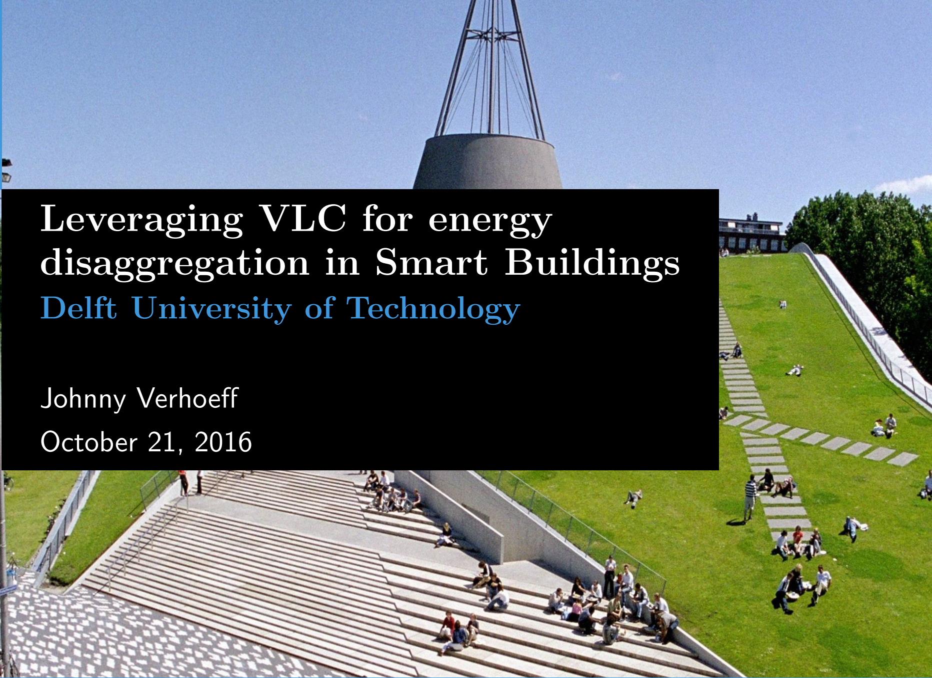


Leveraging VLC for energy disaggregation in Smart Buildings

Delft University of Technology

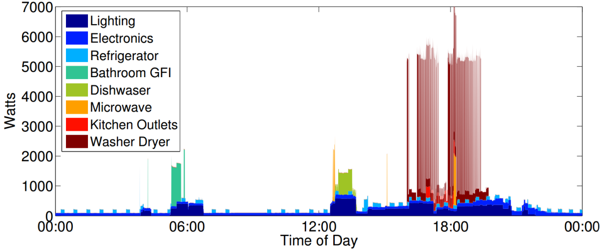
Johnny Verhoeff

October 21, 2016

Energy Disaggregation

Energy consumption is a most pressing issue.

- To reduce it, understanding the usage of that energy is needed.
- Smart-meter can disaggregate the energy usage in a household.
- This is done by recognizing the unique signatures of appliances.



Energy Consumption Lighting

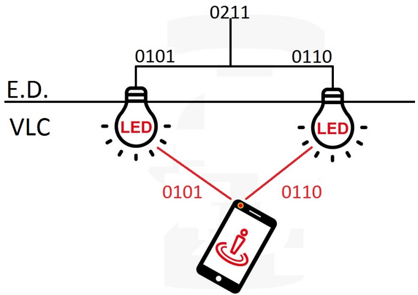
Individual lights cannot be disaggregated (yet).

- The reason: Lighting does not have a unique signature.
- Instead there are many lights with the same signature.
- Still important to be able to disaggregate individual lights: Lighting consumes 19 % of the power in an average household.

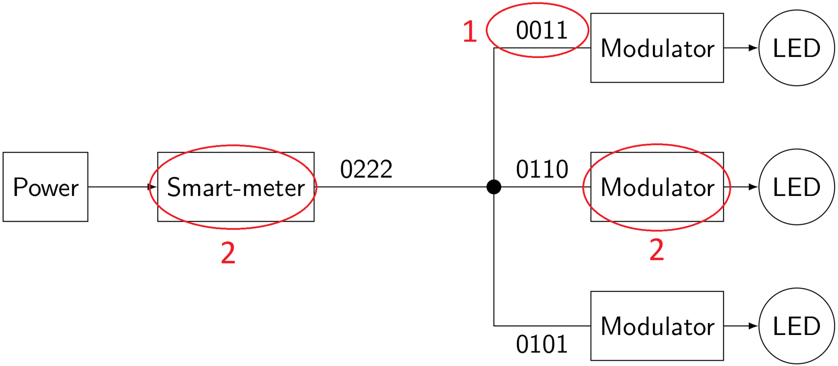
VLC Piggybacking

VLC is a communication method which uses visible light to transmit data.

- This data can be unique IDs for LED beacons used for indoor localization.
- This data will also propagate through the current draw.



Contributions



1. Investigation of codes that can be used.
2. Design of hardware to modulate and sample the current.
3. Evaluate the solutions.

Code Investigation

- Problem:
  - Multiple transmitters (LEDs) on the same channel at the same time.
  - Only the aggregated energy can be measured.
- Very similar to:
  - Multiple cell phones transmitting to the same base station.
  - Base station receives the combined signals.

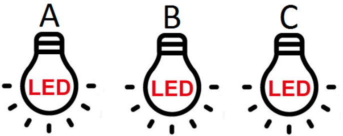
Requirements for Codes

- Scalability
- Balance
- Synchronous and Asynchronous
- Resilience

Correlation

Measuring the similarity between a code and a received signal:

$$R(\tau)_{xs} = \sum_{i=0}^{L-1} x(i) \times s(i+\tau) \text{ with } \tau = 0, 1, 2, \ldots, L$$



- $S = A + B + C$
- $R_{AS} = R_{AA} + R_{AB} + R_{AC}$

Orthogonal Codes

- Creation via Hadamard matrix:

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{bmatrix}$$

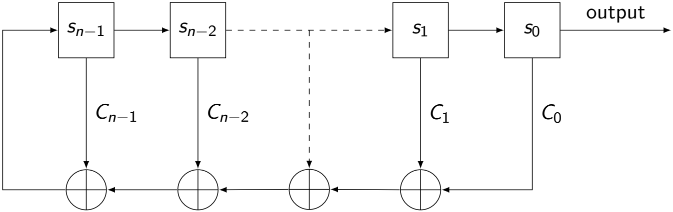
$$H_1 = \begin{bmatrix} 1 \end{bmatrix} \qquad H_2 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$$

- Properties:
  - Scalable: ✓
  - Balance: ✗
  - Correlation: ✓ (Only synchronous)

TU Delft

PN Codes

- Creation of a PN code via LFSR:



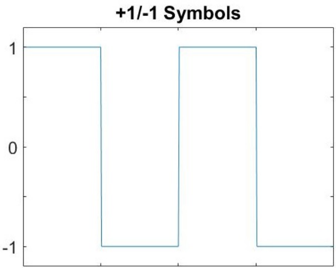
- Properties:
  - Scalable: ✗
  - Balance: ✓
  - Auto-correlation: ✓
  - Cross-correlation: ✗

Gold Codes

- Creation of a Gold code via two LFSRs.
- Properties:
  - Scalable: ✓
  - Balance: ✓
  - Auto-correlation: ✓
  - Cross-correlation: ✓

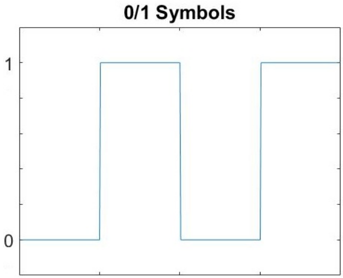
Mapping Problem

Wireless:



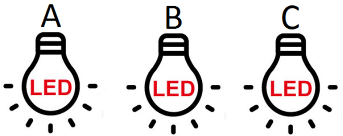
- Normal correlation function: R_{XY}

Our Scenario:



- Mapping of symbols: $b = \frac{1-r}{2}$
- New correlation function: $\hat{R}_{XY}$
- $R_{XY} = -m - 2 \times \hat{R}_{XY}$

Interference Solution



- $S = A + B + C$
- $R_{AS} = R_{AA} + R_{AB} + R_{AC}$

- Determine max. no. of modulating LEDs $m = \frac{L}{2\times\phi}$
- Threshold: $T = \frac{L}{2}$
- Make sure the no. of modulating LEDs $\leq m$:
  - Continuous Method
  - Probabilistic Method

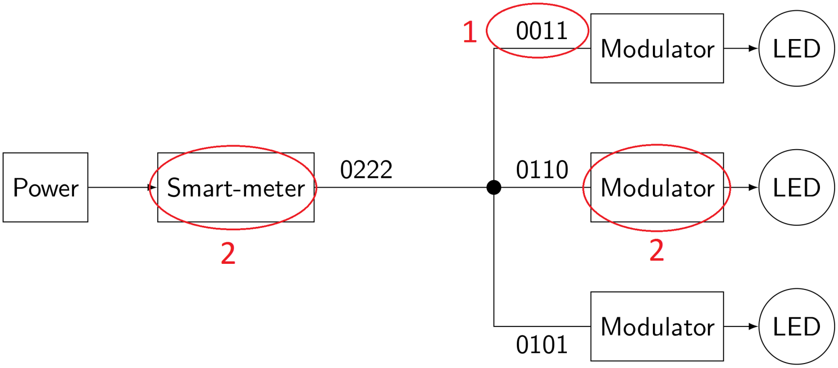
Continuous Method

- Maximum of m LEDs in system.
- Appropriate code length: $L \propto m^2$.
- Examples with modulating frequency $f = 10$ kHz:
  - $m = 7$ LEDs $\rightarrow L = 1023 \rightarrow t = 0.05$ s.
  - $m = 1023$ LEDs $\rightarrow L = 2^{23} = 8388608 \rightarrow t = 14$ min.

Probabilistic Approach

- Accuracy $(1 - \epsilon)$ outputs a probability p.
- p is chosen such that no. of modulating LEDs $\leq m$.
- Example:
  - 1025 LEDs $\rightarrow L = 1023 \rightarrow t = 53$ s for 99.9 % accuracy or $t = 22$ s for 99 % accuracy.

Hardware Components



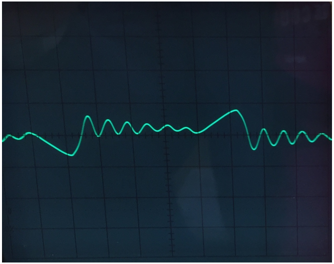
1. Codes
2. Hardware

Modulator Requirements

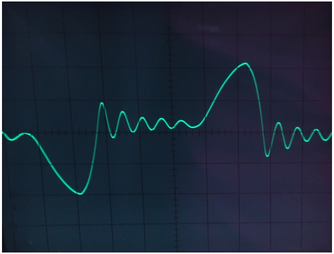
Modulator must translate ones and zeros of ID into current draw.

- $0 \rightarrow$ no current draw.
- $1 \rightarrow$ some constant current draw.

Existing Modulator Hardware



Switching Mode Power Supply modulating a '0'

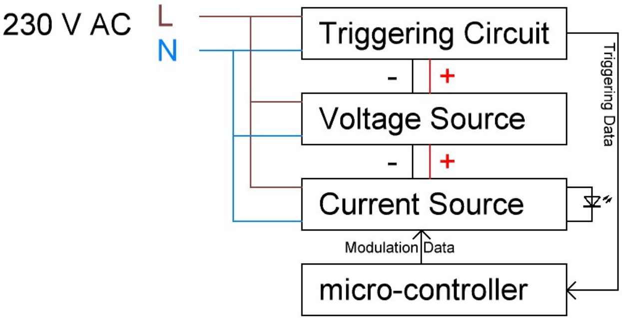


Switching Mode Power Supply modulating a '1'

Very hard to distinguish and will not yield nice aggregated results when multiple of these SMPS will be used.

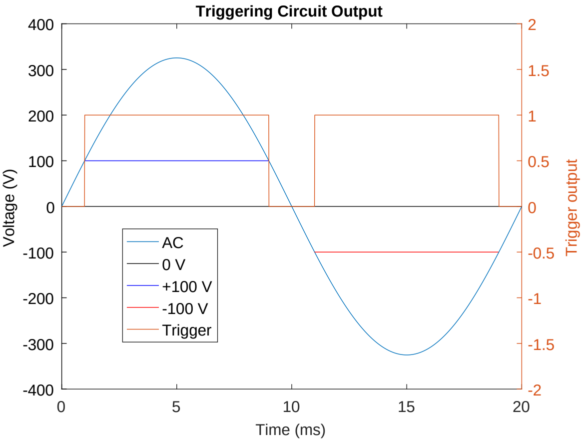
TU Delft

Custom Modulator



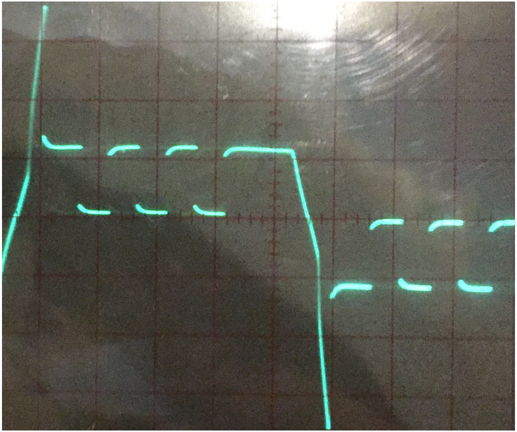
Detecting When to Modulate

- AC Voltage is zero crossing.
- LEDs require some voltage before the current starts flowing.



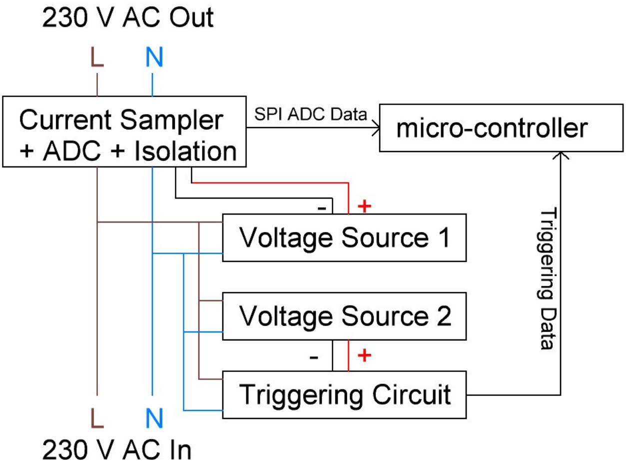
Constant Current Draw

- AC Voltage is not constant.
- For disaggregation a constant current is desired.



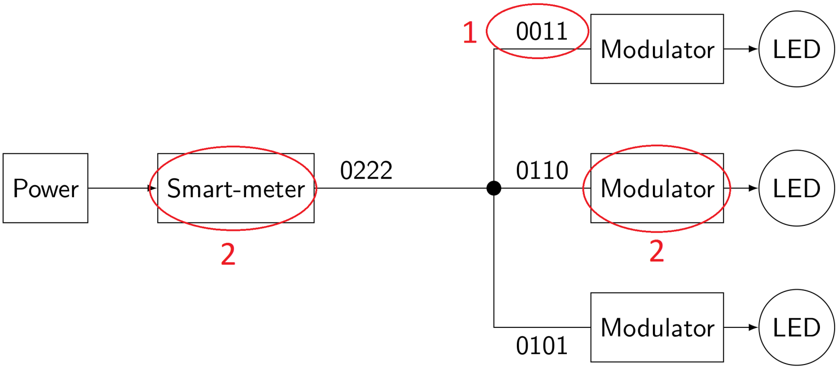
TU Delft

Smart-meter



230 V AC Out
L
N
Current Sampler + ADC + Isolation
SPI ADC Data
micro-controller
-
+
Voltage Source 1
Voltage Source 2
-
+
Triggering Circuit
Triggering Data
L
N
230 V AC In

Recap

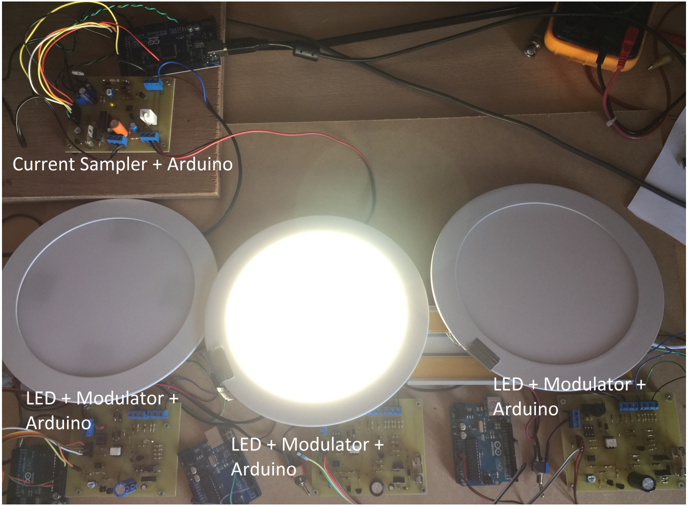


1. Codes
2. Hardware
3. Evaluate the system

Evaluation Outline

- Hardware evaluation
- Software simulation

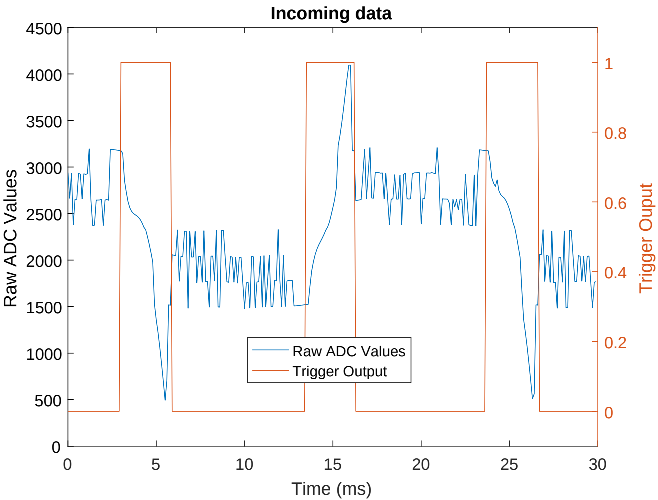
AC Testbed


Current Sampler + Arduino
LED + Modulator + Arduino
LED + Modulator + Arduino
LED + Modulator + Arduino

Setup for Hardware Evaluation

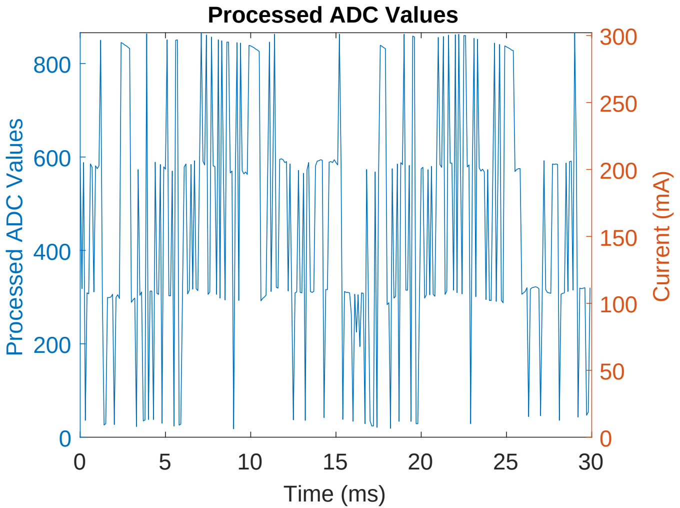
- Setup:
  - 4 distinct codes will be used, 3 for the LEDs and one will represent an LED in an off state.
  - Modulation via continuous method with $m \geq 3$ code.
- Goals:
  - Correctly identify state of LEDs in a timely manner.

Raw Data



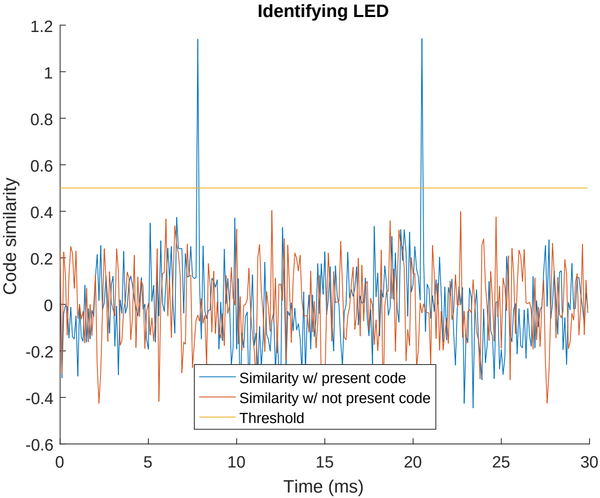
TU Delft

Processed Data



TU Delft

Identifying LEDs

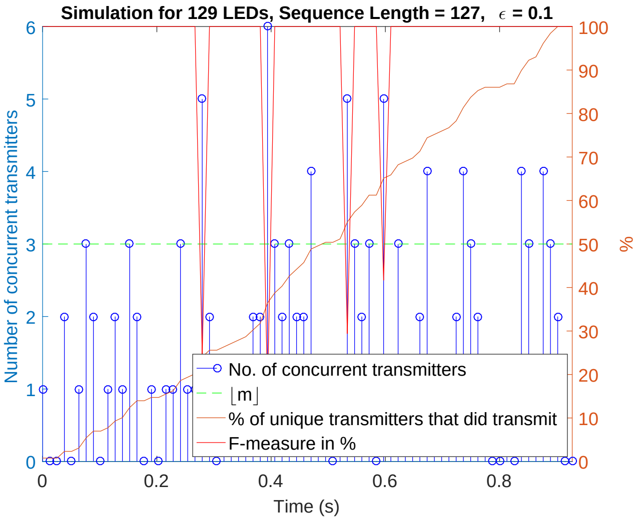


Simulation

Software simulation:

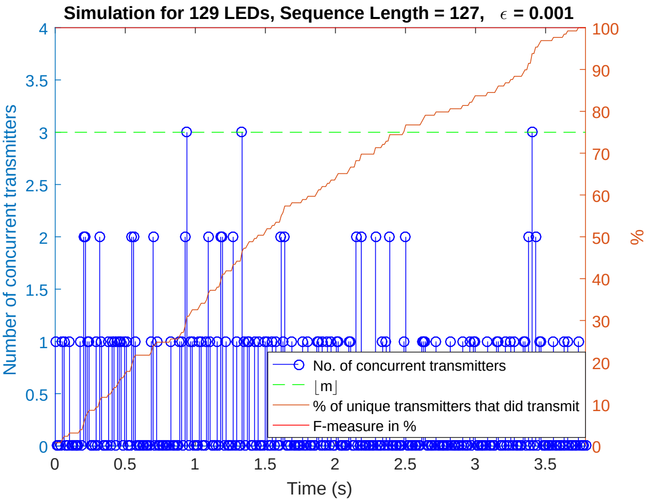
- 129 LEDs.
- Modulation via probabilistic method.
- Identify state of all LEDs by correlating all IDs with aggregated signal.

Fast but Inaccurate Simulation



TU Delft

Slow but Accurate Simulation



TU Delft

Conclusion and Future Work

- Conclusion:
  - Codes have been investigated.
  - Hardware is designed to encode and decode the IDs.
  - The software and hardware is evaluated along with a simulation for scalability.
- Future Work:
  - Other appliances
  - Dimming lights

TU Delft