# SYSTEM ARCHITECTURE DIRECTIONS FOR A SOFTWARE-DEFINED LIGHTING INFRASTRUCTURE

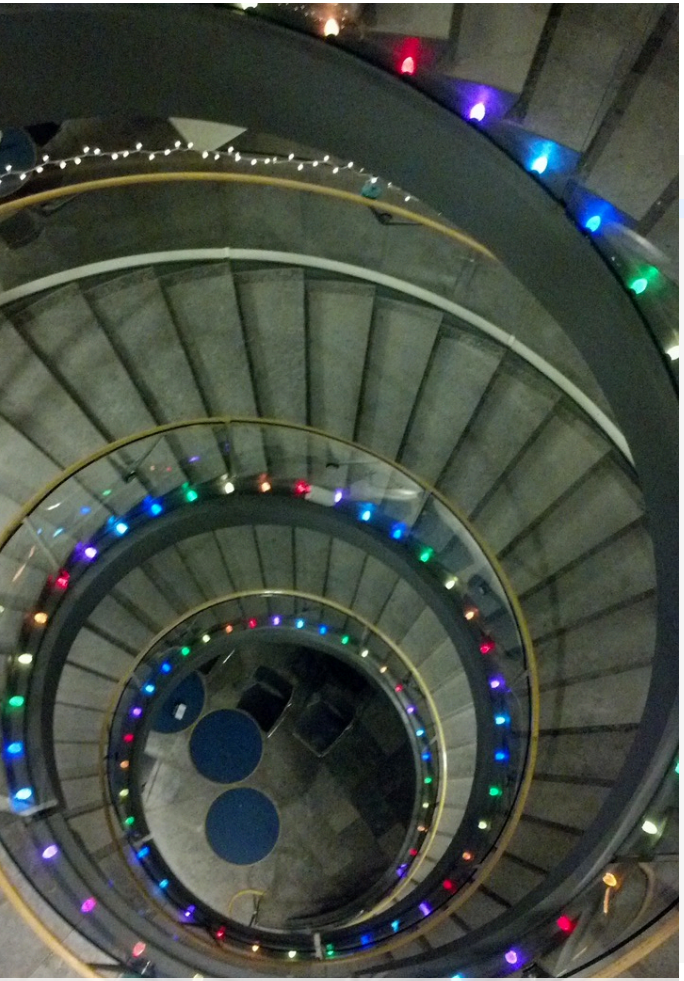
**PAT PANNUTO, WITH YE-SHENG KUO AND PRABAL DUTTA**

**UNIVERSITY OF MICHIGAN**

**1ST ACM WORKSHOP ON VISIBLE LIGHT COMMUNICATIONS SYSTEMS (VLCS '14)**

**SEPTEMBER 7, MAUI, HI**

# Blinken: Software-Defined Lighting (@ the Bob and Betty Beyster Building)



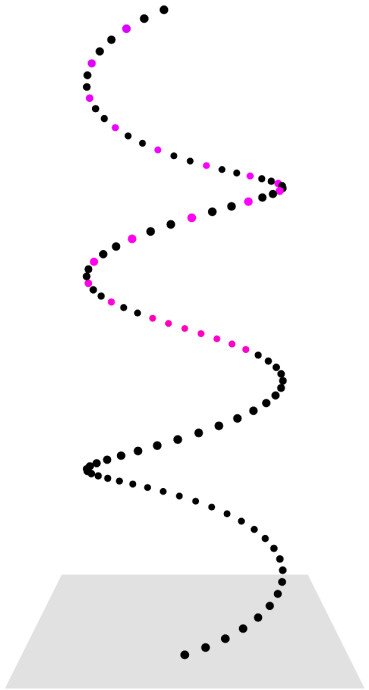
JavaScript

```
// Simulation of a 2-symbol Turing Machine, executing the
// Busy Beaver function (https://en.wikipedia.org/wiki/Busy_beaver)
//
// The tape head is always in the middle light, and the lights
// always show the 50 lights to the left (above) and right (below)
// the head.
//
// Color of a written "1" is white (saturated) immediately after
// write, but fades to a color determined by when it was written.
// For example, early values in the tape will fade to red,
// while later values will fade to yellow, green, blue, etc.

// BB(1), BB(2), BB(3), and BB(4) are known and quite short.
// BB(5) has a contender that runs for 47 million steps - not
something
// we complete in our short simulation, but looks nice nonetheless
:)

(new Blinken({title: "Busy Beaver",
              author: "Alan Turing"})).run(function () {
    // A. Turing machine

    var tape;
    var tape_head;
    var cur_state;

  // From https://stackoverflow.com/a/17243070
  function HSVtoRGB(h, s, v, obj) {
    var r, g, b, i, f, p, q, t;
    if (h && s === undefined && v === undefined) {
        s = h.s, v = h.v, h = h.h;
    }
    i = Math.floor(h * 6);
    f = h * 6 - i;
    p = v * (1 - s);
    q = v * (1 - f * s);
    t = v * (1 - (1 - f) * s);
    switch (i % 6) {
        case 0: r = v, g = t, b = p; break;
        case 1: r = q, g = v, b = p; break;
```

Output

Run with JS

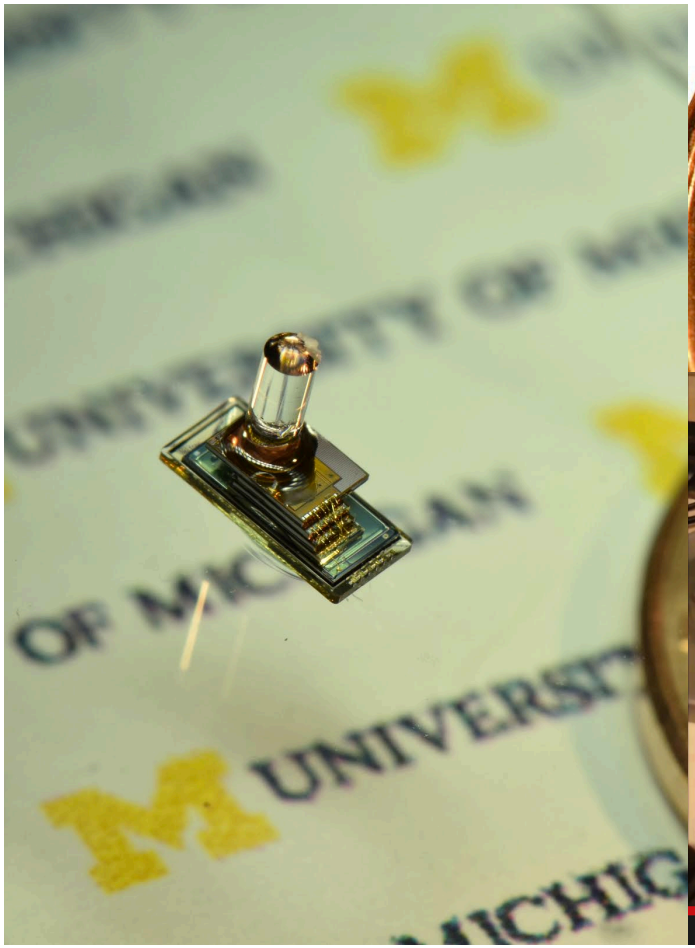
Run on Stairs

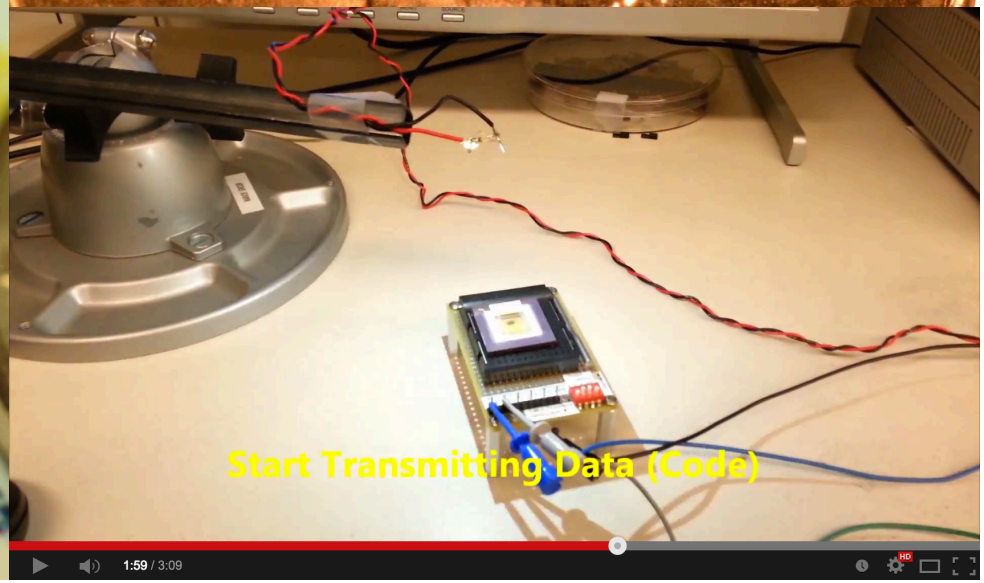


http://blinken.eecs.umich.edu/

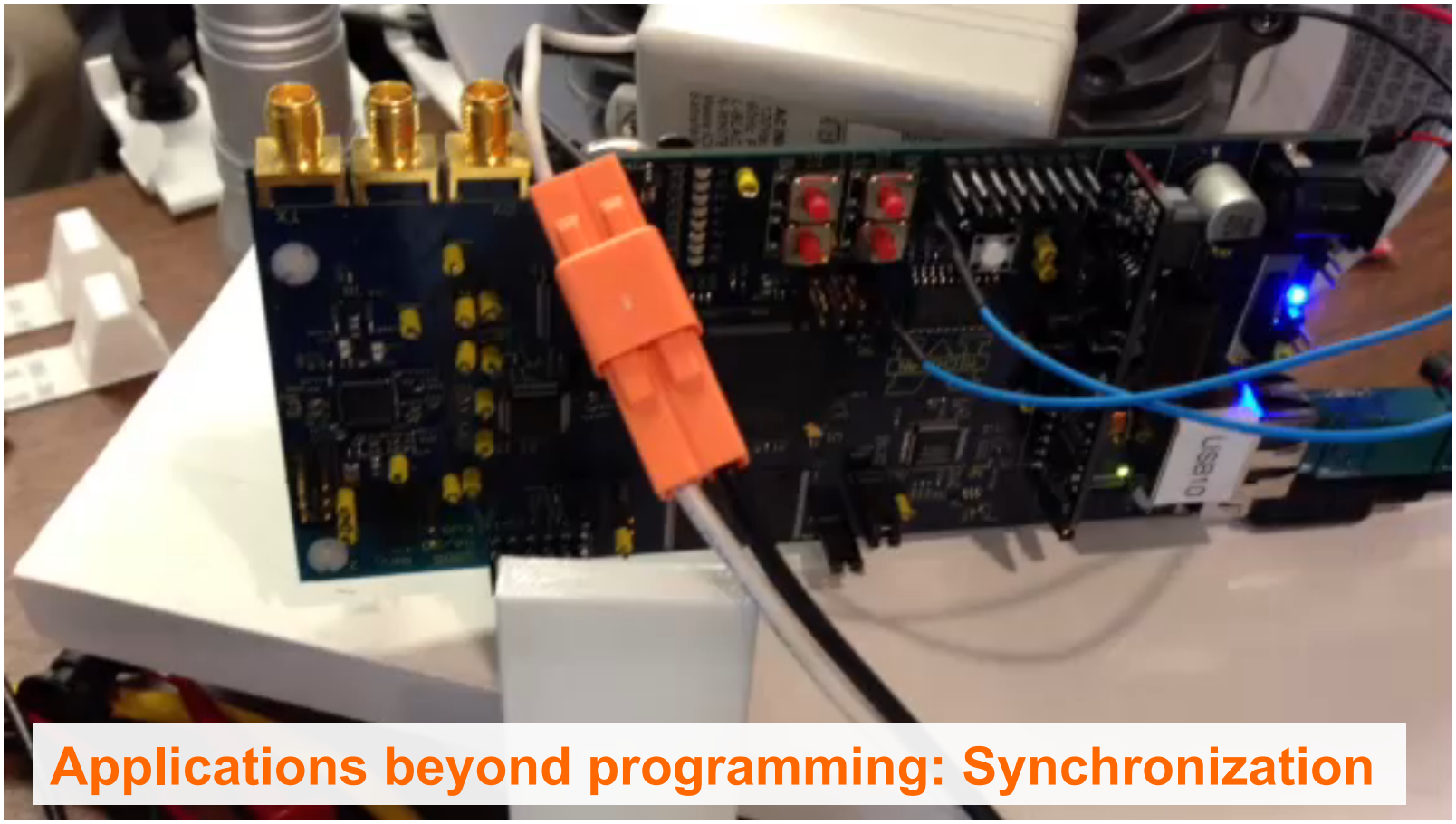
# M³: Programming Smart Dust with VLC

https://www.youtube.com/watch?v=OM8WgnhcyOo#t=118

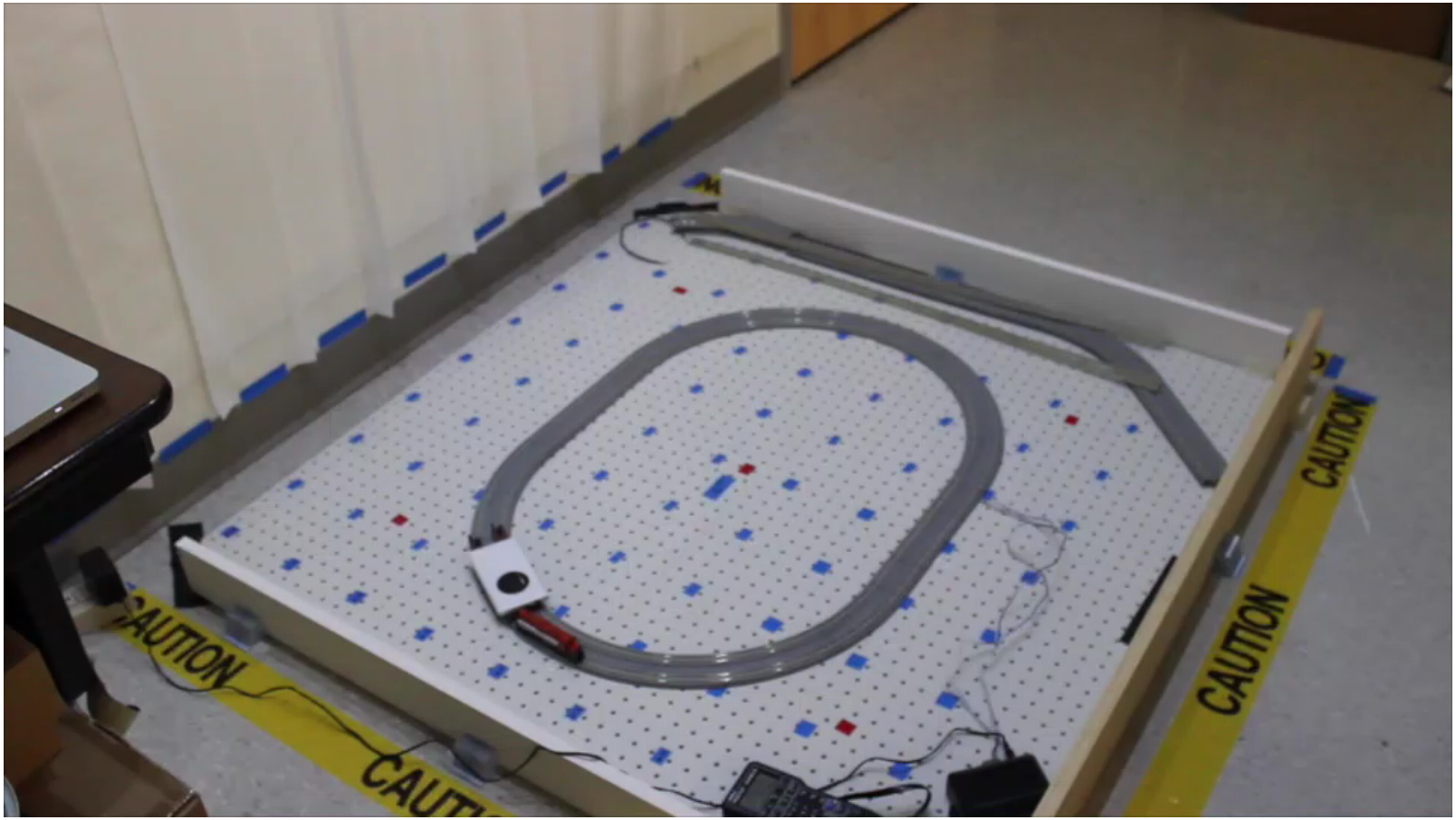




# Electric Imp: Commercial systems also employ VLC for programming

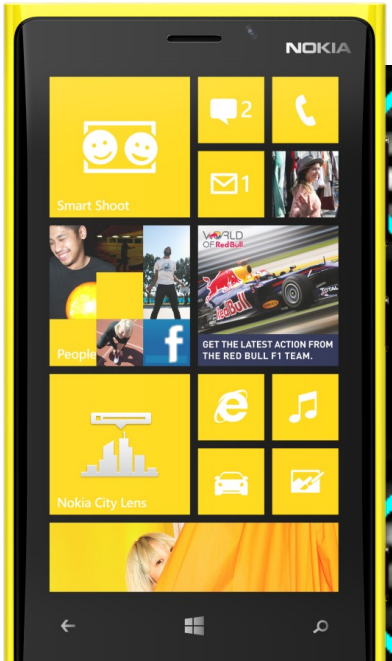


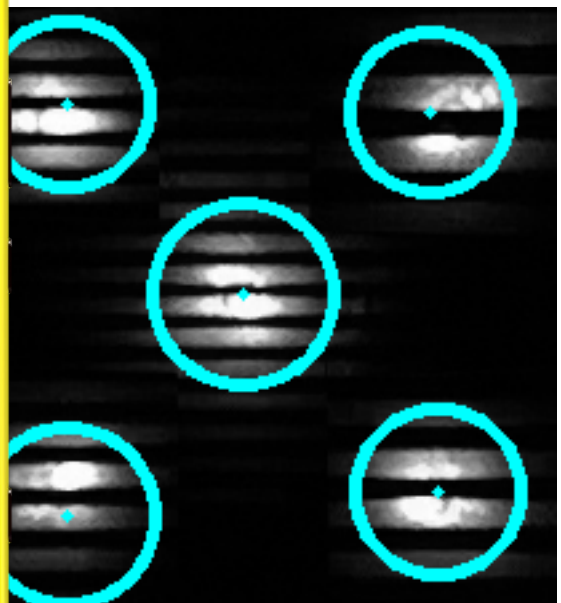
# Luxapose: Accurate Indoor Positioning with VLCP



# What *do* all of these examples have in common?

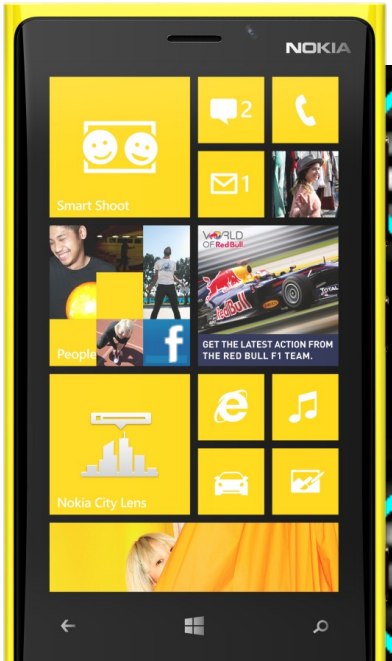


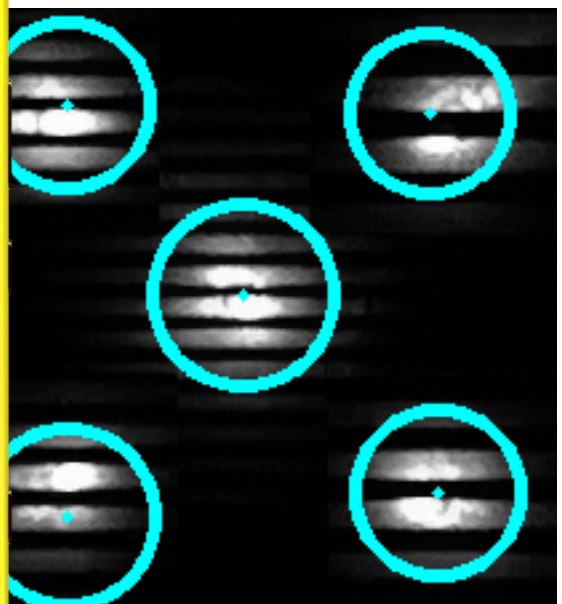



# What *don't* all of these examples have in common?



# Show of hands: Are you using someone else's infrastructure?


Home | **Program** | Keynote | Demos and Posters | Organization | Registration | Authors

## Technical Program

**8:45 - 9:00 AM Opening Remarks**

Workshop Introduction by Chairs

Edward Knightly, Rice University, USA

Harald Haas, University of Edinburgh, UK

Hsin-Mu (Michael) Tsai, National Taiwan University, Taiwan

**9:00-10:00 AM Keynote**

The Future of VLC: Potential and Limitations

Maite Brandt-Pearce, University of Virginia, USA

**10:00-10:30 AM Networking Break**

**10:30-12:00 PM Paper Session 1: VLC Systems**

System Architecture Directions for a Software-Defined Lighting Infrastructure

Ye-Sheng Kuo (University of Michigan, USA)

Pat Pannuto (University of Michigan, USA)

Prabal K Dutta (University of Michigan, USA)

Using Consumer LED Light Bulbs for Low-Cost Visible Light Communication Systems

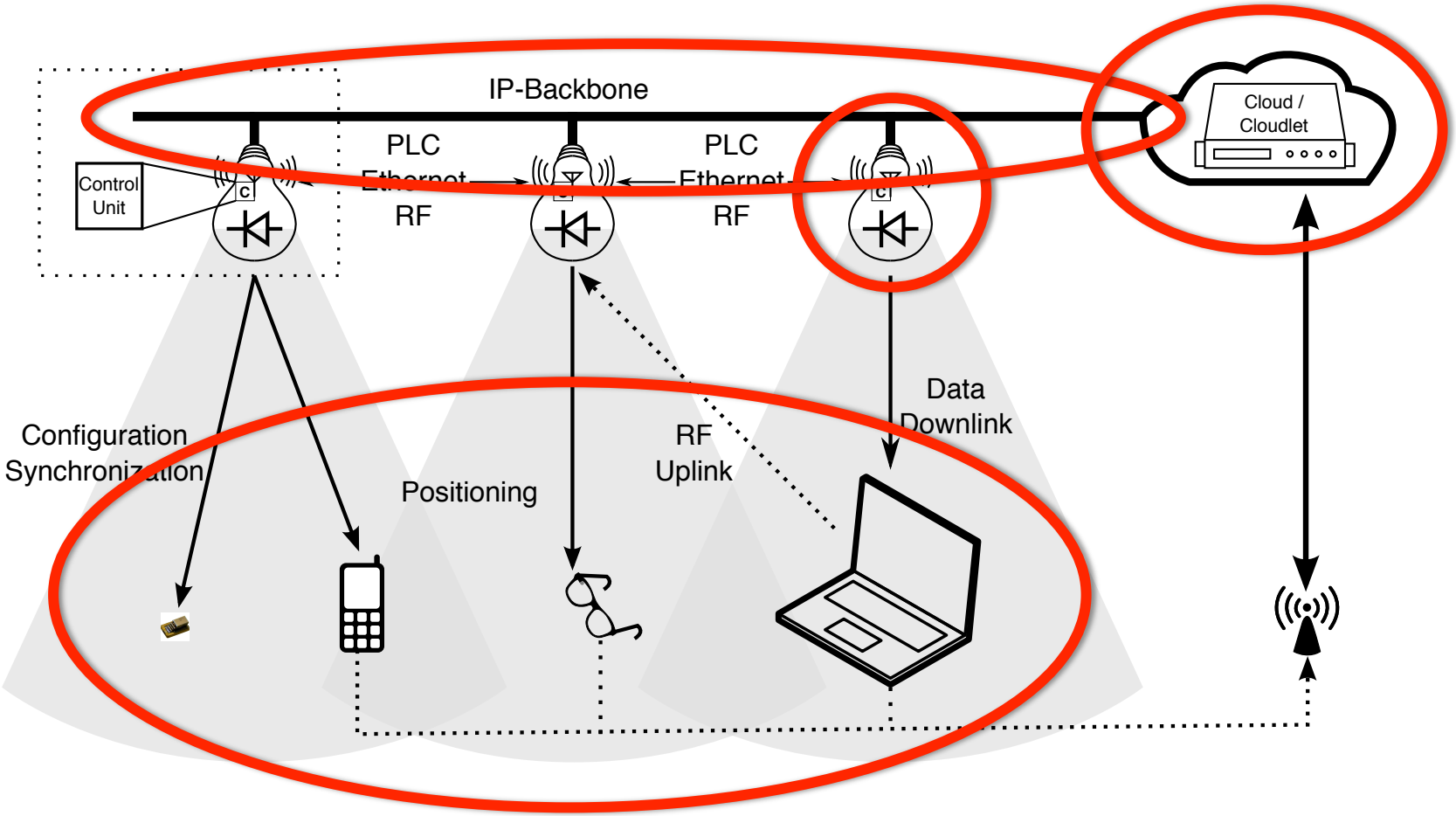
Stefan Schmid (ETH Zurich, Switzerland)

Josef Ziegler (ETH Zurich, Switzerland)

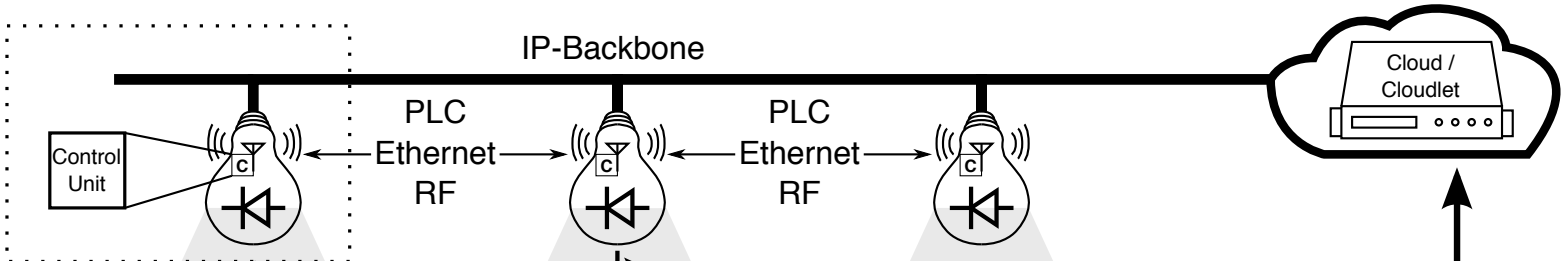
Giorgio Corbellini (Disney Research Zurich, Switzerland)

Thomas R. Gross (ETH Zurich, Switzerland)

# Vision for a *modular* SDL architecture

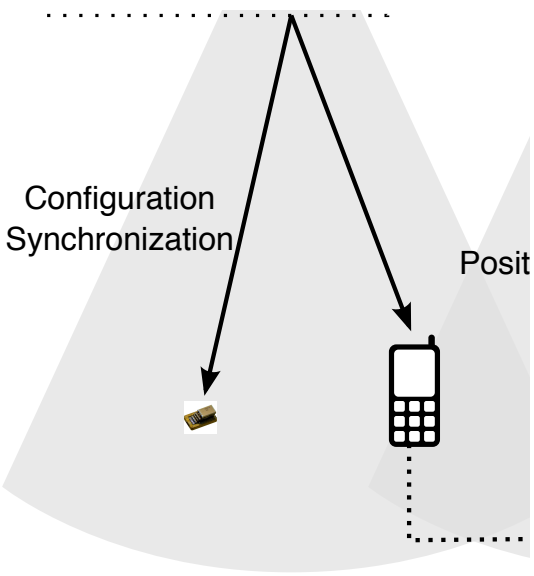


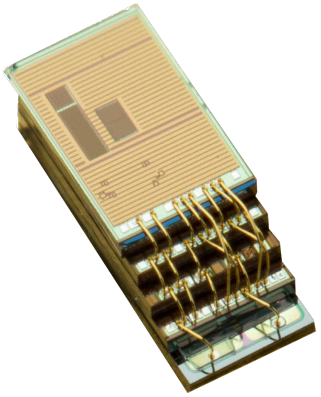
# Taking lessons from Software Defined Networking into Software Defined Lighting




- **Separate Control and Data Planes**
  - Preserves Flexibility
  - Installed lights do not need to know every protocol a priori

# The Capabilities of VLC Receivers Vary Greatly



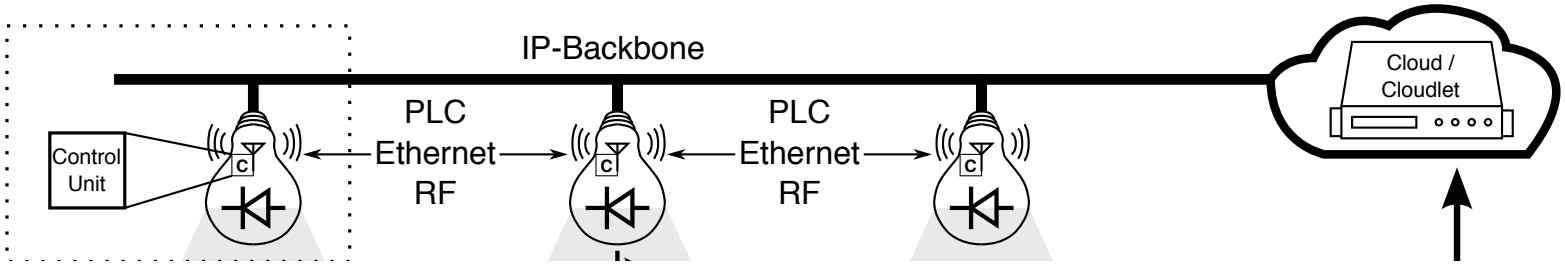
**Diffusing (single photodiode)**

- Simpler devices
  → Less computation capability
- Cannot distinguish transmitters
- Requires temporal signal diversity

**Array (multiple photocell)**

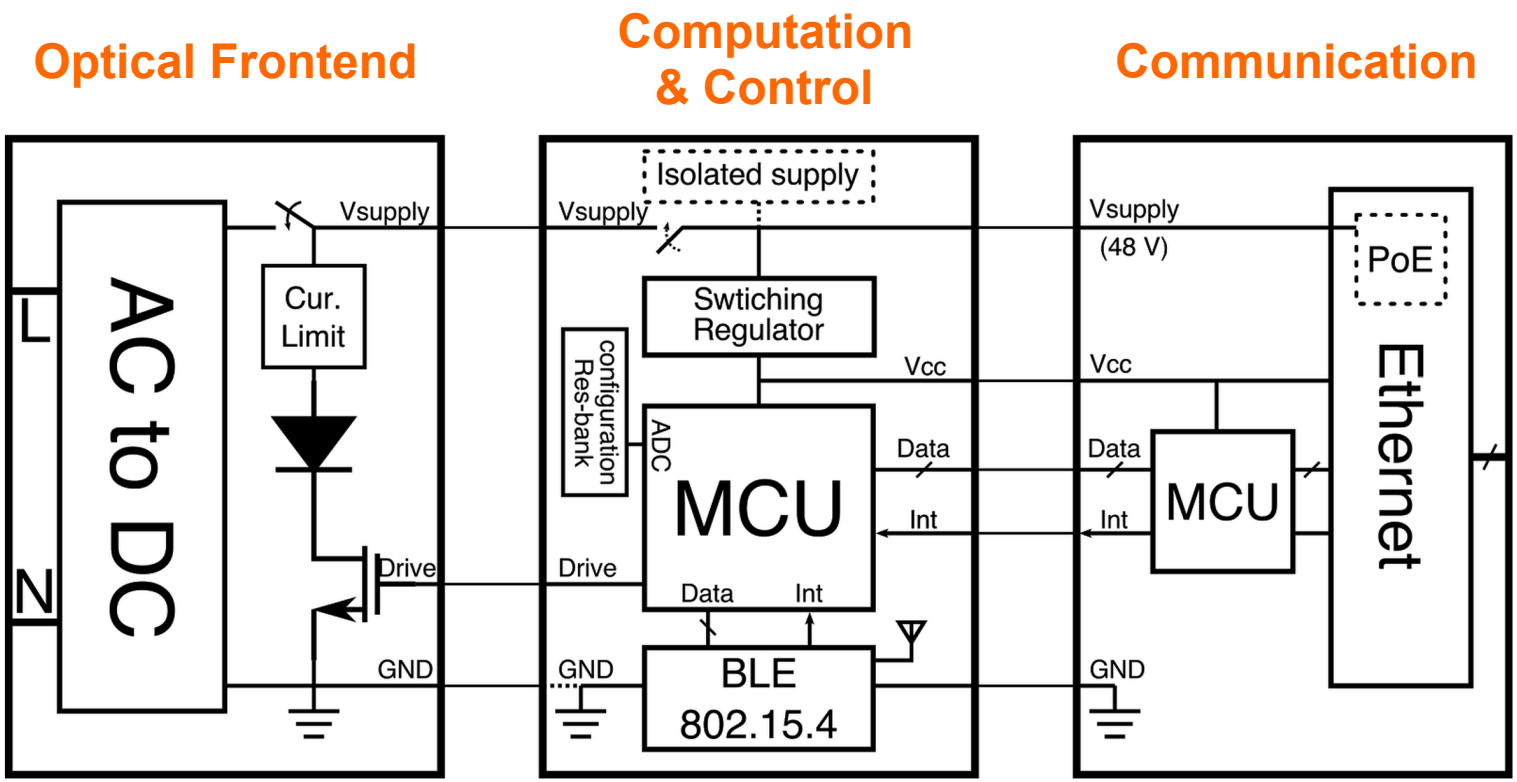
- Can distinguish transmitters
- Temporal or spatial diversity

# The Backbone Design Can Have Far-Reaching Implications on SDL Capability




- **Ethernet vs PLC vs RF**
  - Infrastructure cost, per-node cost
  - Bandwidth, throughput, and latency tradeoffs
  - Impact on synchronization capabilities

# The Luminary Decomposes into Three Independent Modules



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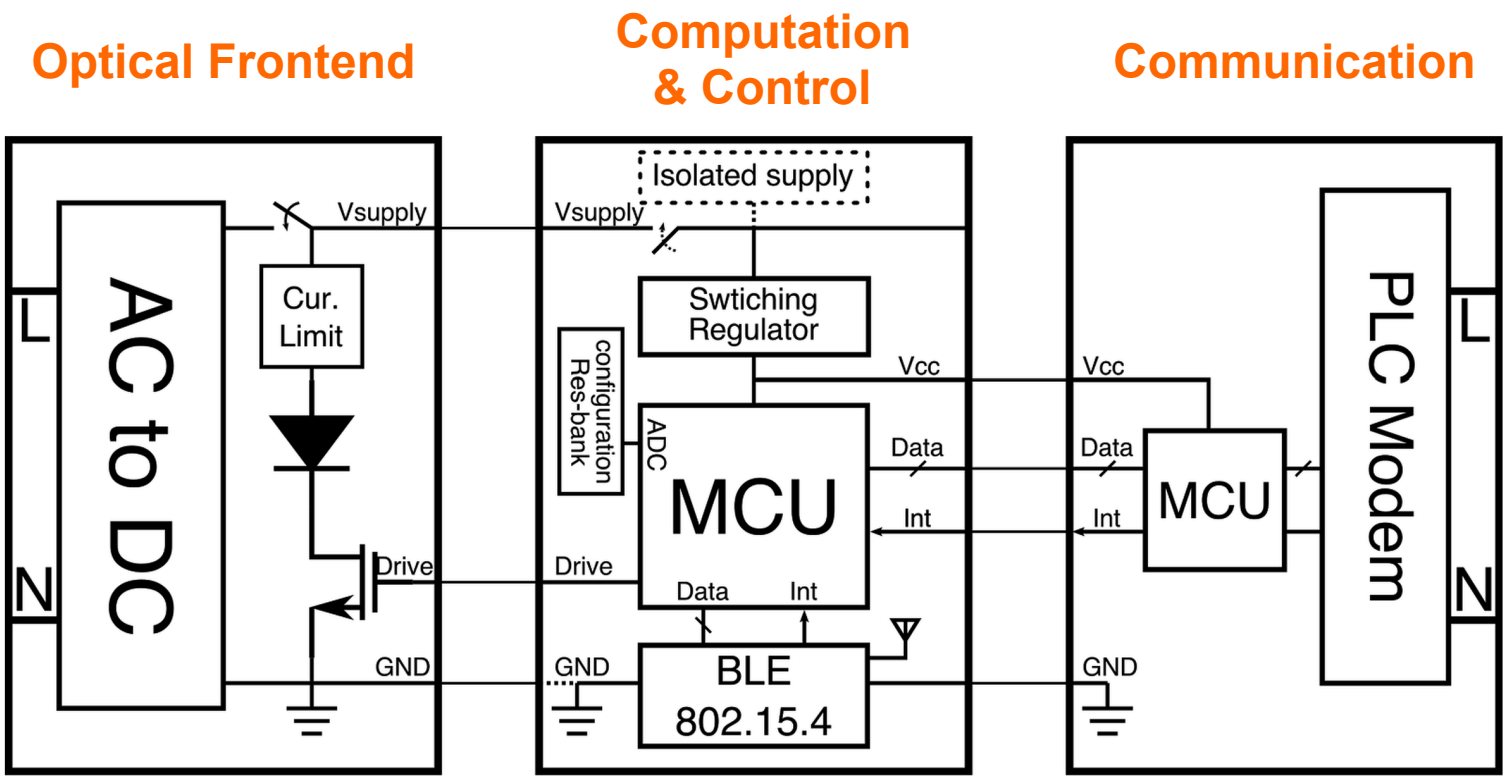

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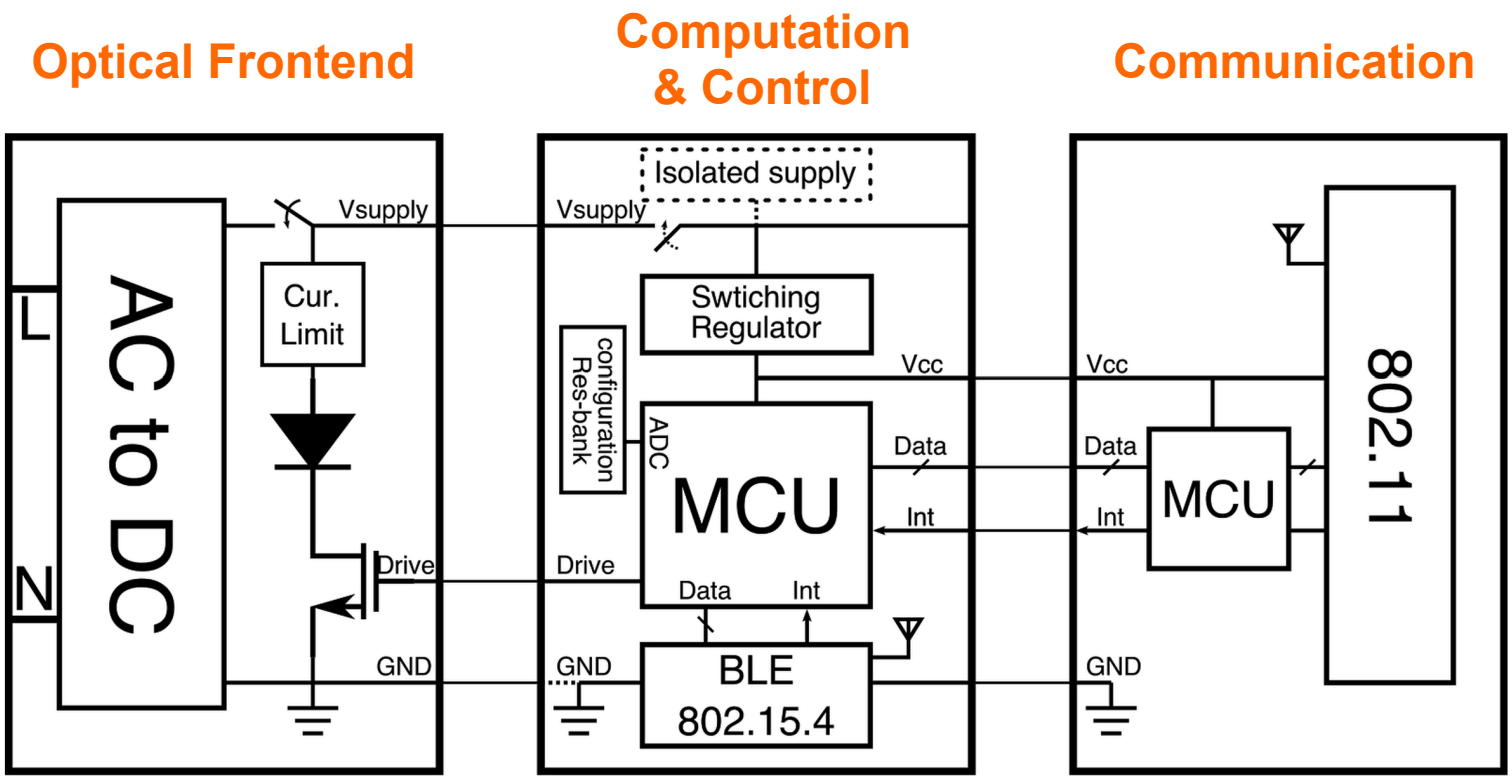
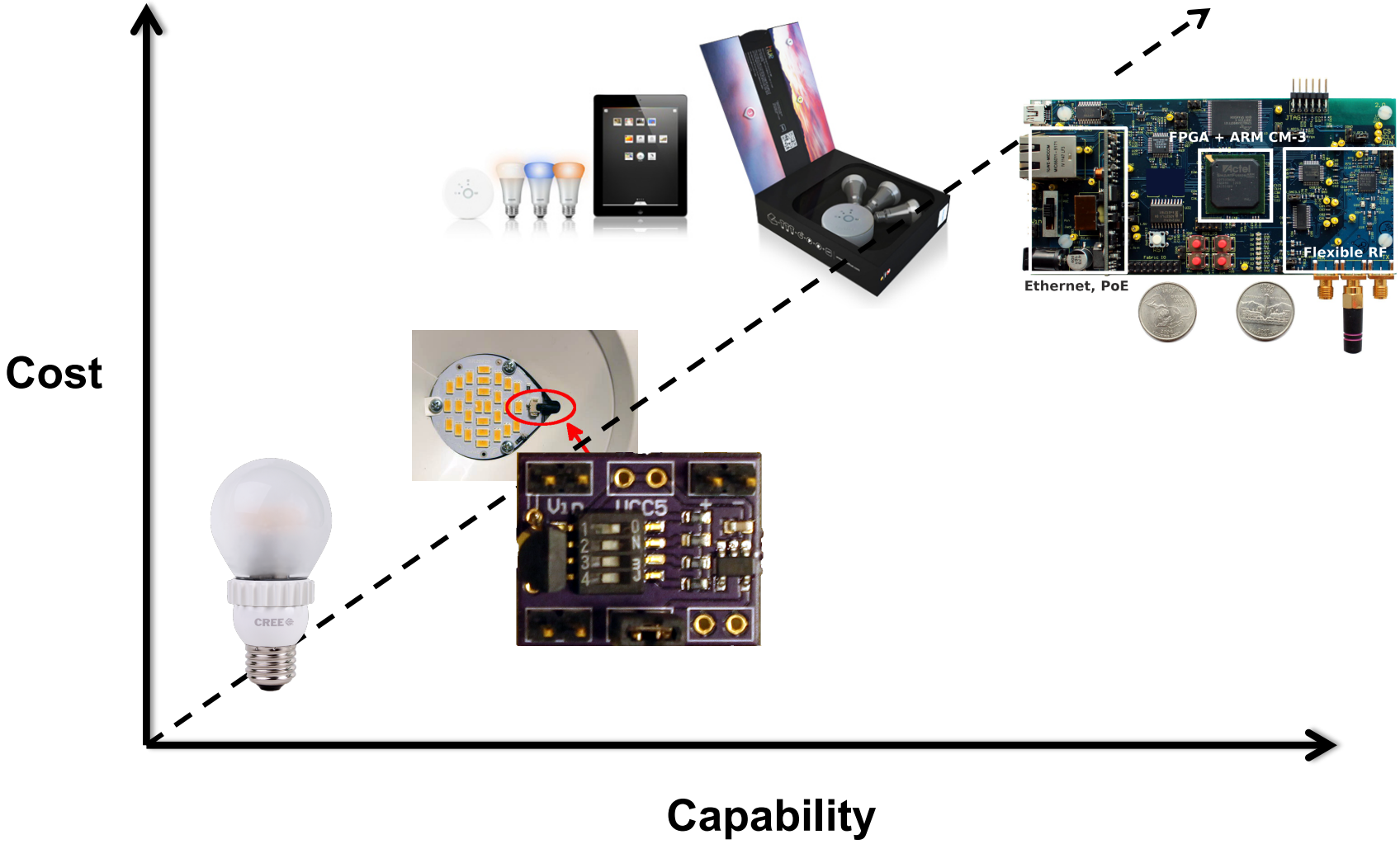


# Different Modules Add Different Costs to Each Bulb

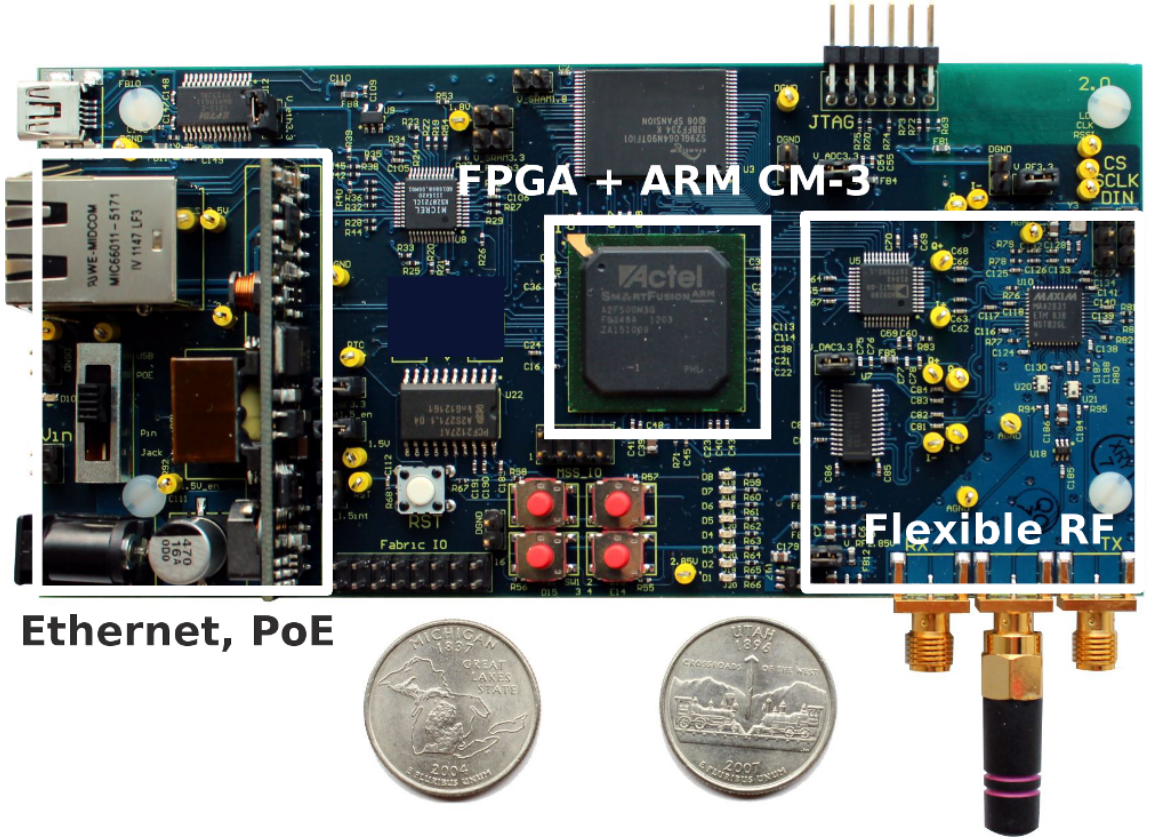
- **Communication**
  - PHY frontend
    - Antenna?
    - Coupled transformer?
  - Baseband processor
- **Computation & Control**
  - General-purpose (MCU)
  - Flexible fixed function (e.g., tunable oscillator)
- **Power Supply**
  - Above likely require lower voltage, perhaps isolation
  - Perhaps a 4$^{th}$ module?

# Evaluating the value-add of the smart bulb



# How to determine what costs make sense to pay in LED bulbs?

**Start with the kitchen sink and see what's useful**

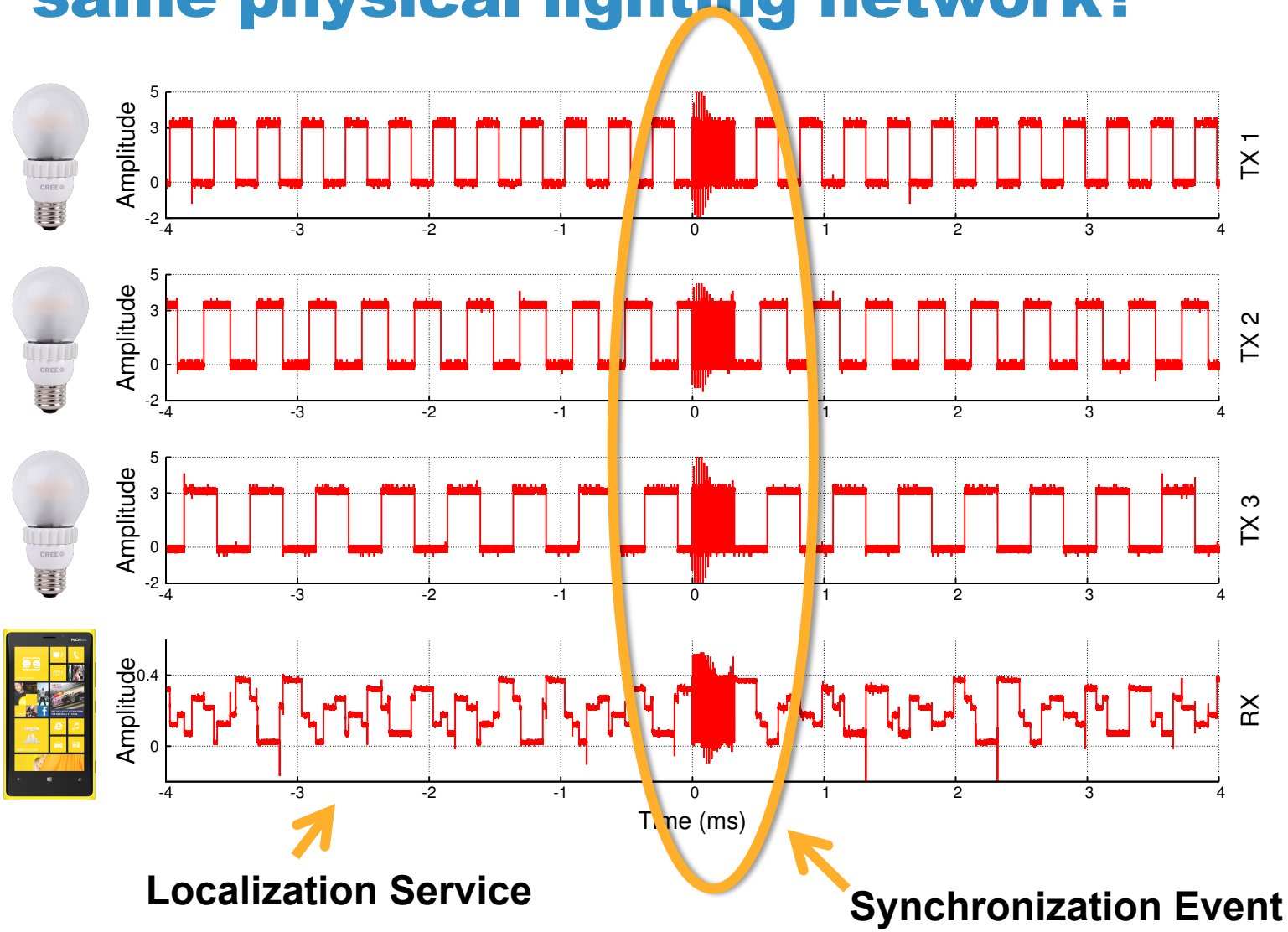



# Lights are rarely isolated, and the whole must be greater than the sum of its parts

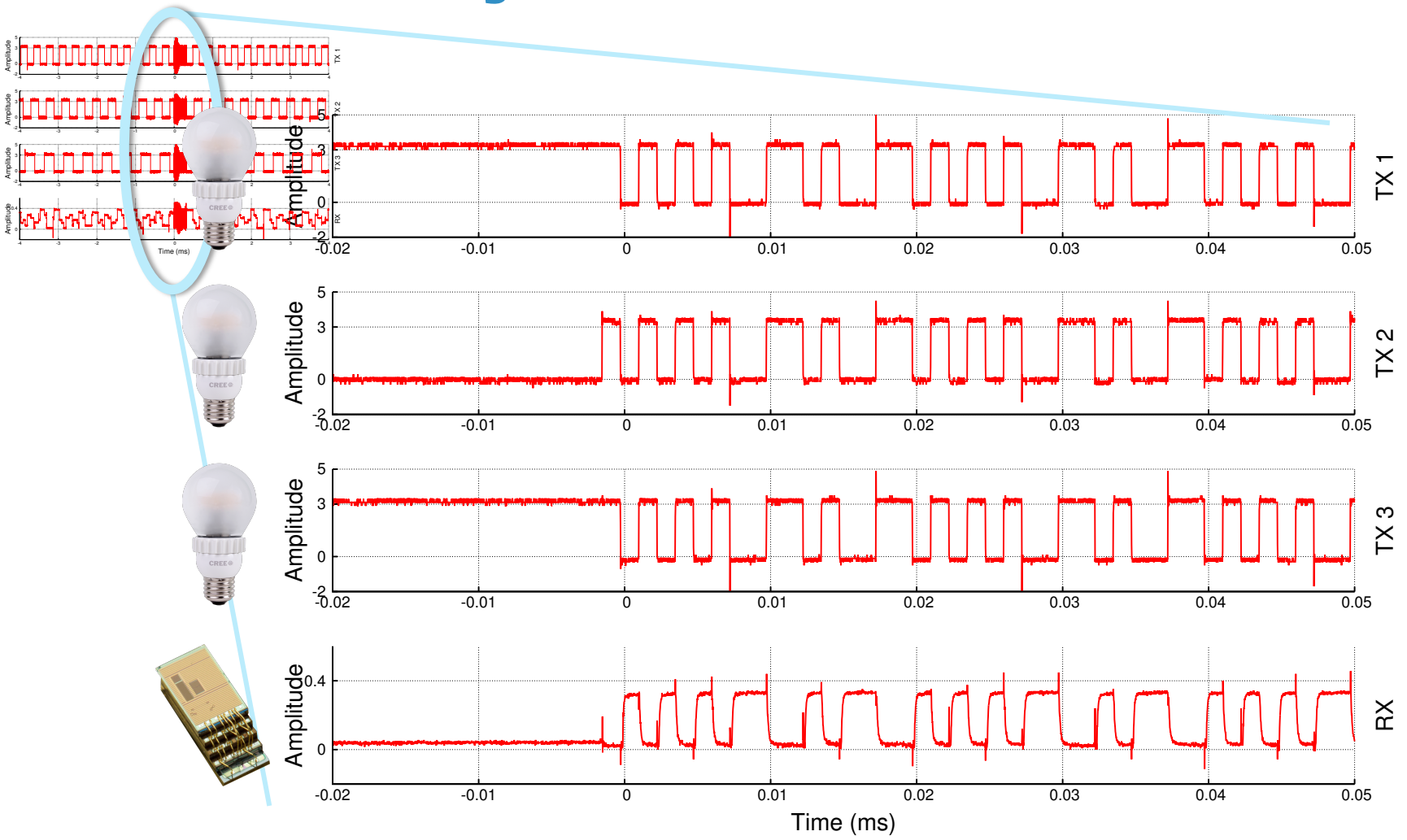

# Mapping Applications onto a Network of Software Defined Lights

- **Health**
  - Passive, Continuous Background Service
  - Targets Humans
- **Localization**
  - Passive, Continuous Background Service
  - Targets Array Receivers (Phones)
- **Synchronization**
  - Passive, Continuous Background Service
  - Targets Diffusing Device
- **Location Attestation**
  - Active, One-Shot Service
  - Targets Active Device, Diffusing or Array

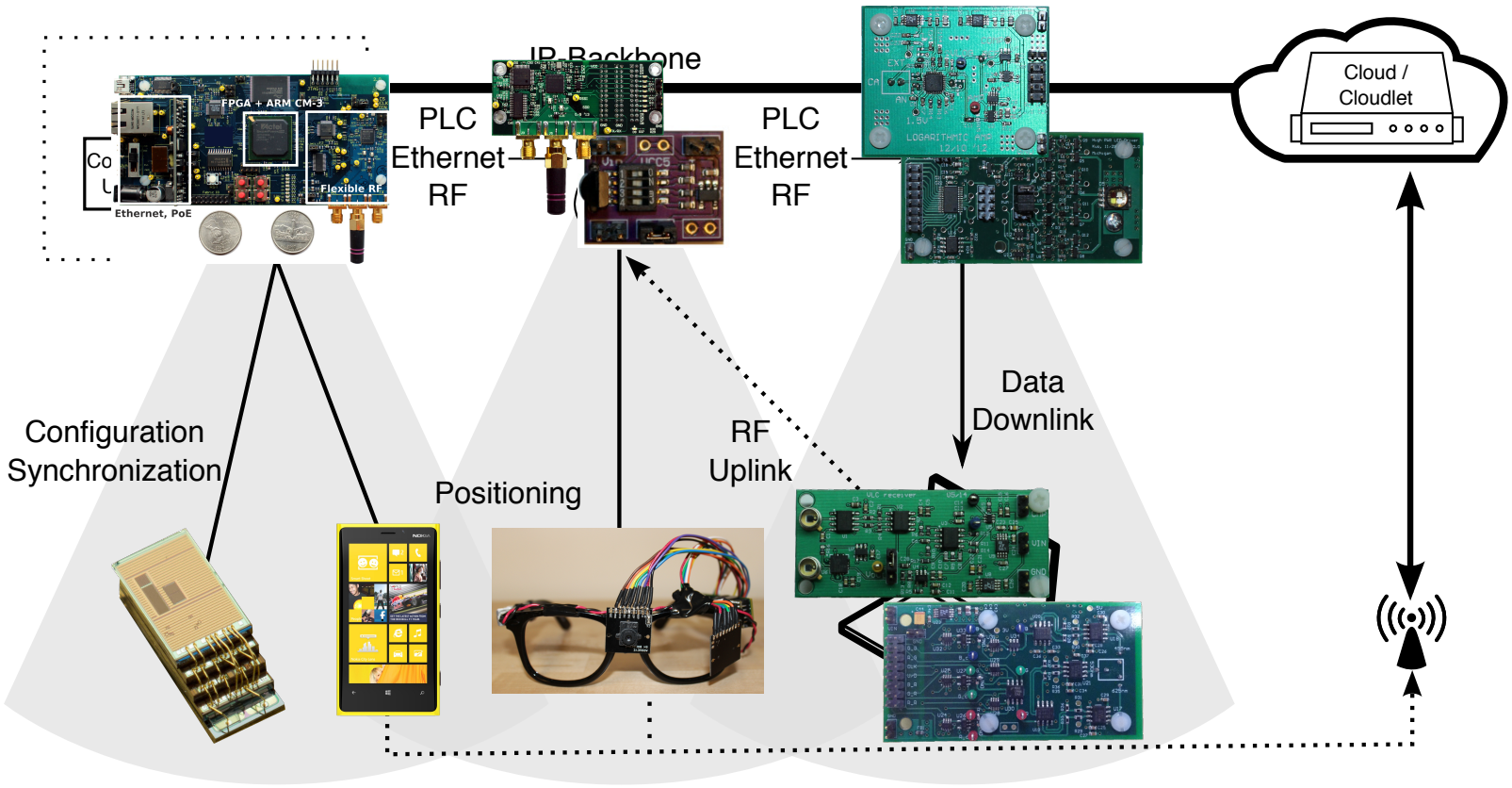
# Can disjoint services multiplex on the same physical lighting network?



# With sufficient synchronization, transmitted signals can constructively interfere



# First Steps Towards Realizing an SDL Architecture



# Why are LED bulbs such celebrated technology?

- **Efficient:**
  - 100 lm/W
- **Durable:**
  - lifetimes > 50,000 hours
- **Form Factor:**
  - Compact and flexible
- **High Color Rendering Index (CRI):**
  - Natural, pleasant light
- **Wide Temperature Range:**
  - Performs even in cold temperatures
- **Environmentally Friendly:**
  - No Mercury

# They are so much better, that you cannot legally purchase incandescents


**European Commission. Commission adopts two regulations to progressively remove from the market non-efficient light bulbs.**

http://europa.eu/rapid/press-release_IP-09-411_en.pdf

**Ministerial Council for Energy. *Energy Labelling and MEPS Program Regulatory Ruling*. Australian Government – Department of Industry.**

http://www.innovation.gov.au/Energy/EnergyEfficiency/Documents/energy-efficiency/Regulatory-Ruling-Incandescent-Final-v1.pdf

**The 100th Congress. *Energy Independence and Security Act of 2007*. Public Law 110-140. U.S. Government Printing Office.**

http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/html/PLAW-110publ140.htm

# The LED Renaissance is a Once-in-a-Century Opportunity

**1880s:**

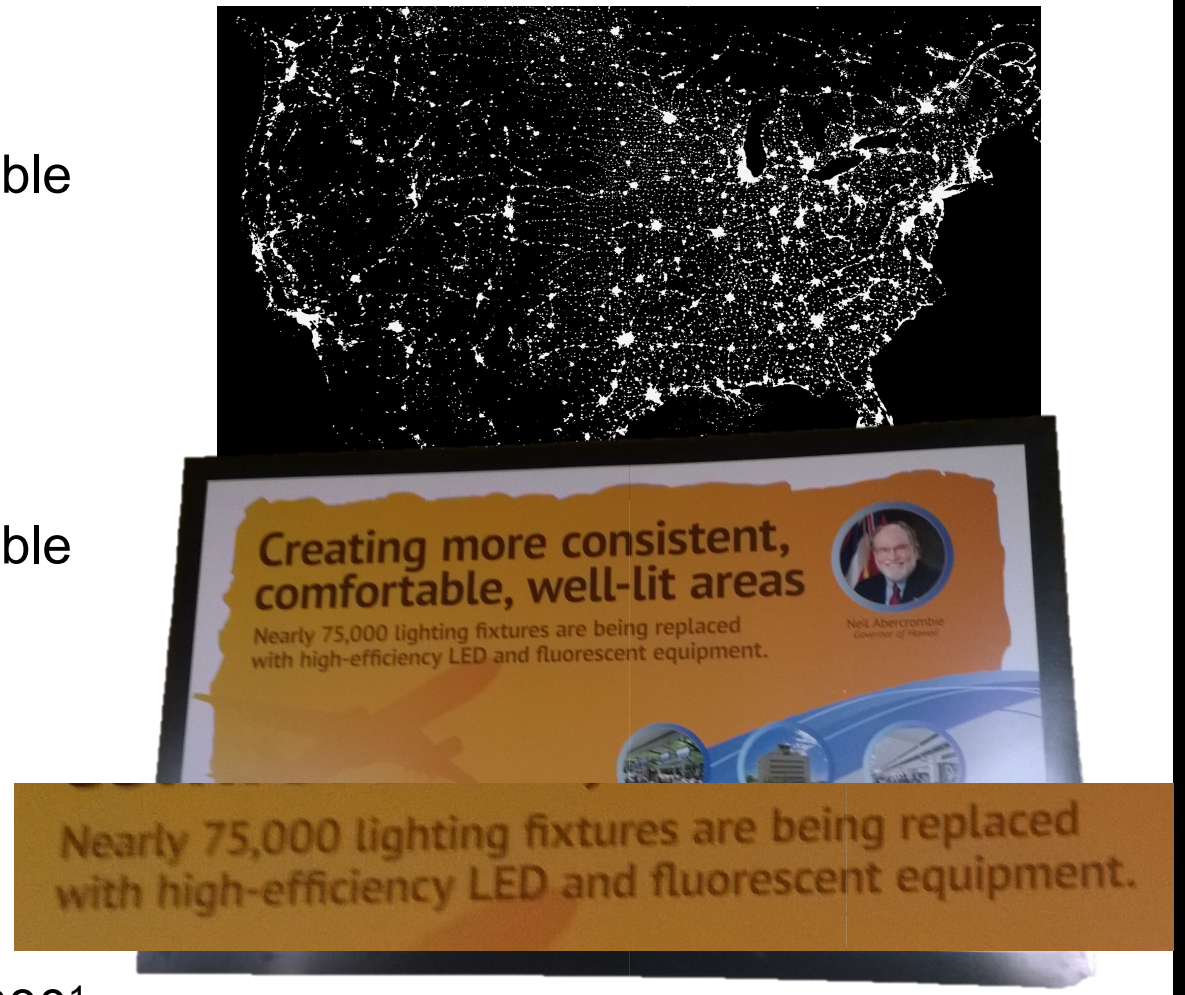
The first commercially viable light bulbs are produced

**1990s:**

The first commercially viable LED bulbs are produced

**Soon:**

LED lighting will achieve ~75% market share by 2030[1]

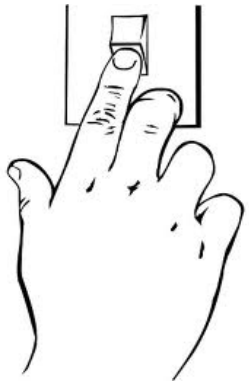



[1]N. Consulting. Energy savings potential of solid-state lighting in general illumination applications. *U.S. Department of Energy*, 2012.

# We cannot allow the solid state lighting revolution to be a simple substitute good

≠


~$10^{-4}$ Hz



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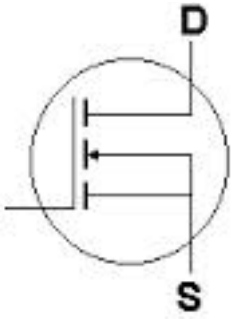


~$10^{4}$ Hz

lab11.eecs.umich.edu

# Unknowns in SDL design

# Call to arms?

# But why are *we* so excited about LEDs?

**Because they're *diodes*!**

**For the first time, we can modulate data – imperceptible to humans – on shared lighting infrastructure**

# The $10 Billion Question: Is this architecture good for anything?