Technical Report

An IEEE 802.15.4 protocol implementation (in nesC/TinyOS): Reference Guide v1.0

André CUNHA
Mário ALVES

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André CUNHA, Mário ALVES

IPP-HURRAY!
Polytechnic Institute of Porto (ISEP-IPP)
Rua Dr. António Bernardino de Almeida, 431
4200-072 Porto
Portugal
Tel.: +351.22.8340509, Fax: +351.22.8340509
E-mail: {arec,mjf}@isep.ipp.pt
http://www.hurray.isep.ipp.pt

Abstract

This technical report is to provide a reference guide to the implementation of the IEEE 802.15.4 protocol in nesC/TinyOS for the MICAz motes. The implementation is provided as a tool that can be used to implement, test and evaluate the current functionalities defined in the protocol standard as well as to enable the development of functionalities not yet implemented and new add-ons to the protocol.

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Acronyms and abbreviations

ACL	access control list
AES	advanced encryption standard
BE	backoff exponent
BER	bit error rate
BI	beacon interval
BO	beacon order
BPSK	binary phase-shift keying
BSN	beacon sequence number
CAP	contention access period
CBC-MAC	cipher block chaining message authentication code
CCA	clear channel assessment
CFP	contention-free period
CID	cluster identifier
CLH	cluster head
CRC	cyclic redundancy check
CSMA-CA	carrier sense multiple access with collision avoidance
CTR	counter mode
CW	contention window (length)
DSN	data sequence number
DSSS	direct sequence spread spectrum
ED	energy detection
FCS	frame check sequence
FFD	full-function device
FH	frequency hopping
FHSS	frequency hopping spread spectrum
GTS	guaranteed time slot
IFS	interframe space or spacing
LAN	local area network
LIFS	long interframe spacing
LLC	logical link control
LQ	link quality
LQI	link quality indication
LPDU	LLC protocol data unit
LR-WPAN	low-rate wireless personal area network
LSB	least significant bit
MAC	medium access control
MCPS MAC	common part sublayer
MCPS-SAP	MAC common part sublayer-service access point
MFR	MAC footer
MHR	MAC header
MLME	MAC sublayer management entity
MLME-SAP	MAC sublayer management entity-service access point
MSB	most significant bit
MSC	message sequence chart
MPDU MAC	protocol data unit
MSDU MAC	service data unit
NB	number of backoff (periods)
OSI	open systems interconnection
PAN	personal area network
PD-SAP	PHY data service access point
PDU	protocol data unit
PER	packet error rate
PHR	PHY header
PHY	physical layer
PIB	PAN information base
PLME	physical layer management entity
PLME-SAP	physical layer management entity-service access point
PPDU	PHY protocol data unit
PSDU	PHY service data unit
RF	radio frequency
RFD	reduced-function device
RSSI	received signal strength indication
RX	receive or receiver
SAP	service access point
SD	superframe duration
SPDU	SSCS protocol data units
SDU	service data unit
SFD	start-of-frame delimiter
SHR	synchronization header
SIFS	short interframe spacing
SO	superframe order
SRD	short-range device
SSCS	service specific convergence sublayer
TRX	transceiver
TX	transmit or transmitter
WLAN	wireless local area network
WPAN	wireless personal area network

1. General Notes

1.1. Context

The purpose of this technical report is to provide a reference guide to the implementation of the IEEE 802.15.4 protocol [1] in nesC/TinyOS[2,3] for the MICAz[4] motes.

During this description some parts of the protocol standard are explained and referenced, nevertheless it is important to have a previous knowledge on the functionalities of the IEEE 802.15.4 protocol.

This implementation is provided as a tool that can be used to implement, test and evaluate the current functionalities defined in the protocol standard as well as to enable the development of functionalities not yet implemented and new add-ons to the protocol.

This technical report is structured based on the different IEEE 802.15.4 mechanisms implemented.

The component graphs shown in this document are automatically generated by the nesdoc application (associated with the nesC programming environement in TinyOS).

In Reference [5] there is a technical overview of the IEEE 802.15.4 protocol.

1.2. Functionalities currently supported

The current version of the implementation (v1.0) supports the following IEEE 802.15.4 functionalities:

- CSMA/CA algorithm – slotted version;
- GTS Mechanism;
- Indirect transmission mechanism;
- Direct / Indirect / GTS Data Transmission;
- Beacon Management;
- Frame construction – Short Addressing Fields only and extended addressing fields in the association request;
- Association/Disassociation Mechanism;
- MAC PIB Management;
- Frame Reception Conditions;

1.3. Functionalities that are not implemented yet

The following functionalities are not implemented or tested in the current version of the implementation (v1.0):

- Unslotted version CSMA/CA – Implemented but not fully tested;
- Extended Address Fields of the Frames;
- IntraPAN Address Fields of the Frames;
- Channel Scan;
- Orphan Devices;
- Frame Reception Conditions (Verify Conditions);
- Security – Out of the scope of this implementation;

Besides these missing functionalities, many improvements can be made to optimize this implementation especially in terms of memory usage. For example, one option to save memory could be removing the components wiring modules and replace them with only one that wires them all. Another option is to optimize the buffers because they are the most memory consuming entities.

1.4. Programming environment

This implementation was developed for TinyOS version 1.1.15 under the Cygwin for Windows XP environment.

The application used to write code was the Programmers Notepad 2 that provides code highlighting.

The hardware used was the Crossbow MICAz motes. These "IEEE 802.15.4-compliant" motes operate in the 2.4 GHz ISM band and have a 16 Mhz Atmel ATMega128L microcontroller [6] (with 128 kB of program Flash) and a Chipcon CC2420 802.15.4 radio transceiver [7] (allowing a 250 kbps data rate).

The MIB510 programming board was used to program the motes. This programmer can upload the applications to motes through the COM port and allow a debug mechanism by sending data through the COM port and reading it in a COM port software listener, like the ListenRaw (found in the TinyOS distribution) or the Windows HiperTerminal. This debug mechanism raises a problem concerning the hardware operation because the relaying of data through the COM port blocks all the other mote operations, while this data is being send. This can cause synchronization problems. We also use the MIB600 programmer to program the motes through the IP network.

In order to overcome the COM debug problems we use an IEEE 802.15.4 packet sniffer provided by Chipcon the CC2420 Packet Sniffer for IEEE 802.15.4 v1.0. This application works in conjunction with a CC2400EB board with a CC2420 radio transceiver. This sniffer shows the packets transmitted and provide a good debug mechanism by transmitting debug data in the packets payloads.

A JTAG adapter can also be used for debug purposes but that was not used during the development of this implementation.

1.5. Organization of the implementation / File structure diagram

The implementation uses files already provided in TinyOS and its located in the contrib/hurray folder. The directory structure is similar to the TinyOS root folder. The next list shows all the files created for this implementation and their respective location.

contrib/hurray/tos/interfaces – Generic Interfaces

- TimerAsync.nc – Interface for the TimerAsyncM component

contrib/hurray/tos/interfaces/ieee802154.mac – Connection interfaces between the MAC and the upper layer.

- MCPS_DATA.nc – MAC Common Part Sublayer Data-Service Access Point;
- MCPS_PURGE.nc - MAC Common Part Sublayer Purge Service Access Point;
- MLME_ASSOCIATE.nc – MAC Layer Management Entity Associate Service Access Point;
- MLME_BEACON_NOTIFY.nc - MAC Layer Management Entity Beacon Notify Service Access Point;
- MLME_COMM_STATUS.nc - MAC Layer Management Entity Communication Status Service Access Point;
- MLME_DISASSOCIATE.nc – MAC Layer Management Entity Disassociate Service Access Point;
- MLME_GET.nc - MAC Layer Management Entity Get Service Access Point;
- MLME_GTS.nc - MAC Layer Management Entity Guaranteed Time Slot Service Access Point;
- MLME_POLL.nc - MAC Layer Management Entity Poll Service Access Point;
- MLME_RESET.nc - MAC Layer Management Entity Reset Service Access Point;
- MLME_SCAN.nc - MAC Layer Management Entity Scan Service Access Point;
- MLME_SET.nc - MAC Layer Management Entity Set Service Access Point;
- MLME_START.nc - MAC Layer Management Entity Start Service Access Point;
- MLME_SYNC.nc - MAC Layer Management Entity Synchronize Service Access Point;
- MLME_SYNC_LOSS.nc - MAC Layer Management Entity Synchronization Loss Service Access Point.

contrib/hurray/tos/interfaces/ieee802154.phy - Connection interfaces between the MAC and PHY layers.

- PD_DATA.nc – Phy Data-Service Access Point;
- PLME_CCA.nc - Physical Layer Management Entity - Clear Channel Assessment -Service Access Point;
- PLME_ED.nc - Physical Layer Management Entity – Energy Detection - Service Access Point;
- PLME_GET.nc - Physical Layer Management Entity Get-Service Access Point;
- PLME_SET.nc - Physical Layer Management Entity Set -Service Access Point;
- PLME_SET_TRX_STATE.nc - Physical Layer Management Entity Set Transceiver State-Service Access.

contrib/hurray/tos/lib/mac – MAC layer implementation files

- Mac.nc – Configuration of the MacM implementation module;
- MacM.nc – MAC layer implementation;

- mac_const.h – MAC layer constants;
- mac_enumerations.h – MAC layer enumerations.

contrib/hurray/tos/lib/phy – Physical layer implementation files

- Phy.nc – Configuration of the PhyM implementation module;
- PhyM.nc – Physical layer implementation;
- phy_const.h – Physical layer constants;
- phy_enumerations.h – Physical layer enumerations.

contrib/hurray/tos/system – Generic system modules

- TimerAsyncC.nc – Configuration of the TimerAsyncM implementation module;
- TimerAsyncM.nc – Asynchronous timer implementation;
- mac_func.h – Generic functions used mainly by the MAC layer implementation;
- frame_format.h – Frame format definition.

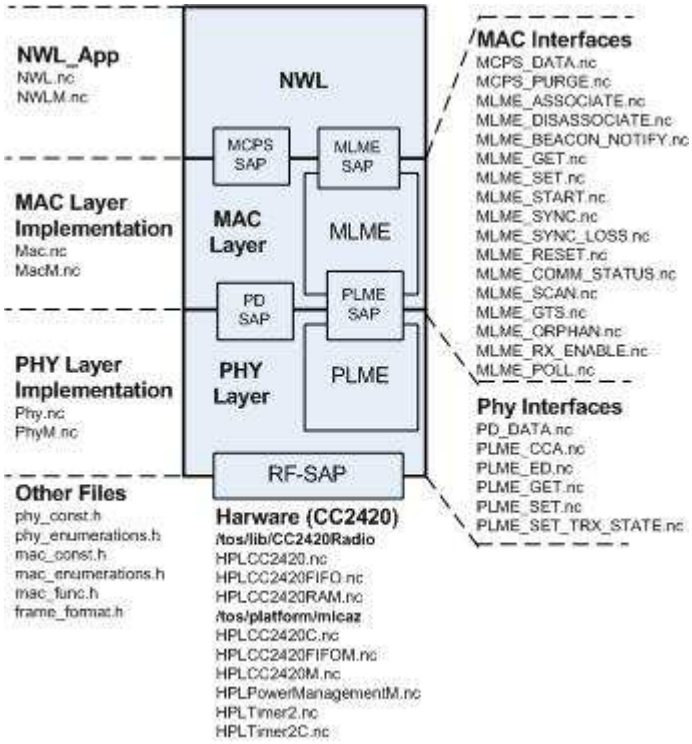


Figure 1 - Protocol Stack Architecture.

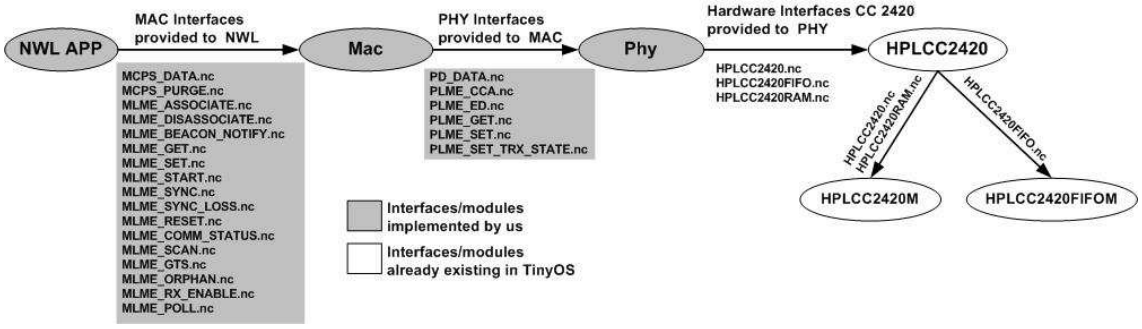


Figure 2 - TinyOS Implementation Diagram

2. Physical Layer Implementation

The IEEE 802.15.4 physical layer is responsible for the implementation of the following functionalities:

- Activation and deactivation of the radio transceiver;
- Energy Detection(ED) within the current channel;
- Link quality indicator (LQI) for received packets;
- Clear Channel Assessment (CCA) for Carrier Sense Multiple Access – Collision Avoidance (CSMA-CA);
- Channel frequency selection;
- Data transmission and reception;

2.1. Reference Model

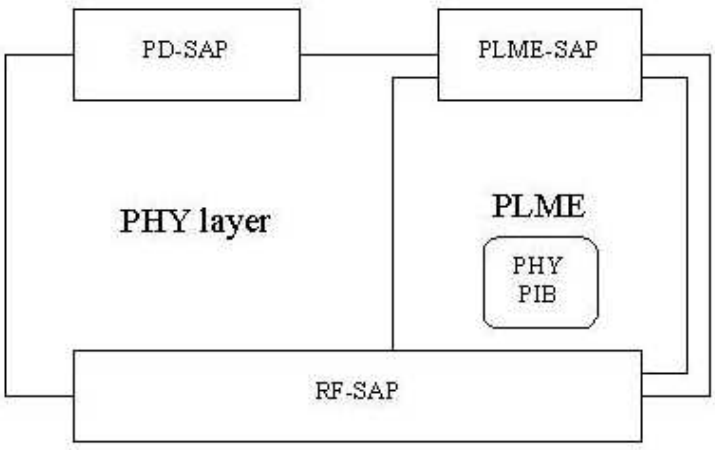


Figure 3 - Physical Layer reference model.

The RF-SAP comprehends the interface with the physical radio via the RF firmware of the CC2420 and hardware, already provided in the TinyOS implementation.

The files included are the following:

Interfaces under the *contrib.hurray.tos.lib.CC2420Radio* directory:

- HPLCC2420
- HPLCC2420FIFO
- HPLCC2420RAM

Components under *contrib.hurray.tos.platform.MICAz* directory:

- HPLCC2420C
- HPLCC2420FIFOM
- HPLCC2420M
- HPLPowerManagementM
- HPLTimer2
- HPLTimer2C

The PD-SAP comprehends the interface to exchange data packets between MAC and PHY. The interface file is under *contrib.hurray.tos.interfaces.ieee802154.phy* directory:

- PD_DATA – data transfer between the Phy layer and the MAC layer.

The next table summarizes the primitives supported by PD-SAP interface [1 pag 32]

Interface Name	Request	Indication	Response	Confirm
PD_DATA	X	X		X

Table 1 - Summary of the primitives supported by each PD-SAP interface.

The Physical Layer Management Entity –SAP (PLME-SAP) comprehends the interfaces between the MAC and the PHY used for exchanging management information. The interface files are under *contrib.hurray.tos.interfaces.ieee802154.phy* directory:

- PLME_CCA – clear channel assessment
- PLME_ED - energy detection
- PLME_GET - retrieve PHY PIB parameters
- PLME_SET– set PHY PIB parameters
- PLME_TRX-ENABLE – enable/disable transceiver

The next table summarizes the primitives supported by each PLME-SAP interface [1 pag 34]

Interface Name	Request	Indication	Response	Confirm
PLME_CCA	X			X
PLME_ED	X			X
PLME_GET	X			X
PLME_SET	X			X
PLME_TRX-ENABLE	X			X

Table 2 - Summary of the primitives supported by each PLME-SAP interface.

The PHY PAN Information Base (PHY PIB) is maintained in the physical layer and is a database of its managed objects. The PLME-SAP interfaces are used by the MAC layer to manage this information. The PIB stores the following information:

- Current Channels;
- Channels Suported;
- Transmit power;
- CCA Mode.

2.2. Components Phy and PhyM

The physical layer is implemented in two files. There file are located under *contrib.hurray.tos.lib.phy*:

Phy.nc – Component wiring the interfaces to the implementation on the component PhyM

PhyM.nc – Component that implements the physical layer functions and wired then to the hardware components.

2.3. Component Phy

2.3.1. Provided Interfaces

The provided interfaces of the Phy component are the following:

- PD_DATA [1 pag. 32] – PHY data service – The PD-SAP supports the transport of MPDUs between peer MAC sublayer entities.
- PLME_ED [1 pag. 36] – Implements the reading of energy measurements in the previous selected channel.
- PLME_CCA [1 pag. 35] – Implements the reading of the CCA in the previous selected channel.
- PLME_GET [1 pag. 37] – Implements the reading of information concerning the PHY PIB.
- PLME_SET [1 pag. 40] – Implements the functionalities for changing information concerning the PHY PIB.

- PLME_SET_TRX_STATE [1 pag. 39] – Implements the functionalities for changing the internal operating state of the transceiver.

2.3.2. Component Graph

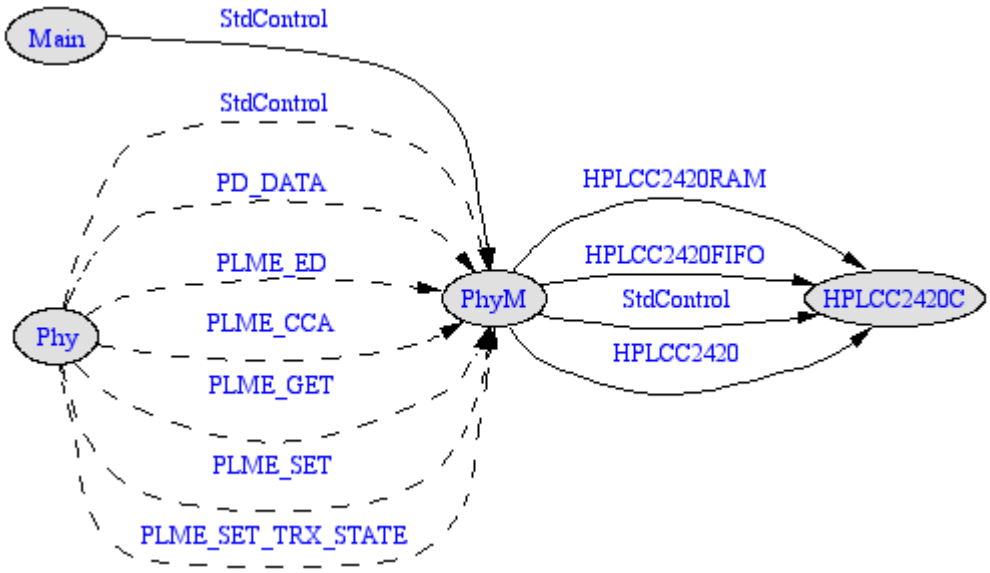


Figure 4 - Phy - Component Graph

2.4. Component: PhyM

2.4.1. Required Interfaces

The required interfaces of the PhyM component are the following:

- HPLCC2420 – Implements the functionalities for managing the memory records of the CC2420 transceiver.
- HPLCC2420FIFO – Implements the functionalities for managing the FIFO memory records, used for sending or receiving data.
- HPLCC2420RAM – Implements the functionalities for managing the RAM memory records.

2.4.2. Provided Interfaces

The provided interfaces of the PhyM component are the following:

- PD_DATA
- PLME_ED
- PLME_CCA

- PLME_GET
- PLME_SET
- PLME_SET_TRX_STATE

2.4.3. Variables

The component global variables are described in the following list:

- *norace uint16_t gCurrentParameters[14]* - Used to store the transceiver global parameters.
- *phyPIB phy_PIB* – Used to store the physical layer PAN Information Base. The phyPIB structure is defined in the phyConst.h file

- *uint8_t currentRxTxState = PHY_TRX_OFF* – Gives information about the current transceiver state.
- *norace MPDU rxmpdu* – Temporary variable that stores receiving data.
- *MPDU *rxmpdu_ptr* - Pointer for the *rxmpdu* variable

2.4.4. Functions Implemented

Common Functions:

command result_t StdControl.init (void)

This function is called on the initialization of the component. In this function the hardware components are initialized and the transceiver global parameters are assigned (variable *gCurrentParameters*). The Phy PIB is assigned with the init values. The constants defined to access the memory positions of the transceiver, provided in TinyOS, are located in the CC2420const.h file under *contrib.hurray.tos.lib.CC2420Radio* directory.

command result_t StdControl.start (void)

This function is called on the start of the component. The transceiver module are started with the initial values and all is parameters are set.

command result_t StdControl.stop (void)

This function is called on the stop of the component. Stops all the transceiver activity and disables all FIFO interrupts.

Interface implementations (command implementations):

- PD_DATA [1 pag. 32]

*async command result_t PD_DATA.request (uint8_t psduLength, uint8_t *psdu)*

This command is used when the MAC layer need to send data. The data, pointed by the second argument, is transferred to the output buffer of the transceiver and a transmit command is issued to the hardware components.

This command is issue asynchronously because of the time constrains for issuing a frame. The Phy layer must send the data almost immediately after the request to send.

- PLME_ED [1 pag. 36]

command result_t PLME_ED.request (void)

This command is used when the MAC layer need to read the RSSI registry of the transceiver. The Phy layer just issues a command to the hardware modules to read the RSSI memory position.

- PLME_CCA [1 pag. 35]

command result_t PLME_CCA.request (void)

This command is used when the MAC layer need to check is the channel is clear. The function *TOSH_READ_CC_CCA_PIN()* is called in order to do that. If the return of the function is 1 then the channel is busy otherwise the channel is idle. This macro functions, provided in TinyOS, are defined in the avrhardware.h under the *contrib..hurray.tos.platform.avrmote* directory.

- PLME_GET [1 pag. 37]

command result_t PLME_GET.request (uint8_t PIBAttribute)

This command is used when the MAC layer need to read the values of the PHY PIB.

- PLME_SET [1 pag. 40]

command result_t PLME_SET.request (uint8_t PIBAttribute, uint8_t PIBAttributeValue)

This command is used when the MAC layer need to change the values of the PHY PIB.

- PLME_SET_TRX_STATE [1 pag. 39]

command result_t PLME_SET_TRX_STATE.request (uint8_t state)

This command is used when the MAC layer need to change the current state of the transceiver.

Hardware Event Functions:

async event result_t HPLCC2420.FIFOPIntr (void)

Asynchronous hardware interrupt indicating the reception of data. When this event is triggered the data in the input FIFO is pointed by the *rxmpdu_ptr* variable pointer.

*async event result_t HPLCC2420RAM.readDone (uint16_t addr, uint8_t length, uint8_t *buffer)*

Asynchronous hardware interrupt indicating the completion of a read command. Meanwhile we have no use for this hardware event.

*async event result_t HPLCC2420RAM.writeDone (uint16_t addr, uint8_t length, uint8_t *buffer)*

Asynchronous hardware interrupt indicating the completion of a write command. Meanwhile we have no use for this hardware event.

*async event result_t HPLCC2420FIFO.RXFIFODone (uint8_t length, uint8_t *data)*

Asynchronous hardware interrupt indicating the completion of a read command in the input buffer of the transceiver (received data). Meanwhile we have no use for this hardware event.

*async event result_t HPLCC2420FIFO.TXFIFODone (uint8_t length, uint8_t *data)*

Asynchronous hardware interrupt indicating the completion of a write command in the output buffer of the transceiver (data for transmission). Meanwhile we have no use for this hardware event.

Other Functions:

bool SetRegs(void) Function used to configure the CC2420 registers with current values - Readback 1st register written to make sure electrical connection OK

uint8_t GetRFPower(void) Function used to get the RF power value from the *gCurrentParameters* variable.

result_t SetRFPower(uint8_t power) Function used to set the RF power value of the CC2420 transceiver. The *power* argument indicates the power level. Admissible values varies between 31, full power (0dbm gain) and 3, minimum power (-25dbm gain).

result_t VREFOn (void) Turns on the 1.8V references on the CC2420.

result_t VREFOff (void) Turns off the 1.8V references on the CC2420.

result_t TunePreset (uint8_t chnl) Function used to select the current radio channel. Valid channel values are 11 through 26.

result_t TuneManual (uint16_t DesiredFreq) Function used to tune the radio to a given frequency.

result_t setShortAddress(uint16_t addr) Function used to assign the short address of the mote. In the init function the short address of the mote is assigned with the *TOS_LOCAL_ADDRESS*. This constant is assigned during compilation time.

2.4.5. Auxiliary Files (Under contrib.hurray.tos.lib.phy):

phy_const.h

This file contains the protocol constants definition related with the Phy layer. These constants are defined in next table. [1 pag. 44]

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets)	127

	the PHY shall be able to receive	
aTurnaroundTime	RX-to-TX or TX-to-RX maximum turnaround time	12 symbol periods

Table 3 - Physical layer constants.

There is also the definition of the initial values for the PHY PIB along with the structure of the PHY PIB. The PIB attributes are defined in the next table. [1 pag 45] Note that the transmit power is hardware constrained and it has to be within the values accepted, in this case, by the *SetRFPower* function.

Attribute	Type	Range	Description
phyCurrentChannel	Integer	0–26	The RF channel to use for all following transmissions and receptions.
phyChannelsSupported	Bitmap		The 5 most significant bits (MSBs) (b27,... , b31) of phyChannelsSupported shall be reserved and set to 0, and the 27 LSBs (b0,b1, ... b26) shall indicate the status (1=available, 0=unavailable) for each ofthe 27 valid channels (bk shall indicate the status of channel k as in 6.1.2).
phyTransmitPower	Bitmap	0x00-0xbf	The 2 MSBs represent the tolerance on the transmit power: 00 = ± 1 dB 01 = ± 3 dB 10 = ± 6 dB The 6 LSBs represent a signed integer in twos-complement format, corresponding to the nominal transmit power of the device in decibels relative to 1 mW. The lowest value of phyTransmitPower shall be interpreted as less than or equal to –32 dBm.
phyCCAMode	Integer	1–3	The CCA mode.

Table 4 - Physical PAN Information Base attributes.

phy_enumerations.h

This file contains the enumeration values used in the PHY layer. There are two enumeration tables: one represents the general PHY enumeration description [1 pag.42] and the other represents the values used in the PLME_SET and PLME_GET functions for referring to the PHY PIB attributes.

The following tables describe the enumerations.

Enumeration	Value	Description
PHY_BUSY	0x00	The CCA attempt has detected a busy channel.

PHY_BUSY_RX	0x01	The transceiver is asked to change its state while receiving.
PHY_BUSY_TX	0x02	The transceiver is asked to change its state while transmitting.
PHY_FORCE_TRX_OFF	0x03	The transceiver is to be switched off.
PHY_IDLE	0x04	The CCA attempt has detected an idle channel.
PHY_INVALID_PARAMETER	0x05	A SET/GET request was issued with a parameter in the primitive that is out of the valid range.
PHY_RX_ON	0x06	The transceiver is in or is to be configured into the receiver enabled state.
PHY_SUCCESS	0x07	A SET/GET, an ED operation, or a transceiver state change was successful
PHY_TRX_OFF	0x08	The transceiver is in or is to be configured into the transceiver disabled state.
PHY_TX_ON	0x09	The transceiver is in or is to be configured into the transmitter enabled state
PHY_UNSUPPORTED_ATTRIBUTE	0x0a	A SET/GET request was issued with the identifier of an attribute that is not supported.

Table 5 - PHY general enumeration descriptions.

Enumeration	**Value**	**Description**
PHYCURRENTCHANNEL	0x00	The GET/SET reference of the PIB phyCurrentChannel.
PHYCHANNELSSUPPORTED	0x01	The GET/SET reference of the PIB phyChannelsSupported.
PHYTRANSMITPOWER	0x02	The GET/SET reference of the PIB phyTransmitPower.
PHYCCAMODE	0x03	The GET/SET reference of the PIB phyCCAMode.

Table 6 - PHY GET/SET reference PIB enumerations.

3. MAC Layer Implementation

The IEEE 802.15.4 MAC layer is responsible for the implementation of the following functionalities:

- Generating network beacons if the device is a coordinator;
- Synchronizing to the beacons;
- Supporting PAN association and disassociation;
- Supporting device security;
- Employing the CSMA-CA mechanism for channel access;
- Handling and maintaining the GTS mechanism;
- Providing a reliable link between two peer MAC entities.

3.1. Reference Model

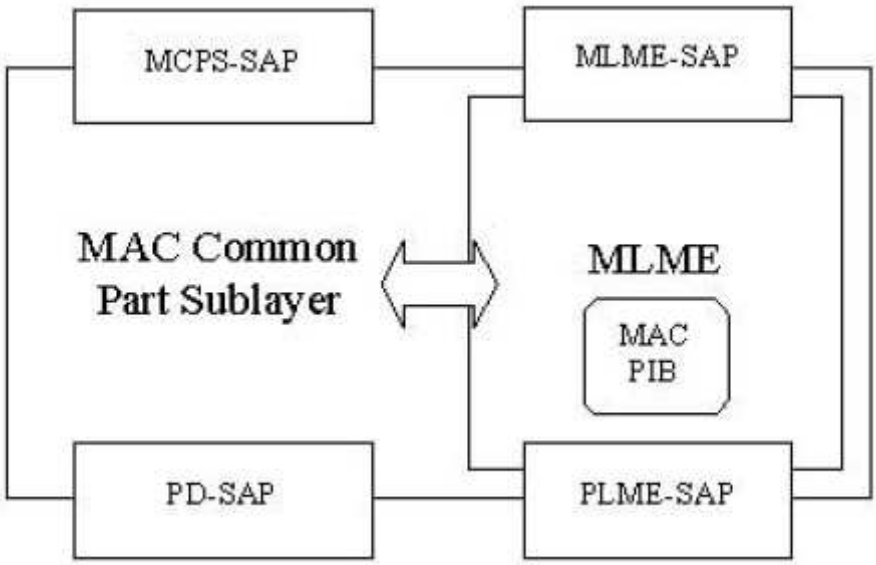


Figure 5 - MAC Layer Reference Model

The MAC layer provides to the upper layer two SAP. The MAC Common Part Sublayer (MCPS-SAP) and the MAC Layer Management Entity (MLME-SAP).

The PD-SAP and the PLME-SAP are used to connect the MAC Layer with the functionalities provided by the PHY Layer.

The MCPS-SAP comprehends the MSDU data transfer between the MAC layer and the upper layer. The files included in the interfaces for the MCPS-SAP are the following and are located under *contrib.hurray.tos.interfaces.ieee802154.mac* directory:

- MCPS_DATA - exchange data packets between MAC and PHY;
- MCPS_PURGE - purge an MSDU from the transaction queue.

The next table summarizes the primitives supported by each MCPS-SAP interface [1 pag 56]

Interface Name	Request	Indication	Response	Confirm
MCPS_DATA	X	X		X
MCPS_PURGE	X			X

Table 7 - Summary of the primitives supported by each MCPS-SAP interface.

The MLME-SAP comprehends the exchange of management commands between the MAC layer and the upper layer. The files included in the interfaces for the MLME-SAP are the following and are located under *contrib.hurray.tos.interfaces.ieee802154.mac* directory:

- MLME_ASSOCIATE - network association
- MLME_DISASSOCIATE – network association
- MLME_BEACON-NOTIFY – beacon notification
- MLME_GET - retrieve MAC PIB parameters
- MLME_GTS - GTS management
- MLME_ORPHAN - orphan device management (NOT IMPLEMENTED)
- MLME_RESET – request for MLME to perform reset
- MLME_RX-ENABLE - enabling/disabling of radio system
- MLME_SCAN - scan radio channels (NOT IMPLEMENTED)
- MLME_COMM_STATUS – communication status
- MLME_SET– retrieves MAC PIB parameters
- MLME_START – beacon generation management
- MLME_SYNC – synchronization request
- MLME_SYNC-LOSS - device synchronization
- MLME-POLL - beaconless synchronization

The next table summarizes the primitives supported by each MLME-SAP interface [1 pag. 64].

Interface Name	Request	Indication	Response	Confirm
MLME_ASSOCIATE	X	X	X	X
MLME_DISASSOCIATE	X	X		X
MLME_BEACON-NOTIFY		X		
MLME_GET	X			X
MLME_GTS	X	X		X
MLME_ORPHAN		X	X	
MLME_RESET	X			X
MLME_RX-	X			X
MLME_SCAN	X			X
MLME_COMM_STATUS		X		
MLME_SET	X			X
MLME_START	X			X
MLME_SYNC	X			
MLME_SYNC-LOSS		X		

MLME-POLL	X			X

Table 8 - Summary of the primitives supported by each MLME-SAP interface.

The MAC PAN Information Base (MAC PIB) is maintained in the MAC layer and is a database of its managed objects. The MLME-SAP interfaces are used by the MAC upper layer to manage this information. The PIB stores the following information:

- Acknowledgment Wait Duration;
- Association Permit;
- Automatic Data Request;
- Battery Life Extension Option;
- Battery Life Extension Periods;
- Beacon Payload;
- Beacon Payload Length;
- Beacon Order;
- Beacon Transmit Time;
- Beacon Sequence Number;
- Coordinator Extended Address;
- Coordinator Short Address;
- Data Sequence Number;
- GTS Permit Option;
- Maximum CSMA Backoffs Attempts;
- Minimul Backoff Exponent;
- PAN identifier;
- Promiscuous Mode Option;
- Receive mode when the transceiver is idle option;
- Short Address;
- Superframe Order;
- Transaction Persistence Time;.

3.2. Components Mac and MacM

The MAC layer is implemented in two files. There file are located under *contrib.hurray.tos.lib.mac*:

Mac.nc – Component wiring the interfaces to the implementation on the component MacM

MacM.nc – Component that implements the MAC layer functions that will be provided to the upper layer.

3.3. Component Mac

3.3.1. Provided Interfaces

The provided interfaces of the Mac component are the following:

- MLME_START [1 pag. 100] – Used for the coordinator to start sending beacons or use a new superframe configuration.
- MLME_ASSOCIATE [1 pag. 64] – Used to create an association request directed to the coordinator.
- MLME_DISASSOCIATE [1 pag. 71] – Used to create a disassociation requent directed to the coordinator.
- MLME_SYNC [1 pag. 104] – Used to enable the MAC layer to start synchronizing the coordinator by always keep track of the beacon.
- MLME_SYNC_LOSS [1 pag. 105] – Used by the MAC layer to inform the upper layer about the loss of synchronization with a coordinator.
- MLME_SCAN [1 pag. 92] - Implements the channel scan mechanist in order to inform the upper layer about the energy detection on each channel.
- MLME_RESET [1 pag. 88] – Used to request a reset operation in the MAC layer.
- MLME_BEACON_NOTIFY [1 pag. 75] – Used by the MAC layer to inform the upper layer about the PAN descriptor and pending addresses contained in the beacon received.
- MLME_COMM_STATUS [1 pag. 96] – Used by the MAC layer to inform the upper layer about the communication status.
- MLME_SET [1 pag. 98] - Used to write in the attributes of the MAC PAN Information Base.
- MLME_GET [1 pag. 78] – Used to read the attributes of the MAC PAN Information Base.
- MLME_GTS [1 pag.79] – Used to create a GTS allocation request directed to the coordinator. This interface also informs the MAC upper layer about the status of the allocation.
- MCPS_DATA [1 pag. 56] – Implement the data exchange between the MAC layer and the next upper layer.
- MCPS_PURGE [1 pag. 61] – Used to purge a data frame from the transaction queue.

3.3.2. Component Graph

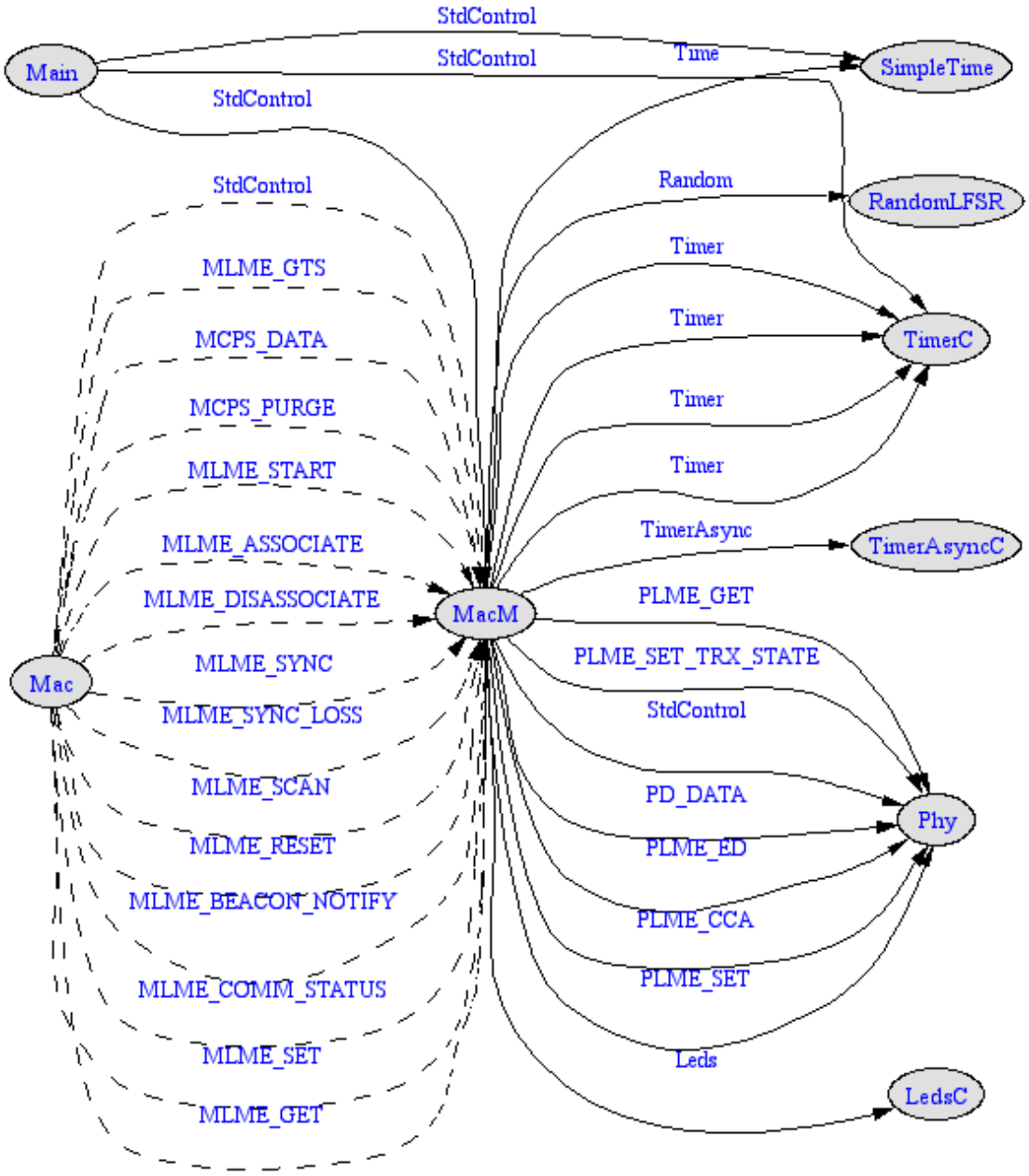


Figure 6 - MacM component graph.

3.4. Component: MacM

3.4.1. Required Interfaces

The required interfaces of the MacM component are the following:

- PD_DATA - PHY data service. Implemented in the PhyM.nc.
- PLME_CCA – Clear Channel Assessment. Implemented in the PhyM.nc.
- PLME_SET – Set PHY PIB attributes. Implemented in the PhyM.nc.

- PLME_SET_TRX_STATE – Set the transceiver state. Implemented in the PhyM.nc.
- PLME_GET – Get PHY PIB attributes values. Implemented in the PhyM.nc.
- PLME_ED – Perform Energy Detection. Implemented in the PhyM.nc.
- Random - Interface to a simple pseudorandom number generator. Currently this interface is implemented by the RandomLFSR, which uses a linear feedback shift register to generate the sequence and mote address to initialize the register. Already developed in TinyOS.
- Leds – Mote Leds interface.
- Timer - T_scan_duration timer. TinyOS generic timer component (TimerC).
- Timer - T_ResponseWaitTime timer. TinyOS generic timer component (TimerC).
- Timer - T_ackwait timer. TinyOS generic timer component (TimerC).
- TimerAsync – Asynchronous timer component. Refer to section TimerAsync and Synchronization.

3.4.2. Provided Interfaces

The provided interfaces of the MacM component are the following:

- MLME_START
- MLME_ASSOCIATE
- MLME_DISASSOCIATE
- MLME_SYNC
- MLME_SYNC_LOSS
- MLME_SCAN
- MLME_RESET
- MLME_BEACON_NOTIFY
- MLME_COMM_STATUS
- MLME_SET
- MLME_GET
- MLME_GTS
- MCPS_DATA
- MCPS_PURGE

3.4.3. Variables

The component global variables are described in the following list.

General variables:

- *uint32_t aExtendedAddress0* – Extended address of the device (first 4 bytes);
- *uint32_t aExtendedAddress1* - Extended address of the device (last 4 bytes);
- *macPIB mac_PIB* – Mac PAN Information Base, this variable is a structure of the MAC PIB [1 pag. 135];
- *bool PANCoordinator* – 1 if the device is a pan coordinator;

- *bool Beacon_enabled_PAN* – 1 if the device is sending beacons;
- *bool SetDefaultPIB* – Upon receiving a reset command the device checks whether(1) or not(0) to reset the PIB
- *bool SecurityEnable* – The device uses security;
- *bool pending_reset* – A reset command has been received and the device must reset;
- *uint8_t current_channel* – The current channel where the device is operating;
- *uint8_t original_channel* – The default channel of the device;
- *uint8_t trx_status* – Transceiver status;
- *bool beacon_enabled* – The device is sending beacons;

Association variables

- *uint8_t associating* – 1 if the association procedure is being executed;
- *uint8_t association_cmd_seq_num* – Association request command message sequence number;
- *uint8_t a_LogicalChannel* – Logical channel where the device is associated;
- *uint8_t a_CoordAddrMode* – Type of address (short/long) of the coordinator where the device is associated;
- *uint16_t a_CoordPANId* – PANId of the coordinator where the device is associated;
- *uint32_t a_CoordAddress[2]* – Address of the coordinator where the device is associated. The address can be an extended or short address depending on the *a_CoordAddrMode* parameter;
- *uint8_t a_CapabilityInformation* – Capability information of the device;
- *bool a_securityenable* – 1 if security is enable;

Synchronization variables

- *bool TrackBeacon* – The device will track the beacon. It will enable its receiver just before the espected time of each beacon;
- *bool beacon_processed* – 1 if the beacon is already processed. This variable is set to 0 when the device receives a beacon and to 1 after the process_beacon() function execution;
- *uint8_t beacon_loss_reason* – The reason the beacon was lost;
- *bool findabeacon* – 1 if the device is trying to lacate one beacon
- *uint8_t missed_beacons* - number of beacons lost before sending a Beacon-Lost indication when the value is equal to aMaxLostBeacons
- *uint8_t on_sync* – 1 if the device is synchronized with the PAN coordinator;

GTS variables

- *uint8_t gts_request* – 1 if the GTS request procedure is being executed;
- *uint8_t gts_request_seq_num* – GTS request command message sequence number;
- *bool gts_confirm* – The GTS request was confirmed in the beacon;
- *uint8_t GTS_specification* – GTS specification of the device included in the GTS request
- *bool GTSCapability* – The device is a coordinator and has GTS allocation capability;

- *uint8_t final_CAP_slot* –CAP final time slot;
- *GTSinfoEntryType GTS_db[7]* – Allocated GTS descriptors database (coordinator only);
- *uint8_t GTS_descriptor_count* – Number of allocated GTS descriptors (coordinator only);
- *uint8_t GTS_startslot* – Number of the first GTS time slot allocated;
- *uint8_t GTS_id* – GTS unique id used in the GTS descriptor database;
- *GTSinfoEntryType_null GTS_null_db[7]* -Deallocated GTS descriptors database (coordinator only);
- *uint8_t GTS_null_descriptor_count* - Number of deallocated GTS descriptors (coordinator only);
- *uint8_t s_GTSss* – Device transmit GTS start slot;
- *uint8_t s_GTS_length* – Number of time slots for the transmit GTS allocation;
- *uint8_t r_GTSss* - Device receive GTS start slot;
- *uint8_t r_GTS_length* - Number of time slots for the receive GTS allocation;
- *uint8_t on_s_GTS* - used to state that the device is on its transmit slot;
- *uint8_t on_r_GTS* - used to state that the device is on its receive slot;
- *uint8_t next_on_s_GTS* - used to determine if the next time slot is used for transmission;
- *uint8_t next_on_r_GTS* - used to determine if the next time slot is used for reception;
- *uint8_t allow_gts* - 1 if the coordinator allows GTS allocations;
- *gts_slot_element gts_slot_list[7]* – List of pointers to the coordinator GTS buffer;
- *uint8_t available_gts_index[GTS_SEND_BUFFER_SIZE*] – List of available indexes in the coordinator GTS buffer;
- *uint8_t available_gts_index_count* – Number of messages in the coordinator GTS buffer;
- *uint8_t coordinator_gts_send_pending_data* – After a GTS send procedure (*start_coordinator_gts_send()*) the coordinator still has data to be send;
- *uint8_t coordinator_gts_send_time_slot* – Number of the current time slot allocated for the coordinator transmission;
- *norace MPDU gts_send_buffer[GTS_SEND_BUFFER_SIZE*] - GTS buffer used to store the GTS messages both for the coordinator and non-coordinator devices;
- *uint8_t gts_send_buffer_count* – Number of messages in the device GTS buffer message (non-coordinator only);
- *uint8_t gts_send_buffer_msg_in* – Pointer index of the next available slot in the GTS buffer.
- *uint8_t gts_send_buffer_msg_out* - Pointer index of the next available message ready to be send;
- *uint8_t gts_send_pending_data* - 1 if there is data send in the allocated GTS time slot;

Channel Scan variables

- *bool scanning_channels* – 1 if the channel scan procedure is being executed;
- *uint32_t channels_to_scan* – List of the channels to scan;
- *uint8_t current_scanning* – Current channel being scanned;
- *uint8_t scan_count* – Number of channels scaned;
- *uint8_t scanned_values[16]* – List of the LQI of the channels already scanned

- *uint8_t scan_type* – Scan type definition;
- *uint8_t scan_duration* – Duration of scan on each channel;

Timer variables

- *uint32_t response_wait_time* – Duration of the maximum time for a response to a request;
- *uint32_t BI* – Beacon interval parameter;
- *uint32_t SD* – Superframe duration parameter;
- *uint32_t time_slot* - backoff boundary timer duration;
- *uint32_t backoff* - backoff timer duration;
- *uint8_t number_backoff* – total number of backoffs in the active period;
- *uint8_t number_time_slot* – current time slot;
- *bool csma_slotted* – 1 if the slotted version of CSMA/CA is applied during the CAP;

CSMA/CA variables

- *uint8_t delay_backoff_period* – random number of backoff that the CSMA/CA algorithm must wait during the step 2 (Refer to the CSMA/CA section);
- *bool csma_delay* – Used in the TimerAsync.backoff_fired() timer event to activate the delay (Refer to the CSMA/CA section);
- *bool csma_locate_backoff_boundary* – Used in the TimerAsync.backoff_fired() timer event to locate the backoff bondary in the application of the slotted version of the CSMA/CA (Refer to the CSMA/CA section);
- *bool csma_cca_backoff_boundary* - Used in the TimerAsync.backoff_fired() timer event to locate the backoff bondary in the application of the slotted version of the CSMA/CA (Refer to the CSMA/CA section);
- *bool performing_csma_ca* – 1 if the device is performing the application of the CSMA/CA;
- *uint8_t BE* – Backoff exponent used in the CSMA/CA;
- *uint8_t CW* - Contention window used in the CSMA/CA (number of backoffs to clear the channel in the slotted version);
- *uint8_t NB* – Number of backoff used in the CSMA/CA;

Indirect Transmission buffers

- *indirect_transmission_element indirect_trans_queue[INDIRECT_BUFFER_SIZE*] – Indirect transmission buffer used to store the messages that are going to be transmitted upon the request of the destination device;
- *uint8_t indirect_trans_count* – Total number of messages in the indirect transmission buffer;

Receive buffers

- *norace MPDU buffer_msg[RECEIVE_BUFFER_SIZE]* – Receive buffer used to store the messages received;
- *int current_msg_in* - Pointer index of the next available slot in the receive buffer;
- *int current_msg_out* - Pointer index of the next available message ready to be processed;
- *int buffer_count* – Number of messages in the receive buffer;

Send buffers

- *norace MPDUBuffer send_buffer[SEND_BUFFER_SIZE]* - Send buffer used to store the messages ready to be transmitted;
- *uint8_t send_buffer_count* - Number of messages in the send buffer;
- *uint8_t send_buffer_msg_in* - Pointer index of the next available slot in the send buffer;
- *uint8_t send_buffer_msg_out* - Pointer index of the next available message ready to be send;
- *uint8_t send_ack_check* – An acknowledge is requested in the transmitted frame;
- *uint8_t retransmit_count* – Number of retransmission of the transmitted frame;
- *uint8_t ack_sequence_number_check* – Current transmission sequence number;
- *uint8_t send_retransmission* – 1 if the current message being send can be retransmitted if the transmission fails;
- *uint8_t send_indirect_transmission* – 1 if the current message being send is an indirect transmission;

Reception and Transmission variables

- *uint8_t pending_request_data* – 1 if the device can only send one request data command.
- *uint8_t ackwait_period* – Duration of the time frame to receive an acknowledgment of a transmitted frame;
- *uint8_t link_quality* – LQI of the current received message frame;
- *norace ACK mac_ack* – Acknowledgment frame memory allocation;
- *ACK *mac_ack_ptr* – Pointer for the acknowledgment frame memory position;
- *uint8_t I_AM_IN_CAP* – 1 if the device in in the CAP;
- *uint8_t I_AM_IN_CFP* – 1 if the device is in the CFP;
- *uint8_t I_AM_IN_IP* – 1 if the device is in the inactive period;

Beacon management variables

- *norace MPDU mac_beacon_txmpdu* - Beacon frame memory allocation;
- *MPDU *mac_beacon_txmpdu_ptr* – Pointer for the beacon frame memory position;
- *uint8_t *send_beacon_frame_ptr* – Beacon pointer;
- *uint8_t send_beacon_length* – Beacon length;

3.4.4. Functions description

General functions

- *void init_MacCon()* – Function used to initialize the internal MAC constants;
- *void init_MacPIB()* - Function used to initialise the MAC PAN Information Base constants;
- *uint8_t min(uint8_t val1, uint8_t val2)* – Returns the minimum value between val1 and val2 arguments;
- *task void set_trx()* – Task function used to change the transceiver state. This function is called from an asynchronous event making its execution synchronous.
- *task void signal_loss()* – Task function used to signal the synchronous primitive *MLME_SYNC_LOSS.indication* indicating a synchronization loss. This function is called from an asynchronous event making its execution synchronous.
- *task void pd_data_confirm()* – Task function called when the MAC layer receives the *PD_DATA.confirm* primitive.
- *void create_data_request_cmd()* - Function used to create a data request command frame. The created frame is inserted in the send buffer and will be ready to send;
- *void create_beacon_request_cmd()* – Function used to create a beacon request command frame. The created frame is inserted in the send buffer and will be ready to send;
- *void create_gts_request_cmd(uint8_t gts_characteristics)* – Function used to create a GTS request command frame. The created frame is inserted in the send buffer and will be ready to send;
- *void create_data_frame(uint8_t SrcAddrMode, uint16_t SrcPANId, uint32_t SrcAddr[], uint8_t DstAddrMode, uint16_t DestPANId, uint32_t DstAddr[], uint8_t msduLength, uint8_t msdu[],uint8_t msduHandle, uint8_t TxOptions,uint8_t on_gts_slot,uint8_t pan)* – Function used to create a data frame. This function is called from the MCPS_DATA.request primitive that was previously requested by the MAC upper layer. The created frame is inserted in the send buffer and will be ready to send;
- *void build_ack(uint8_t sequence,uint8_t frame_pending)* – Function used to create an acknowledgment frame. The frame is created in the mac_ack variable and its send directly without any CSMA/CA.
- *void list_mac_pib()* – Function used to list the MAC PIB attributes through the UART. Debug propose only.

Association functions

- *void create_association_request_cmd(uint8_t CoordAddrMode,uint16_t CoordPANId,uint32_t CoordAddress[]))* – Function used to create an association request command frame. The created frame is inserted in the send buffer and will be ready to send. This function is used only by the devices that want to associate;
- *result_t create_association_response_cmd(uint32_t DeviceAddress[],uint16_t shortaddress, uint8_t status))* – Function used to create an association response command frame. The created frame is inserted in the send buffer and will be ready to

send. This function is used only by the PAN coordinator in the response of an association request;

- *void create_disassociation_notification_cmd(uint32_t DeviceAddress[],uint8_t disassociation_reason))* – Function used to create a dissociation notification command frame. The created frame is inserted in the send buffer and will be ready to send. This function is used only by the devices that are associated;
- *void process_dissassociation_notification(MPDU *pdu)* – Function used to process the disassociation request. This function will signal the MAC upper layer with the *MLME_DISASSOCIATE.indication* primitive;

GTS functions

- *void process_gts_request(MPDU *pdu)* – Function used to process a GTS request. This function will signal the MAC upper layer with the *MLME_GTS.indication* primitive;
- *void init_available_gts_index()* – Function used to initialize the available indexes of the GTS send buffer. The available indexes will depend on the *GTS_SEND_BUFFER_SIZE* variable. This function is only used by the PAN coordinator.
- *task void start_coordinator_gts_send()* -Function used to send the GTS messages of the coordinator GTS send mechanism. This function is called when the coordinator has a transmit GTS time slot allocated. The send procedure of this function will only send if there are messages to send. This function is only used by the PAN coordinator;
- *result_t remove_gts_entry(uint16_t DevAddressType)* – Function used to deallocate a GTS time slot. The remaining allocated time slots will be rearranged. This function is only used by the PAN coordinator;
- *result_t add_gts_entry(uint8_t gts_length,bool direction,uint16_t DevAddressType)* – Function used to allocate a GTS time slot. This function is only used by the PAN coordinator;
- *result_t add_gts_null_entry(uint8_t gts_length,bool direction,uint16_t DevAddressType)* - Function used to add deallocated GTS descriptor to the GTS null database. This function is called when the PAN coordinator deallocates a device adding in its beacon a null descriptor with the device address and an allocated length of zero. This function is only used by the PAN coordinator;
- *task void increment_gts_null()* – Function used to increment the GTS expiration time (measured in superframes) of the GTS deallocated devices. This function is only used by the PAN coordinator;
- *task void start_gts_send()* - Function used to send GTS messages. This function is called when a non-coordinator device has a transmit time slot allocated. The send procedure of this function will only send if there are messages to send. This function is only used by non-coordinator devices;
- *uint32_t calculate_gts_expiration()* – Function used to calculate the expiration time of the allocated GTSs. Each allocated GTS will expire if there are no transmissions during a calculated superframe count. This function is only used by the PAN coordinator;
- *task void check_gts_expiration()* – Function used to verify if the allocated GTS time slots are expired or not. If a GTS expires it will be placed in the GTS null descriptors. This function is only used by the PAN coordinator;

- *void init_gts_slot_list()* – Used to initialize the *gts_slot_element* buffer array of the GTS allocated time slots. This function is only used by the PAN coordinator;
- *void init_GTS_null_db()* - Used to initialize the *GTS_null_db* buffer array of the GTS deallocated time slots. This function is only used by the PAN coordinator;
- *void list_gts_null()* - Function used to list the GTS null descriptors (*GTS_null_db*) through the UART. Debug propose only.
- *void list_gts()* - Function used to list the GTS allocated descriptors (*GTS_db*) through the UART. Debug propose only.
- *void init_GTS_db()* – Function used to initialize the GTS allocated descriptors (*GTS_db*). This function is only used by the PAN coordinator;
- *void list_my_gts()* - Function used to list the device allocated GTS time slots through the UART. Debug propose only.

CSMA/CA functions

- *void init_csma_ca(bool slotted)* – Function used to initialize the CSMA/CA mechanism variables;
- *void perform_csma_ca()* – Function used to start the CSMA/CA mechanism;
- *task void perform_csma_ca_unslotted()* - Function used to execute the final steps of the application of the unslotted version of CSMA/CA mechanism;
- *task void perform_csma_ca_slotted()* - Function used to execute the final steps of the application of the slotted version of CSMA/CA mechanism;
- *task void start_csma_ca_slotted()*- Function used to execute the first step (STEP 2) of the application of the slotted version of CSMA/CA mechanism;

Indirect Transmission functions

- *void init_indirect_trans_buffer()* - Function used to initialize the indirect transmission buffer. This function is only used by the PAN coordinator;
- *void send_ind_trans_addr(uint32_t DeviceAddress[])* - Function used to search and send an existing indirect transmission message. This function is only used by the PAN coordinator;
- *result_t remove_indirect_trans(uint8_t handler)* - Function used to remove an existing indirect transmission message. This function is only used by the PAN coordinator;
- *void increment_indirect_trans()* - Function used to increment the transaction persistent time on each message. If the transaction time expires the messages are discarded. This function is only used by the PAN coordinator;
- *void list_indirect_trans_buffer()* – Function used to list all the handles in the indirect transmission buffer. Debug purposes only;

Receive functions

- *task void message_out()* – Task function used to increment the *current_msg_out* pointer of the receive messages buffer when a message is processed;
- *task void message_in()*– Task function used to increment the *current_msg_in* pointer of the receive messages buffer when a message is received;

- *task void data_indication()* – Task function called when the MAC layer receives from the PHY the asynchronous *PD_DATA.indication* primitive. This function will synchronously process the type of message receives and will call the appropriate function to process it;
- *void indication_beacon(MPDU *pdu, int8_t ppduLinkQuality)* – Function called from the *data_indication()* function and is used to pre-process a beacon frame received;
- *void indication_cmd(MPDU *pdu, int8_t ppduLinkQuality)* – Function called from the *data_indication()* function and is used to process a command frame received;
- *void indication_ack(MPDU *pdu, int8_t ppduLinkQuality)* – Function called from the *data_indication()* function and is used to process an acknowledge frame received;
- *void indication_data(MPDU *pdu, int8_t ppduLinkQuality)* – Function called from the *data_indication()* function and is used to process a data frame received. This function will signal the MAC upper layer with *MCPS_DATA.indication* primitive.

Reception and Transmission functions

- *task void send_frame_csma()* - Function used to start the send mechanism of the messages that are in the send buffer during the CAP period of the superframe and using the CSMA/CA algorithm;
- *uint8_t check_csma_ca_send_conditions(uint8_t frame_length,uint16_t frame_control)* – Function used to compute the conditions necessary to send a message in the CAP period. This function will calculate is a message can be send by adding the frame length and the correspondent ifs symbols or also adding the acknowledgment length and the respective turnaround time if the message requires an acknowledgment. The function will return true if there is enough time to send the message otherwise it will return false;
- *uint8_t check_gts_send_conditions(uint8_t frame_length)* – Function used to compute the conditions necessary to send a message in an allocated transmit GTS time slot. This function will calculate is a message can be send by adding the frame length and the correspondent ifs symbols or also adding the acknowledgment length and the respective turnaround time if the message requires an acknowledgment. The function will return true if there is enough time to send the message otherwise it will return false;
- *uint8_t calculate_ifs(uint8_t pk_length)* – Function used to calculate the ifs symbols. The ifs will depend on the frame length;

Beacon management functions

- *task void create_beacon()* - Function to create the beacon. This function is only used by the PAN coordinator;
- *void process_beacon(MPDU *packet)* - Function to process the beacon information.

3.5. Implementation of the protocol functionalities

3.5.1. Buffers

The IEEE 802.15.4 protocol has no reference concerning the implementation of the buffer mechanisms. The buffers implementation has an important role in the good performance of the protocol. On one hand, the protocol must avoid excessive memory copy operations because it can cause synchronization problems and is very time consuming. On the other hand, the buffers have to be small and very well managed because of the devices memory constrains. The MICAz motes only have approximately 4 Kbytes of RAM memory available and the maximum packet length is about 127 bytes if we increase the buffer size the free memory of the mote will decrease rapidly.

This implementation uses 4 buffers:

- *buffer_msg* – Used to store the received messages;
- *send_buffer* – Used to store the messages that are ready to be send;
- *indirect_trans_queue* – Used by the coordinator to store the messages that are send using the indirect transmission procedure. The messages stored need to be requested by the destination device in order to be send. The coordinator sends one of these messages by transferring it to the *send_buffer* queue.
- *gts_send_buffer* – Used to store the messages that are ready to be sent in one GTS during the CFP.

Sending and Receiving

The buffers used for receiving and sending are FIFO (First In First Out) buffers. The implementation consists on an array with a constant length, the buffer size, and two pointers. The first pointer (in) point to the next available slot to store a new message, and the second (out) points to the oldest message in the queue. There is also one variable that contains the current message count in the buffer, if its equal to the buffer size it means that the buffer is full.

The next figure explains the implementation of these buffers.

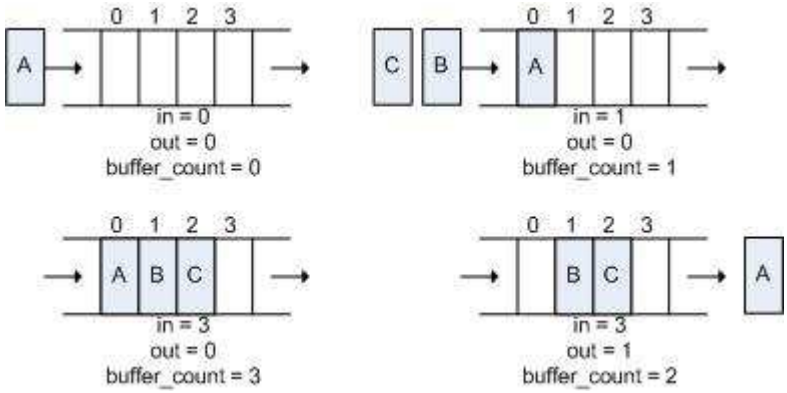


Figure 7 - Buffer management example.

There are two ways for sending a message, using the CSMA/CA algorithm or sending the message without any channel assessment. The second way is only used to send beacons and acknowledgments frames. The CSMA/CA is used to send command and data frames. If the sent frame requires an acknowledgment the sender must wait for it before sending a new message. The wait or the retransmission mechanism consists on a timer that is activated after a transmission that requires an acknowledgment. This procedure is described in detail in [1 pag 157]. The event *T_ackwait.fired()* is used to activate the retransmission of the last sent and not acknowledge frame. If the frame is acknowledged in the available time frame the *T_ackwait()* event is stopped, otherwise the event will fire until the frame is acknowledge or until is reaches the maximum allowed retransmissions (the number of retransmissions is defined in the *aMaxFrameRetries* constant).

The time frame available for the acknowledgement is defined in the *macAckWaitDuration* variable of the MAC PIB. This value is very important because we must take into account the processing time of the device, otherwise the device could be pre-processing the message after sending the acknowledgment and the source of the message may try to retransmit it again.

The next charts illustrate the MAC-PHY interaction when sending messages, either from the originator and the receiver. [1 pag 185-186].

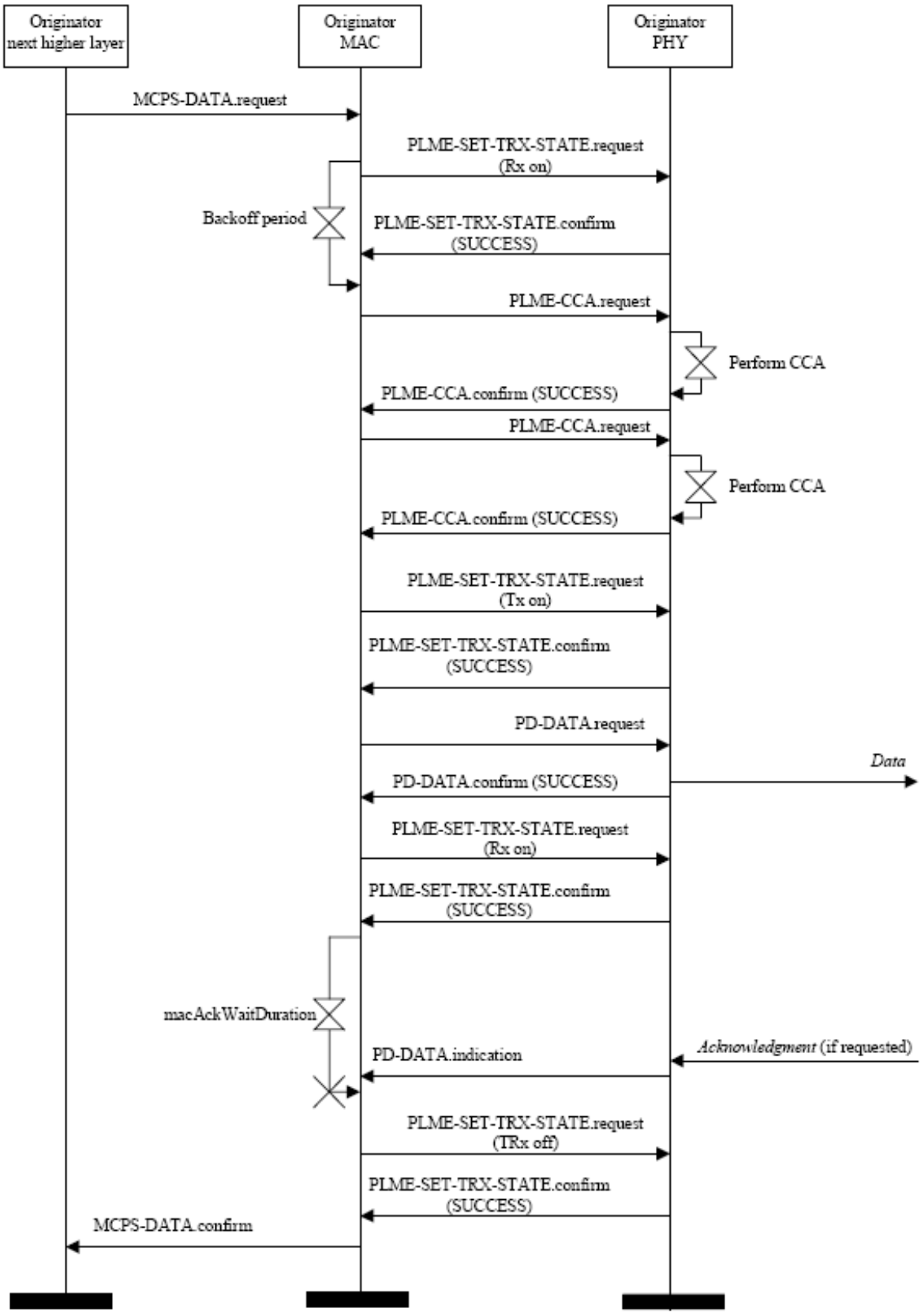


Figure 8 - Data transmission sequence chart - originator.

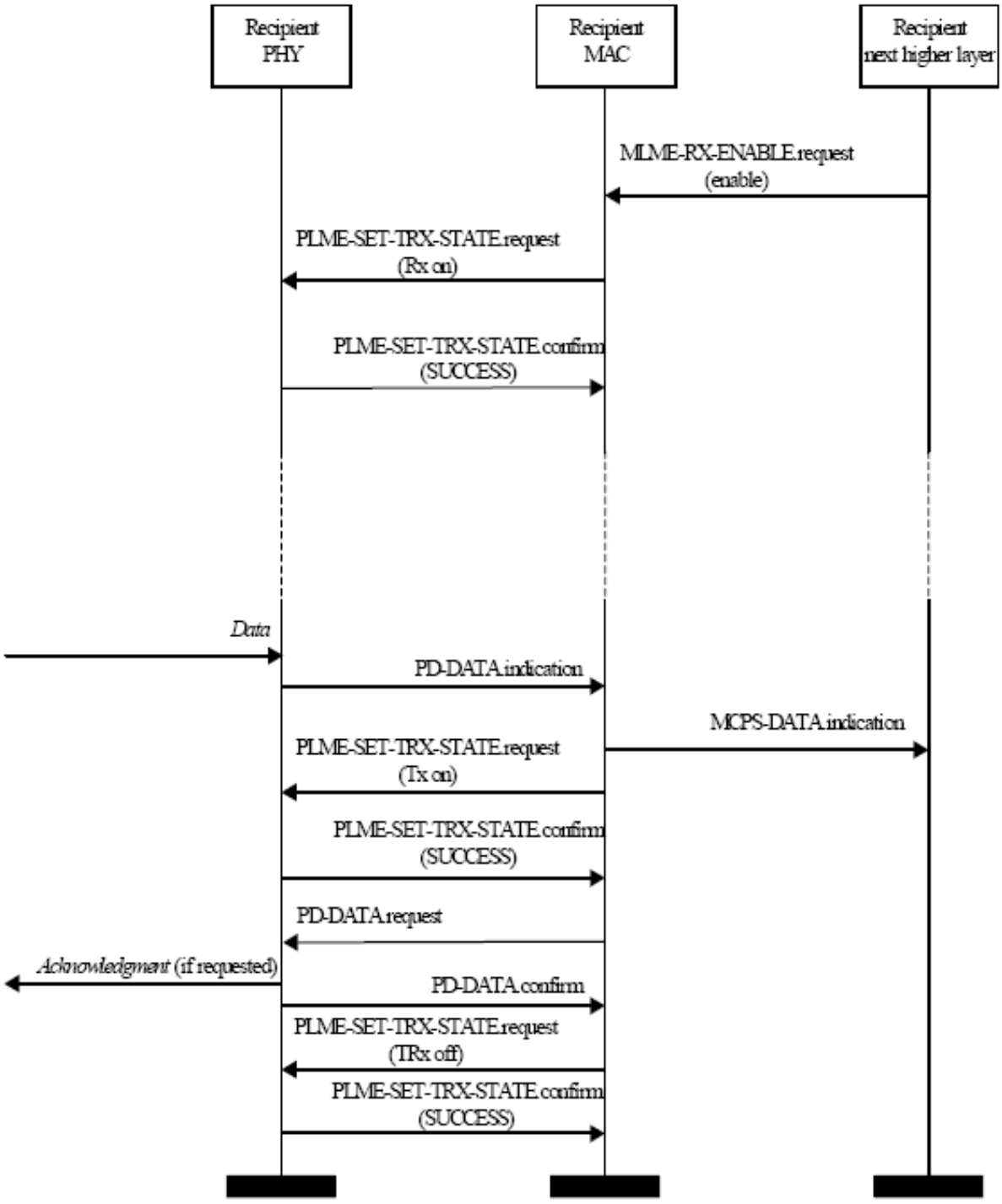


Figure 9 - Data transmission sequence chart - recipient.

Indirect Transmissions

The buffer used for the indirect transmissions is defined as a structure. When the coordinator needs to send an indirect transmission it needs to search in the buffer the correct message to send. This procedure goes through all the positions of the message array comparing the destinations addresses until it finds the correct message or, ignores the indirect transmission request if there are no messages for the requested address.

The structure defined is the following:

```
typedef struct
{
    uint8_t handler;
    uint16_t transaction_persistent_time;
    uint8_t frame[127];
}indirect_transmission_element;
```

Code Example 1 - Indirect transmissiton structure definition.

Each indirect transmission element has a unique handler to identify each position. The *transaction_persistent_time* variable is used to count, in number of superframes, the time that the message is stored in the buffer. If this number reaches the *macTransactionPersistenceTime* defined in the MAC PIB the message is discarded. For a more detailed explanation of this procedure refer to [1 pag 155].

The functions used for maintaining the indirect transmission buffer are the following:

- *void init_indirect_trans_buffer()* – This function is used to initialize the indirect transmission buffer, all the positions of the buffer are reset to the initialization values.

- *void send_ind_trans_addr(uint32_t DeviceAddress[])* - This function is used to search and send an existing indirect transmission message. If the message does not exist the request is ignored, if it exists, the message is inserted in the *send_buffer* and will be removed from the indirect buffer. Then, the message is treated like a "normal" message to be sent by the device.

- *result_t remove_indirect_trans(uint8_t handler)* - This function is used to remove an existing indirect transmission message.

- *void increment_indirect_trans()* – This function is used to increment the transaction persistent time on each message, if the transaction time expires the messages are discarded. This function is called at the end of every superframe on the *sd_fired* event.

- *void list_indirect_trans_buffer()* - This function list all the handlers in the indirect transmission buffer and is used for debug purposes only

The different transmission scenarios are described in [1 pag. 158].

GTS Buffer

The GTS buffer is used in two different ways. If the device is not a coordinator the buffer is FIFO and its used like the send and receive buffer with two pointers indicating the in and out of the messages and the total number of messages in the buffer. The messages are sent in the appropriate GTS allocated transmit time slot. If the device is a coordinator the buffer is maintained by an auxiliary structure with index pointers

pointing to the appropriate message in the buffer. Also the auxiliary structure *gts_slot_list* is indexed with the available timeslots that can be used for GTS transmission. This mechanism is used to avoid performing sequential and time consuming searches in the buffer to find the desired packet. Along with the *gts_send_buffer* buffer there is also one auxiliary array declared as *available_gts_index[GTS_SEND_BUFFER_SIZE]* storing the available indexes in the GTS buffer. The *GTS_SEND_BUFFER_SIZE* constant variable defines the GTS maximum size. If the coordinator wants to send data in the GTS, it must check if there are available indexes to store the message. When the message is send, its *gts_send_buffer* position becomes available by inserting in the *available_gts_index* list the *gts_send buffer* index.

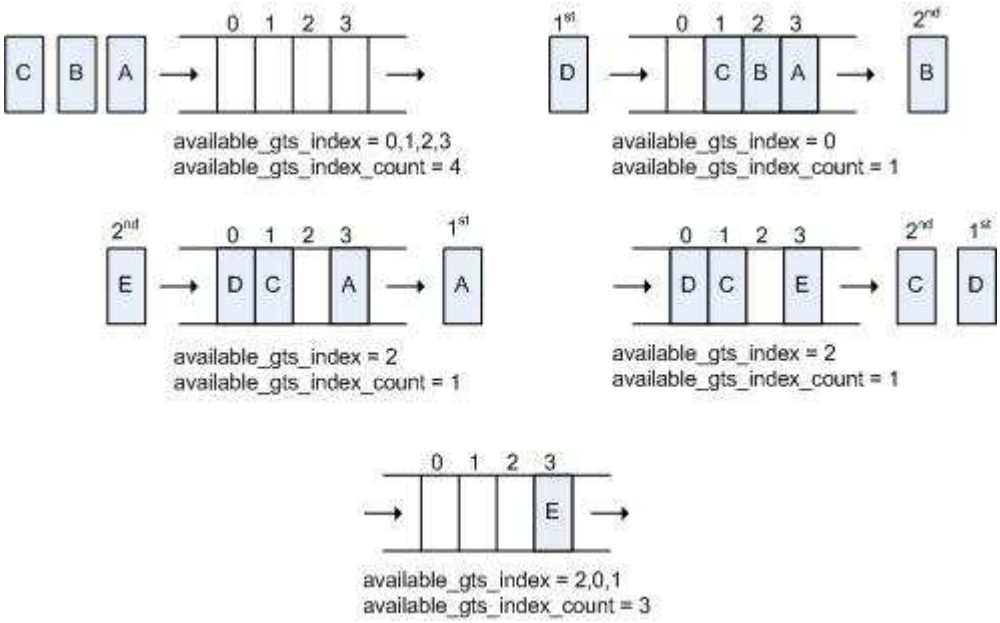


Figure 10 - GTS buffer management - PAN coordinator.

The *gts_slot_list* is defines as an array of *gts_slot_element*. The *gts_slot_element* is defined in the *mac_const.h* file and has the following structure:

```
typedef struct gts_slot_element
{
    uint8_t element_count;
    uint8_t element_in;
    uint8_t element_out;
    uint8_t gts_send_frame_index[GTS_SEND_BUFFER_SIZE];

}gts_slot_element;
```

Code Example 2 - gts_slot_element structure definition.

Each element in the *gts_slot_list* array represents one GTS time slot, up to the maximum of seven, defined in the protocol as the maximum number of GTS time slots available for GTS allocation. The *gts_slot_element* defines a FIFO buffer used to store indexes that reference positions in the *gts_send_buffer*, and it is maintained as the send and receive buffers.

3.5.2. Data Reception

The SFD pin going high means that the transceiver is starting to receive a frame. If the frame check sequence is ok (hardware condition, implemented by the CC2420 transceiver and all the IEEE 802.15.4 compliant transceivers) the PHY layer will be signalled by the FIFO interrupt (*async event result_t HPLCC2420.FIFOPIntr()*). Upon the reception of this event, the PHY will signal the MAC layer with the *PD_DATA.indication* primitive, which will copy the received frame to the *buffer_msg* buffer. The functions tasks *message_out* and *message_in* are used for the buffer management queue operations. These functions must be tasks because of the asynchronous processing of the *PD_DATA.indication* event. After the message is copied to the buffer, the MAC will call the *data_indication* function to pre-process the frame headers, selecting the frame type received, in order to call the appropriate function to fully process the frame. The *data_indication* function also do a pre-evaluation, stating if the message can be acepted of not. For example, if the MAC is in the middle of the CSMA/CA algorithm or performing a channel scan the frame will be discarded.

Depending on the frame type the *data_indication* function will select one of the following functions:

- *indication_data* – if the frame type is a TYPE_DATA;
- *indication_ack* – if the frame type is a TYPE_ACK;
- *indication_cmd* – if the frame type is a TYPE_CMD;
- *indication_beacon* – if the frame type is a TYPE_BEACON.

According to the IEEE 802.15.4 the MAC will only accept frame if the satisfy the following requirements [1 pag 155]:

- The frame type subfield of the frame control field shall not contain an illegal frame type;
- If the frame type indicates that the frame is a beacon frame, the source PAN identifier shall match *macPANId* unless *macPANId* is equal to *0xffff*, in which case the beacon frame shall be accepted regardless of the source PAN identifier;
- If a destination PAN identifier is included in the frame, it shall match *macPANId* or shall be the broadcast PAN identifier (*0xffff*);
- If a short destination address is included in the frame, it shall match either *macShortAddress* or the broadcast address (*0xffff*). Otherwise, if an extended destination address is included in the frame, it shall match *aExtendedAddress*;
- If only source addressing fields are included in a data or MAC command frame, the frame shall be accepted only if the device is a PAN coordinator and the source PAN identifier matches *macPANId*.

Some of these conditions are verified after the *data_indication* function selects the proper function.

The next figure illustrates the data reception operations.

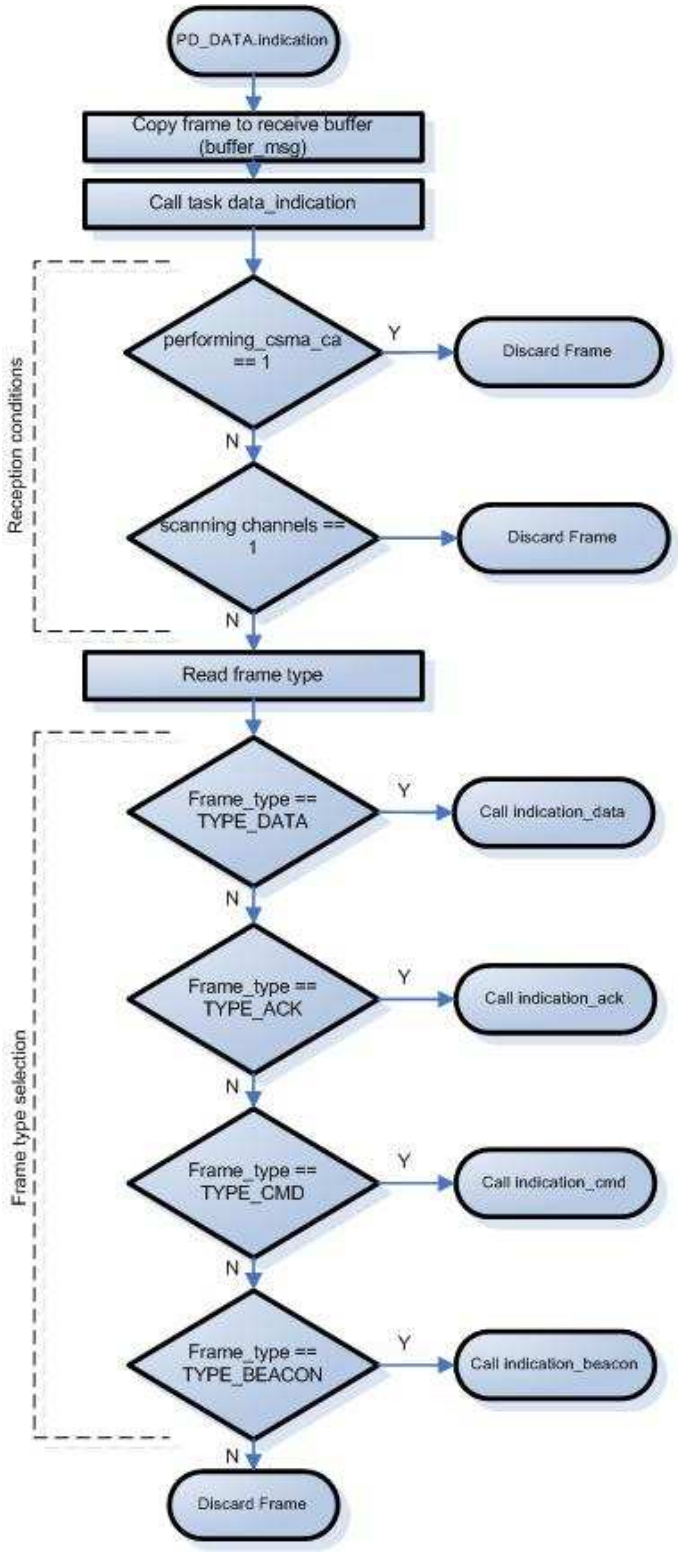


Figure 11 - Data reception flow chart.

3.5.3. TimerAsync and Synchronization

An important aspect of this protocol is the synchronization. A first difficulty in the implementation of the beacon-enabled mode was related to the TinyOS management of hardware timer provided by the MICAz motes, which does not allow having the exact values in millisecond of the beacon interval, superframe, time slots and backoffs durations as specified by the IEEE 802.15.4 standard. To accomplish a precise synchronization a timer component was developed, with an asynchronous behaviour regarding the code execution, based on the hardware clock

Considering that there are two different types of timers in this implementation. The synchronous timers are used in the implementation for events that doesn't need precision and the asynchronous timers that are more precise due to their asynchronous behaviour.

The synchronous timer use the TinyOS provided timer component, the *TimerC* and the asynchronous use our custom timer, based on the *TimerJiffy* timer component, the *TimerAsyncC*. This timer is uses the TinyOS Clock component, located in the *contrib.hurray.tos.system* directory. This component uses the hardware clock component *HPLTimer2C* located in the *contrib.hurray.tos.platform.MICAz* directory.

The TimerAsyncC component is located under the *contrib.hurray.tos.system* directory and the TimerAsync interface is located under the *contrib.hurray.tos.interfaces* directory.

TimerAsyncC Component

This component is used to wire the TimerAsync interface with the TimerAsyncM of the timer implementation.

The next figure represents the component graph.

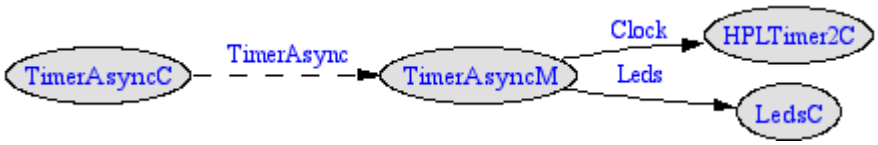


Figure 12 - TimerAsyncC component graph.

TimerAsyncM Component

Implementation notes:

The *TimerAsync* component is one timer that is used to trigger 7 asynchronous timer events. The events signalled are used mainly for maintaining protocol synchronization related to the slotted version.

All the events are signalled inside the *Timer.fire()* event that is generated by the usage of the hardware clock timers in the HPLTimer2C component. The protocol events have the following purpose:

signal TimerAsync.bi_fired() – Timer used to signal the end of the beacon interval.

signal TimerAsync.before_bi_fired() – Timer used to signal a time defined constant (*BEFORE_BI_INTERVAL*) before the beacon interval fired. This is used to turn the transceiver on before the beacon interval fires so that if the device is a pan coordinator the transceiver will be ready to transmit the beacon and if the device is a normal node the transceiver will be ready to receive the beacon.

signal TimerAsync.sd_fired() – Timer used to signal the end of the superframe duration. This is used for the device to enter the sleep period (if applied) It's also used to disable the time slot and backoffs events because during the sleep period there is no activity (if applied).

signal TimerAsync.time_slot_fired() - Timer used to signal each time slot. This is used for the GTS mechanism.

signal TimerAsync.before_time_slot_fired() – Timer used to signal a time defined constant (*BEFORE_BB_INTERVAL*) before the time slot fired. This is used to switch the transceiver state before each time slot so that the transceiver is ready to transmit/receive when the time slot starts.

signal TimerAsync.backoff_fired() – Timer used to signal each backoff. This is used for the CSMA/CA algorithm.

signal TimerAsync.sfd_fired() – Timer used to signal the start-of-frame delimiter upon the arrival of data. This is used to know exactly when the transceiver starts receiving data and is prior to the FIFO interrupt that is triggered only when the full length of the frame is received.

The next figure represents the timer events in the superframe structure.

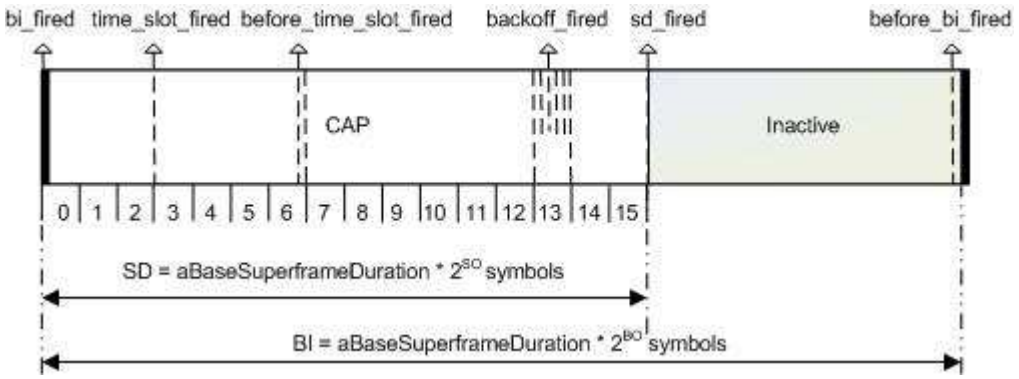


Figure 13 - Timer events in superframe structure.

This timer component is based on the hardware clock timer configuration defined in two constants:

- SCALE – This constant defines the scale division of the ATMEL microprocessor.
- INTERVAL – This constant defines the number of clock ticks per clock firing.

The clock tick granularity of the MICAz mote that best fit our requirements is equal to 69.54 microseconds, which approximately corresponds to four symbols (configuration with SCALE equal to 4 and INTERVAL equal to 1). In fact, the four symbols duration have a theoretical value of 64 microseconds which leads to a cumulative effect on the discrepancy with theoretically values of beacon interval, superframe durations and time slot durations in millisecond for high superframe and beacon orders. For instance, the theoretical time of a superframe duration with SO=3 is equal to 122.88 ms, while it is equal to 133.36 ms using the MICAz motes and the TinyOS time management of the clock granularity.

MICAZ		
	Effective	Teorical
Backoff Symbols	20	20
Symbol Duration (us)	17,362	16
Backoff Duration (us)	347,24	320
Granularity (us)	69,54	64
Backoff Clock Ticks	5	5

Table 9 - MICAz clock ticks granularity comparison.

MICAz Time Slot Durations (Effective Values)				
SO	Symbols	Backoff Periods	Timeslot Duration (us)	Clock Ticks
0	60	3	1041,72	15
1	120	6	2083,44	30
2	240	12	4166,88	60
3	480	24	8333,76	120
4	960	48	16667,52	240
5	1920	96	33335,04	479
6	3840	192	66670,08	959
7	7680	384	133340,16	1917
8	15360	768	266680,32	3835
9	30720	1536	533360,64	7670
10	61440	3072	1066721,28	15340
11	122880	6144	2133442,56	30679
12	245760	12288	4266885,12	61359
13	491520	24576	8533770,24	122717
14	983040	49152	17067540,48	245435

Table 10 - MICAz time slot durations - Effective values.

MICAz Time Slot Durations (Theoretical Values)				
SO	Symbols	Backoff Periods	Timeslot Duration (us)	Clock Ticks
0	60	3	960	15
1	120	6	1920	30
2	240	12	3840	60
3	480	24	7680	120
4	960	48	15360	240
5	1920	96	30720	480
6	3840	192	61440	960

7	7680	384	122880	1920
8	15360	768	245760	3840
9	30720	1536	491520	7680
10	61440	3072	983040	15360
11	122880	6144	1966080	30720
12	245760	12288	3932160	61440
13	491520	24576	7864320	122880
14	983040	49152	15728640	245760

Table 11 - MICAz time slot durations - Theoretical values.

MICAz Beacon Interval Durations (Effective Values)				
BO	Symbols	Backoff Periods	Duration (us)	Clock Ticks
0	960	48	16667,52	240
1	1920	96	33335,04	479
2	3840	192	66670,08	959
3	7680	384	133340,16	1917
4	15360	768	266680,32	3835
5	30720	1536	533360,64	7670
6	61440	3072	1066721,28	15340
7	122880	6144	2133442,56	30679
8	245760	12288	4266885,12	61359
9	491520	24576	8533770,24	122717
10	983040	49152	17067540,48	245435
11	1966080	98304	34135080,96	490870
12	3932160	196608	68270161,92	981739
13	7864320	393216	136540323,8	1963479
14	15728640	786432	273080647,7	3926958

Table 12 - MICAz beacon interval durations - Effective values.

MICAz Beacon Interval Durations (Theoretical Values)				
BO	Symbols	Backoff Periods	Duration (us)	Clock Ticks
0	960	48	15360	240
1	1920	96	30720	480
2	3840	192	61440	960
3	7680	384	122880	1920
4	15360	768	245760	3840
5	30720	1536	491520	7680
6	61440	3072	983040	15360
7	122880	6144	1966080	30720
8	245760	12288	3932160	61440
9	491520	24576	7864320	122880
10	983040	49152	15728640	245760
11	1966080	98304	31457280	491520
12	3932160	196608	62914560	983040
13	7864320	393216	125829120	1966080
14	15728640	786432	251658240	3932160

Table 13 - MICAz beacon interval durations - Theoretical values.

Required Interfaces

The required interfaces of the TimerAsyncM component are the following:

- Clock Timer
- Leds

Provided Interfaces

The provided interfaces of the TimerAsyncM component are the following:

- TimerAsync

Variables

- *uint32_t ticks_counter* – current number of clock ticks on each beacon interval.
- *uint32_t bi_ticks* – number of clock ticks needed to reach the beacon interval boundary.
- *uint32_t bi_backoff_periods* – number of backoffs in one beacon interval.
- *uint32_t before_bi_ticks* – number of clock ticks needed to reach the boundary defined by the *bi_ticks – BEFORE_BI_INTERVAL* (constant).
- *uint32_t sd_ticks* – number of clock ticks needed to reach the superframe duration interval boundary.
- *uint32_t time_slot_backoff_periods* – number of backoffs in one time slot.
- *uint32_t time_slot_ticks* –total number of clock ticks needed to reach the beacon interval boundary.
- *uint32_t before_time_slot_ticks* - number of clock ticks needed to reach the boundary defined by the *bi_ticks – BEFORE_BB_INTERVAL* (constant).
- *uint32_t time_slot_tick_next_fire* – number of clock ticks needed to reach the next time slot boundary.
- *uint32_t backoff_symbols* – number of symbols in one backoff.
- *uint32_t backoff_ticks* – number of clock ticks in one backoff.
- *uint32_t backoff_ticks_counter* – current number of clock ticks on each backoff.
- *uint8_t current_time_slot* – current time slot number.
- *uint32_t current_number_backoff_on_time_slot* – current backoff number on each time slot.
- *uint32_t current_number_backoff* – current number of backoff on each beacon interval.
- *bool backoffs* – enable/disable backoff events .
- *uint8_t previous_sfd* – temporary variable that stores the SFD pin reading .
- *uint8_t current_sfd* – temporary variable that stores the SFD pin reading.
- *uint32_t process_frame_tick_counter* – current number of clock ticks needed to fully receive a data frame.
- *uint32_t total_tick_counter* – current number of clock ticks.

Function description

async command result_t TimerAsync.start (void)

Command used to start the component.

command result_t TimerAsync.init (void)
Command used in the initialization of the component.

async command result_t TimerAsync.stop (void)
Command used to stop the component.

async command result_t TimerAsync.reset (void)
Command used to reset the global timer variable. This function zeroes the *tick_counter* variable.

async command result_t TimerAsync.reset_process_frame_tick_counter (void)
Command used to reset the process frame timer variable. This function zeroes the *process_frame_tick_counter* variable.

async command uint8_t TimerAsync.reset_start (uint32_t start_ticks)
Command used to reset the global timer variable. This function initializes the *tick_counter* variable with the values of the *start_ticks* argument.

async command result_t TimerAsync.set_bi_sd (uint32_t bi_symbols, uint32_t sd_symbols)
Command used to set the duration, in symbols, of the beacon interval and superframe.

async command result_t TimerAsync.set_backoff_symbols (uint8_t Backoff_Duration_Symbols)
Command used to set the duration, in symbols, of the backoff interval.

async command result_t TimerAsync.set_enable_backoffs (bool enable)
Command used to enable/disable the backoff events interrupts.

async command uint32_t TimerAsync.get_current_ticks (void)
Command used to read the *current_ticks* variable.

async command uint32_t TimerAsync.get_sd_ticks (void)
Command used to read the *sd_ticks* variable.

async command uint32_t TimerAsync.get_bi_ticks (void)
Command used to read the *bi_ticks* variable.

async command uint32_t TimerAsync.get_backoff_ticks (void)
Command used to read the *backofft_ticks* variable.

async command uint32_t TimerAsync.get_time_slot_ticks (void)
Command used to read the *time_slot_ticks* variable.

async command uint32_t TimerAsync.get_current_number_backoff (void)
Command used to read the *curren_number_backoff* variable.

async command uint32_t TimerAsync.get_time_slot_backoff_periods (void)
Command used to read the *time_slot_backoff_periods* variable.

async command uint32_t TimerAsync.get_current_time_slot (void)
Command used to read the *current_time_slot* variable.

async command uint32_t TimerAsync.get_current_number_backoff_on_time_slot (void)
Command used to read the *current_number_backoff_on_time_slot* variable.

async command uint32_t TimerAsync.get_total_tick_counter (void)
Command used to read the *total_tick_counter* variable.

async command uint32_t TimerAsync.get_process_frame_tick_counter (void)
Command used to read the *process_frame_tick_counter* variable.

async event result_t Timer.fire (void)

The *Timer.fire* event is triggered by the Clock component if the interrupts notification is enabled. The *TimerAsync* module maintains several variables in order to create as many timers as needed based on one event fired. The next diagram represents the computation flow chart for every timer fired event.

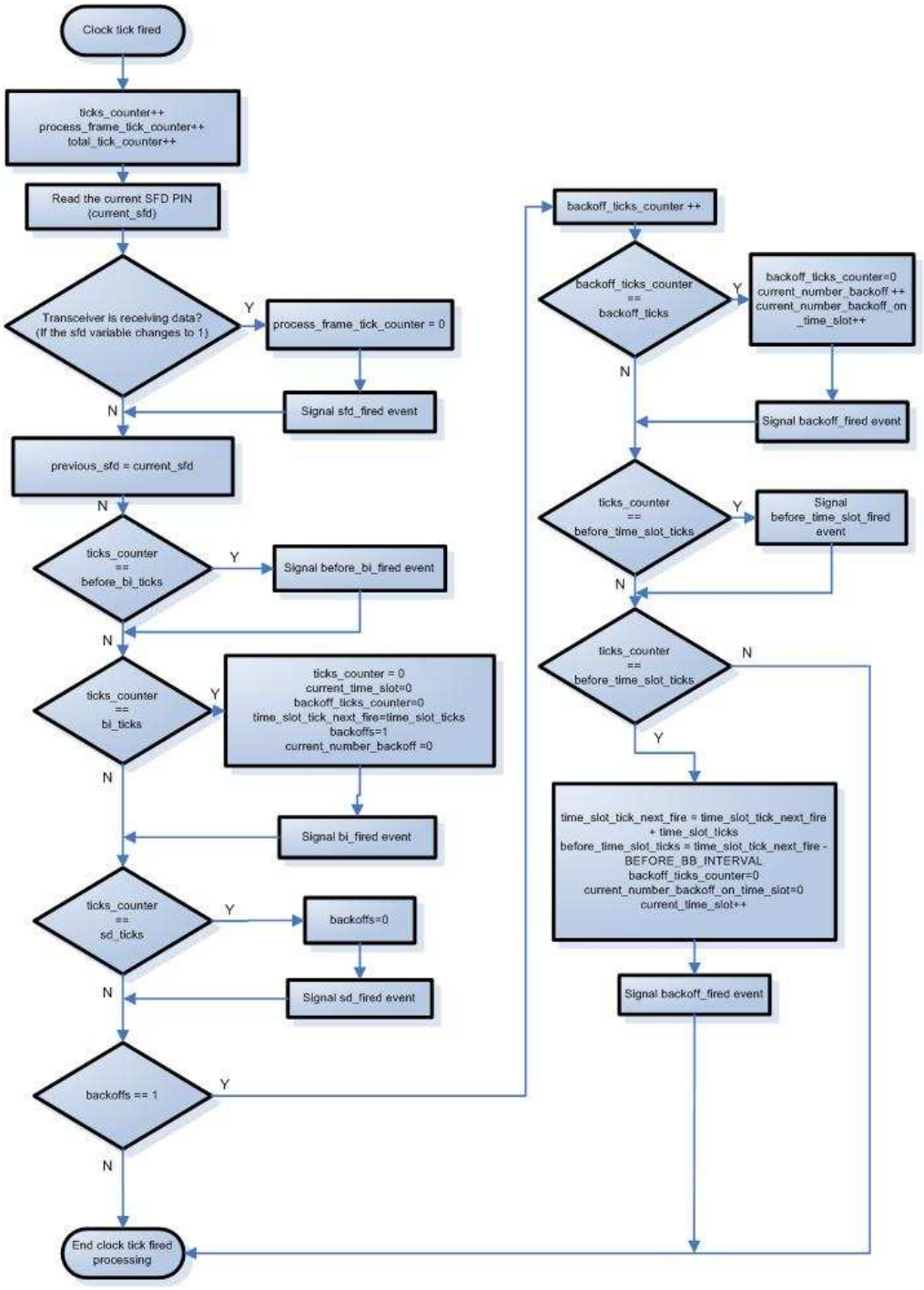


Figure 14- Timer.fire flow chat of the TimerAsync component.

TimerAsync Interface

This component exposes the function implemented in the *TimerAsyncM* and is used to wire the *MacM* to the *TimerAsyncC*.

The commands provided by this interface are the following:

- *result_t start(void)*
- *result_t stop(void)*
- *result_t init(void)*

- *uint32_t get_current_ticks(void)*
- *uint32_t get_sd_ticks(void)*
- *uint32_t get_bi_ticks(void)*
- *result_t reset(void)*
- *uint8_t reset_start(uint32_t start_ticks)*
- *uint32_t get_time_slot_ticks(void)*
- *result_t set_backoff_symbols(uint8_t symbols)*
- *uint32_t get_backoff_ticks(void)*
- *result_t set_enable_backoffs(bool enable_backoffs)*
- *uint32_t get_current_number_backoff(void)*
- *uint32_t get_time_slot_backoff_periods(void)*
- *uint32_t get_current_time_slot(void)*
- *uint32_t get_current_number_backoff_on_time_slot(void)*
- *result_t set_bi_sd(uint32_t bi_symbols, uint32_t sd_symbols)*
- *result_t reset_process_frame_tick_counter(void)*
- *uint32_t get_process_frame_tick_counter(void)*
- *uint32_t get_total_tick_counter(void)*

3.5.4. MAC Timer Events

Asynchronous Timers

TimerAsync.before_bi_fired()

The implementation of this timer is used to turn the transceiver on receive/transmit mode before the *bi_fired* event. The time before is defined in the *TimerAsyncM* component in the variable *BEFORE_BI_INTERVAL*. Because of the time needed to switch the state of the transceiver before sending or receiving data this event tries to minimize that effect. If the device is a coordinator the transceiver is switch to the transmit state so that the beacon frame, that is already constructed, is sent when the *bi_fired* event is triggered. If the device is not a coordinator the transceiver is switched to the receive mode, therefore, when the *bi_fired* event is triggered the device will be ready to receive the beacon. The exception in this case is when the beacon order (BO) is equal to the superframe order (SO) and there is no change in the transceiver state.

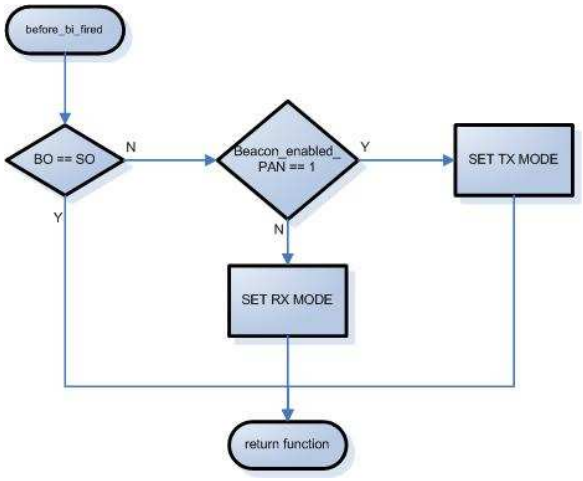


Figure 15 - before_bi_fired event flow char.

TimerAsync.bi_fired()

This event indicates the beginning of a new superframe. If the device is a PAN coordinator it must transmit a beacon, otherwise the device will receive the beacon and process it. The devices that are trying to synchronize with the PAN will have the *findabeacon* variable enabled. If the device cannot find a beacon after the *aMaxBeaconLost*, the MAC layer issues the *MLME_SYNC_LOSS.indication* primitive with the status of *MAC_BEACON_LOST*. The same procedure occurs if the device is associated with the PAN and tracking the beacons. If the beacon is received, it must be processed before the verifications of these conditions. The synchronization procedures are described in [1 pag 151].

After the synchronization processing, the device calls the *send_frame_csma()* function to start sending the frames that could be stored in the *send_buffer* that could not be sent in the last superframe.

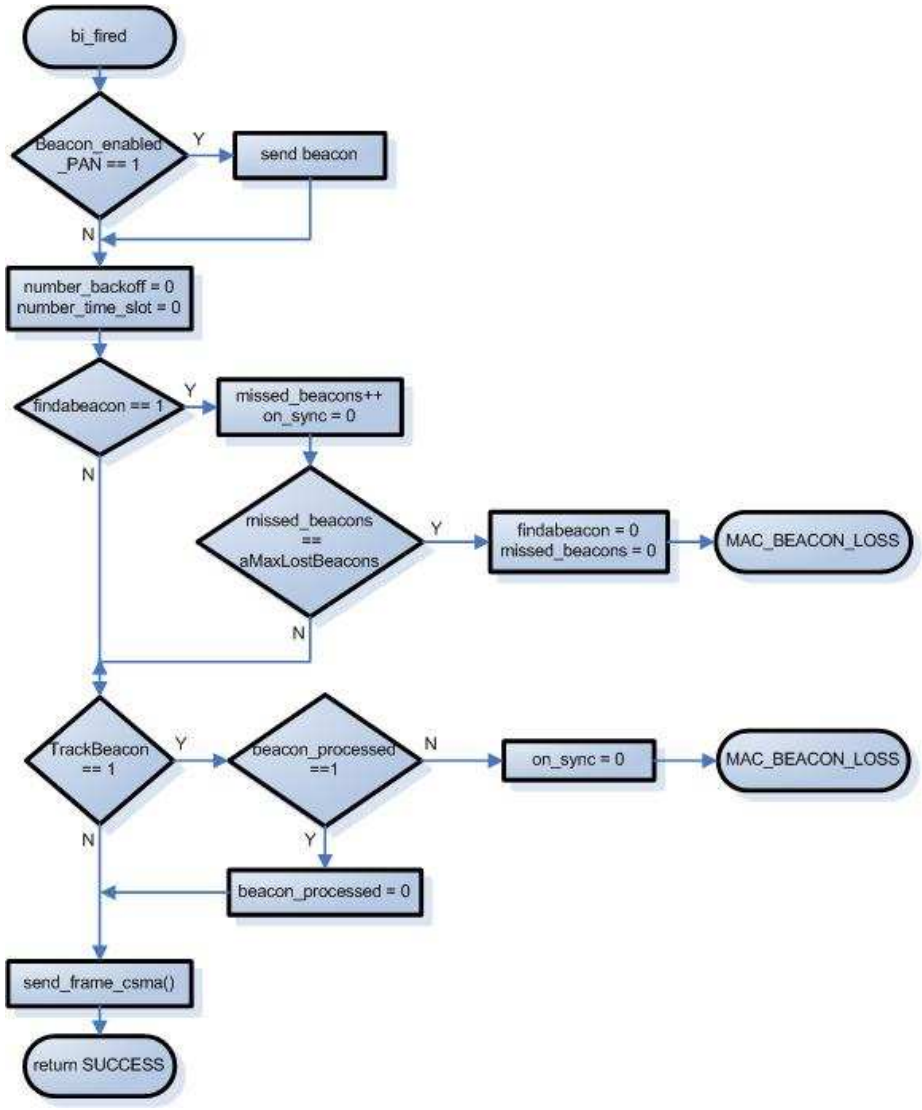


Figure 16 - bi_fired event flow chart.

TimerAsync.sd_fired()

This timer event indicates the end of the active period of the superframe duration. In this event if the device is not on promiscuous mode and the BO is different than the SO, the transceiver is switched to idle mode. If the device is a coordinator the following maintenance procedures are triggered:

- *increment_gts_null()* – if there are deallocation GTS descriptors the coordinator need to check their transaction persistence time deciding if the keep showing in the beacon or not;
- *check_gts_expiration()* – if there are allocated GTS time slots that weren't used the coordinator must calculate and evaluate their expiration time. If one allocation expires the corresponding GTS descriptor if moved to the deallocated GTS descriptors. This procedure is described in [1 pag 162];
- *create_beacon()* – the device created the beacon that will be stored until the *bi_fired* event is triggered.

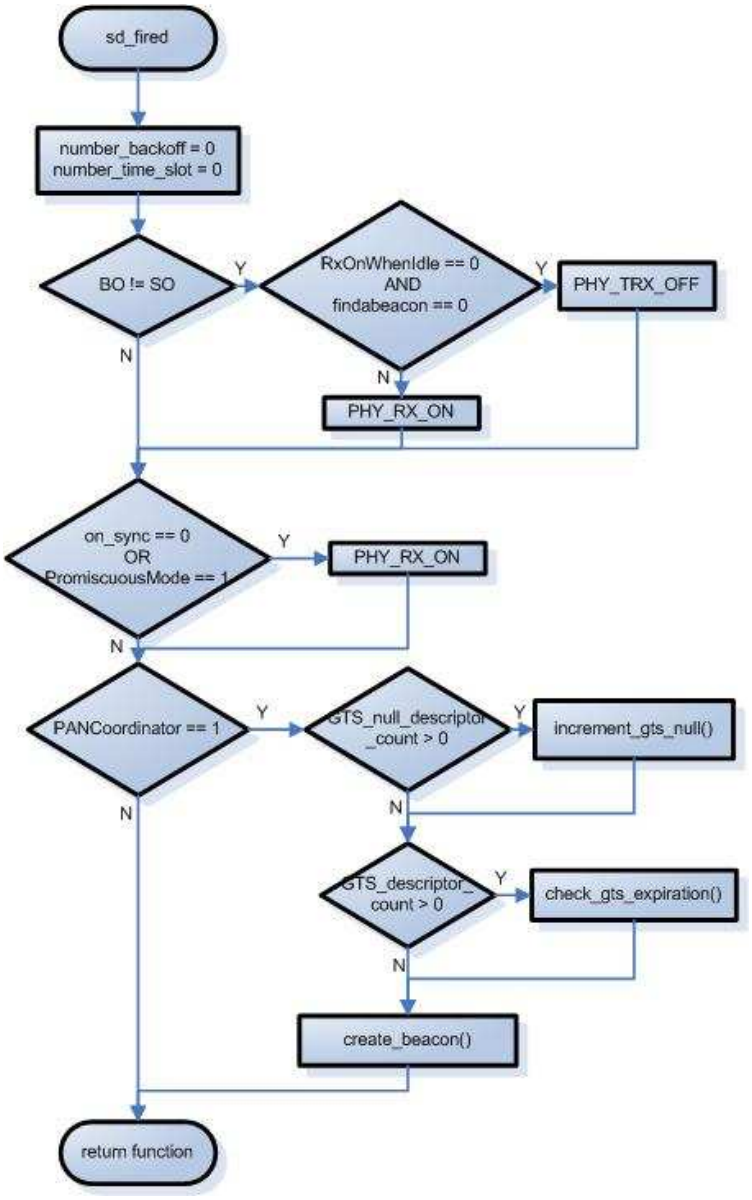


Figure 17 - sd_fired event flow chart.

TimerAsync.before_time_slot_fired()

The implementation of this timer is used to turn the transceiver on receive/transmit mode before the time_slot_*fired* event. This event is used when the device, being a coordinator or not, has a GTS time slot allocated and when the time slot starts the transceiver is already ready for transmission or reception, depending on the allocated time slot. The time before is defined in the *TimerAsyncM* component in the variable *BEFORE_BB_INTERVAL* This event is needed because of the time necessary to switch the state of the transceiver before sending or receiving data.

The variables *next_on_s_GTS* and *next_on_r_GTS* determine that the next slot will be available for transmission and for reception respectively.

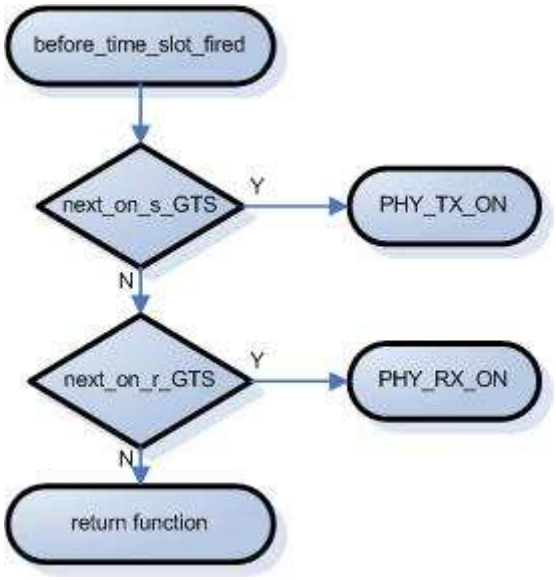


Figure 18 - before_time_slot_fired event flow chart.

TimerAsync.time_slot_fired()

This event is triggered on every time slot and is mainly used to perform the GTS management. On every execution of the timer, the *number_time_slot* variable is maintained with the current time slot information. When the time slot number reaches a GTS slot, the device will try to send data if there are packets to transmit. After the activation of the send mechanism the device will evaluate if the next slot is also a GTS slot. In this event there are two distinct operation modes: the coordinator operation and the non-coordinator operation. The GTS management on these two modes is different, if the device is a coordinator it must be ready to transmit or receive on every GTS slot to and from the appropriate device. If the device is not a coordinator it only needs to check the time slot number, previously allocated on the coordinator and confirmed in the beacon GTS descriptors, and take the appropriate action, transmit data if it has an allocation for transmission or receive data.

The *s_GTSss* and *r_GTSss* variables indicate the timeslot number of the device allocated send/receive GTS slot. The *number_backoff* variable keeps count of the number of backoffs in the time slot.

For a more detailed explanation about the GTS management refer to the GTS Management section.

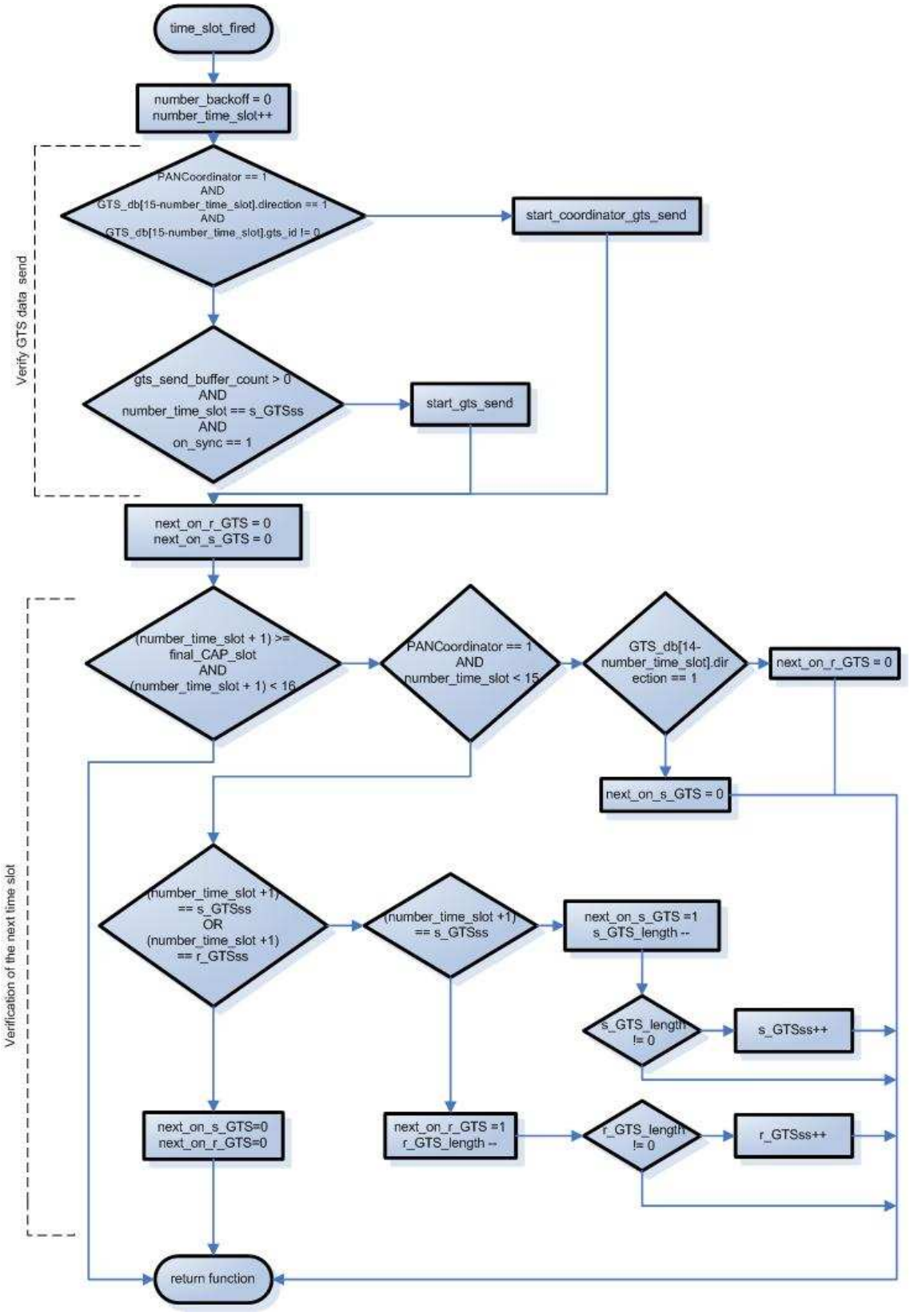


Figure 19 - time_slot_fired event flow chart.

TimerAsync.sfd_fired()

This event indicates that the transceiver is starting to receive data. Currently there is no processing in this event.

TimerAsync.backoff_fired()

This event is triggered on every backoff during the active period of the superframe. The code processing is related to the implementation of the CSMA/CA algorithm. This event maintains the *number_backoff* variable counting the number of backoffs in the time slot and a number of states that are defined in the functions concerning the CSMA/CA implementation algorithm.

For a more detailed explanation about the CSMA/CA implementation refer to the CSMA/CA section.

Synchronous Timers

T_ResponseWaitTime.fired()

This timer event is activated each time the device needs to execute a procedure involving a request command or a response within a defined time frame. This event will trigger if no response is received, executing the appropriate actions depending on the procedure being executed. For example, if the device tries to associate, the coordinator must respond to the request inside the response wait time frame.

The constant variable *aResponseWaitTime* defines the time frame in symbols for a device to receive a response for its request.

In the current status of the implementation, the response wait time event is only used when the device wishes to associate with the PAN coordinator. If the device does not receive an association response command, the MAC layer will signal the upper layer by issuing the *MLME_ASSOCIATE.confirm* primitive with the status of *NO_DATA*.

T_ackwait.fired()

This event is triggered when a device sends a transmission requesting an acknowledgment from the destination. The variable *mac_PIB.macAckWaitDuration* in the MAC PIB defines the maximum wait time in symbols to receive an acknowledgment, before initiate a retransmission or report a transmission failure.

The main purpose of this event is to control the data retransmission and inform the upper layer about a possible data transmission failure.

The variables used to control the retransmission procedures are the following:

- *send_ack_check* – variable stating that the current transmission requires an acknowledgment;
- *retransmit_count* – number of retransmissions of the current frame transmission;
- *send_indirect_transmission* – variable stating that the current transmission is an indirect transmission and doesn't require a retransmission if the first transmission fails;
- *ack_sequence_number_check* – current transmission frame sequence number.

The function *send_frame_csma()* is used to send the next frame in the send buffer. When the frame is being send the variables *send_ack_check*, *send_indirect_transmission* and *ack_sequence_number_check* are initialized.

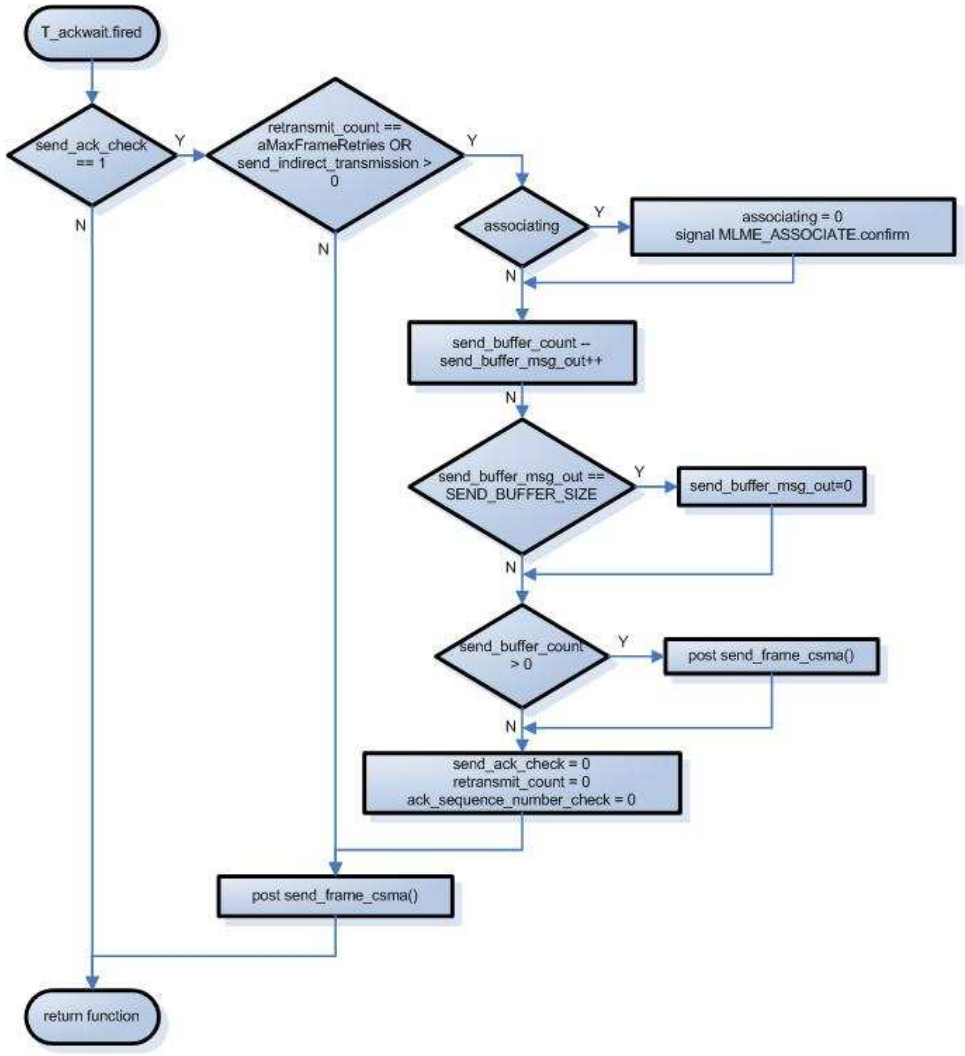


Figure 20 - T_ackwait.fired event flow chart.

3.5.5. Frame Construction

The frame formats are composed of a MHR, a MAC payload and a MFR. The fields of the MHR appear in a fixed order; however, the addressing fields may not be included in all frames. The general MAC frame shall be formatted as illustrated in next figure. [1 pag. 112].

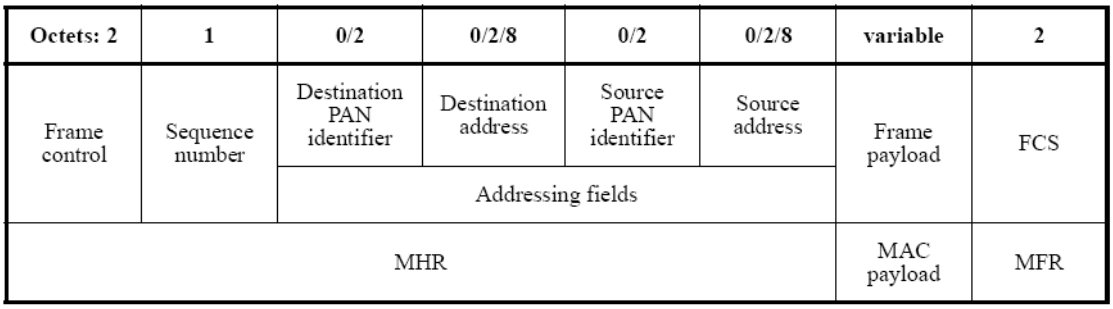


Figure 21 - General MAC frame format.

The structure definitions and structure size constants used to construct all the frames are defined in the *frame_format.h* file under the *contrib.tos.system*. In the mac_func.h file there are auxiliary functions used for constructing/retrieving fields that require bit operations.

The frame control field is 16 bits length and contains information defining the frame type, addressing fields and other control flags. This field in constructed using the following set function located in the mac_func.h file.

```
uint16_t set_frame_control(     uint8_t frame_type,
                                uint8_t security,
                                uint8_t frame_pending,
                                uint8_t ack_request,
                                uint8_t intra_pan,
                                uint8_t dest_addr_mode,
                                uint8_t source_addr_mode)
{
        uint8_t fc_b1=0;
        uint8_t fc_b2=0;
        fc_b1 = ( (intra_pan << 6) | (ack_request << 5) | (frame_pending << 4) |
                        (security << 3) | (frame_type << 0) );
        fc_b2 = ( (source_addr_mode << 6) | (dest_addr_mode << 2));
        return ( (fc_b2 << 8 ) | (fc_b1 << 0) );

}
```

Code Example 3 - Mac frame control construction function.

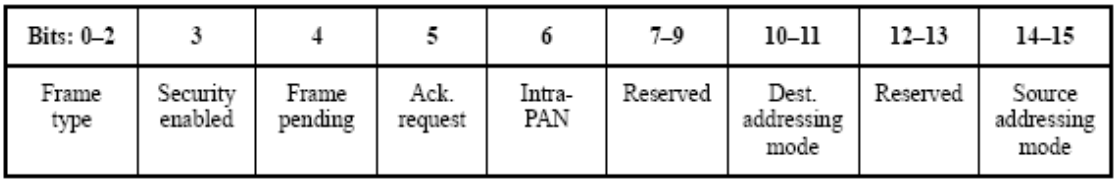


Figure 22 - Format of the frame control field.

Because of the variety of combination that can be used in constructing a frame we adopted the strategy of using a generic frame format structure for all frames that we defined as MPDU. The MPDU structure is the following:

```
typedef struct MPDU
{
        uint8_t length;
        uint16_t frame_control;
        uint8_t seq_num;
        uint8_t data[121];
}MPDU;
```

Code Example 4 - MPDU structure definition in the frame_format.h.

The strategy used for the construction of the frame lies on pointing the corresponding structure to the position zero of the 8 bit data array in the MPDU structure and so on, so that the frame is built according to the needs. The constants defined in this file are used for associating the correspondent structure to its byte length.

The main problem constructing frames is the number of possible combinations of the Addressing Fields. The definition of these fields is very time consuming due to the different possibilities, especially in the reception of the frame where the device must be prepared to process all the different addressing scenarios. The next graph illustrates the possible combinations with the indication of the address field length in bytes.

Address Field Size (Bytes)			INTRA PAN			No INTRA PAN		
			Source					
			No	Short	Long	No	Short	Long
Intra/No intraPAN	Destination	No	-	2	8	-	4	10
		Short	4	6	12	4	8	14
		Long	8	12	18	10	14	20

Table 14 - Address fields - possible sizes and combinations.

	Size (Bytes)
Addressing Short	4
Addressing Long	10
Intra PAN Source Short	2
Intra PAN Source Long	8

Table 15 - Address fields - size reference.

For example (nesC code), if we want to build a data frame with a short destination address and a long source address we have to create first an MPDU variable and its correspondent MPDU type pointer. Then, we also have to create a structure pointer for the short destination and another for the long source addressing fields.

The next code example shows the relevant structure definitions in the frame_format.h relevant for this example.

```
#define DEST_SHORT_LEN 4
#define SOURCE_LONG_LEN 10

typedef struct dest_short
{
        uint16_t destination_PAN_identifier;
        uint16_t destination_address;
```

```
}dest_short;


typedef struct source_long
{
        uint16_t source_PAN_identifier;
        uint32_t source_address0;
        uint32_t source_address1;
}source_long;
```

Code Example 5 - frame_format.h structure definition example.

```
MPDU frame_pkt;
MPDU * frame_pkt_ptr;
dest_long *dest_long_ptr;
source_short *source_short_ptr;

frame_pkt_ptr = (MPDU *) &frame_pkt;

dest_short_ptr = (dest_short *) &frame_pkt->data[0];

source_long_ptr = (source_long *) &frame_pkt->data[DEST_SHORT_LEN];

frame_pkt->length = data_len + msduLength + MPDU_HEADER_LEN;
frame_pkt->frame_control = set_frame_control(TYPE_DATA,0,0,get_txoptions_ack(TxOptions)
                                                    ,0, SHORT_ADDRESS, LONG_ADDRESS);
frame_pkt->seq_num =/*Data Sequence Number*/;

dest_short_ptr->destination_PAN_identifier= /*Destination PAN Address*/;
dest_short_ptr->destination_address=/*Destination Address*/;

source_long_ptr->source_PAN_identifier=/*Source PAN Address*/;
source_long_ptr->source_address0=/*Source Address*/;
source_long_ptr->source_address1=/*Source Address*/;
```

Code Example 6 - Data frame construction example.

In the MacM.nc file all the functions that start with create_<something> are used in the construction of frames.

The data frame format is illustrated in [1 pag.120], the command frame format in [1 pag.122] and the beacon frame in [1 pag.116].

3.5.6. Beacon Management

Creating Beacon (Coordinators Only)

The function *create_beacon()* is used by the PAN coordinator to construct the beacon frame that will be ready to send in the next *bi_fired* event, indicating the beginning of a new superframe. The beacon contains information about the PAN, such as beacon intervals, beacon orders and other information included in the superframe specification; information about the allocated/deallocated GTS time slots on the CFP in

the GTS fields; information about the devices that have pending data in the coordinator in the pending address fields and other data in the beacon payload.

The next figure represents the structure of a beacon [1 pag. 116]

Octets: 2	1	4/10	2	variable	variable	variable	2
Frame control	Sequence number	Addressing fields	Superframe specification	GTS fields (Figure 38)	Pending address fields (Figure 39)	Beacon payload	FCS
MHR			MAC payload				MFR

Figure 23 - Beacon frame format

The beacon frame is divided into two parts: the MHR that contains the frame control field containing the general frame information, the beacon sequence number and the addressing fields; and the specific beacon MAC payload that contains the superframe specification field, the GTS fields, pending address fields and optional beacon payload data.

The superframe specification field, as seen in the next figure, can be constructed using the function *set_superframe_specification* implemented in the *mac_func.h* file and the values can be retrieved with the respective get functions implemented in the same file.

Bits: 0-3	4-7	8-11	12	13	14	15
Beacon order	Superframe order	Final CAP slot	Battery life extension	Reserved	PAN coordinator	Association permit

Figure 24 - Superframe Specification Format

The header of the GTS fields is composed by three fields: the GTS specification with the information of the number of GTS descriptors in the GTS list and the GTS permit; the GTS directions field with the information about the directions of the allocations, if there are GTS descriptor on the list; and the GTS list of descriptors.

Octets: 1	0/1	variable
GTS specification	GTS directions	GTS list

Figure 25 - GTS fields format.

Bits: 0-2	3-6	7
GTS descriptor count	Reserved	GTS permit

Figure 26- GTS specification field format.

Bits: 0-6	7
GTS directions mask	Reserved

Figure 27 - GTS directions field format.

The GTS descriptors contain information about the short address of the devices allocation GTS, the start slot in the CFP and the number of slots allocated.

Besides the allocated GTS slots, the GTS descriptors list include the deallocated GTS with the GTS descriptors containing information about the device address and with zero values in the start slot and length.

Bits: 0-15	16-19	20-23
Device short address	GTS starting slot	GTS length

Figure 28 - GTS descriptor field format.

The pending addresses field contains information of the data stored in the coordinator. This data must be requested by the receiver device in order to be sent. To construct the pending address list the *indirect_trans_queue* buffer is read and the correspondent address is created for each valid entry.

Octets: 1	variable
Pending address specification	Address list

Figure 29 - Pending addresses field format.

Bits: 0—2	3	4—6	7
Number of short addresses pending	Reserved	Number of extended addresses pending	Reserved

Figure 30 - Pending address specification field format.

The next flow chart represents the steps for building a beacon frame in the *create_frame* function. The procedure for building the pending addresses list is described in the Pending Data / Indirect Transmission section.

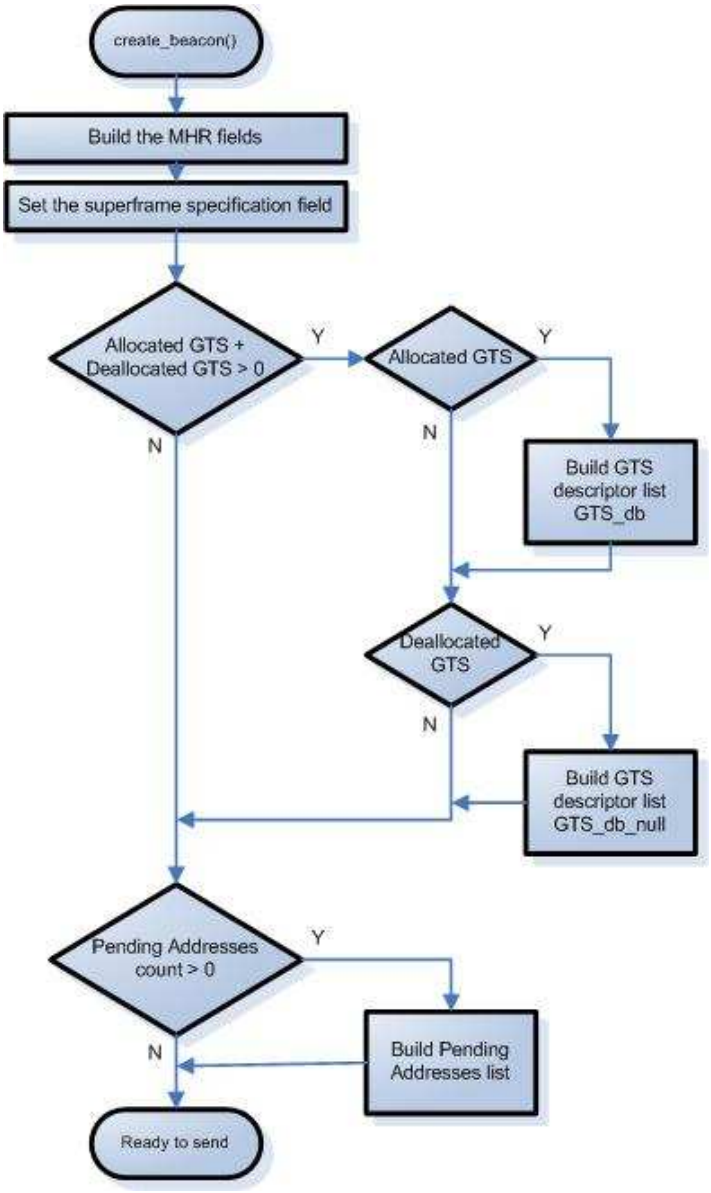


Figure 31 - Beacon creation flow chart.

After the creation of the beacon the frame is stored in the variable *mac_beacon_txmpdu* and will be ready to send.

The creation of the beacon only takes place if the device is a PAN coordinator and after the next higher layer, above the MAC, issues the *MLME-START.request* primitive. The beacon generation procedure is described in [1 pag.100].

The next figure illustrates the sequence of messages between layers when the PAN coordinator starts the beacon generation [1 pag 180].

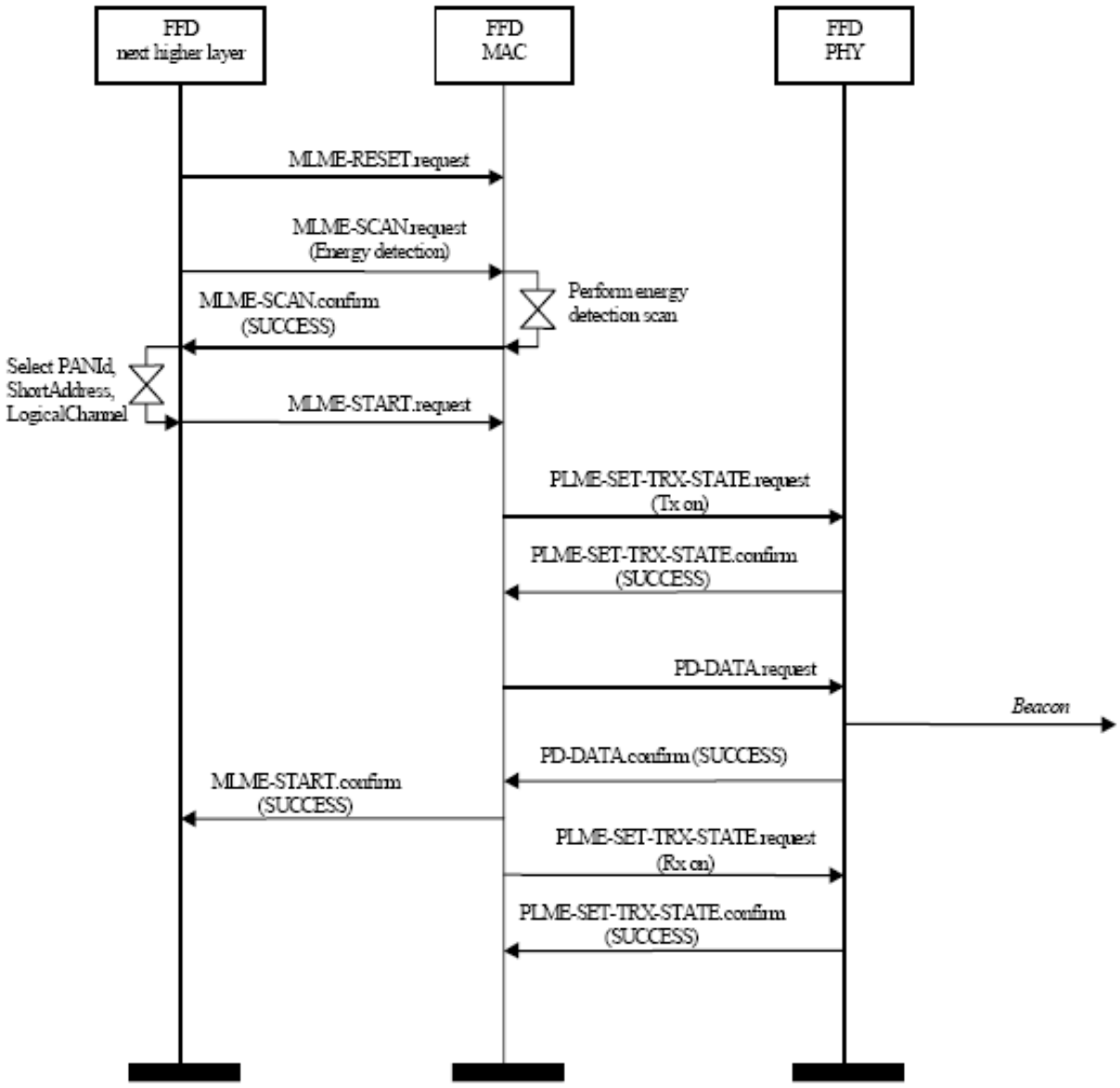


Figure 32 - Beacon generation sequence chart.

The next figure shows a sample transmission sequence of beacons.

Time (us)	Length	Frame control field							Sequence number	Dest. PAN	Dest. Address	Source Address	Superframe specification						GTS fields		LQI	FCS
		Type	Sec	Pnd	Ack req		Intra PAN						BO	SO	F.CAP	BLE	Coord	Assoc	Len	Permit		
+2132805																						
=10664021	15	BCN	0	0	0		1		0xA3	0x0001	0xFFFF	0x0001	07	06	15	0	1	0	0	1	120	OK
Time (us)	Length	Frame control field							Sequence number	Dest. PAN	Dest. Address	Source Address	Superframe specification						GTS fields		LQI	FCS
		Type	Sec	Pnd	Ack req		Intra PAN						BO	SO	F.CAP	BLE	Coord	Assoc	Len	Permit		
+2132804																						
=12796825	15	BCN	0	0	0		1		0xA4	0x0001	0xFFFF	0x0001	07	06	15	0	1	0	0	1	116	OK
Time (us)	Length	Frame control field							Sequence number	Dest. PAN	Dest. Address	Source Address	Superframe specification						GTS fields		LQI	FCS
		Type	Sec	Pnd	Ack req		Intra PAN						BO	SO	F.CAP	BLE	Coord	Assoc	Len	Permit		
+2132804																						
=14929629	15	BCN	0	0	0		1		0xA5	0x0001	0xFFFF	0x0001	07	06	15	0	1	0	0	1	120	OK

Figure 33 - Beacon transmission example.

Processing beacon (Devices)

In the beginning of each superframe interval, the devices receive a beacon frame in order to synchronize and to update the PAN information. After the processing of the beacon, the upper layer is signalled with the information retrieved from the beacon processing.

The processing of the beacon information is made in the *process_beacon(MPDU *packet)* function. This processing is divided into the following steps:

1. Processing of the superframe specification field in order to read the values of the beacon order, the superframe order and the final cap slot;
2. Compute the superframe duration, the beacon interval, the time slot and the backoff period in symbols;
3. Process the GTS characteristics and, if there are GTS descriptors in the GTS list, compute each one in order to verify and search the correspondent device address. If the address is present the device evaluates the descriptor information and updates its own GTS information, either for an allocation, deallocation or a confirmation of the current allocation request. This update is very important because the time slot(s) assigned to the device may change due to a reorder of the GTS descriptors on the PAN coordinator;
4. Process the pending addresses information;
5. Build the PAN descriptor information to inform the upper layer;
6. Synchronize the device asynchronous timer with the PAN coordinator. In order to have a correct synchronization the device must take into account the transmission time, transmission delay, the packet reception time and the packet processing time. On each *timer.fire()* event in the *TimerAsync* component a counter is set to zero when the transceiver starts receiving data or the SFD pin goes high. When the device wants to synchronize it reads the SFD counter (*process_frame_tick_counter* variable in the *timer.fire()* function) to compute the processing time of the frame. The synchronization also takes into account the possible variables so that the internal time of the *TimerAsync* component can be set with the appropriate start value.
7. Signal the upper layer using the *MLME_BEACON_NOTIFY.indication* primitive with the PAN descriptor information.

The *MLME_BEACON_NOTIFY.indication* primitive has the following semantic [1 pag 75]:

```
event result_t indication(    uint8_t BSN,
                              PANDescriptor pan_descriptor,
                              uint8_t PenAddrSpec,
                              uint8_t AddrList,
                              uint8_t sduLength,
                              uint8_t sdu[]);
```

Code Example 7 - MLME_BEACON_NOTIFY indication event .

The *BSN* is the beacon sequence number, the *pan_descriptor* is a structure with the description of the PAN, the *PenAddrSpec* contains the pending addresses specification field and the *AddrList* the address list, the *sduLength* is the number of

bytes in the MAC payload and the *sdu* is the MAC payload that will be transferred to the upper layer.

The PANDescriptor structure is defined in the *mac_func.h* file under the *contrib.hurray.tos.lib.mac* directory.

The next table describes the PANDescriptor attributes [1 pag 76]:

Attribute	Type	Range	Description
CoordAddrMode	Integer	0 x 02–0 x 03	The coordinator addressing mode corresponding to the received beacon frame. This value can take one of the following values: 2 = 16 bit short address. 3 = 64 bit extended address.
CoordPANId	Integer	0 x 0000–0 x ffff	The PAN identifier of the coordinator as specified in the received beacon frame.
CoordAddress	Device address	As specified by the CoordAddrMode parameter	The address of the coordinator as specified in the received beacon frame.
LogicalChannel	Integer	Selected from the available logical channels supported by the PHY	The current logical channel occupied by the network.
SuperframeSpec			The superframe specification as specified in the received beacon frame.
GTSPermit	Boolean	TRUE or FALSE	TRUE if the beacon is from a PAN coordinator that is accepting GTS requests
LinkQuality	Integer	0 x 00–0 x ff	The LQ at which the network beacon was received. Lower values represent lower LQI
TimeStamp	Integer	0 x 000000–0 x ffffff	The time at which the beacon frame was received, in symbols. This value is equal to the timestamp taken when the beacon frame was received
SecurityUse	Boolean	TRUE or FALSE	An indication of whether the received beacon frame is using security
ACLEntry	Integer	0 x 00–0 x 08	The macSecurityMode parameter value from the ACL entry associated with the sender of the data frame
SecurityFailure	Boolean	TRUE or FALSE	TRUE if there was an error in the security processing of the frame or FALSE otherwise

Table 16 - PAN Descriptor attributes description.

3.5.7. Scanning through channels

This version of the implementation (v1.0) does not implement the channel scan mechanism. The scanning procedure is described in [1 pag. 145].

3.5.8. Association and Disassociation

The association and disassociation procedures are described in [1 pag 149].

The association procedure occurs when the device wants to associate with a PAN coordinator. To proceed with the association the device must scan all the channels for radio transmissions, so that it can select the most suitable PAN. The association is necessary if the device wants to transmit data in the PAN. As a result of the association mechanism, the device is assigned with a short address allowing it to transmit in the PAN and, depending on the network topology, transmit to other PANs and devices.

The association request frame command is constructed in the *create_association_request_cmd* function that is called after the upper layer issue the *MLME_ASSOCIATE.request* primitive.

Besides the standard MAC frame fields, the frame has an addressing field, a command frame identifier field and the capability information of the device. The frame is illustrated in the next figure [1 pag 124]:

octets: 17/23	1	1
MHR fields	Command frame identifier (see Table 67)	Capability information

Figure 34 - Association request frame format.

The capability information field, as seen in the next figure, can be constructed using the function *set_capability_information* implemented in the *mac_func.h* file.

bits: 0	1	2	3	4-5	6	7
Alternate PAN coordinator	Device type	Power source	Receiver on when idle	Reserved	Security capability	Allocate address

Figure 35 - Capability information field format.

Upon the reception of the association request command frame, the coordinator will process the command in the *indication_cmd* function that will signal the upper layer using the *MLME_ASSOCIATE.indication* primitive. The upper layer will process the request and will issue the MAC layer with the *MLME_ASSOCIATE.request* primitive stating the result of the request. If the request is successful the coordination will call the *create_association_response_cmd* function in order to construct the association response command. The command is stored in the indirect transmission buffer (*indirect_trans_queue*) and will be transmitted after a data request from the associating device.

Besides the update of the MAC PIB, the MAC layer of the device stores the association parameters in the following variables.

- uint8_t a_LogicalChannel – Logical channel of the PAN;
- uint8_t a_CoordAddrMode – Coordination address mode;

- uint16_t a_CoordPANId – Coordinator PAN id;
- uint32_t a_CoordAddress[2] – Coordinator address, depending on the address mode;
- uint8_t a_CapabilityInformation – Capability information of the device when the association request was sent.
- bool a_securityenable – Security enable stating if the device is using security or not.

The next charts illustrate the MAC-PHY interaction when association occurs, either from the device that is trying to associate and the coordinator that is associating. [1 pag 182-183].

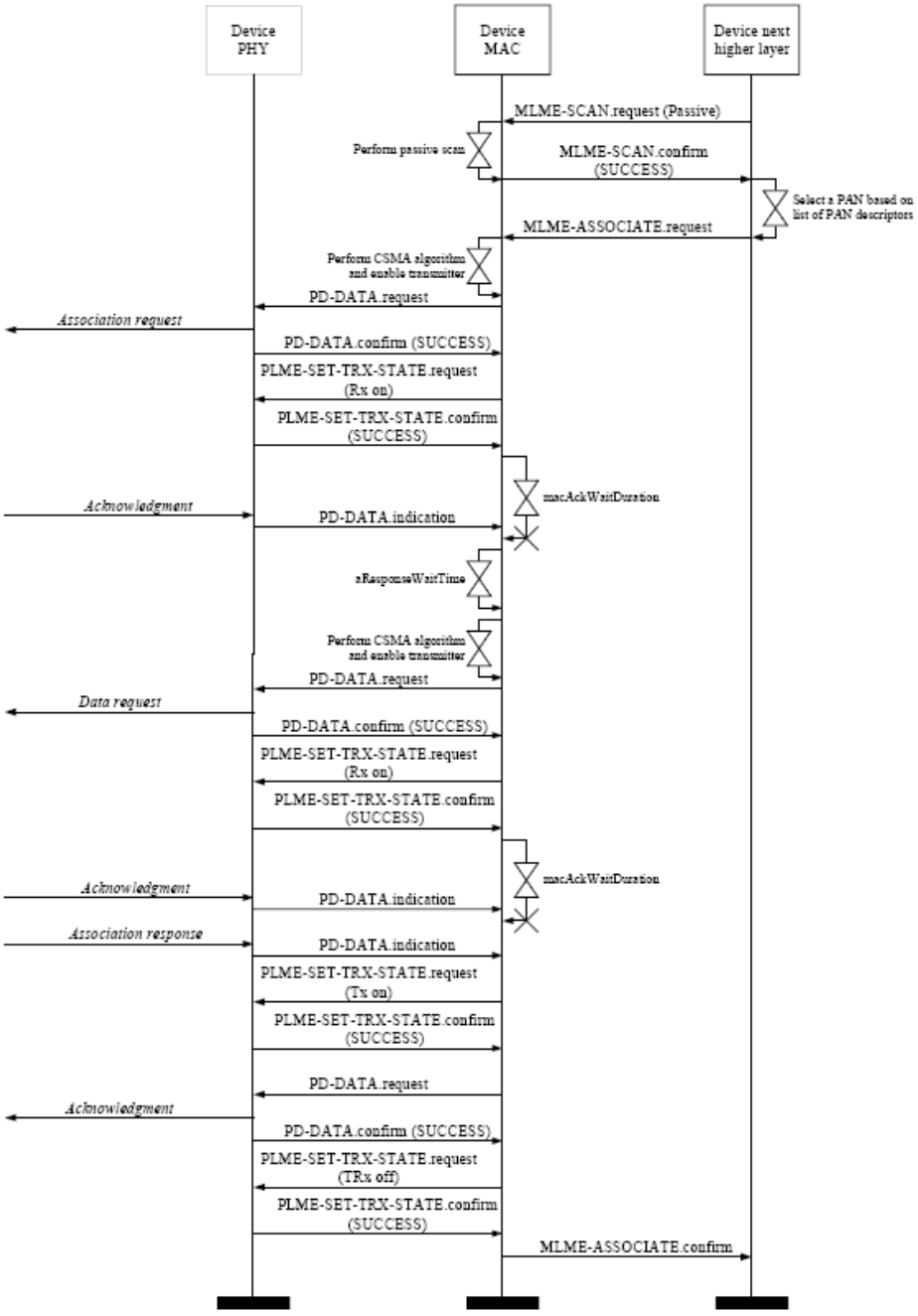


Figure 36 - Device association message sequence chart.

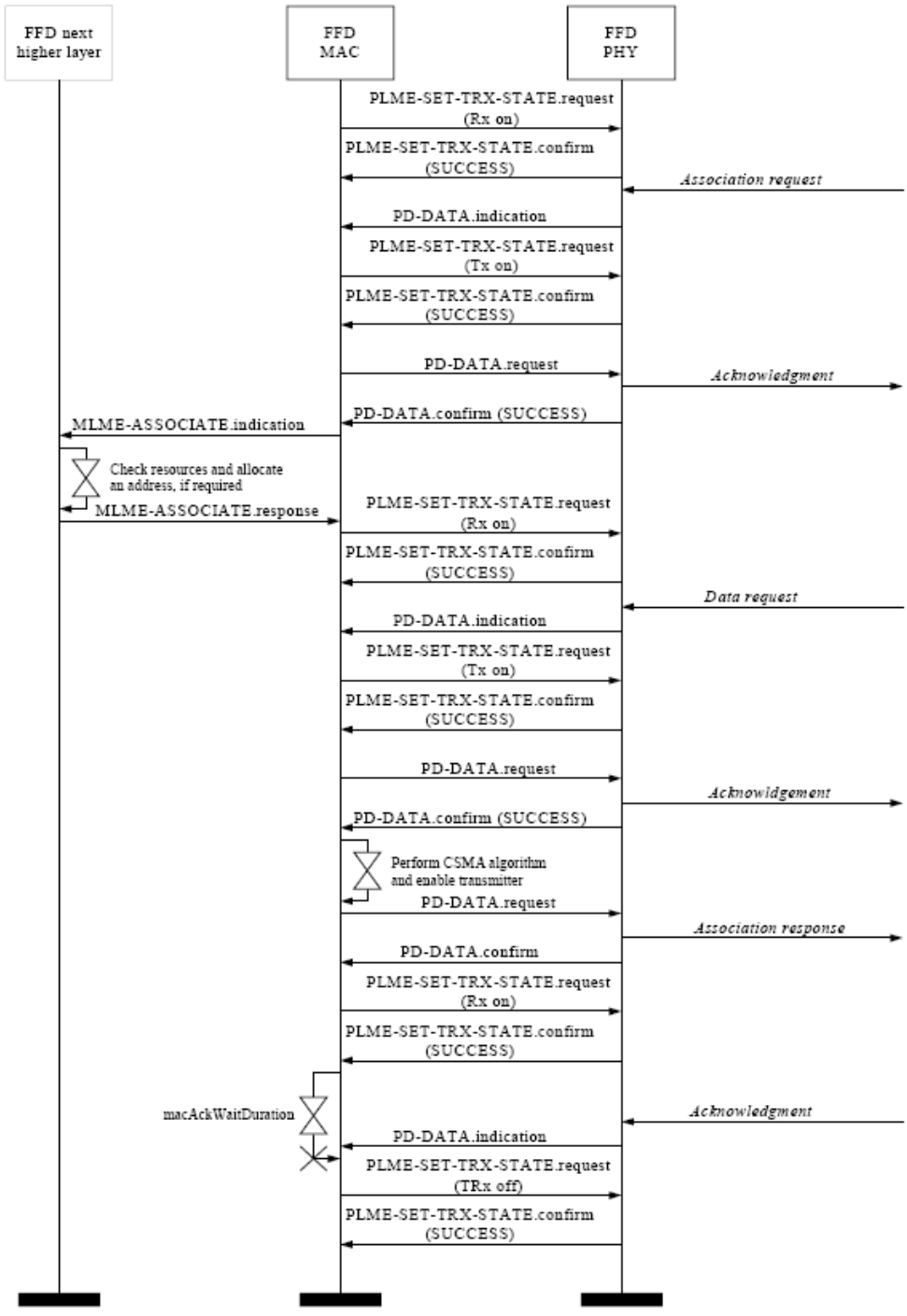


Figure 37 - Coordinator association message sequence chart.

The next figure shows a sample transmission sequence of a successful association request followed by a data transmission.

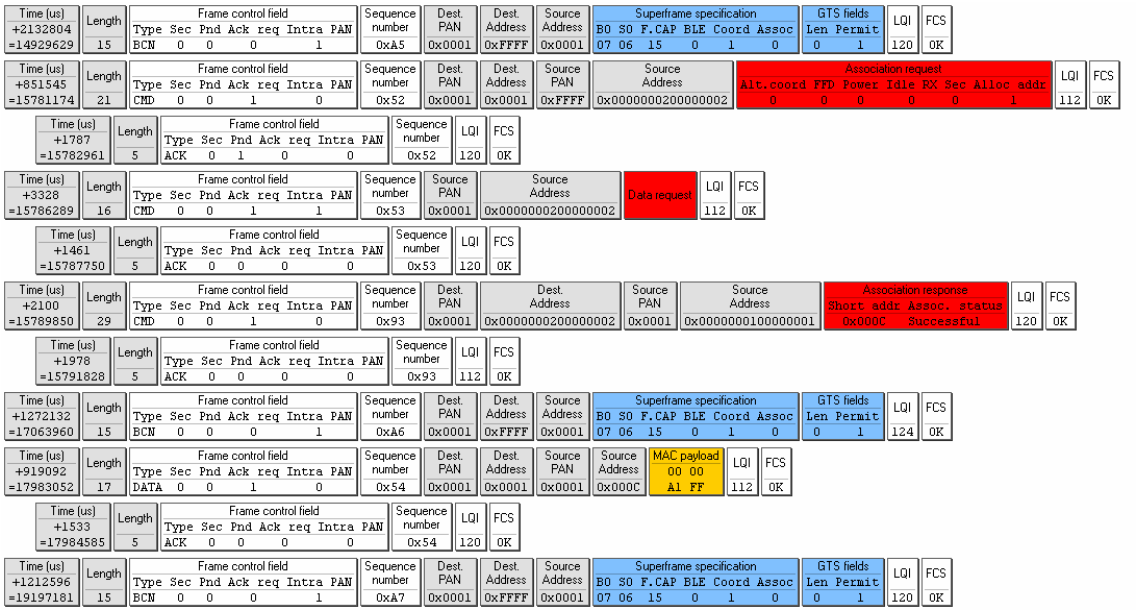


Figure 38 - Association mechanism example.

The disassociation request command frame can be generated either by the device, trying to leave the PAN, or by the coordinator, wishing that the device leaves the PAN. After the disassociation procedure the device will lose its short address and will not be able to communicate in the PAN and the coordinator will update the list of associated devices, but it call still store the device information for a future re-association.

The disassociation command frame if constructed in the *create_disassociation_notification_cmd* function.

The next figure shows a sample transmission sequence of a disassociation request.

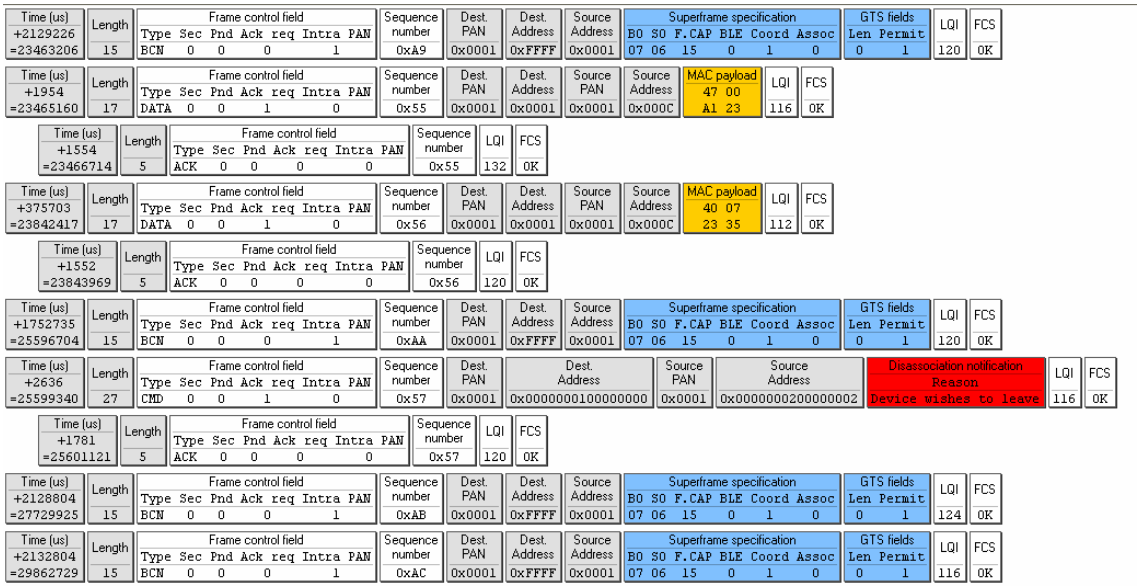


Figure 39 - Disassociation mechanism example.

3.5.9. CSMA/CA

The CSMA/CA algorithm is used when the device wants to transmit frames within the CAP. The transmission of beacon frames, acknowledgement frames and data frames in the CFP will not use the CSMA/CA algorithm instead they will be send directly without any channel assessment. The CSMA/CA mechanism is described in [1 pag. 144].

The application of the algorithm is illustrated in the following flow chart.

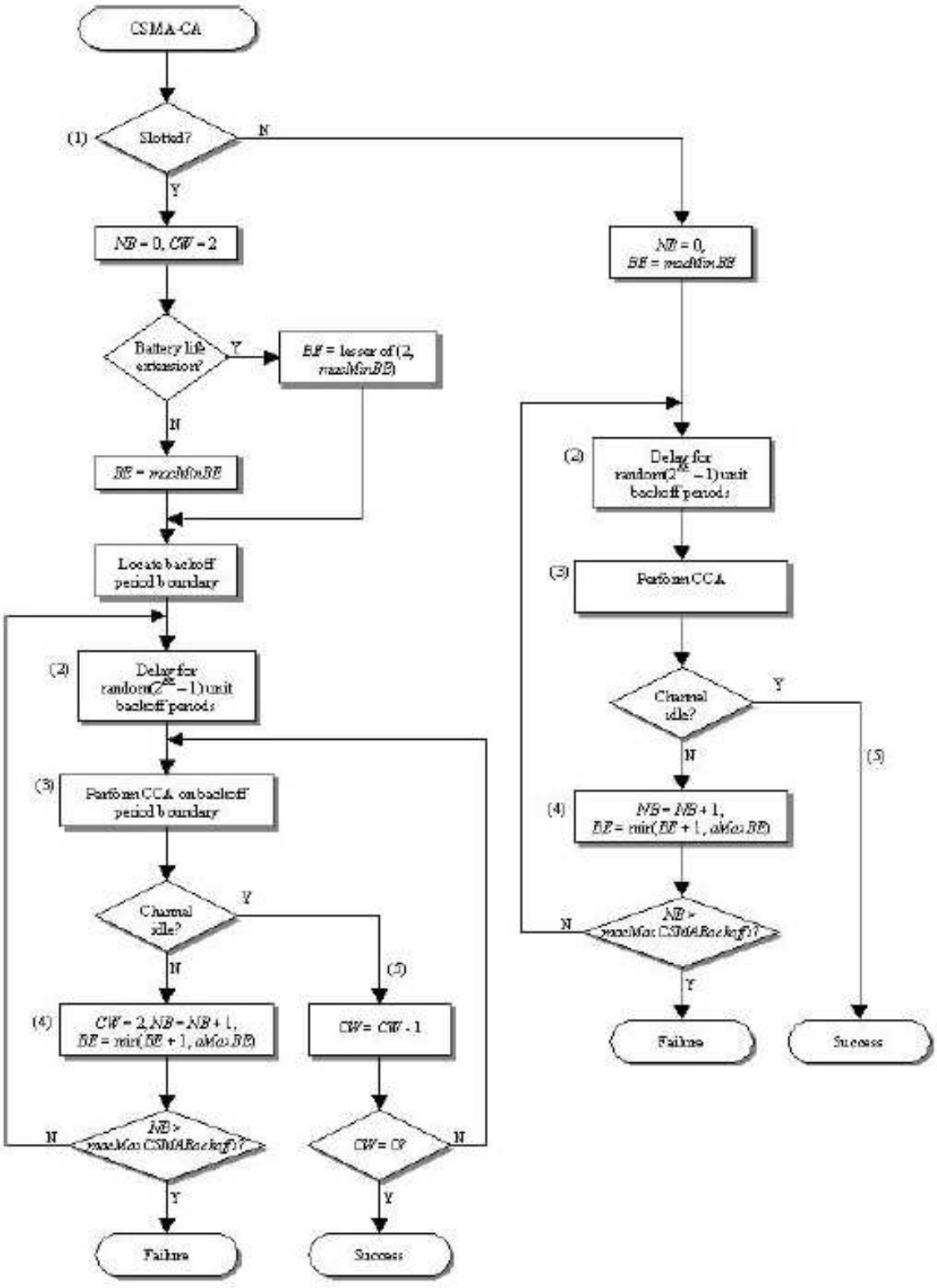


Figure 40 - CSMA/CS algorithm.

The implementation of the CSMA/CA involves several functions and global variables used in conjunction with the *TimerAsync.backoff_fired()* timer events.

The function *send_frame_csma* is called to start the application of the CSMA/CA mechanism and if the channel is clear and there is data to be send it will

send the frame. If there is no data in the *send_buffer*, the send procedure will abort. The function *send_frame_csma* is called in the following cases:

- When a frame is created and it is already in the send buffer ready to be send;
- When the last frame was successfully transmitted and there is still data in the buffer ready to be send;
- In the beginning of the CAP when the *TimerAsync.bi_fired()* timer event fires;
- In the retransmission of a frame requiring an acknowledgment;
- After a failed transmission and there is still data in the buffer ready to be send.

When the function is called, it will check if the device is in the CFP and if there is data ready to be sent. If the conditions check true, the function will set the *Boolean* variable *performing_csma_ca* to true, meaning that the application of algorithm is in progress, and will call the *perform_csma_ca()* function to proceed with the application of the algorithm. Although the receiver of the device is enabled during the channel assessment portion of this algorithm, the device shall discard any frames received during this time. At this point the algorithm is in step 1 (Last figure).

The function *perform_csma_ca()* will choose the application of the slotted or the unslotted version.

In the unslotted version the function will call the function *init_csma_ca()* to initialize the variables NB (number of backoffs) and BE (backoff exponent). The function will also initialize the variable *delay_backoff_period* with a random value and will set the *csma_delay* Boolean variable to start the delay mechanism, implemented in the *TimerAsync.backoff_fired()* timer event.

In the slotted version, the function calls the init_csma_ca() to initialize the variables needed for the application of the algorithm, namely the contention window (CW), the number of backoffs (NB) and other auxiliary variables. The backoff exponent (BE) is set depending on the battery life parameter. The boolean variable *csma_locate_backoff_boundary* is set to true triggering the location on the backoff boundary implemented in the *TimerAsync.backoff_fired()* timer event.

At this point the algorithm is in step 2 (Last figure).

The next steps of the algorithm will be triggered in the *TimerAsync.backoff_fired()* timer event depending on the state of the auxiliary variables of the implementation.

The next figure shows the flow chart for the *perform_csma_ca()* function.

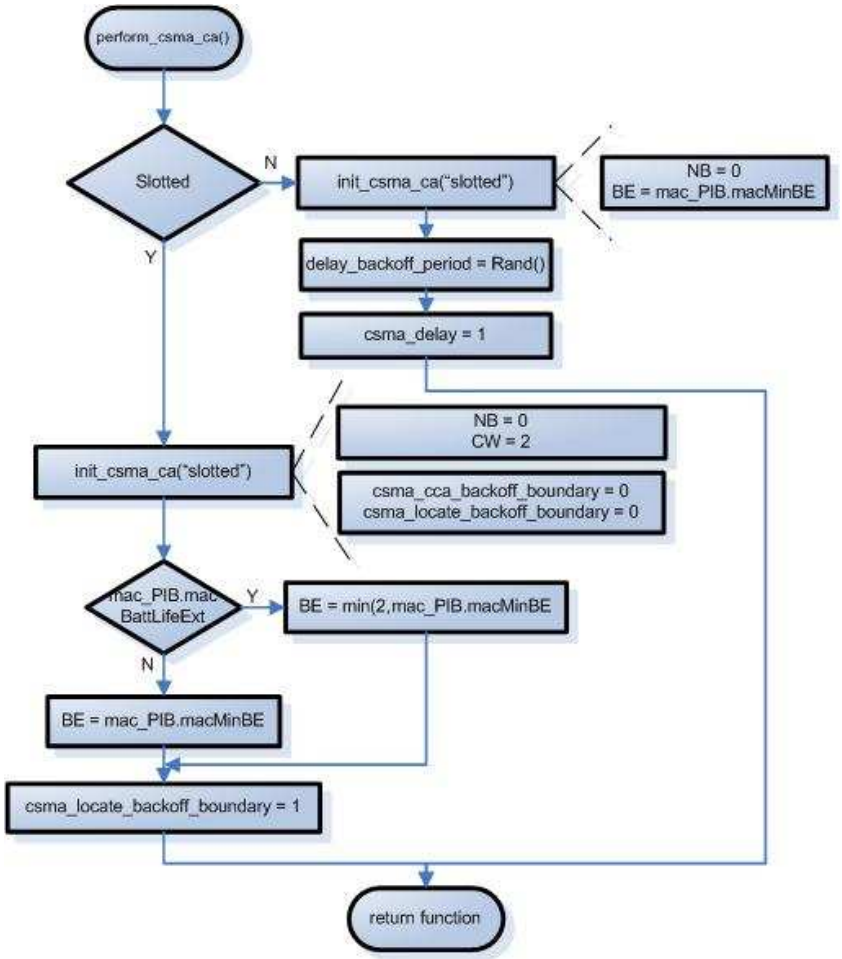


Figure 41 - perform_csma_ca() function flow chart.

The *TimerAsync.backoff_fired()* timer event will be triggered on every backoff of the CAP and will call the functions *start_csma_ca_slotted()* / *perform_csma_ca_slotted()* or *perform_csma_ca_unslotted()* for the application of the slotted or unslotted version respectively.

The auxiliary variables used in the implementation of the timer event are the following:

- *csma_delay* – Used in the step 2 of the algorithm to trigger the count down of the delay backoff periods;
- *csma_cca_backoff_boundary*– Used in the step 3 of the algorithm after the delay period is over to perform the channel assessment;
- *delay_backoff_period* – Number of backoff interval of the delay period;
- *csma_locate_backoff_boundary* – Used to locate the backoff boundary of the first channel assessment in the slotted version of the algorithm.

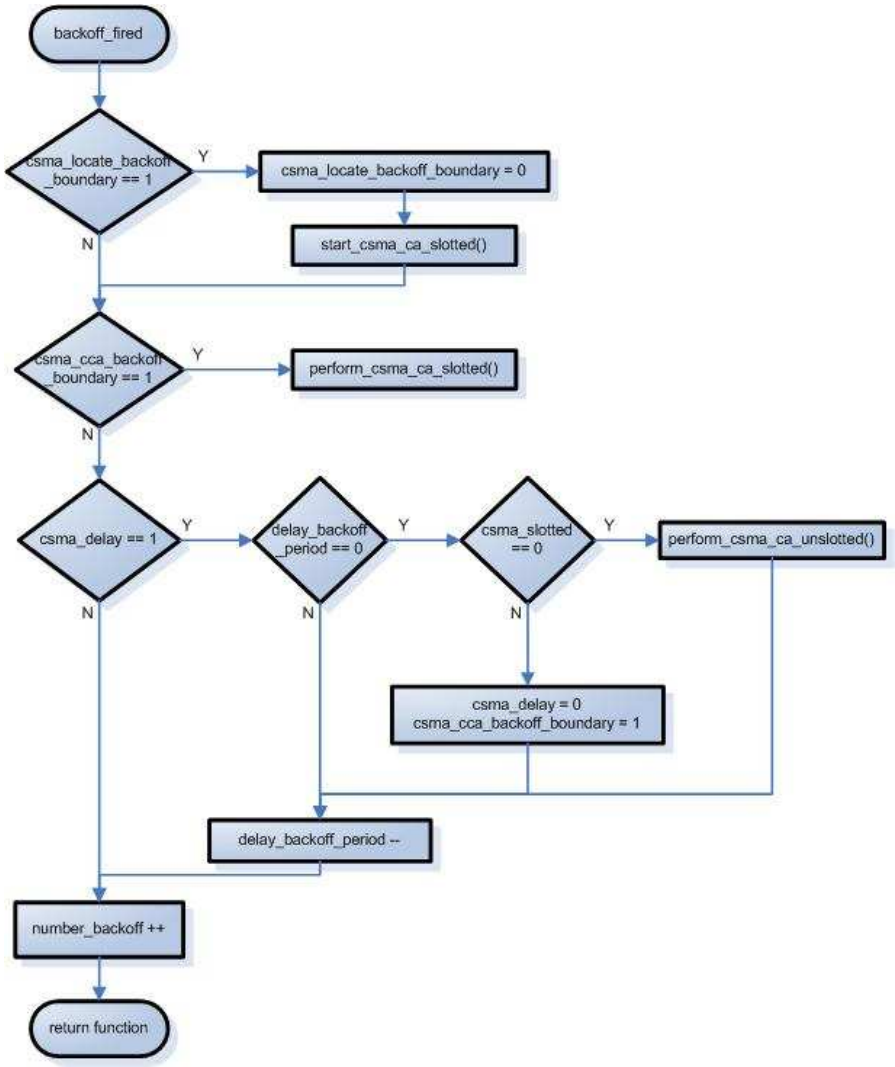


Figure 42 - backoff_fired event flow chart.

The slotted version of the algorithm implements two functions; the *start_csma_ca_slotted()* and the *perform_csma_ca_slotted()*. The first function is called once when the *csma_locate_backoff_boundary* is set to 1 and it is to set the *delay_backoff_period* variable with a random value before entering the step 2 of the algorithm.

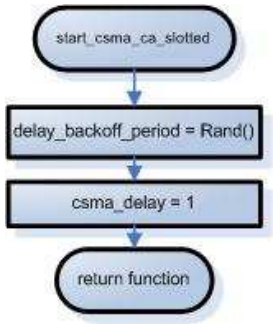


Figure 43 – start_csma_ca_slotted() function flow chart.

The function *perform_csma_ca_slotted()* implements the final steps of the algorithm. This function updates the global variables of the algorithm and sets the timer

auxiliary variables, so that it can be called several times to accomplish the application of the CSMA/CA. The function *TOSH_READ_CC_CCA_PIN(),* available in TinyOS, is used to perform the clear channel assessment and evaluate if the channel is clear (1) or not (0). The next figure illustrate the operation of the *perform_csma_ca_slotted()* function.

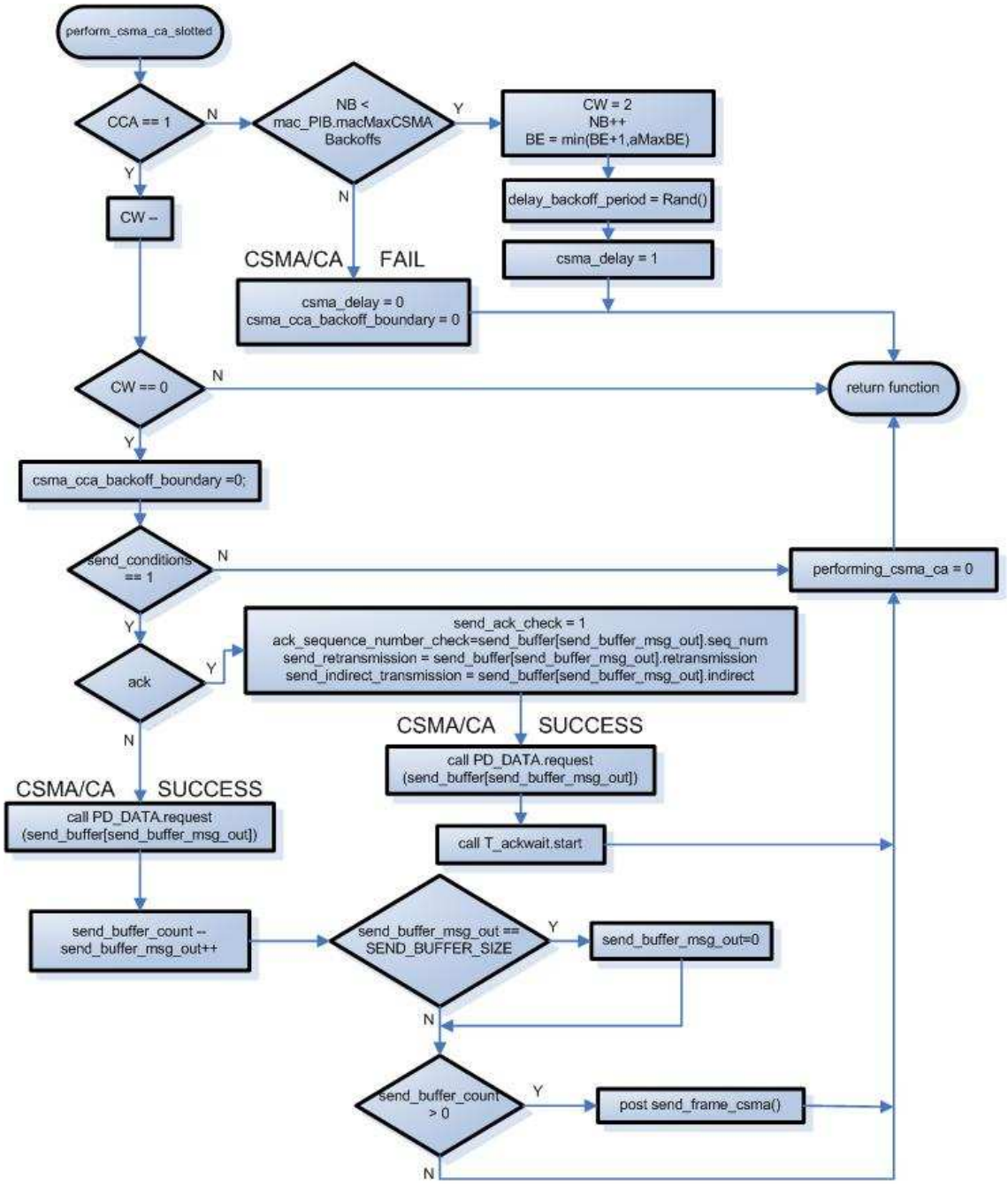


Figure 44 - perform_csma_ca_slotted() function flow chart.

3.5.10. GTS Management

The GTS Management procedures are described in [1 pag 159].

The GTS is a dedicated time slot allocated in the CAP by the PAN coordinator. There are two types of allocations, for reception and for transmission. Each allocation can only be used for reception or transmission. The PAN coordinator receives and processes the GTS allocation requests up to the maximum of seven time slots allocated. Each device associated to the PAN can only allocate one receive slot and one transmit slot. The allocated receive slot is used for the reception of transmissions by the PAN coordinator and the allocated transmit slot is used to transmit to the coordinator. The management of the GTS is made in the coordinator and transmitted to the devices in the GTS fields of the beacon. The deallocation of a GTS time slot can be requested by the device or by the coordinator. The coordinator can deallocate a device by simply remove it from the GTS list, without any reason or based in the inactivity of the time slot. Every time a device is deallocated, the coordinator updates the GTS descriptor list with the information of the device GTS descriptor with the slot length of zero.

All the transmissions in an allocated GTS use short addressing fields. The device allocates a GTS time slot by issuing the *MLME_GTS.request,* to the MAC layer, with its GTS characteristics descriptions that include the following information:

- The GTS time slot length;
- The direction of the allocation;
- Type of request (allocation/deallocation).

The function *set_gts_characteristics* implemented in the *mac_func.h* file is used to construct the 8 bit GTS characteristics fields. The *mac_func.h* also implements the respective get functions used to retrieve the respective information from the field.

GTS Allocation

Upon the reception of the GTS allocation request, the PAN coordinator will update it GTS descriptors database, implemented in the GTS_db array.

The GTS_db contains all the device GTS descriptors that have GTS allocations. Each element of the array is defined in the GTSinfoEntryType containing information about the incremental id of the GTS allocation, stating slot in the CFP, number of slots allocated, direction of the allocation, the address of the allocated device and the expiration counter.

```
typedef struct
{
  uint8_t gts_id;
  uint8_t starting_slot;
  uint8_t length;
  uint8_t direction;
  uint16_t DevAddressType;
  uint8_t expiration;

}GTSinfoEntryType;
```

Code Example 8- GTSinfoEntryType structure definition.

The next charts illustrate the MAC-PHY interaction when GTS allocation request occurs. [1 pag 84].

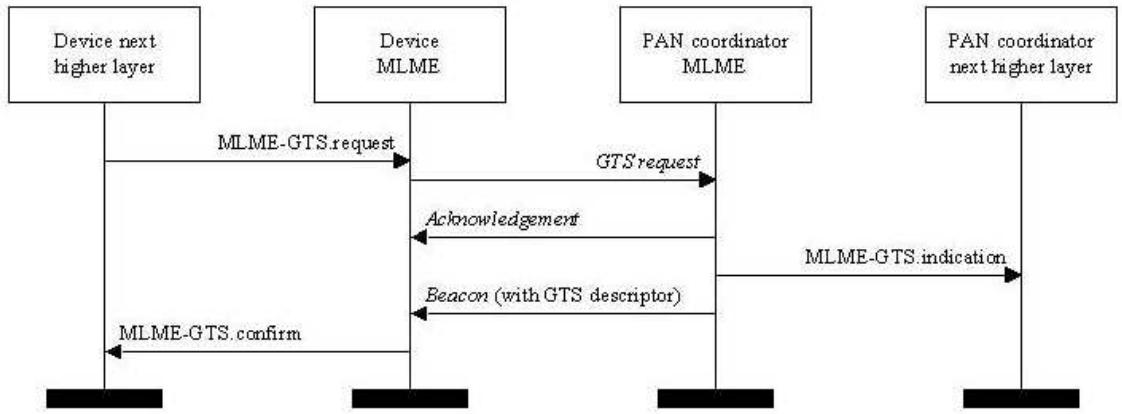


Figure 45 - GTS allocation request flow chart.

The next figure shows a sample transmission sequence of a GTS allocation request.

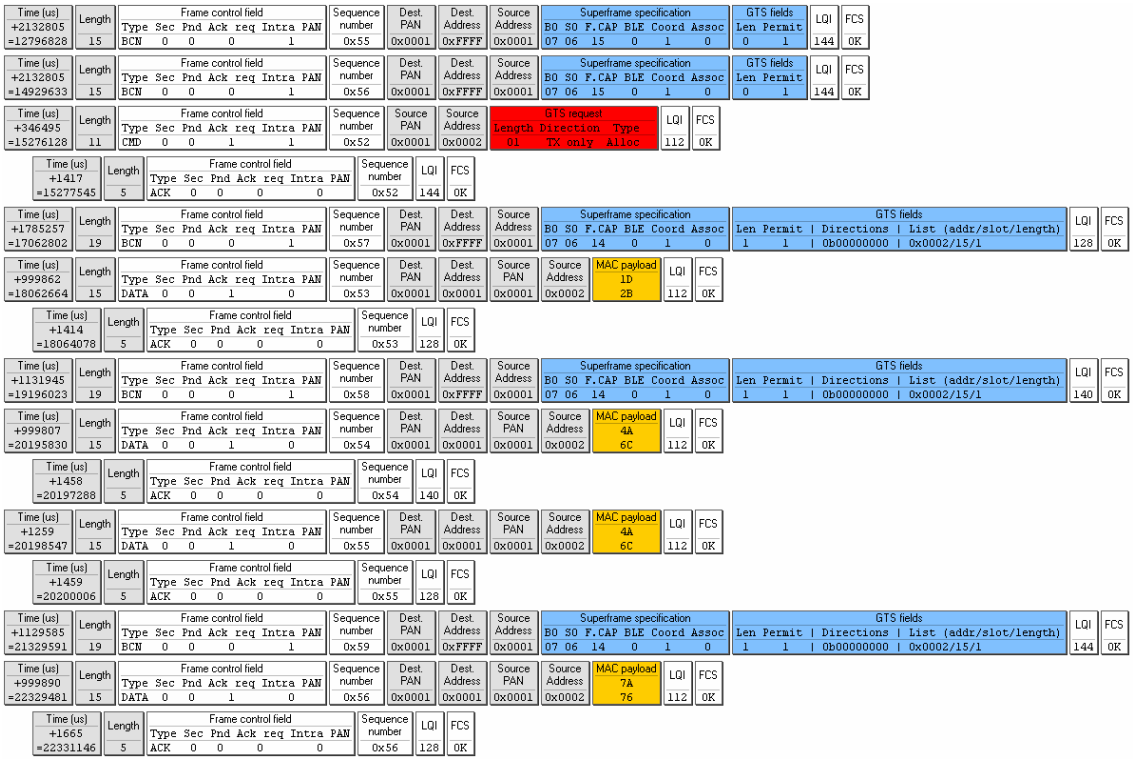


Figure 46 – GTS allocation mechanism example.

As seen in the above figure, the device successfully requests a GTS allocation. The GTS descriptors field of the next beacon confirm its allocation information.

GTS Deallocation

The GTS deallocation procedure in described in [1 pag 162].

Upon the reception of the deallocation request the PAN coordinator will update the GTS descriptor list removing the previous allocated slot and rearranging the

remaining allocation starting slots. The arrangement of the time slots is made in the *result_t remove_gts_entry(uint16_t DevAddressType)* function located in the MAC layer. The arrangement of the CFP consists in shifting right the allocated GTS descriptors witch have a starting slot less that the recent deallocated GTS descriptor and consequently the final_CAP_slot variable is updated. The next figure illustrates an example of this procedure [1 pag. 163].

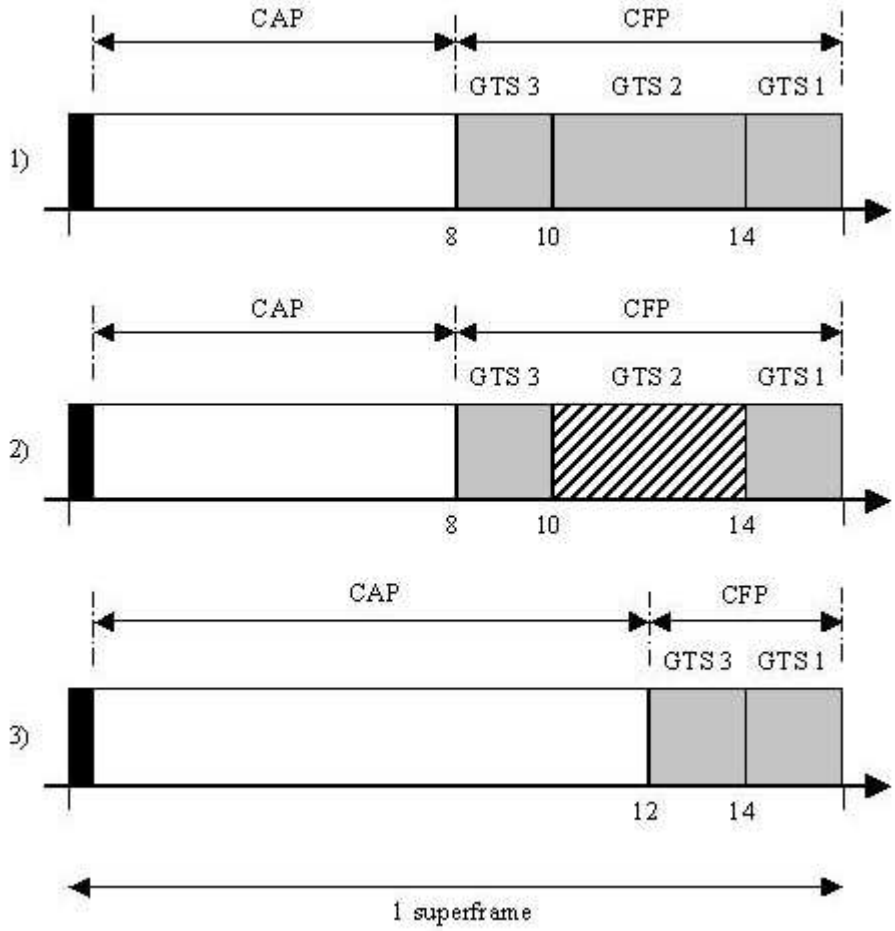


Figure 47 - CFP defragmentation on GTS deallocations.

In the above figure, the 1st point represent the three allocated GTS. The 2nd point shows the deallocation of the GTS 2 that start on the 10th time slot and with duration of 4 time slots. The final point show the GTS 3 shifted right 4 time slots. The final CAP slot that was 8 with on the 1st point now is 12 on the 3rd.

The PAN coordinator will monitor the GTS activity and if there are no transmissions during a defined number of time slots the GTS allocation expires.
The expiration occurs if there is no data frame is received and no acknowledgement by the device or the coordinator respectively, on every *2*n* superframes. The n is defined as:

- $n = 2^{(8-macBeaconOrder)}$, if $0 \leq macBeaconOrder \leq 8$
- $n = 1$, if $9 \leq macBeaconOrder \leq 14$

The deallocated GTS descriptor will move to the GTS deallocated descriptors database, defined as *GTS_db_null* and will appear in the beacon with the starting slot

equal to zero. Each element of the *GTS_db_null* array is defined as a *GTSinfoEntryType_null* variable that has the following attributes. A GTS identification number, a starting slot equal to zero, the duration of time slots, the deallocated device address and the persistence time counter with the number of superframes after witch the PAN coordinator will remove the descriptor from the beacon. The persistence of the descriptos is defined in the *aGTSDesPersistenceTime* constant variable.

```
typedef struct
{
  uint8_t gts_id;
  uint8_t starting_slot;
  uint8_t length;
  uint16_t DevAddressType;
  uint8_t persistencetime;

}GTSinfoEntryType_null;
```

Code Example 9- GTSinfoEntryType_null structure definition.

The next charts illustrate the MAC-PHY interaction when GTS deallocation request occurs. [1 pag 84].

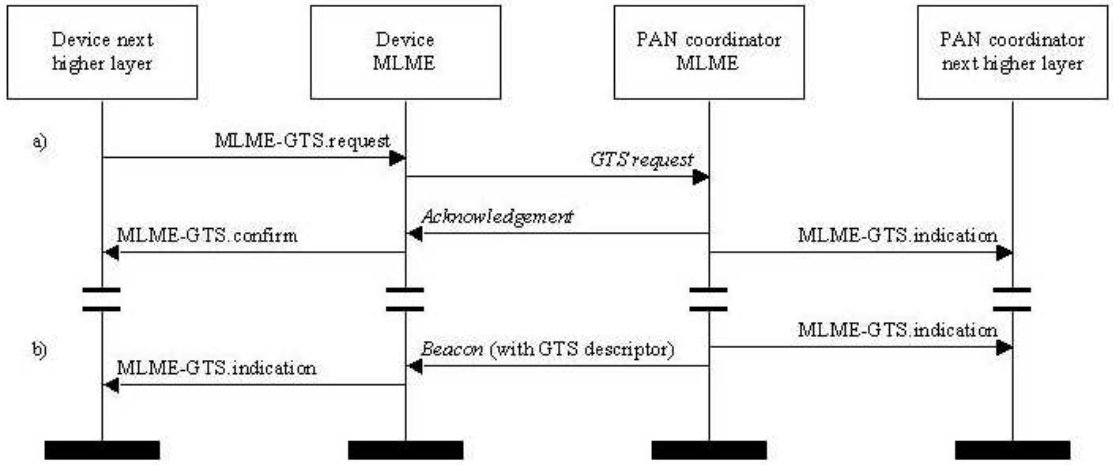


Figure 48 - GTS deallocation request flow chart.

The next figure shows a sample transmission sequence of a GTS deallocation request.

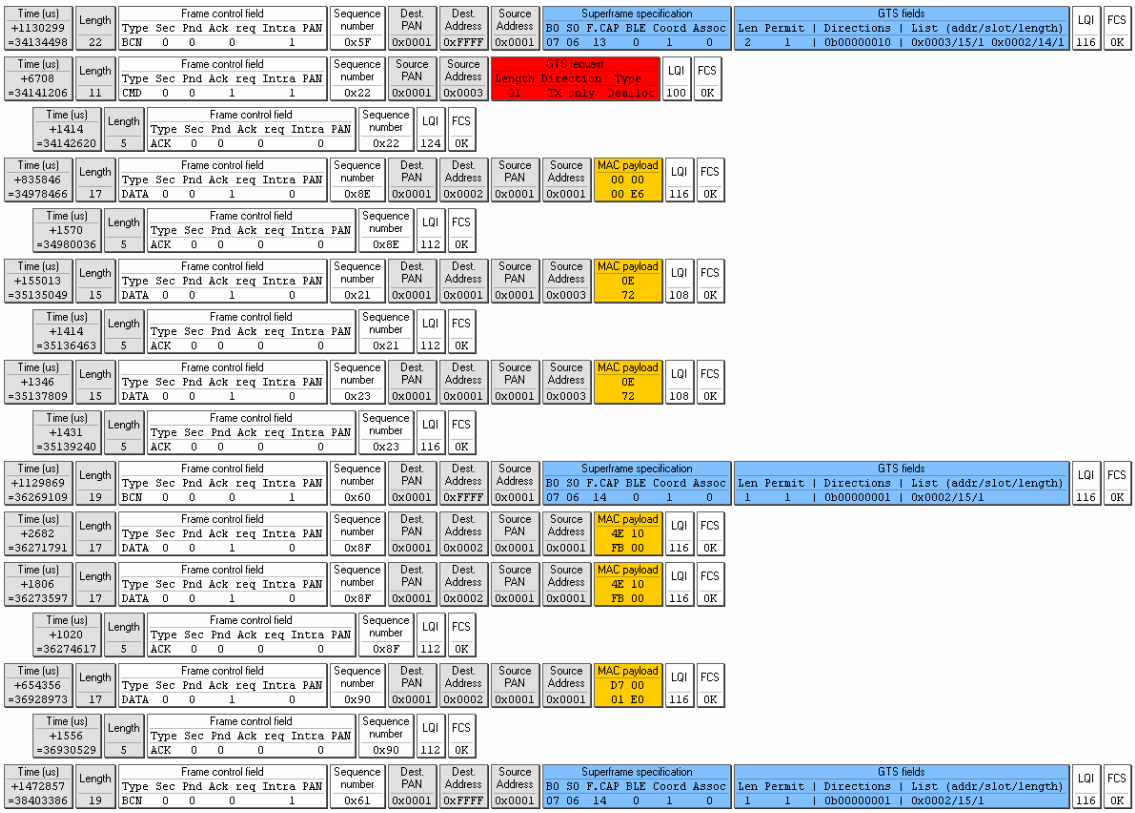


Figure 49 – GTS deallocation mechanism example.

As seen in the above figure, the device successfully request a GTS deallocation. The next beacon will not contain the deallocated GTS descriptor and the device stops its transmissions. Note that the GTS descriptors in the beacon were rearranged and the device 0x0002 that was transmitting in the 14th slot now is transmitting in the 15th.

3.5.11. Pending data / Indirect Transmissions

The pending data mechanism is used by the PAN coordinator to inform, the devices associated, that they have data pending. The pending data information is described, in the beacon, on the pending data fields. A device will know that it has pending data by examining the beacon payload. The device can request the pending data by sending a data request command frame. Upon receiving the request, the coordinator will search the indirect transmissions buffer for the destination address and send the frame if it finds it. The coordinator ignores the request if it does not find the correct address.

The data extraction mechanism is described in [1 pag. 155].

The indirect transmissions are stored in the *indirect_trans_queue* buffer, on the coordinator, and each message stays in the buffer for a defined amount of superframes.

When the coordinator is constructing the beacon, if there are pending addresses to be send, it will construct a list containing there addresses. The following diagram illustrates the construction of the pending addresses list if the *indirect_trans_count* variable, containing the number of pending addresses, is greater than zero. The variables *short_addr_pending* and *long_addr_pending* contains the number of frames with short and long destination addressing fields respectively. The add processes in the next

diagram, indicate that the address is copied to the beacon payload and it length is updated. In the final procedure the pending addresses specification field must be updated with the short and long counters. In the address list, the short addresses must appear first and that is why the buffer is searched twice, the first time is to count and construct the short address list and the second is for the long addresses.

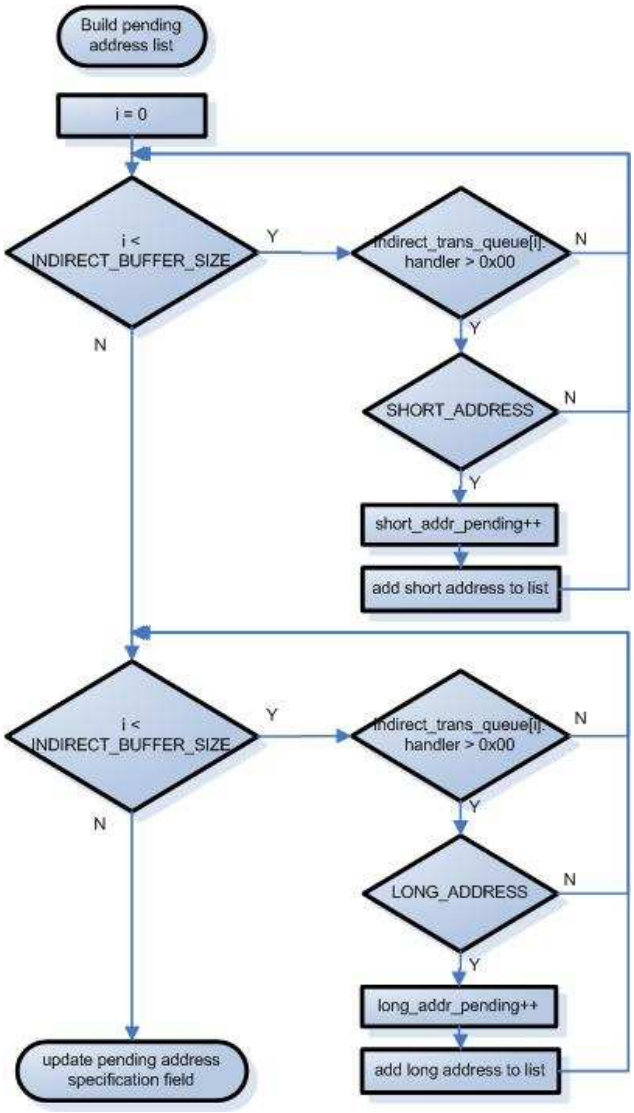


Figure 50 - Pending address list construction diagram.

The next figure shows a sample transmission sequence of data request.

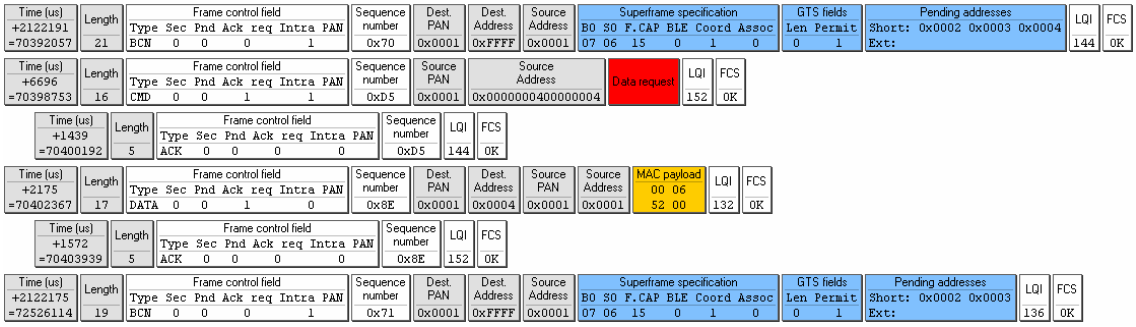


Figure 51 – Data request example.

3.6. Auxiliary Files (Under contrib.hurray.tos.lib.mac):

mac_const.h

This file contains data structures definition used in the MAC and protocol constants definition related with the MAC layer along with auxiliary constants.

The MAC protocol constants defined are the described in the next table. [1 pag. 134]. Note that some of these constants assignments make use of PHY constants defined in the *phy_const.h* file under the *contrib.hurray.tos.lib.phy* directory.

Constant	Value	Description
aBaseSlotDuration	60	The number of symbols forming a superframe slot when the superframe order is equal to 0
aBaseSuperframeDuration	aBaseSlotDuration * aNumSuperframeSlots	The number of symbols forming a superframe when the superframe order is equal to 0
aMaxBE	5	The maximum value of the backoff exponent in the CSMA-CA algorithm.
aMaxBeaconOverhead	75	The maximum number of octets added by the MAC sublayer to the payload of its beacon frame
aMaxBeaconPayloadLength	aMaxPHYPacketSize - aMaxBeaconOverhead	The maximum size, in octets, of a beacon payload
aGTSDescPersistenceTime	4	The number of superframes in which a GTS descriptor exists in the beacon frame of a PAN coordinator.
aMaxFrameOverhead	25	The maximum number of octets added by the MAC sublayer to its payload without security.
aMaxFrameResponseTime	1220	The maximum number of CAP symbols in a beaconenabled PAN, or symbols in a nonbeacon-enabled PAN, to wait for a frame intended as a response to a data request frame.
aMaxFrameRetries	3	The maximum number of retries allowed after a transmission failure.

aMaxLostBeacons	4	The number of consecutive lost beacons that will cause the MAC sublayer of a receiving device to declare a loss of synchronization.
aMaxMACFrameSize	aMaxPHYPacketSize - aMaxFrameOverhead	The maximum number of octets that can be transmitted in the MAC frame payload field.
aMaxSIFSFrameSize	18	The maximum size of an MPDU, in octets, that can be followed by a short interframe spacing (SIFS)
aMinCAPLength	440	The minimum number of symbols forming the CAP. This ensures that MAC commands can still be transferred to devices when GTSs are being used. An exception to this minimum shall be allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance
aMinLIFSPeriod	40	The minimum number of symbols forming a long interframe spacing (LIFS) period.
aMinSIFSPeriod	12	The minimum number of symbols forming a SIFS period.
aNumSuperframeSlots	16	The number of slots contained in any superframe.
aResponseWaitTime	32 * aBaseSuperframeDuration	The maximum number of symbols a device shall wait for a response command to be available following a request command.
aUnitBackoffPeriod	20	The number of symbols forming the basic time period used by the CSMA-CA algorithm.

Table 17 - Protocol MAC layer constants description.

The next table describes auxiliary constants used in the MAC layer.

Constant	Value	Description
TYPE_BEACON	0	Beacon type definition.
TYPE_DATA	1	Data type definition.
TYPE_ACK	2	Acknowledg type definition.
TYPE_CMD	3	Command type definition.
SHORT_ADDRESS	2	Short address mode definition.
LONG_ADDRESS	3	Long address mode definition.
RESERVED_ADDRESS	1	Reserved address mode definition.
NUMBER_TIME_SLOTS	16	Number of time slots in the superframe.
ACK_LENGTH	5	Length of the acknowledge frame.
MAX_GTS_BUFFER	7	GTS buffer maximum size.
INDIRECT_BUFFER_SIZE	2	Indirect transmission maximum buffer size.
RECEIVE_BUFFER_SIZE	5	Receive buffer maximum size.
SEND_BUFFER_SIZE	4	Send buffer maximum size
GTS_SEND_BUFFER_SIZE	3	GTS buffer maximum size.
BACKOFF_PERIOD_MS	0.34724	Duration of a backoff period in milliseconds.

BACKOFF_PERIOD_US	347.24	Duration of a backoff period in microseconds.

Table 18 - MAC layer auxiliary constants description.

The next table describes the structures defined in this file.

Structure Name	Attributes	Description
macPIB	uint8_t macAckWaitDuration; bool macAssociationPermit; bool macAutoRequest; bool macBattLifeExt; uint8_t macBattLifeExtPeriods; uint8_t macBeaconPayload [aMaxBeaconPayloadLength]; uint8_t macBeaconPayloadLenght; uint8_t macBeaconOrder; uint32_t macBeaconTxTime; uint8_t macBSN; uint32_t macCoordExtendedAddress0; uint32_t macCoordExtendedAddress1; uint32_t macCoordShortAddress; uint8_t macDSN; bool macGTSPermit; uint8_t macMaxCSMABackoffs; uint8_t macMinBE; uint16_t macPANId; bool macPromiscuousMode; bool macRxOnWhenIdle; uint32_t macShortAddress; uint8_t macSuperframeOrder; uint32_t macTransactionPersistenceTime;	MAC PAN Information Base. [1 pag. 135]
ACLDescriptor	uint32_t ACLExtendedAddress[2]; uint16_t ACLShortAddress; uint16_t ACLPANId; uint8_t ACLSecurityMaterialLength; uint8_t ACLSecurityMaterial; uint8_t ACLSecuritySuite;	ACL entry descriptor [1 pag. 138]. Not Used.
macPIBsec	ACLDescriptor macACLEntryDescriptorSet; uint8_t macACLEntryDescriptorSetSize; bool macDefaultSecurity; uint8_t macDefaultSecurityMaterialLength; uint8_t macDefaultSecurityMaterial; uint8_t macDefaultSecuritySuite; uint8_t macSecurityMode;	MAC PAN information Base security Attributes [1 pag. 138]. Not Used.
PANDescriptor	uint8_t CoordAddrMode; uint16_t CoordPANId; uint32_t CoordAddress0; uint32_t CoordAddress1; uint8_t LogicalChannel; uint16_t SuperframeSpec;	Description of the PAN, used to store its characteristic [1 pag. 76].

	bool GTSPermit; uint8_t LinkQuality; uint32_t TimeStamp; bool SecurityUse; uint8_t ACLEntry; bool SecurityFailure;	
GTSinfoEntryType	uint8_t gts_id; uint8_t starting_slot; uint8_t length; uint8_t direction; uint16_t DevAddressType; uint8_t expiration;	Allocated GTS element type of each position of the GTS database maintained by coordinator.
GTSinfoEntryType_null	uint8_t gts_id; uint8_t starting_slot; uint8_t length; uint16_t DevAddressType; uint8_t persistencetime;	Dealocated GTS element type of each position of the GTS database maintained by coordinator.
indirect_transmission_element	uint8_t handler; uint16_t transaction_persistent_time; uint8_t frame[127];	Indirect transmission element of each position in the indirect transmission buffer (indirect_trans_queue).
gts_slot_element	uint8_t element_count; uint8_t element_in; uint8_t element_out; uint8_t gts_send_frame_index[GTS_SEND_BUFFER_SIZE];	GTS element of each position in the gts buffer. Used by the PAN coordinator only.

Table 19 - Structure definitions on the mac_const.h file.

mac_enumerations.h

This file contains the enumeration values used in the MAC layer. The following tables describe the enumerations and their usage.

General MAC enumeration description table [1 pag 110].

Enumeration	Value	Description
MAC_SUCCESS	0x00	The requested operation was completed successfully. For a transmission request, this value indicates a successful transmission.
MAC_BEACON_LOSS	0xE0	The beacon was lost following a synchronization request.
MAC_CHANNEL_ACCESS_FAILURE	0xE1	A transmission could not take place due to activity on the channel, i.e., the CSMA-CA mechanism has failed
MAC_DENIED	0xE2	The GTS request has been denied by the PAN coordinator
MAC_DISABLE_TRX_FAILURE	0xE3	The attempt to disable the transceiver has failed
MAC_FAILED_SECURITY_CHECK	0xE4	The received frame induces a failed security check according to the security suite.
MAC_FRAME_TOO_L	0xE5	The frame resulting from secure processing has a length that

ONG		is greater than aMACMaxFrameSize
MAC_INVALID_GTS	0xE6	The requested GTS transmission failed because the specified GTS either did not have a transmit GTS direction or was not defined
MAC_INVALID_HANDLE	0xE7	A request to purge an MSDU from the transaction queue was made using an MSDU handle that was not found in the transaction table.
MAC_INVALID_PARAMETER	0xE8	A parameter in the primitive is out of the valid range
MAC_NO_ACK	0xE9	No acknowledgment was received after aMaxFrameRetries.
MAC_NO_BEACON	0xEA	A scan operation failed to find any network beacons
MAC_NO_DATA	0xEB	No response data were available following a request.
MAC_NO_SHORT_ADDRESS	0xEC	The operation failed because a short address was not allocated.
MAC_OUT_OF_CAP	0xED	A receiver enable request was unsuccessful because it could not be completed within the CAP.
MAC_PAN_ID_CONFLICT	0xEE	A PAN identifier conflict has been detected and communicated to the PAN coordinator.
MAC_REALIGNMENT	0xEF	A coordinator realignment command has been received
MAC_TRANSACTION_EXPIRED	0xF0	The transaction has expired and its information discarded.
MAC_TRANSACTION_OVERFLOW	0xF1	There is no capacity to store the transaction.
MAC_TX_ACTIVE	0xF2	The transceiver was in the transmitter enabled state when the receiver was requested to be enabled
MAC_UNAVAILABLE_KEY	0xF3	The appropriate key is not available in the ACL.
MAC_UNSUPPORTED_ATTRIBUTE	0xF4	A SET/GET request was issued with the identifier of a PIB attribute that is not supported.

Table 20 - General MAC enumeration description.

Disassociation enumeration reasons description table [1 pag 127].

Enumeration	Value	Description
MAC_PAN_COORD_LEAVE	0x01	The disassociation reason was that the coordinator wishes the device to leave the PAN.
MAC_PAN_DEVICE_LEAVE	0x02	The disassociation reason was that the device wishes to leave the PAN.

Table 21 - Disassociation status enumeration decription.

Command type enumeration description table [1 pag 123].

Enumeration	Value	Description
CMD_ASSOCIATION_REQUEST	0x01	Association request command type.
CMD_ASSOCIATION_RESPONSE	0x02	Association response command type.
CMD_DISASSOCIATION_NOTIFICATION	0x03	Disassociation notification command type.

CMD_DATA_REQUEST	0x04	Data request command type.
CMD_PANID_CONFLICT	0x05	PANID conflict notification command type.
CMD_ORPHAN_NOTIFICATION	0x06	Lost synchronization notification command type.
CMD_BEACON_REQUEST	0x07	Beacon request command type.
CMD_COORDINATOR_REALIGNMENT	0x08	Coordinator realignment command type.
CMD_GTS_REQUEST	0x09	GTS request command type.

Table 22 - Command type enumerations description.

Association response enumerations description table [1 pag 126].

Enumeration	Value	Description
CMD_RESP_ASSOCIATION_SUCCESSFUL	0x00	The association was successful.
CMD_RESP_PAN_CAPACITY	0x01	The association was denied because the PAN is at full capacity.
CMD_RESP_ACCESS_DENIED	0x02	The association was denied because the PAN denied access.

Table 23 - Association response status enumerations description.

Mac PIB attributes enumerations description table used in the MLME_GET and MLME_SET primitives.

Enumeration	Value	Description
MACACKWAITDURATION	0x40	The GET/SET reference of the PIB macAckWaitDuration.
MACASSOCIATIONPERMIT	0x41	The GET/SET reference of the PIB macAckWaitDuration.
MACAUTOREQUEST	0x42	The GET/SET reference of the PIB macAutoRequest
MACBATTLIFEEXT	0x43	The GET/SET reference of the PIB macBattLifeExt
MACBATTLIFEEXTPERIODS	0x44	The GET/SET reference of the PIB macBattLifeExtPeriods
MACBEACONPAYLOAD	0x45	The GET/SET reference of the PIB macBeaconPayload
MACMAXBEACONPAYLOADLENGTH	0x46	The GET/SET reference of the PIB macMaxBeaconPayloadLength
MACBEACONORDER	0x47	The GET/SET reference of the PIB macBeaconOrder
MACBEACONTXTIME	0x48	The GET/SET reference of the PIB macBeaconTxTime
MACBSN	0x49	The GET/SET reference of the PIB macBSN
MACCOORDEXTENDEDADDRESS	0x4a	The GET/SET reference of the PIB macCoordExtendedAddress
MACCOORDSHORTADDRESS	0x4b	The GET/SET reference of the PIB macCoordShortAddress
MACDSN	0x4c	The GET/SET reference of the PIB macDSN
MACGTSPERMIT	0x4d	The GET/SET reference of the PIB macGTSPermit
MACMAXCSMABACKOFFS	0x4e	The GET/SET reference of the PIB macMaxCSMABackoffs

MACMINBE	0x4f	The GET/SET reference of the PIB macMinBE
MACPANID	0x50	The GET/SET reference of the PIB macPANId
MACPROMISCUOUSMODE	0x51	The GET/SET reference of the PIB macPromiscuousMode
MACRXONWHENIDLE	0x52	The GET/SET reference of the PIB macRxOnWhenIdle
MACSHORTADDRESS	0x53	The GET/SET reference of the PIB macShortAddress
MACSUPERFRAMEORDER	0x54	The GET/SET reference of the PIB macSuperframeOrder.
MACTRANSACTIONPERSISTENCETIME	0x55	The GET/SET reference of the PIB macTransactionPercistenceTime

Table 24 - MAC GET/SET reference PIB enumerations description.

GTS direction enumerations description table.

Enumeration	Value	Description
GTS_TX_ONLY	0x00	GTS direction from device to coordinator.
GTS_RX_ONLY	0x01	GTS direction from coordinator to device

Table 25 - GTS direction enumeration descriptions.

Auxiliary Files (Under *contrib.hurray.tos.system*):

frame_format.h

This file contains the frame structure definitions. All the frames structures used by the protocol, being command, data, acknowledgment and beacon frames are defined in this file.

The next table describes the structures defined in this file:

Structure Name	Attributes	Description
MPDU	uint8_t length; uint16_t frame_control; uint8_t seq_num; uint8_t data[121];	
beacon_addr_short	uint16_t destination_PAN_identifier; uint16_t destination_address; uint16_t source_address; uint16_t superframe_specification;	
beacon_struct	uint8_t length; uint16_t frame_control; uint8_t seq_num; uint16_t source_PAN_identifier; uint16_t destination_address; uint16_t source_address; uint16_t superframe_specification;	

beacon_addr_long	uint16_t source_PAN_identifier; uint32_t source_address0; uint32_t source_address1; uint16_t superframe_specification;	
ACK	uint8_t length; uint16_t frame_control; uint8_t seq_num;	
cmd_association_request	uint8_t command_frame_identifier; uint8_t capability_information;	
cmd_association_response	uint8_t command_frame_identifier; uint16_t short_address; uint8_t association_status;	
cmd_disassociation_notification	uint16_t destination_PAN_identifier; uint32_t destination_address0; uint32_t destination_address1; uint16_t source_PAN_identifier; uint32_t source_address0; uint32_t source_address1; uint8_t command_frame_identifier; uint8_t disassociation_reason;	
cmd_beacon_request	uint16_t destination_PAN_identifier; uint16_t destination_address; uint8_t command_frame_identifier;	
cmd_gts_request	uint16_t source_PAN_identifier; uint16_t source_address; uint8_t command_frame_identifier; uint8_t gts_characteristics;	
dest_short	uint16_t destination_PAN_identifier; uint16_t destination_address;	
dest_long	uint16_t destination_PAN_identifier; uint32_t destination_address0; uint32_t destination_address1;	
intra_pan_source_short	uint16_t source_address;	
intra_pan_source_long	uint32_t source_address0; uint32_t source_address1;	
source_short	uint16_t source_PAN_identifier; uint16_t source_address;	
source_long	uint16_t source_PAN_identifier; uint32_t source_address0; uint32_t source_address1;	

Table 26 - frame_format.h structures descriptions.

The next table describes the constants defined in this file.

Constant Name	Values	Description
MPDU_HEADER_LEN	5	
DEST_SHORT_LEN	4	

DEST_LONG_LEN	10	
INTRA_PAN_SOURCE_SHORT_LEN	2	
INTRA_PAN_SOURCE_LONG_LEN	8	
SOURCE_SHORT_LEN	4	
SOURCE_LONG_LEN	10	

Table 27 - frame_format.h constants descriptions.

mac_func.h

This file contains auxiliary functions used in the implementation of the protocol. Some functions are used in the construct or retrieve some particular fields in the frame construction, like the frame control field, that require bit operations.

The functions defined are the following:

uint8_t set_capability_information(uint8_t alternate_PAN_coordinator, uint8_t device_type, uint8_t power_source, uint8_t receiver_on_when_idle, uint8_t security, uint8_t allocate_address)

Function used to build the 8 bit capability information of the device requesting an association.

uint16_t set_frame_control(uint8_t frame_type,uint8_t security,uint8_t frame_pending,uint8_t ack_request,uint8_t intra_pan,uint8_t dest_addr_mode,uint8_t source_addr_mode)

Function used to build the frame control of the MAC frames.

uint8_t get_frame_control_dest_addr(uint16_t frame_control)

Function used to return the type of destination address specified in the frame control.

uint8_t get_frame_control_source_addr(uint16_t frame_control)

Function used to return the type of source address specified in the frame control.

bool get_security(uint8_t frame_control)

Function used to return the security parameter specified in the frame control.

bool get_frame_pending(uint8_t frame_control)

Function used to return the frame pending parameter specified in the frame control.

bool get_ack_request(uint8_t frame_control)

Function used to return the acknowledge request parameter specified in the frame control.

bool get_intra_pan(uint8_t frame_control)

Function used to return the Intra PAN request parameter specified in the frame control.

uint16_t set_superframe_specification(uint8_t beacon_order,uint8_t superframe_order,uint8_t final_cap_slot,uint8_t battery_life_extension,uint8_t pan_coordinator,uint8_t association_permit)

Function used to build the 16 bit beacon superframe duration field.

uint8_t get_beacon_order(uint16_t superframe)

Function used to return the beacon order parameter specified in the beacon superframe specification.

uint8_t get_superframe_order(uint16_t superframe)

Function used to return the superframe order parameter specified in the beacon superframe specification.

bool get_pan_coordinator(uint16_t superframe)

Function used to return the PAN coordinator parameter specified in the beacon superframe specification.

bool get_association_permit(uint16_t superframe)

Function used to return the association permit parameter specified in the beacon superframe specification.

bool get_battery_life_extention(uint16_t superframe)

Function used to return the battery life extension parameter specified in the beacon superframe specification.

uint8_t get_final_cap_slot(uint16_t superframe)

Function used to return the final CAP slot parameter specified in the beacon superframe specification.

uint8_t set_txoptions(uint8_t ack, uint8_t gts, uint8_t indirect_transmission,uint8_t security)

Function used to build the 8 bit transmit option field used in the MCPS_DATA.request primitiv issued by the MAC upper layer.

bool get_txoptions_ack(uint8_t txoptions)

Function used to return the acknowledgment parameter specified in the data transmission options.

bool get_txoptions_gts(uint8_t txoptions)

Function used to return the GTS parameter specified in the data transmission options.

bool get_txoptions_indirect_transmission(uint8_t txoptions)

Function used to return the indirect transmission parameter specified in the data transmission options.

bool get_txoptions_security(uint8_t txoptions)

Function used to return the security parameter specified in the data transmission options.

uint8_t set_pending_address_specification(uint8_t number_short, uint8_t number_extended)

Function used to build the pending addresses specification fields used in the beacon payload

uint8_t get_number_short(uint8_t pending_specification)

Function used to return the number of short addresses of the pending addresses list.

uint8_t get_number_extended(uint8_t pending_specification)

Function used to return the number of extended addresses of the pending addresses list.

uint8_t set_gts_specification(uint8_t gts_descriptor_count, uint8_t gts_permit)

Function used to build the 8 bit GTS specification field included in the beacon payload.

uint8_t get_gts_permit(uint8_t gts_specification)

Function used to return the GTS permit parameter of the GTS specification field.

uint8_t set_gts_descriptor(uint8_t GTS_starting_slot, uint8_t GTS_length)

Function used to build the 8 bit allocation/ deallocation device descriptor that is included in the beacon GTS descriptor list..

uint8_t get_gts_descriptor_len(uint8_t gts_des_part)

Function used to return the length parameter of the GTS descriptor.

uint8_t get_gts_descriptor_ss(uint8_t gts_des_part)

Function used to return the start slot parameter of the GTS descriptor.

uint8_t set_gts_characteristics(uint8_t gts_length, uint8_t gts_direction, uint8_t characteristic_type)

Function used to build the GTS characteristics field used in the beacon payload.

uint8_t get_gts_length(uint8_t gts_characteristics)

Function used to return the GTS total length parameter of the GTS characteristics field.

bool get_gts_direction(uint8_t gts_characteristics)

Function used to return the GTS direction list parameter of the GTS characteristics field.

uint8_t get_characteristic_type(uint8_t gts_characteristics)

Function used to return the characteristic type parameter of the GTS characteristics field.

4. Example Applications

This section refers to the example applications located under *contrib.app.<AppName>Example* directory. The objective of these examples is to provide a demonstration/testing of the protocol functionalities and allowing a simple understanding of the implementation functions.

On every example the yellow led is on during the active period.

4.1. AssociationExample application

This simple application is used to illustrate an association/disassociation of a device. The device starts by trying to synchronize with the beacon. Then it sends an association request and waits for the association response. After the association procedure the device already has a short address and enables a timer to start sending data messages to the coordinator. At the same time the device enables another timer that will trigger a dissociation request to the coordinator.

This application is linked directly to the MAC layer. The next figure illustrates the component wiring to the Mac component.

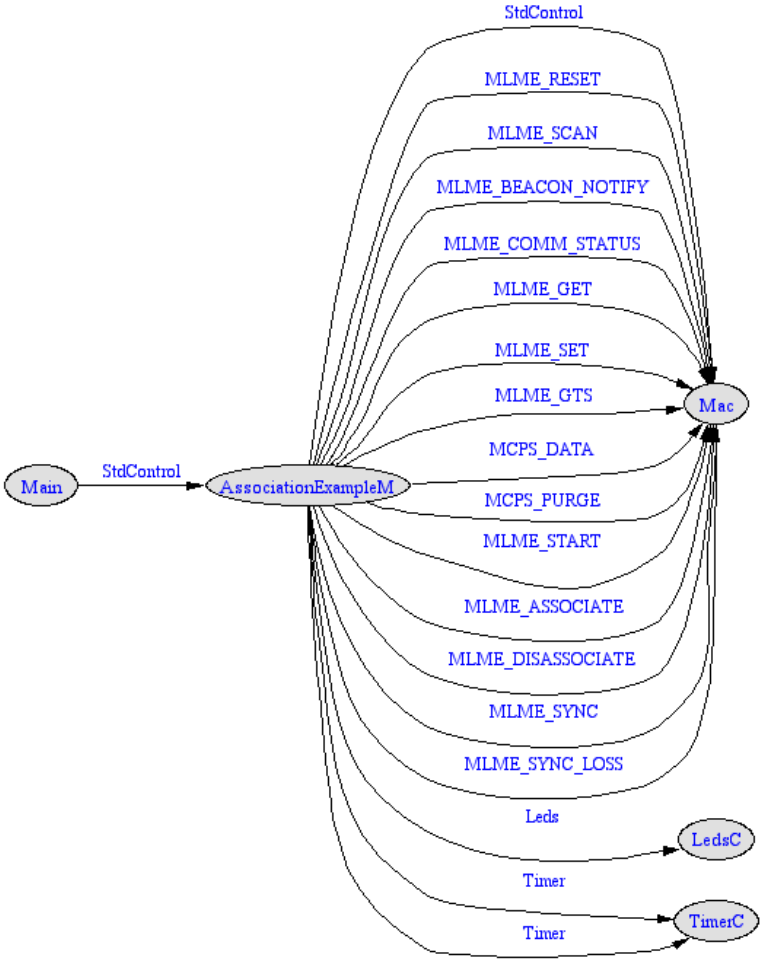


Figure 52 - AssociationExample component graph.

To complete this example there must be a PAN coordinator device, with an id 1, and several devices. The PAN coordinator will accept association requests and will reply with an association response.
The following sniffer output shows this interaction.

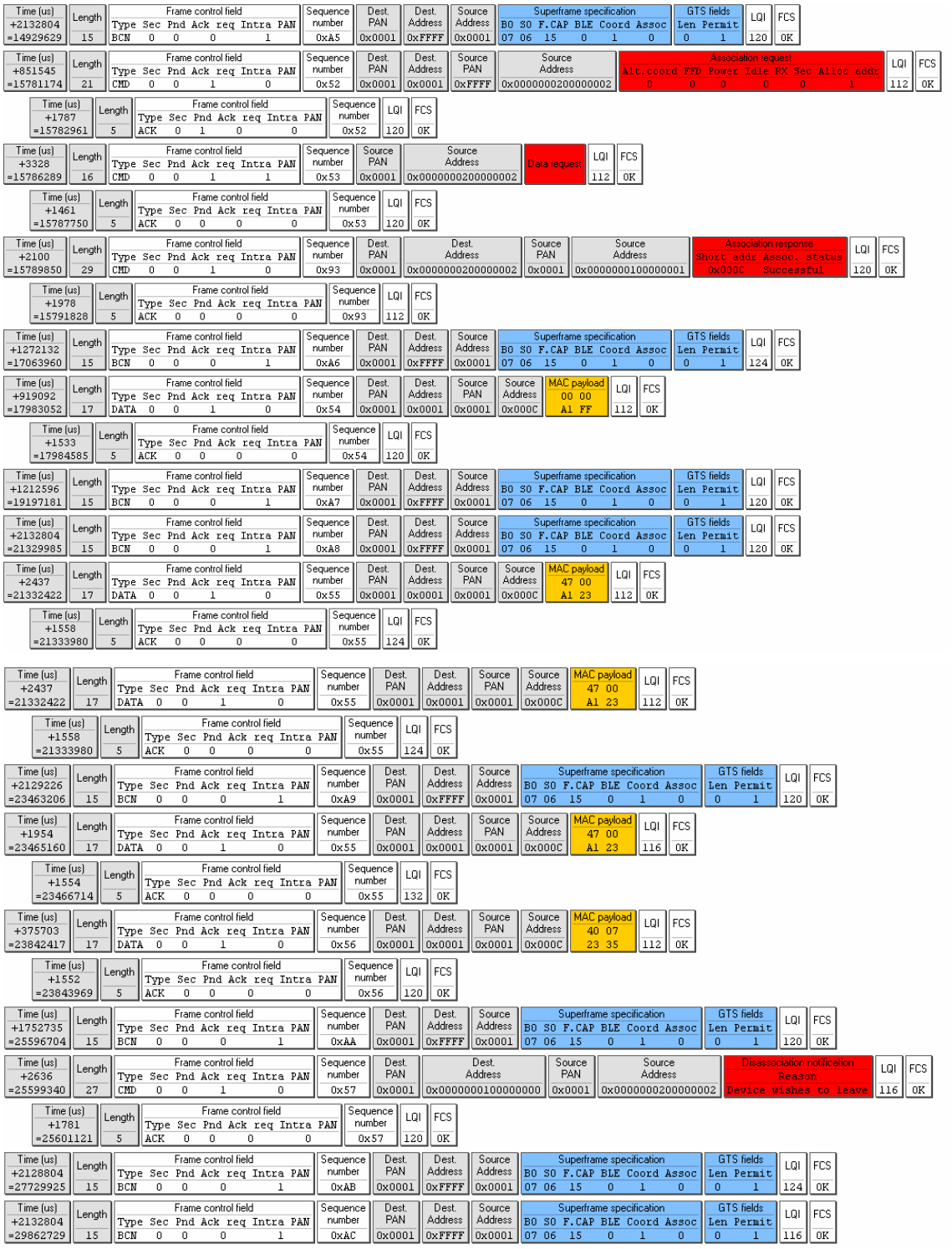


Figure 53 - AssociationExample sniffer output.

4.2. GTSManagementExample application

This simple application demonstrates the usage of the GTS allocation request. The device already has a manually assigned short address and tries to request a transmit GTS allocation. After the allocation is successfully acknowledge and the PAN coordinator updates the GTS descriptors list in the beacon, the device will start to send

data messages to the coordinator. After 10 superframe counts the device will cease to transmit data and send a GTS deallocation request. If the device with the short address 0x0002 requests a receive GTS allocation the coordinator will start to send data frames to that device.

This application is linked directly to the MAC layer. The next figure illustrates the component wiring to the Mac component.

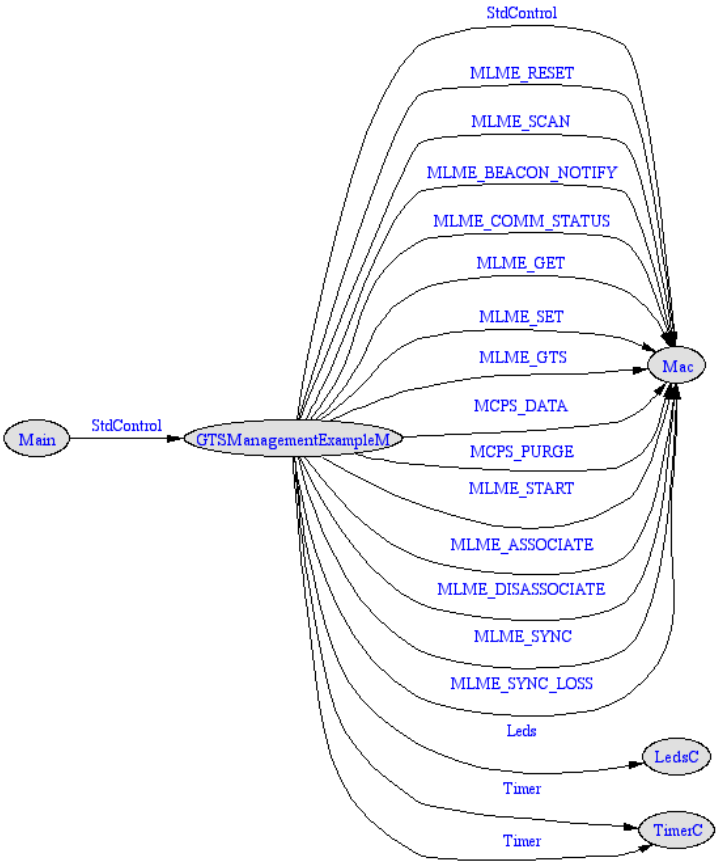
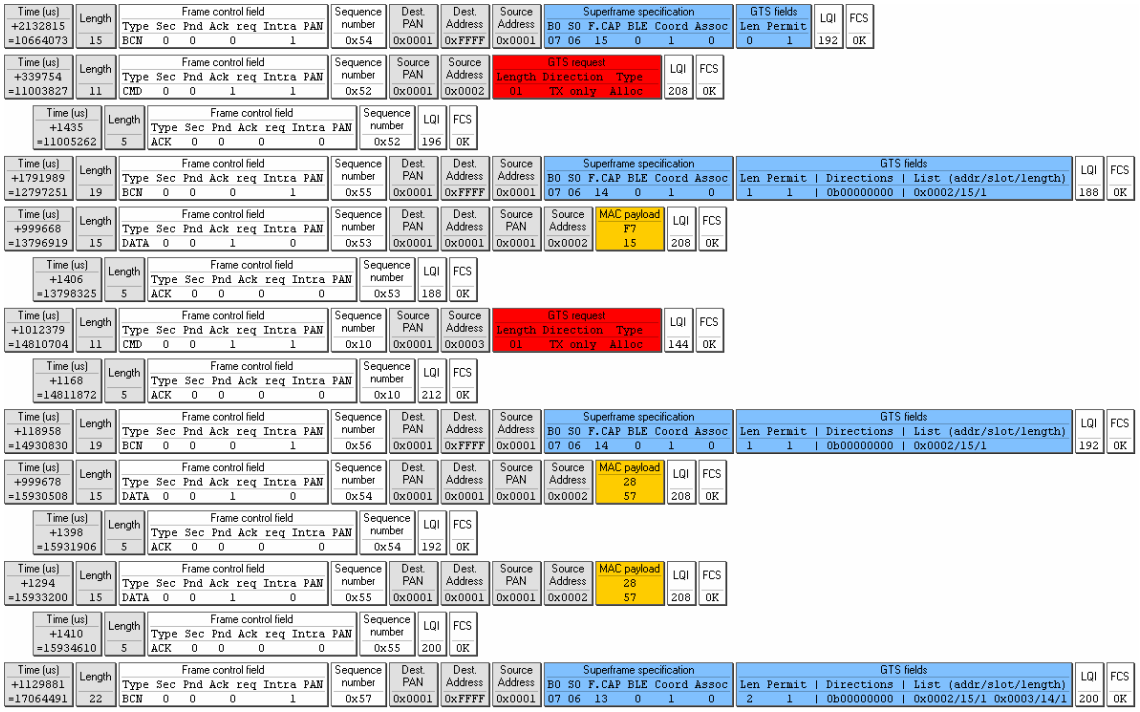
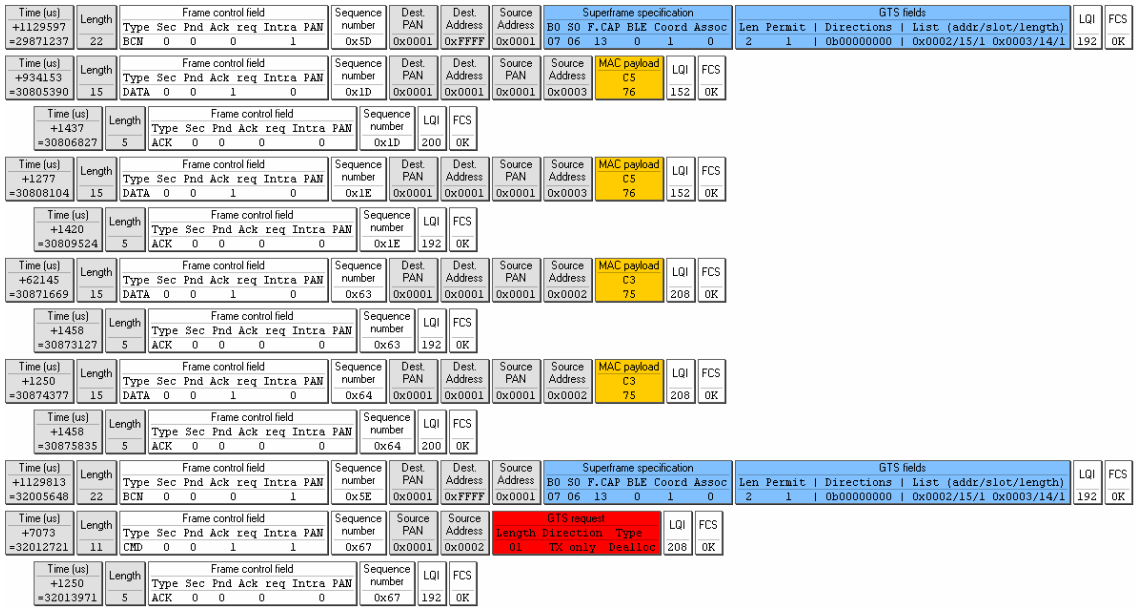


Figure 54 - GTSManagementExample component graph.

To complete this example there must be a PAN coordinator device, with an id 1, and several devices. The PAN coordinator will accept GTS requests up to 7. The devices will try to allocate a GTS time slot to send data. The allocation will last for 10 superframe periods after which the device will deallocate the time slot. During the period of the allocation the device will light the green led. The following sniffer output shows this interaction.


Time (us) | Length | Frame control field | Sequence number | Dest. PAN | Dest. Address | Source Address | Superframe specification | GTS fields | LQI | FCS
Type Sec Pnd Ack req Intra PAN
BO SO F.CAP BLE Coord Assoc
Len Permit
GTS request
Length Direction Type
Source PAN
Source Address
MAC payload
Directions | List (addr/slot/length)
+2132815 =10664073 15 BCN 0 0 0 1 0x54 0x0001 0xFFFF 0x0001 07 06 15 0 1 0 0 1 192 OK
+339754 =11003827 11 CMD 0 0 1 1 0x52 0x0001 0x0002 01 TX only Alloc 208 OK
+1435 =11005262 5 ACK 0 0 0 0 0x52 196 OK
+1791989 =12797251 19 BCN 0 0 0 1 0x55 0x0001 0xFFFF 0x0001 07 06 14 0 1 0 1 1 0b00000000 0x0002/15/1 188 OK
+999668 =13796919 15 DATA 0 0 1 0 0x53 0x0001 0x0001 0x0001 0x0002 F7 15 208 OK
+1406 =13798325 5 ACK 0 0 0 0 0x53 188 OK
+1012379 =14810704 11 CMD 0 0 1 1 0x10 0x0001 0x0003 01 TX only Alloc 144 OK
+1168 =14811872 5 ACK 0 0 0 0 0x10 212 OK
+118958 =14930830 19 BCN 0 0 0 1 0x56 0x0001 0xFFFF 0x0001 07 06 14 0 1 0 1 1 0b00000000 0x0002/15/1 192 OK
+999678 =15930508 15 DATA 0 0 1 0 0x54 0x0001 0x0001 0x0001 0x0002 28 57 208 OK
+1398 =15931906 5 ACK 0 0 0 0 0x54 192 OK
+1294 =15933200 15 DATA 0 0 1 0 0x55 0x0001 0x0001 0x0001 0x0002 28 57 208 OK
+1410 =15934610 5 ACK 0 0 0 0 0x55 200 OK
+1129881 =17064491 22 BCN 0 0 0 1 0x57 0x0001 0xFFFF 0x0001 07 06 13 0 1 0 2 1 0b00000000 0x0002/15/1 0x0003/14/1 200 OK

•••


Time (us) | Length | Frame control field | Sequence number | Dest. PAN | Dest. Address | Source Address | Superframe specification | GTS fields | LQI | FCS
Type Sec Pnd Ack req Intra PAN
BO SO F.CAP BLE Coord Assoc
Len Permit
GTS request
Length Direction Type
Source PAN
Source Address
MAC payload
Directions | List (addr/slot/length)
+1129597 =29871237 22 BCN 0 0 0 1 0x5D 0x0001 0xFFFF 0x0001 07 06 13 0 1 0 2 1 0b00000000 0x0002/15/1 0x0003/14/1 192 OK
+934153 =30805390 15 DATA 0 0 1 0 0x1D 0x0001 0x0001 0x0001 0x0003 C5 76 152 OK
+1437 =30806827 5 ACK 0 0 0 0 0x1D 200 OK
+1277 =30808104 15 DATA 0 0 1 0 0x1E 0x0001 0x0001 0x0001 0x0003 C5 76 152 OK
+1420 =30809524 5 ACK 0 0 0 0 0x1E 192 OK
+62145 =30871669 15 DATA 0 0 1 0 0x63 0x0001 0x0001 0x0001 0x0002 C3 75 208 OK
+1458 =30873127 5 ACK 0 0 0 0 0x63 192 OK
+1250 =30874377 15 DATA 0 0 1 0 0x64 0x0001 0x0001 0x0001 0x0002 C3 75 208 OK
+1458 =30875835 5 ACK 0 0 0 0 0x64 200 OK
+1129813 =32005648 22 BCN 0 0 0 1 0x5E 0x0001 0xFFFF 0x0001 07 06 13 0 1 0 2 1 0b00000000 0x0002/15/1 0x0003/14/1 192 OK
+7073 =32012721 11 CMD 0 0 1 1 0x67 0x0001 0x0002 01 TX only Dealloc 208 OK
+1250 =32013971 5 ACK 0 0 0 0 0x67 192 OK

•••

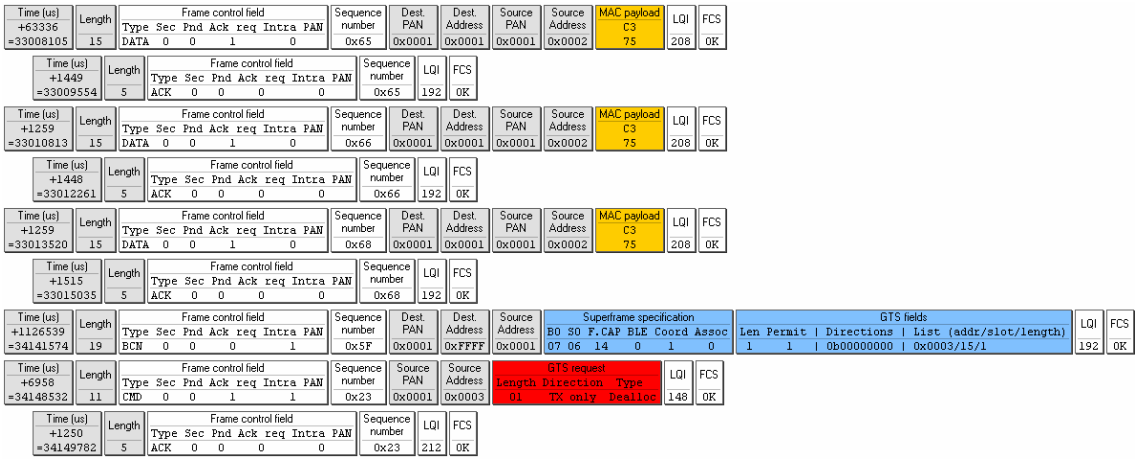


Figure 55 - GTSManagementExample sniffer output.

4.3. DataSendExample application

These simple applications demonstrate the different forms to send a data packet with several types of transmission options combinations. In this application the devices already have a short address meaning they are associated with the PAN coordinator. When the application starts the short address and the PANId is assigned to the device and a repeat timer starts. On each execution of the timer there are two different operation modes depending if the device is the coordinator or not. The application starts to send a message by issuing the *MCPS_DATA.request* primitive. The transmit options or *TxOptions* parameter, last argument of the primitive, define the transmission options for the data frame, allowing the frame to be send in the GTS or during the CAP period using the CSMA/CA or like an indirect transmission. The frame can also be send with an acknowledgment request. The function *set_txoptions(ack, gts, indirect_transmission, security)* is used to build the TxOptions 8 bit variable.

This application is linked directly to the MAC layer. The next figure illustrates the component wiring to the Mac component.

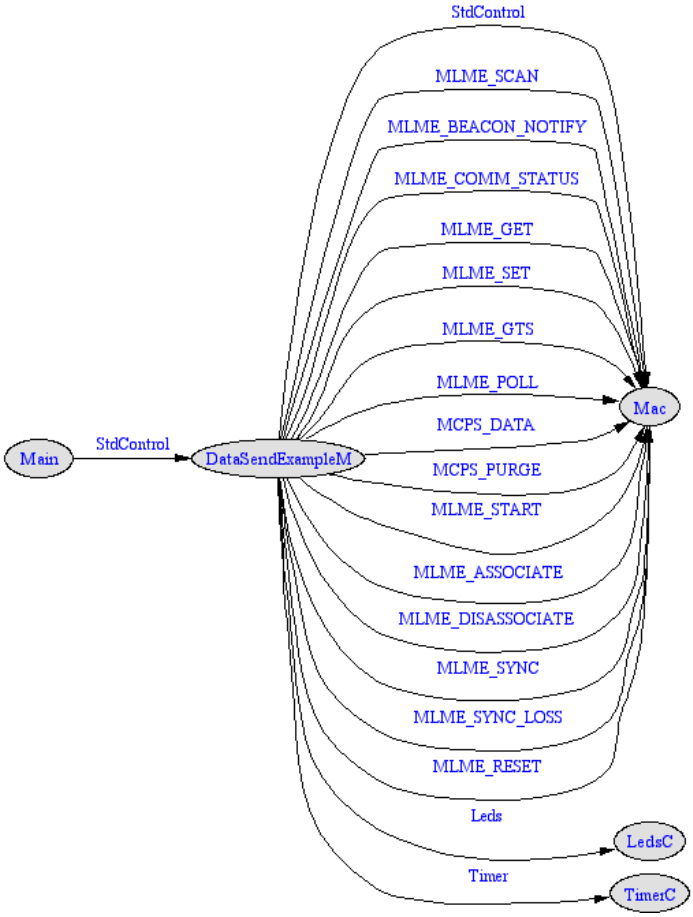


Figure 56 - DataSendExample component graph.

To complete this example there must be a PAN coordinator device, with an id 1, and up to three normal devices with an id from 2 to 4. The PAN coordinator will send data packets indirectly. The device descriptors will show in the pending addresses fields of the beacon. The normal devices will send periodic data packets and if their address is in the pending addresses descriptor of the beacon, they will request the data packet. Every time the primitive MCPS_DATA.request is issued by the MAC upper layer the green led will toggle and when a message is received the red led will toggle. The following sniffer output shows this interaction.

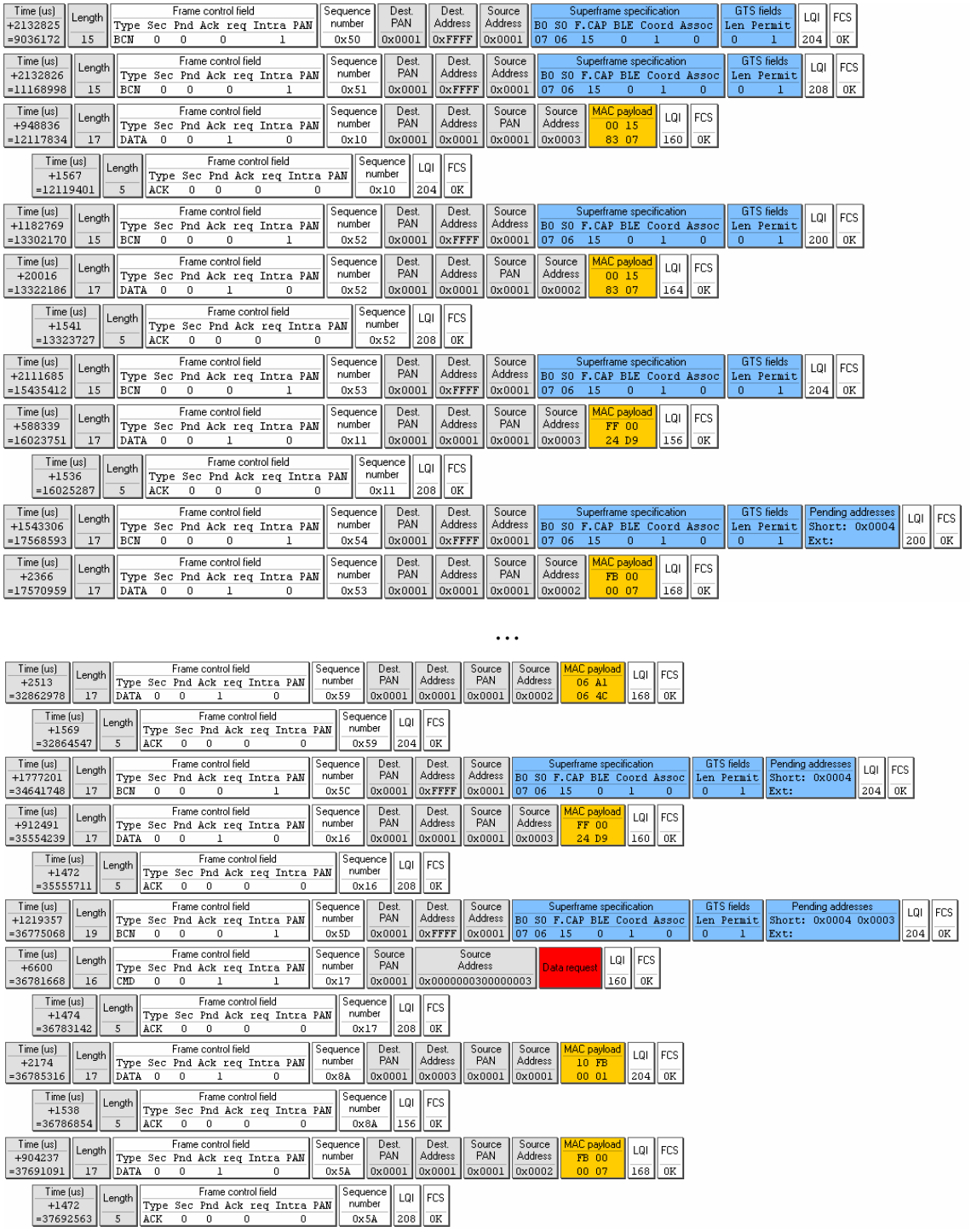


Figure 57 - DataSendExample sniffer output

4.4. SimpleRoutingExample application

This simple application demonstrates how to route data messages in a cluster tree topology. Each device sends data messages to the PAN coordinator with the first 2 bytes of the data payload as a routing field with the destination address of the desired device. When the PAN coordinator receives the data frame, it will read the payload and create a new data frame with the destination source address of the short address located

in the 2 bytes of the data payload. The coordinator will insert in the data payload the number of routed packets. The device already has a manually assigned short address. This application is linked directly to the MAC layer. The next figure illustrates the component wiring to the Mac component.

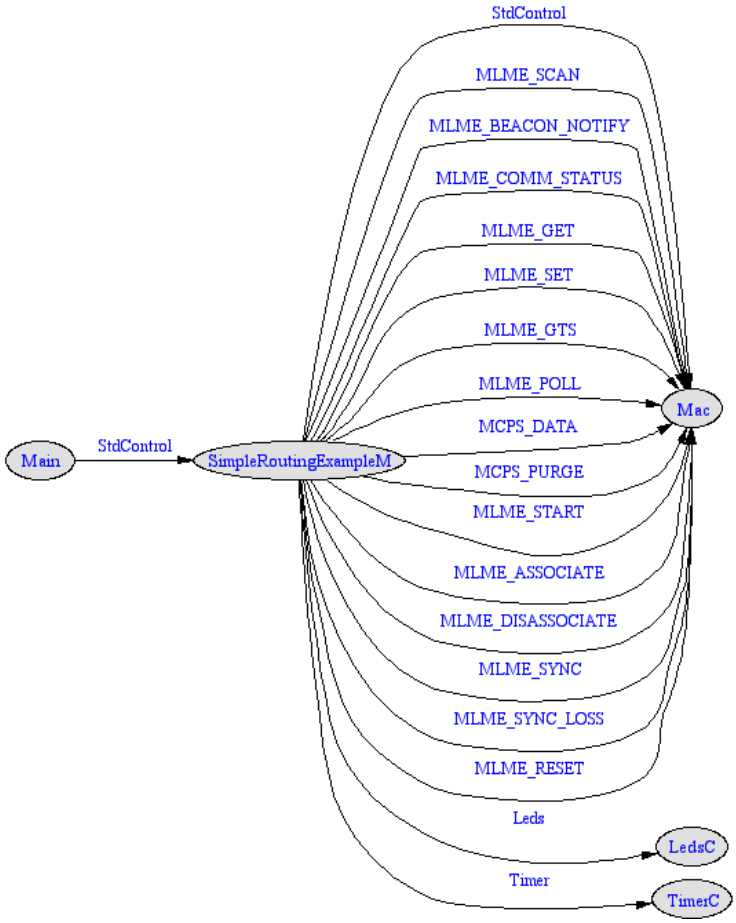


Figure 58 -SimpleRoutingExample component graph.

To complete this example there must be a PAN coordinator device, with an id 1, and two normal devices one with an id 2 and 3. If the device has an id of 2 it will try to send data messages to the coordinator, toggling the green led for each packet send. The coordinator will read the data payload and will send a packet to the mote id 3. This mote will toggle the red led for each packet received.
The following sniffer output shows this interaction.

Figure 59 - SimpleRoutingExample sniffer output.

5. References

[1] IEEE 802.15.4 Standard-2003, "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)", IEEE-SA Standards Board, 2003.

[2] D. Gay, P. Levis, R. Behren, M. Welsh, E. Brewer, D. Culler, “The nesC Language: A Holistic Approach to Networked Embedded Systems”, in PLDI’03.

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[4] Crossbow Technologies INC. http://www.xbow.com

[5] A. Koubaa , M. Alves, E. Tovar, “Lower Protocol Layers for Wireless Sensor Networks: A Survey”, IPP-HURRAY Technical Report, HURRAY-TR-051101, Nov 2005.

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http://www.chipcon.com