | Lng |

Figure 2: Beacon optional part

# LORA CONCLUSIONS 1

For what applications is LoRa a good option?

- solar or mains-powered nodes transmitting every 10 or 15 minutes in networks with low or medium number of nodes
- very wide networks, with long-range links (Up to 22km, Sensitivity -134dBm)

# LORA CONCLUSIONS 2

For what applications is NOT LoRa a good option?

- projects which require high data-rate and/or very frequent transmissions (e.g., each 10 seconds)
- including receipt of ACK message, mode 10 (the fastest), takes twice the time of XBee (<200ms)
- due to low data-rates OTA re-programming is not easily achieved (3G, GPRS may be better choiches)

# TESTING MOTE RUNNER

# POINTS TO EXPLORE

- MR v.13 offers:
  - Radio interface IEEE 802.15.4 compliant
  - Hopi
  - An IRIS-friendly simulation environment
  - Many nice features (Debugger, Logger and so on)

# PROGRAMMING THE RADIO

- com.ibm.saguaro.system.Radio
  - This is a generic class in the IBM saguaro system to use the device radio
  - It offers a low level API with the following functionality:
    - open: opens the radio, once opened no other assembly can use it
    - close: releases the radio so that others can use it
    - setter and getters for channel and network parameters (addresses, panid...)
    - startReceive: listens the channel (in one of the many receiption mode)
    - transmit: begin to transmit a pdu

# TRANSMISSION & RECEPTION

- These operations require much attention:
  - The radio permits to transmit every type of pdu, but it's possible to receive only packets with 802.15.4 well formed headers
  - It's also possible to receive in promiscuous mode to sniff for every packet, but this exposes to interferences
- Each mote holds 3 addresses:
  - a 16-bit PAN identifier
  - a 64-bit extended address that uniquely identifies a mote
  - a 16-bit short address that's application and protocol specific

# TRANSMISSION & RECEPTION

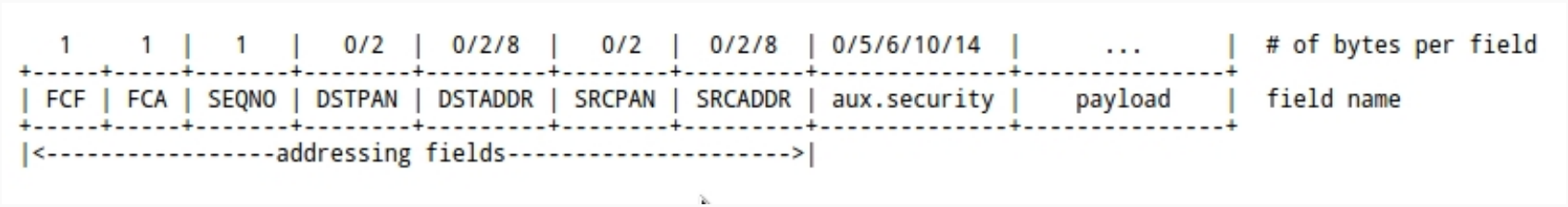



**Figure 3:** PDU header format

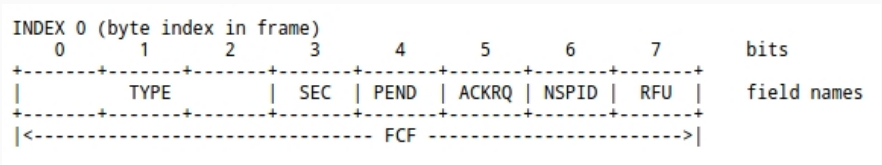



**Figure 4:** Frame Control Flags

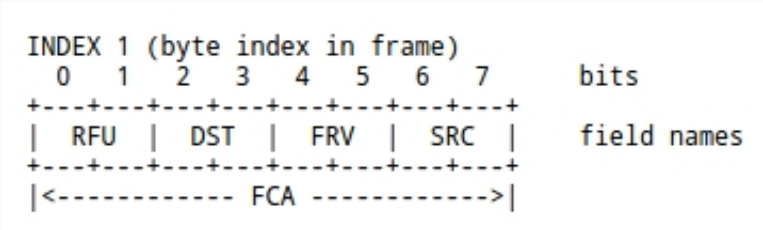



**Figure 5:** Frame Control Address Flags

# TX/RX REAL AND REAL TIME CONSTRAINTS

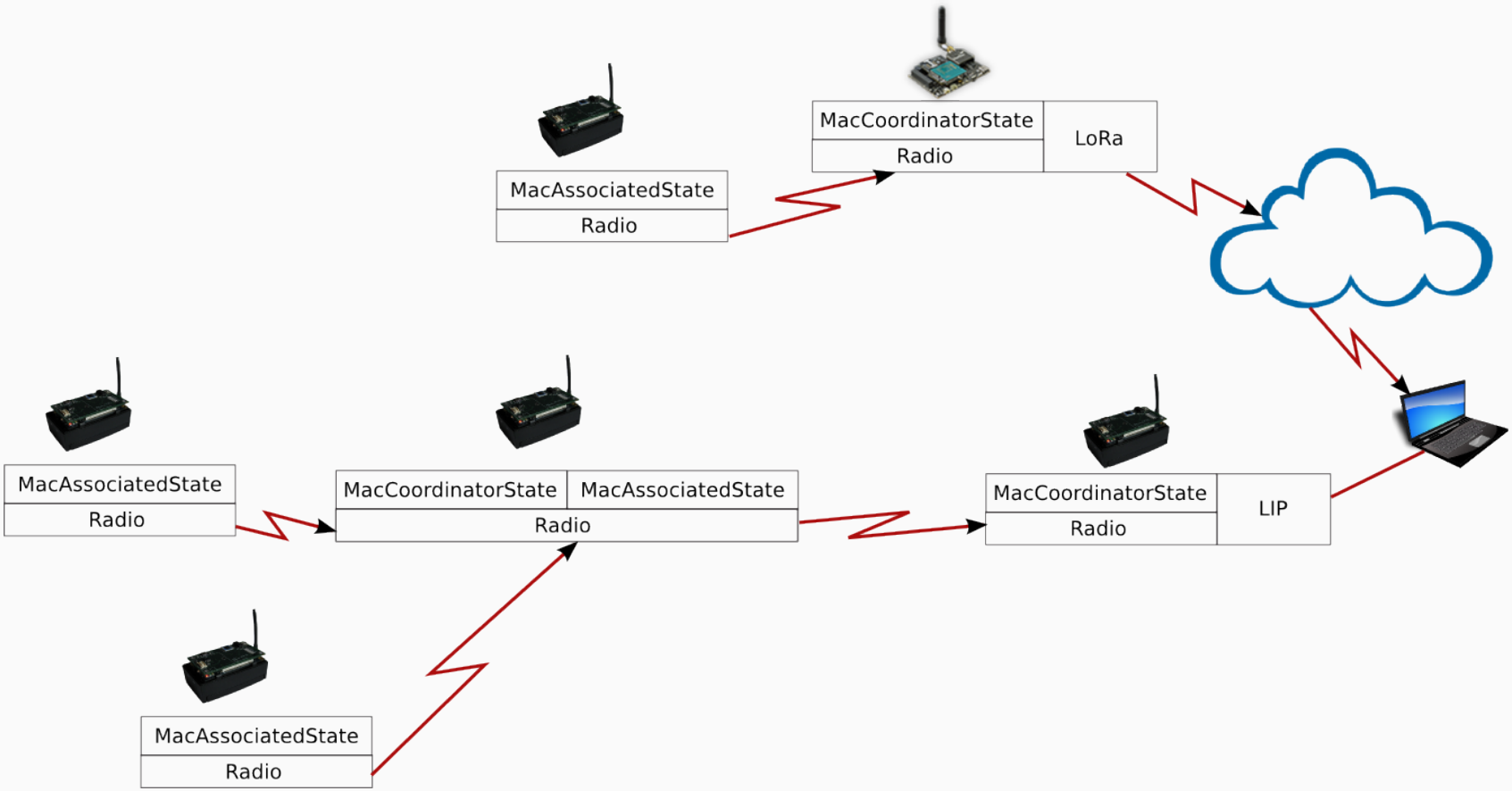
- It’s possible to operate in many different ways with regards to real time constraints:
  - It’s possible to receive/transmit ASAP (As Soon As Possible) or EXACTLY at the specified time or ...
  - Rx/Tx require a start operation time and an end one
  - MR manages autonomously all warm up and ramp up to make the device ready at the specified time
  - The device turn off at the end and an event is raised to be managed with delegation
  - If the device cannot be ready at the specified time or an error occurs which reports this status

# A MAC LAYER IN MOTE RUNNER

# DESIGN STRATEGY

- Mac class behaviours:
  - Coordinator -> Beacon enabled, Slotted CSMA/CA
  - Unassociated -> Handles association with a Coordinator
  - Associated -> Sends data from upper layer and receives data from Coordinator
- Flexibility:
  - State changes are ruled by Mac class through events
  - Mac can handle more than one state -> Mac - entities
    - e.g.: Coordinator - Associated

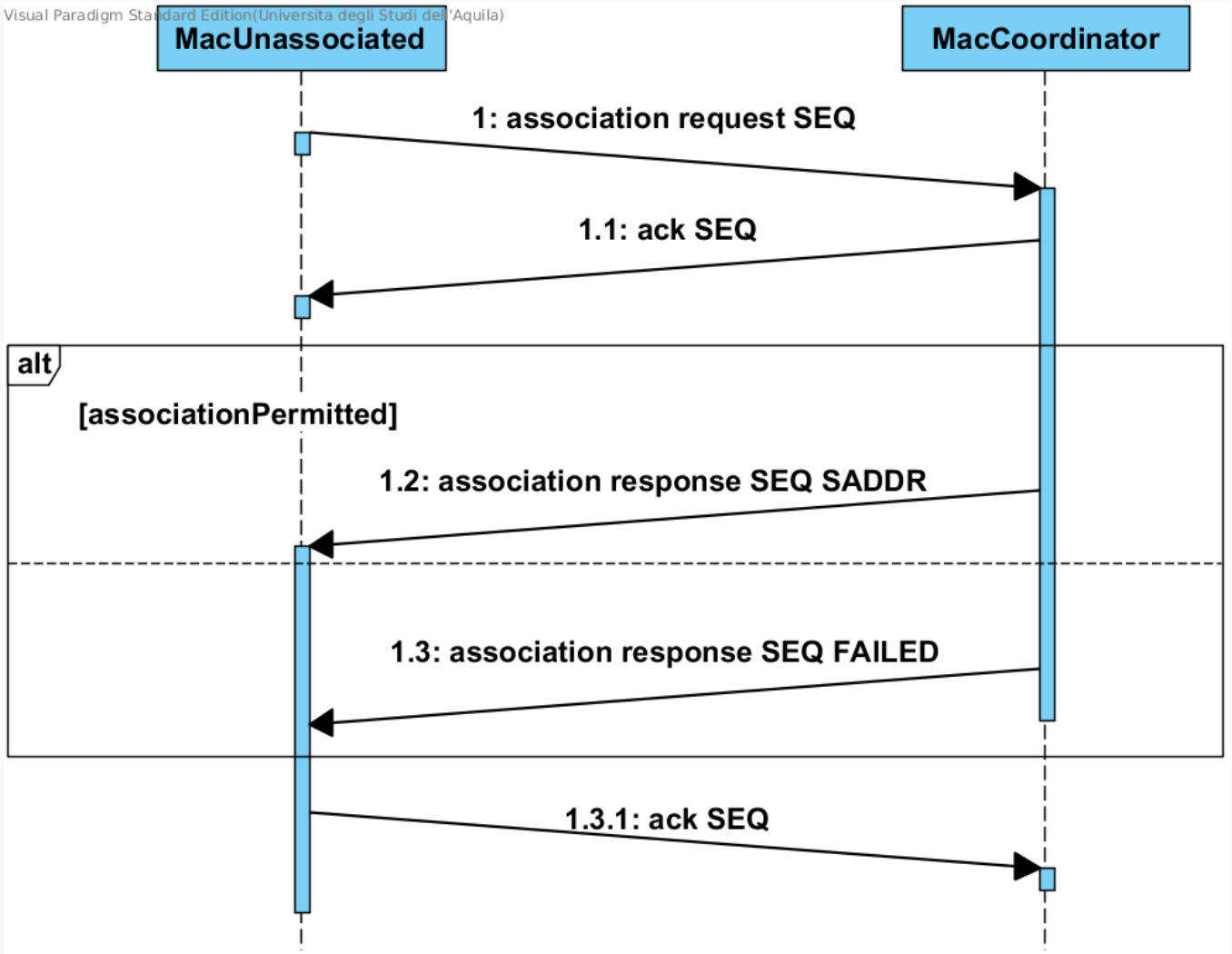
# THE CONCEPT


MacAssociatedState
Radio
MacCoordinatorState
Radio
LoRa
MacAssociatedState
Radio
MacCoordinatorState
MacAssociatedState
Radio
MacCoordinatorState
Radio
LIP
MacAssociatedState
Radio

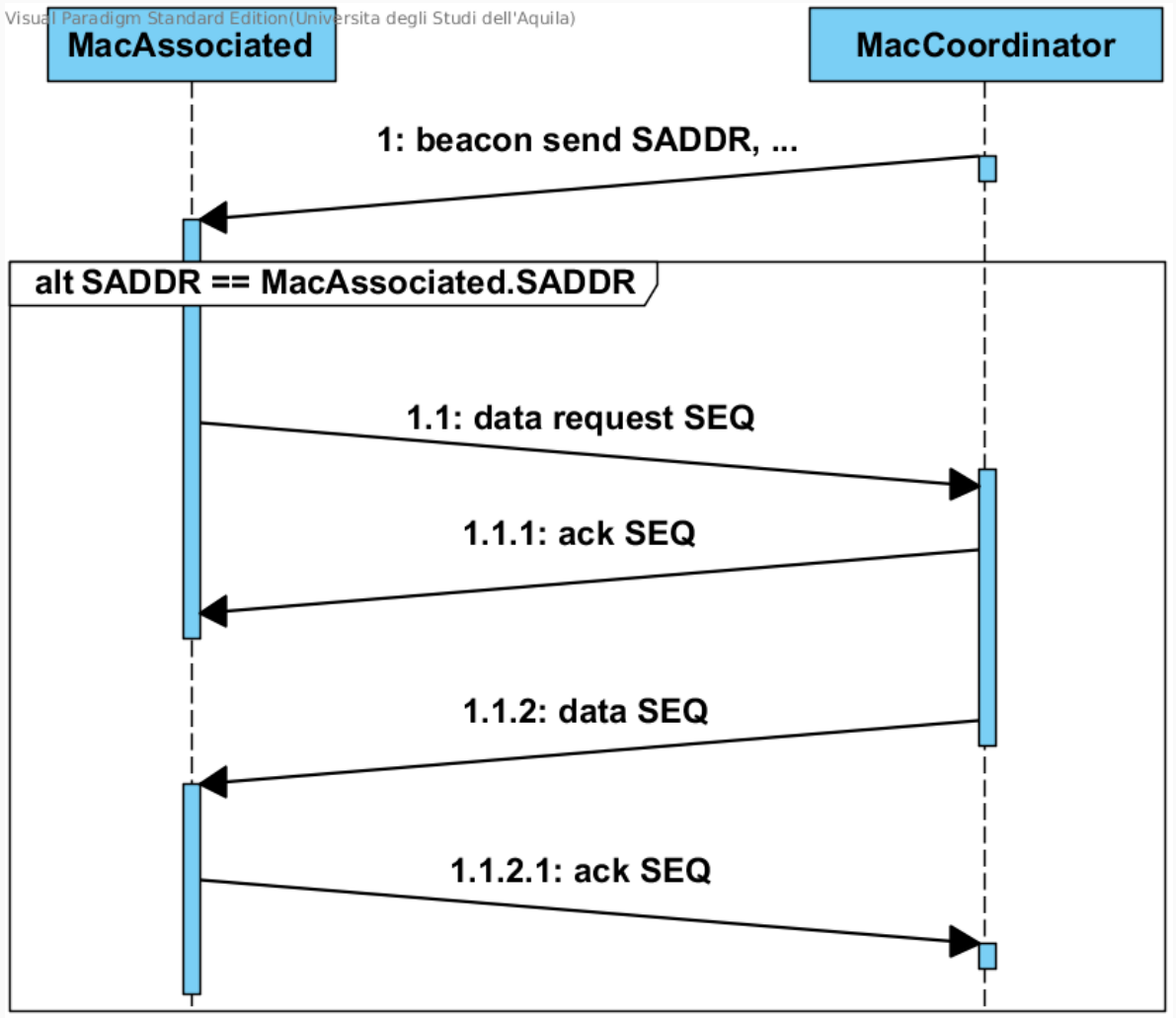
# ABOUT THE CONCEPT

- Motes have to be subdivided into PANs
  - Every PAN has a PAN Id
  - Every mote has a unique short address (SADDR) inside the PAN
- To obtain the SADDR the mote must associate with the PAN coordinator
- To grant communication between motes synchronization is crucial
  - Beacon + Superframe
- The adopted procedures follow 802.15.4 standard

# ASSOCIATION

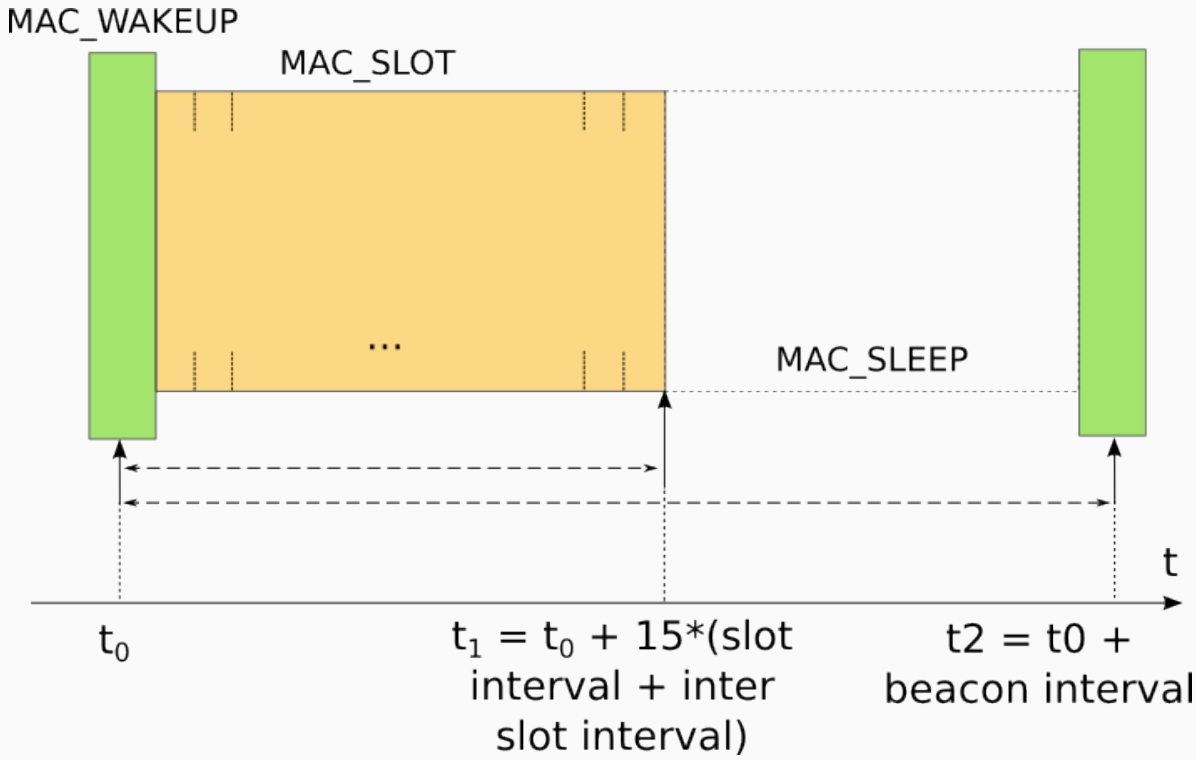


# DATA INDIRECT



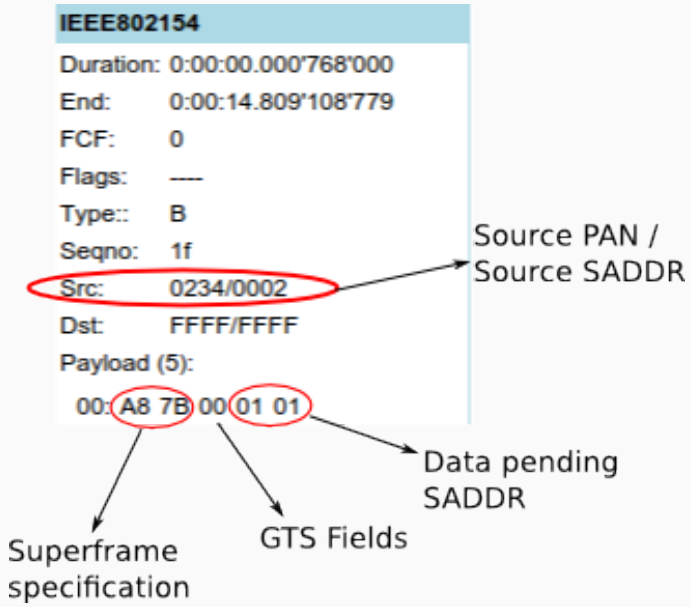
# TIMING WITH BEACON

- Grants synchronization between mote and coordinator
- Realized with a timer and scheduled events



# BEACON

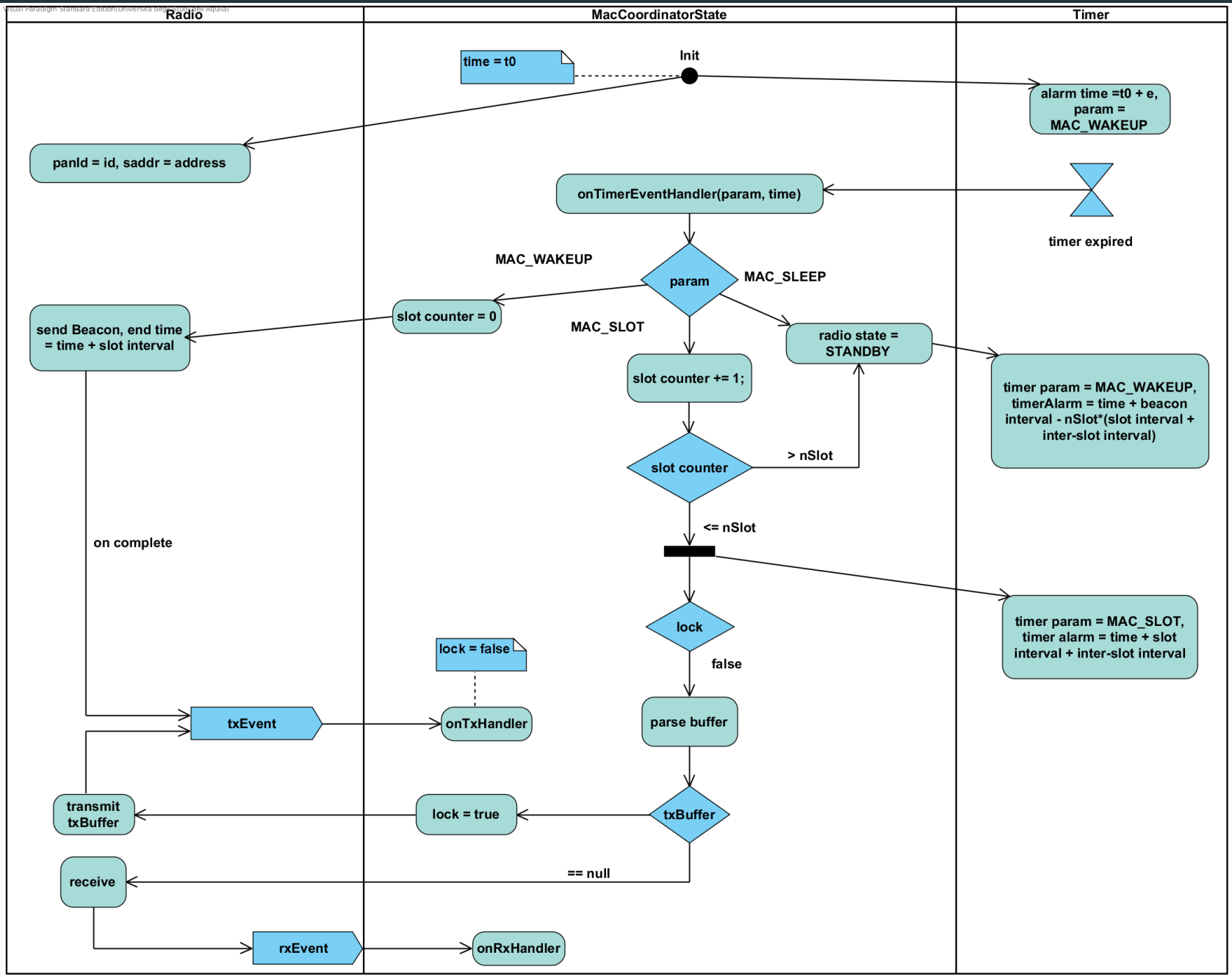
- Superframe Specification:
  - Beacon Order -> BO
  - Superframe Order -> SO
  - Association permitted




$$\text{Beacon Interval} = \frac{60sym \cdot n.Slot \cdot 2^{BO}}{20\text{kbps}}$$

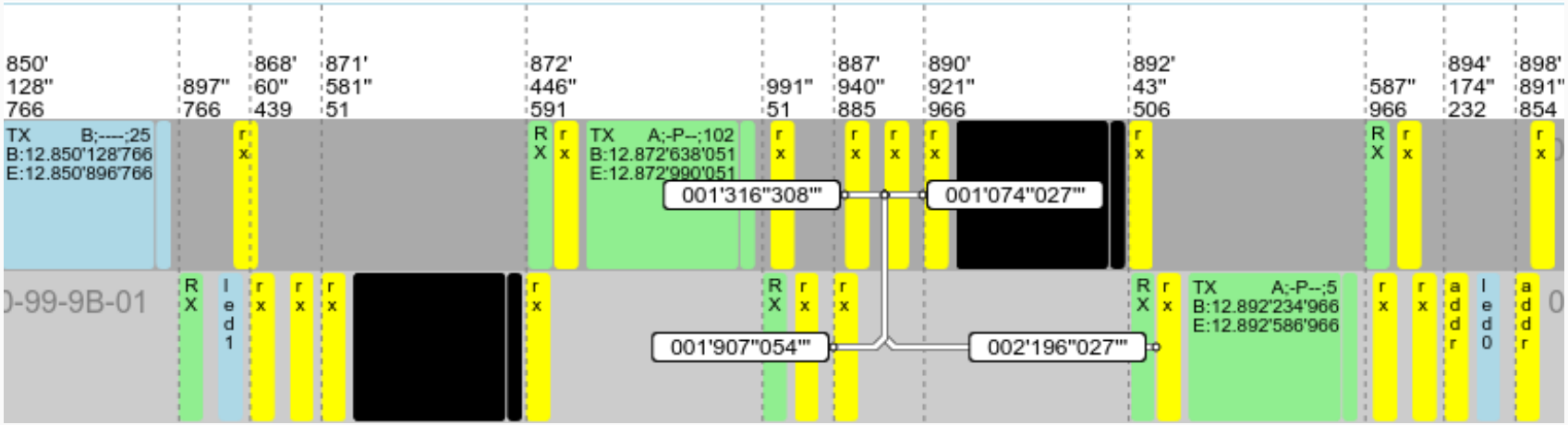
$$\text{Superframe Duration} = \frac{60sym \cdot n.Slot \cdot 2^{SO}}{20\text{kbps}}$$

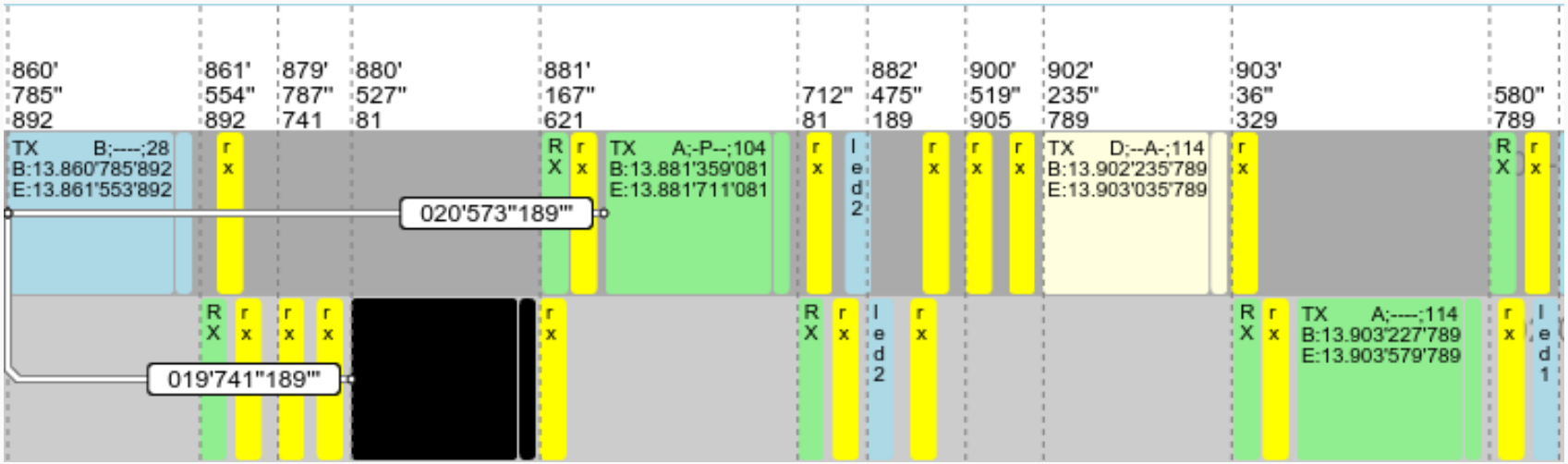
# MAC COORDINATOR BEHAVIOUR



# EXAMPLE

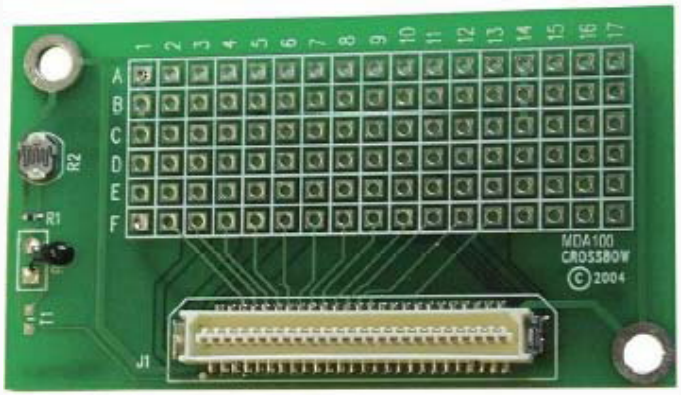
The node associates with coordinator, then responds to beacon pending list and gets data.



# OSCILLOSCOPE

- Periodically reads values of TEMPERATURE and LIGHT
- Read interval and type can be setted by master
- Readings are sent through MAC once associated to master
- Readings done by MDA100 board



# MASTER OSCILLOSCOPE

- It creates a PAN with the MAC layer
- It listens LIP for commands that sends to associated motes
- MAC layer sends readings to Master Oscilloscope that are redirected through LIP
- A JavaScript Socket running on Sonoran process displays the readings

# 6LoWPAN implementation in Mote Runner

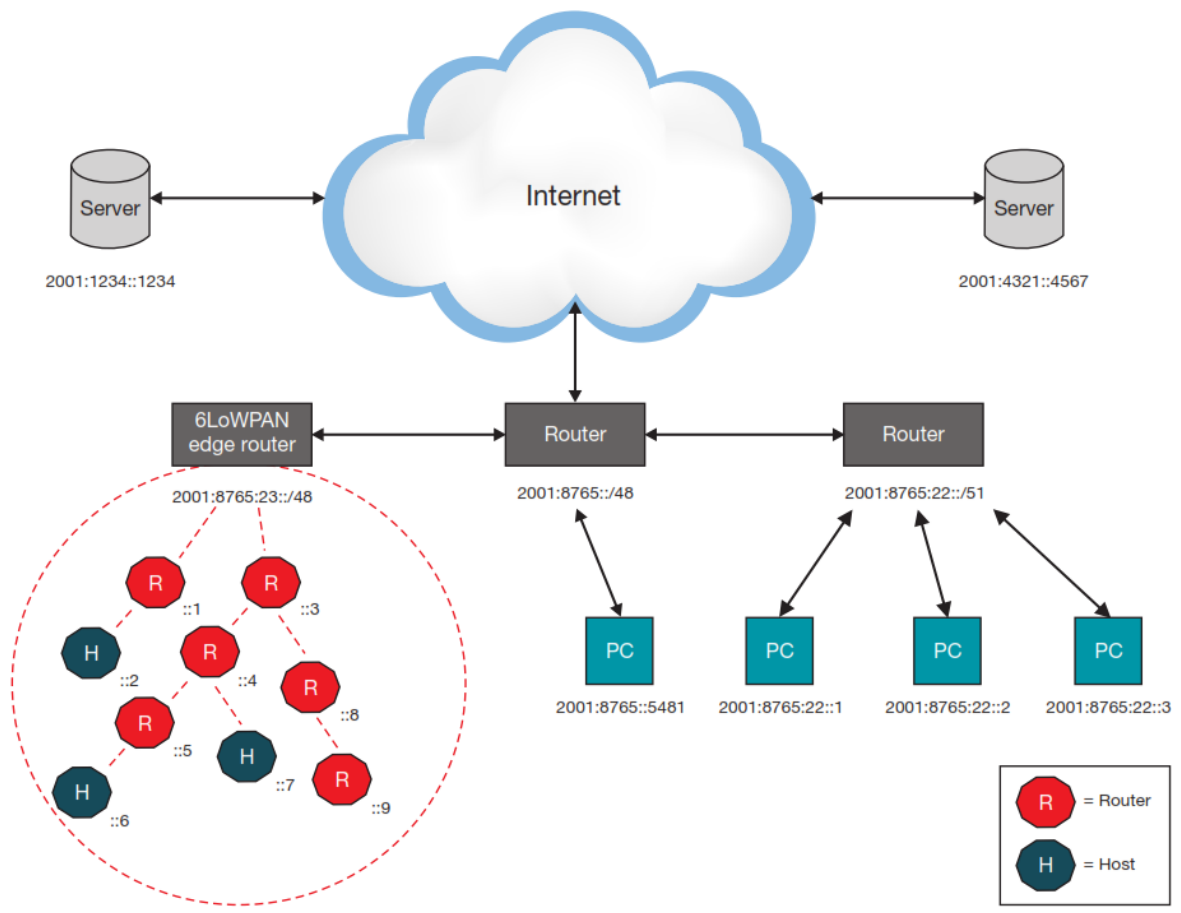
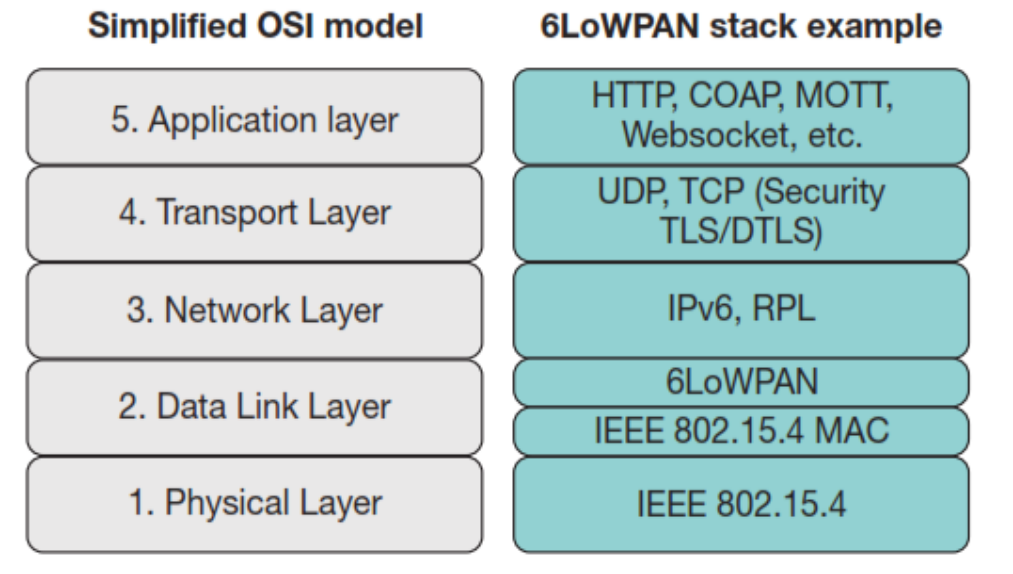



Figure 6: IPv6 network with a 6LoWPAN mesh network

# 6LoWPAN stack



# MRv6: an implementation of 6LoWPAN in MR

- TDMA and beacon based multi-hop network which allows for an IPv6 based communication between motes
- Is not a builtin MR component, but fully implemented in C#
- Datagram packets exchanged adheres to a subset of the 6LoWPAN specifications
- The edge mote decides upon:
  - Association requests
  - Assigns communication schedules between wireless nodes
  - Determines the routes in the network

# MRV6: LIMITATIONS

- Only the transmission of UDP packets within the 6LoWPAN network is supported
- Exists only a proprietary broadcast operation to reach all motes in the network
- Is not suited for low latency application
- Does not support packet segmentation, reassembly and flow control
- Has been deployed in 900MHz or 2.4GHz frequency ranges and uses a single channel in the 2.4GHz band yet

# SCHEDULING

- The network tree is only know to the edge
- The communication slots between parent and children are globally assigned by the edge and do never overlap

| SF edge | SF mote 1 | SF mote 2 | ... | SF max mote |
|---|---|---|---|---|

# SUPERFRAME

- At the beginning of their communication period parent motes send out beacon messages
- Other then a fixed exclusive slot, parent offers a shared slot (e.g. association requests and responses, broadcast messages)
- Beacon, shared and fixed slots form the superframe whose timings are assigned by the edge

| Beacon slot | Shared slot | Child slot 0 | ... | Child slot n | Gap |
|---|---|---|---|---|---|

# ASSOCIATION

- The joining mote evaluates information in the beacons (e.g. number of children or hops to the edge)
- Mote sends and association request in the shared slot of the potential parent
- Parent forward the request to the edge with the EUI-64 of the joining mote
- When the edge accepts the mote:
  - It allocates short address and superframe timings for the mote
  - The parent forwards the response to the new child in its shared slot and adds it to its list

# SHORT COMPARISON

| Our Mac-Like | MRv6 |
|---|---|
| Contention based | Scheduled |
| Trasmitt only when requested | TDMA based |
| Association managed by pan-coordinator | Association managed by the edge |
| ... | ... |

# CONCLUSION

# FINAL CONSIDERATIONS ABOUT MOTE RUNNER

- Pro:
  - Good simulation environment
  - It allows to develop mote applications in high-level object-oriented languages
  - Good assumptions and expectations with respect to LoRa
- Con:
  - It's still in beta
  - Low support (docs, API, ...)

# MAC STATUS

- Only three states are supported, there are others (orphan,..)
- Superframe parameters can't be dinamically changed
- In the associated state motes are not energy aware
- Some funtionality have not been implemented (e.g. disassociation, channels scan,...)
- Transmission from PAN-C to devices seems to require EUI64, but SADDRs are more suited

Let’s try it!

Thank’s for the attention :)