The Case of Dynamic Street Lighting

An exploration of long-term data collection

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Where innovation starts

Content

Introduction – dynamic street lighting

- Advent of LED lighting enables more control
  - fine-grained dimming, color temperature

- Cities wish to renew lighting installations
  - reduce energy consumption – CO2 emissions – and costs
  - become a Smart City … intelligent behavior

- Lighting is integrated with ICT, becomes an ICT technology
  - multiple start-ups provide solutions

- Different flavors of dynamic street lighting
  - fixed schedule, traffic density, reactive / intelligent
  - … are they cost effective?

ISLES project

- **Intelligent Street Lighting for Energy Saving & Safety**
  - support control responses to changes in the environment with the explicit goal to reduce energy consumption.
  - in a realistic testbed
  - their impact on users (residents)

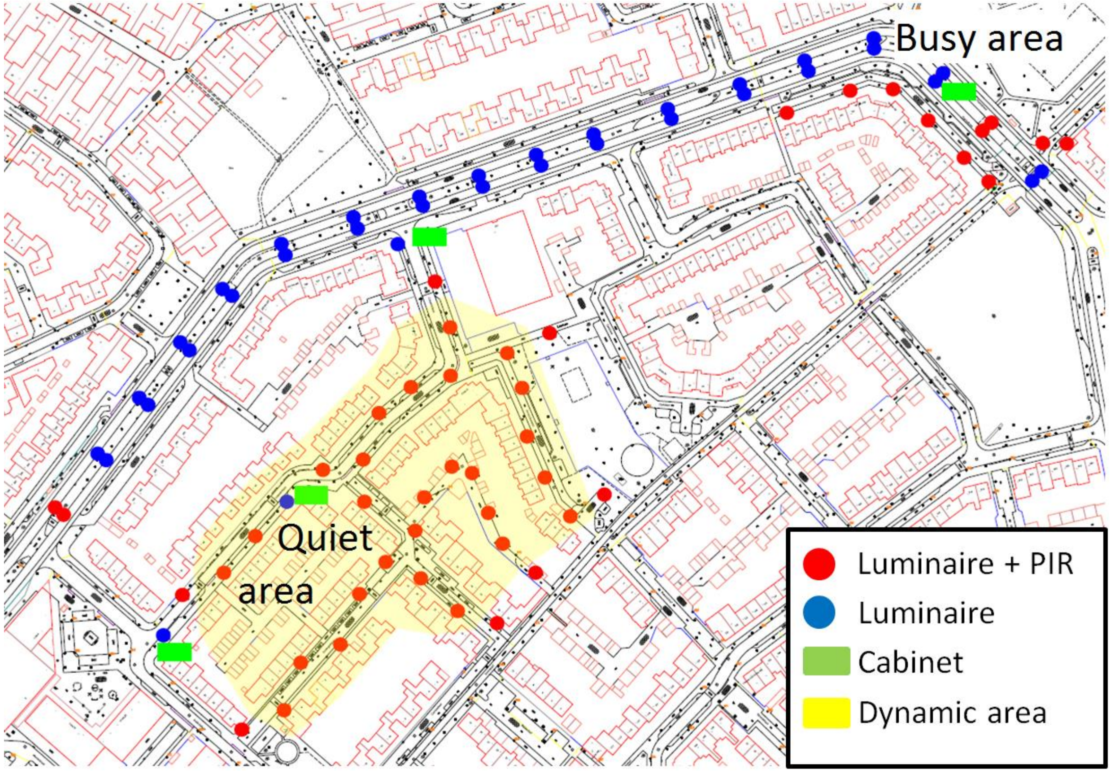
Motivation and goal

- *Claim validation*
  - what are possible savings, and under which conditions?
  - what is the impact of different dynamic strategies?

- Develop a *simulation/evaluation method* for dynamic street lighting
  - input: activity data
  - output: behavior, and metrics

- Gather *ground truth* about activity on the street
  - as input to the simulation method
  - outcomes based on real data

System setup



- 18 dual-luminaire
- 45 single luminaire
- 46 PIR sensors
- 4 cabinets
    - Cameras
    - Packet sniffers

- Installed: July 2013
- Reduced: July 2014

System setup – in action (movie)

Data Set - content

Locally:

- Camera images – every 2 seconds
- Radio communication – collected by 4 sniffers
- PIR detections
- part of 2013, 2014

Online:

- Weather reports for Eindhoven – every 10 minutes
- Rain intensity – every 5 minutes
- Traffic information – every minute
    - major roads of Eindhoven

Data Set - completeness

Radio communication: partial

- Depends on distance between source and cabinets
- 16-bit CRC filtering is not sufficient

PIR detections: partial

- Complete for poles near cabinets, partial for others
- Partial reconstruction from radio packets
- Cabinet in busy area was removed in July 2014

Weather: complete

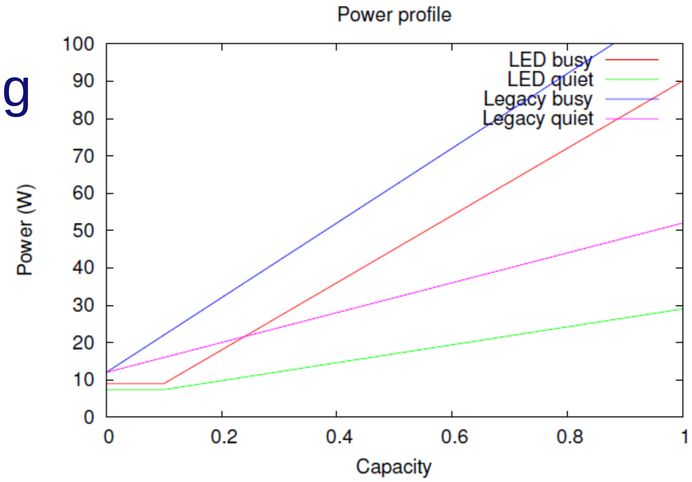
Traffic information: 95%

- Missing data can be acquired

System Model – Luminaire and Schedules

- Each luminaire l has a power profile mapping a capacity fraction to a power level (i.e., the power corresponding to a fraction of light)

$$\rho^l(c) \in [0..1] \rightarrow R^+$$



- We use a linear model for all luminaires: $\rho_{a,b}(c) = a \times c + b$
- A static dimming schedule $\lambda^l(t)$ selects a capacity level based on the time of day. We used for all luminaires:

$\Lambda_{0.5,1.0}$: 50% between 10pm and 7am, 100% otherwise

System Model – Energy Usage

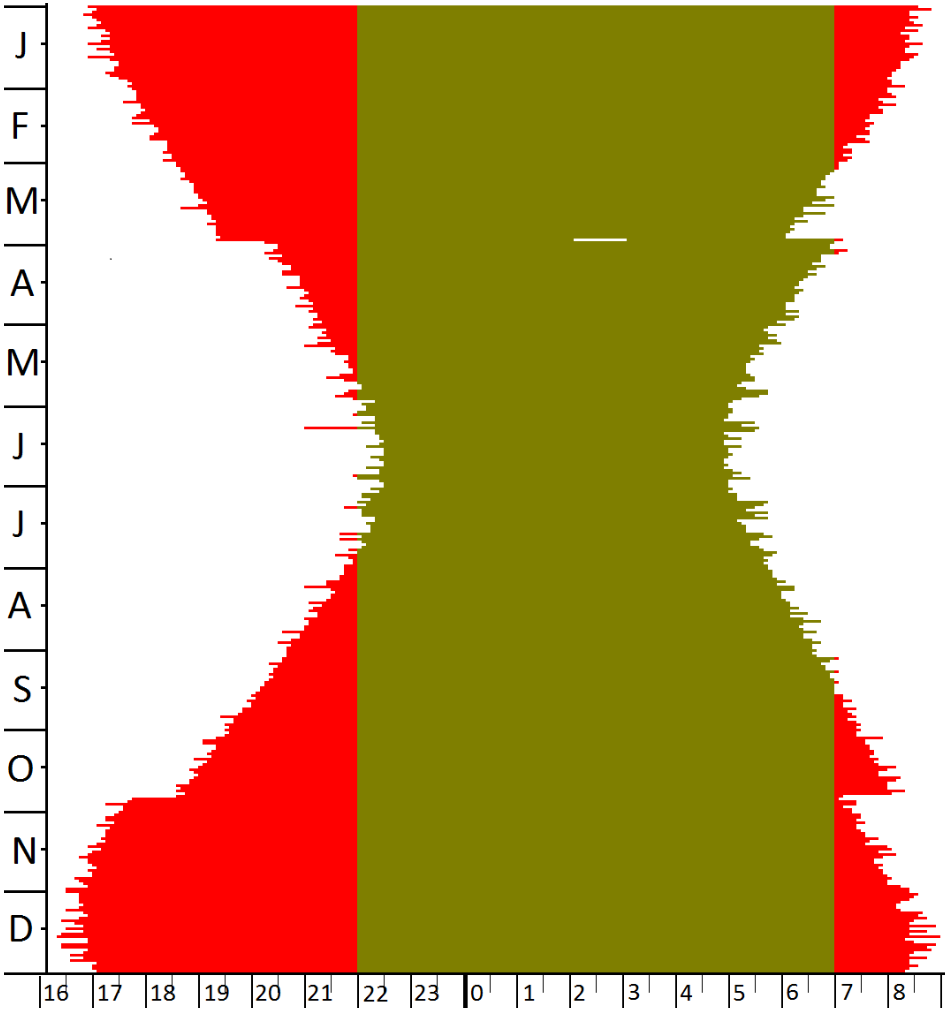
- The system is activated based on daylight

$$\Delta(t) = \begin{cases} 0 & \text{if the lighting system is off} \\ 1 & \text{otherwise} \end{cases}$$

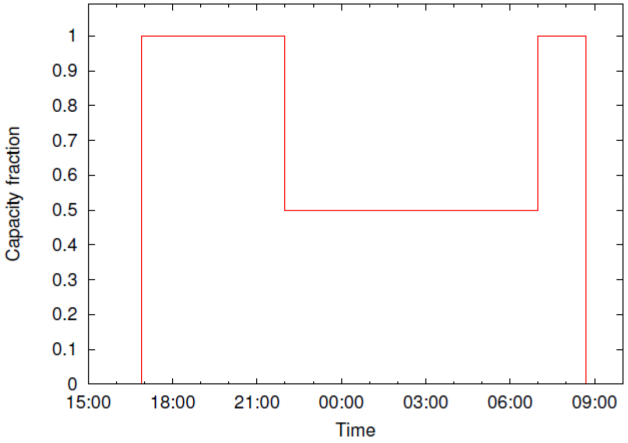
- The total energy consumption of a luminaire l in an interval

$$E^l([T_1, T_2]) = \int_{T_1}^{T_2} \Delta(t)\rho^l\big(\lambda^l(t)\big)\,\mathrm{d}t$$

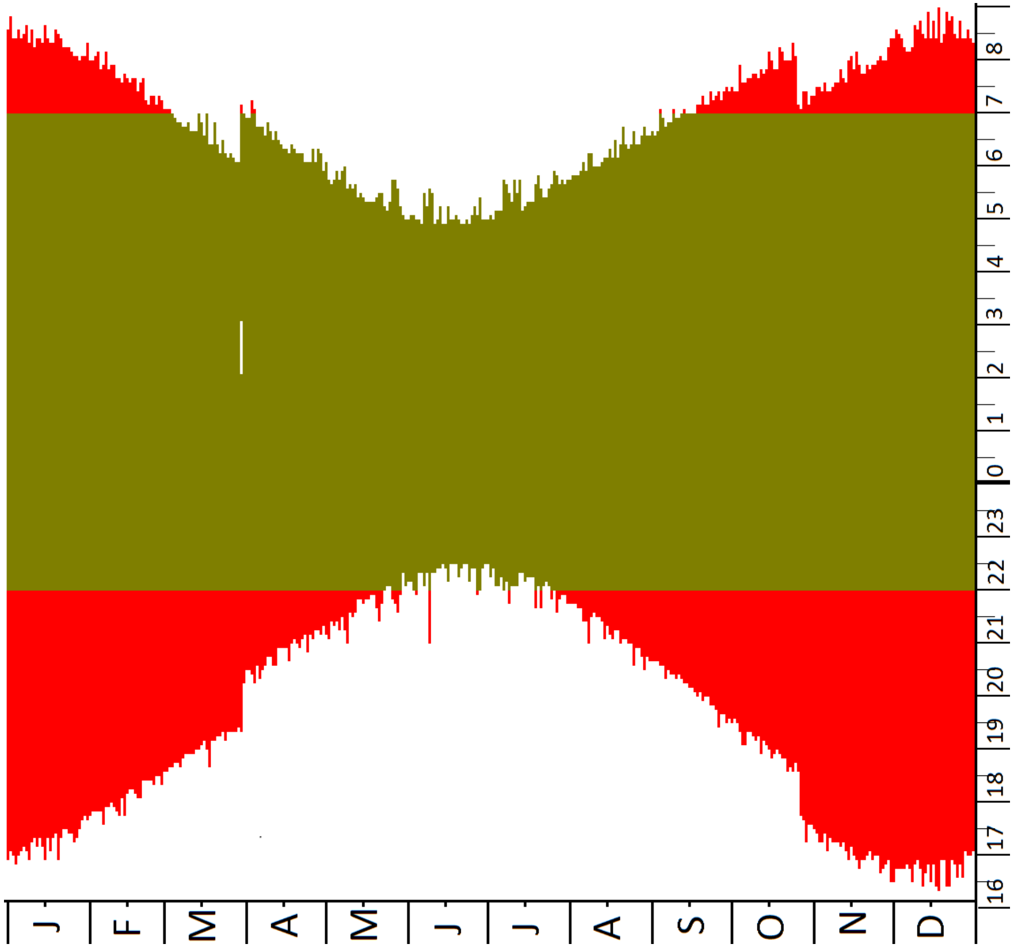
Capacity profile



- Each pole has a capacity profile over the year and over a day
- Average over 5min intervals
- For this static case: no variations



Capacity profile



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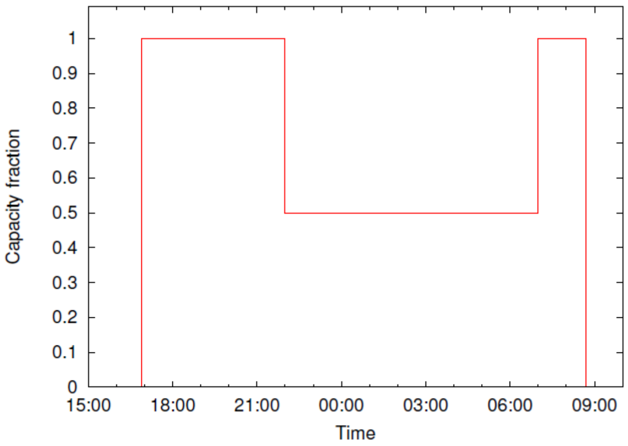
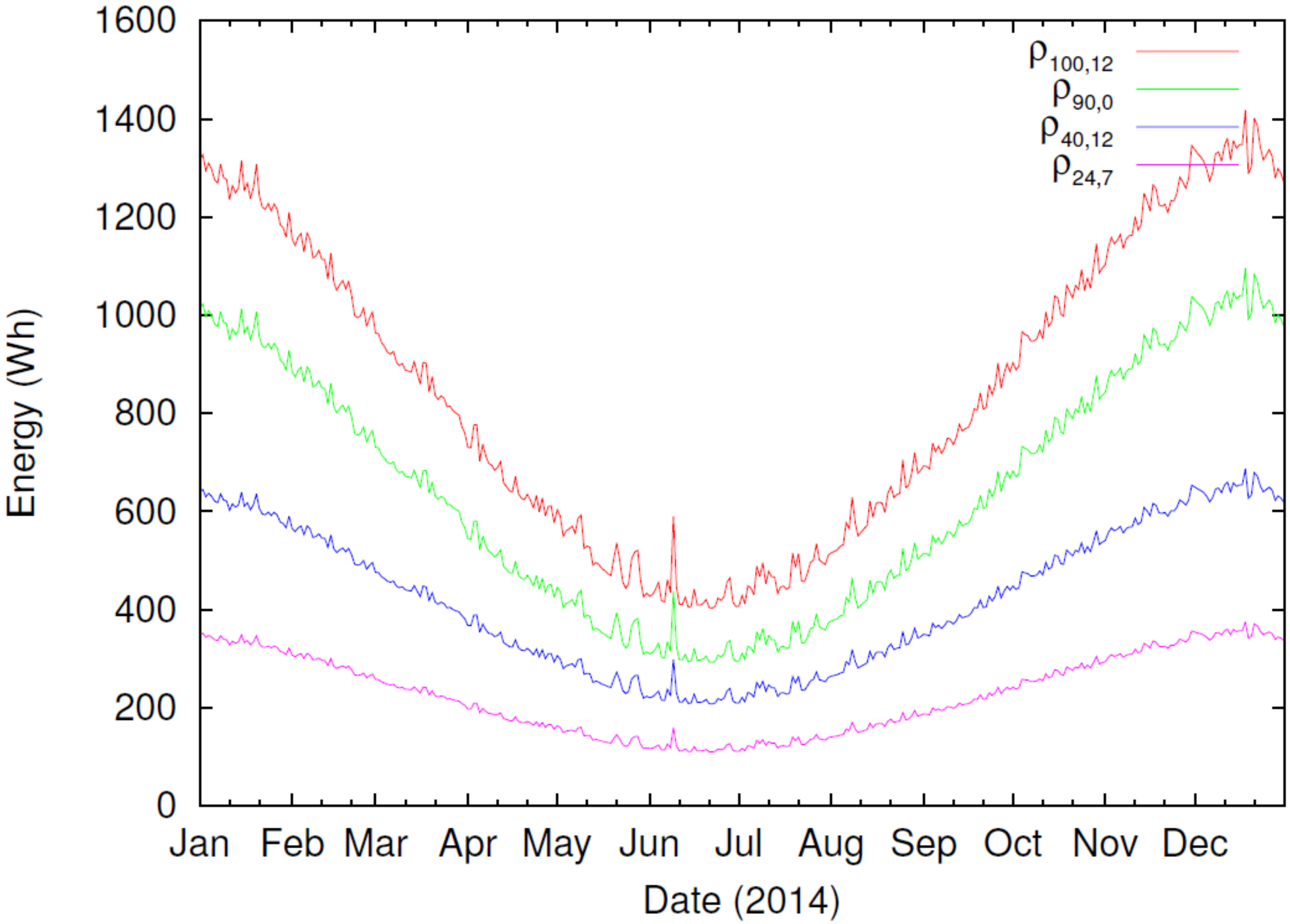


Energy consumption of static lighting



- Two poles (representative ones)
- Red and blue: legacy
- Green and purple: new LED based system

- Daily and seasonal variation
    - thunderstorm in June

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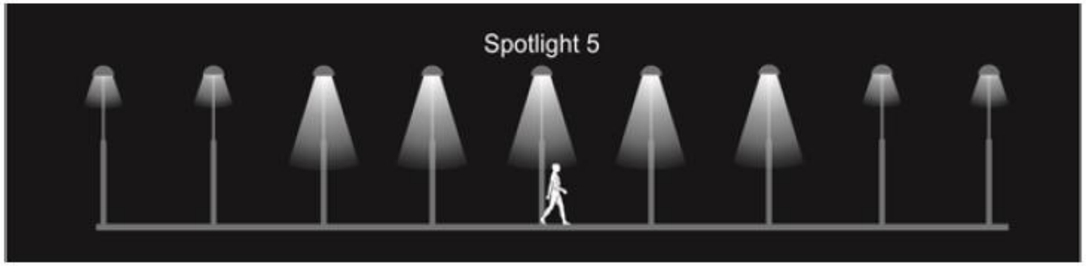
Dynamic lighting

- Algorithm:
  - Each pole is set to a certain minimum capacity
  - When a sensor triggers the pole
    - it goes to a maximum capacity
    - after a while it dims slowly to the minimum
  - This is superimposed on the static lighting
- Each sensor triggers a group of poles



- The dynamic schedule therefore depends on:
  - sensor traces
  - dimming scheme parameters
  - the static scheme

System Model – Sensors and dynamics

- Set of (PIR) sensors P
- Each sensor p has a detection sequence (on/off): $\sigma^p(t)$

- The system has a set of sequences: $\Sigma = \{\, \sigma^p : p \in P \,\}$

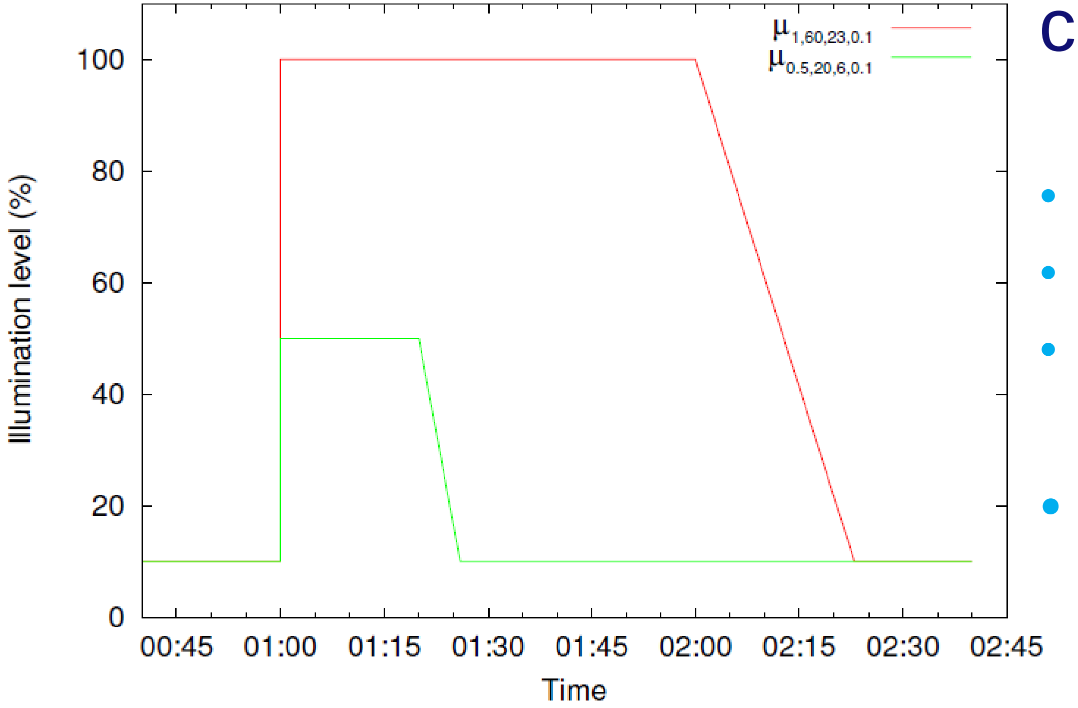
- A dynamic schedule depends on all sequences and on the static schedule:

$$\mu^l_{\Sigma,\lambda^l}(t)$$

- The total energy consumption for dynamic lighting:

$$E^l([T_1, T_2]) = \int_{T_1}^{T_2} \Delta(t)\rho^l\left(\mu^l_{\Sigma,\lambda^l}(t)\right)\mathrm{d}t$$

System model - Dynamic lighting

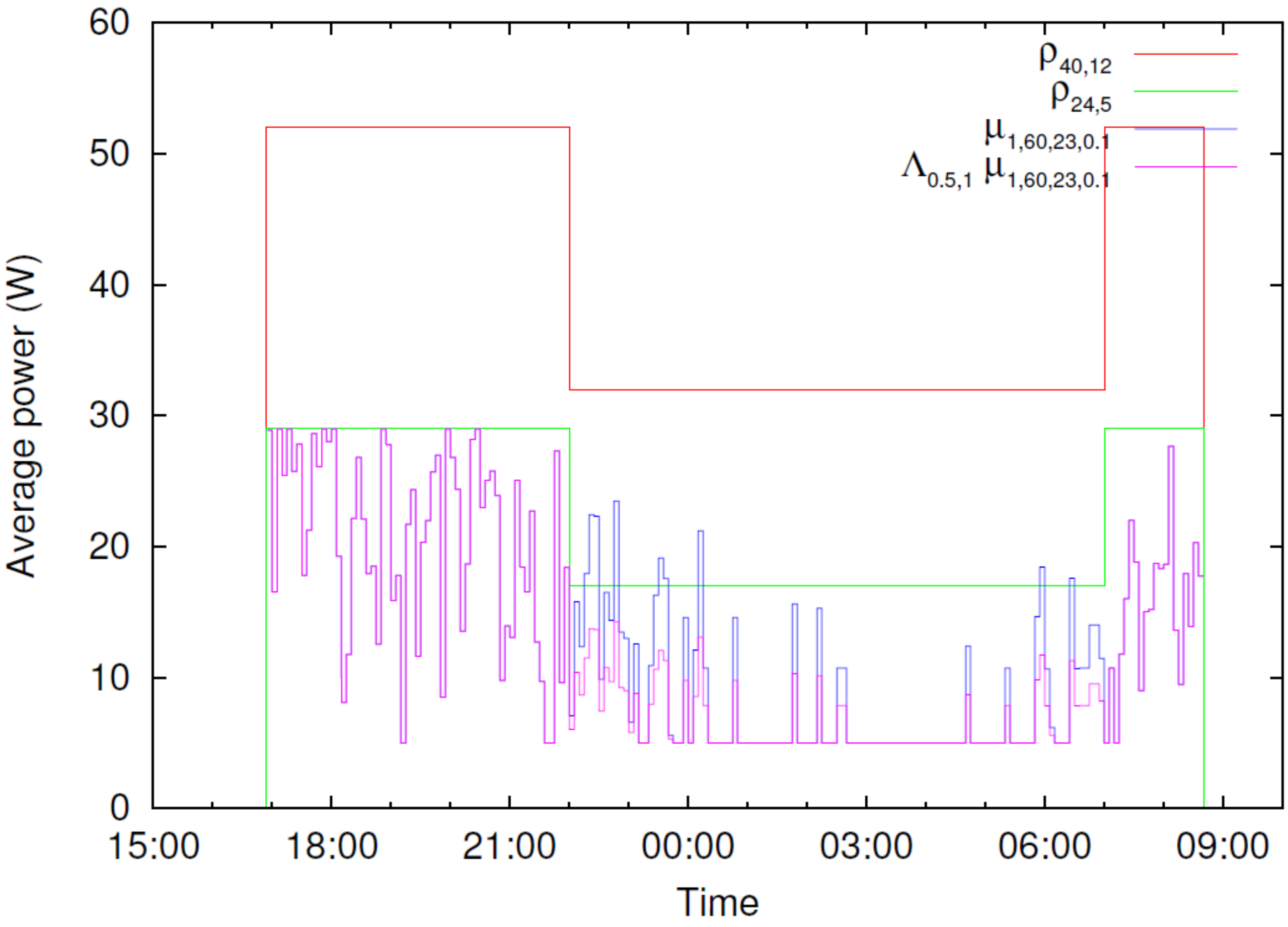


capacity: $\mu_{M,h,d,m}(t)$

- *M:* maximum, *m:* minmum
- *h:* hold time
- *d:* dim down time

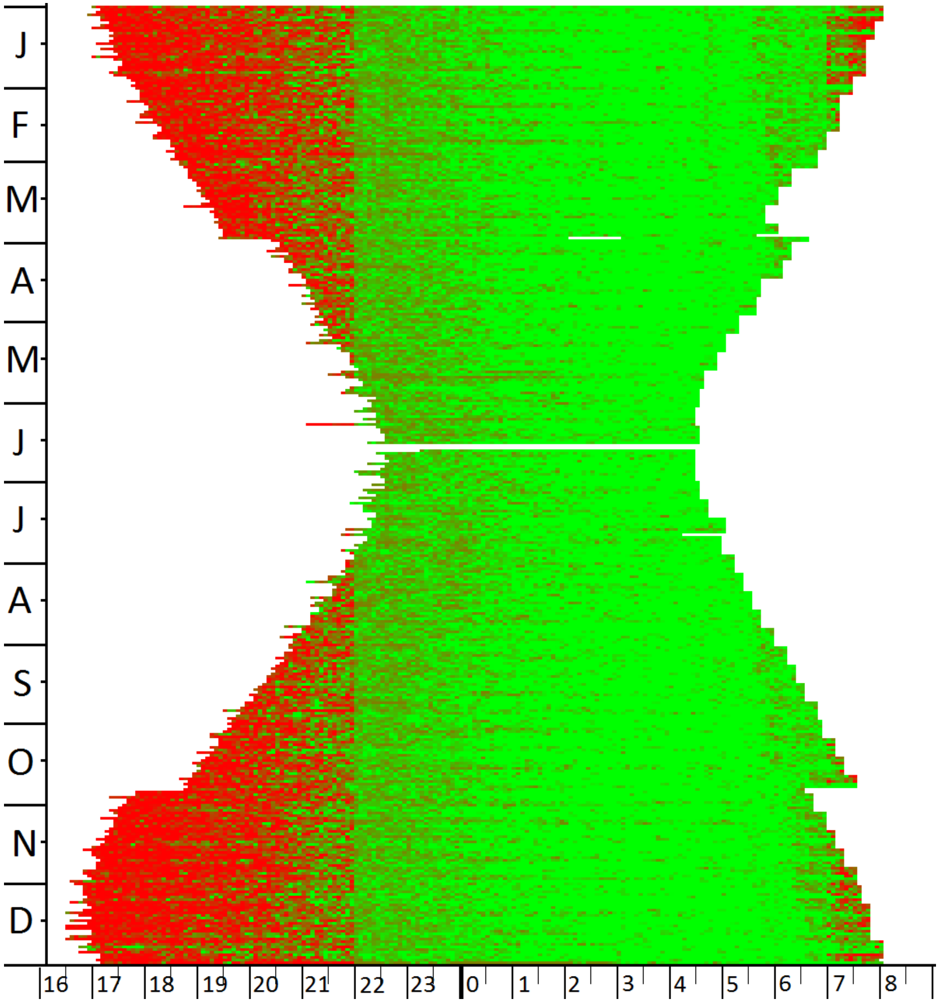
- $\mu_{M,h,d,m}(t) =$
  $m + (M - m) \times \mu_{1,h,d,0}(t)$

Static versus dynamic lighting



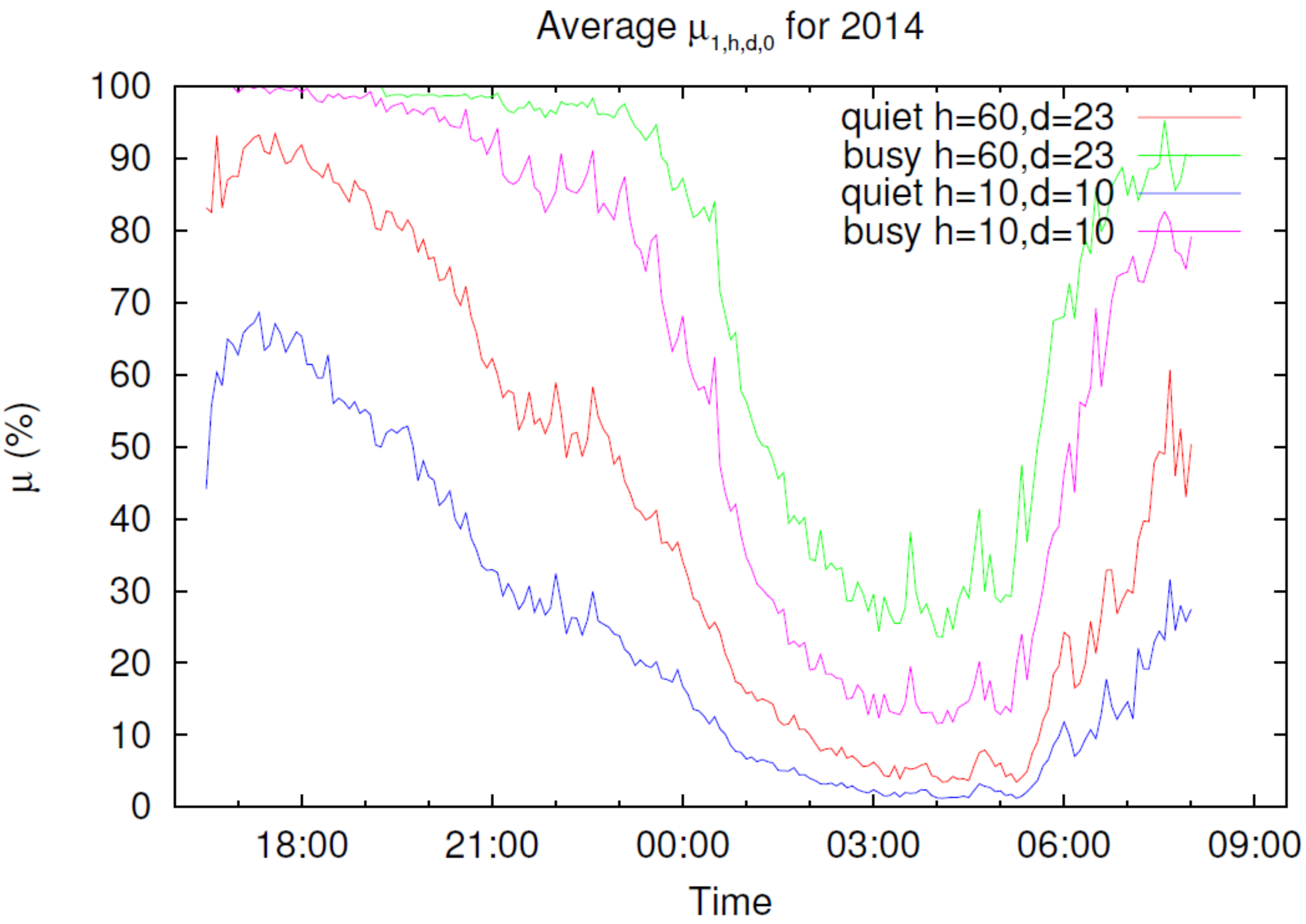
- Specific day, specific pole
- Red to Green: legacy to LED
- Standard dimming scheme: 50% at 10pm
- Dynamic:
  - based on averages over 5min intervals
  - improvement if less than the green integral
  - blue: average over 5min periods
  - purple: idem, but superimposed over a static dimming scheme

Results for dynamic dimming



- Specific pole (in quiet area)
- Simulate area based on activity information
  - resp. with / without static lighting
- Per pole and 5 minute interval, determine average $\boldsymbol{\mu_{1,h,d,0}(t)}$
  - color: $(100 - \boldsymbol{\mu})$ green, $\boldsymbol{\mu}$ red
- Determine average $\boldsymbol{\mu_{1,h,d,0}(t)}$ during a day by vertical averaging

Capacity in case of dynamic lighting



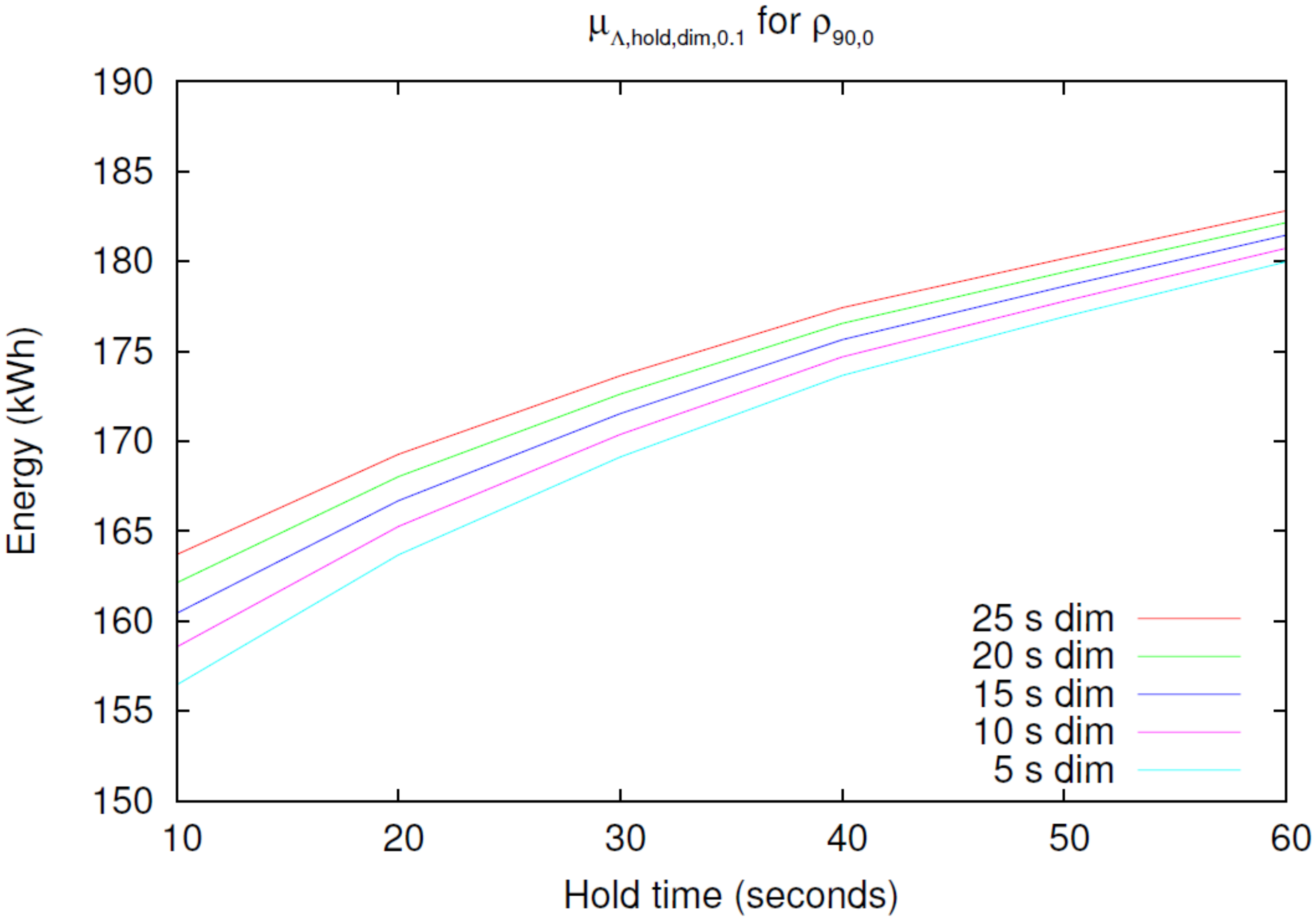
- 2 specific poles
- % of capacity used by several dynamic schemes
- average over 5 minute intervals during the year
- spikes
  - bus line
  - early workers

Energy consumption per luminaire

Schedule	Busy, legacy	Busy, LED	Quiet, legacy	Quiet, LED
Static	312.1 kWh	236.1 kWh	154.7 kWh	83.7 kWh
Dynamic, max		259.9 kWh		59.5 kWh
Dynamic		184.1 kWh		52.4 kWh
Static, 60%		141.7 kWh		58.5 kWh
Dynamic, 60%		115.3 kWh		42.4 kWh

- Energy savings of LED are significant
- 60%: to compensate for over capacity
- Uncertain about dynamic lighting
    - At € 0.10 / kWh, (additional) cost saving of € 2.50 - € 5.20 / year / pole
    - Sensor hardware should be very robust and cheap.

Alternative hold and dimming times



- dynamic scheme (graphs based on sensed activity)
- can use gains for more light or for cost reduction
- low values give rapid changes
  - disadvantage

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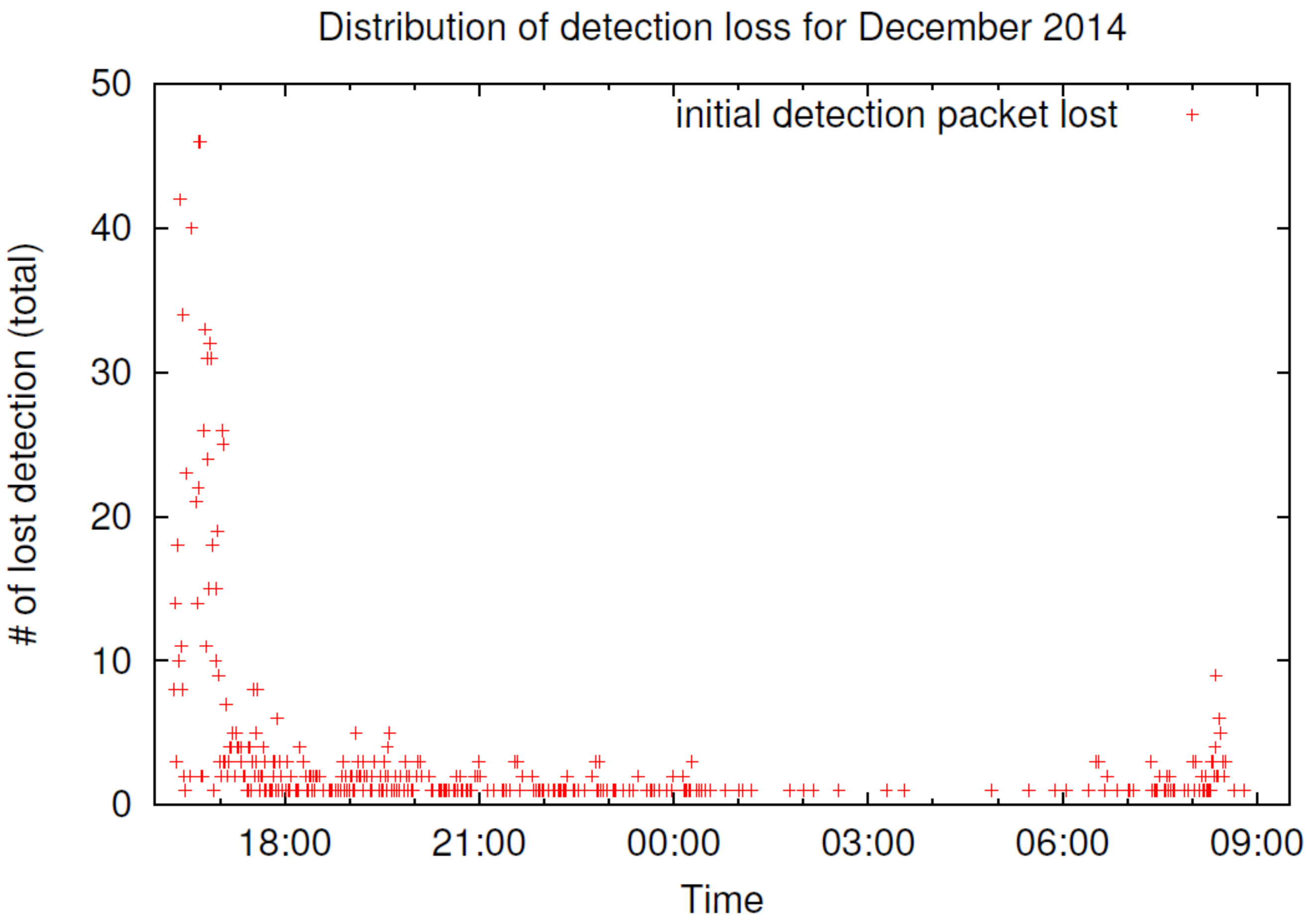
Impact of packet loss



Initial packet:

- the signal to switch on

Start-up:

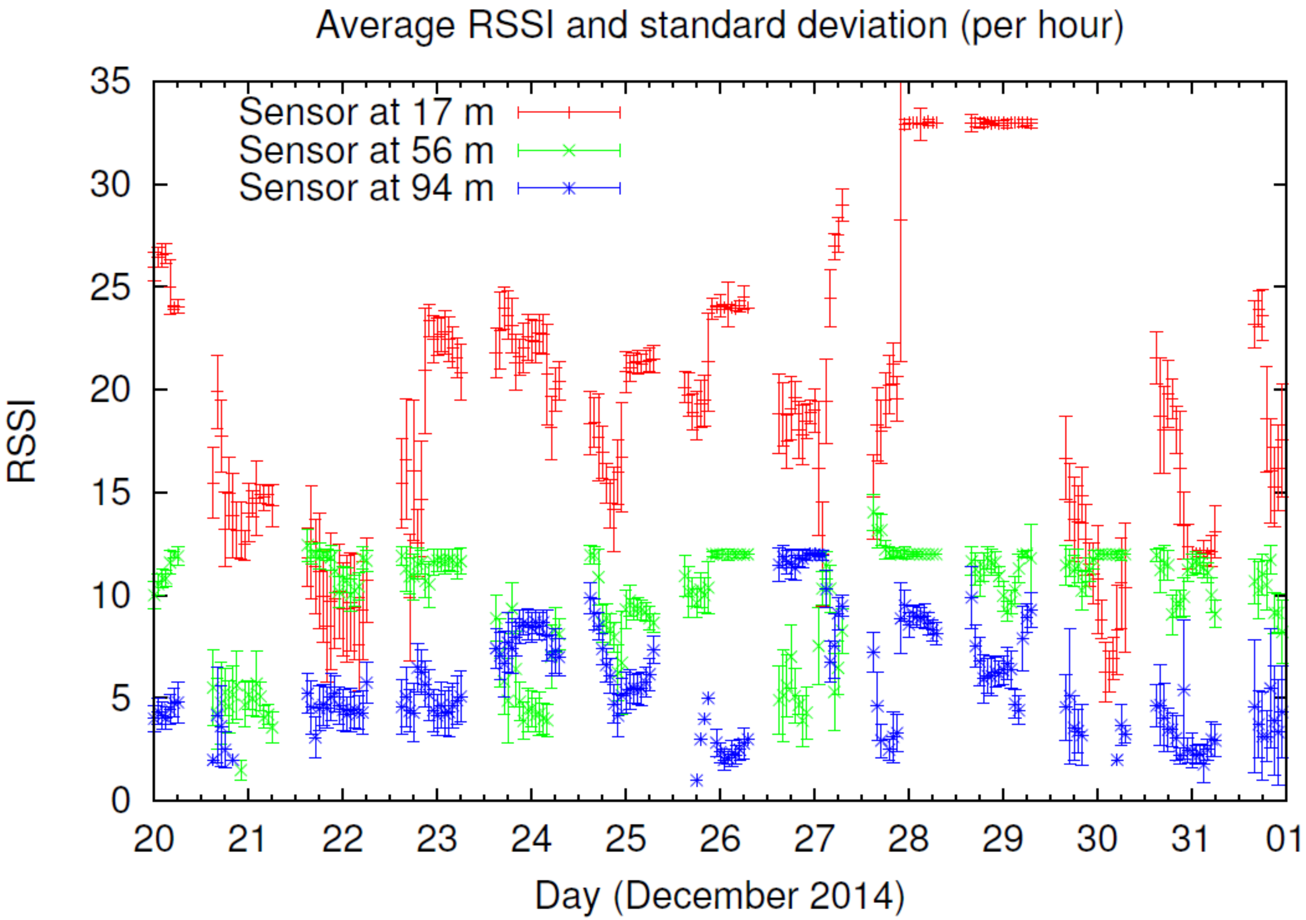
- Calibration
- Network setup

Operation:

- Collisions in busy times
- During night: 0.5% loss

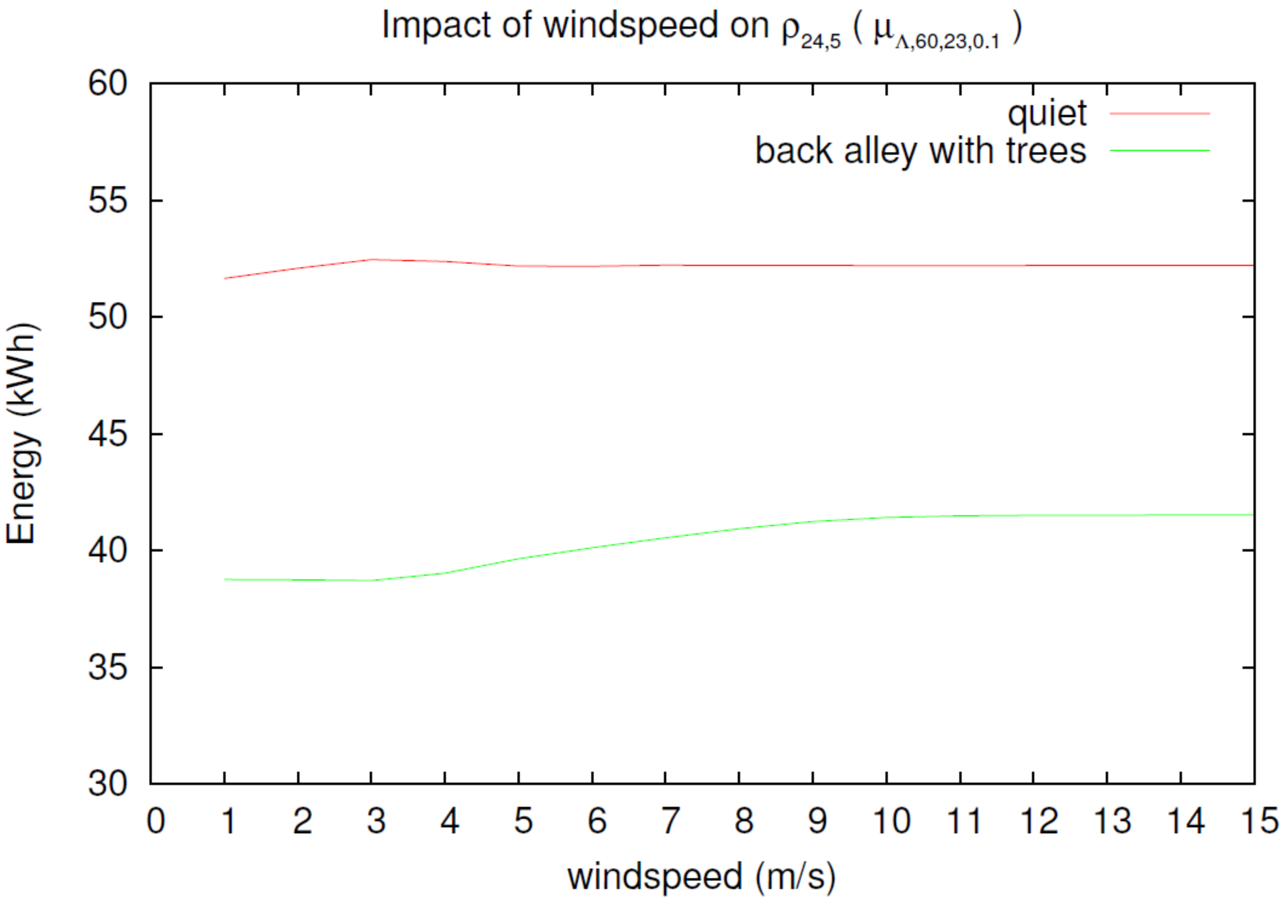
- Protocol deals well with occasional losses

Quality of radio signals



- RSSI correlation with distance not simple
    - even order not constant

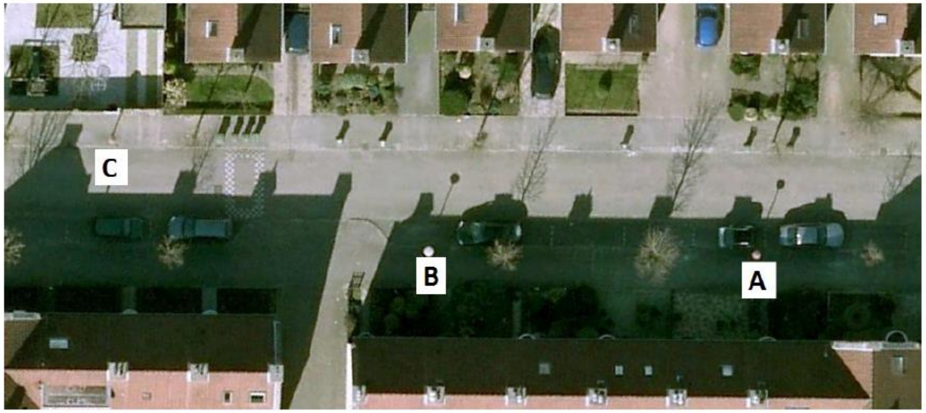
Wind sensitivity of PIR

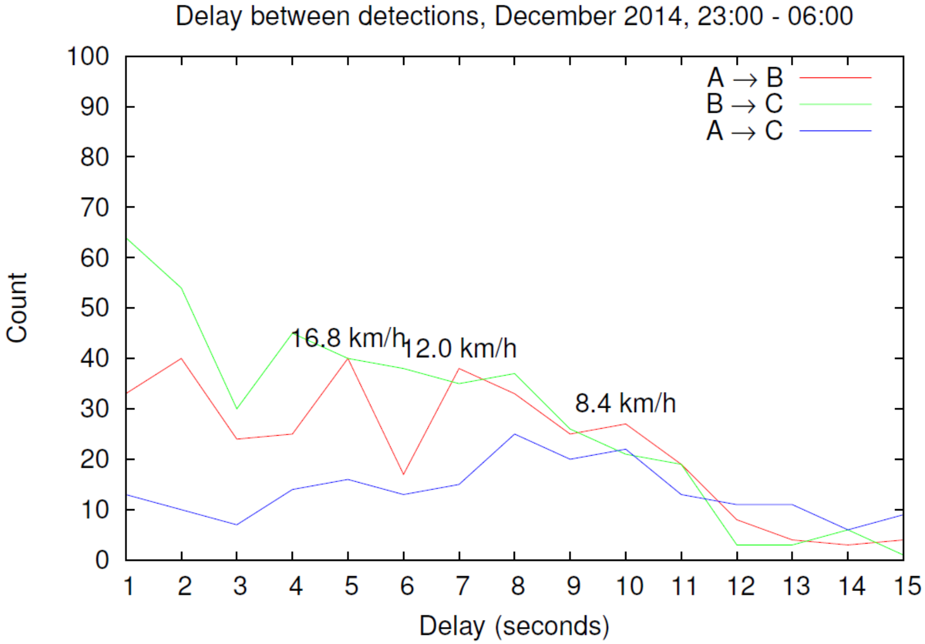


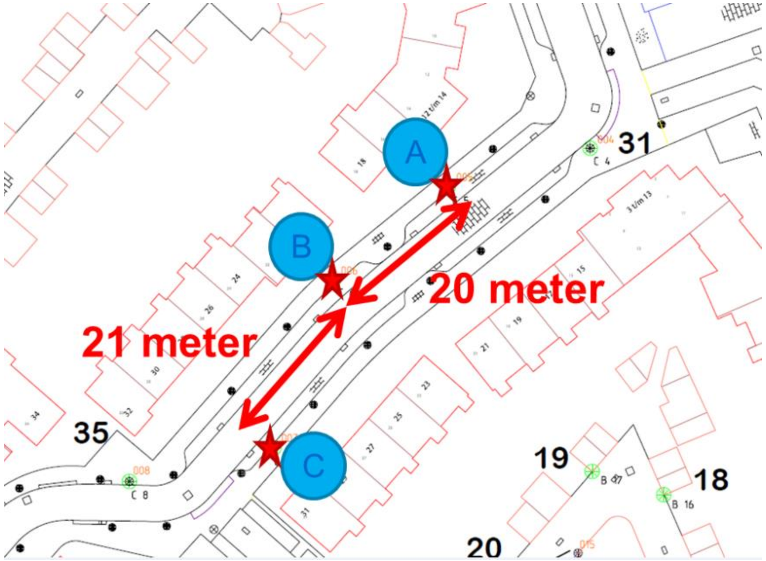
- one sensor influences a few light poles
- badly placed sensor affects larger area
    - ignore measurements above a certain wind speed

- Extrapolate total energy consumption

Speed detection and classification







- The graph shows histograms of delays
- More sophistication is required
  - to classifiy (vehicles, bicycles, pedestrians)
  - to track

Conclusions

- Energy savings of 55-63% for LED vs. legacy
    - additional 8-10% for dynamic lighting

- Savings of 28-38% for dynamic vs. static
    - however, not expected to be cost effective

- Collected data very useful for detailed analysis
    - What-if questions, new strategies
    - Correlations between data traces
    - In fact, useful for all activity-related questions

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