Improving IEEE 802.15.4 MAC management support in the Linux kernel

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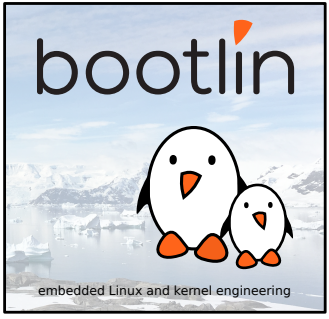


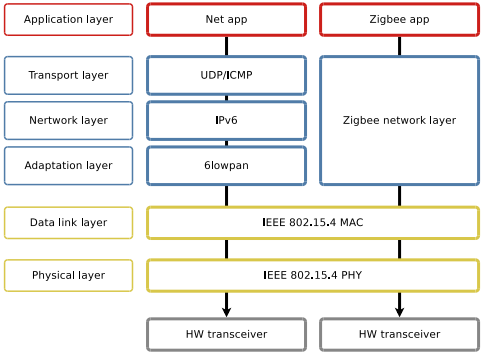
Miquel Raynal

- Embedded Linux engineer at Bootlin
  - Embedded Linux **expertise**
  - **Development**, consulting and training
  - Strong open-source focus
- Open-source contributor
  - Maintainer of the NAND subsystem
  - Co-maintainer of the MTD subsystem
  - Kernel support for various ARM SoCs
  - **Active contributor to the WPAN subsystem** with Qorvo support
- Living in **Toulouse**, France

The IEEE 802.15.4 specification in a nutshell

Functional description

- Defines the PHY layer and the MAC sublayer
  - Introduced to build Wireless Personal Area Networks (WPAN)
  - Low power, low range (10m), low rate (up to 250kib/s)
  - Easy connection between sensors and actuators
  - A base for Zigbee and 6LowPan
- Focus on the MAC sublayer:
  - MAC data services
  - MAC management services through the MAC subLayer Management Entity (MLME)



IEEE 802.15.4 stack integration in the OSI model

Personal Area Networks (PAN)

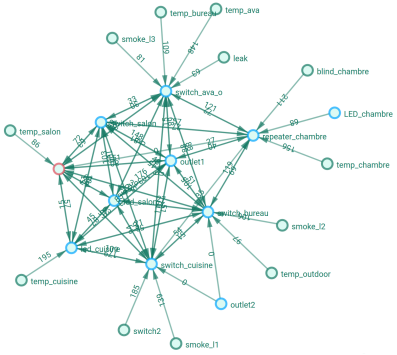
Devices connect together to form PANs

- One PAN coordinator which takes a PAN ID
  - Advertises the PAN
  - Allows devices associations
  - May serve as a bridge with the Internet
- Coordinators
  - Advertise the PAN
  - Allow devices associations
  - Follow the PAN coordinator realignments
- Leaf nodes
  - Follow their coordinator realignments
  - Send data

PAN advertisement and discovery

- Coordinators and PAN coordinators shall advertise their PAN by sending beacons
  - Either upon reception of a `BEACON REQUEST`
  - Or "passively" at a given rate, in beacon-enabled PANs
- Beacons are short frames with information about the emitting device and its PAN

- Devices can scan the various channels they support
  - Passive scans to detect surrounding beacon enabled PANs with their LQI
  - Active scans to detect surrounding beacon and non-beacon enabled PANs with their LQI



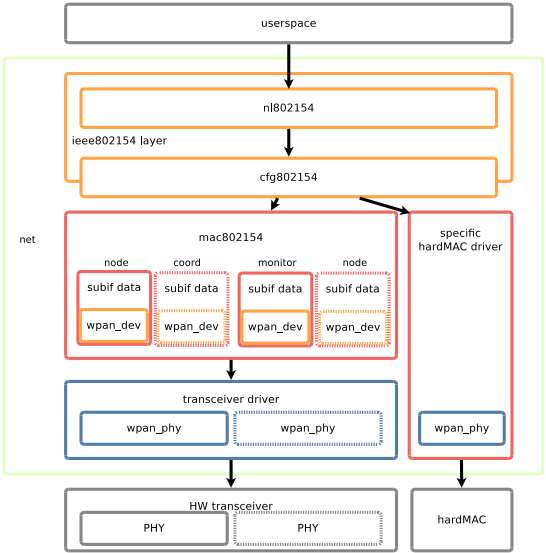
Alexandre Belloni's IEEE 802.15.4 based home network

MLME operations

- MAC management commands
  - Discovering surrounding devices (scanning, beaconing)
  - Enlarging/shrinking the network (associating, dis-associating)
  - Keeping all devices synchronized (beaconing, acknowledgments, etc)
  - Handling faulty situations (loss of contact, conflicts, etc)

The Linux kernel IEEE 802.15.4 stack

Architecture



New MLME interfaces: scanning/beaconing

- Netlink user requests with commands related payloads
  - Type of scan
  - Beacon interval
  - Channels to use
- Once processed, the request is forwarded to the MAC layer:
  - Changes on the ongoing Tx traffic
  - Hardware address filters update
  - Start of a background thread
- Background jobs can be aborted at any moment (netlink command) or may end naturally
  - Upon completion/abort userspace gets notified
  - The interface is set back in its original state

New MLME interfaces: associating/dis-associating

- No background job involved
- MLME commands must be ACKed
- Processing received requests often involves sending a response
- Association requests should be forwarded to userspace for validation (not implemented)

Demo time

Hardware setup:

- One ATUSB device acting like a PAN coordinator (wpan0/coord0)
- One ATUSB device acting like a leaf node (wpan1/coord1)
- One ATUSB device monitoring (wpan2/mon2)
- One Arduino Nano 33 BLE running Zephyr being a leaf node

Upstream proposals, discussions ongoing

- Kernel patches:
  - v2 https://lore.kernel.org/all/20220826144049.256134-1-miquel.raynal@bootlin.com/
  - v3/only filtering https://lore.kernel.org/all/20220905203412.1322947-1-miquel.raynal@bootlin.com/
  - Latest version https://github.com/miquelraynal/linux/tree/wpan-next/scan
- wpan-tools patches:
  - Last patches https://lore.kernel.org/all/20220701143434.1267864-1-miquel.raynal@bootlin.com/
  - Latest version https://github.com/miquelraynal/wpan-tools/tree/wpan-master/scan
- Zephyr changes https://github.com/zephyrproject-rtos/zephyr/pull/49947

No support for orphan notifications/coordinator realignments yet

Major issues, past and present

MLME transmissions 1/2

Description of the problem:

- The wpan core expects transmit callbacks to be asynchronous
  - Only packet offloading to the transceiver is synchronous
    - Errors during this step can be returned
  - The actual packet transmission may happen later
    - Can only happen when the medium is available
    - Perhaps there won't be any timeslot available immediately
    - The transceiver needs to wait for an ACK
    - Possibility to repeat the packet up to 7 times (usually 3)
  - MLME transmissions **must** be ACKed, we need a status
  - We want MLME operations to be over before resuming normal operations
- Asynchronous transmissions cannot work alone, we need an alternative

MLME transmissions 2/2

Solution considered:

- A hot path is considered for data transmission
- Creation of a second, slow and synchronous Tx Path for MLME transmissions
  - Device drivers already call helpers upon completion to:
    - Handle Inter Frame Spacing (IFS), a short inactive period after each frame
    - Consume the skb
  - We could use them to:
    - Follow the count of ongoing transmissions
    - Possibly return an error code, if any?

include/net/mac802154.h

```
void ieee802154_xmit_complete(struct ieee802154_hw *hw, struct sk_buff *skb, bool ifs_handling);
void ieee802154_xmit_error(struct ieee802154_hw *hw, struct sk_buff *skb, int reason);
```

Error codes 1/2

Sub-problem: forwarding errors

- It is important to know if the MLME frame was successfully received
- Example of status register: TRAC
  - Not in the spec
  - Hopefully wide spread

TRAC values

```
TRAC_SUCCESS
TRAC_SUCCESS_DATA_PENDING
TRAC_SUCCESS_WAIT_FOR_ACK
TRAC_CHANNEL_ACCESS_FAILURE
TRAC_NO_ACK
TRAC_INVALID
```

Error codes 2/2

Down side:

- Using ATUSB devices: no `TRAC` register support in the firmware

Bright side:

- The firmware is open source
- Another driver (`at86rf230.c`) is very close and has `TRAC` support
- Alexander Aring (WPAN co-maintainer) does not need sleep and knows very well the firmware
- Patches now available

  https://lore.kernel.org/all/20220906082104.1338694-3-miquel.raynal@bootlin.com/

In general, all devices and drivers should have access to these information, otherwise they are badly designed

Filtering constraints

- Intermediate filtering levels not described
  - Currently supported: “no filtering” or “full filtering”
  - Specific filtering modes shall be entered during scans
  - Must be supported by software if not available in hardware
- Enabling promiscuous mode (the one which disables all checks) also disables `ACK`s for sniffing devices
  - As opposed to filtering levels, `ACK` generation cannot be handled by software
  - Running interfaces in promiscuous mode and non promiscuous mode on the same PHY shall be prevented
- The promiscuous mode alone does not make sense
  - Alexander has proposed a first patch to move towards a more unified filtering API and give to the `drv_start()` hook a filtering level to work with

Lockdep hates me 1/2

There is still an issue with the scan:

- Scanning involves changing channels in the background job
  - Channel changes are protected by the `rtnl`
  - `mac802154_hwsim.c` for instance requires the `rtnl` when changing some of its PIB attributes like the channel/page.
    - Lock dependency: `scan_lock` → `rtnl`
- The `rtnl` is always acquired before changing scan parameters
  - There is an `ASSERT_RTNL()` in the `nl802154_pre_doit()` as soon as we need a `netdev`
    - Lock dependency: `rtnl` → `scan_lock`
- Circular dependency!
- Mandatory to take the `rtnl` before the `scan_lock` in the background job

So the in the end the `scan_lock` is useless, besides showing what needs to be protected if we ever drop the `rtnl` there

Lockdep hates me 2/2

Situation:

- Scanning/beaconing background jobs use the device's workqueue
  - Workqueue completion lock acquired when the job is running
  - The job acquires the `rtnl`
    - Dependency lock: workqueue lock → `rtnl`
  - At `stop()` time the `rtnl` must be acquired
  - Stopping a device involves flushing the workqueue, with its lock acquired
    - Dependency lock: `rtnl` → workqueue lock
  - Circular dependency!

Workaround: using another queue for the MLME background jobs, which must be stopped before removal anyway and does not need to be flushed explicitly with the `rtnl` acquired

Questions? Suggestions? Comments?

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