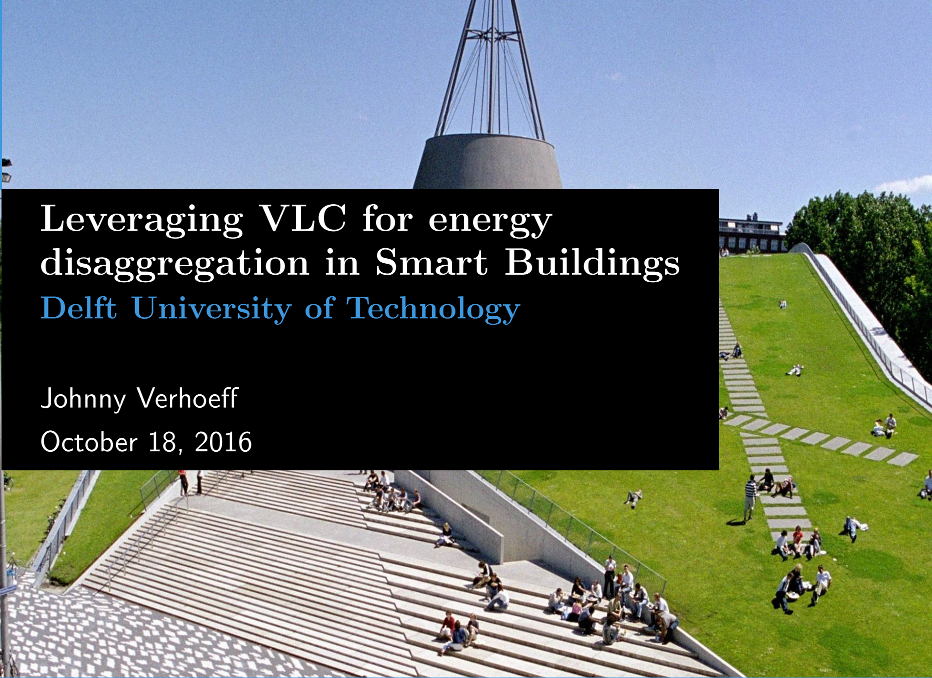

Leveraging VLC for energy disaggregation in Smart Buildings

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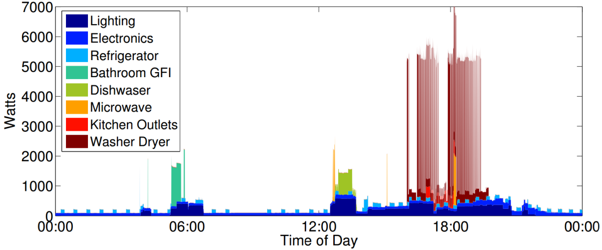
Energy Disaggregation

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.



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Energy Consumption Lighting

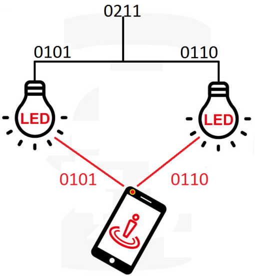
Individual lights cannot be disaggregated (yet).

- 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

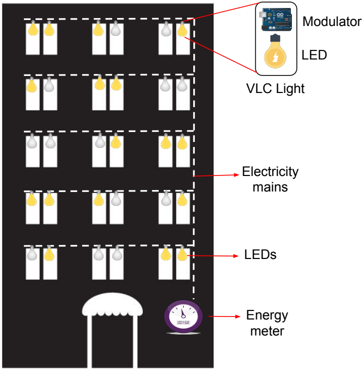
VLC is a communication method which uses visible light to transmit data.

- 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 ?



Contributions

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



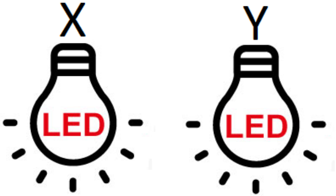
Code Investigation

- Code Theory.
    - How to recognize the IDs ?
    - Requirements for the codes.
    - Analyzing and comparison of codes.
- Symbol mapping problem.
- Interference solution.

Recognizing the IDs

Correlation: Measuring the similarity between a code and a received signal:

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



- Auto-correlation: $R_{XX} = L$
- Cross-correlation: $R_{XY} = 0$

Requirements for Codes

- Correlation:
  - Auto-correlation should be high.
  - Cross-correlation should be low.
- The ability to work in synchronous and asynchronous scenarios.
- The codes should be not too long, the system should be able to identify an ID in a timely manner.
- With code length L: 2^L possible codes. Only small subset suitable for IDs. Size of subset should be proportional to L.

Orthogonal Codes

- Creation via Hadamard matrix:

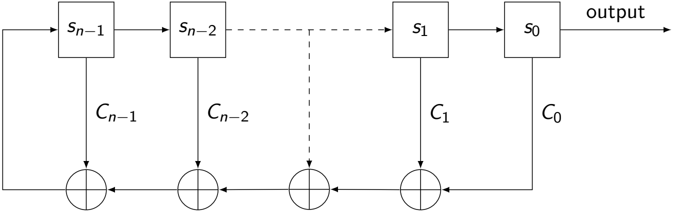
$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & -H_n \end{bmatrix}$$

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

- Properties:
  - Auto-correlation is high, only in synchronous scenario.
  - Cross-correlation is low and math. bounded, only in synchronous scenario.
  - Number of codes $C \propto L$, the length of code, so it scales well.

PN Codes

- Creation of a PN code via LFSR:



- Properties:
  - Auto-correlation is high, in synchronous and asynchronous scenarios.
  - Cross-correlation: Exhaustive analysis is required.
  - Number of codes $C = \frac{1}{n}\prod\{P_i^{(\alpha_i-1)} \times (P_i - 1)\} \rightarrow C \not\propto L$, does not scale well.

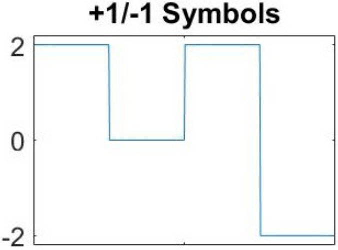
Gold Codes

- Creation of a Gold code via two LFSRs with the output connected to each other.
- Properties:
    - Auto-correlation is high, in synchronous and asynchronous scenarios.
    - Cross-correlation is low and math. bounded in synchronous and asynchronous scenarios.
    - Number of codes $C \propto L$, the length of code, so it scales well.

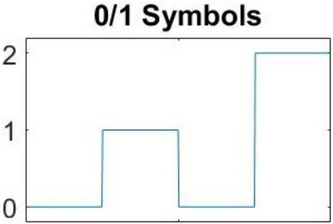
Comparison of Codes

	Orthogonal	PN	Gold
Synchronous Transmission	✓	✓	✓
A-synchronous Transmission	✗	✓	✓
Math. bounded CC (synch.)	✓	✗	✓
Math. bounded CC (asynch.)	✗	✗	✓
Scalability ($C \propto L$)	✓	✗	✓

Mapping Problem



- Normal correlation function: R_{XY}



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

Interference Solution

- $R_{XY} \neq 0$ for Gold codes.
- R_{XY} is bounded.
- Determine the max. no. of concurrent transmitters m such that no interference occurs.
- Example:
  - 1025 LEDs
  - 1023 ID length
  - $m = 7$ LEDs
- Continuous Method: Allows to transmit with all LEDs continuously.
- Probabilistic Approach: Each LED will have a probability to transmit.

Continuous Method

- Based on these m LEDs we can calculate what code length to use: $L \propto m^2$.
- With modulating frequency $f = 10$ kHz:
- Example: System with $m = 7$ LEDs $\rightarrow L = 1023 \rightarrow t = 0.05$ s.
- Example: System with $m = 1023$ LEDs $\rightarrow L = 2^{23} = 8388608$ $\rightarrow t = 14$ min.

Probabilistic Approach

Trade-off must be made by the user between time and accuracy.

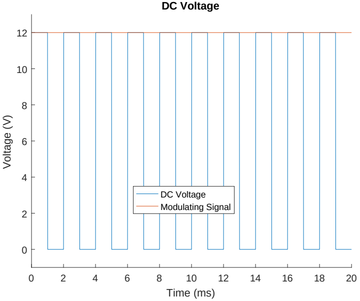
- Accuracy $(1-\epsilon)$: determines the accuracy in identifying which LEDs are on and off. Outputs a probability p for which the LEDs will modulate.
- Each point in time the no. of modulating LEDs $\leq m$.
- Time it will take to successfully identify all LEDs: $t = \frac{L}{f} \times \frac{1}{p}$
  - Example: 1025 LEDs $\rightarrow L = 1023 \rightarrow t = 53$ s for 99.9 % accuracy or $t = 22$ s for 99 % accuracy.

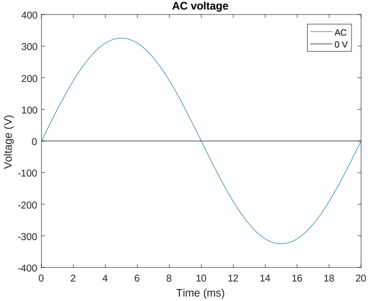
Hardware Components

Things that will be investigated:

- Difference between DC and AC.
- LED modulator:
  - Existing LED modulator solutions.
  - Design of custom modulator:
    - Zero crossing issue.
    - Non constant voltage issue.
- Current sampler (smart-meter):
  - Existing current sample option.
  - Custom solution.

DC vs AC Voltage

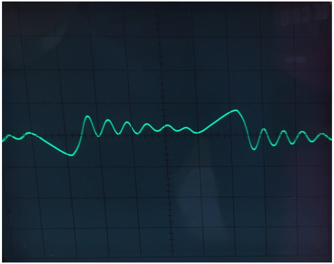




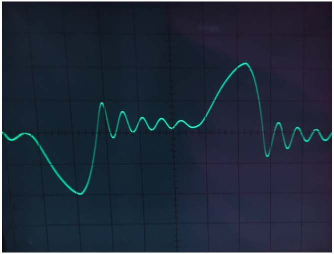
AC characteristics:

- Supplied voltage is not constant.
- Supplied voltage will be both positive and negative.

Existing Modulator Hardware



Switching Mode Power Supply modulating a '0'

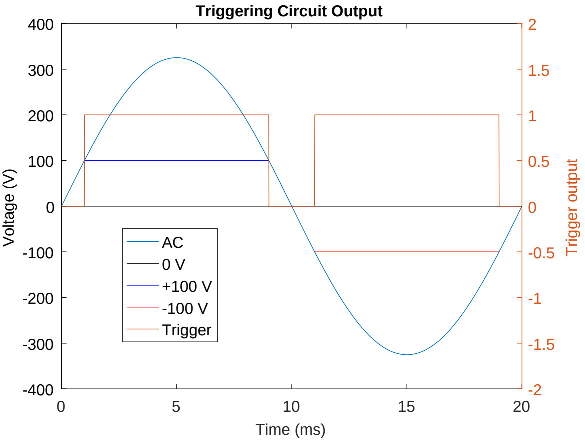


Switching Mode Power Supply modulating a '1'

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

Detecting When to Modulate

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



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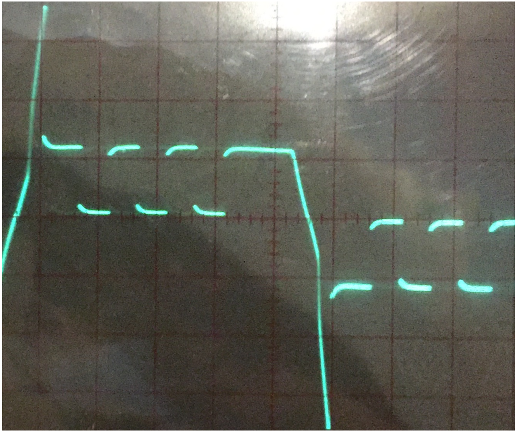
Constant Current Draw

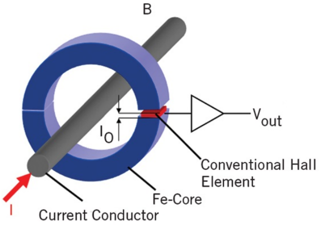
- AC Voltage is not constant.
- For disaggregation a constant current is desired.



Smart meter

AC Current sampler options:

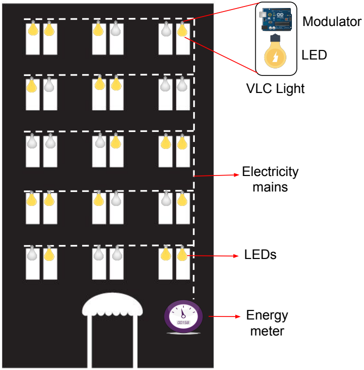
- Hall effect sensor:
  - Sensitivity: 185 mV / A
  - Noise: 21 mV
  - Output: 15 W LED yields 12 mV
  - Noise > output: not a viable option.
- Burden resistor:
  - Sensitivity: 2800 mV / A
  - No noise
  - Output: 15 W LED yields 183 mV
  - Positive and negative voltage output



Recap

Explained:

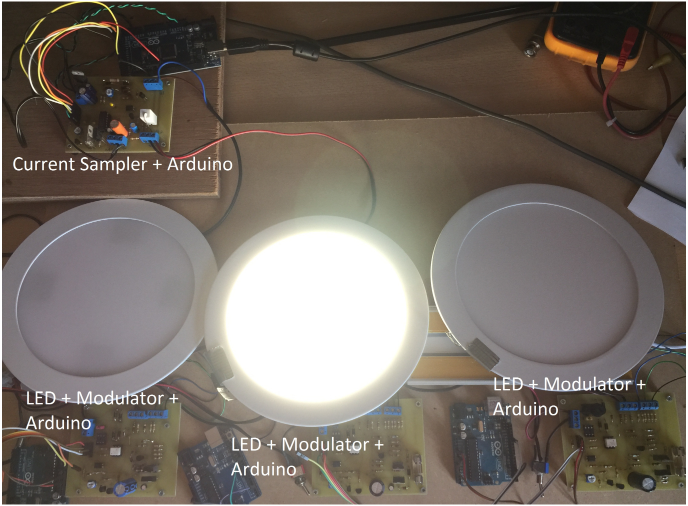
- Coding theory and which codes to use with the hardware.
- Each hardware element on its own.



Evaluation Outline

- Hardware evaluation:
  - Describe the setup.
  - Explain the results.
- Simulation:
  - Describe the simulation.
  - Discuss the results.

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.

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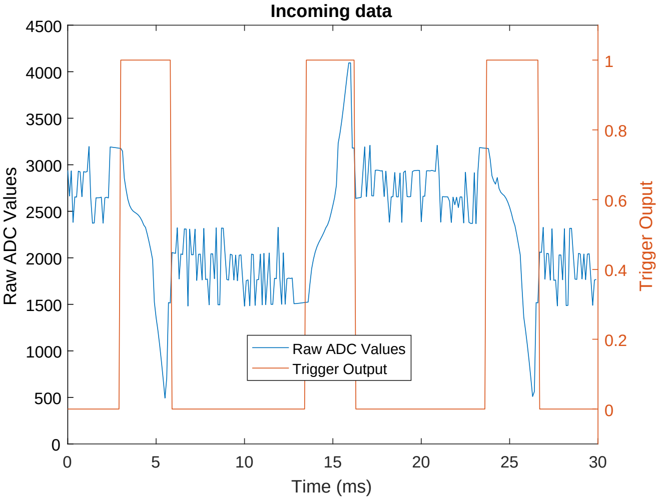
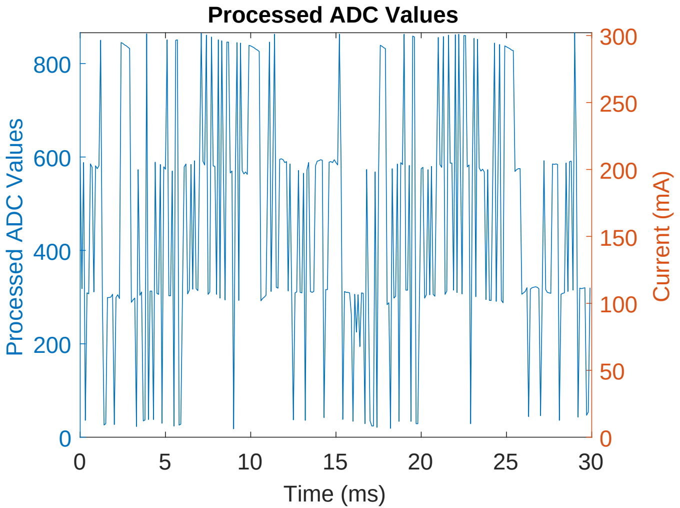
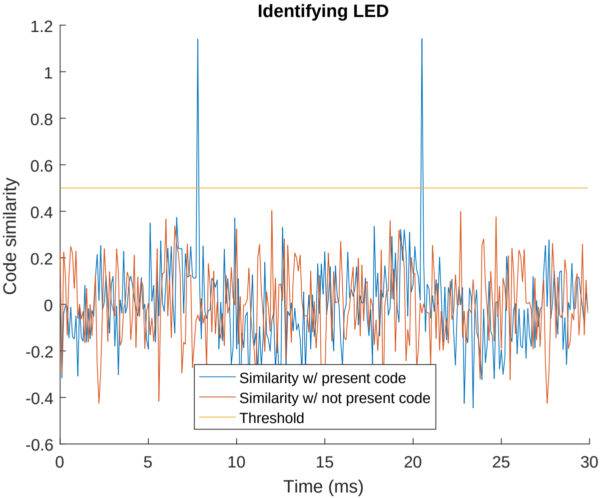
Raw ADC Data


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

Processed ADC Data



Identifying LEDs

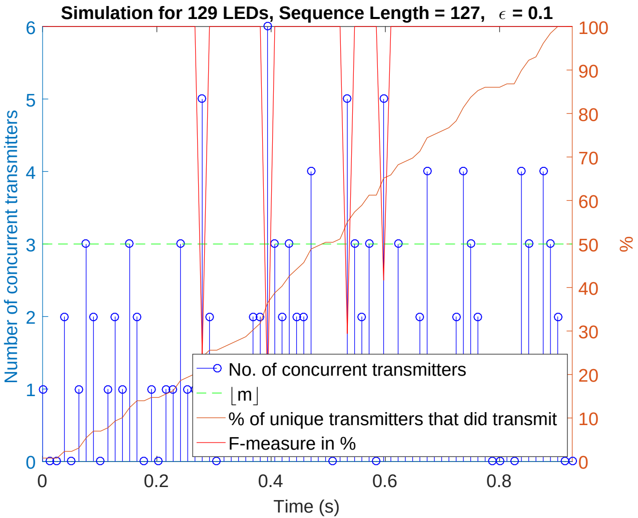


Simulation

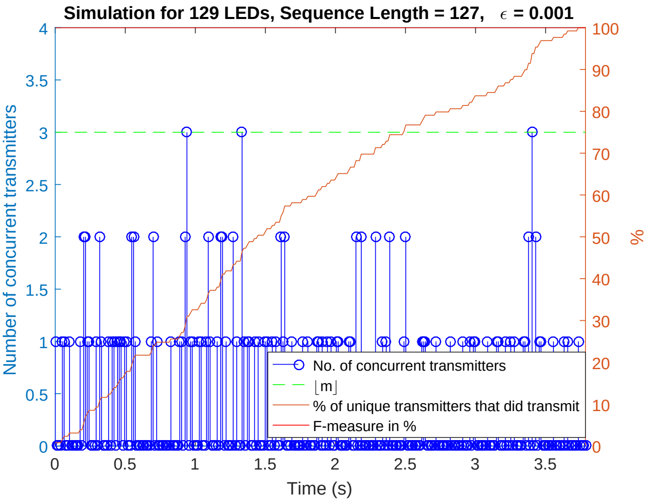
To be able to test larger systems, a software simulation is used:

- Assuming 129 individual LEDs which follow the probabilistic scheme.
- Each LED has its probability p and for each point in time it is determined how many LEDs will be transmitting.
- 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