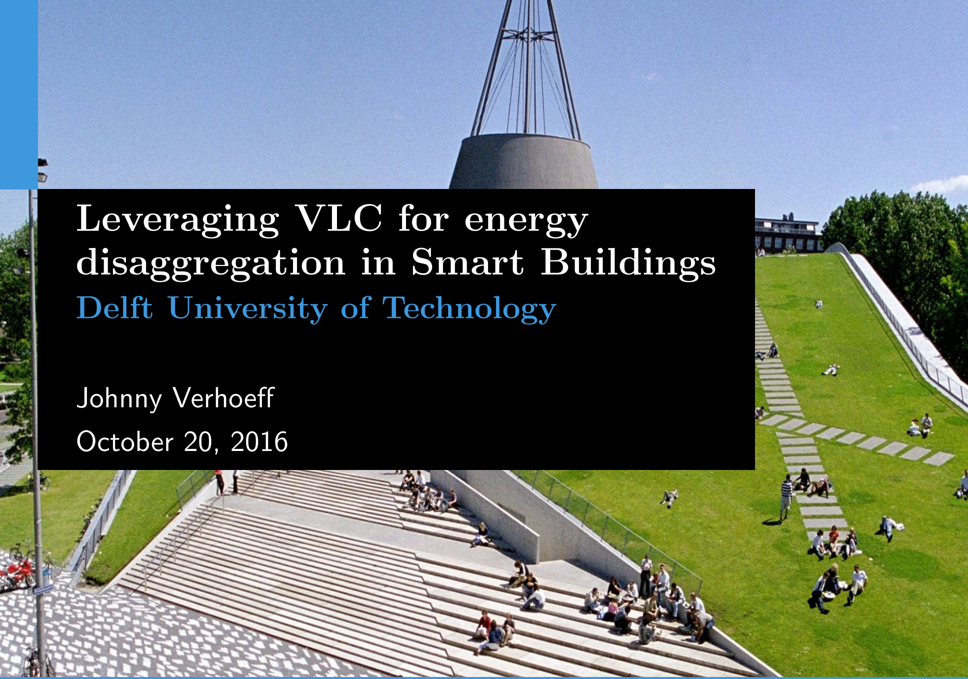

Leveraging VLC for energy disaggregation in Smart Buildings

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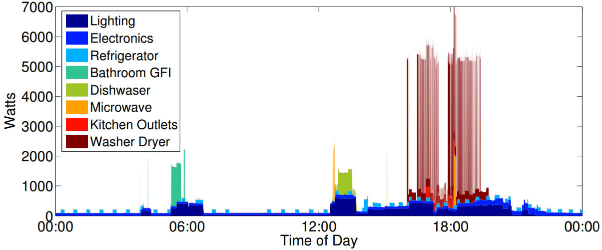
Energy Disaggregation

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

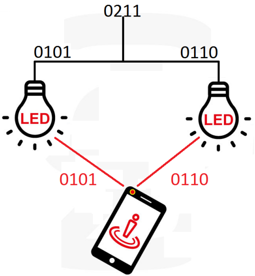
Individual lights cannot be disaggregated (yet).

- 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.
- Can we construct these IDs in such a way that the aggregated current can be disaggregated by a smart-meter ?



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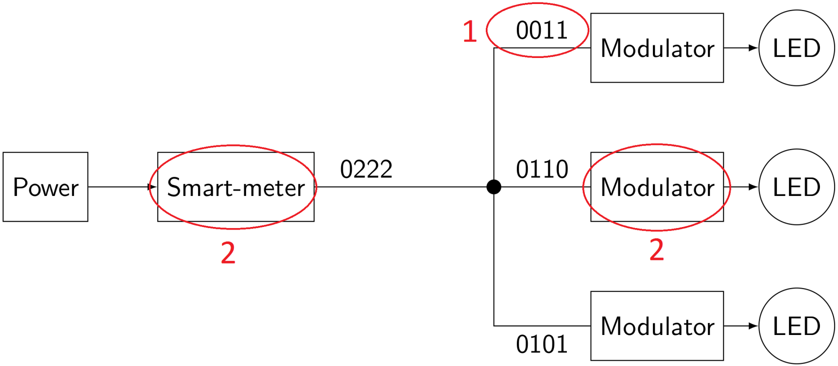
Contributions



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.

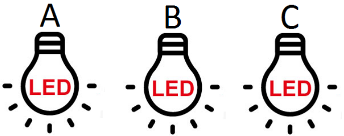
Requirements for Codes

- Scalability
- Balance
- Synchronous and Asynchronous
- Resilience

Correlation

Measuring the similarity between a code and a received signal:

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



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

Orthogonal Codes

- Creation via Hadamard matrix:

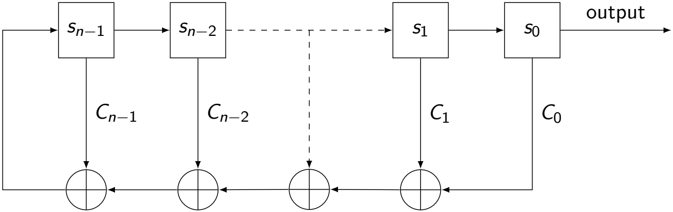
$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{bmatrix}$$

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

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

PN Codes

- Creation of a PN code via LFSR:



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

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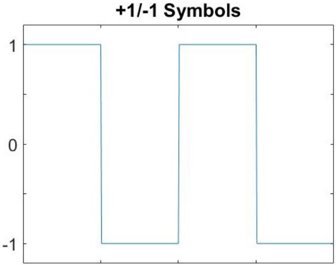
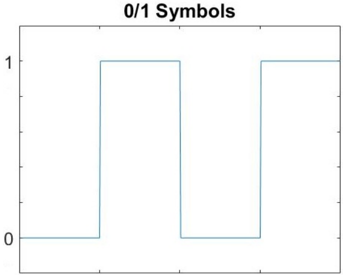
Gold Codes

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

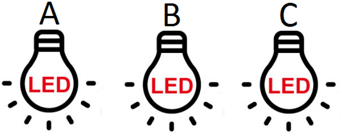
Mapping Problem





- Normal correlation function: R_{XY}
- Mapping of symbols: $b = \frac{1-r}{2}$
- New correlation function: $\hat{R}_{XY}$
- $R_{XY} = f(\hat{R}_{XY})$

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.

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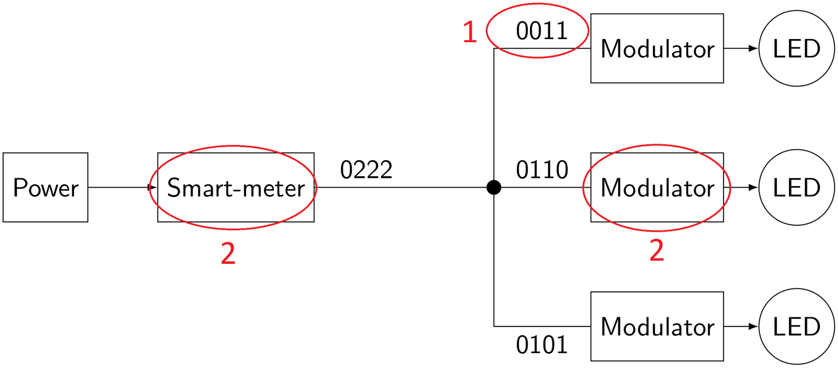
Hardware Components



1. Codes
2. Hardware

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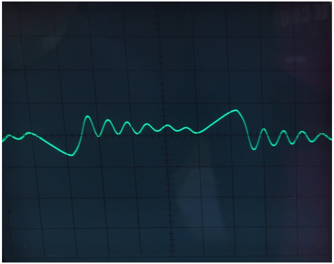
Modulator Requirements

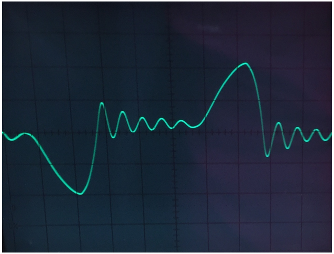
Modulator must translate ones and zeros of ID into current draw.

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

Existing Modulator Hardware



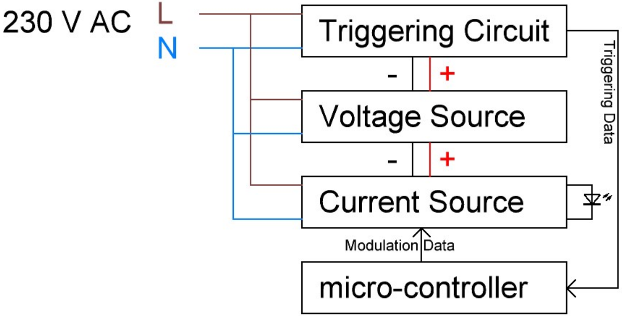
Switching Mode Power Supply modulating a '0'



Switching Mode Power Supply modulating a '1'

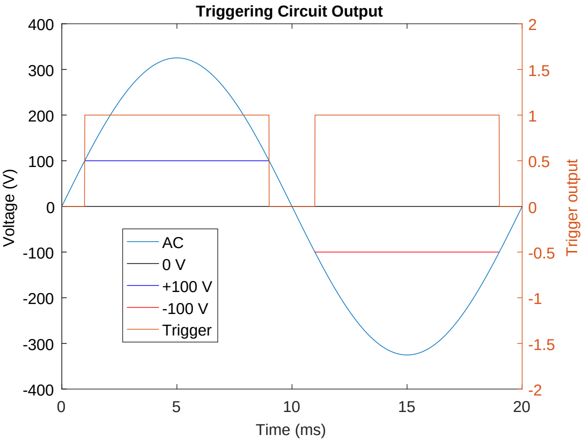
Very hard to distinguish and will not yield nice aggregated results when multiple of these SMPS will be used.

Custom Modulator



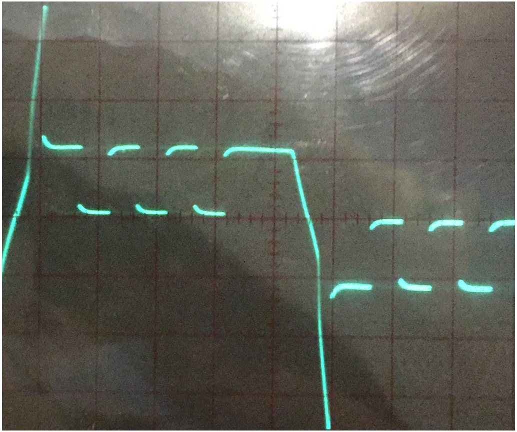
Detecting When to Modulate

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

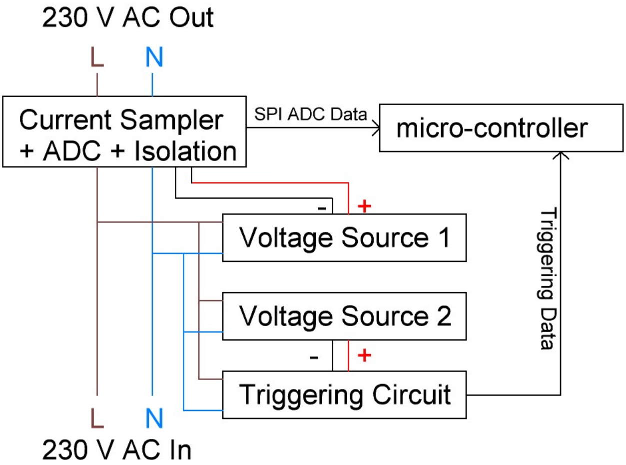


Constant Current Draw

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



Smart-meter



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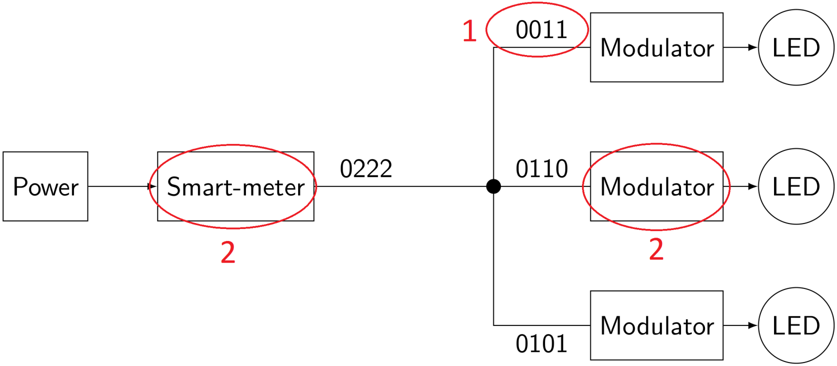
Recap

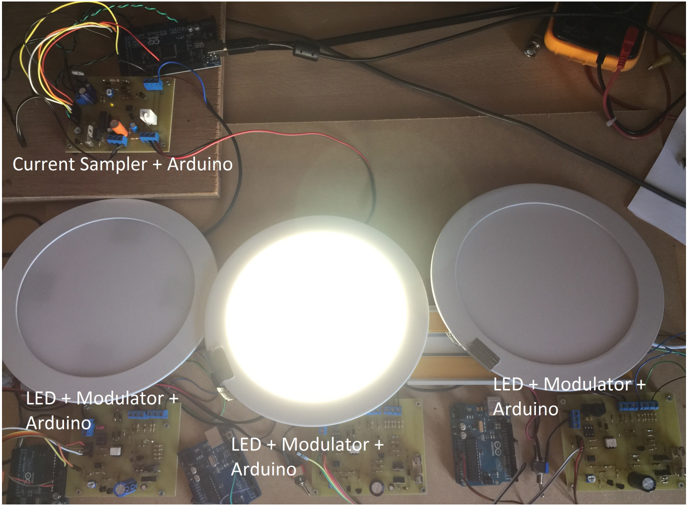


1. Codes
2. Hardware
3. Evaluate the system

Evaluation Outline

- Hardware evaluation
- Software simulation

AC Testbed

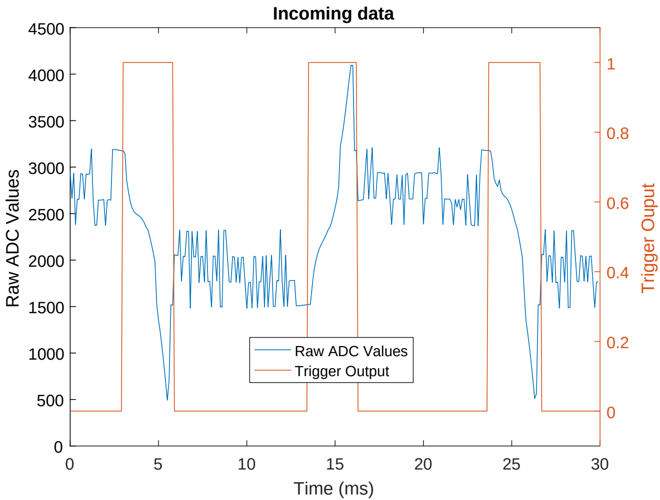


Current Sampler + Arduino
LED + Modulator + Arduino
LED + Modulator + Arduino
LED + Modulator + Arduino

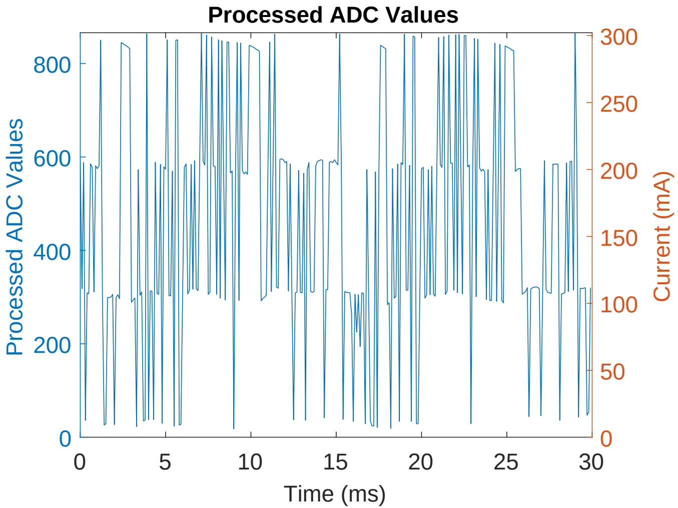
Setup for Hardware Evaluation

- Setup:
  - The setup consists of 3 commercial LEDs + current sampler.
  - 4 distinct codes will be used, 3 for the LEDs and one will represent an LED in an off state.
  - All LEDs are transmitting continuously with a code that support at least $m \geq 3$ concurrent transmitters.
- Goals:
  - Identifying an LED as being on without seeing interference from the other LEDs in a timely manner.
  - Verify that the fourth code cannot be identified as being on.

Raw Data


Incoming data
Raw ADC Values
Trigger Ouput
Time (ms)
Raw ADC Values
Trigger Output
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
1
0.8
0.6
0.4
0.2
0

Processed Data



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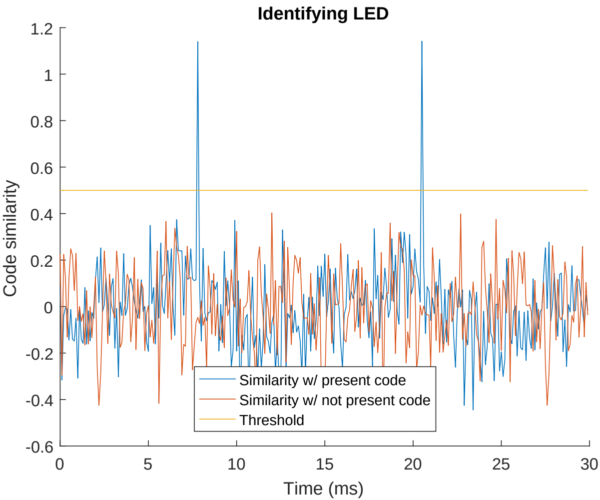
Identifying LEDs



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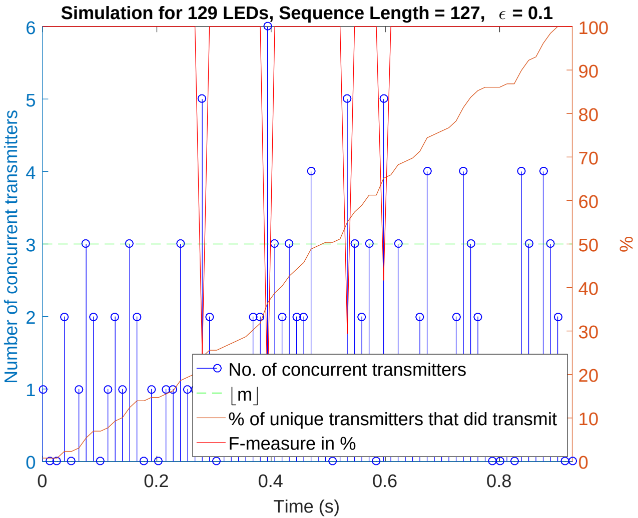
Simulation

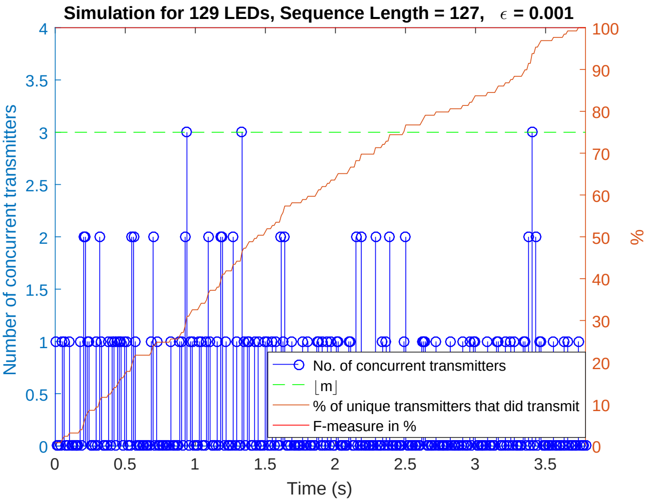
To be able to test larger systems, a software simulation is used:

- Assuming 129 individual LEDs which follow the probabilistic scheme.
- Each LED has its probability p for which it will modulate.
- Those LEDs will then transmit its code.
- The aggregated signal with all the code is then checked to try to identify if any LEDs are on.

Fast but Inaccurate Simulation



Slow but Accurate Simulation



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

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