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Adaptive (Intelligent) Resource Allocation in Visible Light Communication Systems

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01

Visible Light Communication - VLC

Visible Light Communication (VLC): Applications

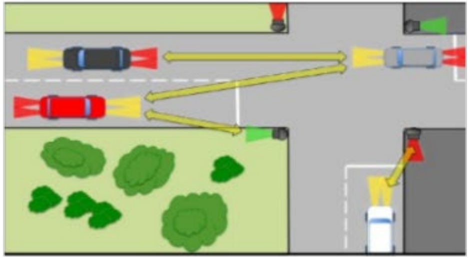
Hospitals and healthcare

Hazardous Environments

Aircraft

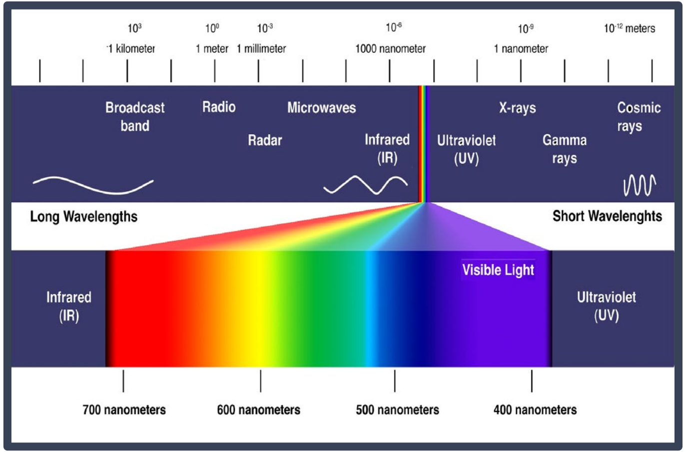
Underwater Communication

Vehicular Area Networks



Visible Light Communication (VLC)

Data communication in the visible spectrum



LEDs

for both lighting and communication

02

Adaptive Intelligent Approach for Synchronization

Main Objectives and Contributions

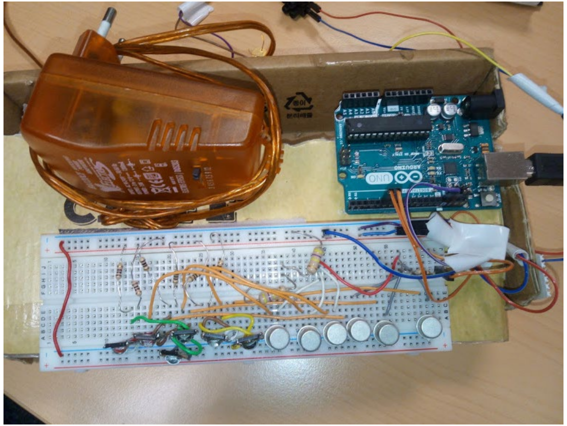
Objective: Dynamic Adapting and Context-Aware VLC System

Contributions [1]

- Analysis of the impact of preamble length for synchronization.
- Modeling of the preamble length as a multi-arm bandit problem with a Thomson Sampling approach.
- Validation of the Machine Learning approach through a software-defined testbed.

[1] A. Costanzo and V. Loscri, "A Learning Approach for Robust Carrier Recovery in Heavily Noisy Visible Light Communication," *2019 IEEE Wireless Communications and Networking Conference (WCNC)*, 2019, pp. 1-6, doi: 10.1109/WCNC.2019.8885568.

Transmitting Stage

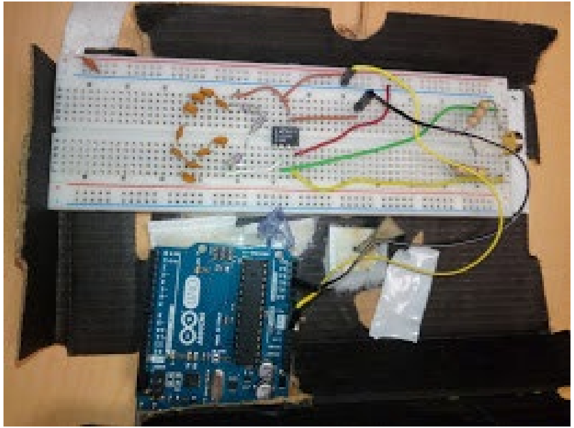


The transmitting front-end is made up of

- An array of 6 low power warm white LEDs.
- A simple driving circuit, composed of low cost transistors and resistances
- An Arduino Uno board
- A 12 V power supply, feeding the led array, is directly connected to the main 50 Hz electrical grid.
- A photo-diode dedicated to the reception of control messages is also mounted on the same box.

Total dimensions of the overall box are around 10cm x 20cm x 5 cm, excluding the power supply and the connection cable.

Receiving Stage



The receiving front-end:

- A low-cost photodiode, a trans-impedance amplifier (mainly made up by an operational amplifier, capacitors and resistances)
- An Arduino Uno board, used for receiving front-end data. Since the photodiode is used in photovoltaic mode, no additional power supplies are needed.
- A red led to send control messages toward the receiver.

Total dimensions of the prototype, are around 10cm x 20cm x 5cm.

Some Motivation Considerations

Some experimental tests:

- Different preamble lengths.
- Same transmission parameters.
- Two different light conditions:
  - Low Noise: artificial lights turned off and windows kept ajar;
  - High Noise: artificial lights turned on and open windows

Some Preliminary Experimental Results

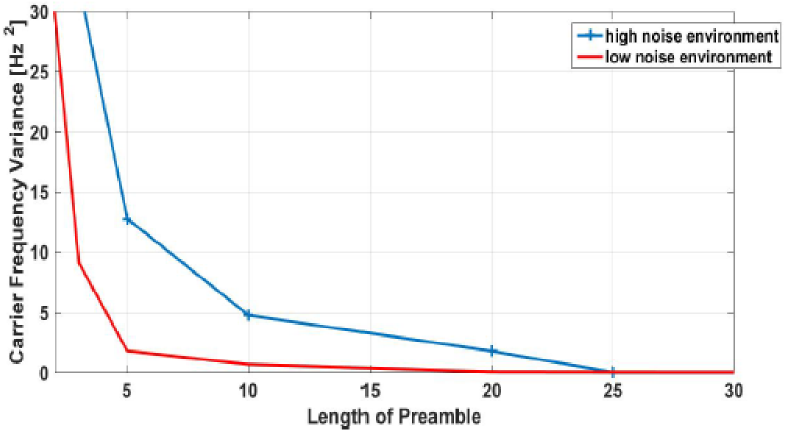


Fig: Variance of recovered central frequency carrier for different preamble lengths

f_c: carrier frequency

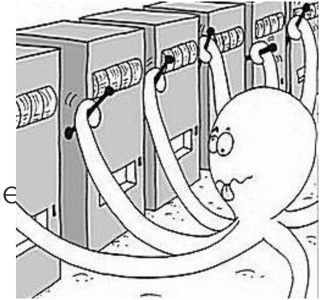
σ^2_f: carrier frequency variance

M: number of frame transmissions (M = 150)

N_p: synchronization preamble length

$$\sigma_f^2 = \frac{\sum_{k=1}^{M} (f_c - \overline{f_c})^2}{M}$$

The Dynamic Preamble Selection Algorithm (1/2)



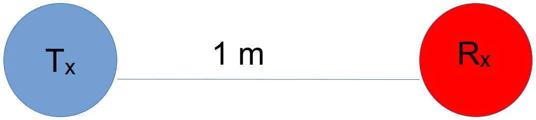
Our approach is based on Multi-Arm Bandit

- The heuristic for the exploration-exploitation dilemma is the Thomson Sampling
- We consider an agent A, representing the actions performed based on the previous observations.
- The played arm is the index of the preamble size ([(1, n=5), (2, n=10), (3, n=20), (4, n=50)])
- The trigger criterion is based on the Instantaneous Normalized Throughput T(j)
- The likelihood function

$$p_j(S_j|\mu_j) = {\mu_j}^{t_j}(1-\mu_j)^{n_j - t_j}$$

- n_j: number of times j_{th} has played after n steps;
- μ_j: expected reward of j_{th} arm;
- S_j: observation vector collecting;
- t_j: number of times the best choice is done;
- Each size selection is a Bernoulli distribution with parameter μ_j

Experimental Results (1/3)



EXPERIMENTAL PARAMETERS

Payload	3000,5000,10000 [bits] 35000,50000
Preamble Length	20, 50, 100, 200, 500, 700, 1000, 2000 [bits]
Environmental Conditions	Diffused Artificial Light Philips TL-D Xtra 18W 840 x4, $72W/m^2$
Transmitting LED	MCEEZW-A1-0000-0000K035H Warm White, $1W/m^2$
Maximum Blinking Frequency	1KHz
Receiving Photodiode	Centronic OSD15-5T 1 nA, 900 nm

Experimental Results (2/3)

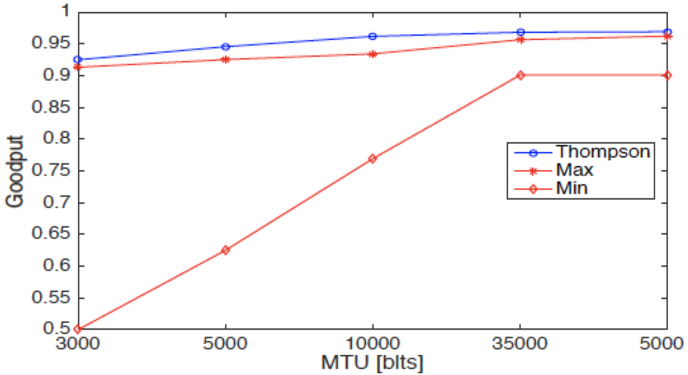


Fig. 2 Maximum, minimum and Thompson throughput with different MTU size.

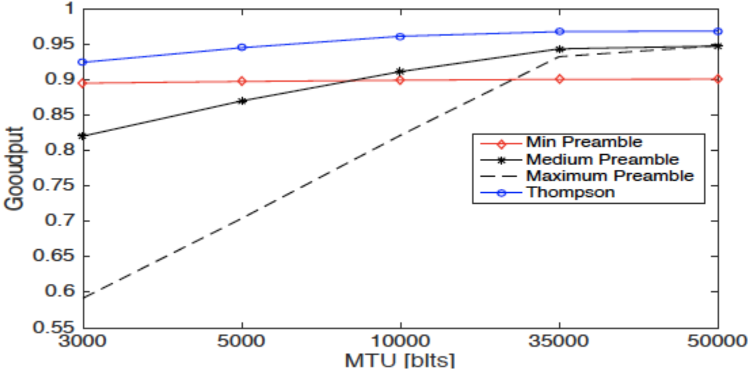


Fig. 3 Goodput evaluation for different values of preamble length. Min Preamble = 20, Medium Preamble = 500, Maximum Preamble = 2000.

Experimental Results (3/3)

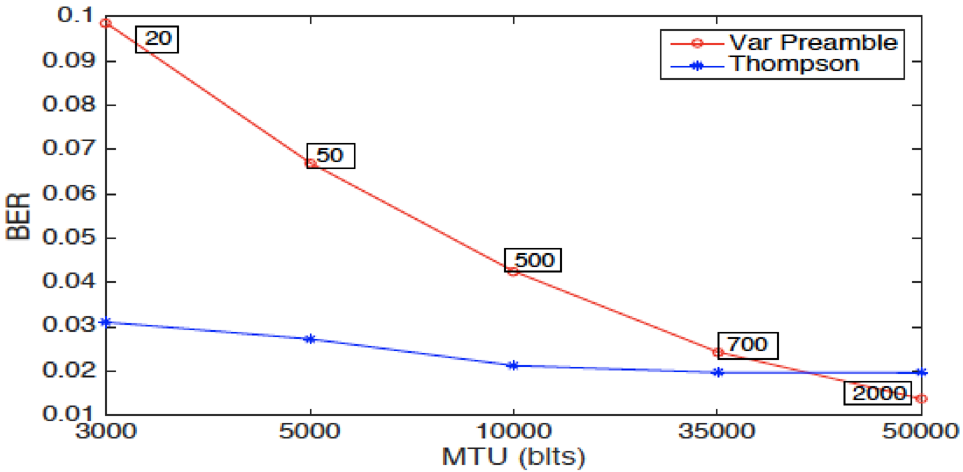


Fig. 4 Bit Error Rate with different preamble lengths [20 – 2000] and with Thompson approach.

03

Adaptive Full-Duplex Architecture

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Main Objectives and Contributions

Objective: Dynamic Control of the Modulation Scheme Selection

Contributions [2]

- A novel bidirectional VLC system capable to select the most suitable modulation scheme according to the reliability level and based on the Signal to Noise Ratio (SNR).
- A noise mitigation approach to work in real time based on a synchronized uplink channel.
- Experimental validation

[2] Antonio Costanzo, Valeria Loscri, Mauro Biagi. Adaptive Modulation Control for Visible Light Communication Systems. Journal of Lightwave Technology, IEEE/Optical Society of America(OSA), 2021, 10.1109/JLT.2021.3056177.

Bi-directional VLC system operations

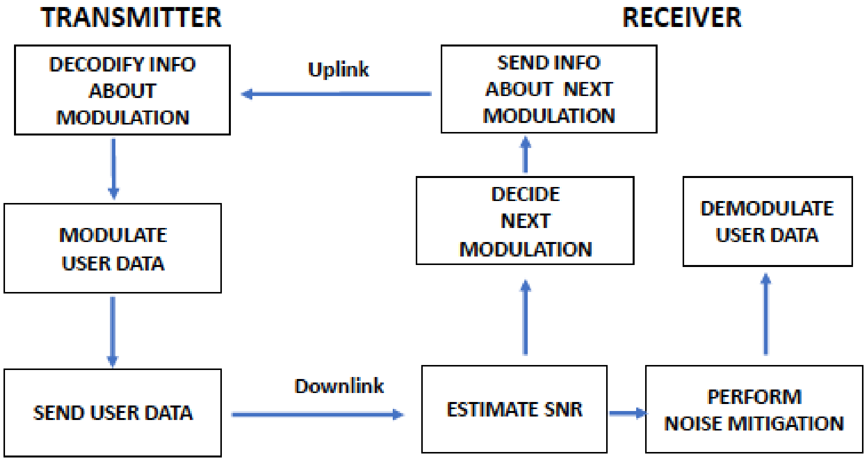


Fig. 1 Main operations of the adaptive modulation VLC control scheme

Some details on the Downlink Channel

- Maximum power of the transmitted signal P^{max}
- Two types of modulation schemes: 2-, 4-, 8-, 16- PAM and 2-, 4-, 8-, 16- PPM

PAM signal

$$s_a(t) = A_\ell x(t)$$

$A_l \in$ the M-ary set amplitudes of the PAM alphabet

$$x(t) = A_0 \Pi(\tfrac{t-T_p}{\tau})$$

Is the rectangular transmitting pulse delayed by T_p and with duration τ

PPM signal

$$s_d(t) = x(t - \Delta_\ell T_p)$$

Δ_l is the delay from 0 to M-1 as multiple integer of T_p.

T_p is the elementary delay equating the pulse length for ensuring orthogonality

Control Words

UPLINK COMMUNICATION: CONTROL MESSAGES AND RELATED SNR RANGES

Modulation	Binary Message	SNR Range [dB]
8 PAM	00100110	>10
4 PAM	01111001	8.3 - 10
2 PAM	00000011	6 - 8.3
2 PPM	00111110	4.7-6
4 PPM	01001101	4 - 4.7
8 PPM	00110011	3 - 4
16 PPM	01000001	<1.7

- Control words have been chosen in order to guarantee Hamming distance
- SNR threshold values have been chosen after a preliminary experimental campaign, in order to avoid oscillations effects and to allow high flexibility in noisy environments.

SNR and channel estimation towards modulation control

- Measure of the variance of the noise (i.e., the noise power), when no transmission is considered $\sigma_y^2 = \frac{1}{N}\sum_{k=1}^{N} |y(k)|^2.$
- The power of the received signal equates the power of the noise $\sigma_y^2 = \sigma_w^2,$
- $\sigma_w^2 = \sigma_n^2 + \sigma_I^2$ (σ_n^2) is the thermal noise and (σ_I^2) is the ambient noise
- When transmission takes place, under the hypothesis of statistical independence between noise and signals, we have $\sigma_y^2 = |h|^2 P_x + \sigma_w^2.$ with h the channel gain
- SNR can be estimated as $\tilde{\beta} = \frac{\sigma_y^2 - \sigma_w^2}{\sigma_w^2} = \frac{\sigma_y^2}{\sigma_w^2} - 1$

Interference Mitigation Procedure (1/2)

- It is possible to lower the values of the whole noise, to increase the real SNR
- Hearing the “interference” is a fundamental stage
- Measure of interference level is not enough for providing statistical elements
- We resort to linear prediction for the interference term in order to have the auto-correlation properties
- The predicted interference can be written as:

$$\tilde{\eta} = \sum_{k=1}^{p} a_k \eta[n-k]$$

$$\sum_{k=1}^{p} a_k r_\eta[j-k] = r_\eta[j]$$

- p is the order of the predictor
- a_k coefficients based on Yule-Walker equations

Interference Mitigation Procedure (2/2)

- The interference predicted is then subtracted to the received signal
- The term $r_\eta[j]$ refers to the autocorrelation of the interference
- It is characterized by both, the thermal noise and ambient noise components
- Correlation can be obtained as: $r_\eta[j] = \frac{1}{N}\sum_{\ell=1}^{N} \eta[\ell]\eta[\ell+j]$
- The SNR value after noise cancellation is obtained as: $\beta_{\mathcal{M}} = \frac{|h|^2 P_x}{\sigma_\epsilon^2}$
- With σ_ϵ^2 the residual noise after mitigation

Proposed Bi-directional Architecture

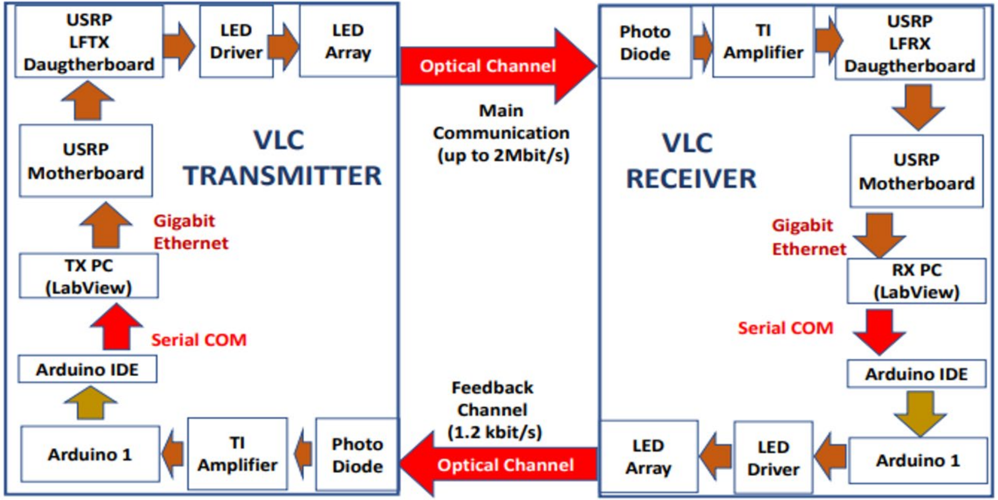


Fig. 3 A simplified scheme of the hardware components

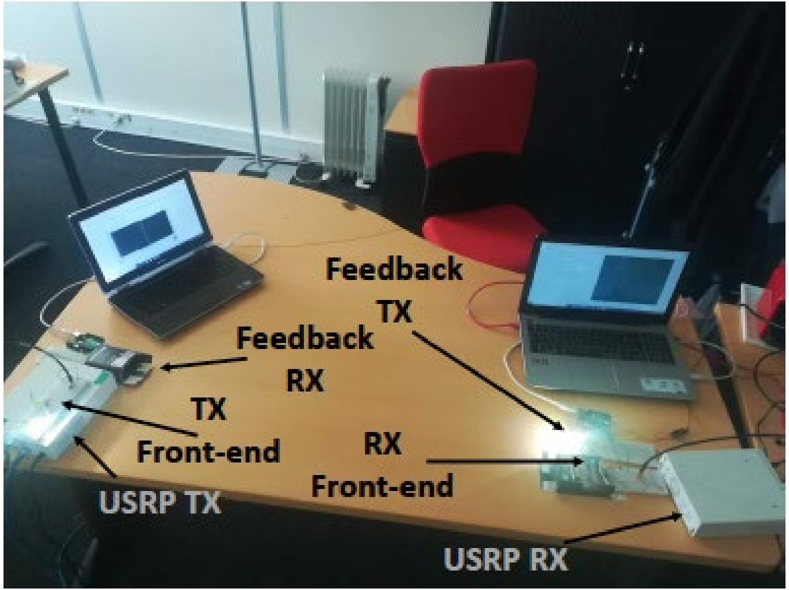


Fig. 4 Hardware Components.

Some Results (2/2)

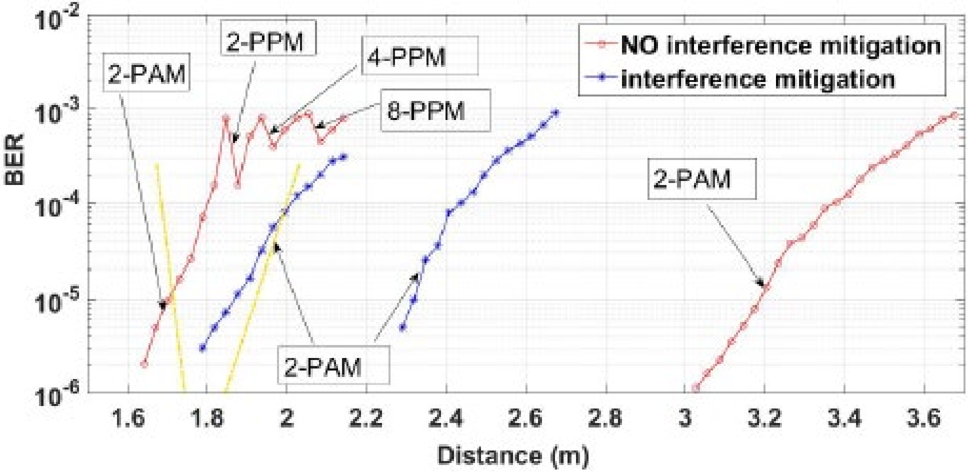


Fig. 7 BER of Adaptive scheme with and without interference mitigation when non-uniform lighting is used. The yellow line describes the propagation of disturbing light source over the distance.

Software Defined Operations

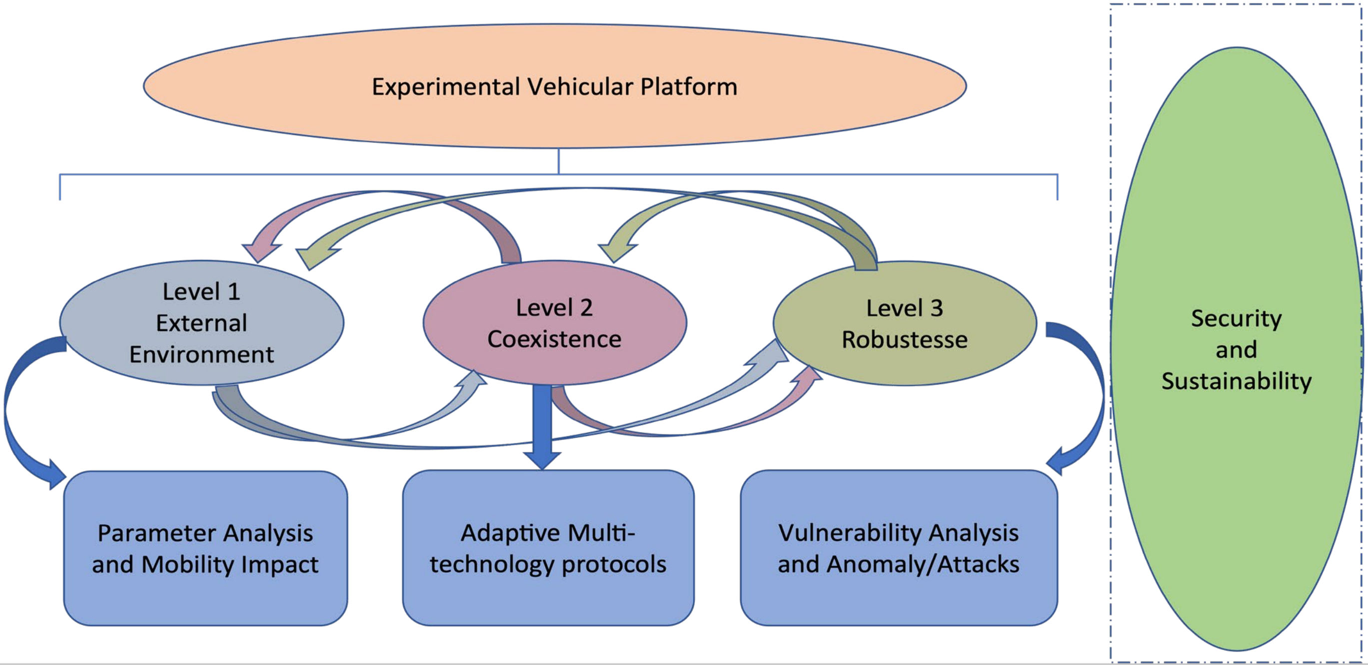
- Most of signal processing operations are realized via software: signal generation, filtering, modulation, demodulation, time recovering, data evaluation, etc.
- The main high data rate is managed through LabView, with ad-hoc LabView subroutines
- Uplink communication is completely managed through Arduino Integrated Development Environment (IDE), with the code directly flashed in Atmel 8-bit AVR microcontroller
- Standard IDE commands have been replaced with appropriate low level instructions for speeding up the access to the registers

Why Software Defined approach

- Software-based Communication are based on simple hardware components.
- High adaptive communication systems for increasing channel capacity and communication performance
- High adaptivity to different external conditions
- Possibility to open to new opportunities to use SD systems in novel scenarios and extend the IoT paradigm to Internet of Everything (IoE)

04

Application of VLC in Vehicular Networks


Experimental Vehicular Platform
Level 1
External
Environment
Level 2
Coexistence
Level 3
Robustesse
Parameter Analysis
and Mobility Impact
Adaptive Multi-
technology protocols
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and Anomaly/Attacks
Security
and
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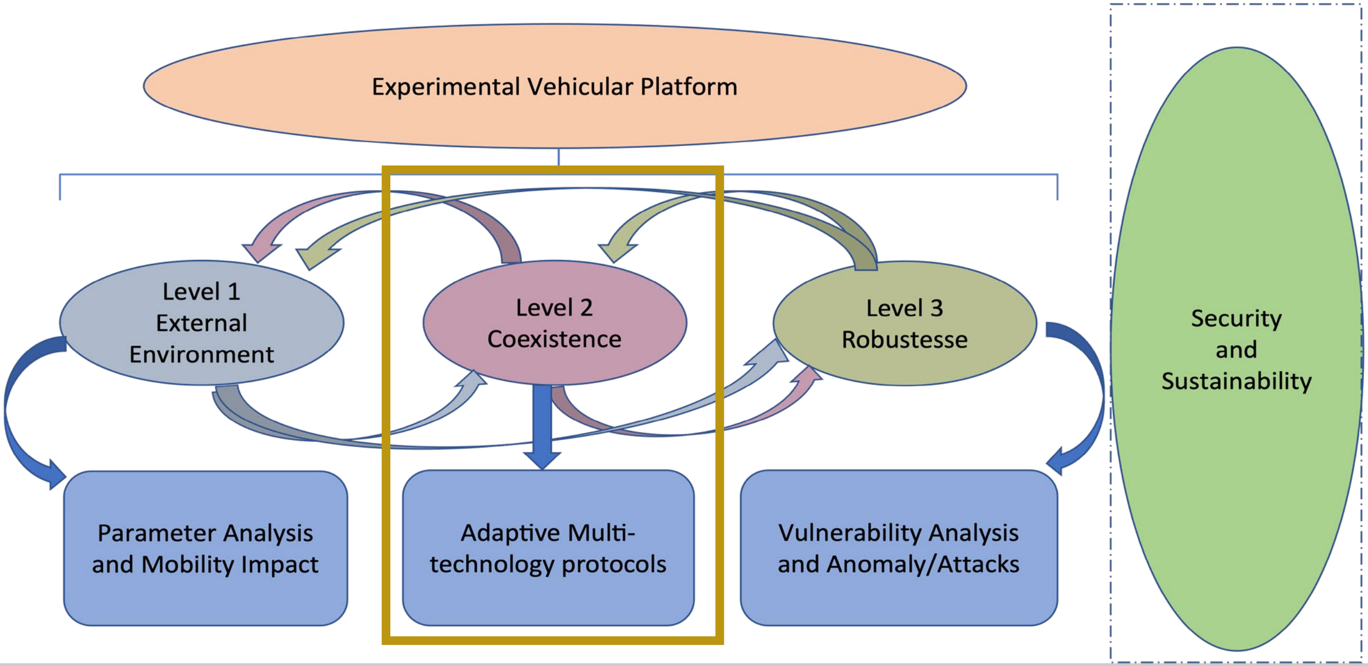
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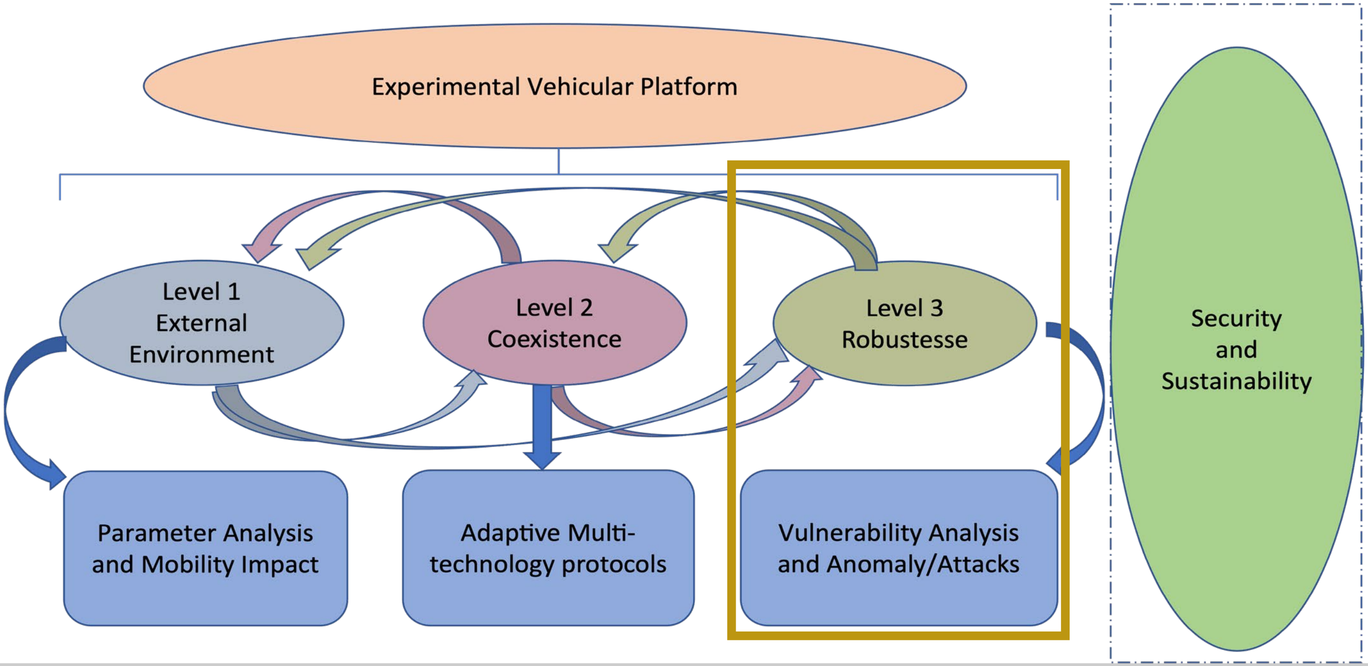

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05

Concluding Remarks

Some Concluding Remarks

- SD approach is a viable way for realizing very flexible context-aware VLC systems and Smart Radio Environment (SRE)
- This approach allows a better convergence of different communication technologies in the perspective of an Internet of Everything (IoE) paradigm

Thank you