UVA ENGINEERING
LINK LAB

A Machine for Living in

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University of Virginia

What are the mechanisms needed to make a building healthy?

Problem

- Americans spend 90% of their lives **indoors** [1], and buildings 40% of the total energy consumption [2]
- When designed around the occupants needs, preferences, and comfort levels, **consumption** reduced significantly [3].
- Indoor environment shown to have a dramatic effect on the occupant's **health** and well-being [4, 5]
- Worthwhile financially, pressing healthfully, so why is **occupant data** still so **vastly under-exploited** [3]?

[1] US Environmental Protection Agency. "Report to Congress on indoor air quality, volume II: assessment and control of indoor air pollution". In:Technical Report EPA/400/1-89/001C(1989).

[2] US EIA. "How Much Energy is Consumed in US Residential and Commercial Buildings?" In:United States Energy Information Administration, Washington, DC, accessed Dec 11 (2017), p. 2018.

[3] Andreas Wagner, William O'Brien, and Bing Dong. "Exploring occupant behavior in buildings". In:Wagner,A., O'Brien, W., Dong, B., Eds(2018).

[4] Billie Giles-Corti and Robert J Donovan. "The relative influence of individual, social and physical environment determinants of physical activity". In:Social science & medicine 54.12 (2002), pp. 1793–1812.

[5] MJ Finnegan, CA Pickering, and PS Burge. "The sick building syndrome: prevalence studies." In:Br Med J (Clin Res Ed)289.6458 (1984), pp. 1573–1575.

State-of-the-art Summary

[1] Jervez Hameed Shaikh et al. “A review on optimized control systems for building energy and comfort management of smart sustainable buildings”. In:Renewable and Sustainable Energy Reviews 3 4 (2014),pp. 409–429.

[2] Joseph G Allen and John D Macomber.Healthy buildings: How indoor spaces drive performance and productivity. Harvard University Press, 2020.

[3] Veli-Pekka Niitamo et al. “State-of-the-art and good practice in the field of living labs”. In:2006 IEEE international technology management conference (ICE). IEEE. 2006, pp. 1–8.

[4] A Habibipour. “Living Lab research: A state-of-the-art review and steps towards a research agenda”. In:OLLD18—OpenLivingLabs Days Research and Innovation Conference, Geneva, Switzerland. 2018.

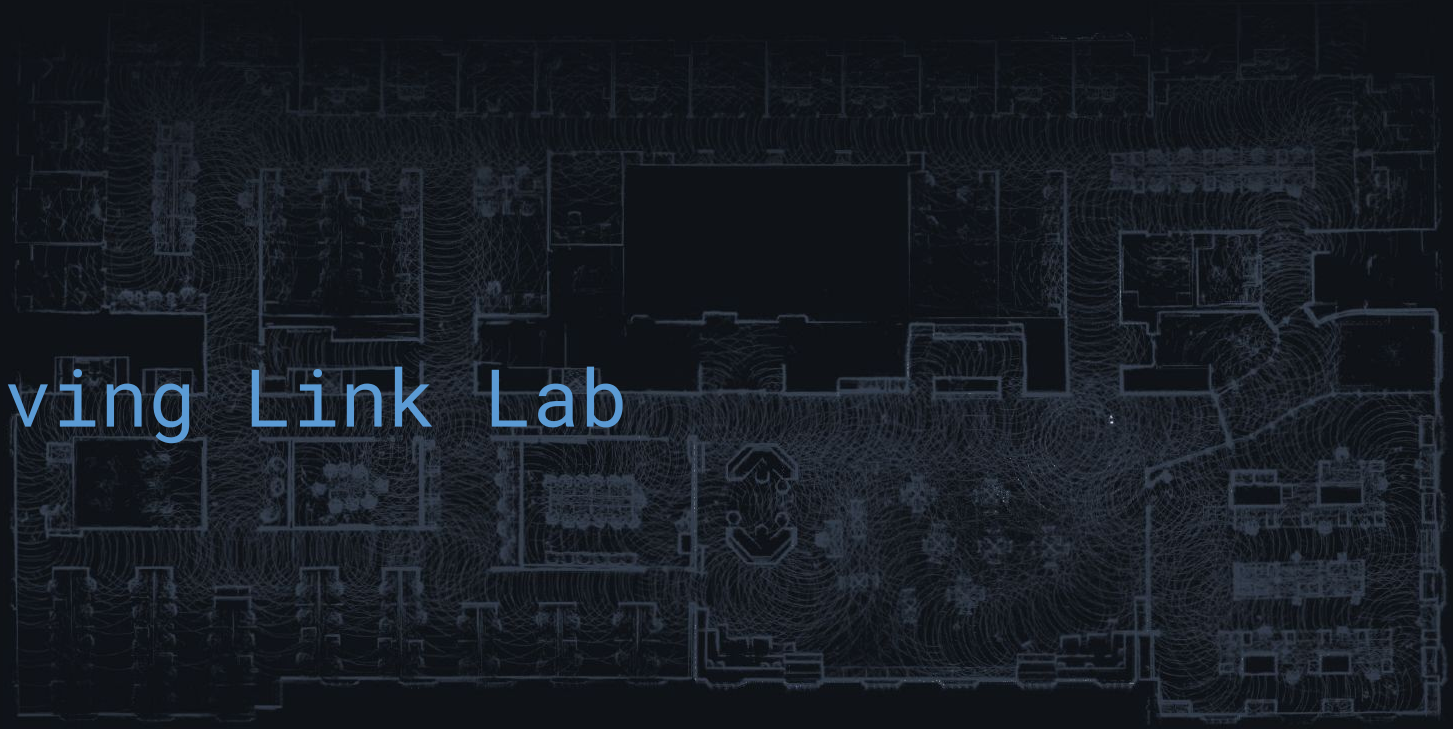
[5] Nguyen, Linh, Guoqiang Hu, and Costas J. Spanos. "Efficient spatio-temporal sensor deployments: A smart building application." In 2017 13th IEEE International Conference on Control & Automation (ICCA), pp. 612-617. IEEE, 2017.

- A 33% **discrepancy** between predicted and actual energy consumed observed due to lack of occupant behavior information [1].
- Lack of **longitudinal commissioning** of buildings, minimum standards, and reliance on self-reports call for healthy buildings movement [2].
- Living Labs proposed as a strategy, but definition **ambiguous** [3, 4]
- **Placement** of sensor important [5]

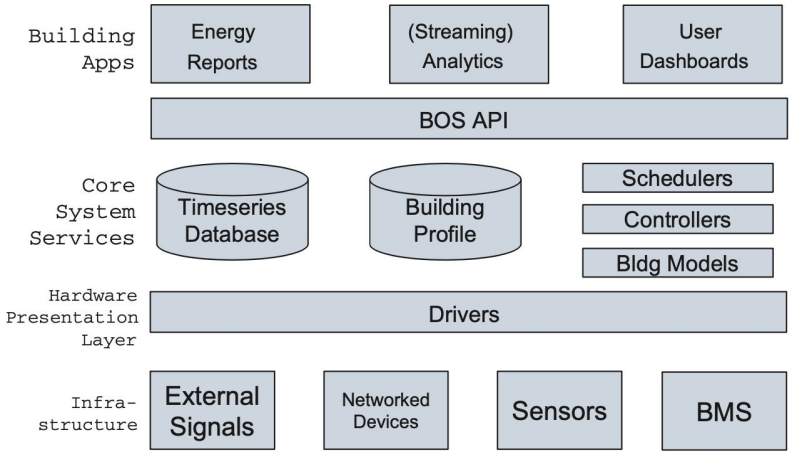
Proposed Approach

- The Living Link Lab
- Maintenance of energy harvesting sensors (EH-Housekeeper)
- Lighting and Sleep in the Hospital

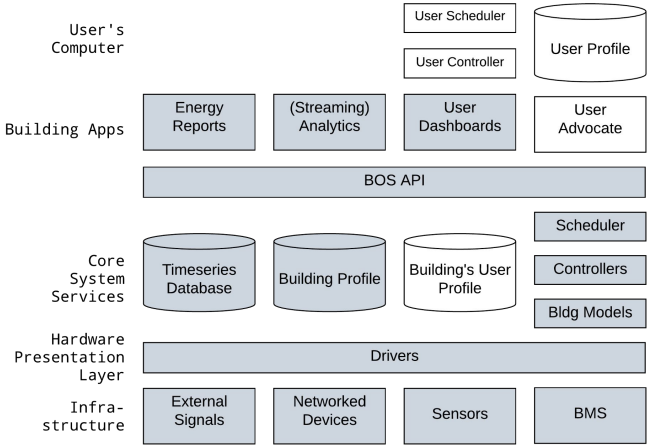
Living Link Lab



Approach: Building Operating Systems (BOS)

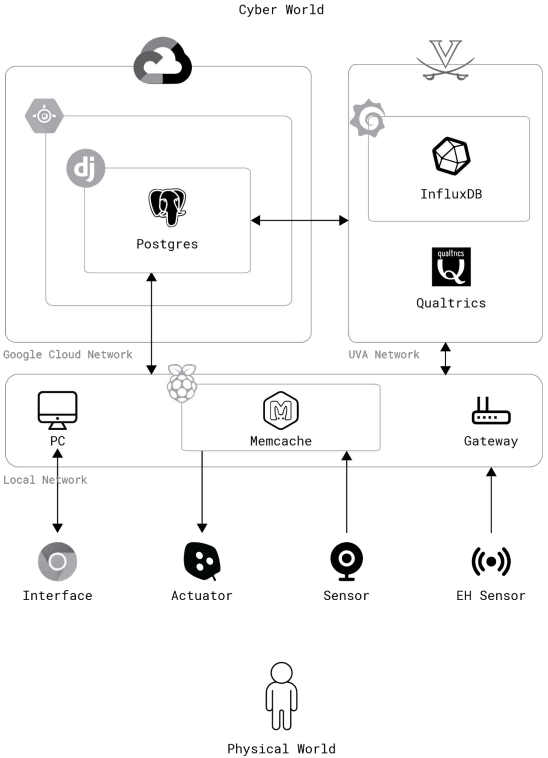


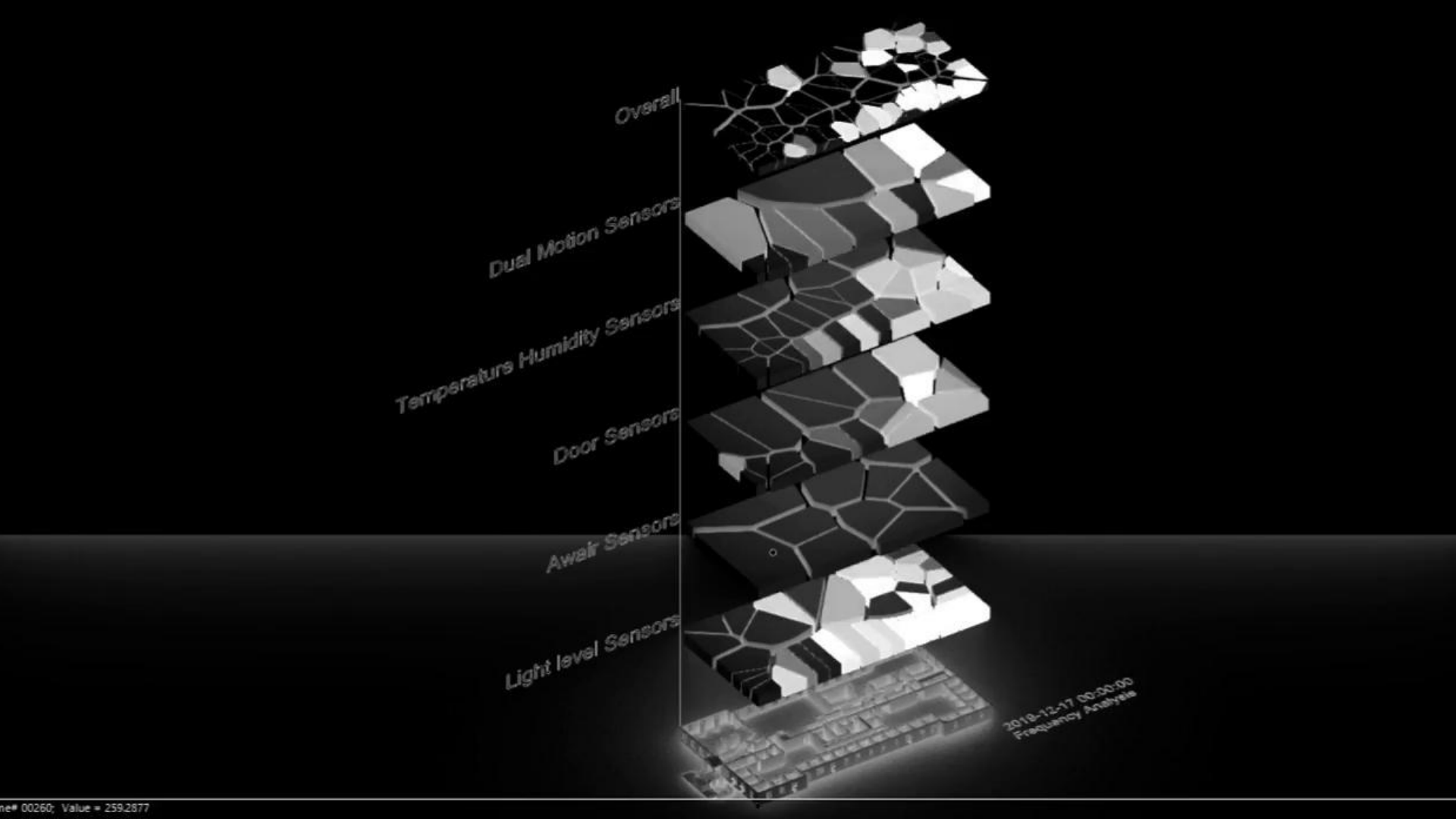
Generic Building Operating System, from Bharathan Balaji et al. "Brick: Metadata schema for portable smart building applications". In:Applied energy 226 (2018), pp. 1273–1292.



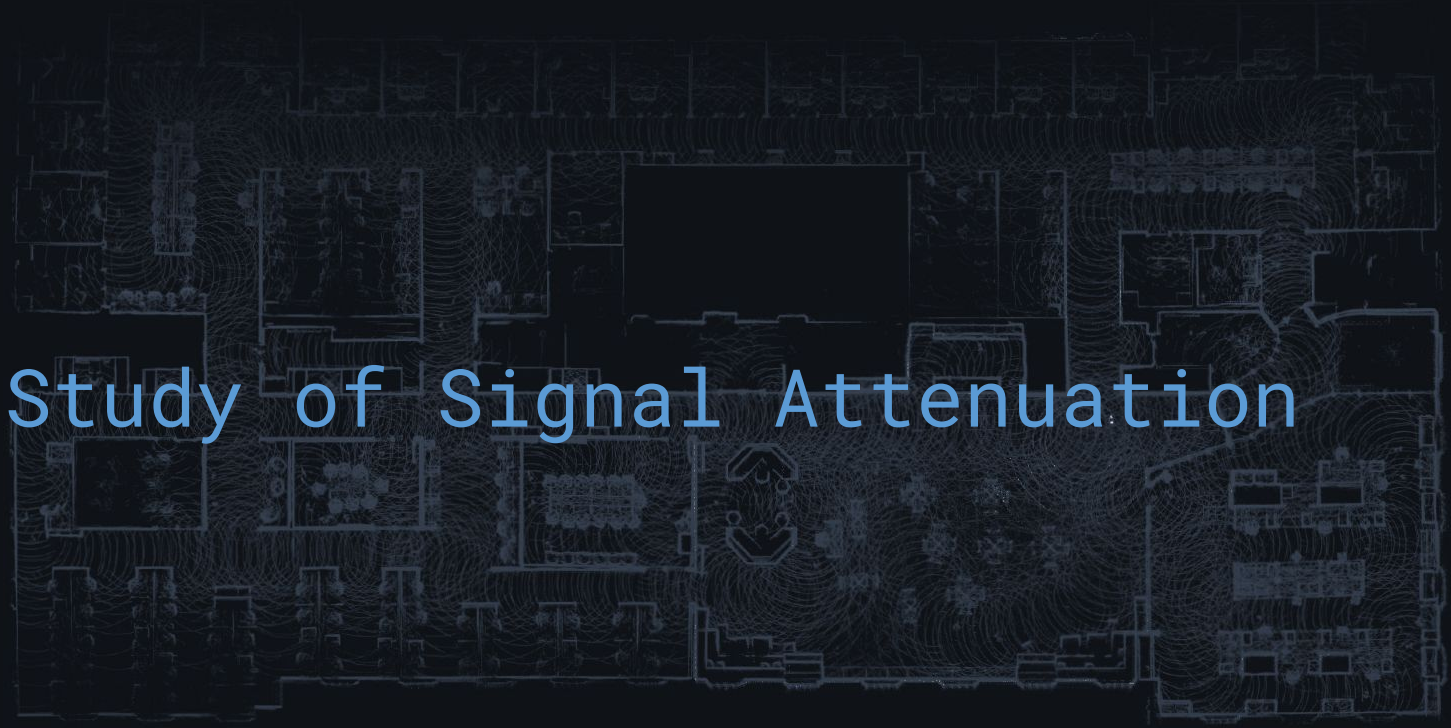
Proposed BOS

Results: Living Link Lab System Architecture




Overall
Dual Motion Sensors
Temperature Humidity Sensors
Door Sensors
Awair Sensors
Light level Sensors
2018-12-17 00:00:00
Frequency Analysis

A Study of Signal Attenuation



Approach: Research Questions

- If the gateway does not detect data from an energy harvesting sensor, is it broken, hibernating, or healthy?
- Given the location of sensors in a building context, where should a gateway be located to minimize packet loss?
- Is it possible to accurately predict the silent rate of the sensor network given the 2D building plan?

Motivation & Related Works

- Better scalability of maintenance compared to mains-powered devices [1]
- Radio signal attenuation in an indoor environment [2,3]
- Longitudinal study of battery-powered devices and silent rates [4]

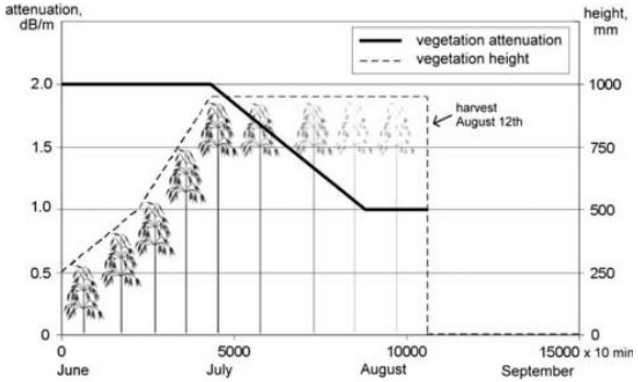


Fig. 3 Oats vegetation attenuation included in the model

Figure from [4]

[1] Timothy W Hnat et al. “The hitchhiker’s guide to successful residential sensing deployments”. In:Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems. 2011, pp. 232–245.

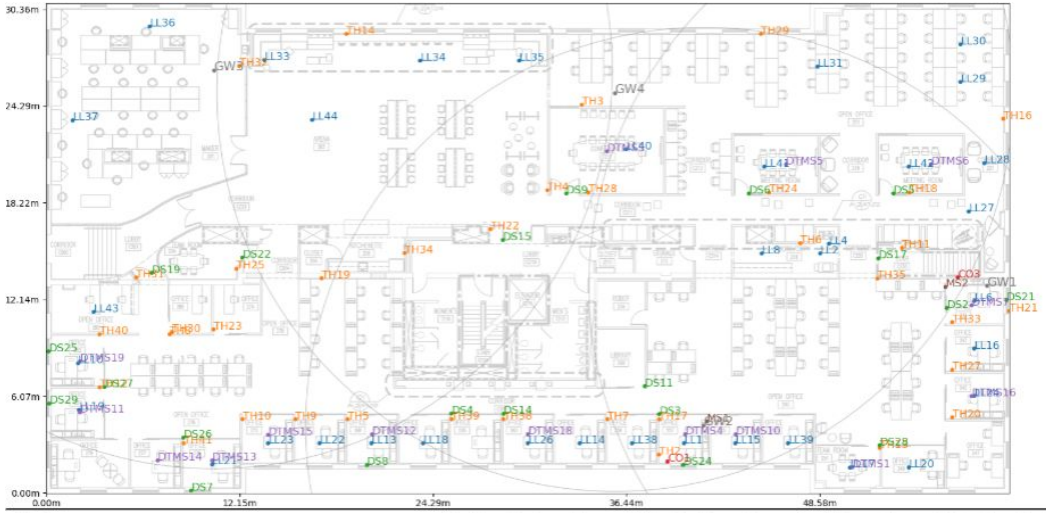
[2] William F Young et al. “Radio-wave propagation into large building structures—Part 1: CW signal attenuation and variability”. In:IEEE Transactions on Antennas and Propagation 58.4 (2010), pp. 1279–1289.

[3] Andr´e GM Lima and Luiz F Menezes. “Motley-Keenan model adjusted to the thickness of the wall”. In:SBMO/IEEE MTT-S International Conference on Microwave and Optoelectronics, 2005.IEEE. 2005, pp. 180–182.

[4] Johannes Tiusanen. “Wireless soil scout prototype radio signal reception compared to the attenuation model”. In:Precision Agriculture 10.5 (2009), pp. 372–381.

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Approach: Energy Harvesting Sensors

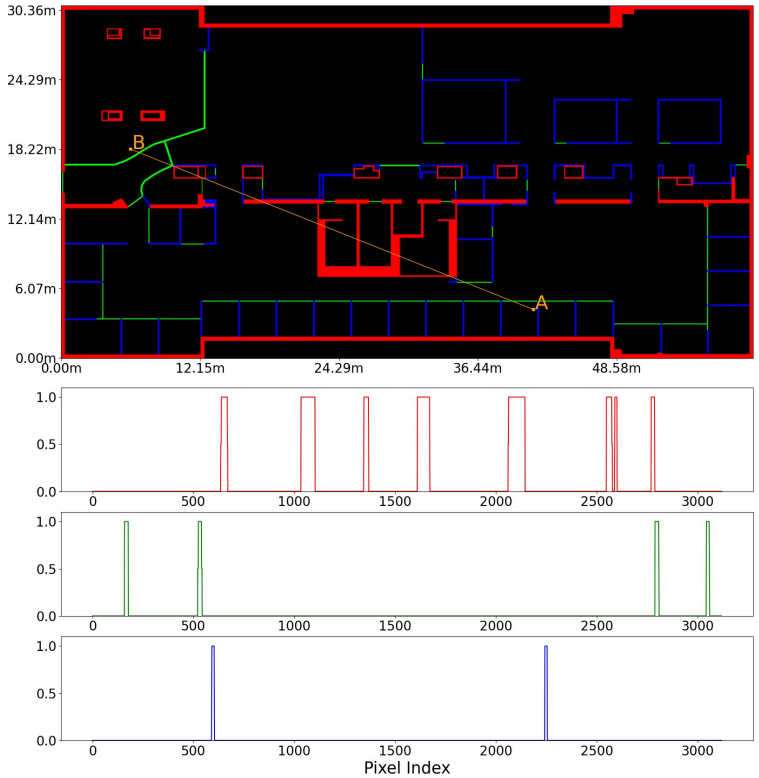


Device	Prefix	Units	Transmission Radius	Operation Time	Largest Heartbeat Interval
Swarm Gateway [22]	GW	4	N/A	N/A	None
EnOcean Light Level Sensor ELLSU-W-EO	LL	40	25 meters	80 hours	30 minutes
Pressac Mini Temp Humidity Sensor (Discontinued)	TH	37	30 meters	4 days	15 minutes
EnOcean Wireless Door/Window Sensor ExT-MDCCP	DS	27	20 meters	5 days	25 minutes
Echoflex Dual Tech Ceiling Mount Sensor MOS-DT	DTMS	17	24 meters	7 days	100 seconds
Pressac Wireless CO2 60.CO2 SLR TMP HUM	CO	2	30 meters	5 hours	15 minutes
Illumra Motion Sensor E9T-OSW	MS	2	25 meters	80 hours	30 minutes

Figure 1: Projected Device Plan and Descriptions

Approach: Methodology

Sensor (B)

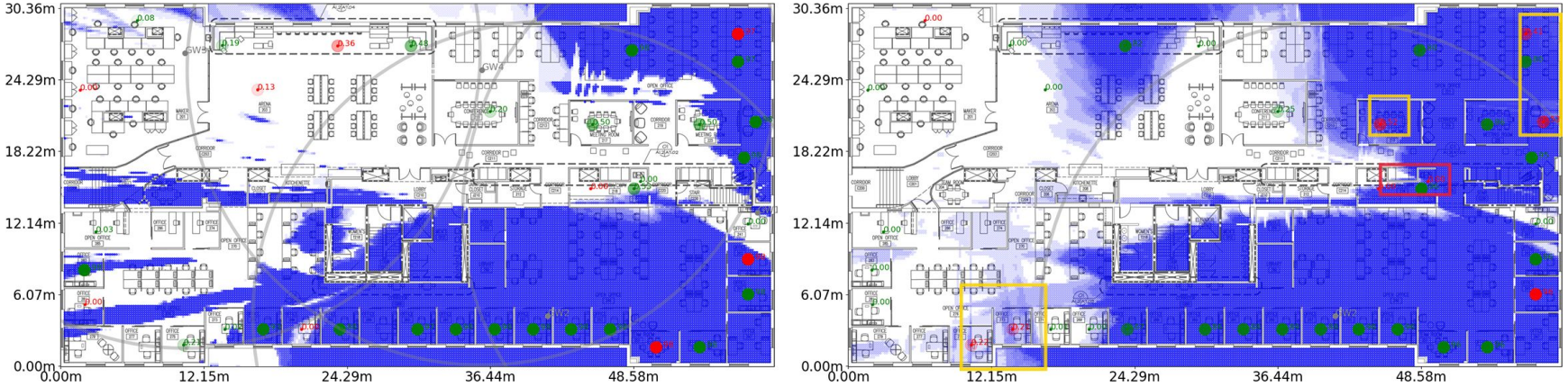


(A) Gateway

Trace the path between the transmitter and receiver by counting pixels that represents different wall materials and open space using the 2D building plan

Example Ray Trace

Results

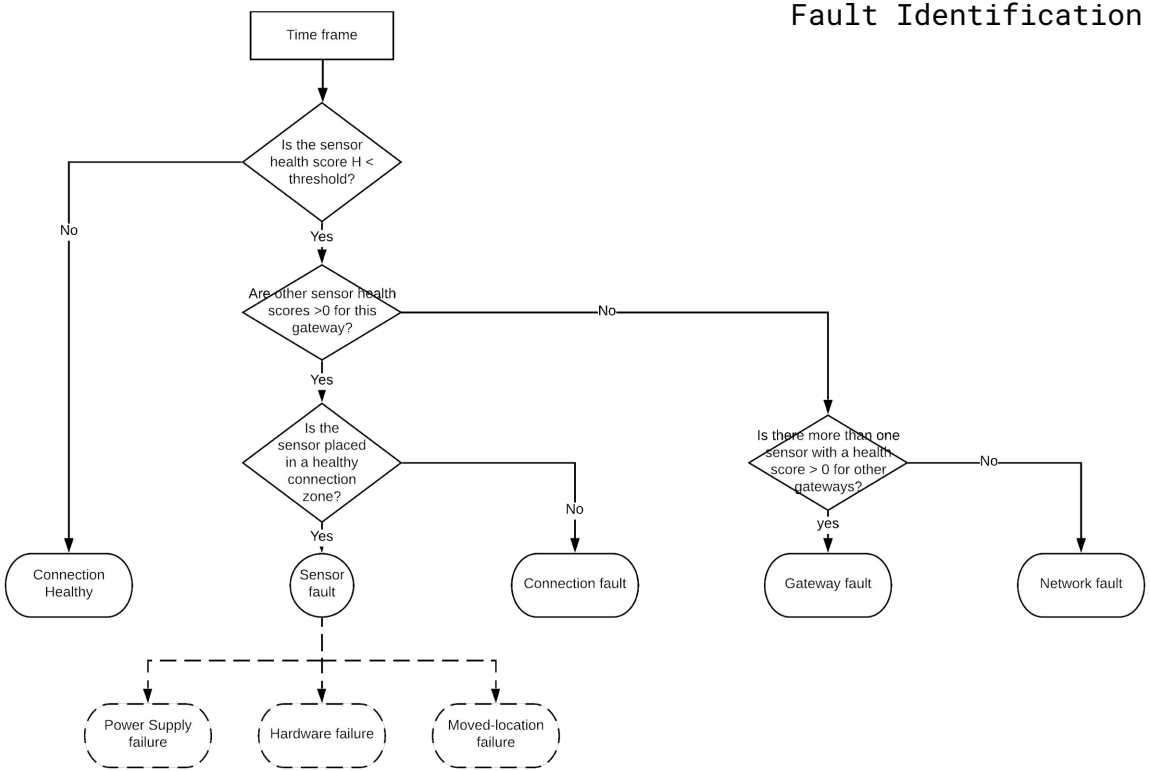


High Accuracy Versus Low Accuracy Assessments

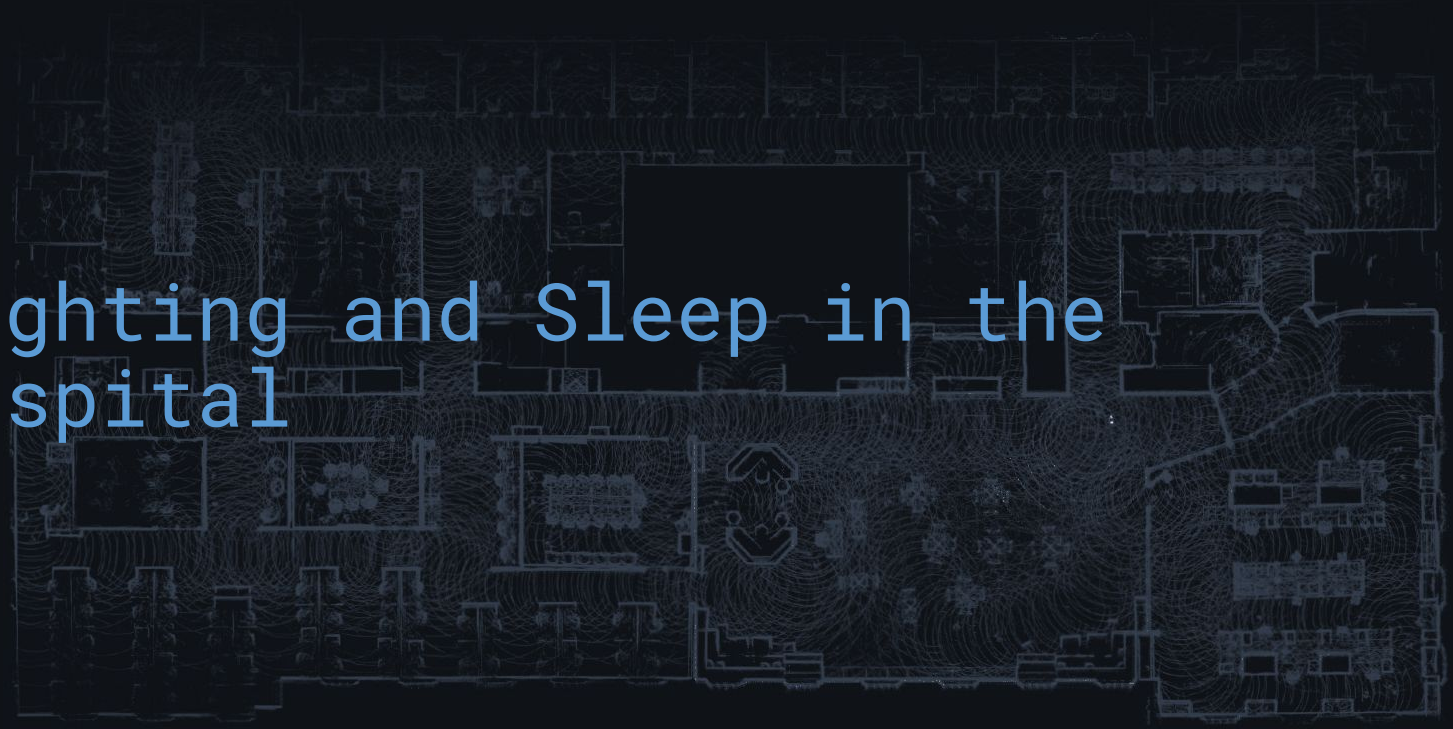
Left shows prediction based on assumed stable sensors, right shows prediction using two poorly placed sensors

Results

Fault Identification Flowchart



Lighting and Sleep in the Hospital



Approach: Research Questions

- Are there statistically significant relationship between sensed environmental conditions and quantifiable health-related metrics like sleep duration and sleep efficiency?

Motivation & Related Works

- Human circadian physiology is influenced by lighting [1]:

Figure 3.3 | Phase Response
Circadian phase response of the pacemaker to time of exposure to optical radiation.

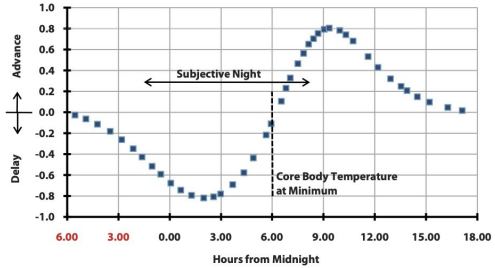


Figure from [1]

- Restorative value of sleep, and lighting's influence on sleep disruptions shown in past studies [2,3,4]

[1] IES Lighting Handbook.DiLaura David.(edit.) 2011.

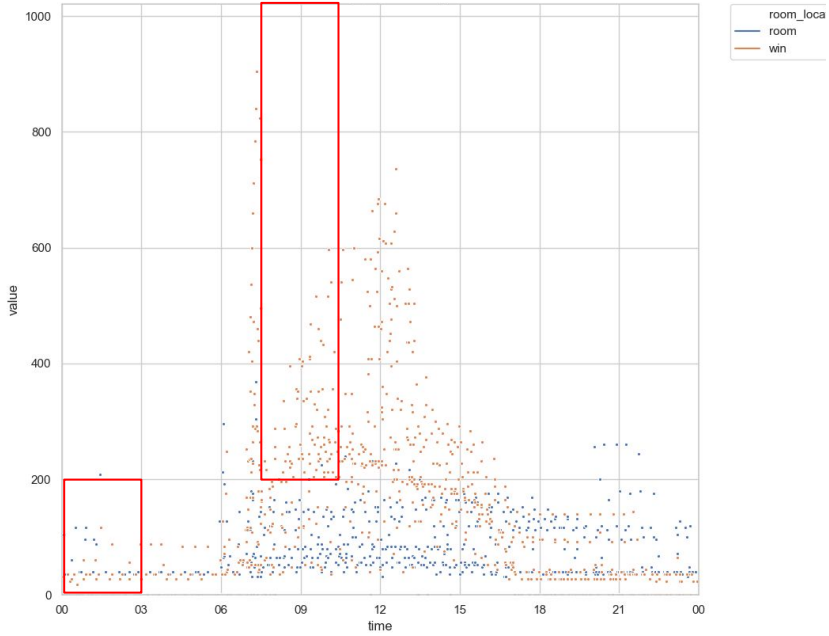
[2] Hilde M Wesselius et al. "Quality and quantity of sleep and factors associated with sleep disturbance in hospitalized patients". In:JAMA internal medicine 178.9 (2018),pp. 1201–1208.

[3] Carlos Aparıcio and Francesca Panin. "Interventions to improve inpatients' sleep quality in intensive care units and acute wards: a literature review". In:British Journal of Nursing 29.13 (2020), pp. 770–776.

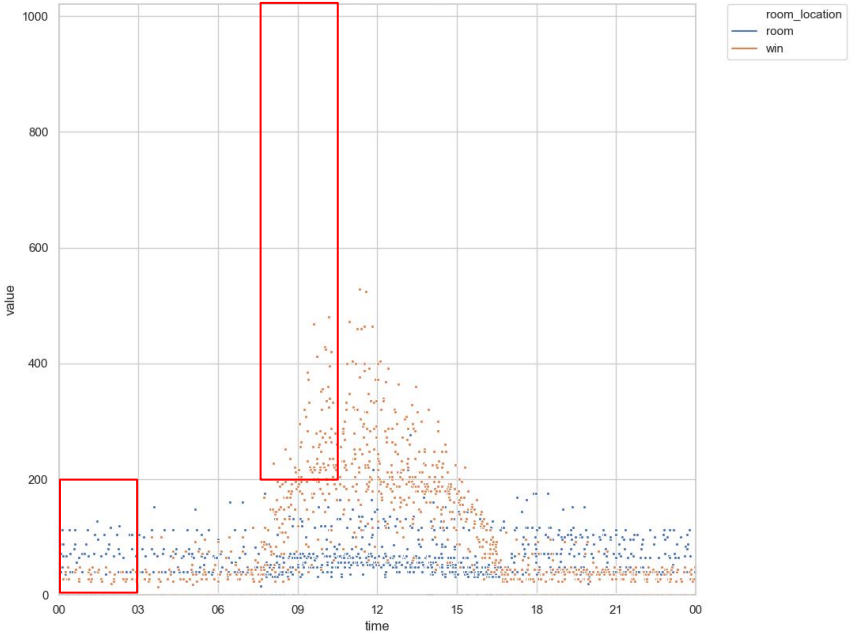
[4] Mila N Grossman et al. "Awakenings? Patient and hospital staff perceptions of night-time disruptions and their effect on patient sleep". In:Journal of Clinical Sleep Medicine 13.2 (2017), pp. 301–306.

Approach: Methodology

- Collect level sensors, temperature humidity sensors, door contact sensors, and air quality sensors in the hospital rooms (General Medicine and Geriatric Care)
- Collect Actiwatch information, tracking wrist-sensed light and sleep quantity information
- Track data from healthcare system dataset (EPIC)
- Combine all three data sets and analyze them



Check nighttime light exposure between 12 am to 3 am



Check daytime light exposure between 8 to 10 am

Conclusions and Future Work

- Proposal demonstrates an important step towards:
  - Optimizing the location of sensor and gateways communicating using ultra-high frequency (UHF) band indoors, helping with maintenance of energy harvesting sensors
  - Connecting environmental variables with quantifiable health metrics
- Currently also investigating ways to improve effectiveness of light sensors through proper placement in buildings

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