# Methods for measuring work surface illuminance in adaptive solid-state lighting networks

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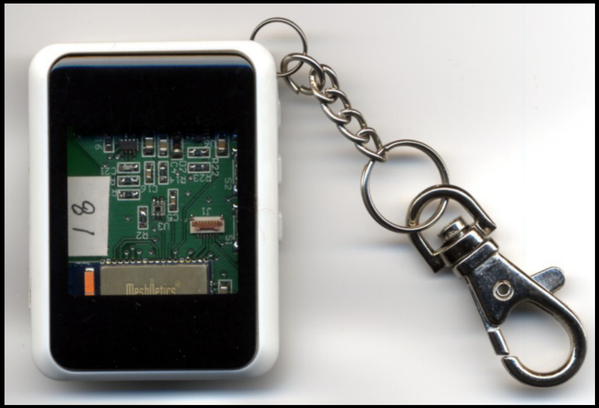
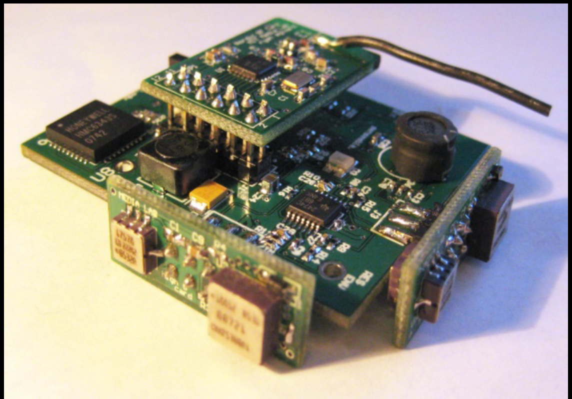
***Session 7, Standards***

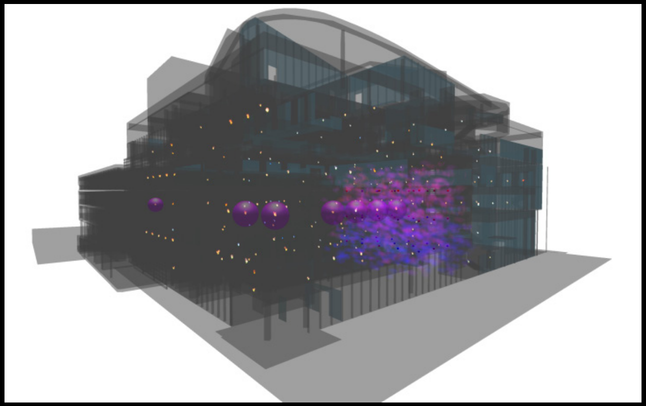
# Introduction

- MIT Media Lab
  - 25 years of multidisciplinary research: organized as 23 unique research groups, each with special research interest.
- Responsive Environments Group
  - Led by Prof. Joseph Paradiso



Feldmeier, Personalized HVAC


Lapinski, Sportsemble


Dublon et. al, DoppelLab

# Solid-State Lighting and Control

Figure 20. Low voltage switch for operating luminaires from desk

1978

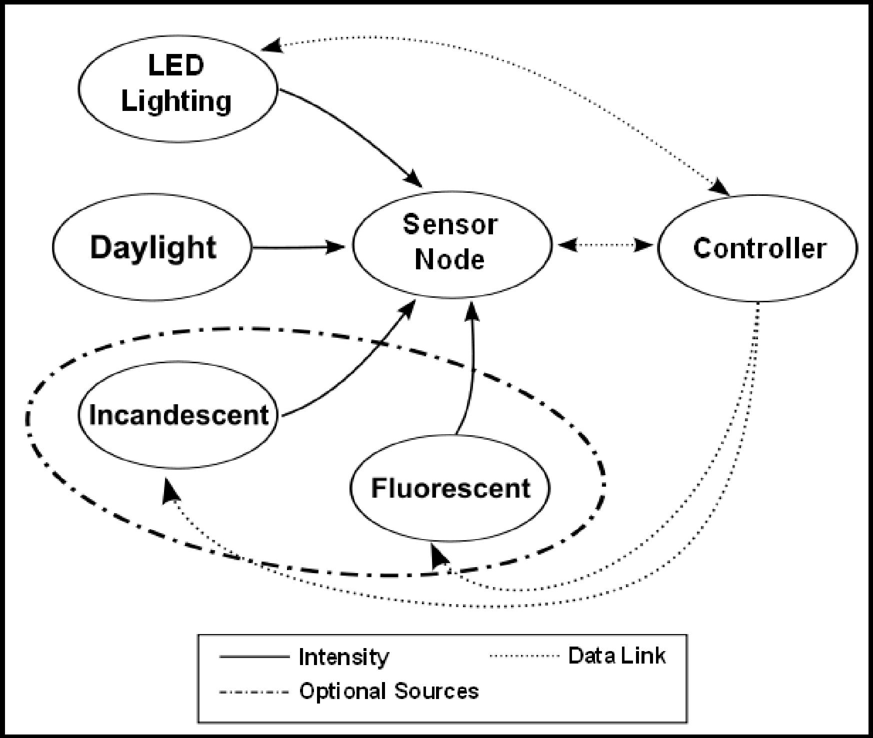
2011

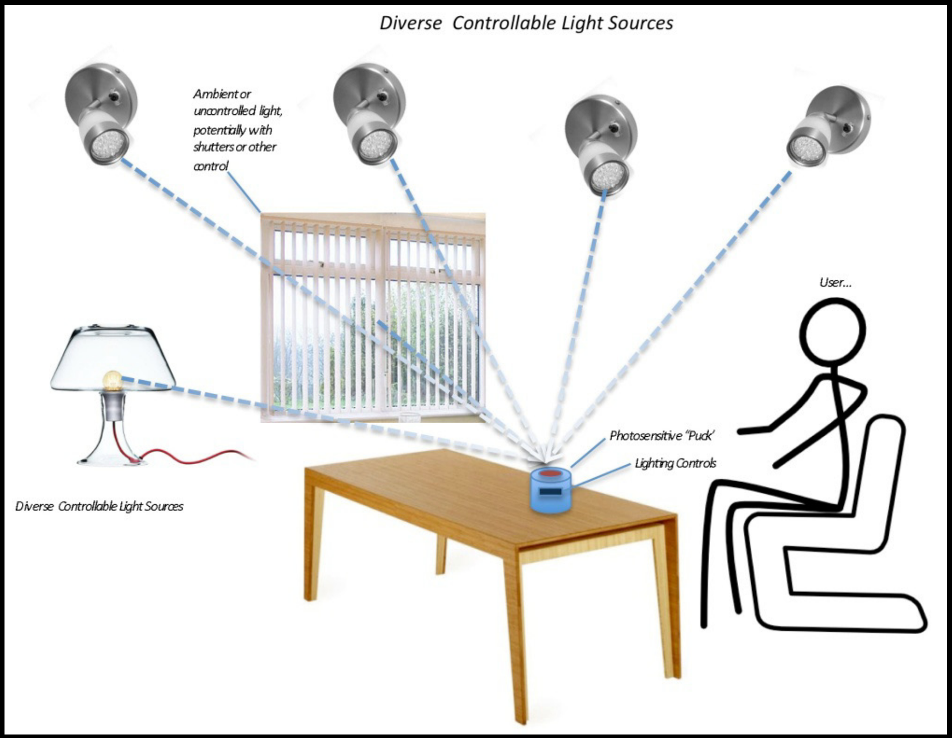
- What progress has been made in the general control and sensing methodology?
- How can LEDs and sensor networks be used to further research?

# The Lighting Control Problem

- Why is lighting control a difficult problem?
  - Designing lit environments that satisfy our basic lighting needs requires a deep understanding of the innate and automatic mechanisms related to satisfying our biological needs. [Lam, 1977]
- Balancing “measurement” and “interaction”
  - Constrained by approach (Human-Computer Interaction)
    - data-centered, expressive-movement, and space-centered [Dugar & Donn, 2011]
  - LEDs fit perfectly into this space because of switching speed and ease of control.
  - Simple question: What do I measure and how do I use it?

# Our Current Approach



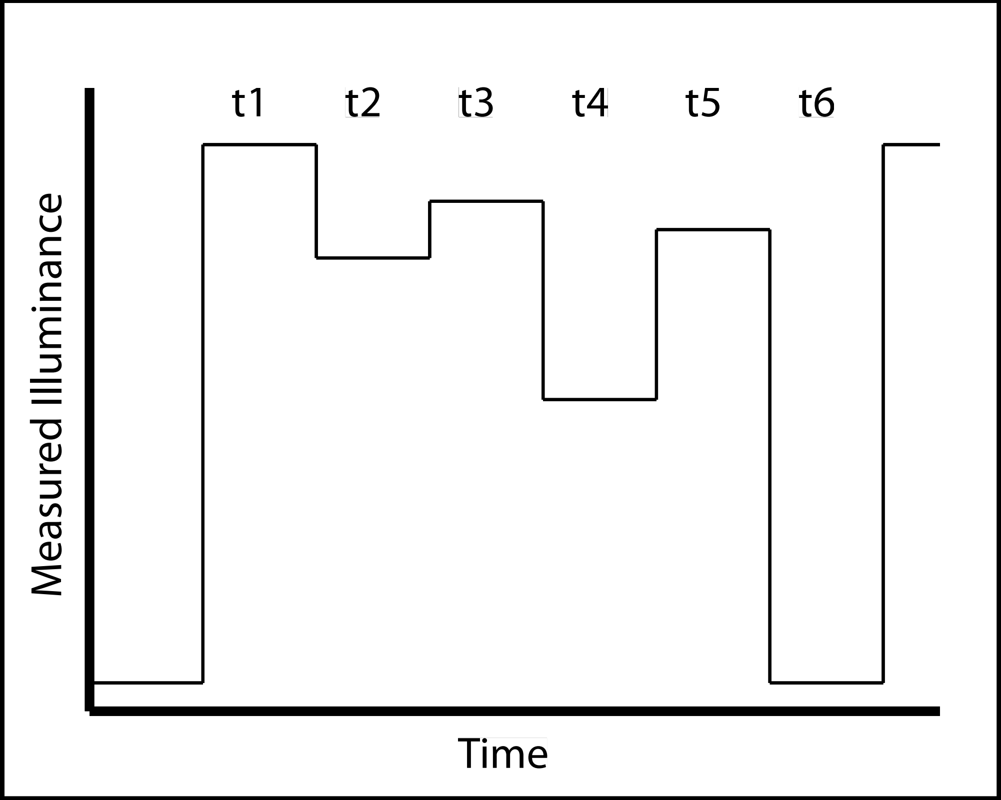



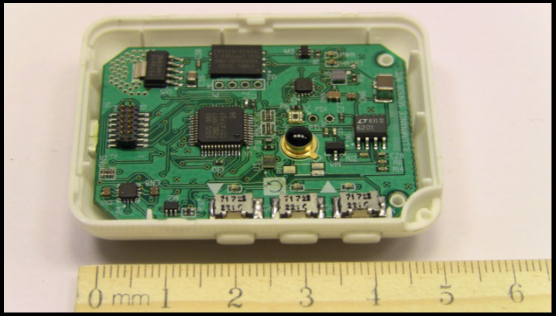

- Intelligent infrastructure for personal control of diverse light sources
- Measurement and interaction are confined to the sensor/specific location

# Background

- Lighting Network Control
  - Crisp and Hunt – Personal control, occupancy, and ambient light (1978)
  - Singhvi et al. – Optimal dimming and prediction of lighting control (2005)
  - Wen et al. – Wireless network based lighting and control (2006, 2010)
  - Park et al. – Intelligent light control for entertainment and media (2007)
  - Miki et al. – Balancing energy consumption with multiple users (2007)
  - Caicedo et al. – Occupancy-based illumination control (2010)
  - Aldrich et al. – Linear and nonlinear optimization of SSL networks (2010)

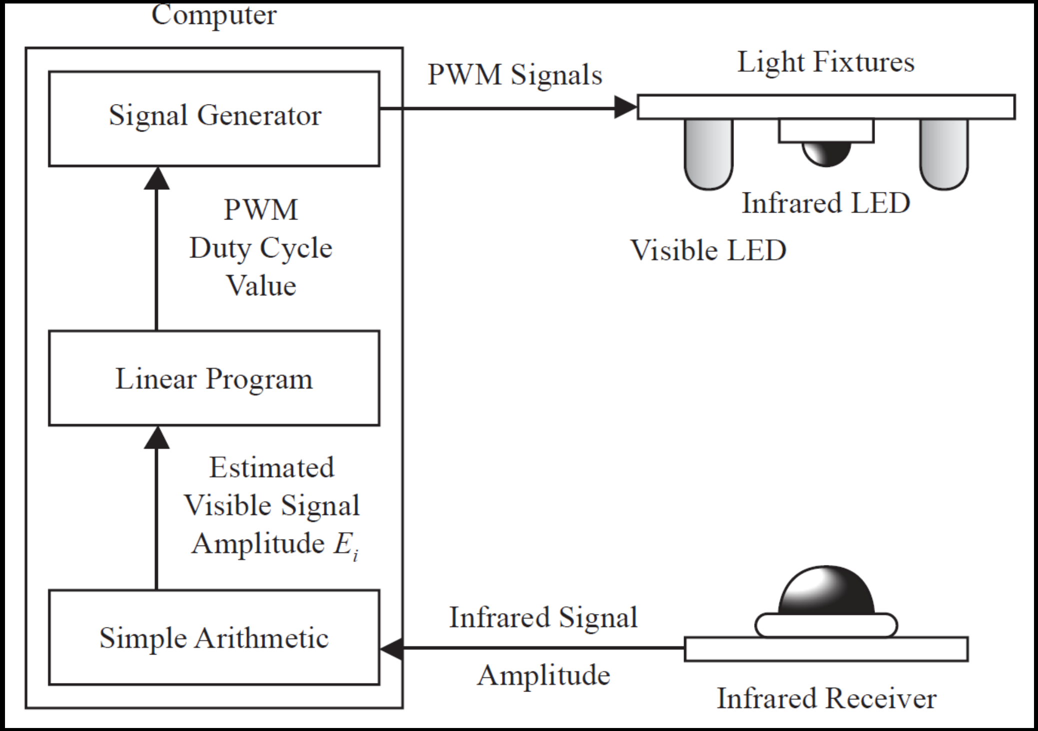
# The Problem: Measurement



- First implemented early 2010, updated in 2011
- A sensor node samples the illuminance over a period of time
- Rapid sampling (>80 Hz) causes visual distraction

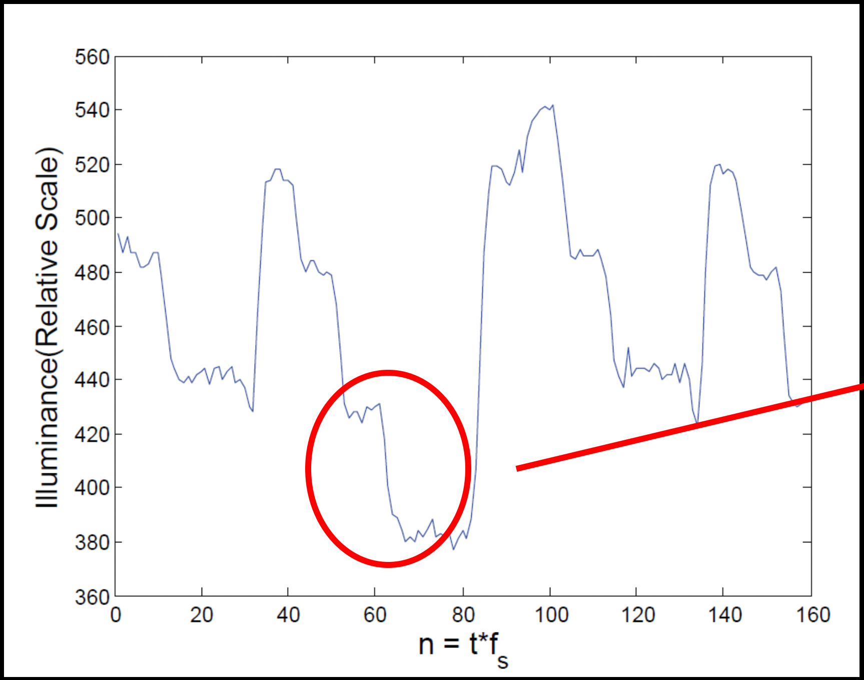
# NIR-based Measurement

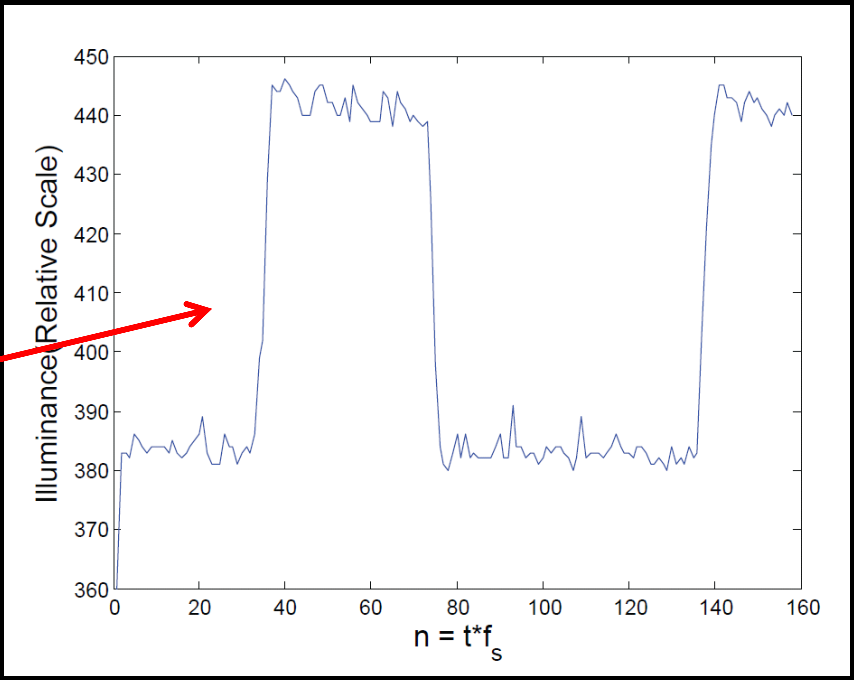



- First implemented in summer of 2010
- A linear transfer function describes the relationship between irradiance and illuminance
- Not necessarily ideal, the cones may not intersect the surface in the same way

# Proposed Idea: Fourier Analysis

- In the ideal system, control and optimization happens seamlessly without distraction to the users – do we really need one more device to control?
- Fourier-based demodulation is a good place to start.



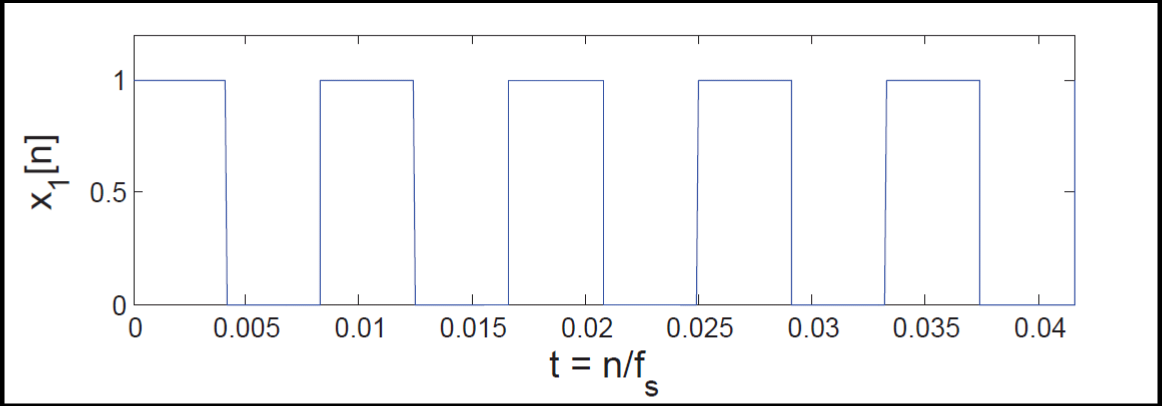

How do we go from this signal… …to this signal (our answer) ?

# Graphical Illustration (1)

Fixture 1

50% duty cycle

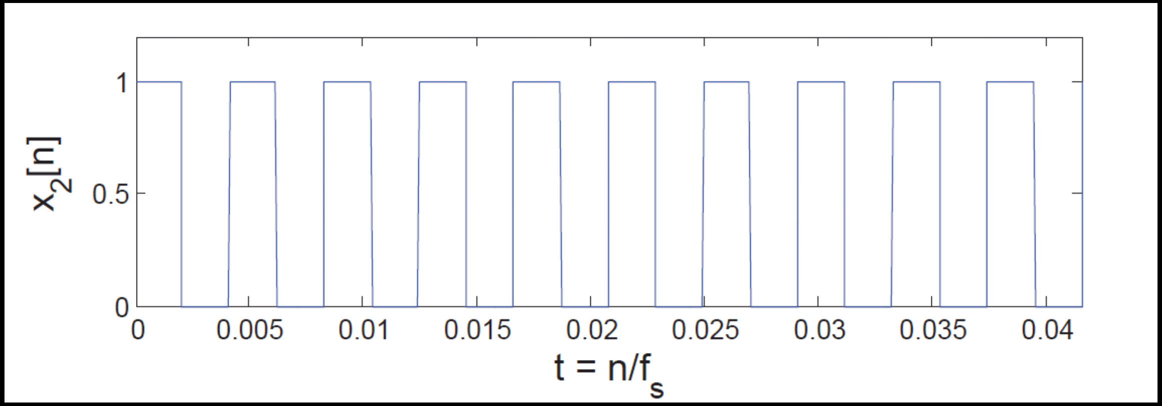
120 Hz.




Fixture 2

50% duty cycle

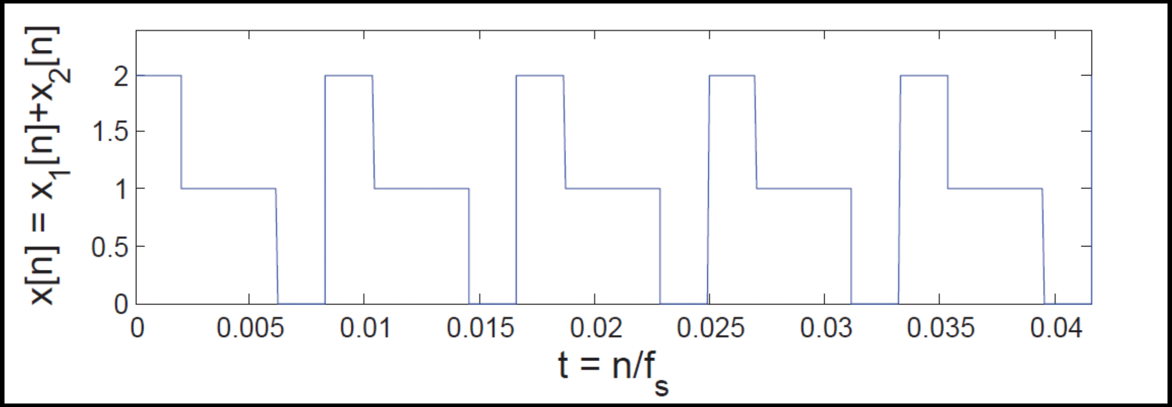
240 Hz.



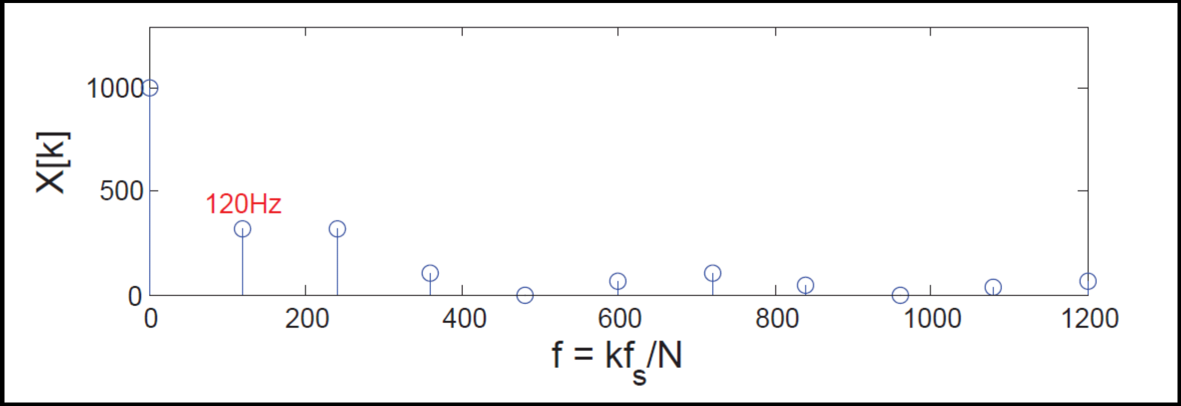

The illumination (1st order) is equivalent for both fixtures since the area defined by the PWM signals is the same for both fixtures.

# Graphical Illustration (2)

Ideal Sensor Measurement




Fourier Transform



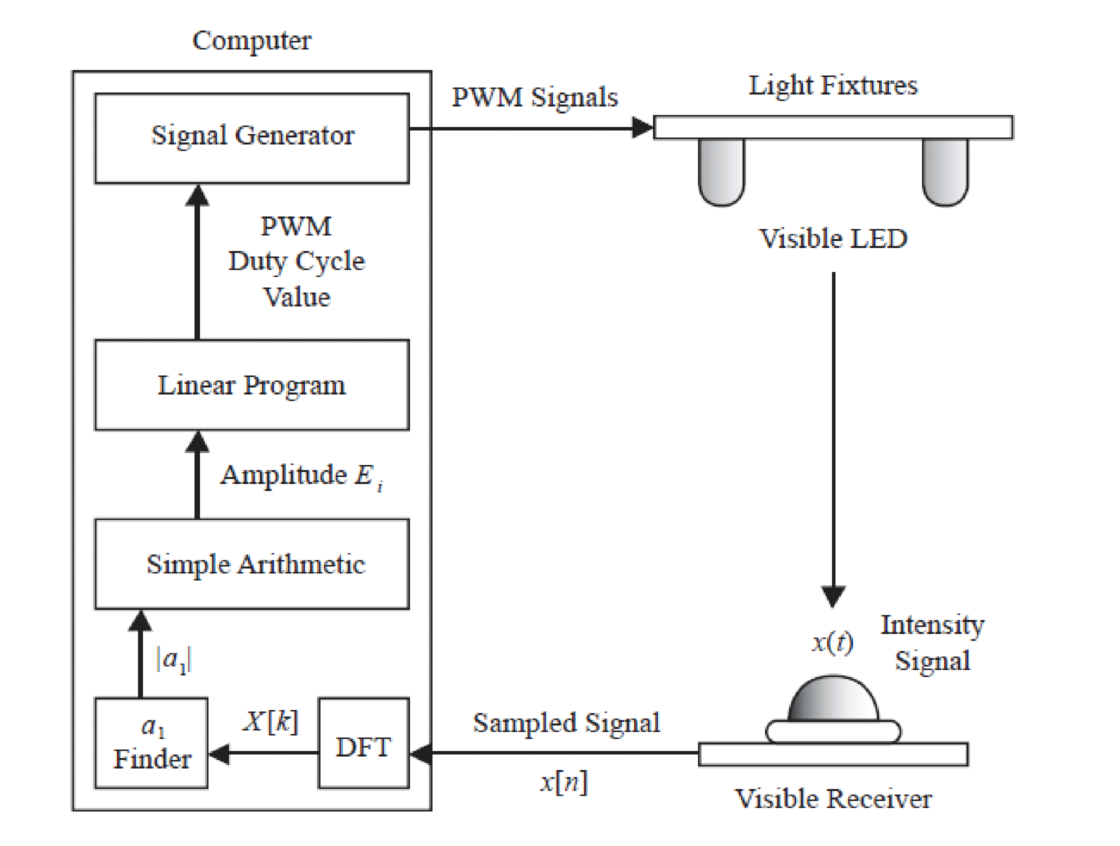

Since the fundamental frequencies are not aliased, we can measure the attenuation in the 120 Hz band.

# Formal Definition

$$x(t) = \begin{cases} E & nT \leq t < (n+d)T \quad \text{for an integer } n \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned} a_1 &= \frac{1}{T} \int_0^T x(t)\; e^{-j\frac{2\pi t}{T}}\; dt \\ &= \frac{1}{2\pi} \int_{u_0}^{u_0+2\pi} x\left(\frac{Tu}{2\pi}\right)\; e^{-ju}\; du \quad \left(u = \frac{2\pi t}{T}\right) \\ &= \frac{1}{2\pi} \int_0^{2\pi d} Ee^{-ju}\; du \\ &= \frac{jE}{2\pi}\left(e^{-j2\pi d} - 1\right) \\ &= -\frac{jE}{\pi}\; e^{-j\pi d}\; \sin(\pi d) \\ \therefore \quad |a_1| &= \frac{E}{\pi}\; \sin(\pi d) \end{aligned}$$

# Implementation




The fixture to be measured must operate a different fundamental frequency than the other fixtures

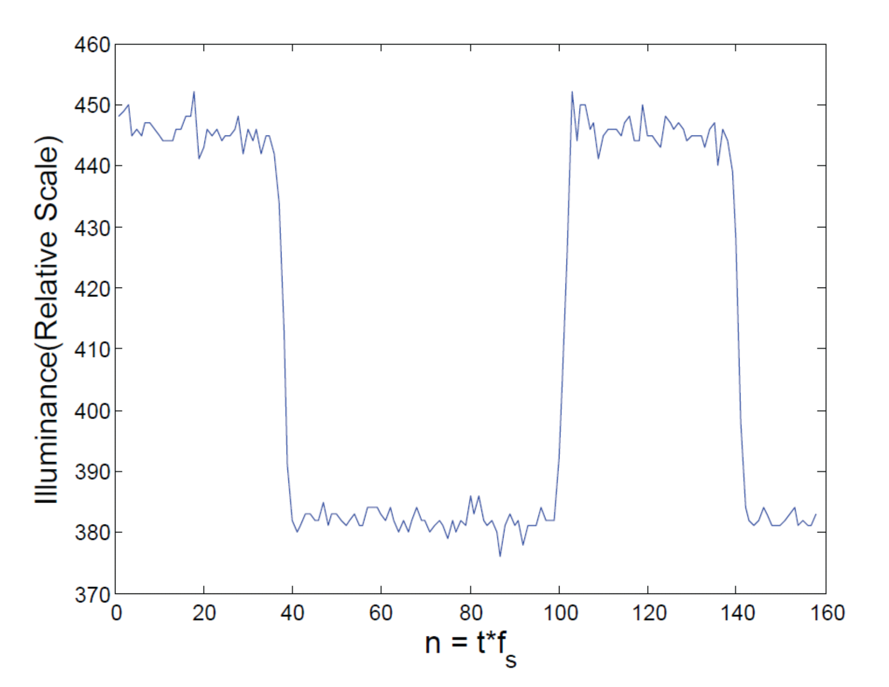
# Implementation Details

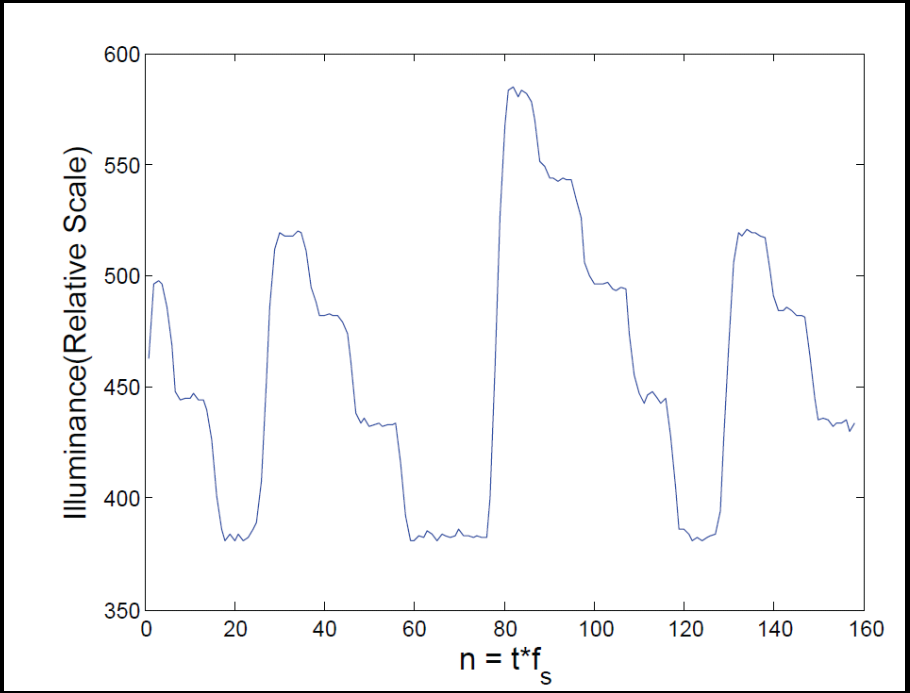
- Tested with 4 Color Kinetics Adjustable White LED Fixtures
- A control computer implemented software-PWM (transmits on/off commands)
  - Limited in resolution, 120 Hz normal, 60 Hz measurement.
  - This limitation ultimately constrained possible brightness settings (0%,20%,40%,60%,80%,100%).

# Testing Details

- Due to duty-cycle constraints, we tested primarily using a 40% duty cycle signal.
- Measured at 3 different distances:
  - 145 cm, 150 cm, and 175 cm.
- We then compared a measurement of the 60 Hz signal with our algorithm.
  - Measure the test fixture at 60 Hz with other fixtures off. Then perform measurement with the other fixtures on at 120 Hz.

# Testing (1)



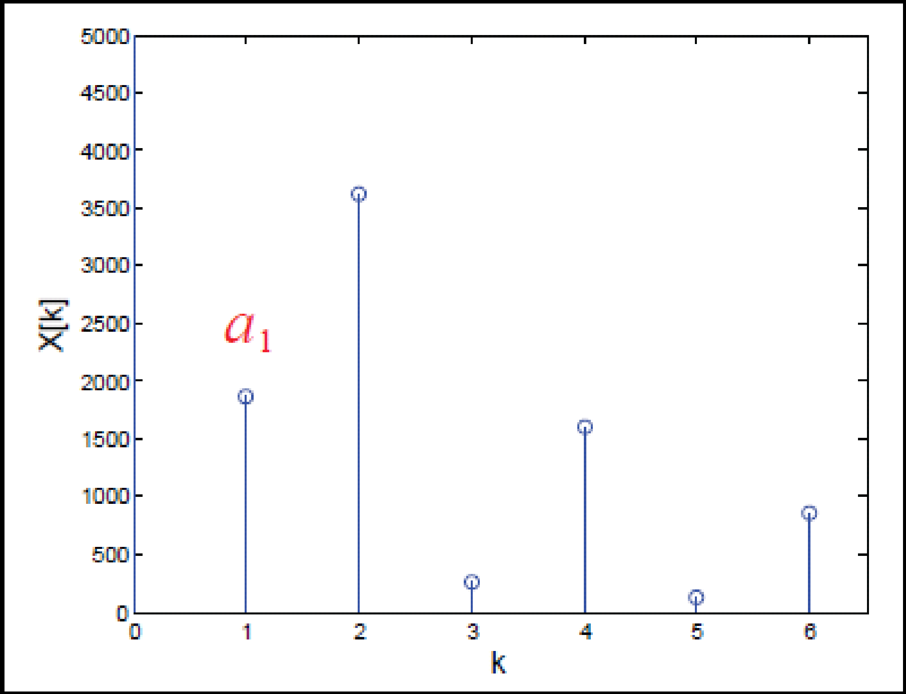




First, the ideal signal is measured by the receiver (left). Then, we measured the embedded signal (right).

(a single example is presented above for readability)

# Testing (2)

- The resulting Fourier transform of the demodulated signal from the previous slide (right).
- A table summarizing the results of testing at 3 distances (below).




| Measurement | Distance (cm) | $\Delta E_t$ (ADC Counts) | $\Delta \hat{E}_t$ (ADC Counts) |
|---|---|---|---|
| 1 | 145 | 60 | 59 |
| 2 | 150 | 55 | 59 |
| 3 | 170 | 28 | 38 |

# Conclusions

- **Contribution 1**: This technique enables remote monitoring of multiple luminaires with only a single receiver, and can be applied to more complicated systems of many wavelengths.
- **Contribution 2**: We derived a precise formula for Fourier-based sensing of a light fixture's illuminance contribution intended for disturbance free measurement and optimization and provided empirical evidence of success.

- With infinite resolution, the measurement error is bounded by the receiver signal-to-noise ratio.
- The sampling frequency and power requirements of the sensor platform will impose limitations on the resolution of the luminaire dimming.
- More testing is needed (preferably with better resolution) to further explore if the system is truly unperceivable by humans.
- No DC-type signals, the fundamental (no harmonics) is assumed adequate.
- Data-driven lighting control offers simplified computer control over many parameters, yet sampling those parameters without user intervention remains a difficult problem.

# Thanks

- MIT Media Lab for direct funding of this research.
- John Warwick and Philips-Color Kinetics for donation of color-tunable white-LED fixtures.
- Responsive Environments Group for testing, editing, and comments.

# Further Reading


- Lam WMC., *Perception and Lighting as Formgivers for Architecture.* New York: Mcgraw Hill, (1977).
- Crisp, V. H. C., "Preliminary study of automatic daylight control of artificial lighting," Lighting Research and Technology 9(1), 31–41 (1977).
- Stephen J. Wright, *Primal-Dual Interior-Point Methods*, SIAM, (1997).
- Dugar, A. M. and Donn, M. R., "Tangible intervention: Improving the effectiveness of lighting control systems" *Lighting Research and Technology (*2011).
- Park, H., Burke, J., and Srivastava M., "Design and implementation of a wireless sensor network for intelligent light control," In *Proceedings of the 6th international conference on Information processing in sensor networks* (2007).