Wireless Connectivity in Lighting: Challenges towards the IoT

Jean-Paul Linnartz

Philips Lighting Research and TU/e

2016

innovation + you

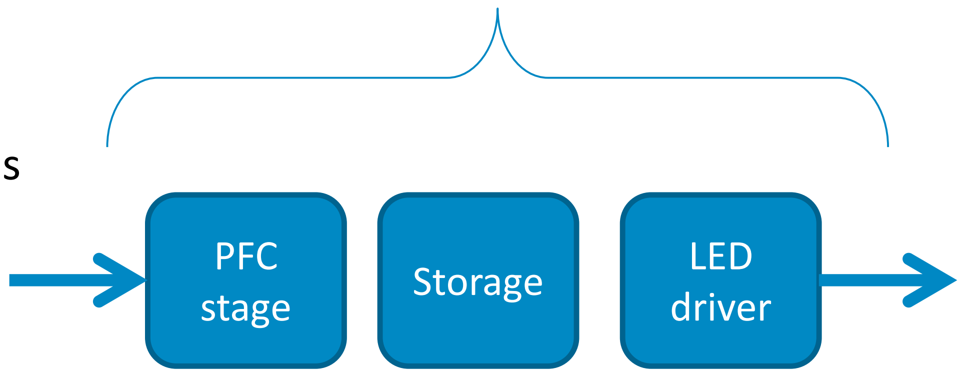
TU/e PHILIPS

The world needs **more light**

- By 2050, two-thirds of the world’s population will live in cities
- By 2050, there will be 2 billion more people on the planet
- New applications are increasing demand for light

LED lamps

Conversion Efficiency 80%..95%
Small, thermally limited?
Thermal stability
Over temperature protected
Low cost
Safe (e.g. isolated)
No audible noise
Tolerant to component spread



Resistive load to mains
Power factor > 0.7
Low harmonics
Low EMC
Universal mains
Surge protected
...

Flicker and strobo free
Good line regulation
Good load regulation
Suitable for OWC
Anti-aging

The world needs **energy-efficient light**

- 75% of street lighting is outdated, inefficient technology
- 50% of a typical city’s electricity consumption goes to lighting
- 19% of global electricity usage is for lighting – switching to LED will reduce it to 11%

N_L LEDs,

N_U users

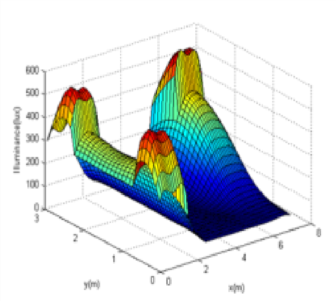
Light output vector **w**: N_L values of dimming levels $\{w_1, w_1, \ldots\ w_{NL}\}$

Vector x of Light levels on all locations in the room

Illuminance transfer matrix I, I_{ij} describes the amount of light from lamp I to location j

Matrix notation

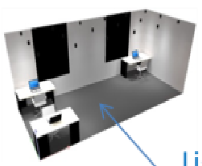
$$x = I^T w + d$$



$$\begin{bmatrix} 1 & 1 & 0.2 & 0.2 & 1 & 1 \\ 1 & 0.2 & 0.2 & 0.2 & 0.2 & 1 \\ 1 & 1 & 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix}$$

Dimming vector w organized as a matrix

But we can also show
this in a 3D rendering tool (DIALUX)



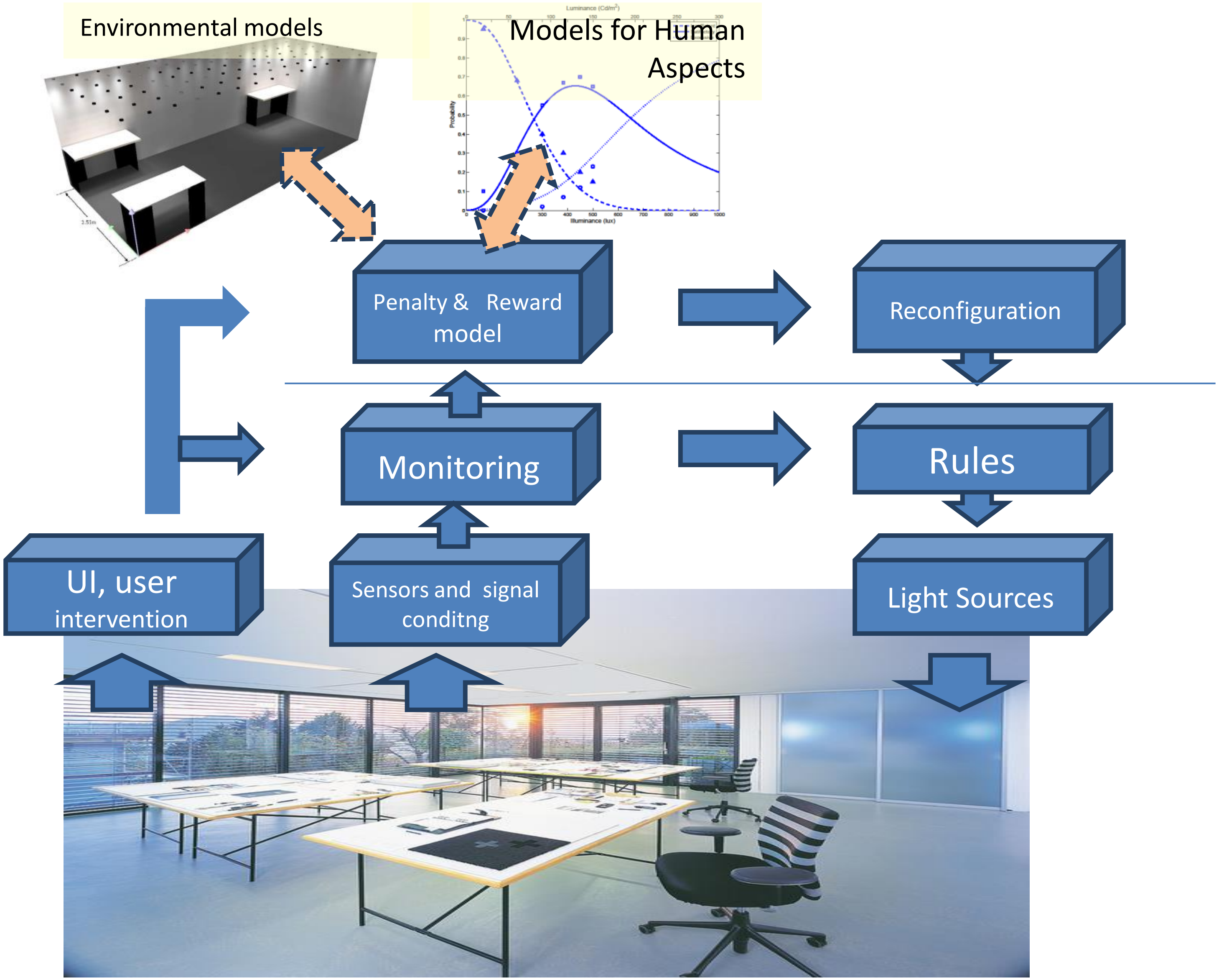
Light x on every location

Towards 200 lm/watt

Improvements in **energy-efficient light**

- Increase lumen per watt (200 lm/watt)
- Less heat → smaller, cheaper products
- Lighting Control Optimizations
    - Regrettably the TCO does not justify too sophisticated solutions

Machine learning & Advanced Control



Research on Light Optimization

- The forward problem: Rendering the effect of light settings
- The inverse problem: Which light setting gives the desired light distribution
- The optimization problem: Which light setting gives the highest user satisfaction for a given user and a given activity
- The light optimization problem with estimation of user :
  Which light setting gives the best satisfaction, based on partial knowledge of the user and activity
- The light optimization problem in a multiuser setting: trade of between users

N_L LEDs,

N_U users

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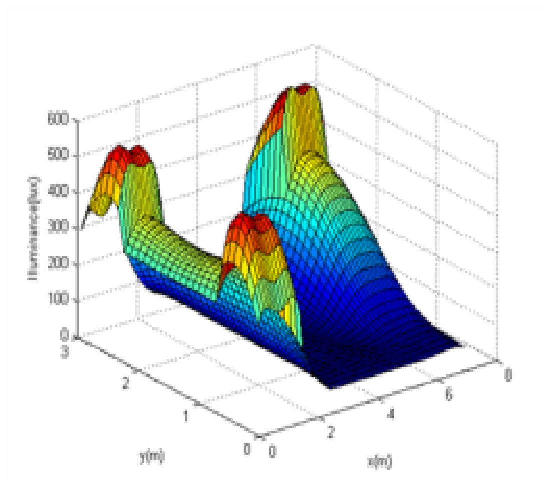

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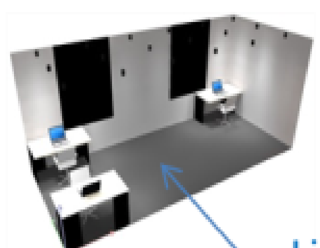
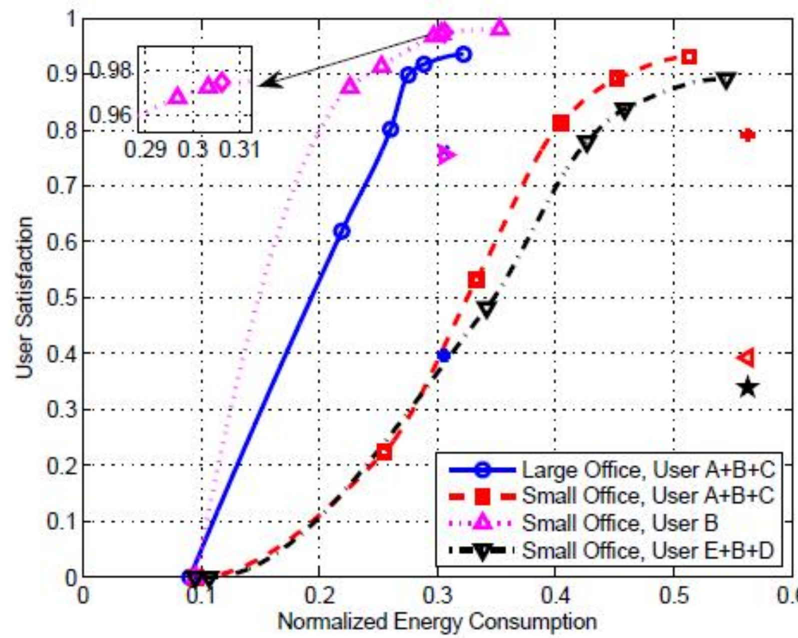


Light x on every location

Optimization of light setting

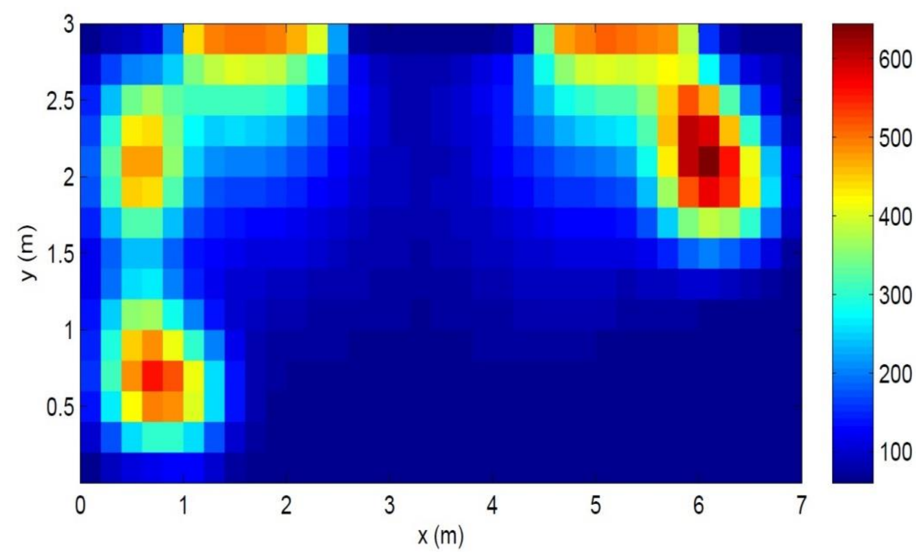
Optimizing the trade-off between power consumption and user satisfaction

$$\begin{aligned} \arg\min_{\mathbf{w}} \quad & (1-\gamma)\mathcal{E}(\mathbf{w}) - \gamma\mathcal{P}(\mathbf{Iw}+\mathbf{d}) \\ \text{subject to} \quad & 0 \preceq \mathbf{w} \preceq 1, \\ & \mathbf{Iw}+\mathbf{d} \succeq \mathbf{r} \end{aligned}$$



User satisfaction has many aspects:

- Task area illumination
- Uniformity of light
- Illumination of surrounding areas
- Glare
- Balance between sun light and artificial light
- Illumination of walls
- Color of light versus time of day



The world needs **more digital light**

Society and lighting are going digital:

- Connected lighting enables new levels of energy efficiency, amazing new experiences, and smarter ways of working
- Connected lighting market worth an estimated $56 billion by 2025
- Less than 1% of street lighting is connected; industry analysts predict nearly 300 million smart home connections by the end of 2015
- Lighting-as-a-Service (LaaS) and other new business models are transforming the way lighting systems are purchased and operated

Insight Real Estate…

As a building contractor / owner my main concern is to decrease project risks, maximizing asset value and increase the building attractiveness.

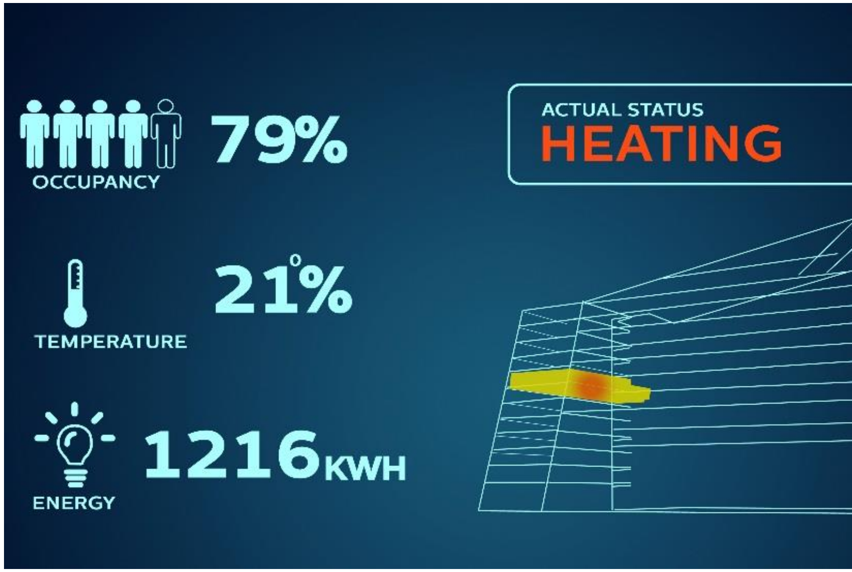
I would consider investing in a lighting system if it has
a good payback,
increases the satisfaction of the users and would be easy to install and maintain ...

Insight Facility Mgt

As a building operator my main concern is to decrease operational cost and to increase the satisfaction of the building users.

Intelligent lighting systems could help me there if it could provide me more detailed and frequent information on actual building use, comfort and quality.

Current systems difficult and expensive to expand.



Sensor Network or
Multihop Broadcast Networks

- Network requirements for Lighting Control and Building automation differ from only a sensor network

  - Hybrid traffic
    - Control (downlink)
      - Low latency, instantaneous response
      - Via multi-hop
      - Very low outage probability
    - Gathering sensor data (uplink)
      - Building usage
      - Maintenance and metering

  - Very large and very dense networks

  - Scaling problem in free-space path loss propagation conditions

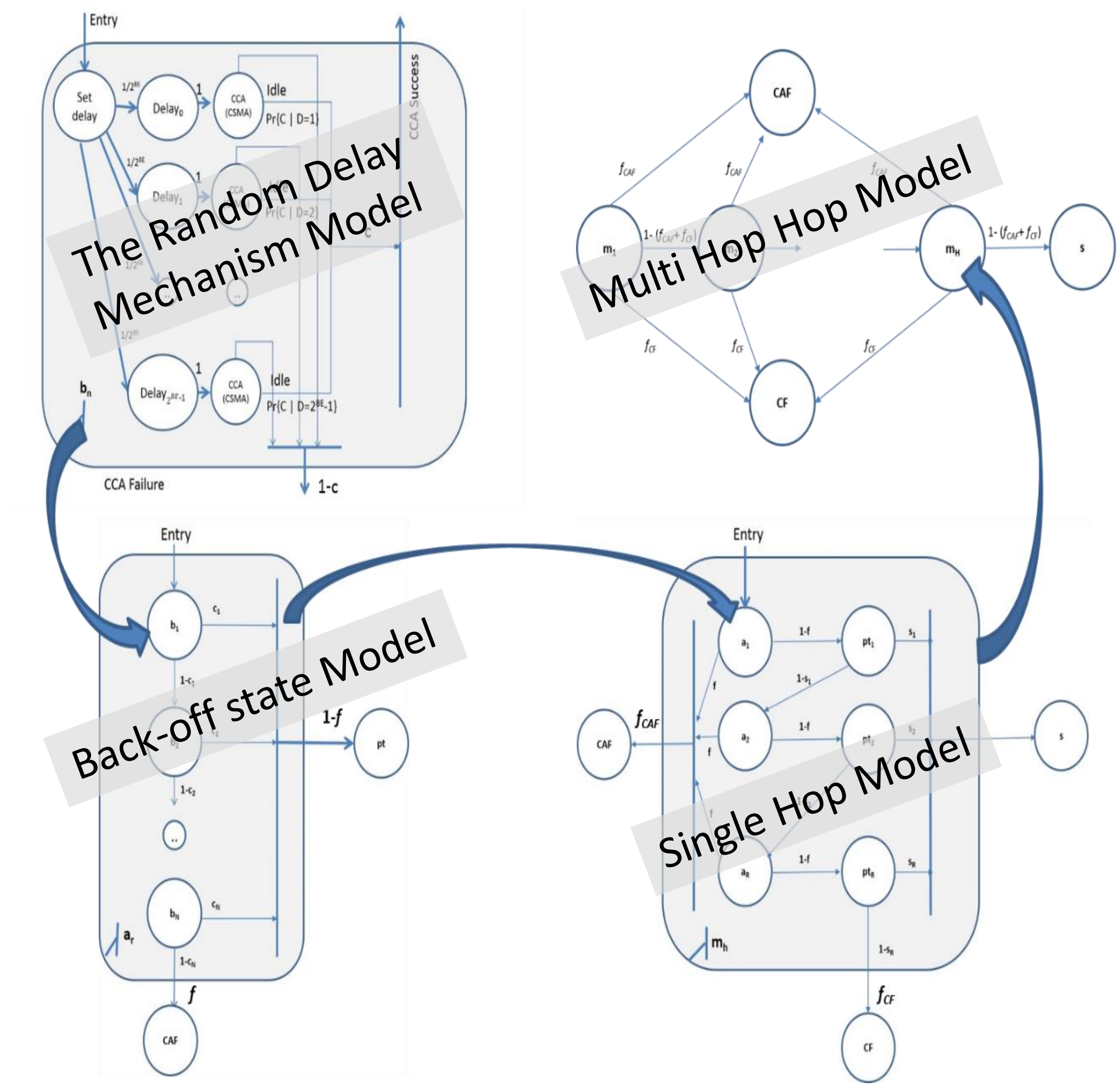
Down link : Multihop Broadcast Networks

The rationale for broadcast messages in wireless networks

- Network management traffic such as a frequency channel change
- Lighting control

300 hue lamps at Light and Building, Frankfurt

Layered Markov State approach to analyze Zigbee



Each node has a large state space

There a many nodes

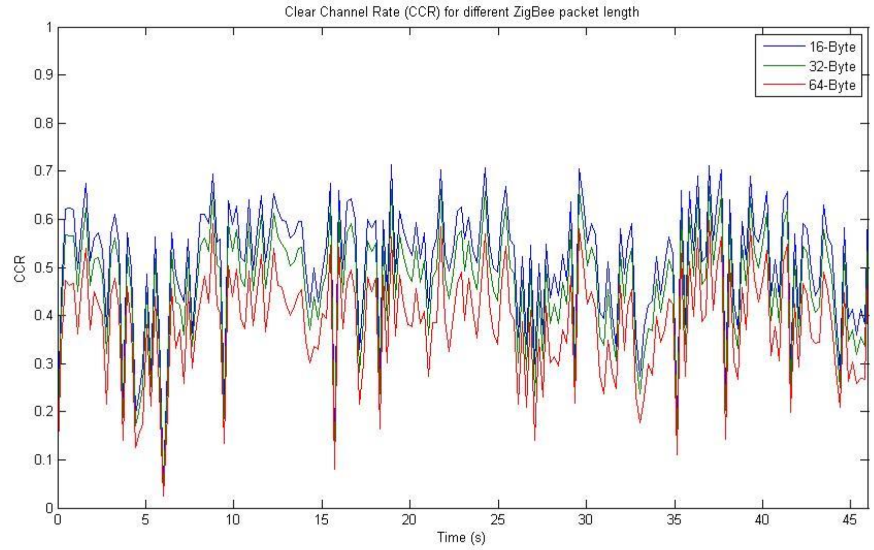
Nodes influence each other

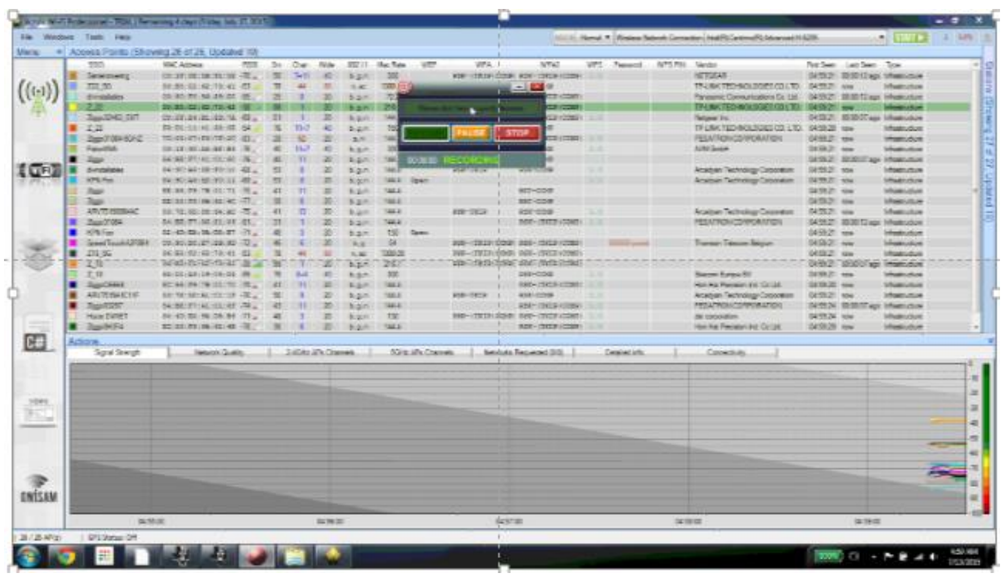
Interference affects the entire system

- Mean-field analysis
- simulations

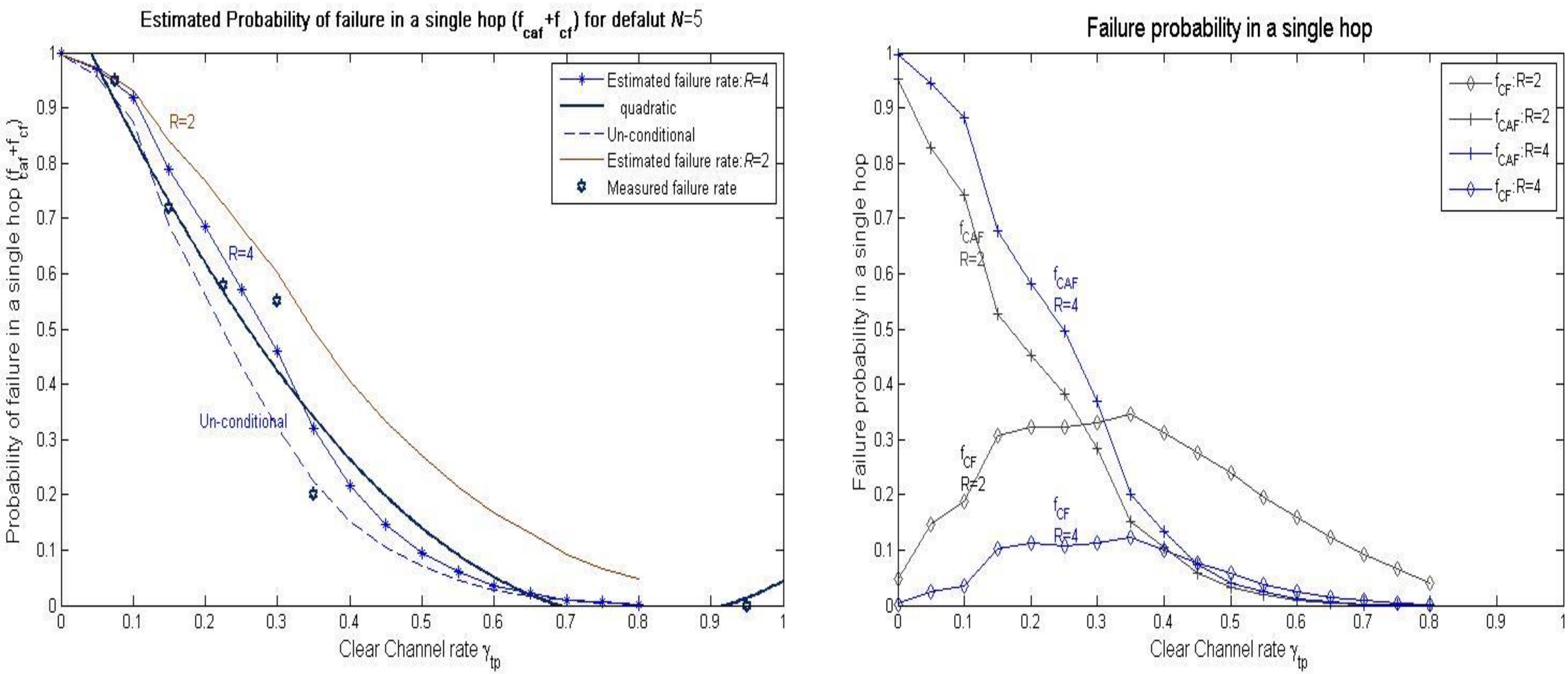
This Zigbee Multihop protocol sees bursts of interference from WiFi

- Wifi signals are stronger
- WiFi does not always see Zigbee
- Wifi is more aggressive: shorter backoffs





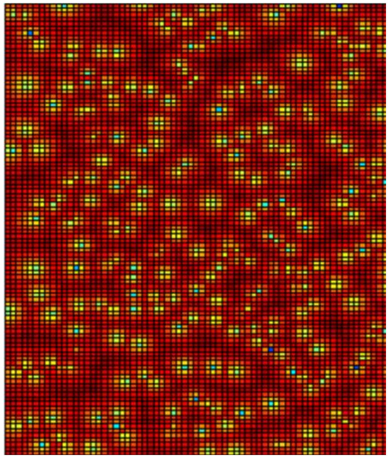
Probability of failure in a single hop (f_{CAF}+f_{CF})



Types of MAC

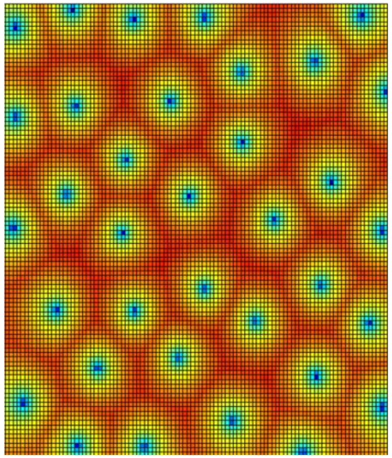
ALOHA

- Nodes transmit without mutual regulation
- Many collisions
- many unnecessary repetitions



CSMA-CA

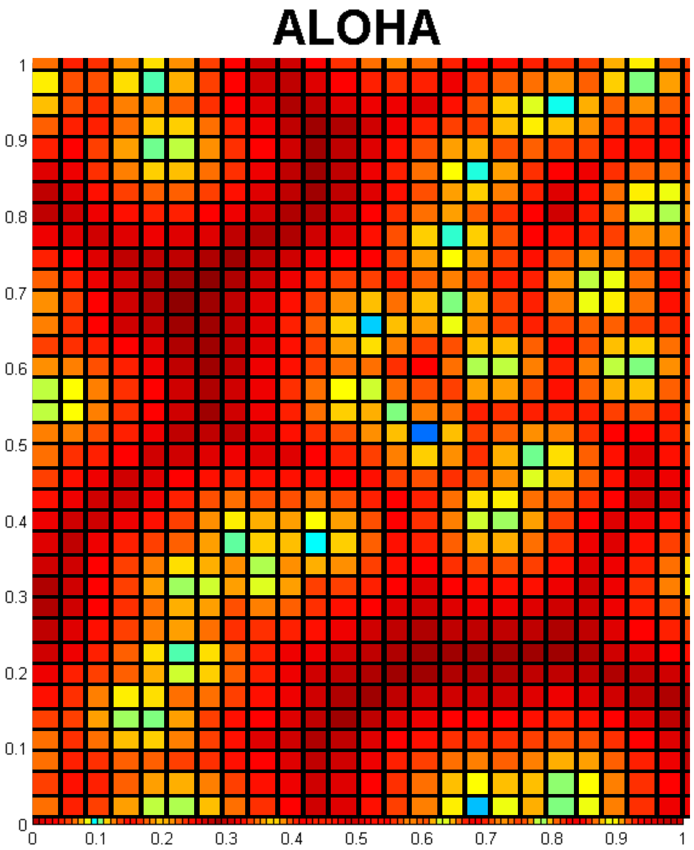
- Clear Channel Assessment (CCA) before transmission.
- Measures power but not content
- Prevents collisions
- *Retransmission only if the channel is found idle.*

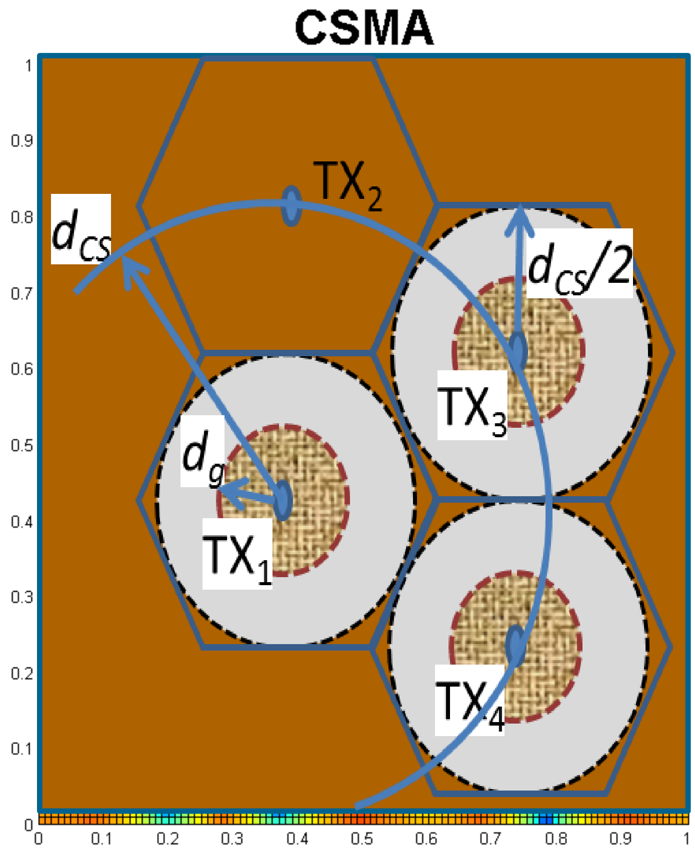


Trickle

- **Counts intensity of gossiping**
- **Measures content but not power**
- **Avoids excessively many transmissions**
- ***Retransmission only if the message has not already been sent often enough***

The spatial distribution of transmitters



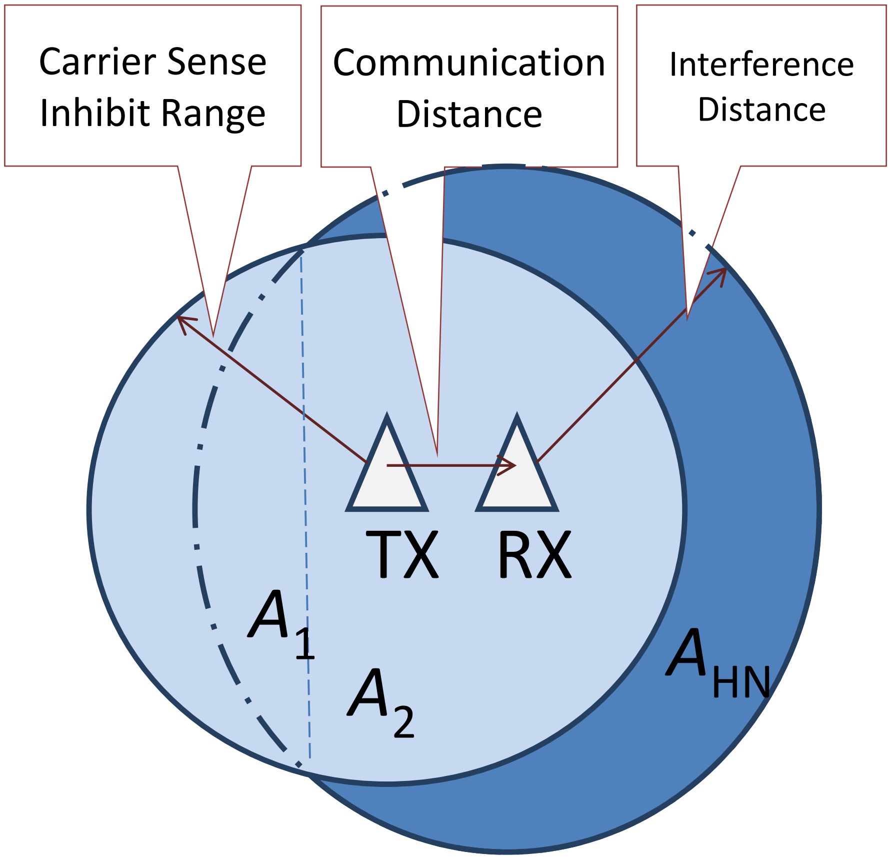


Hidden and Oblivious Nodes

Hidden Node: (**not heard**) an actively transmitting node that is not heard by the transmitter but nonetheless causes harmful interference at the receiver.

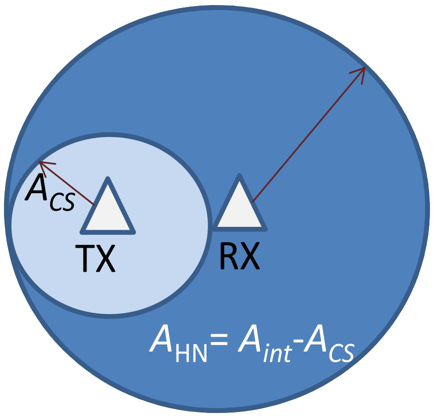
Oblivious Node: (**not hearing**) a node that is not aware that our transmitter becomes active and starts a harmful transmission.

Re-broadcasting: There is no predetermined TX-RX range. TX just hopes to reach many receivers, but it is OK if other transmitters reach those RX's.



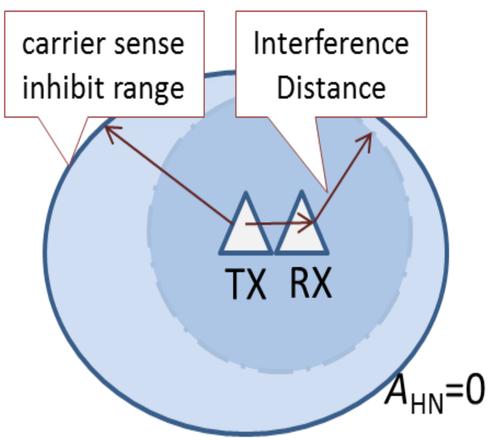
How sensitive does the CS-threshold need to be ??

Limits for a successful transmission



Insensitive carrier sensing
Performance → Aloha

$$S = 2\pi \int_{x=0}^{\infty} x F_0 \exp\{-2\pi x^2 z^{2/\beta} F_0\}\, dx = \frac{1}{2} z^{-\frac{2}{\beta}}$$



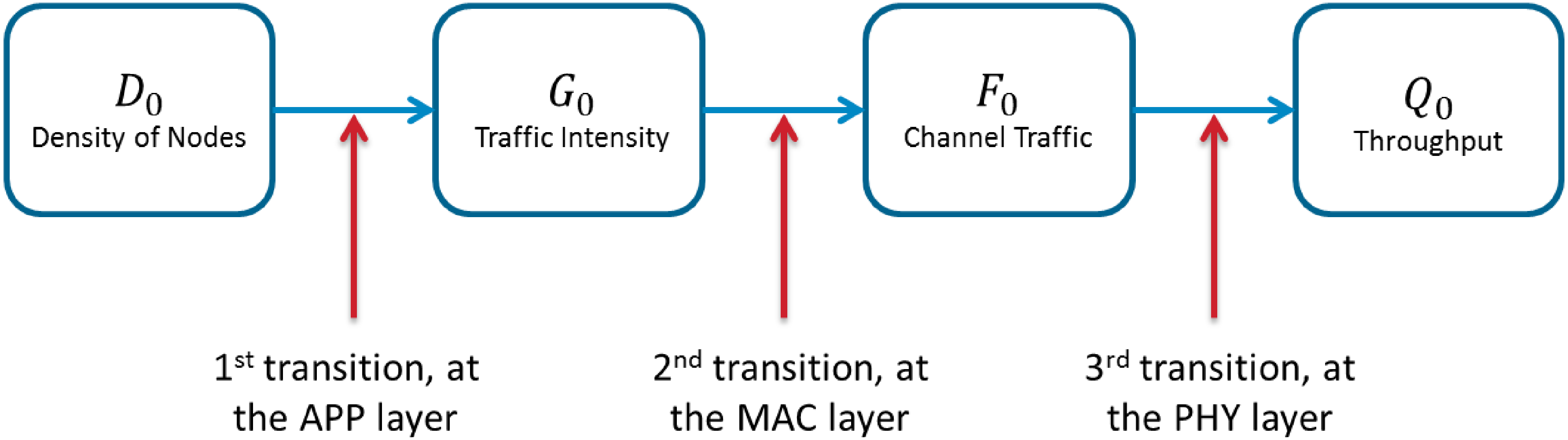
Very sensitive carrier sensing
Performance >> Slotted Aloha

$$Prob = \frac{\pi d_0^2}{A_{CS}} = z^{-\frac{2}{\beta}}$$

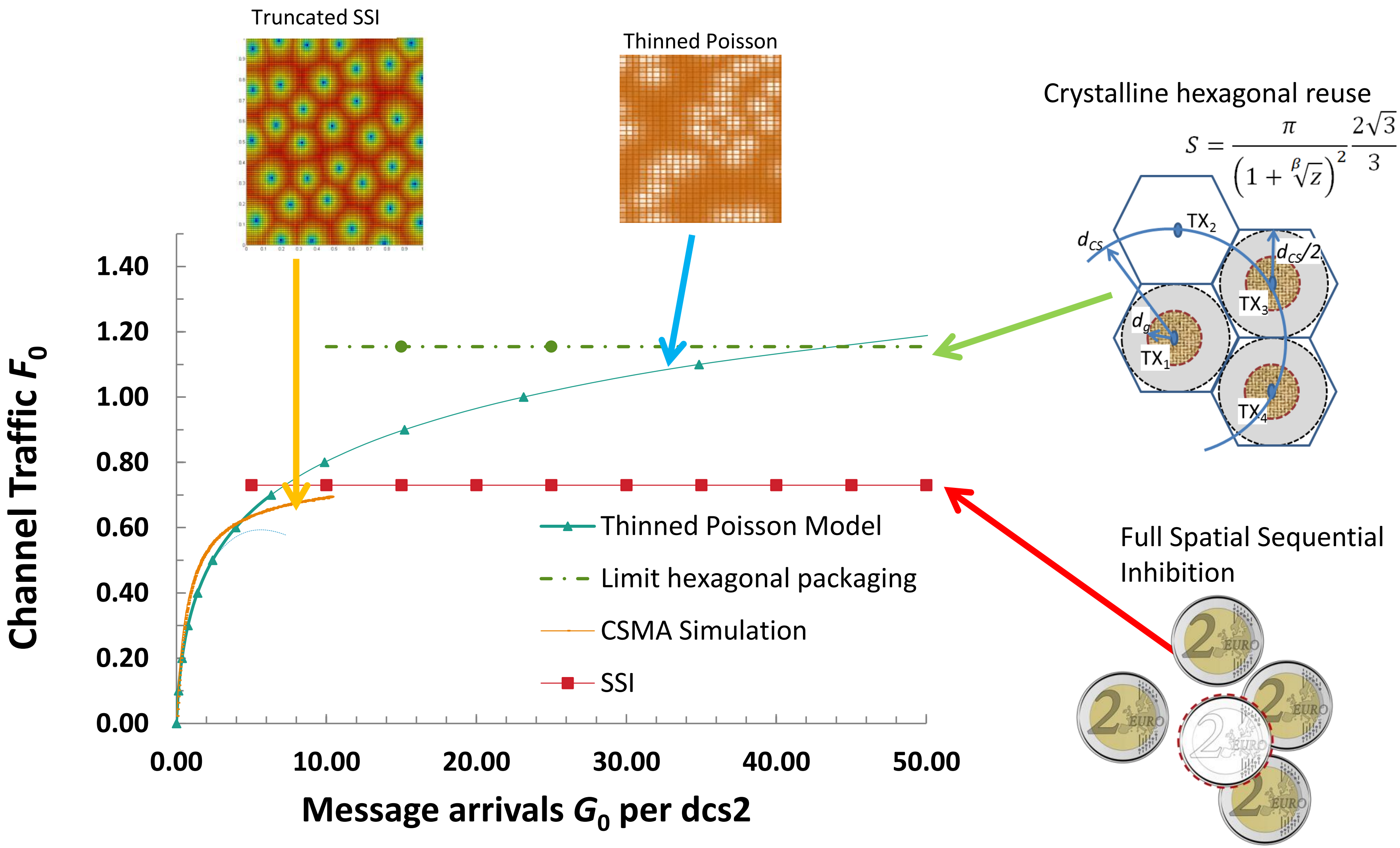
This is pessimistic

- Nodes in $A_{CS} \cap \neg A_{int}$ may get the message via other TX
- highly structured (haxagonal) overlapping A_{cs}

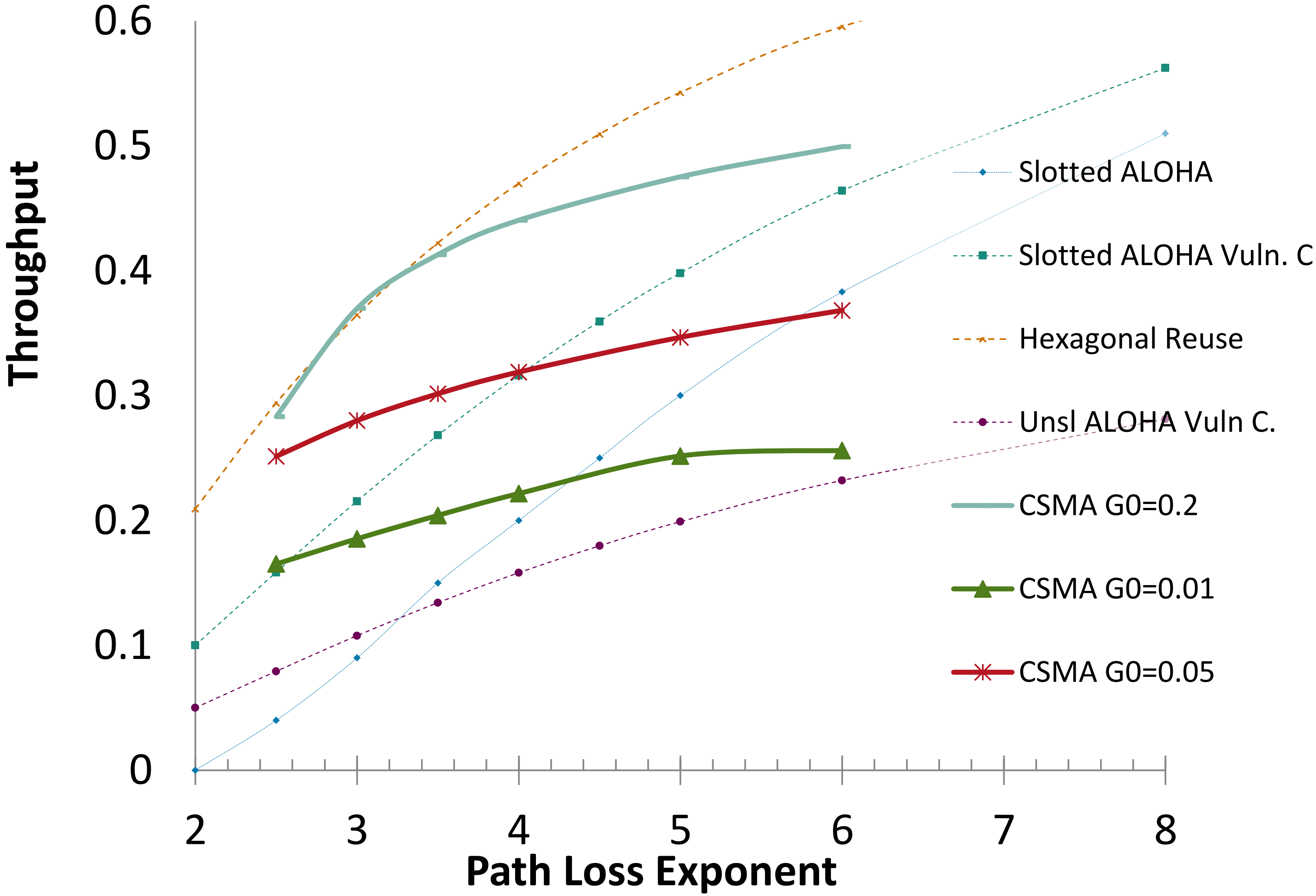
Poisson Model for the Network Traffic



Spatial Patterns of Traffic



Throughput: packet per receiver per unit of time



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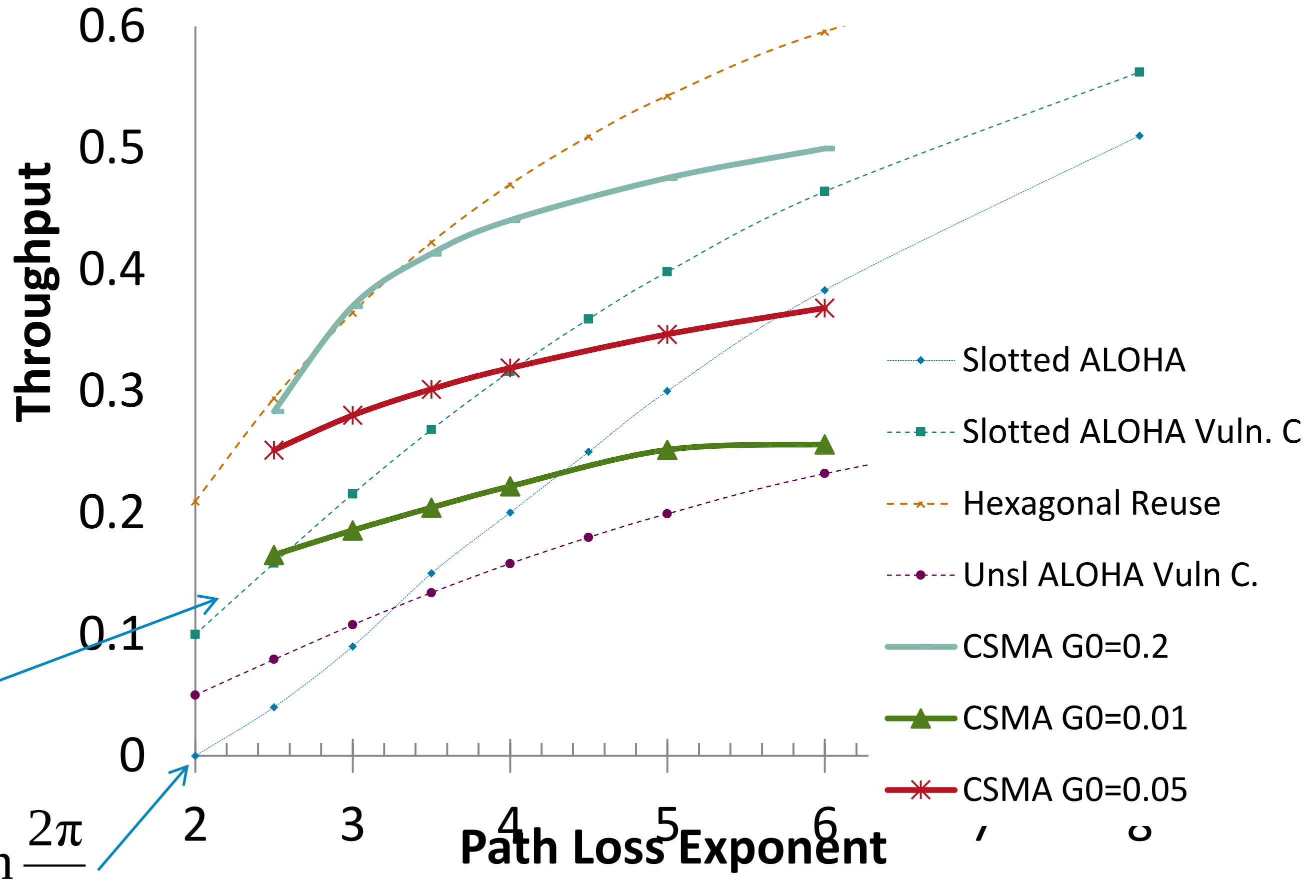
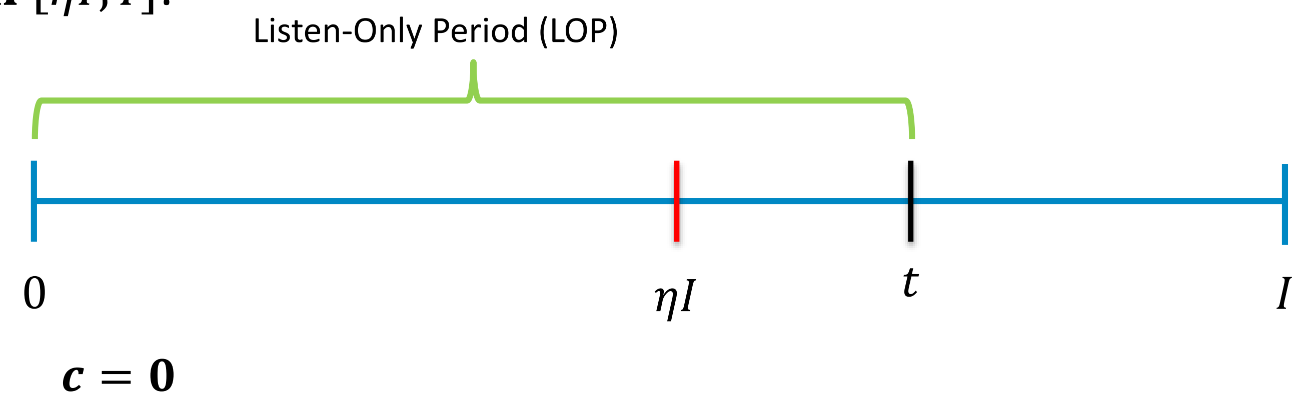


$$S = \frac{1}{Tz^{2/\beta}}$$

$$S = \frac{1}{z^{2/\beta}} \frac{\beta}{2\pi} \sin \frac{2\pi}{\beta}$$

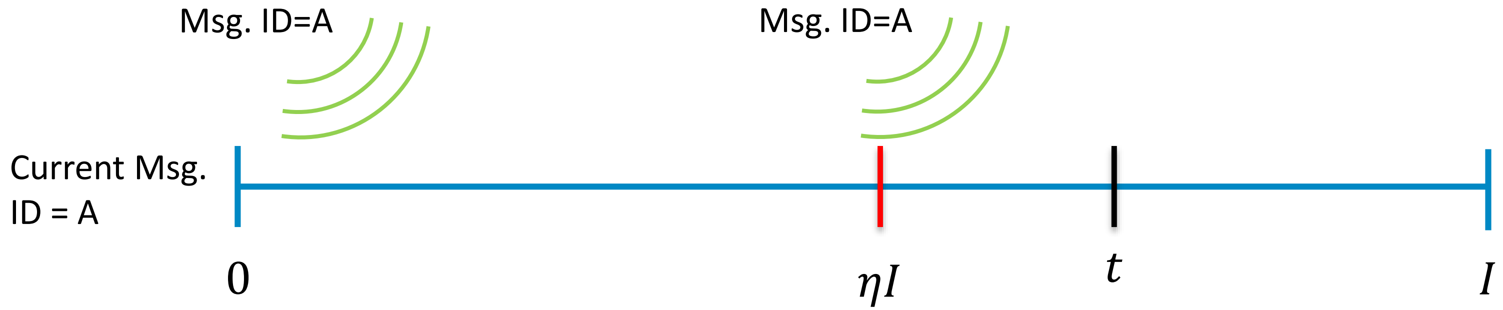
The Trickle Algorithm: A protocol to disseminate Information and Control Commands

2. Every interval, a counter $\boldsymbol{c}$ is reset to zero and a random timer $\boldsymbol{t}$ is set in $[\eta I, I]$.



The Trickle Algorithm: How it works

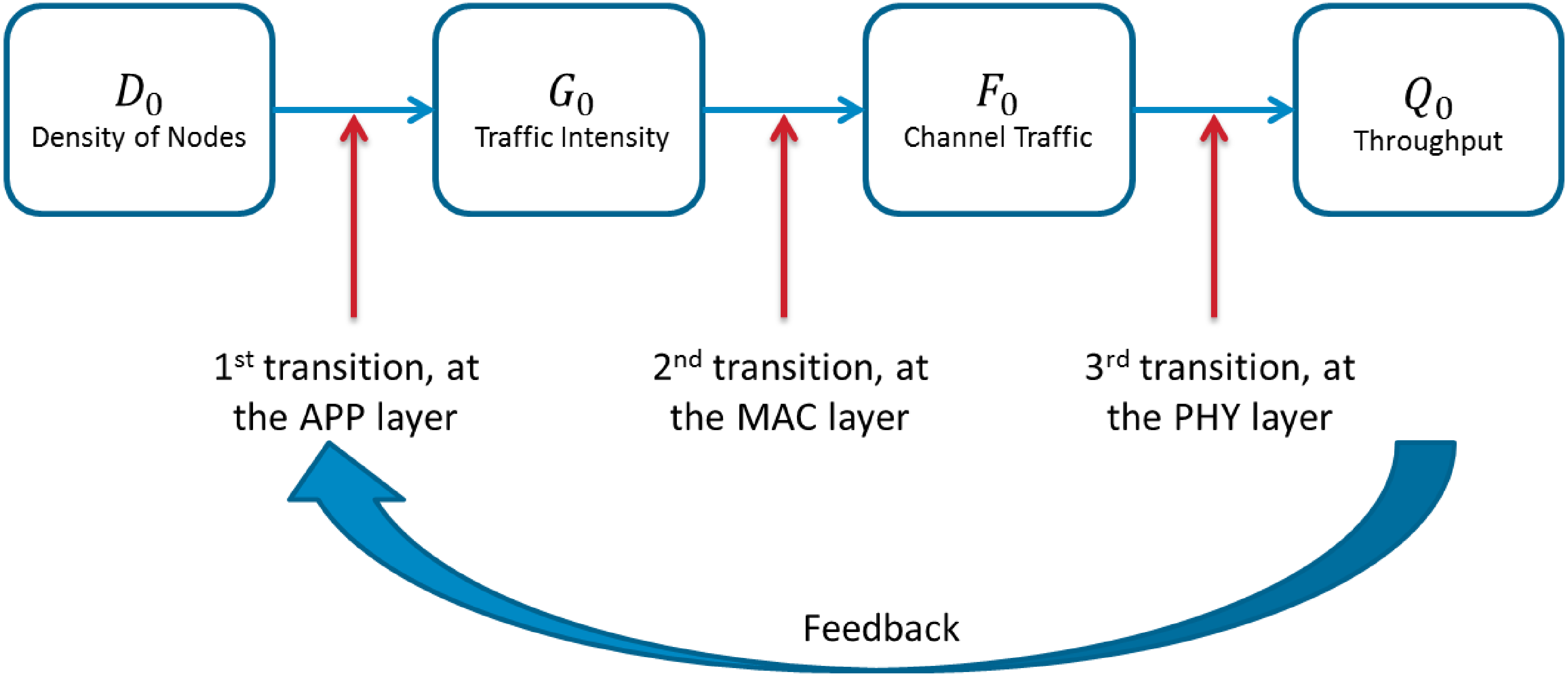
From time 0 to $\boldsymbol{t}$, a node increments counter c if it hears consistent information, and it transmits at time t iff $\boldsymbol{c} < \boldsymbol{K}$.



$\boldsymbol{c} = 0$

Thus, a node only (re-) transmits if (too) few messages have been disseminated

Poisson Model for the Network Traffic

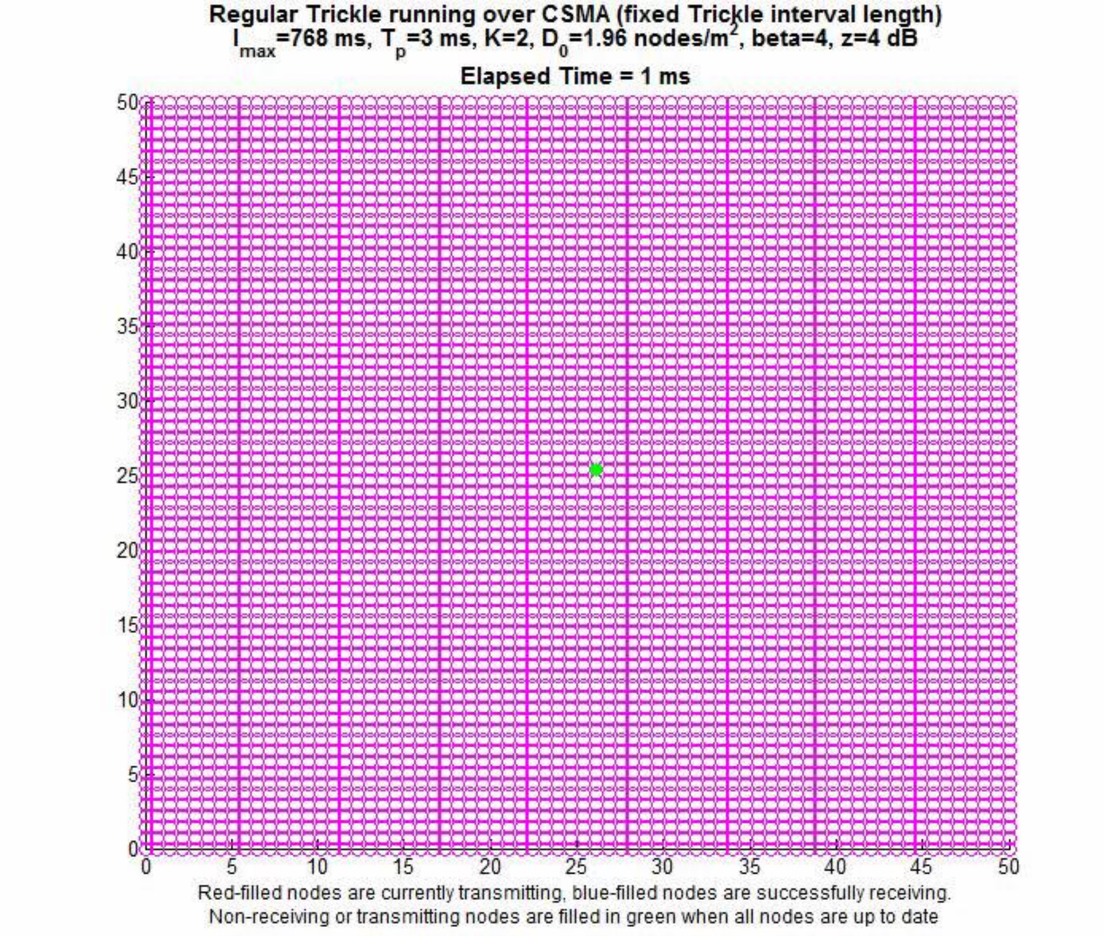


Simulation Environment
Demo: Network Update

Updated via trickle

Sending

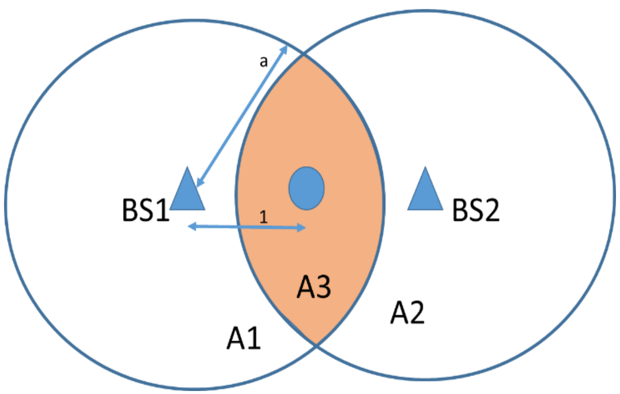
Receiving



IoT nodes to the Infrastructure

Gathering messages in an IoT Setting

- How effective can a system be in which nodes just transmit ALOHA style, without any acknowledgement?
- Key Question : what is the throughput of two neighboring receivers?



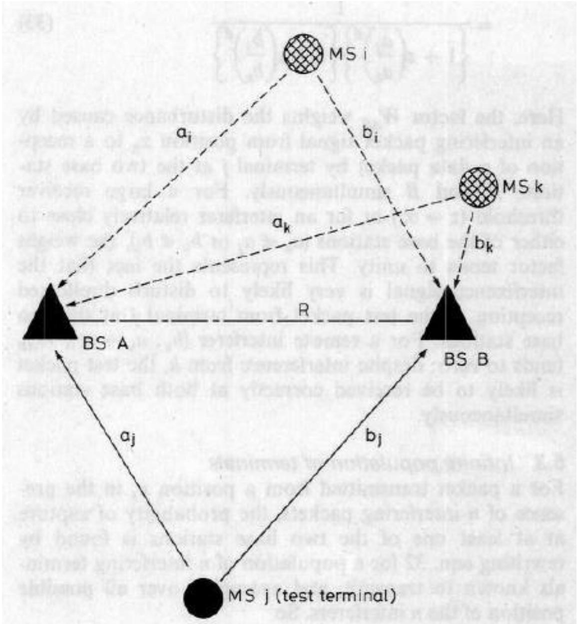
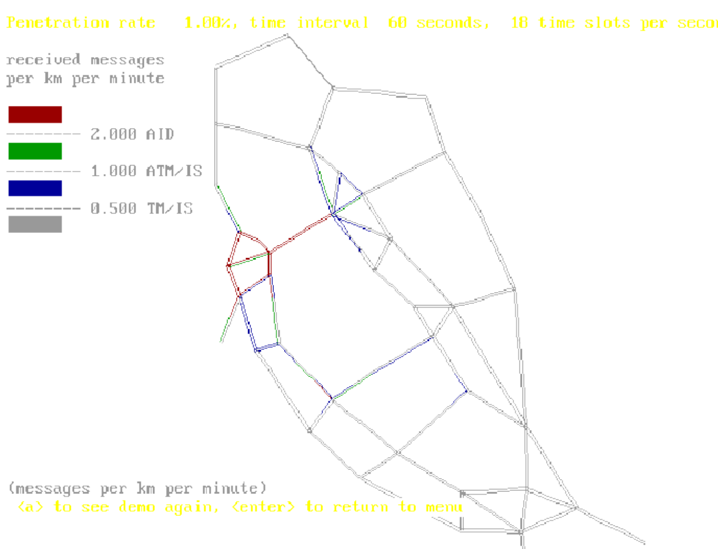
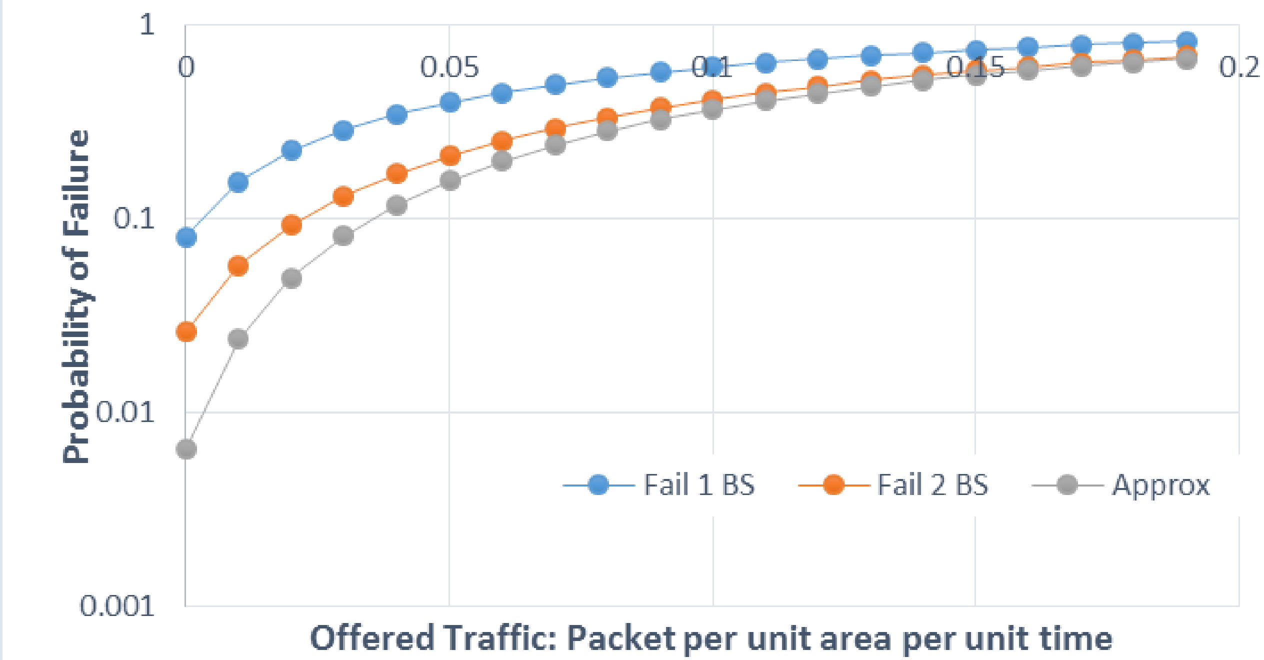


Fig. 7 *Multiple access scenario with mobile terminals and two base stations*
● mobile terminal; ▲ base station



Gathering messages in an IoT Setting



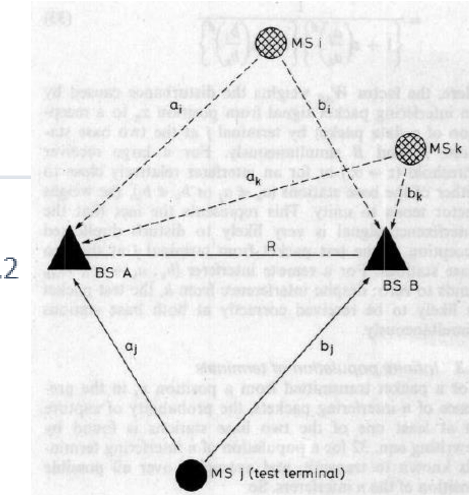
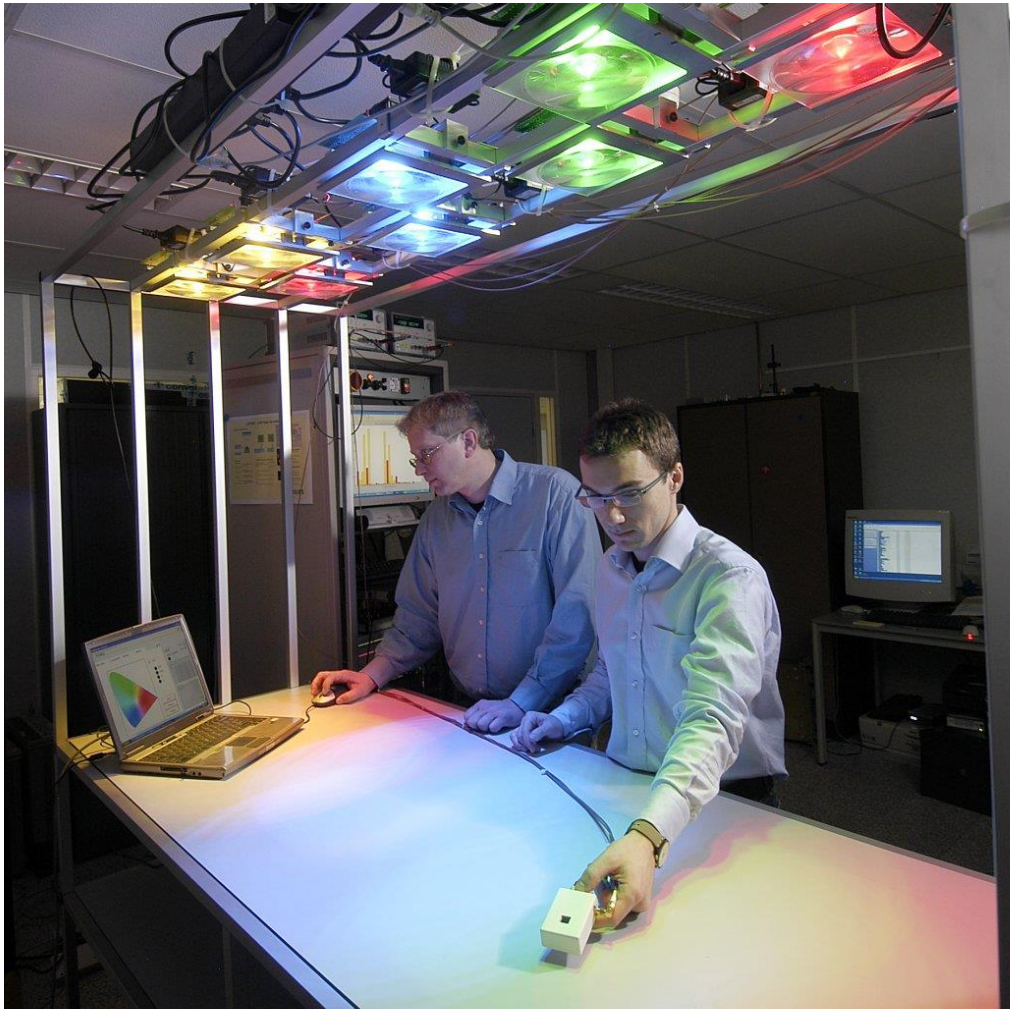


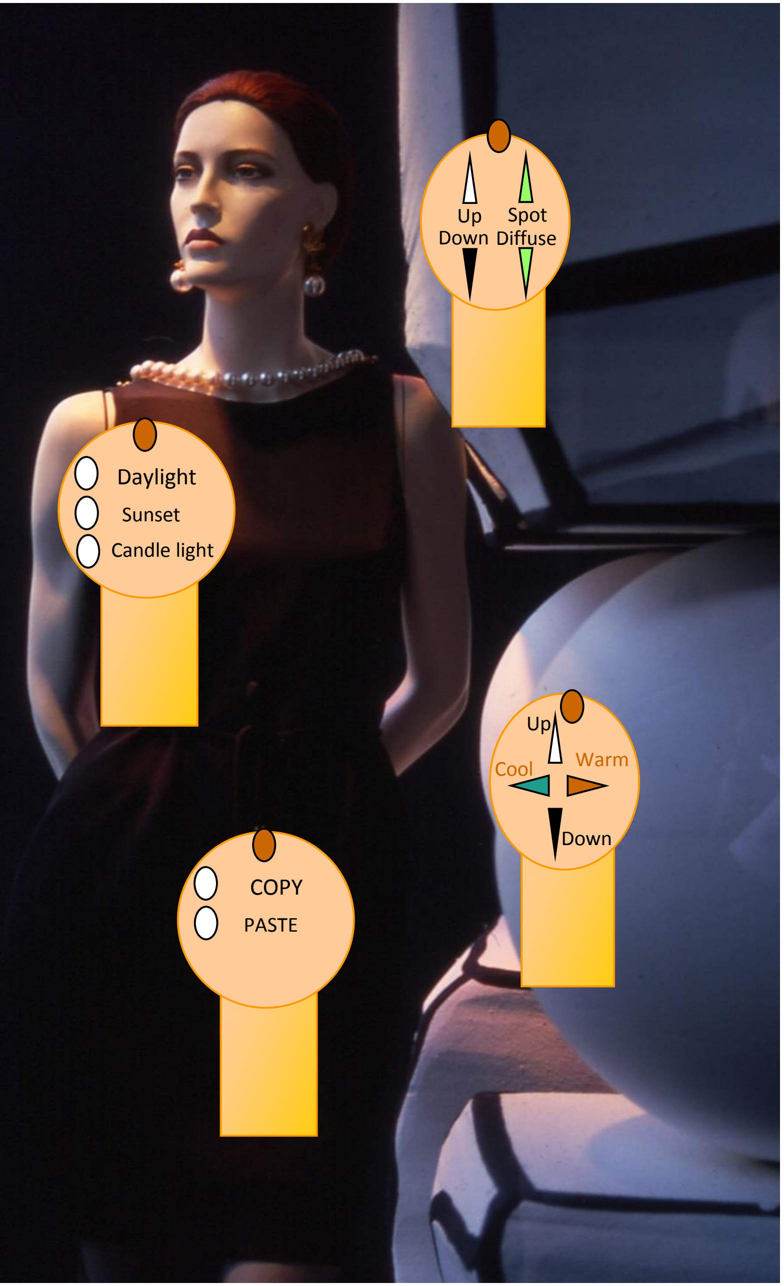
Fig. 7 *Multiple access scenario with mobile terminals and two base stations*
● mobile terminal; ▲ base station

Advantages:

- Simplicity, no frequency planning, no receiver needed
- Effective, scalable
- Spreading would be counterproductive



Wireless Optical Communication and Coded Light



The sense and simplicity * remote control:

- Pick it up
- Hold it where you want to control the illumination
- Adjust the light setting

The remote control automatically knows which LEDs to control

*) 2006

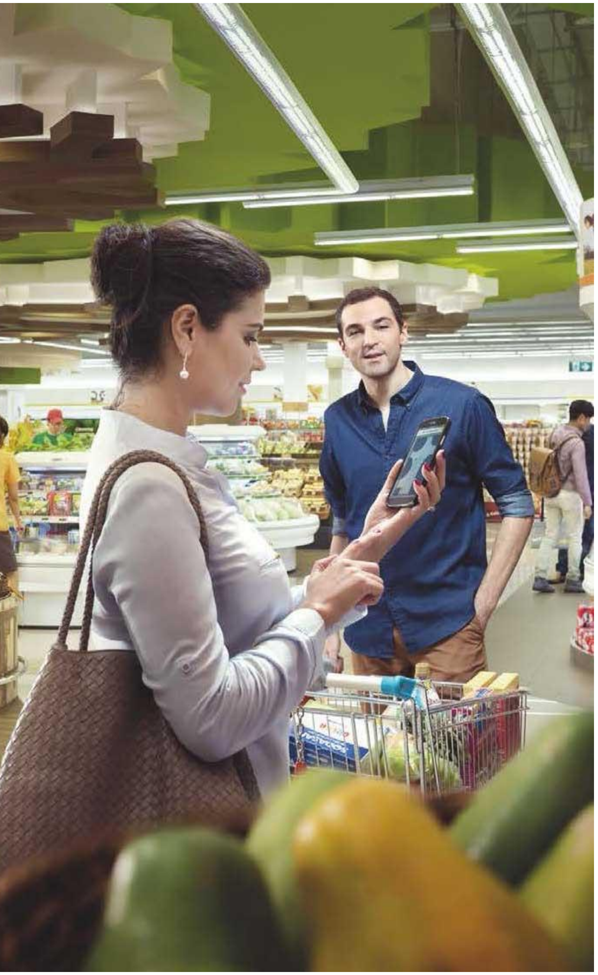
lighting beyond illumination

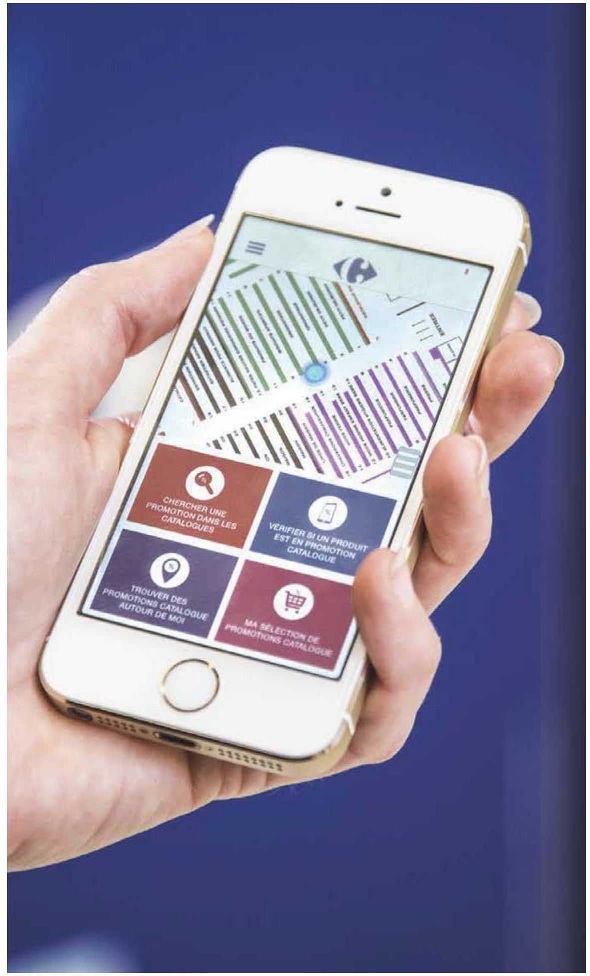
How Philips Connected Lighting can help

Package

Indoor positioning for **retail**

Creating frictionless shopping with location-based services





Personalized experiences means **happier customers, more sales**. Engaged shoppers stay longer, enjoy the experience more, and often spend more.

Retailers can **improve efficiency** through wayfinding and location-based staff and service support.

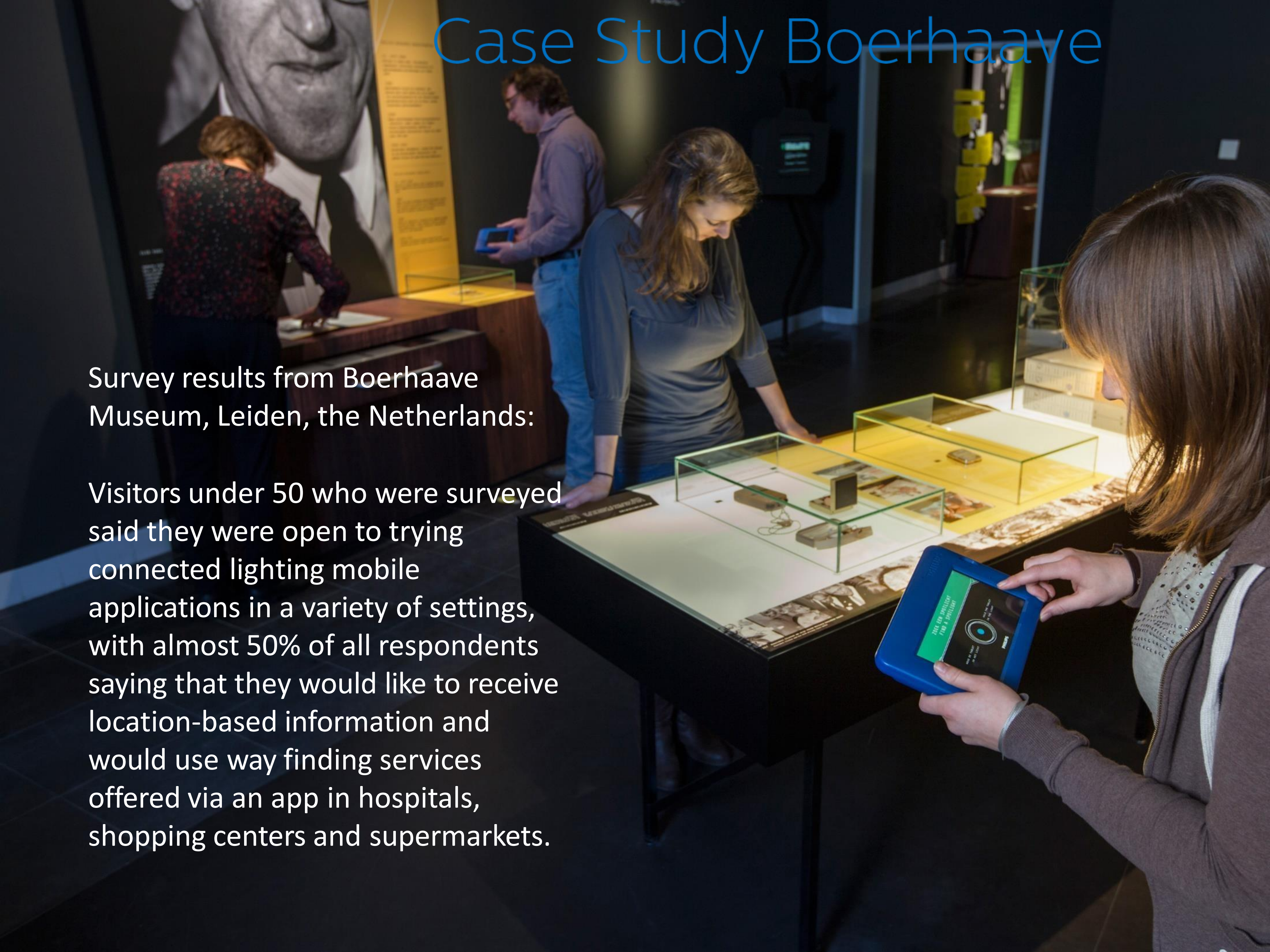
With data analytics, retailers can **optimize store operations** and measure the impact of marketing events.

PHILIPS

Modulation Requirements

- **design a set of modulation sequences**
  - on-off switching (systems that allow just amplitude control for color setting are also interesting)
  - Modulation should work for arbitrary average duty cycle *p:*
    - *p* dictated by illumination, external variable
    - PWM dimming range of at least 1 : 256 (8 bits), preferably 10 .. 12 bits, independently set for each LED
  - no visible flickering
  - Low number of on-off transitions per LED per second
    - every switch (off-to-on on-to-off) creates $CV^2/2$ of heat:
    - Switching should not cover more than a few % of the pulse to prevent color shifting
  - Allow control of illumination faster than with 200msec time constants
  - Bandwidth constraints due to LEDs (10.. 50 nsec response time)
  - Allow multi-user detection for 10^3 .. 10^4 LEDs, robust against mutual interference
  - Robust against cyclo-stationary (50Hz!) environmental lighting, from incandescent and fluorescent lighting
  - Reduce the variations in joint power consumption by multiple LEDs
  - Can measure the local illumination at a color accuracy of >8 bits for 300 lux illumination (number to be checked)

Case Study Boerhaave



Survey results from Boerhaave Museum, Leiden, the Netherlands:

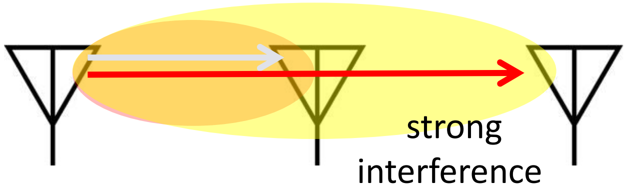
Visitors under 50 who were surveyed said they were open to trying connected lighting mobile applications in a variety of settings, with almost 50% of all respondents saying that they would like to receive location-based information and would use way finding services offered via an app in hospitals, shopping centers and supermarkets.

OWC systems: Communication

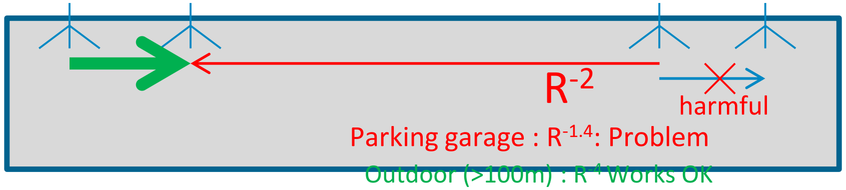
Essential difference No. 1:

Spectrum Reuse and Scalability

Radio (ZLL, …) links

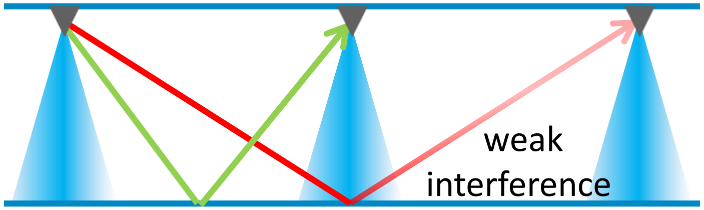


There is a direct link between Tx and Rx
Walls are transparent

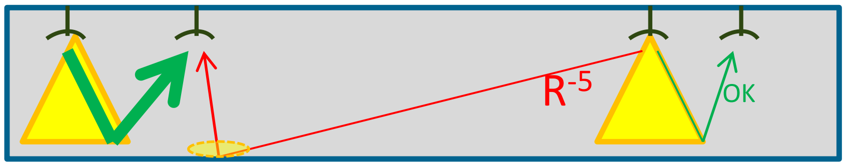


- Each luminaire sees (too) many other nodes
- Interference: also more remote tiers of interferers contribute
- Total interference diverges
- So, Radio has a fundamental problem in being not scalable in “free space” environments (large halls, parking garages)

Optical Light wave (IR, VLC, CL) Link



There is NO direct link between Tx and Rx. Walls are opaque leading to confinement. Reflection coefficients 0.4-0.7



- Each Luminaire sees (the light footprint) of (only) a limited number of other Luminaires: reuse of communication spectrum is possible

Different Mechanisms of Propagation for IR and VLC

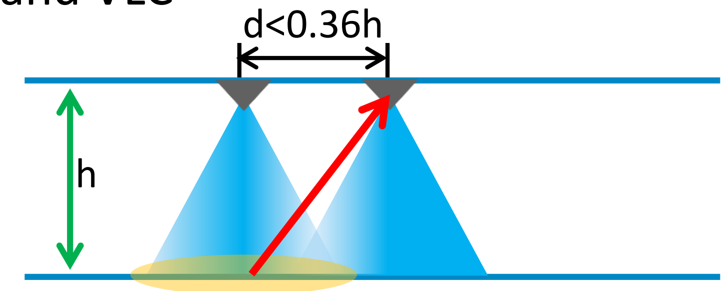
Agis Tsiatmas

Short Range

Complete reflection for small distances

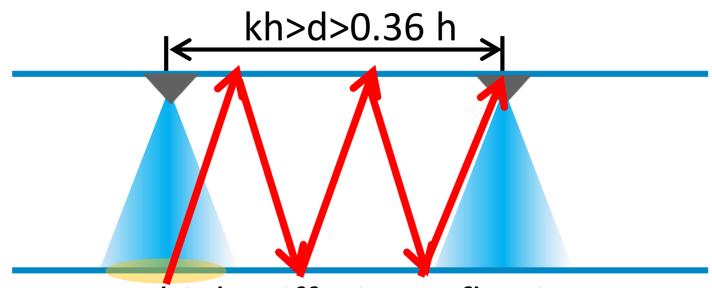
Most of the power emitted by the LED could be considered to look at the detector with a specific angle cosθ≈1→θ<20deg and:

θ↓ for n>1 (lambertian order) of the Rx



Multiple Reflections for LEDs at moderate distances

This is the most difficult region
it spans from ~0.36 h to a few multiples h



Multiple Diffusive Reflections

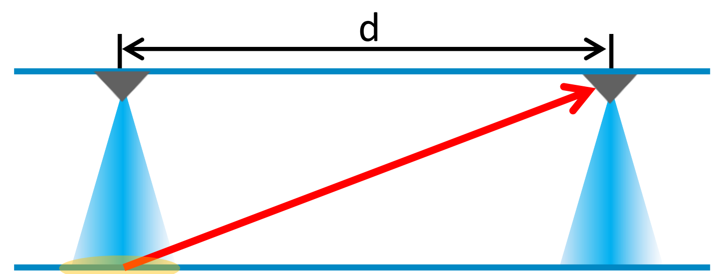
Long Range

Diffusive Reflection (also the symmetric one)

Only the regions below Tx and Rx contribute in the amount of the received power :

$$P_{Rx}(d) = \frac{c_1}{d^{n+5}} + \frac{c_2}{d^{m+5}}$$

m and n the lambertian orders of Rx and Tx



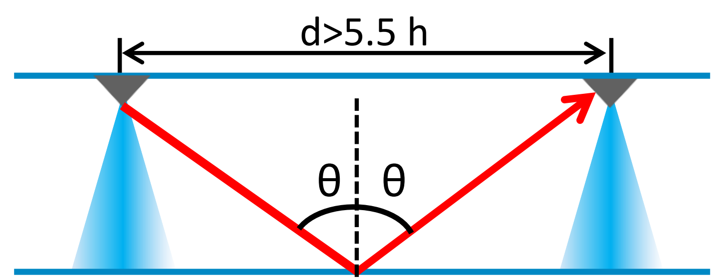
Diffusive Reflection

Specular Reflection for distances d>5.5 h (θ>70deg)

For very swallow angles (θ>70deg) the floor and the walls start supporting specular reflection (diagram in the last page):

$$P_{Rx}(d) = \frac{c_3}{d^{m+n+5}}$$

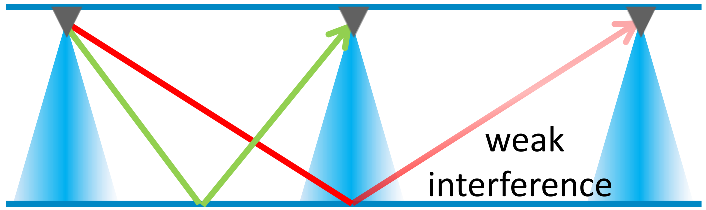
m and n the lambertian orders of Rx and Tx



Snell's Law Applies

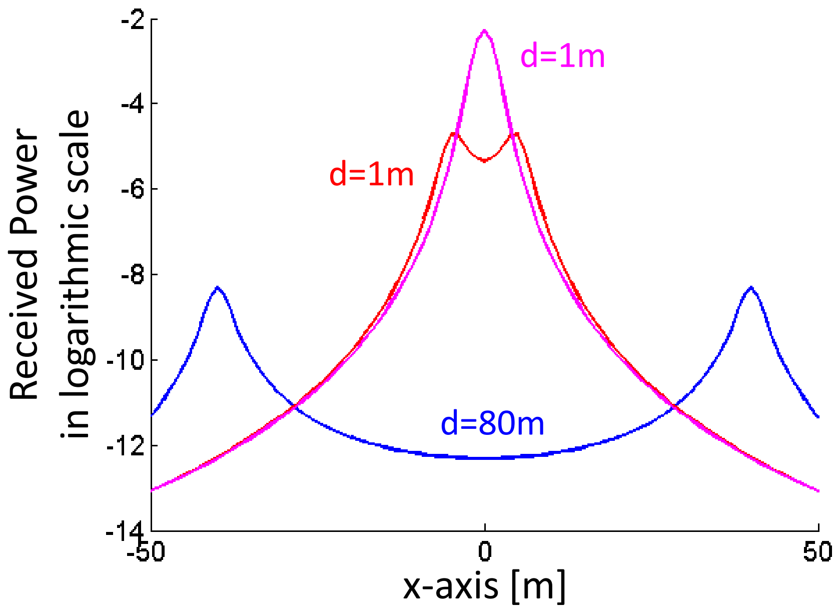
Optical Link

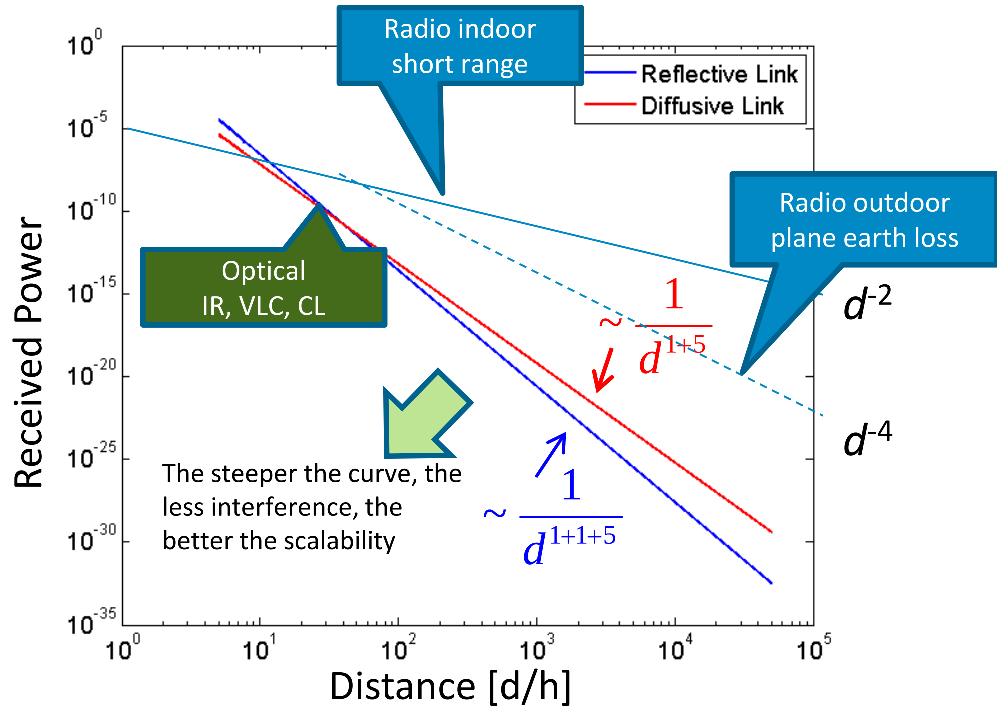
Agis Tsiatmas



There is NO direct link between Tx and Rx

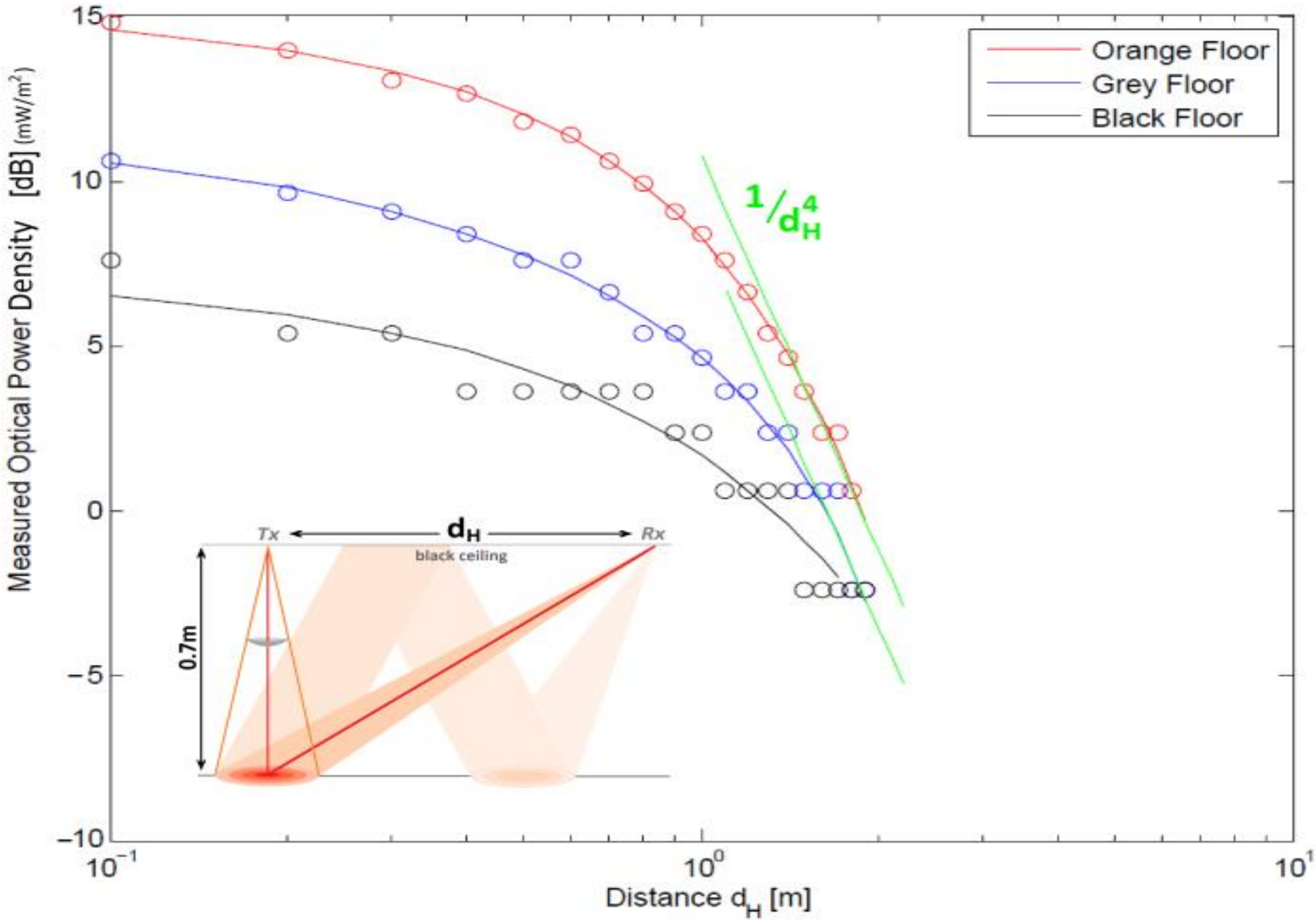
Walls are opaque leading to confinement. Reflection coefficients 0.4-0.7



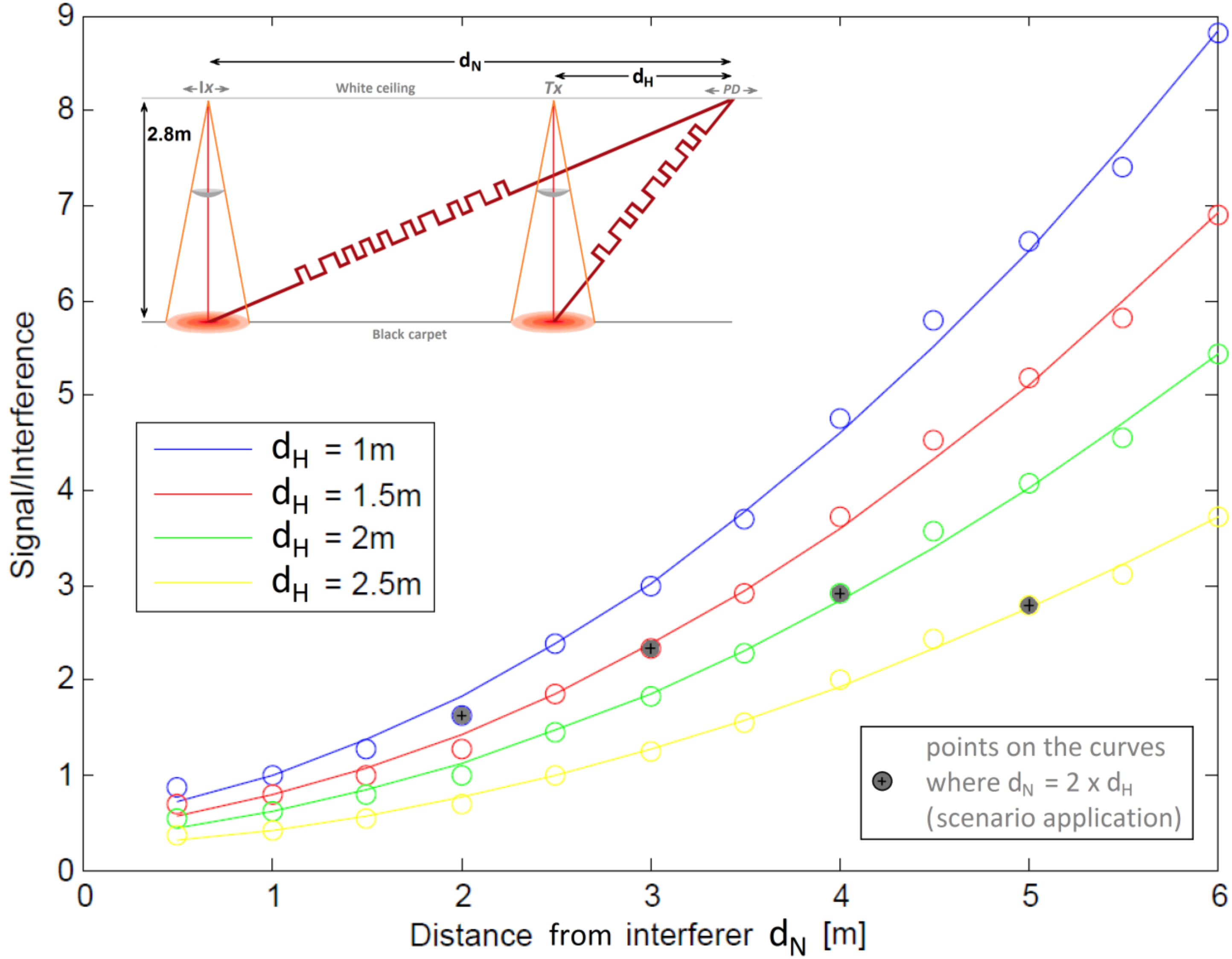


- d is the distance of the Tx and Rx
- the area of main contribution to received power changes with distance
- In long distances only the last two mechanisms

Propagation for Optical Wireless Communication between luminaires

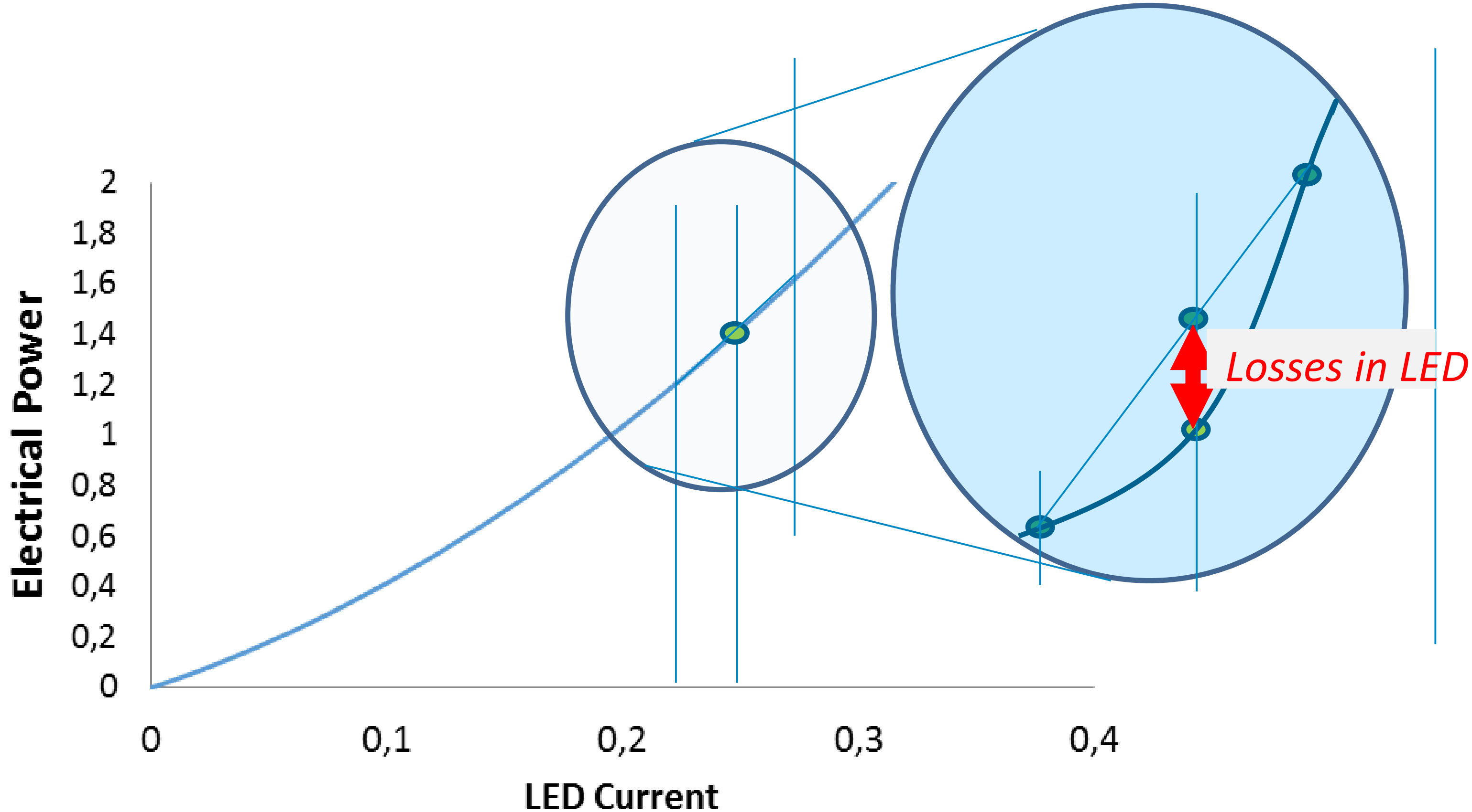


Interference



Circuit Design for Optical Wireless Communication Systems

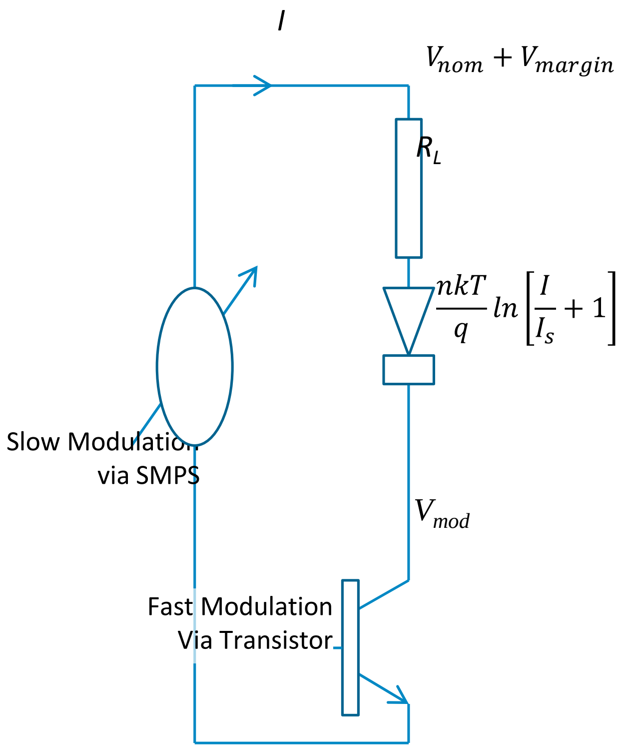
LED Current Modulation over a convex function



The extra losses can best be explained by plotting an I - P_e curve (electrical power versus current). This function is not linear

the extra power consumed in LED is proportional to a_{rms}^2 ($a \ll 1$)

Additional losses in Series Modulator



Circuit model for losses in driver and LED, including non-linear junction and series resistance.

just for our analysis, we interpret the Transistor as a voltage drop V_{mod} between the power supply and the LED(s).

In peak modulation, the transistor is in full saturation ($V_{mod} = 0$), for the highest LED current $I_L(1 + \alpha_{max})$ with I_L the DC current for illumination.

We split the corresponding maximum LED string voltage into

$$V_{max} = V_{nom} + V_{margin},$$

where V_{nom} is the string voltage without modulation.

Analysis of Losses in Driver

The consumed electrical power is

$$\mathrm{E}[P_{el}] = \int_0^\infty [V_{mod}(i) + V_{LED}(i)]\, i f_I(i) di$$

where $f_I(i)$ is the probability density of the LED current.

Here V_{mod} and V_{LED} individually fluctuate with i, ….. but their sum is constant at $V_{margin} + V_{nom}$ and can be taken out of the integral.

$$V_{mod}(i) + V_{LED}(i) = V_{margin} + V_{nom} = \text{Constant}$$

So, the extra power is

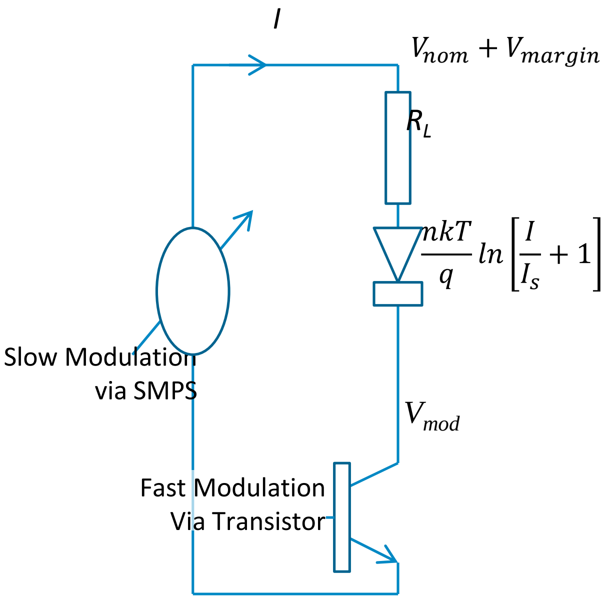
$$\Delta P_{el} = \mathrm{E}[P_{el}] - \mathrm{Pel}_{(\mathrm{unmod})} = \int_0^\infty [V_{Margin}]\, i f_I(i) di$$

$$\Delta P_{el} = V_{margin}\ I_{LED\_unmodulated}$$

Analysis of Losses in Driver+LED

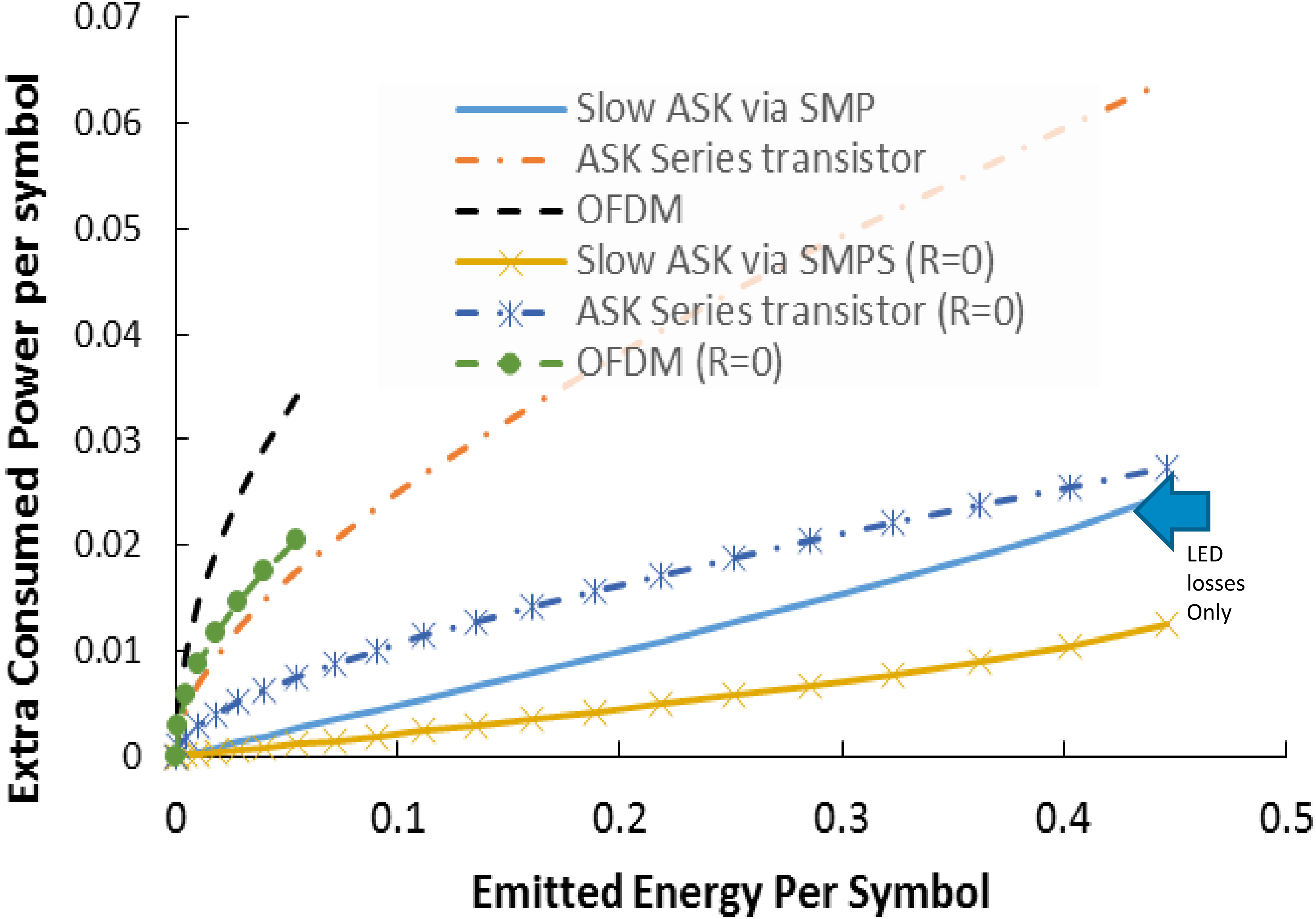
So the extra loss, above the unmodulated power consumption $V_{nom}\, I$, is

$$\Delta P_{el} = V_{margin}\mathrm{E}[I] \approx \left[\frac{nkT}{q} I_L + R_L I_L^2\right] \alpha_{max} + ..$$



$$\Delta P_{el} = V_{margin} \; I_{LED\_unmodulated}$$

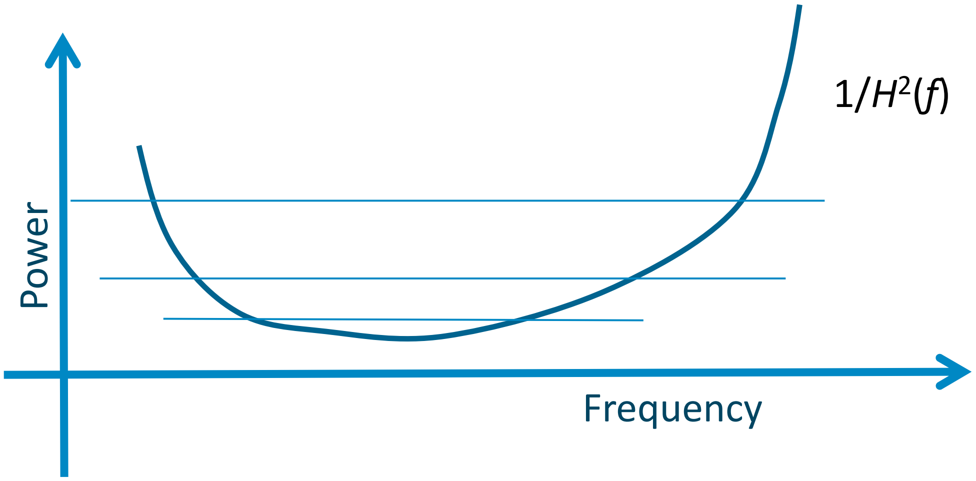
Comparison



Extra Consumed Power per symbol
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.1
0.2
0.3
0.4
0.5
Emitted Energy Per Symbol
Slow ASK via SMP
ASK Series transistor
OFDM
Slow ASK via SMPS (R=0)
ASK Series transistor (R=0)
OFDM (R=0)
LED
losses
Only

Water Pouring

Water pouring is an optimal algorithm for spreading energy across the frequency domain in a linear time invariant, selective channel with white Additive white Gaussian Noise



Is it still OK if the power consumption is a non linear function of the "energy per bit"?

Water Pouring

we optimize the capacity for DC-biased OFDM modulation:

$$C = \sum_{n-1}^{N} \frac{1}{2} \ln \left[1 + \frac{h_n^2 B_n \; P_{op}^2 T_f}{N_0} \right]$$

By appropriately selecting the set of B_n's,

subject to the total extra electrical power ΔP_{el} consumed in LED and driver.

In our case, the *consumed* power scales with $a_{\max}$ times the OFDM headroom γ (typically, $\gamma = 3.2$). Since $a_{max} = \gamma \, a_{rms}$,

$$\Delta P_{el}(I) = \left[\frac{n_0 kT}{q} I_L \; + R_L \, I_L^2 \right] \gamma \sqrt{\sum_{n-1}^{N} B_n} \; + \cdots$$

Optimal bit loading in OFDM over OWC

- Lagrange optimization

$$\Lambda(B_1\ , B_2\ , .. B_N\ )$$
$$= \sum_{n-1}^{N} \frac{1}{2} \ln\left[1 + c\quad h_n\ \frac{A_{RX}^2 B_n\ P_{op}^2 T_s}{N_0}\right] + \lambda\left\{\left[\frac{nkT}{q} I + R_L\, I^2\right] 3 \sqrt{\sum_{n-1}^{N} B_n}\ - P_{TX}\right\}$$

- Taking (partial?) derivatives

$$\frac{1}{2\ln[2]} \frac{1}{B_n\ + \dfrac{N_0}{c\quad h_n\ A_{RX}^2 P_{op}^2 T_s}} + \lambda \frac{\left[\dfrac{nkT}{q} I + R_L\, I^2\right] 3}{2\sqrt{\sum_{n-1}^{N} B_n}} = 0$$

Derivation of Water Pouring if Communication power is not proportional to consumed power

Maximize $$C = \sum_{n-1}^{N} \frac{1}{2} \ln \left[1 + \frac{h_n^2 B_n \; P_{op}^2 T_f}{N_0} \right]$$

Subject to $$\Delta P_{el}(I) = g\left(\sum_{n-1}^{N} B_n \right) < P_{TX}$$

Frans Willems proposed to extend the usual Lagrange optimization by transforming both sides of the constraint equation by $g^{-1}(.)$, thus $g^{-1}\big(\Delta P_{el}(I)\big) \leq g^{-1}(P_{TX})$, and we optimize

$$\sum_{n-1}^{N} \frac{1}{2} \ln \left[1 + \frac{h_n^2 B_n \; P_{op}^2 T_s}{N_0} \right] + \lambda \left\{ g^{-1} \left(g \left(\sum_{n-1}^{N} B_n \right) \right) - g^{-1}(P_{TX}) \right\}$$

Taking derivatives results in $B_n + \frac{A}{h_n^2} = \lambda_2$

So water pouring is still optimal, although the “amount of available water“ changes

Concluding

There are many connectivity challenges in the IoT