SYSTEM ARCHITECTURE DIRECTIONS FOR A SOFTWARE-DEFINED LIGHTING INFRASTRUCTURE

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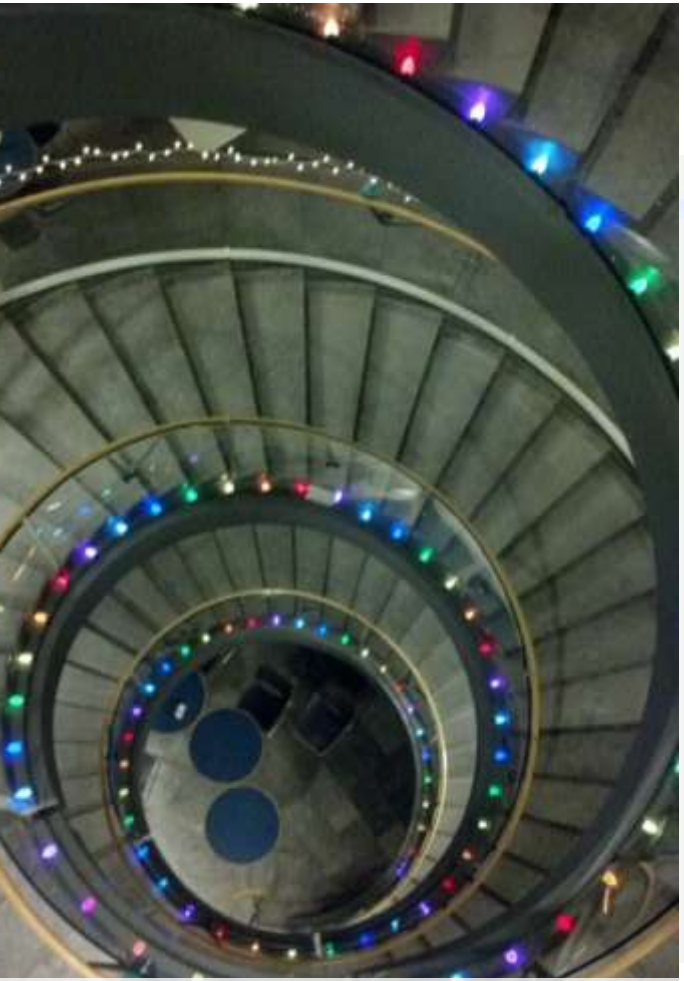
1ST ACM WORKSHOP ON VISIBLE LIGHT COMMUNICATIONS SYSTEMS (VLCS '14)

SEPTEMBER 7, MAUI, HI

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

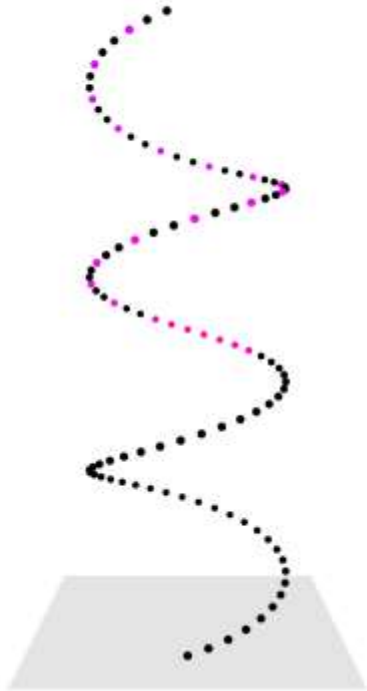


```
JavaScript
// Simulation of a 2-symbol Turing Machine, executing the
// Busy Beaver function (https://en.wikipedia.org/wiki/Busy_beaver)
//
// The tape head is always in the middle light, and the lights
// always show the 50 lights to the left (above) and right (below)
// the head.
//
// Color of 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

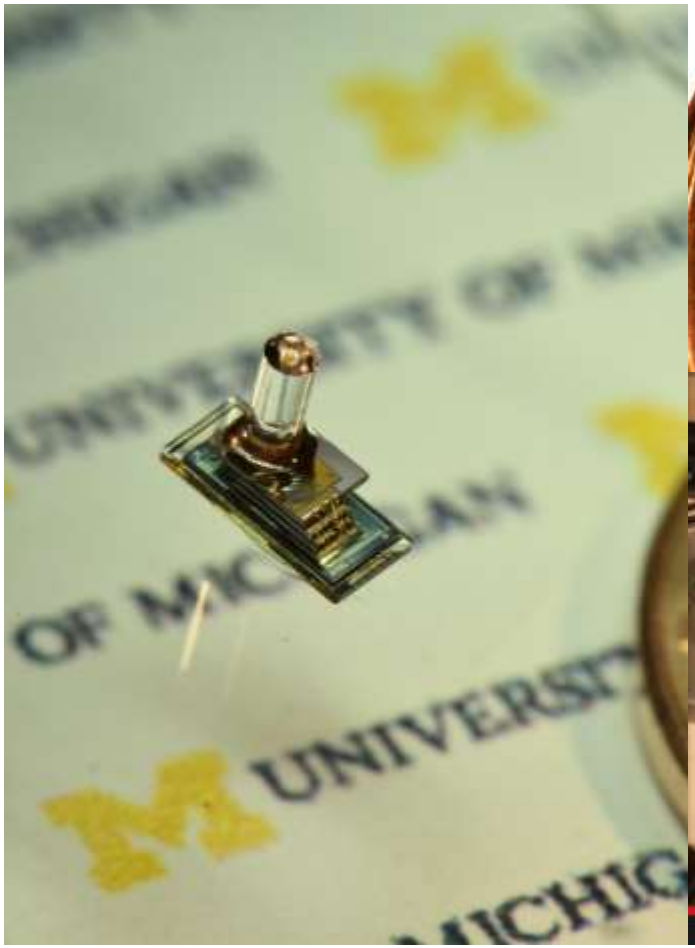
Run on Stairs



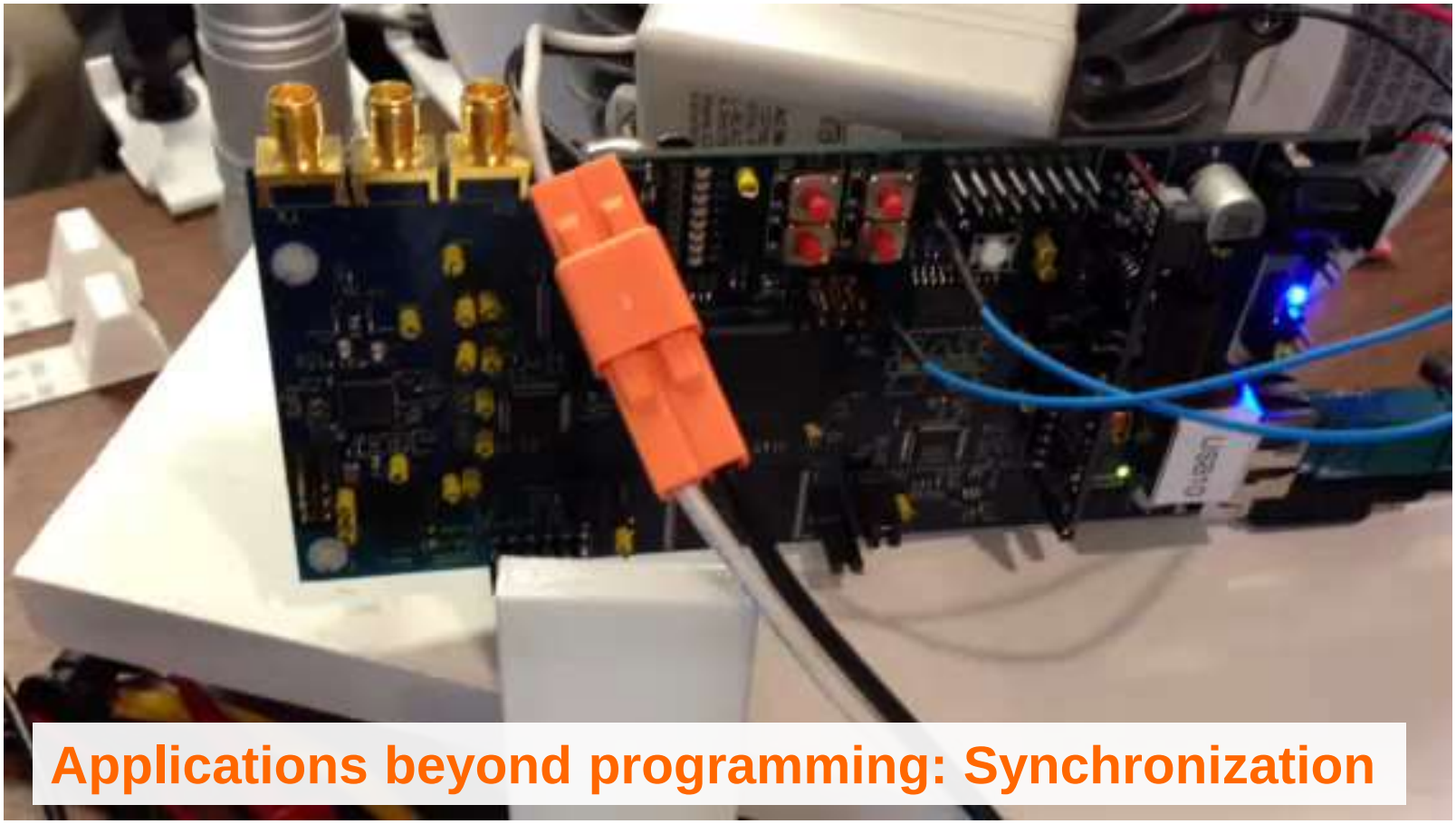
http://blinken.eecs.umich.edu/

M³: Programming Smart Dust with VLC

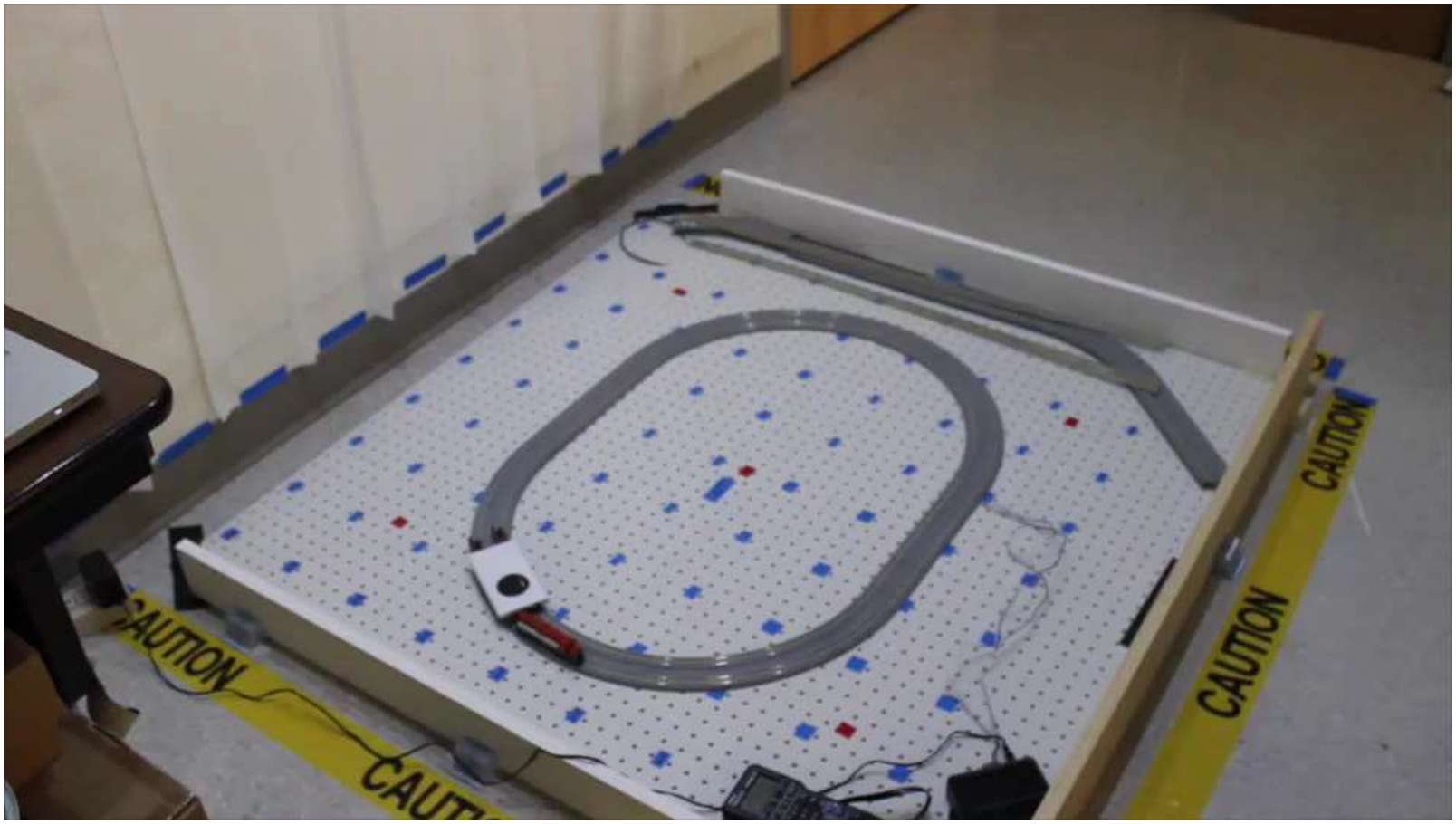
https://www.youtube.com/watch?v=OM8WgnhcyOo#t=118



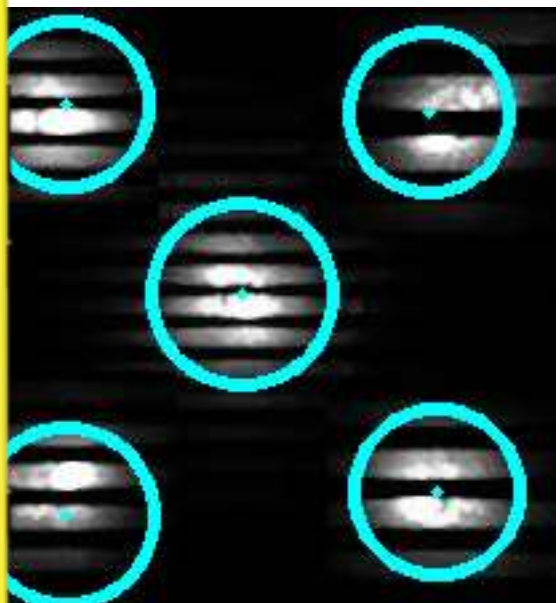
Electric Imp: Commercial systems also employ VLC for programming



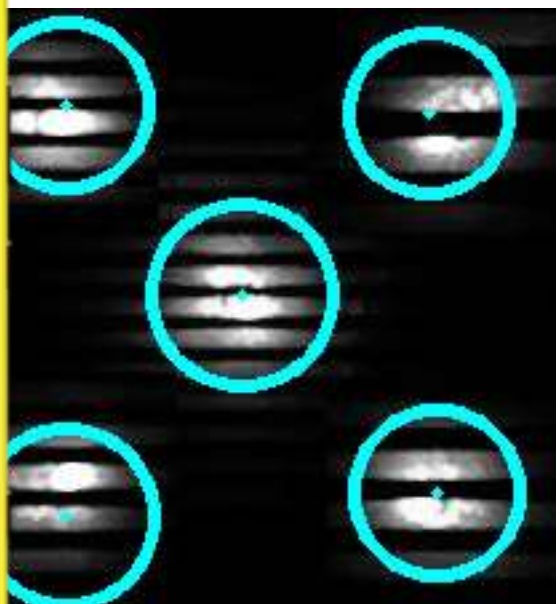
Luxapose: Accurate Indoor Positioning with VLCP



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

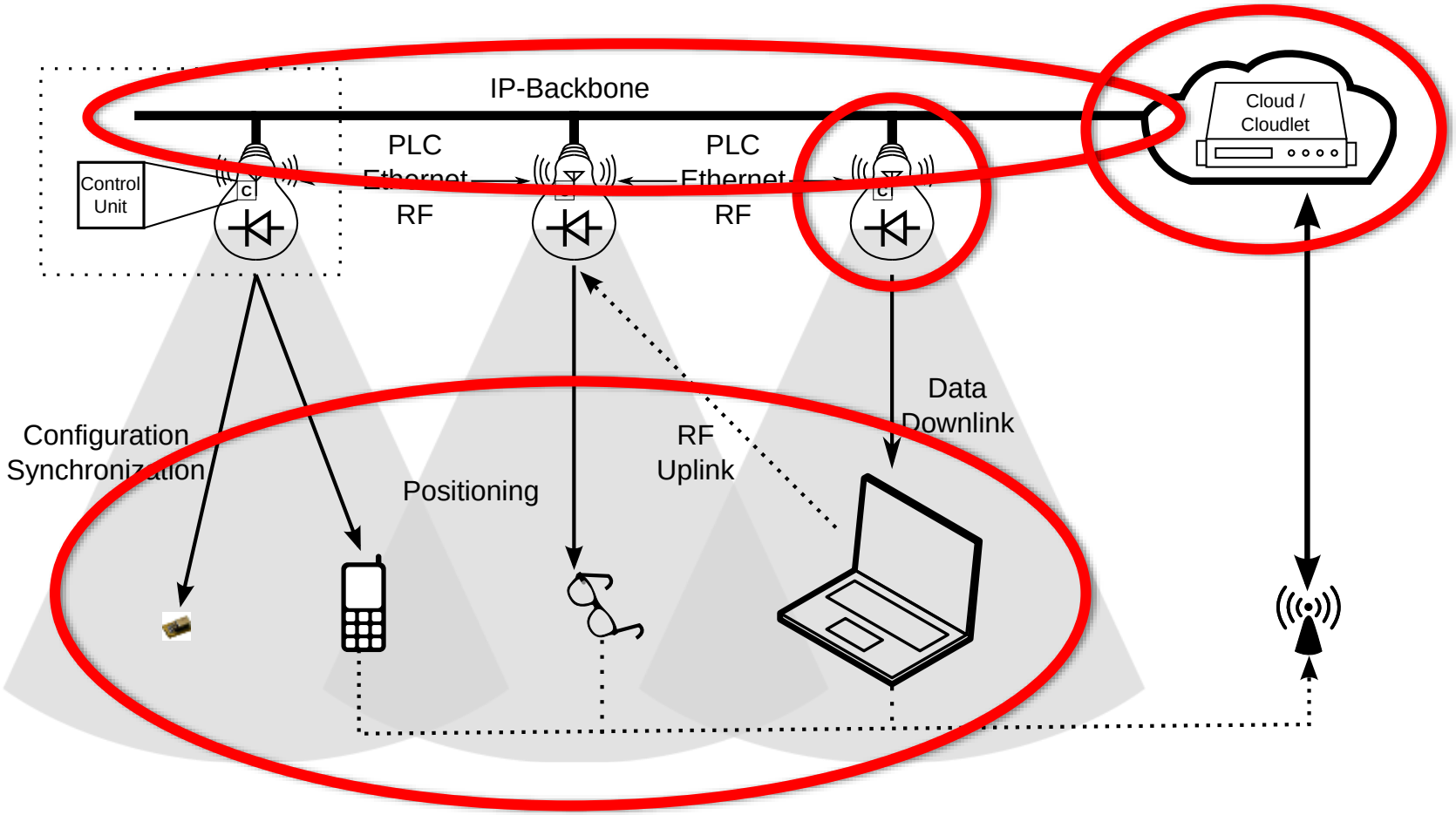
Stefan Schmid (ETH Zurich, Switzerland)

Josef Ziegler (ETH Zurich, Switzerland)

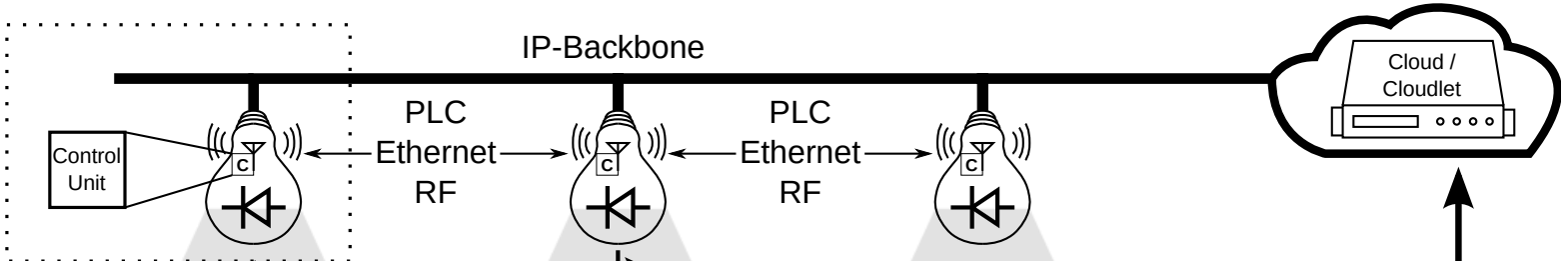
Giorgio Corbellini (Disney Research Zurich, Switzerland)

Thomas R. Gross (ETH Zurich, Switzerland)

Vision for a *modular* SDL architecture

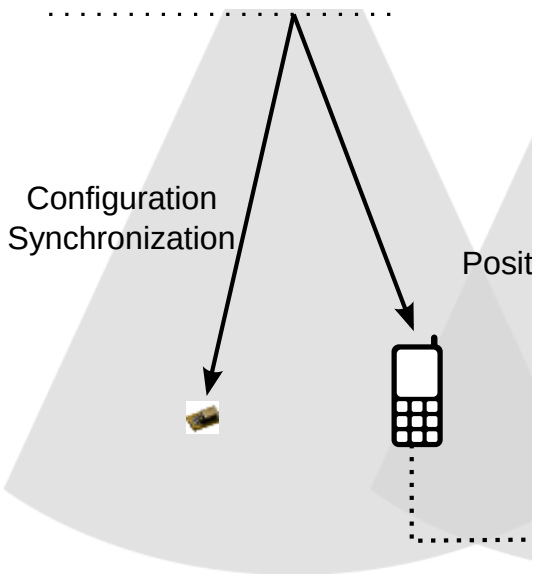


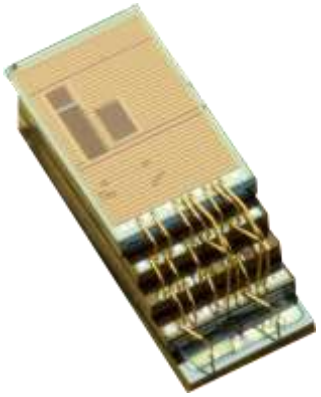
Taking lessons from Software Defined Networking into Software Defined Lighting



- **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





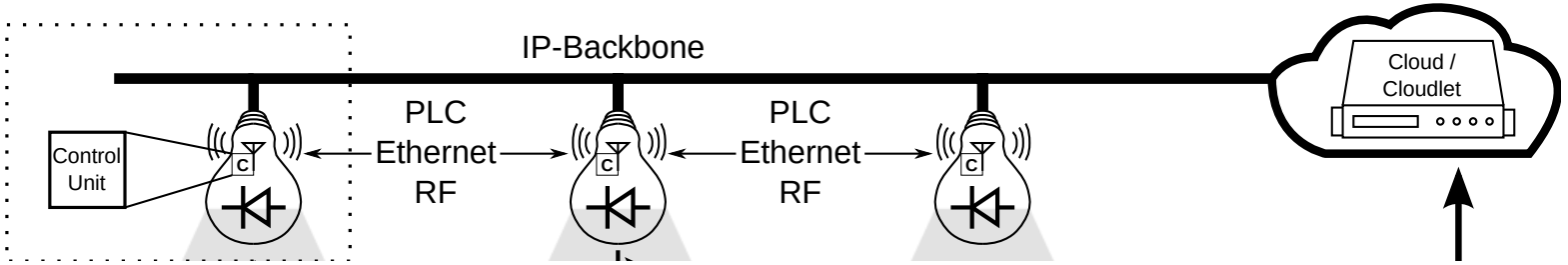
Diffusing (single photodiode)

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

Array (multiple photocell)

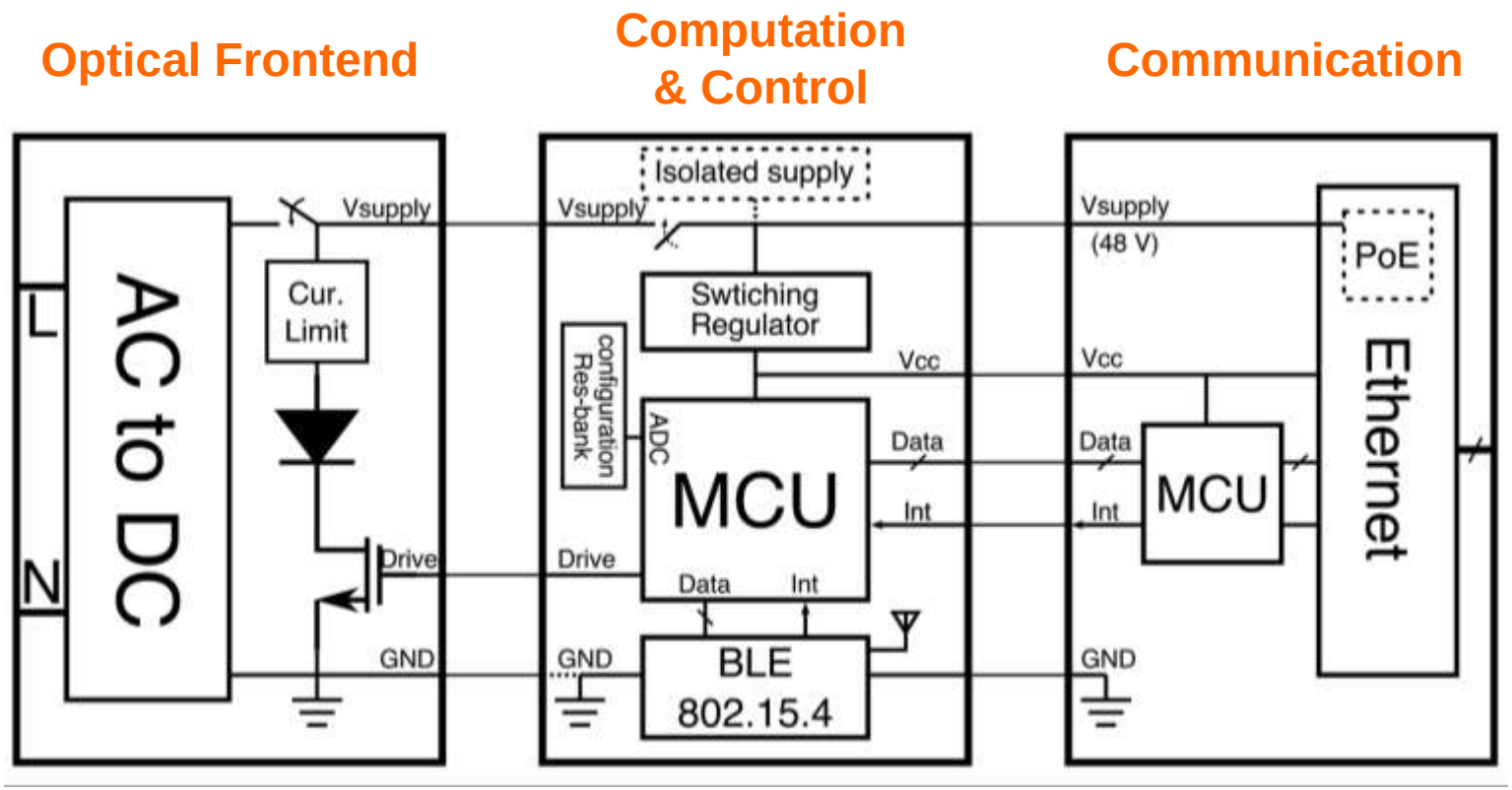
- Can distinguish transmitters
- Temporal or spatial diversity

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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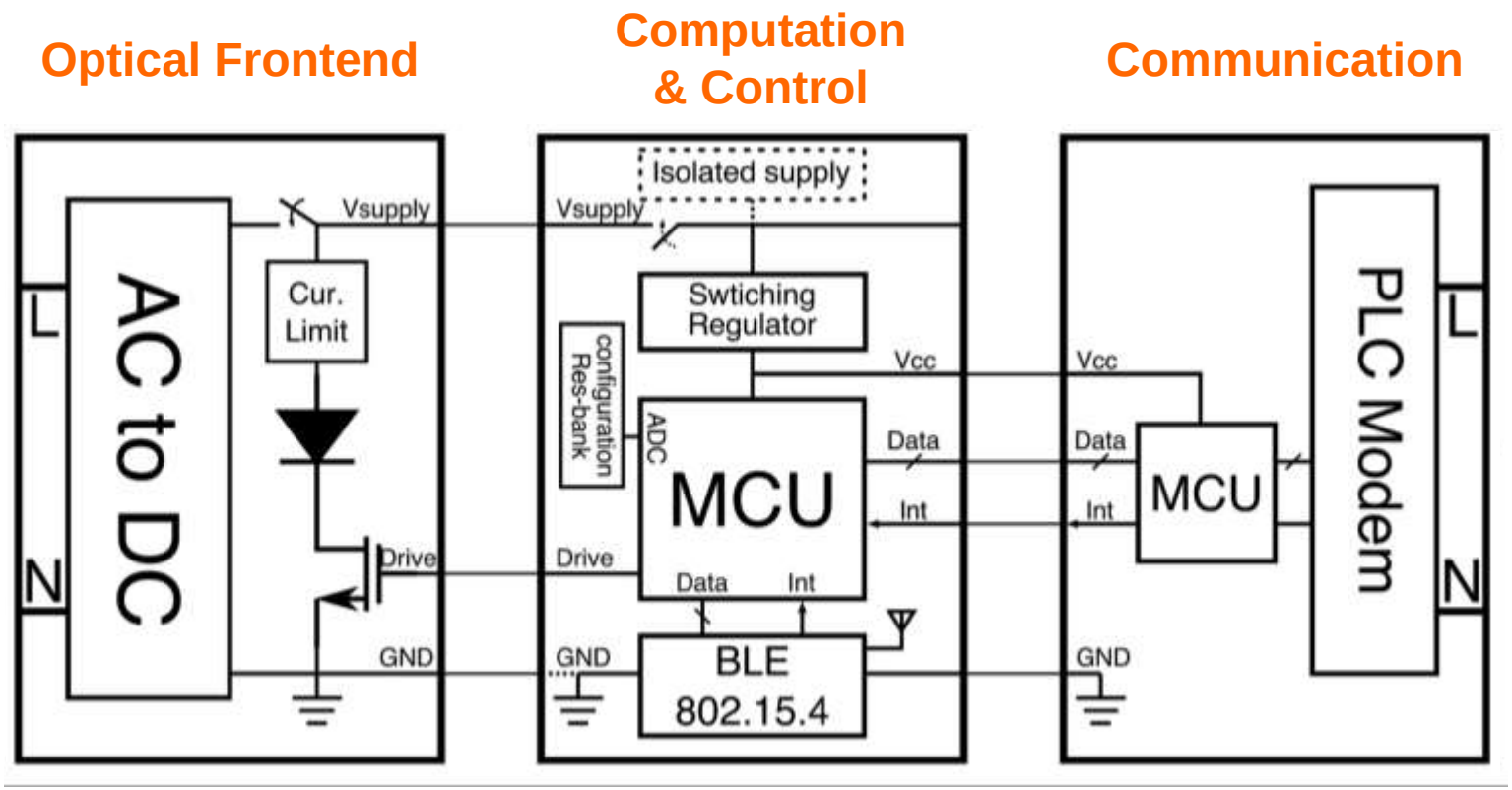

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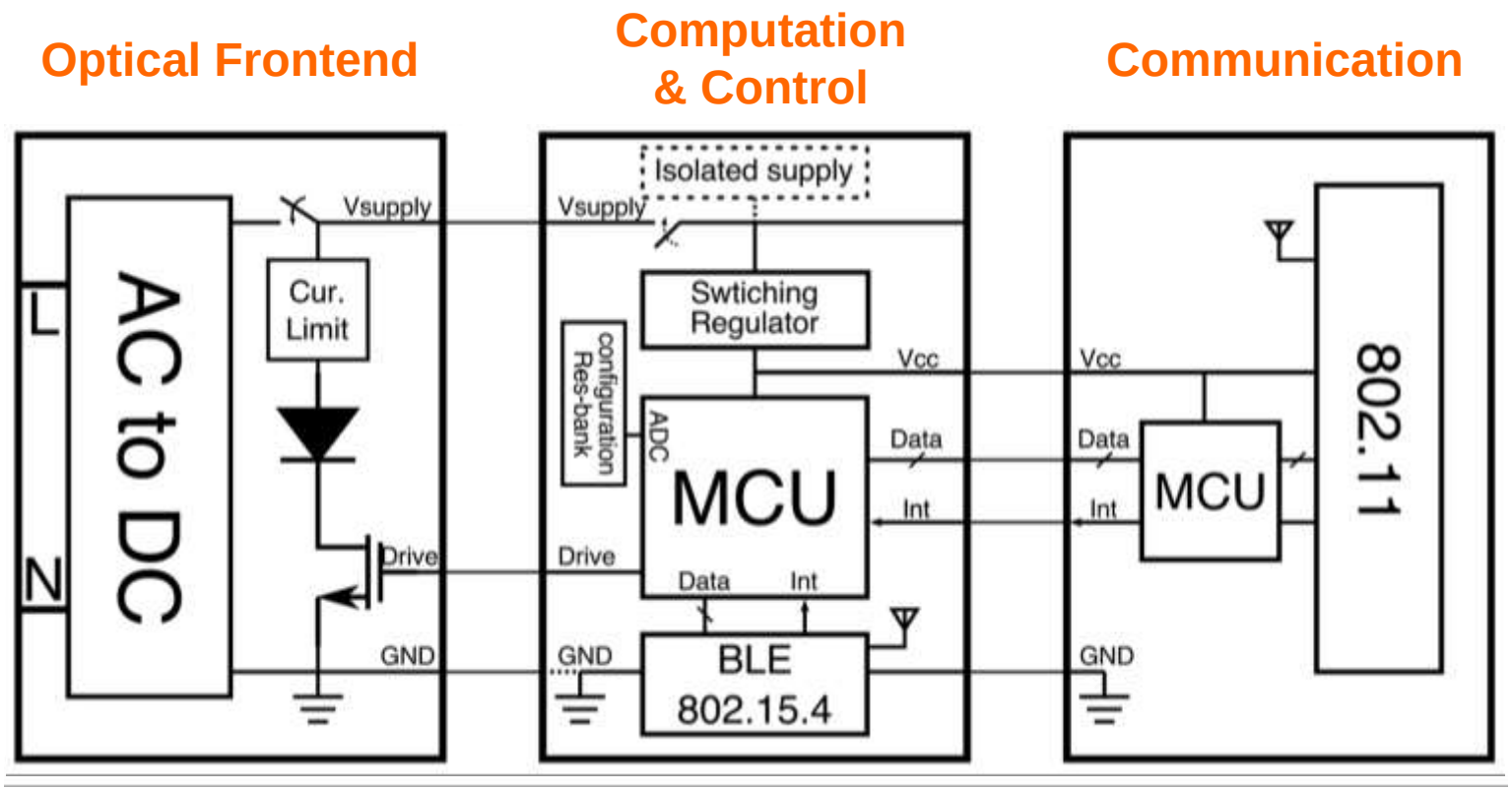
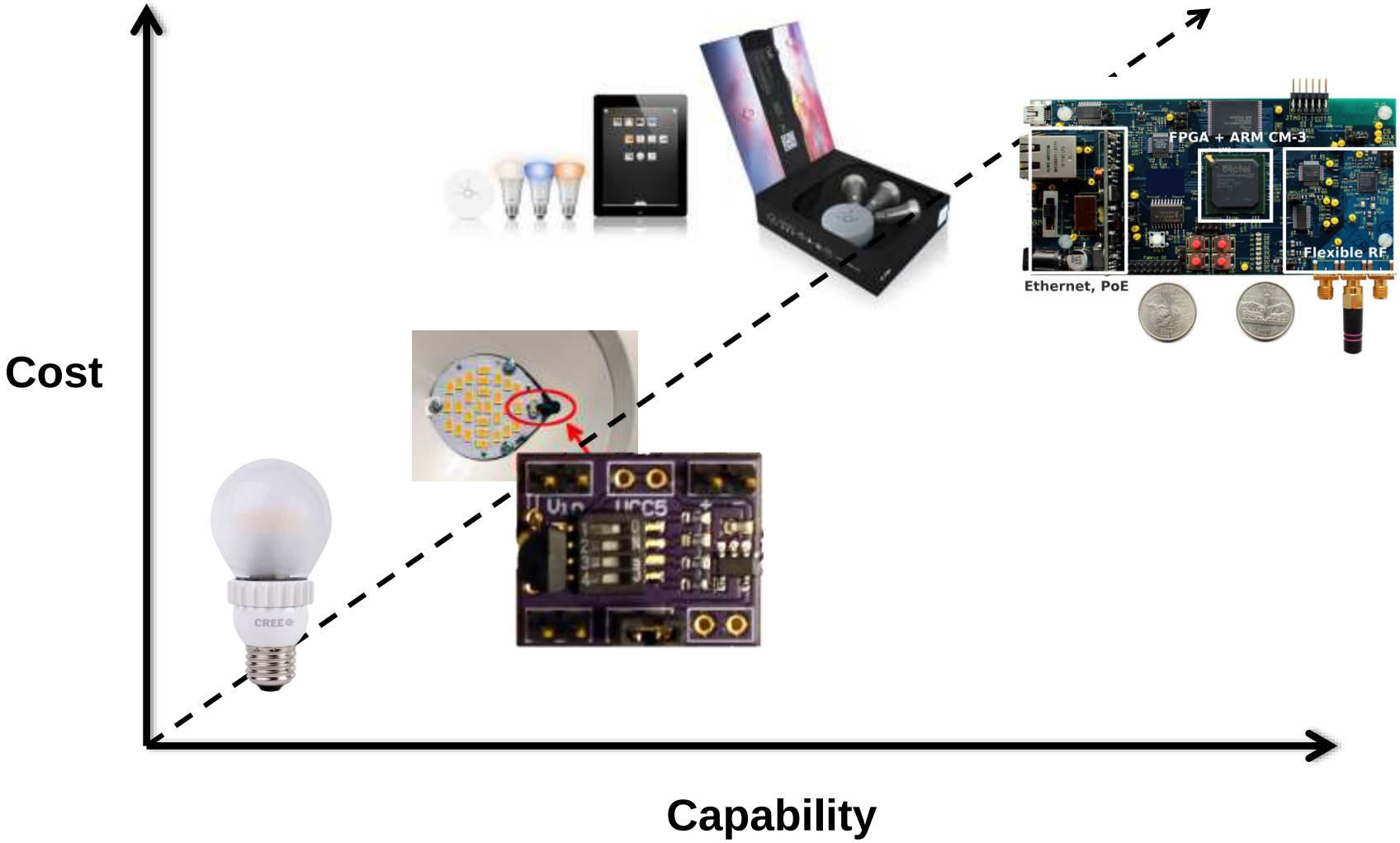


Different Modules Add Different Costs to Each Bulb

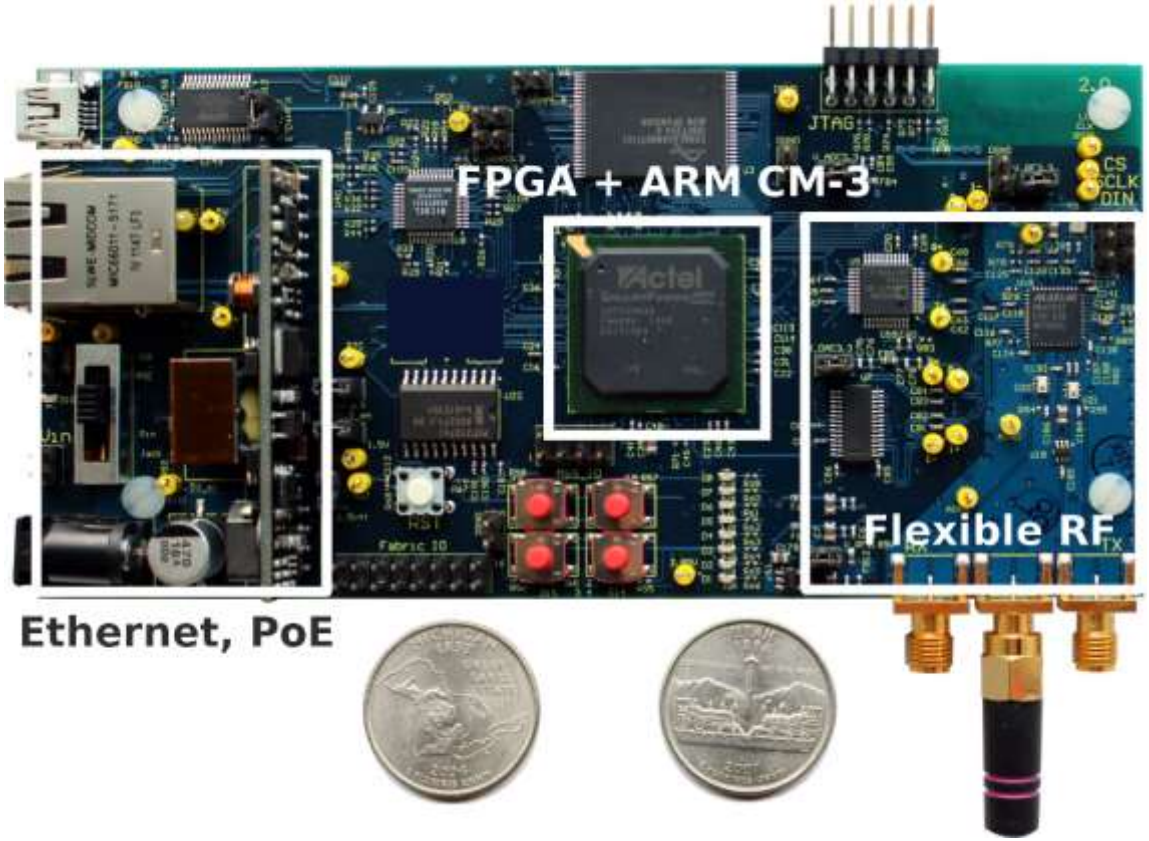
- **Communication**
  - PHY frontend
    - Antenna?
    - Coupled transformer?
  - Baseband processor
- **Computation & Control**
  - General-purpose (MCU)
  - Flexible fixed function (e.g., tunable oscillator)
- **Power Supply**
  - Above likely require lower voltage, perhaps isolation
  - Perhaps a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

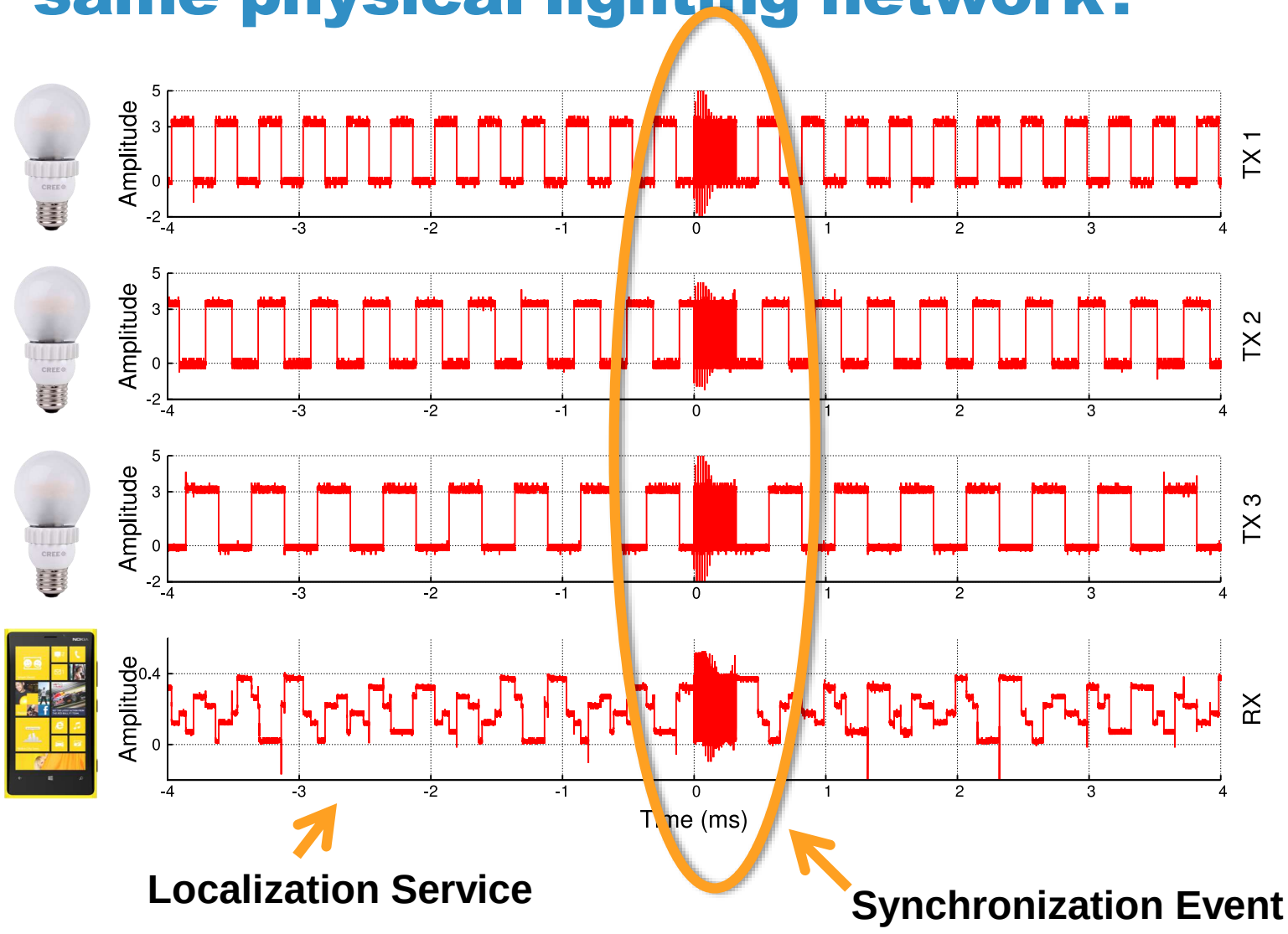


Lights are rarely isolated, and the whole must be greater than the sum of its parts

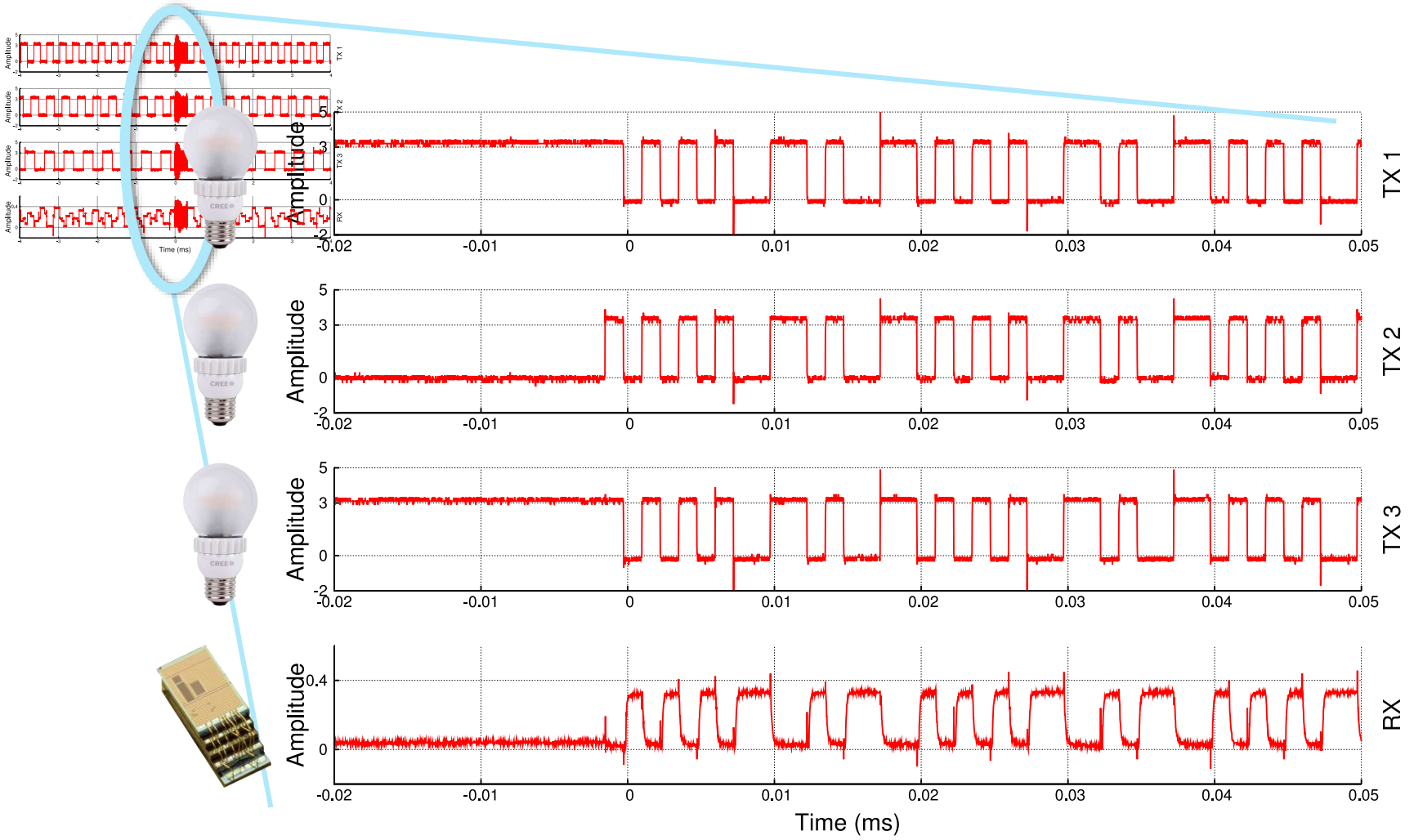
Mapping Applications onto a Network of Software Defined Lights

- **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

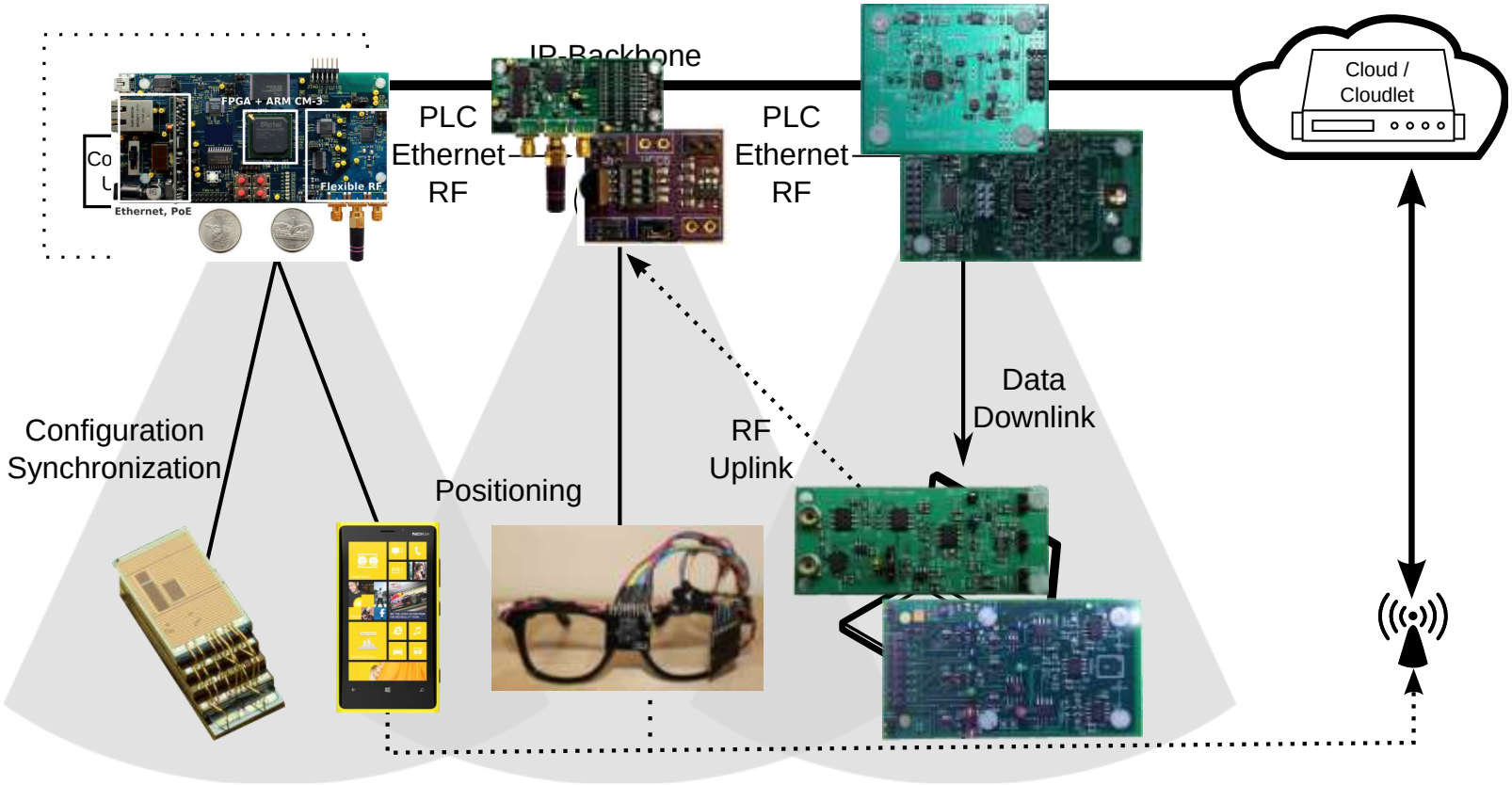
Can disjoint services multiplex on the same physical lighting network?



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:

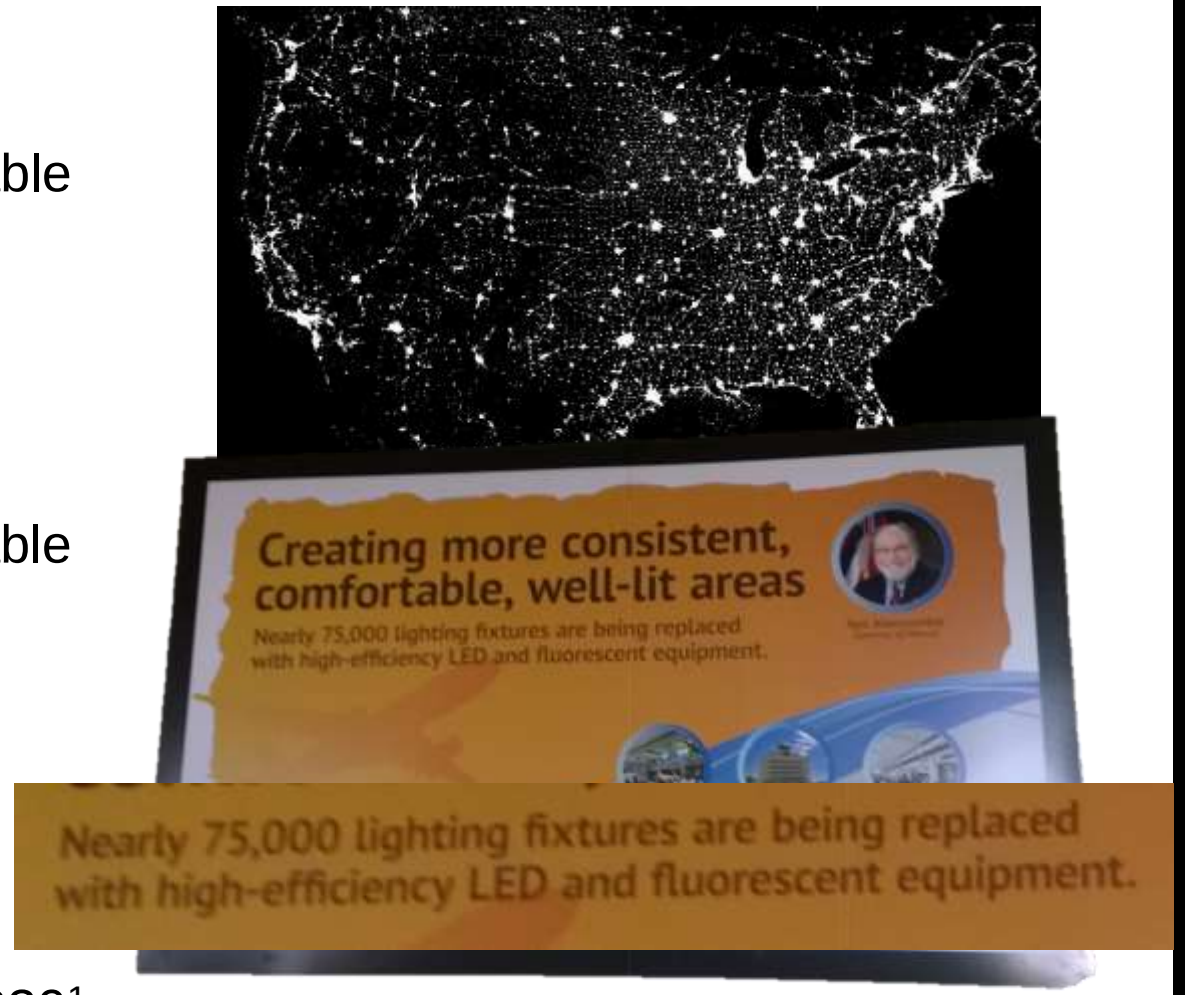
The first commercially viable light bulbs are produced

1990s:

The first commercially viable LED bulbs are produced

Soon:

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

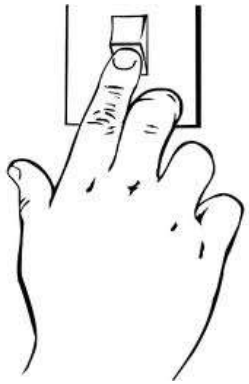


[1]N. Consulting. Energy savings potential of solid-state lighting in general illumination applications. *U.S. Department of Energy*, 2012.

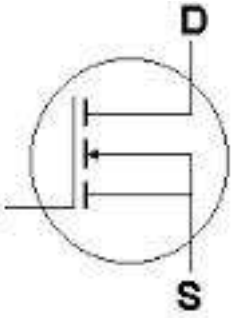
We cannot allow the solid state lighting revolution to be a simple substitute good

≠

~10^{-4} Hz



00010100 → G



~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