Design and implementation of IEEE802.15.7-compliant services in Visible-light Personal Area Networks composed by low-cost embedded systems

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Project work done at TeCIP, Scuola Superiore S'Anna

Outline

- Visible Light Communication
- IEEE802.15.7
- Thesis goal
- Adopted HW / SW
- Reference model
- Optical Transceiver
- uLight
- Performance evaluation
- Conclusions

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VLC / Introduzione

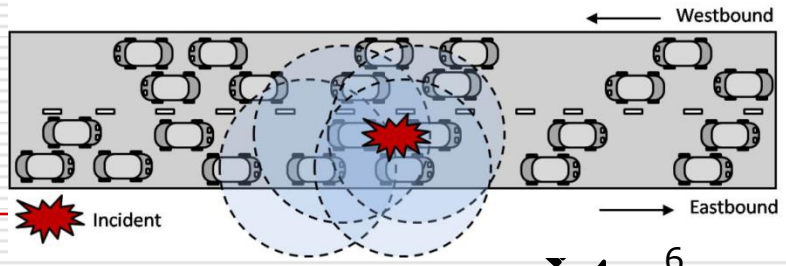
- Communication technology that uses visible light (400 THz – 800 THz) as the transmission medium
  - Unlicensed spectrum
  - No electromagnetic interference
  - High spatial reuse
  - Security
  - Emitting devices are everywhere
- Transmitters: LEDs
- Receivers: Photodiodes, CMOS sensors
- Channel: free space (Line of Sight)

VLC / Applications

- Indoor Networking Systems
- Indoor Positioning Systems
- Underwater VLC
- Intelligent Transportation Systems

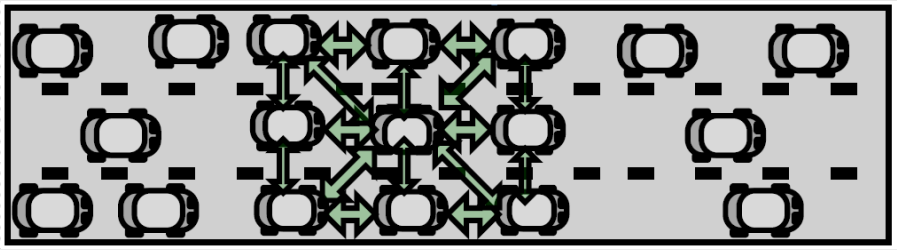
Intelligent Transportation Systems

- Integration among transport services, traffic management, road pricing, safety-critical vehicular systems, systems oriented to infomobility and comfort applications targeted to drivers and citizens
- Cooperative-ITS
  - Vehicle-to-Vehicle (V2V),
  - Vehicle-to-Infrastructure(V2I),
  - Infrastructure-to-Infrastructure (I2I)
- IEEE802.11p-based protocols are used
  - Wireless ad-hoc networks
  - Problem: broadcast storm



ITS e VLC

- Traffic signals and vehicles gradually changing from electric bulbs to LED lights
  - Retrofitting semaphores and car headlights to enable V2V, V2I, and I2I communication
  - Directional light addresses broadcast storm problems



- Outdoor VLC challenges:
  - Relative mobility disrupts LoS
    - Optimize lighting positioning
  - Sun light, artificial lights
    - Use optical filters and optimized electronics

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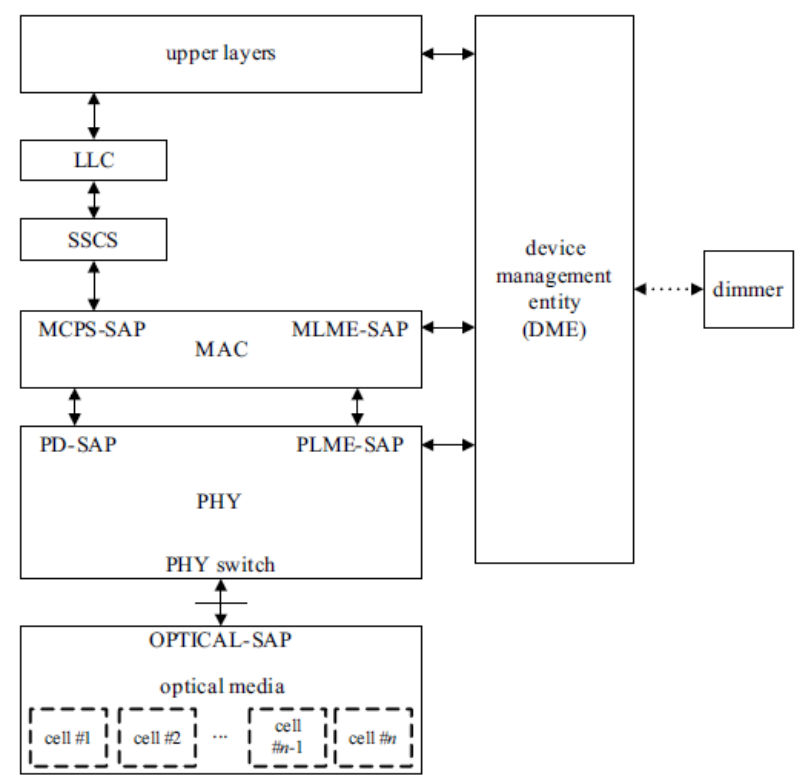
IEEE802.15.7



- Standard for Visible-light Personal Area Networks (VPANs)
- Defines MAC and PHY layers
- 3 physical layers
  - PHY I (outdoor), PHY II e PHY III (indoor)
- Data rate:
  - 11.67 – 266 kb/s (PHY I)
  - 1.25 – 96 Mb/s (PHY II, PHY III)
- Topologies: star, p2p, broadcast
- Addressing: 64 bit (extended unique MAC address), 16 bit (short MAC address)
- Beaconless and beacon-enabled mode
- Visibility support (infrastructure)
- Dimming and flicker-mitigation support

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Thesis goal

- Developing a VLC unidirectional prototype
  - Low-cost
  - Off-the-shelf components
  - Standard-compliant (IEEE802.15.7 MAC e PHY I)

- Vision:

  Developing scalable and pervasive units eligible to be easily integrated in more complex systems like ITS.

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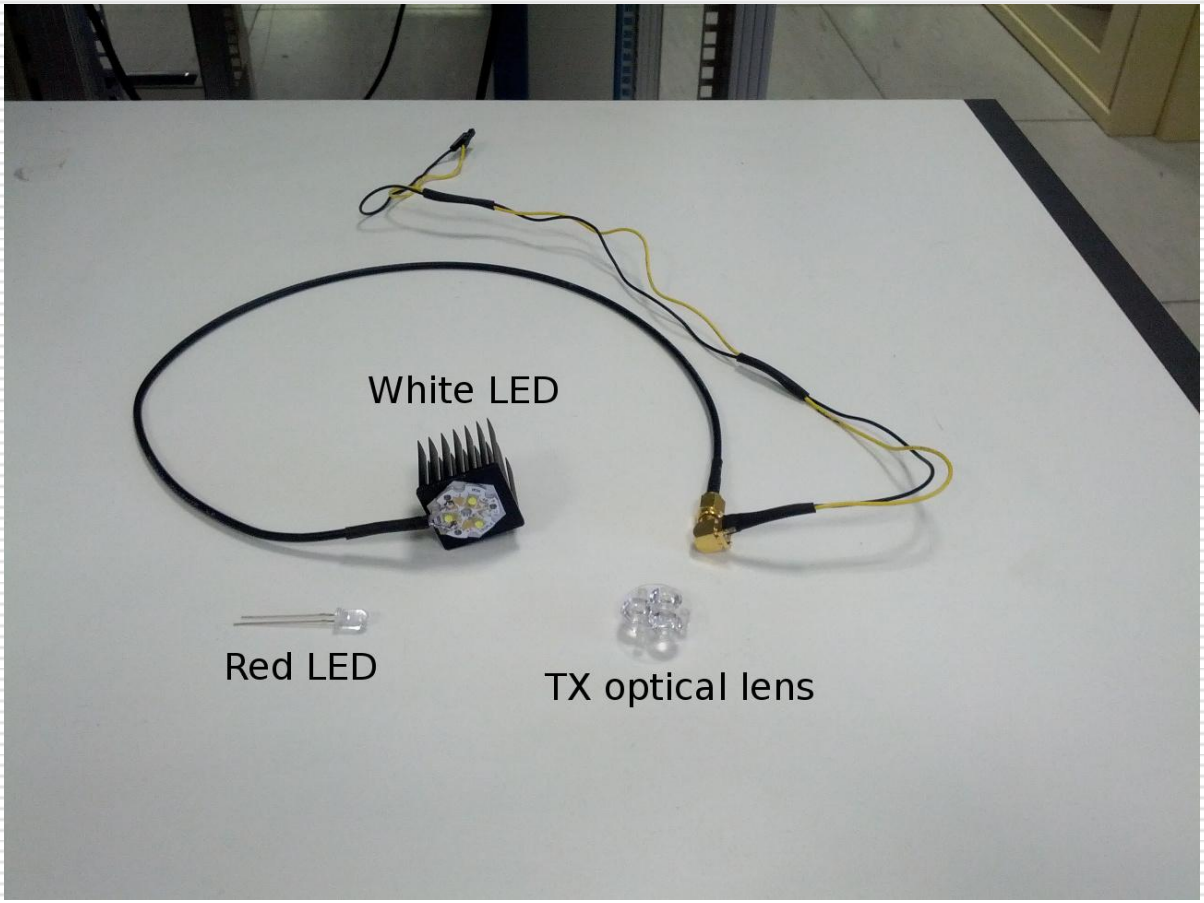
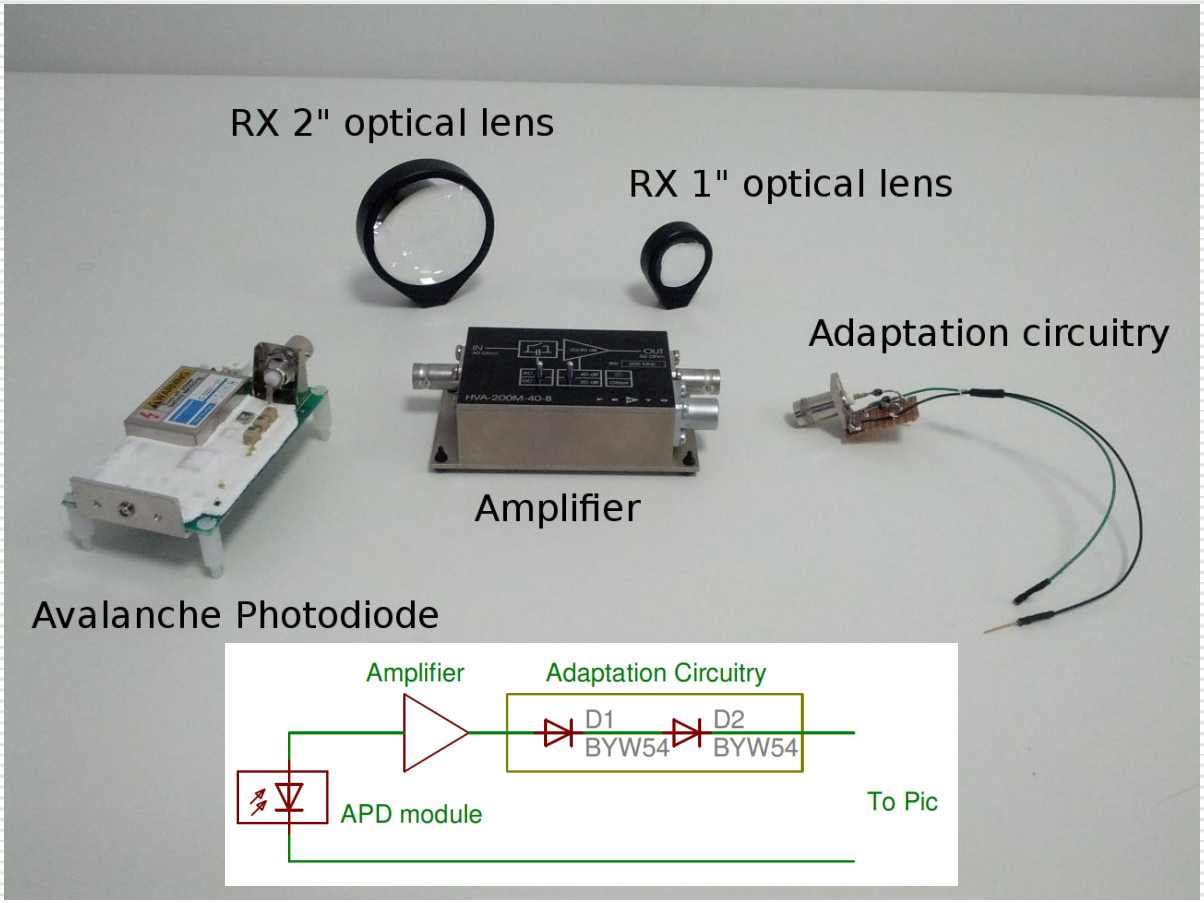
SEED-EYE

- WSN platform
- Developed by Scuola Superiore Sant'Anna and Evidence Srl
- MCU: Microchip PIC32MX795F512L
  - 80 MIPS
  - 512 K Flash Memory, 128 K RAM
  - Interfacce: SPI, UART, I2C, CAN
- IEEE802.15.4 Interface: MRF24J40B
  - Not used in this prototype
  - Possibilità di use R/F as a second channel

Optical Components / Transmission



Optical Components / Reception



Adopted software

- Open source Real-Time Operative System(RTOS)
- Highly modular
- Portable APIs for different microcontrollers

- Official Microchip development environment
- Programming of the SEED-EYEs without OS

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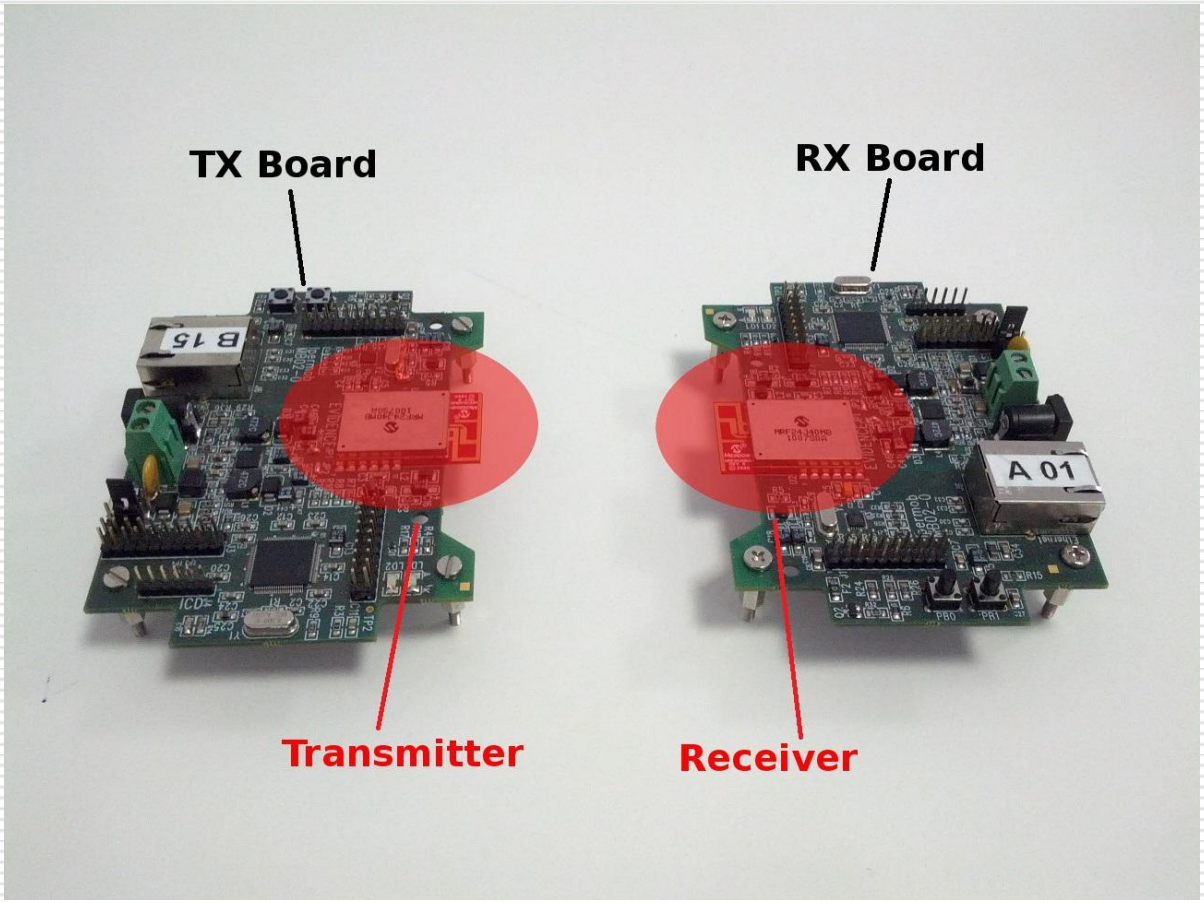
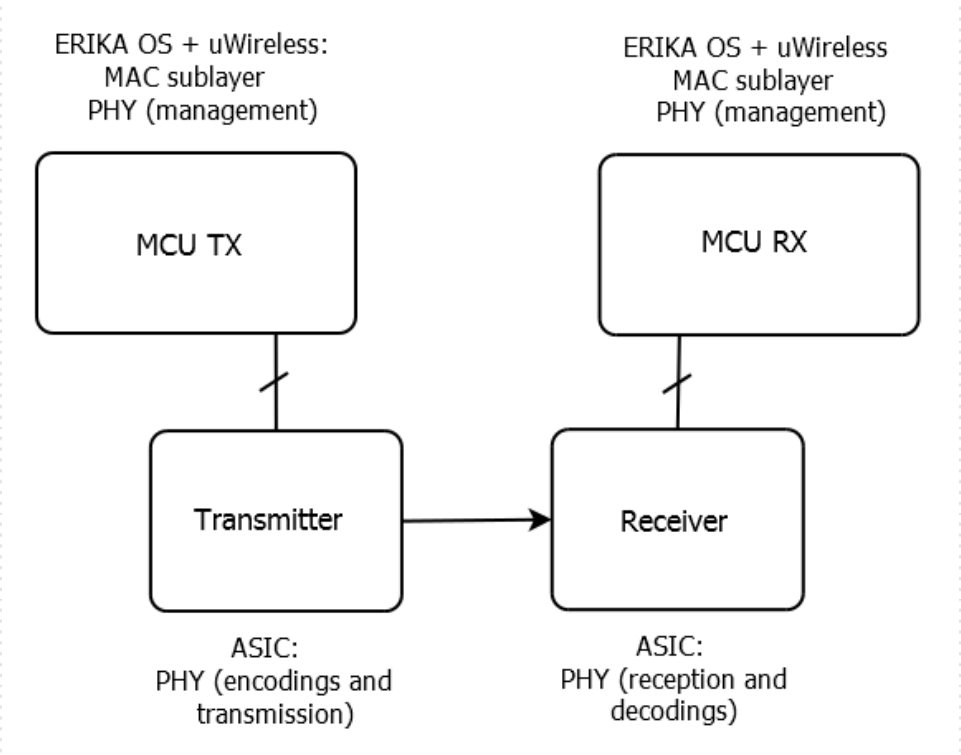
Step 1:
Unidirectional custom 802.15.4 system



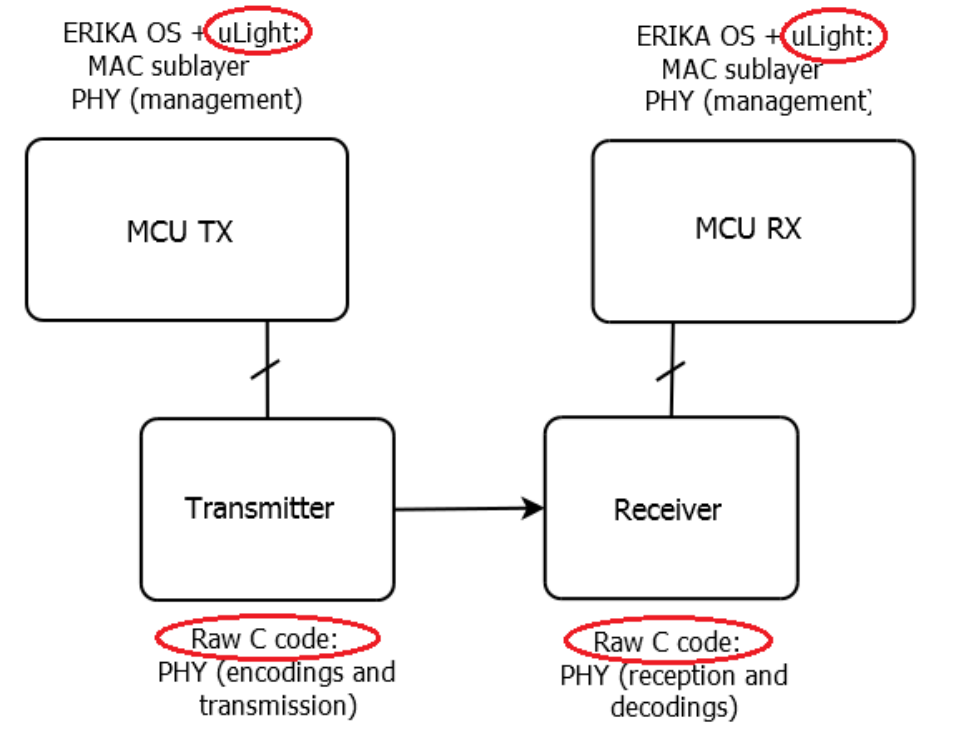
Step 1:
Custom 802.15.4 system / Functional blocks

- One possible partitioning of functions among boards and transceivers:

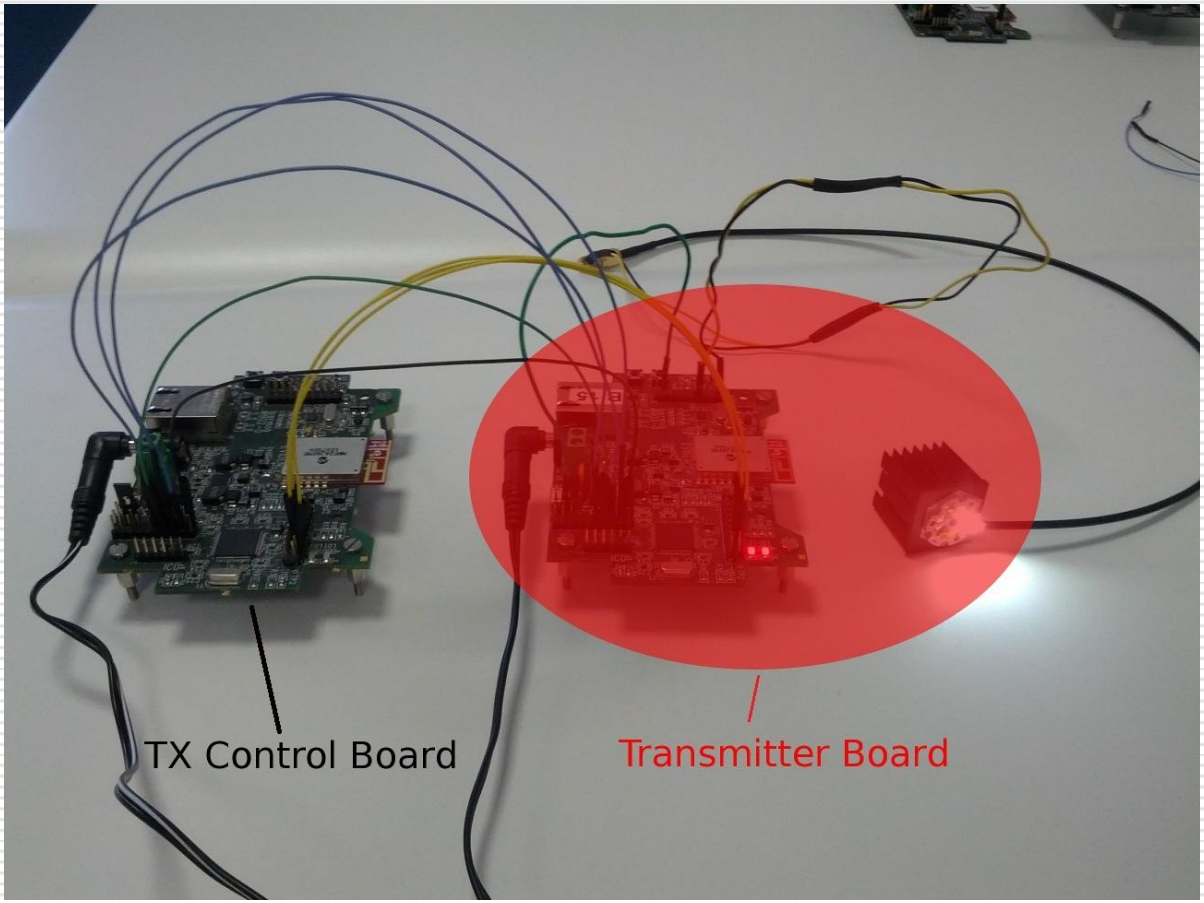


Step 2:
Custom 802.15.7 system / Functional blocks

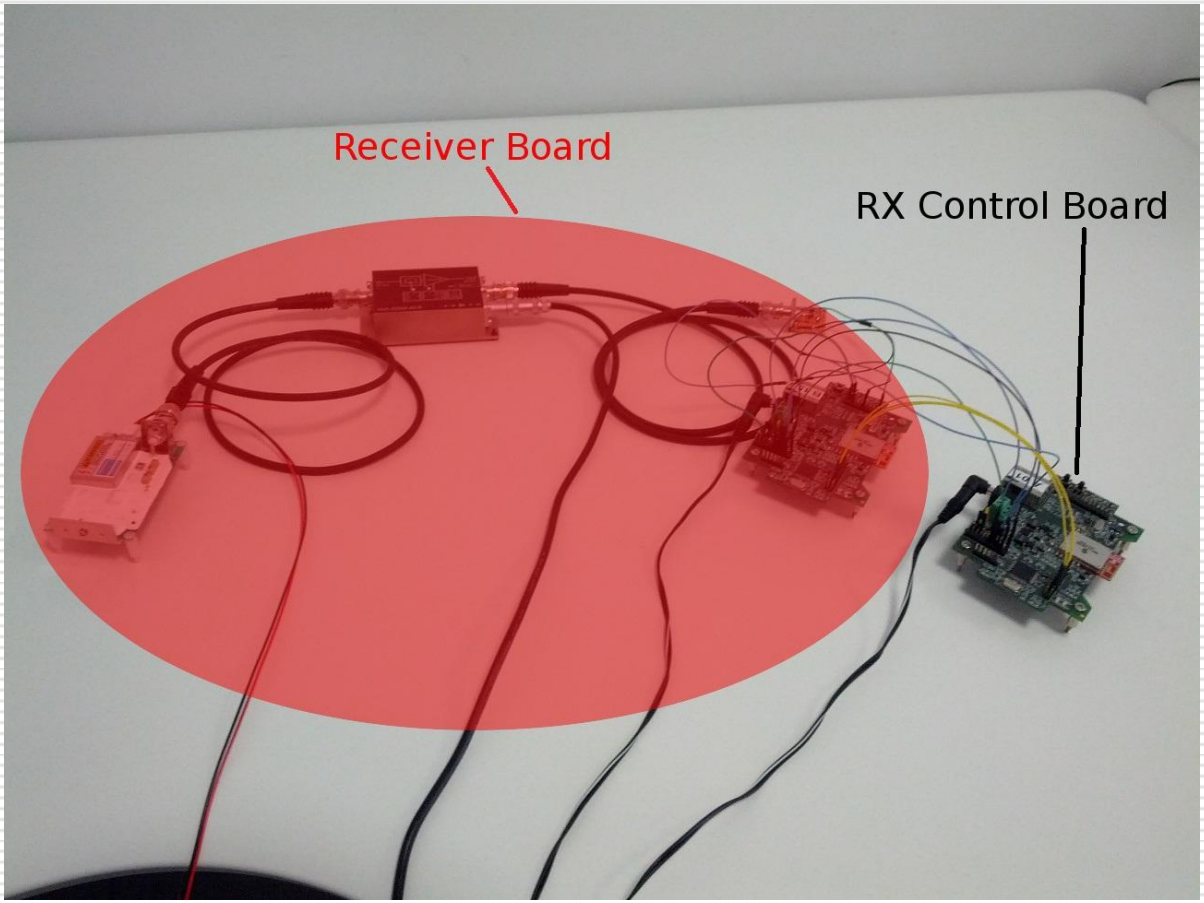
- Mapping of the 802.15.4 system functional blocks into a new 802.15.7 system:



802.15.7 System/ Transmitter



802.15.7 System / Receiver



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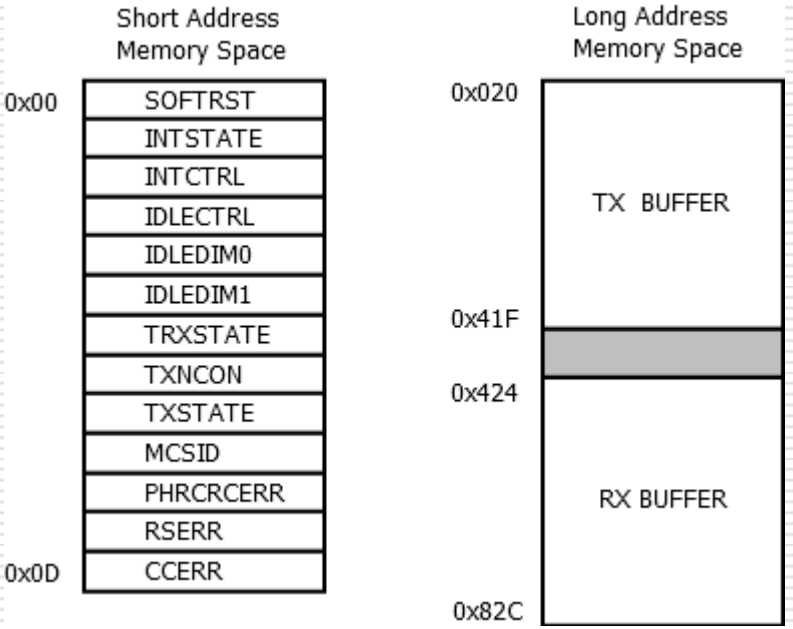
Optical Transceiver / Introduction

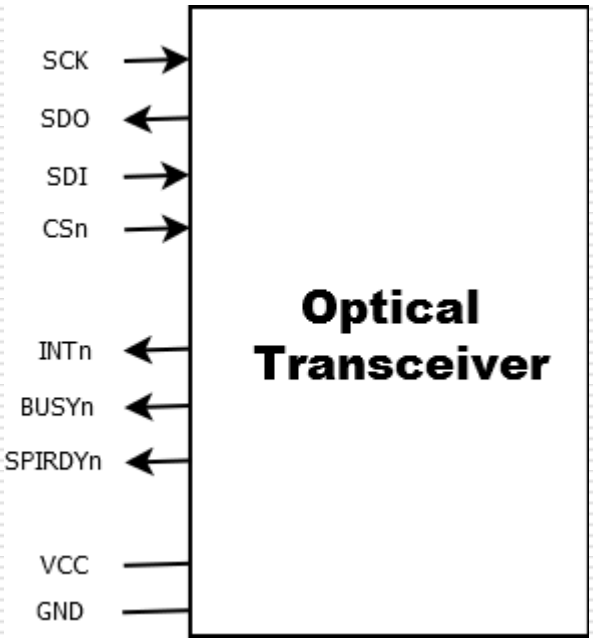
- Software-based optical transmitter / receiver
- Implemented by the Transceiver Boards
- Optical transceiver tasks:
  1. Interface with the Control Board
     - Inspired by the MRF24J40B interface to the PIC
  2. Encode / decode data
  3. Transmit/ receive data with constrained timing

Optical Transceiver / Interface

- Registers and buffers:

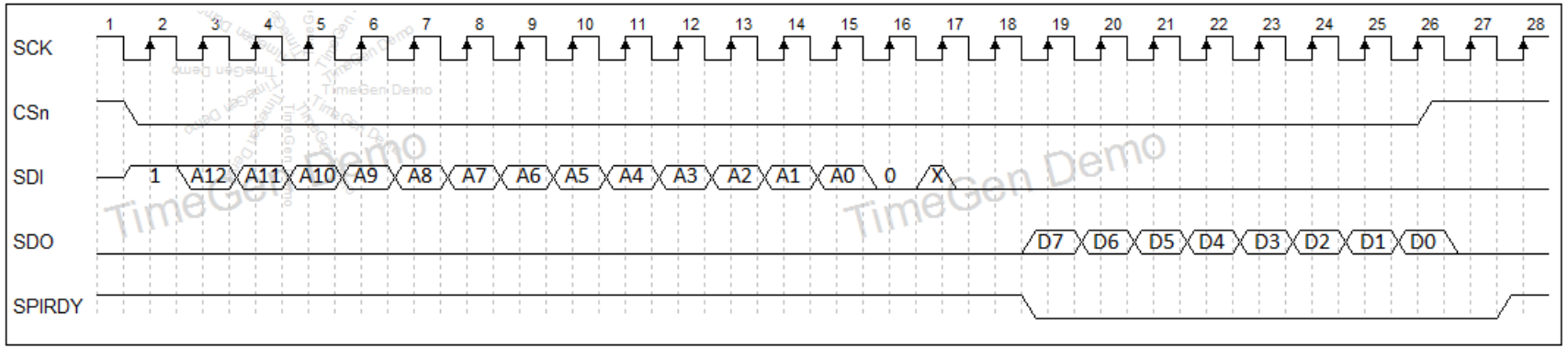


- Pinout diagram:

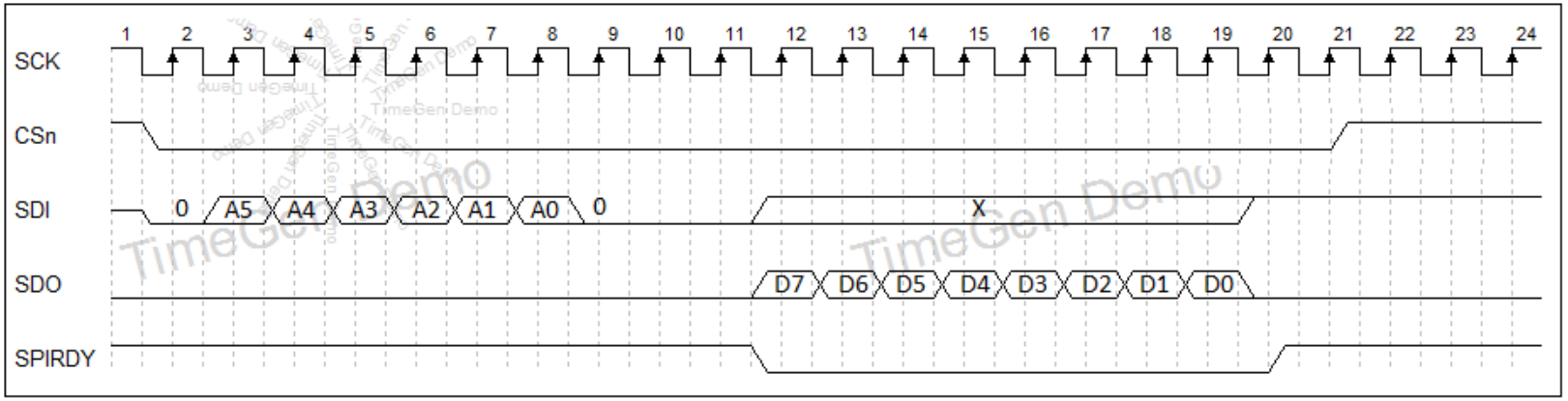


Optical Transceiver /
Communication protocol with the Control Board

LONG ADDRESS READ



SHORT ADDRESS READ

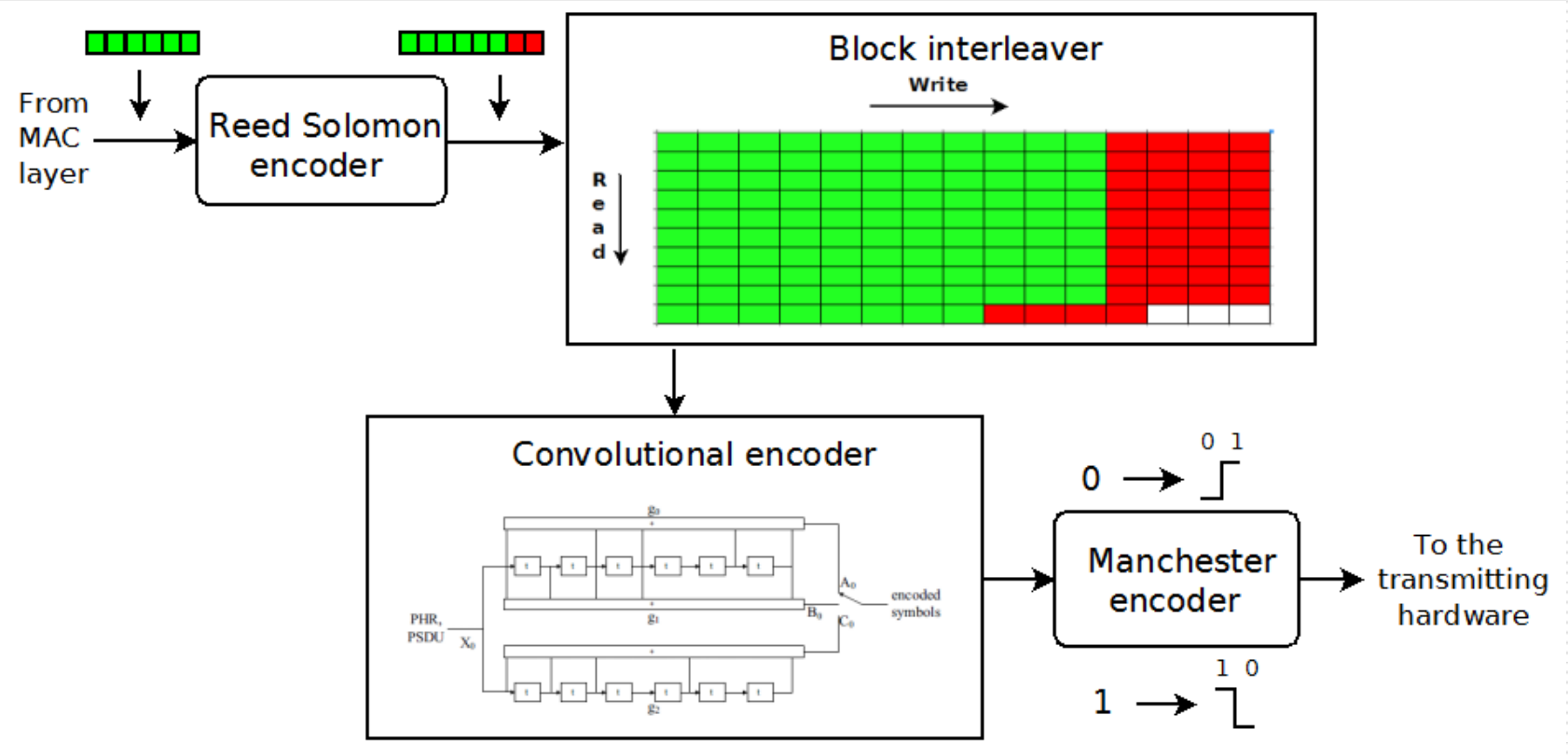


Optical Transceiver / PHY I data rates

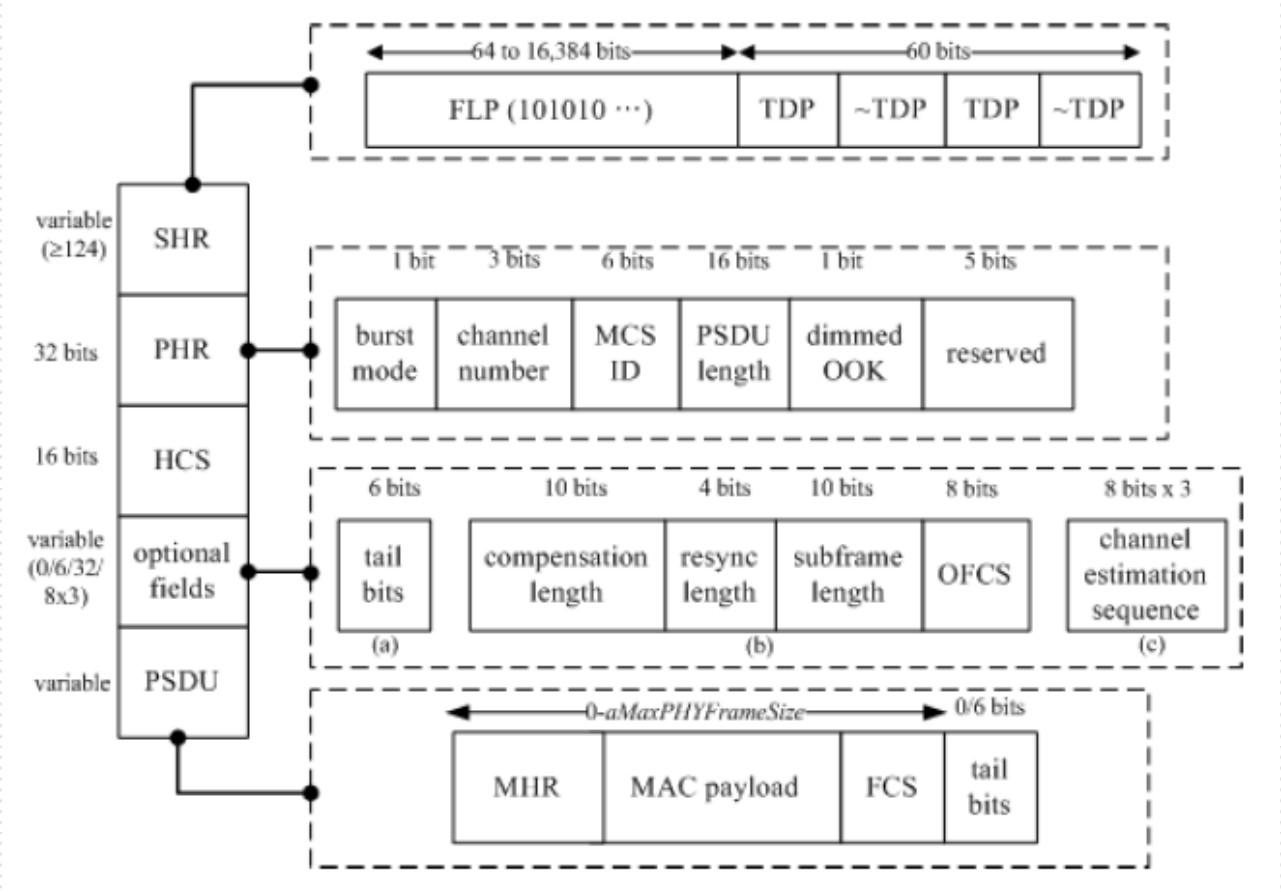
Modulation	RLL code	Optical clock rate	FEC		Data rate
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200 kHz	(15,7)	1/4	11.67 kb/s
			(15,11)	1/3	24.44 kb/s
			(15,11)	2/3	48.89 kb/s
			(15,11)	none	73.3 kb/s
			none	none	100 kb/s
VPPM	4B6B	400 kHz	(15,2)	none	35.56 kb/s
			(15,4)	none	71.11 kb/s
			(15,7)	none	124.4 kb/s
			none	none	266.6 kb/s

- Header always sent at 11.67 kb/s

Optical Transceiver / Encodings



Optical Transceiver / PPDU



Optical Transceiver / Communication

- LED directly connected to SPI:
  - Data is copied inside an SPI buffer within interrupt service routines
  - An hardware clock running at 200 kHz (generated by a timer) lets the SPI transmit data autonomously at a steady frequency
  - Idle pattern used for visibility functions (infrastructure lights)
- Photodiode connected to SPI though the amplifier and the adaptation circuitry
  - The receiver must first synchronize to the transmitter by using the preamble at the beginning of a physical layer packet
  - Data received within interrupt service routines:
    1. Receive header
    2. Decode header while receiving the payload

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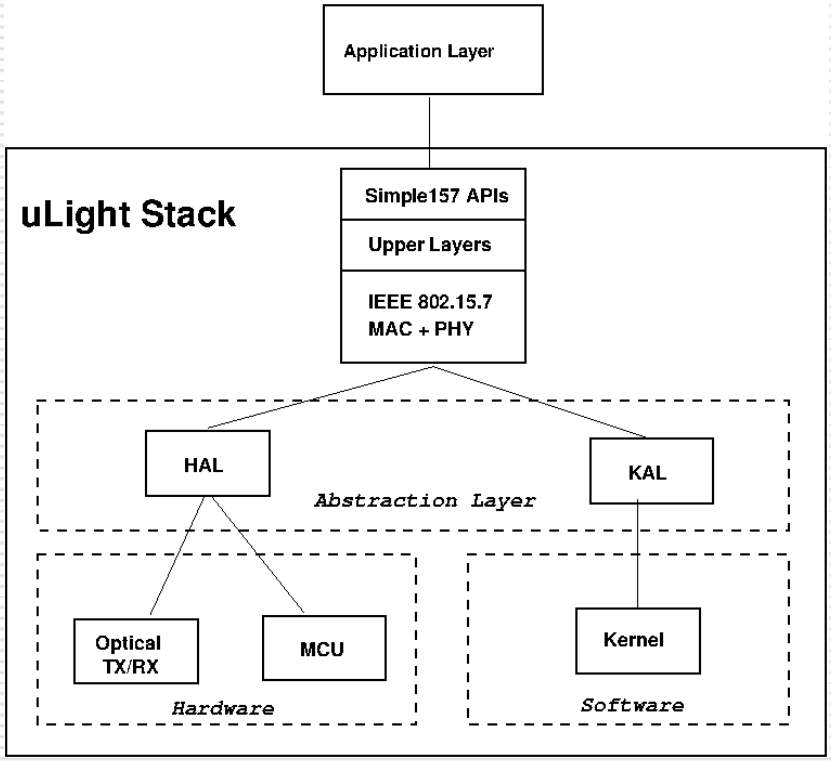
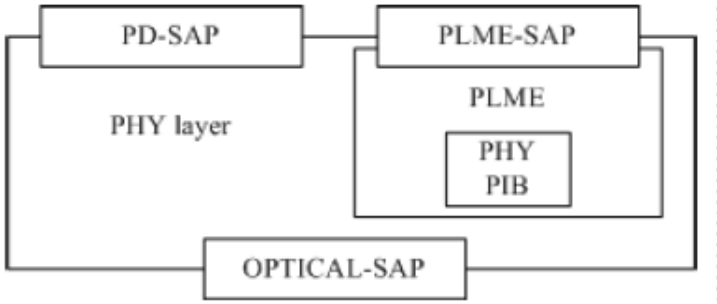
uLight / Introduction

- Stack implementing MAC sublayer and PHY management tasks
- Implemented by the Control Boards
- Requires drivers for controlling the Trasceiver Board
- Shipped with a high level library (Simple157)
- Inspired by uWireless (802.15.4 for ERIKA OS) Architercure



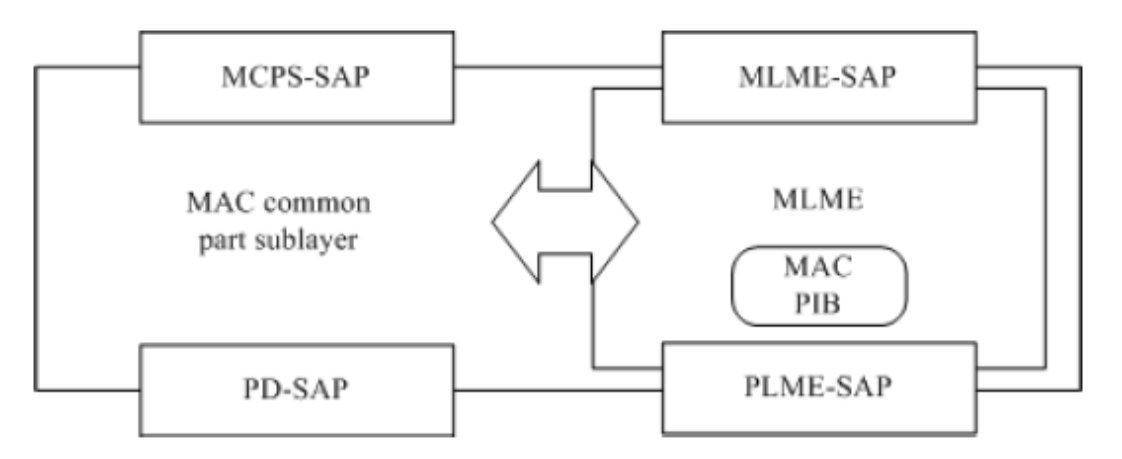
uLight / Implemented PHY



PD-SAP primitive	Request	Confirm	Indication
PD-DATA	9.3.1	9.3.2	9.3.3

PLME-SAP primitive	Request	Confirm
PLME-CCA	9.2.1	9.2.2
PLME-GET	9.2.3	9.2.4
PLME-SET	9.2.5	9.2.6
PLME-SET-TRX-STATE	9.2.7	9.2.8
PLME-SWITCH	9.2.9	9.2.10

uLight / Implemented MAC/ 1



MCPS-SAP primitive	Request	Confirm	Indication
MCPS-DATA	6.2.1	6.2.2	6.2.3
MCPS-PURGE	6.2.4	6.2.5	—

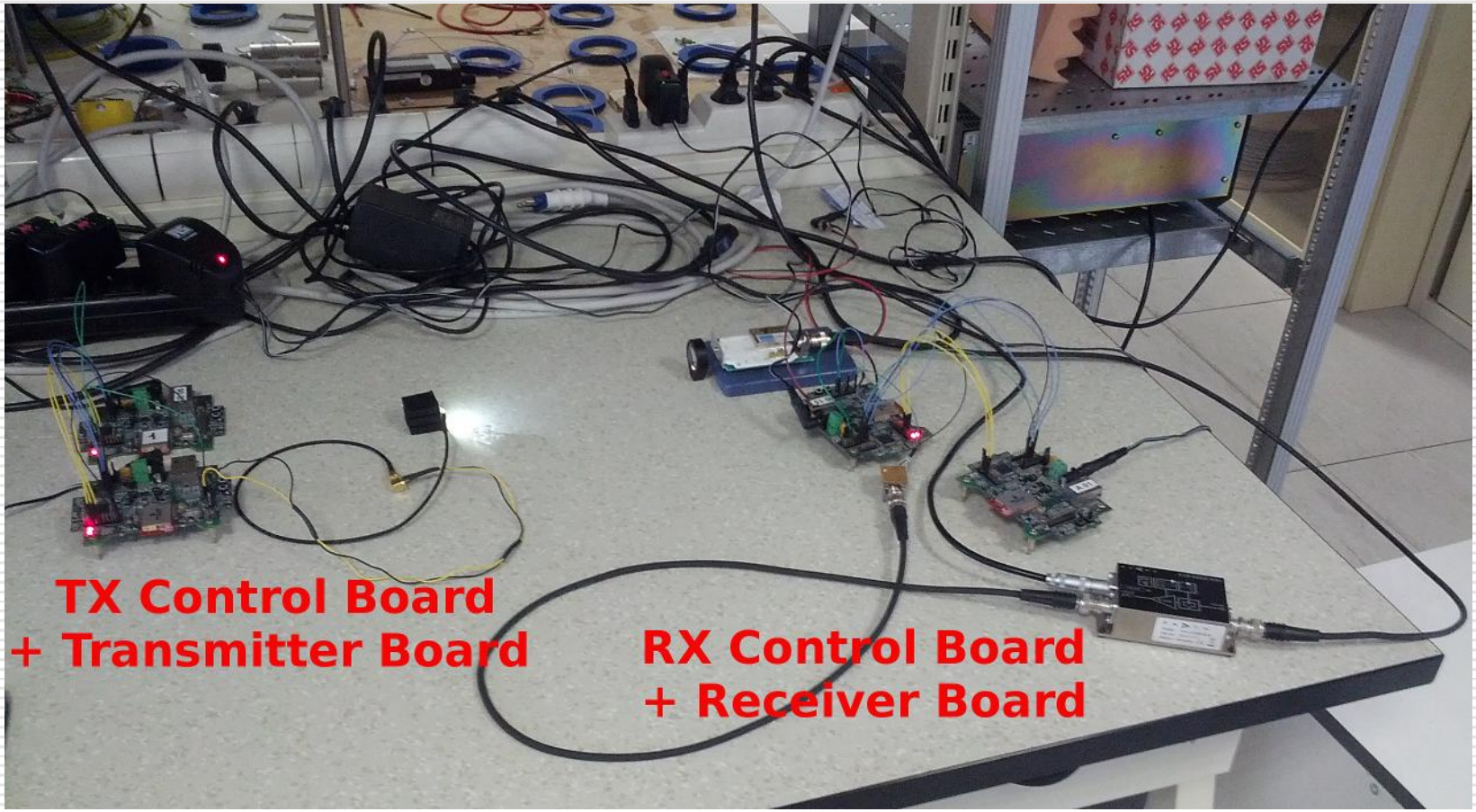
- Frame (MPDU) handling
- Addressing

uLight / Implemented MAC / 2

Name	Request	Indication	Response	Confirm
MLME-ASSOCIATE	6.3.1.1	6.3.1.2♦	6.3.1.3♦	6.3.1.4
MLME-DISASSOCIATE	6.3.2.1	6.3.2.2		6.3.2.3
MLME-BEACON-NOTIFY		6.3.3.1		
MLME-GET	6.3.4.1			6.3.4.2
MLME-GTS	6.3.5.1	6.3.5.2		6.3.5.3
MLME-RESET	6.3.6.1			6.3.6.2
MLME-RX-ENABLE	6.3.7.1			6.3.7.2
MLME-SCAN	6.3.8.1			6.3.8.2
MLME-COMM-STATUS		6.3.9.1		
MLME-SET	6.3.10.1			6.3.10.2
MLME-START	6.3.11.1♦			6.3.11.2♦
MLME-SYNC	6.3.12.1*			
MLME-SYNC-LOSS		6.3.13.1		
MLME-POLL	6.3.14.1			6.3.14.2

- VPAN start and association
- Beaconless and beacon-enabled modes

Complete System



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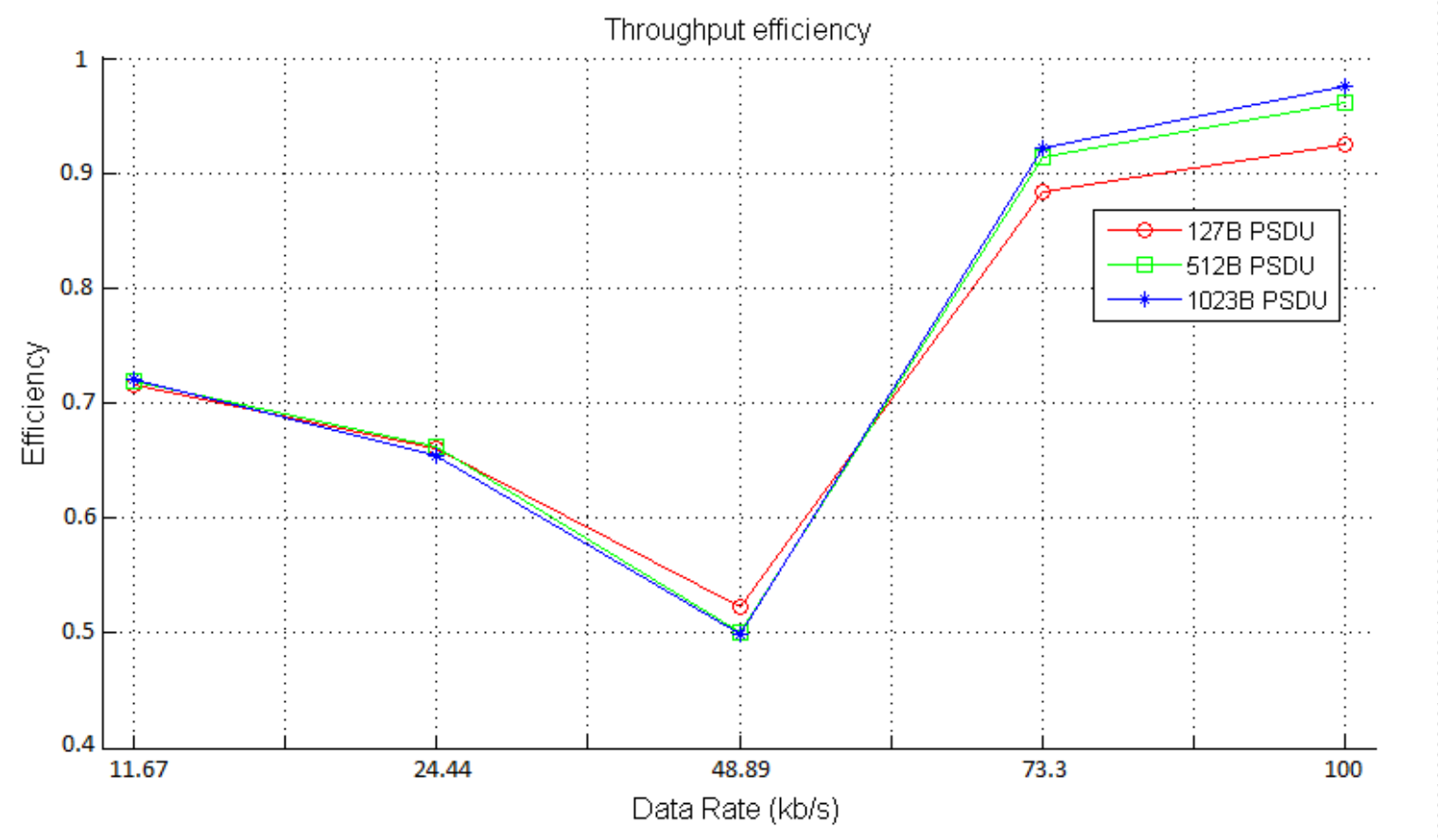
Physical Layer Throughput / 1

PSDU Data rate	PSDU length (B)	Ref. Throughput (kb/s)	Real Throughput (kb/s)
11.67 kb/s	127	11.1	7.94
	512	11.52	8.29
	1023	11.6	8.35
24.44 kb/s	127	22.09	14.6
	512	23.81	15.75
	1023	24.10	15.78
48.89 kb/s	127	40.3	21.08
	512	46.43	23.27
	1023	47.62	23.79
73.3 kb/s	127	55.55	49.08
	512	67.92	62.04
	1023	70.5	64.95
100 kb/s	127	69.64	64.38
	512	90.24	86.78
	1023	94.86	92.58

Physical Layer Throughput / 2



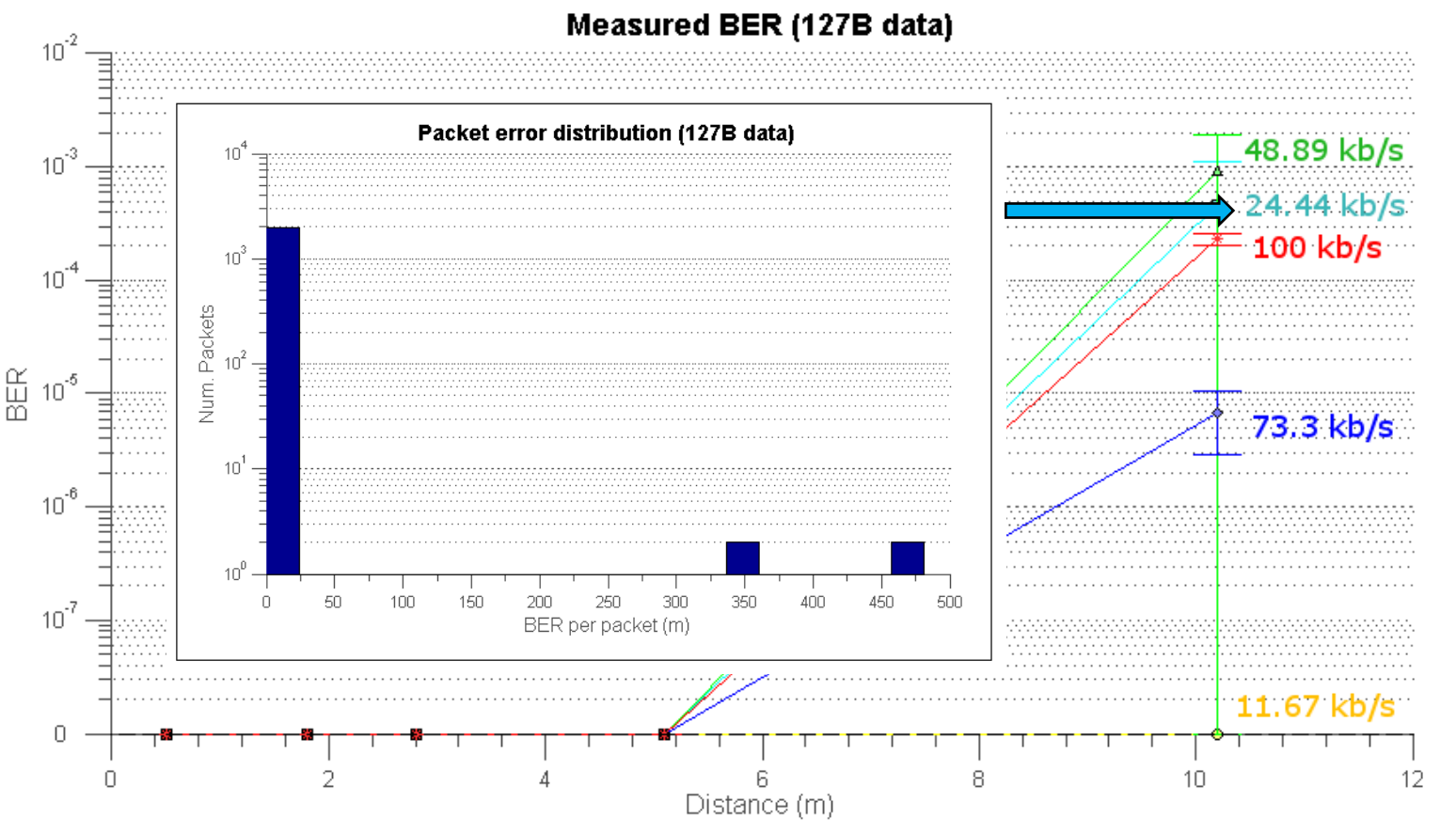
Bit Error Rate

- Measurements were taken at:
  0.5m – 1.8 m – 2.8 m – 5.1 m – 10.2 m – 11.2 m

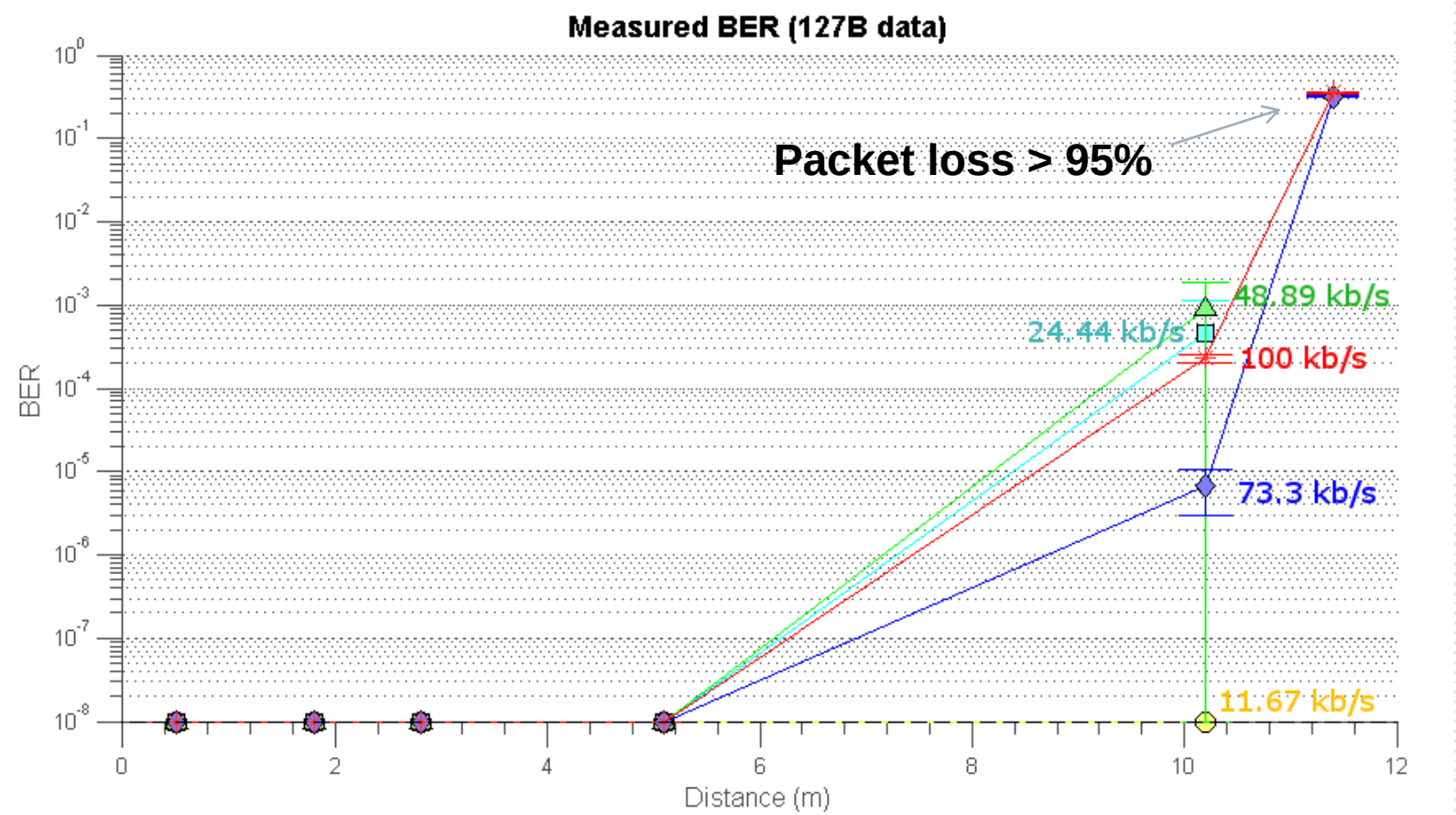
- Packet sizes (PHY payload):
  Small (127B) – Big (950B)

- Optical lenses:
  - TX: 18° divergence lens
  - RX (distance < 5.1 m): 1” lens
  - RX (distance >= 5.1 m): 2” lens

BER / Payload 127B



BER / Payload 127B / Test a 11.2 m



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Conclusions / 1

- A VLC unidirectional prototype has been implemented
- Throughput is close to the reference case when convolutional codes are not used
- BER is acceptable within 10 meters

Conclusions / 2

- BER measurements influenced by a sub-optimal alignment system
  - Photodiodes with a larger active area or telescopic systems on the receiver can inprove these measurements

- With the current hardware, only I2I systems are feasible by now
  - Better equipment allows for V2V and V2I systems to be realized

Future developments

- Complete PHY I implementation
- Porting of the Optical Transceiver on an FPGA, in order to overcome performance limitations due to the software implementation
- Design of an adaptation layer between IPv6 and IEEE802.15.7
- Multichannel systems (R/F + visible light)

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REAL TIME NETWORKS

Thank you!