EnLight – a modular and intelligent luminaire architecture for improvement of lighting quality and energy efficiency in the hospitality demonstrator

Abstract

"The lighting industry is going through a radical transformation, driven by rapid progress in solid-state lighting and semiconductor technologies as well as by changing societal needs such as sustainability, improved energy efficiency and CO_2 reduction. Adaptation must be rapid in an open-innovation ecosystem driving R&D to serve the latest business requirements" [EN10]. To put this in a nutshell, the EnLight vision is "to push the exploitation of the full potential of solid-state lighting through breakthrough innovations in non-conventional, energy efficient and intelligent lighting systems, beyond retrofit applications". This is accompanied by some general trends in lighting, like "Lighting is Going Digital" [PD10], the "Liberation of Light" [EA11], "More Illumination" and "More than Illumination" [GZ10], Light and Quality of Light [DL11], "Human factors analysis for lighting control" [JN12], as well as some trends addressing sustainability like "Going Green" and "Carbon Footprint" [FF11]. For realization, all of them need a "Paradigm Shift in Lighting [KK13].

After identification of user requirements of all stakeholders along the value chain by means of use cases [TN11], a promising system architecture has been derived [FT13], which is in line with above mentioned trends and can fulfill most of the features requested in the use cases. There are basically two architectural cornerstones: From a communication view it is the Lighting Control Network (LCN) as a communication vehicle between area components (user interfaces, sensors,…) and the luminaire. From the luminaire view it is the Intra Luminaire Bus (ILB), which connects ILB-modules like Light Engines, drivers etc. and the embedded luminaire controller. This concept allows for all decision processes to take place locally at each intelligent luminaire.

The concept will be demonstrated and explained in a hospitality application, which will be set up as a "Living Lab" in a hotel in Regensburg, Germany. The main goal of EnLight is energy savings, which should be ≥40% compared to traditional LEDr systems, and is created by using non-conventional luminaires within an intelligent lighting system.

Introduction

Technological Trends

For evaluation of technological trends it is often helpful to look at the life cycle-curves (LC-curves) of products and related technologies. Basically, LC-curves describe the market penetration of a product resp. technology right from its idea until phase out. This is shown in Fig.1 for the bulb and its retrofits available in Halogen (HALr), Fluorescent (CFLi) and LED technology (LEDr). While on the right side the incandescent lamp ("the bulb") has already disappeared in many countries due to legislation, more energy efficient CFLi are on top or already declining. For people who are in love with "the bulb" the possibility remains to use HALr, which save 30% of energy compared to "the bulb", but have the risk to be banned in 2016 after review of the Energy Label. LEDr lamps still strongly profit from ongoing miniaturization of electronics (Moore's Law), increasing efficiency of LED chips (Haitz's Law) and merging with new wireless technologies (price decrease of ZigBee chipsets), therefore boosting the first SSL transition wave. To summarize, up to the vertical line between the two blue arrows, all improvements have been achieved "just by evolution", and the question arises "What will come next". The EnLight project aims to provide an answer on this challenging question. As a "Green Field Approach" it is addressing the 2nd SSL transition wave, neglecting all restrictions of legacy infrastructure.

Fig.2 shows the LC-curve for User Interfaces (UI) used for lighting control, with the relevant technologies shown on top. On the right, there is the light switch, which is by far the easiest and cheapest, but also the most "stupid" solution (on/off only, mechanical trigger). On top of the curve are phase cut dimmers, which have originally been developed for dimming of ohmic loads like incandescent lamps, which are going to be banned. Because retrofits like CFLi and partially also LEDr behave in most cases like capacitive loads, a lot of effort in the driver circuit is needed for emulation of an ohmic load. In order to avoid problems caused by dimmers like flicker (nonlinearity of the dimming curve, restrictions of dim level, noise problems in case of leading edge and last but not least compliance with the standards, including IEC 61000-3-2 (harmonics) and IEC 55015 (RFI)), DLT (Digital Loadline Transmission) as shown on the upper left side has been developed as new technology by EnLight partners OSRAM and Insta, refer to IEC 62756-1 as open standard.

Control panels, which have been developed e.g. for use in combination with (traditional) lamp-ballast-concepts compatible with DALI/KNX, start to appear to the left of the inflection point, followed by remote controls, which are connected wirelessly e.g. via ZigBee to control devices. On the very left side there are "new generation" UIs like Apps running on smart phones or tablets. In all cases, the answer of which UI will be future-proof depends on the application and the concerns shown in the table at the bottom of the figure, showing some acceptance criteria for wired resp. wireless technologies.

EnLight Objectives

As an ENIAC funded project within SP3 (energy saving), energy saving is the cornerstone of EnLight. As shown in Fig.3, there are basically three objectives:

(1) "Optimized LED lighting modules". The challenges are optical design, thermal management, integration of drivers and realization of a communication interface

(2) "Future, non-conventional luminaires": Should allow for freedom of design, integration of novel features, architectural flexibility and serviceability, not limited by retrofit solution constraints

(3) "Intelligent lighting systems": Should provide means for data mining, smart sensors, sensor fusion and also interfacing with the building and the IoT (Internet of Things)

It is important to note that the EnLight objectives are clearly beyond Zhaga, which focuses on the standardization of mechanical, electrical and thermal interfaces on the components level only. However, Zhaga products can be used also in EnLight as long as they fulfill the system architecture requirements as described below.

EnLight Energy Saving target

EnLight has promised to realize an energy saving of ≥ 40% compared to a baseline, which already can be realized today by using "traditional LED lighting", refer to Fig.4. This can be realized by the combined actions of (1) improved thermal design (lower T_j), where heat sinks may be part of the luminaire or building material, (2) improved Light Output Ratio (LOR) of luminaires, which may be realized by more efficient optics resp. reflectors and finally (3) the addition of intelligence to the system, which is assumed to contribute about 20% additional energy saving. The achieved energy saving has to be validated in the demonstrators (see below) and will be measured according to the LENI standard by using the metrics kWh/a*m^2, which is reciprocal to lm/W in Fig.4.

EnLight System Architecture

At the heart of the EnLight partners' endeavors is a modular intelligent luminaire architecture where the system intelligence is distributed in the end nodes - without the need for a central controller - and the luminaire is built from re-usable and exchangeable building blocks with a digital (I^{2}C/ILB) bus interface. Thus, EnLight represents a quest for a future ecosystem for ILB-based intra-luminaire building blocks and for intelligent nodes at area level.

Decentralized intelligence

EnLight has chosen a decentralized intelligence architecture, using the Lighting Control Network (LCN) as a communication vehicle, refer to Fig.5. This concept allows for all decision processes to take place locally at each intelligent luminaire. No central node or general knowledge of the network topology is required. This means that intelligent luminaires react autonomously to events instead of being instructed by a centrally placed controller. Events can be raised e.g. by internal resp. external sensors or user controls, which are connected to the area controller e.g. locally or via the Internet of Things (IoT), allowing for control of luminaires also via Apps from smart phones. At the end, as a result of an event, the luminaire could automatically adjust for example brightness, color or beam shape if some conditions are fulfilled, which are described in a "set of rules", see below. Thus, the behavior of luminaires is determined basically "by software" instead of traditional and often complex "manipulation of a control unit". This allows aligning and optimizing the behavior of luminaires to the special needs of the application or the personal preferences of end users, like allowing selection of preferred color/CCT or increased Lux for elderly people, as requested in many use cases. Programming of rules is done during the commissioning phase via the area configurator, which is presently done by uploading an XML-file.

Communication within the LCN on area level is wireless, based on Zigbee, whereas the wired communication is based on IP. Subsystems based on other technologies like DALI or DLT can be connected to the LCN by means of technology bridges (adaptors), which will allow the subsystem to behave like an EnLight system. The area is connected via the area controller to the next higher building level, where e.g. energy monitoring, load shedding and also data mining and data analysis can be organized, which are prerequisites for self learning features, as requested in many use cases.

Modular luminaire architecture

EnLight has chosen an Intra-Luminaire Bus (ILB) architecture concept for developing and managing a portfolio of re-usable and exchangeable luminaire building blocks, refer to Fig.6. These building blocks include LED light engines (LLE), embedded sensors, high and low-power supplies, and - most important - an embedded controller, see below. The intra-luminaire communication bus has an I^2C physical layer, with ILB/ILI as the communication protocol. The modular approach helps to manage the diversity and complexity of luminaires and makes it possible to offer innovative functionality enabled by the integration of local intelligence into silicon. Among others, motivation for introduction of the ILB has been:

(1) To decouple lifecycles of independent technologies by using a modular approach with standard interfaces. This will allow for example the user to add sensors using much less effort compared to a DALI solution
(2) Enabling market players to contribute, differentiate and compete, which is essential for dissemination and a successful market introduction

Reasons for the design choice of the power supply as separate high and low power supplies, which are realized on the same hardware board, are as follows: (1) The galvanic insulation is needed only once, (2) PF, EMI and harmonics are addressed only once, (3) the high power supply should be SELV (≤60V) and switchable for minimization of standby power.

Embedded controller

As mentioned above, the backbone for realization of system intelligence as outlined on the right column of Fig.3 is the embedded controller. This is shown from a functional view in Fig.7. Basically, the embedded controller is the interface between the LCN on the area level (Fig.5) and the ILB on the luminaire level (Fig.6). The Embedded Controller fulfills the following tasks:

(1) Receiving and handling of information from the area controller, like events from global sensors (e.g. brightness has changed) or the IoT via smart phones (e.g. switch lamps off or in “vacation mode”)
(2) Receiving and handling of rules from the area configurator; the rules are the cornerstone for generating intelligence, allowing luminaires to be programmed according to special applications and individual customer needs
(3) Receiving and handling of information from local UIs and external sensors within the area level
(4) Receiving and handling of information from the ILB like power consumption or failure messages
(5) Handling of all information in a decision and fusion machine

Summary System Architecture

To summarize, the basic advantages of the decentralized architecture are the following:

“Internet of Things” architectural design pattern:

- No central node & no global knowledge of network topology is required
- All decision processes take place locally at each node and no global knowledge of the network is required

“Intelligent luminaire” as cornerstone building block:

- Autonomously controls brightness, CCT, color, beam shape,…
- Reacts to events instead of being instructed by e.g. a central controller
- All nodes in network can raise events

“Intelligence by configuration”:

- Rules based behavior, configured during commissioning phase
- Flexible: ability to adapt or change behavior per node
- Self learning: ability to adapt behavior as result of global data mining

EnLight Demonstrators

For demonstration and validation of energy saving, three demonstrator types will be set up as “living labs”: two demo’s office at Philips/Eindhoven and VTT/Oulu, one demo hospitality in a hotel in Regensburg, Germany, where OSRAM is in the lead role of the application champion, and one demo for grid effects at ENEL in Milan.

Demonstrator Hospitality

In this section the demo hospitality is explained in more detail, with focus on "non-conventional luminaires (Objective #2 in Fig.3) and its technical realization.

As explained above, the concept of building blocks is a key feature in EnLight, where the ILB-modules are just one example. The whole range of building blocks is shown in Fig.8 for different levels. On the system level, there are the demonstrators as mentioned above. On the fixture level, there are intelligent luminaires, external sensors/controls and components of the area level. On the module level, there are LED driver modules, PSUs and the ILB embedded sensors. On the lowest component level we have a mixture of HW components like antennas or external sensors, but also SW components like the ILB development kit and components of the embedded controller like "decision engine" and "logical luminaire" (Fig.7). The arrows in the figure are the "shopping list" of the "cooking recipe for the hospitality demonstrator". On the right side of Fig. 8, the upper three levels show HW components that were available at Plugfest #1, a demonstration workshop held in 5/13. It is important to note that the availability of reliable SW components is a prerequisite for a successful market approach, as it can be re-used and integrated into one µC allowing for reduction of BOM cost.

Fig.9 shows the guest room of the hospitality demo (left side), and the luminaires used in the demonstration (right side). In contrast to "Ledification" of existing luminaires, OSRAM decided to design non-conventional luminaires as requested in EnLight objective #2 (Fig.3). Because most hotels restrict access to ceilings, and floor luminaires consume space which hampers the daily cleaning process, we decided to redesign already existing doors as "Shiny doors" and to upgrade already existing furniture above the bed as "Shiny walls" with integrated bed lamps. This resulted in the design of door resp. wedge tile luminaires, shown as #1,2,3 and 5 in Fig.9. By using LEDs with 4 colors (mint, red, blue and yellow resp. ww), it is possible to realize a color rendering of >90 from a broad range of colors. This allows for the possibility to tune the color of the wall and the doors to the seasons or the actual color temperature of the sky. Doing so it is possible to address physiological aspects like "Circadian active lighting" [DL11], which has been requested in many use cases.

In Fig.10 the expanded wedge tile concept is shown, which is also used in demo office @ VTT. Each wedge is controlled by two NXP UBA3077 boost drivers, which are located inside the wedge. Four wedges can be controlled by one NXP JN5186 by using the double I^2C HW bus. One wedge will host a combined Valopaa PIR/Lux-sensor for automated presence and brightness control. The PSUs and the luminaire controller with the antenna are located behind the panel. The tile concept demonstrates how complex an intelligent "EnLight-luminaire" can be by just "stock-picking some ingredients" from the building block inventory shown in Fig.8.

The door panels will be illuminated by side coupling of 8 LED-boards (2*3=6 on each side, 2 on top/bottom) into a diffuser plate (EndLighten). As the LED boards are electrically identical to the wedges, they can be operated by 12 NXP UBA3077 boost drivers. The doors can be illuminated by predefined scenes like "Energy saving" or "sunrise" (wake up light), which has been requested in many use cases. Two Valopaa PIR/Lux-sensors will be used for brightness, presence and distance control.

As another example, in Fig.11 the spot module is shown. The outstanding features are (1) a replaceable LLE, (2) a very effective heat sink which is part of the luminaire and (3) a lens with an outstanding optical efficiency of 95%, very good color mixing and homogeneous radiation pattern. The driver is of the same architecture like the buck driver shown in Fig.8, but with an opening in the center for accepting the LLE, which is directly connected to the heat sink and thermally insulated from the electronics.

Validation

The validation of energy savings will be started after the demo is setup in the hotel. Fig.12 shows as a benchmark the energy saving potential associated with different state of the art technologies. EnLight will add comfort elements like CRI/CCT tuning and task resp. circadian active lighting. The table shows the estimated energy budget of OSRAM luminaires, all of them exceeding the EnLight target of ≥40% savings (refer to Fig.4), and even if the negative rebound effect [ST13] is taken into account. The system intelligence will be improved by adding luminaire embedded sensors and sensor fusion, which are key elements for getting the right light at right place at the right time [FF11].

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[JN12] Jason Nawyn, Maria Thompson, Nancy Chen, Kent Larson, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, September 2012, vol. 56, no. 1, 541-545

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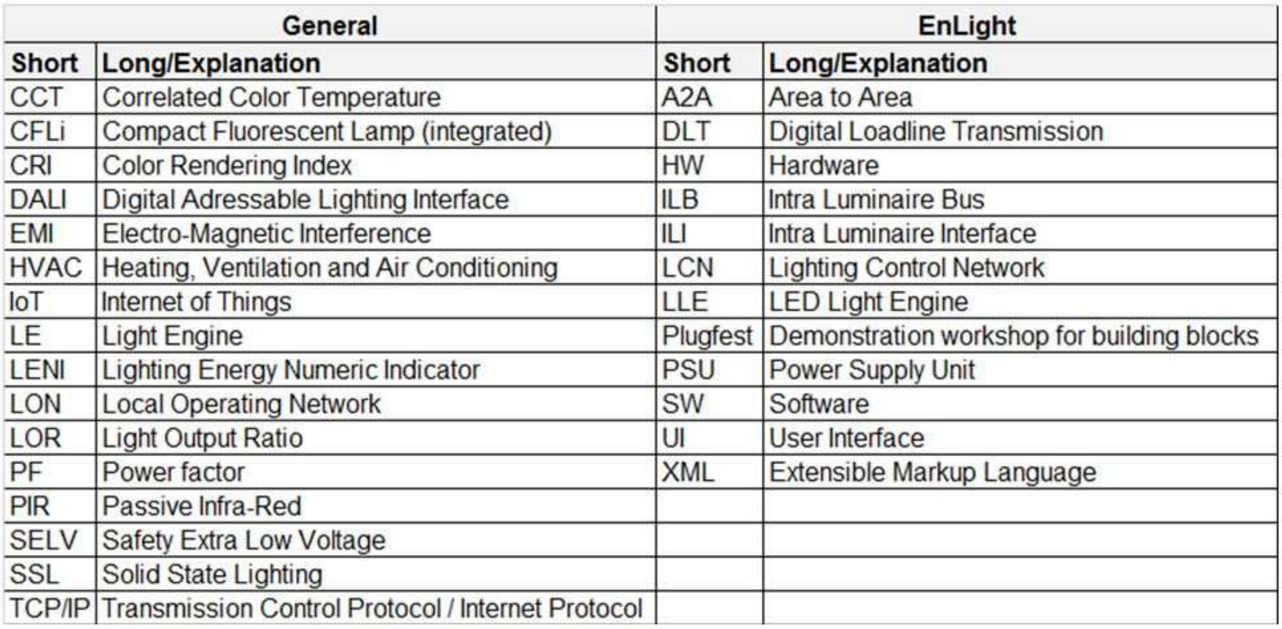


General		EnLight	
Short	**Long/Explanation**	**Short**	**Long/Explanation**
CCT	Correlated Color Temperature	A2A	Area to Area
CFLi	Compact Fluorescent Lamp (integrated)	DLT	Digital Loadline Transmission
CRI	Color Rendering Index	HW	Hardware
DALI	Digital Adressable Lighting Interface	ILB	Intra Luminaire Bus
EMI	Electro-Magnetic Interference	ILI	Intra Luminaire Interface
HVAC	Heating, Ventilation and Air Conditioning	LCN	Lighting Control Network
IoT	Internet of Things	LLE	LED Light Engine
LE	Light Engine	Plugfest	Demonstration workshop for building blocks
LENI	Lighting Energy Numeric Indicator	PSU	Power Supply Unit
LON	Local Operating Network	SW	Software
LOR	Light Output Ratio	UI	User Interface
PF	Power factor	XML	Extensible Markup Language
PIR	Passive Infra-Red		
SELV	Safety Extra Low Voltage		
SSL	Solid State Lighting		
TCP/IP	Transmission Control Protocol / Internet Protocol		

Table 1. List of acronyms

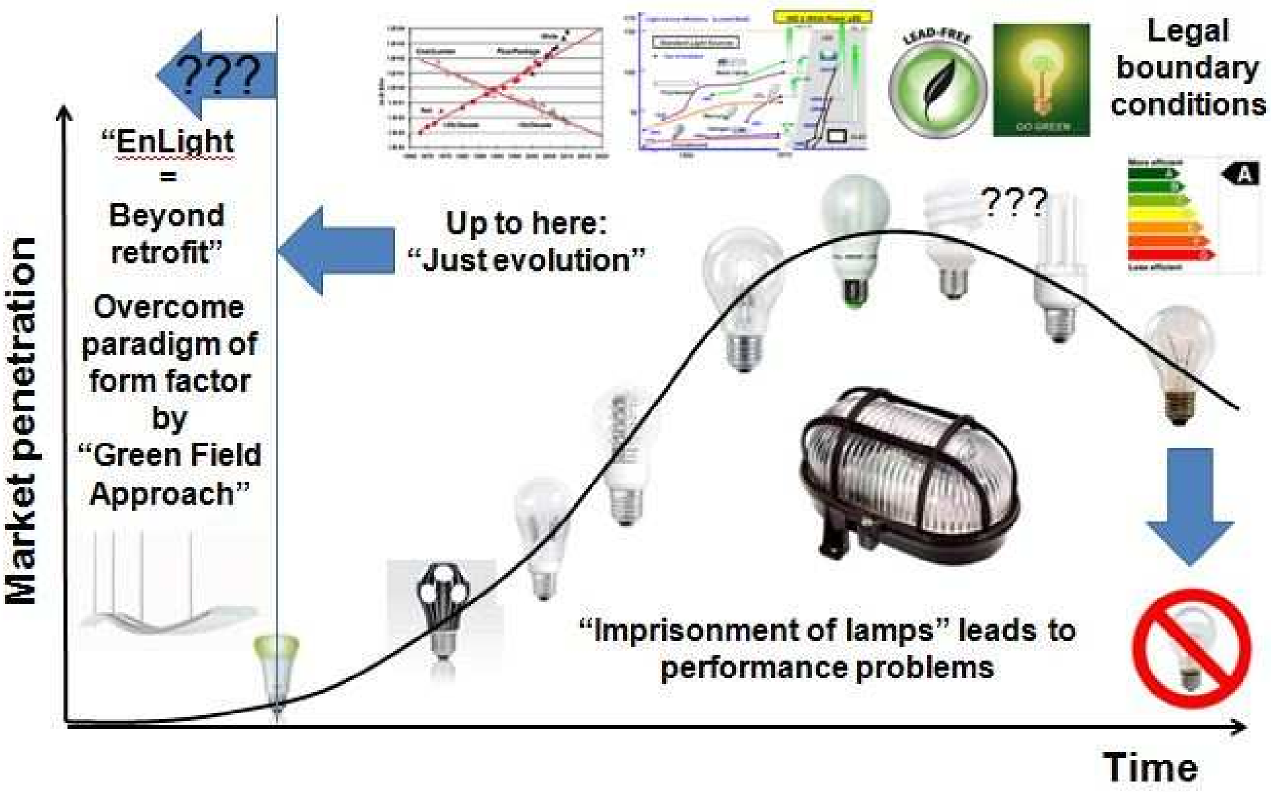


Figure 1: Product Life Cycle-Curve of "the bulb" and 1st wave of SSL transformation

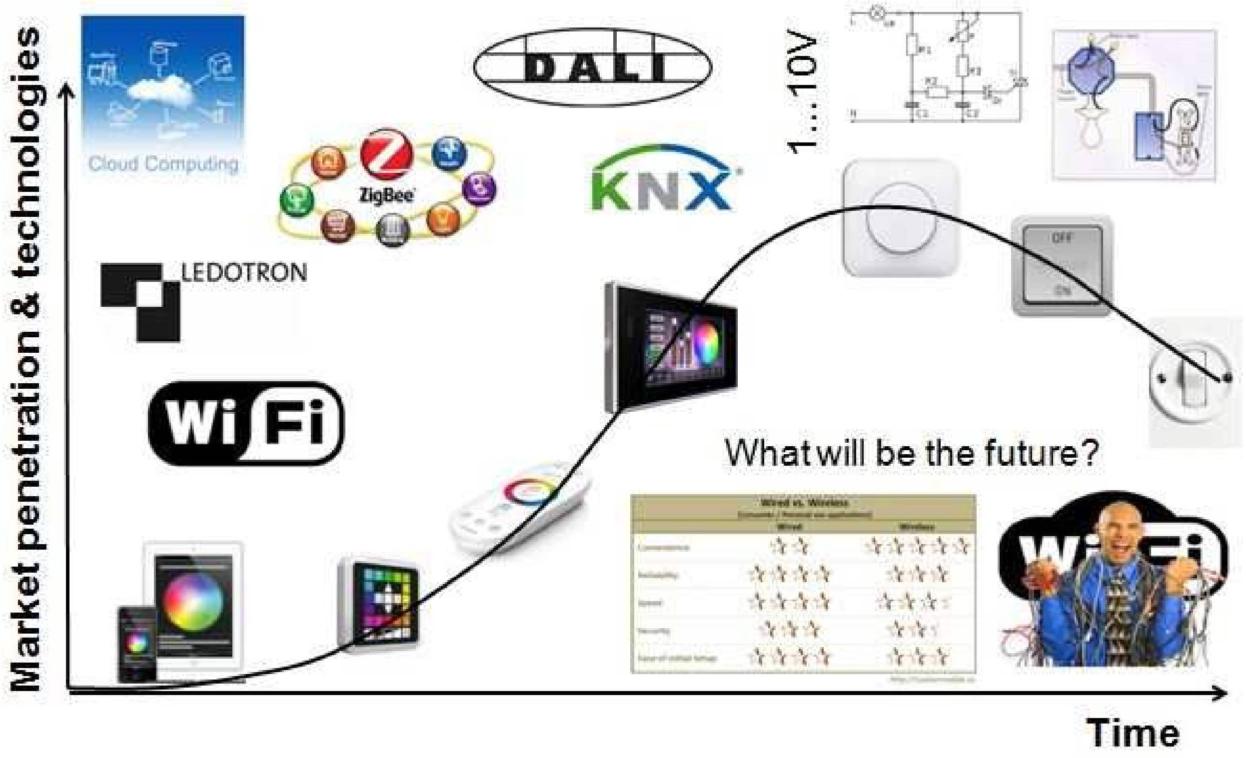


Figure 2: Product Life Cycle-Curve of "User Interfaces" in lighting and related technologies

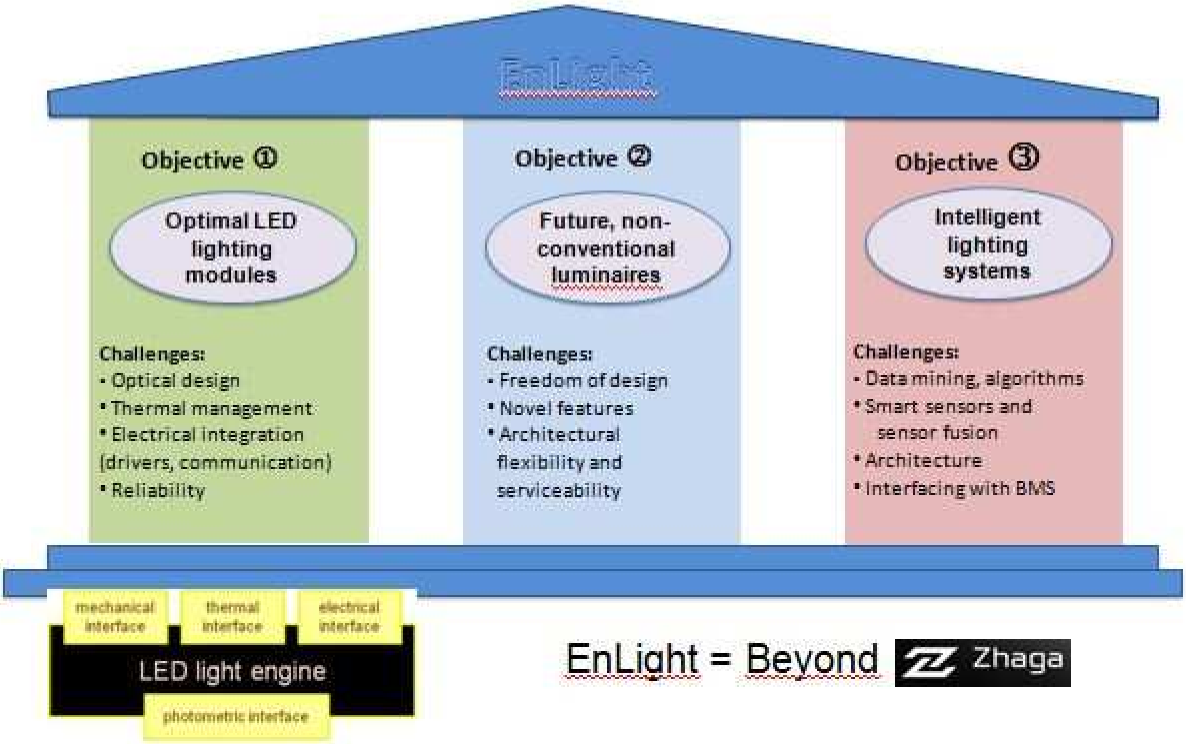


Figure 3: EnLight objectives

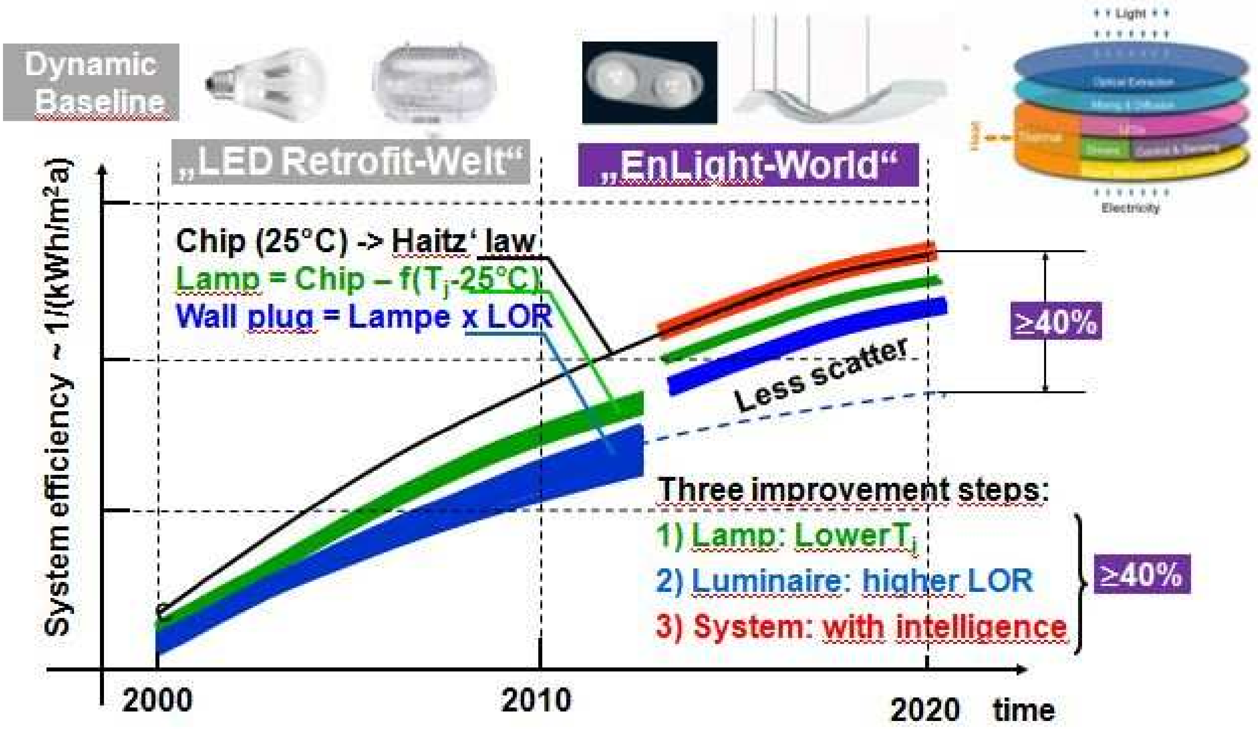


Figure 4: EnLight energy saving target

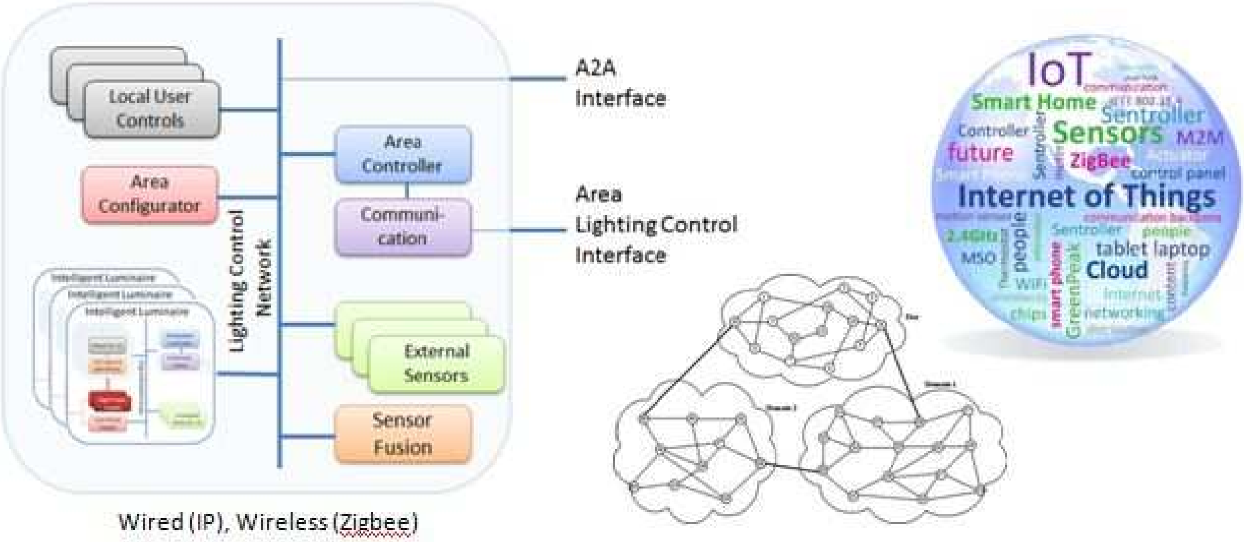


Figure 5: Lighting Control Network (LCN) on area level, connecting to the Internet of Things (IoT)

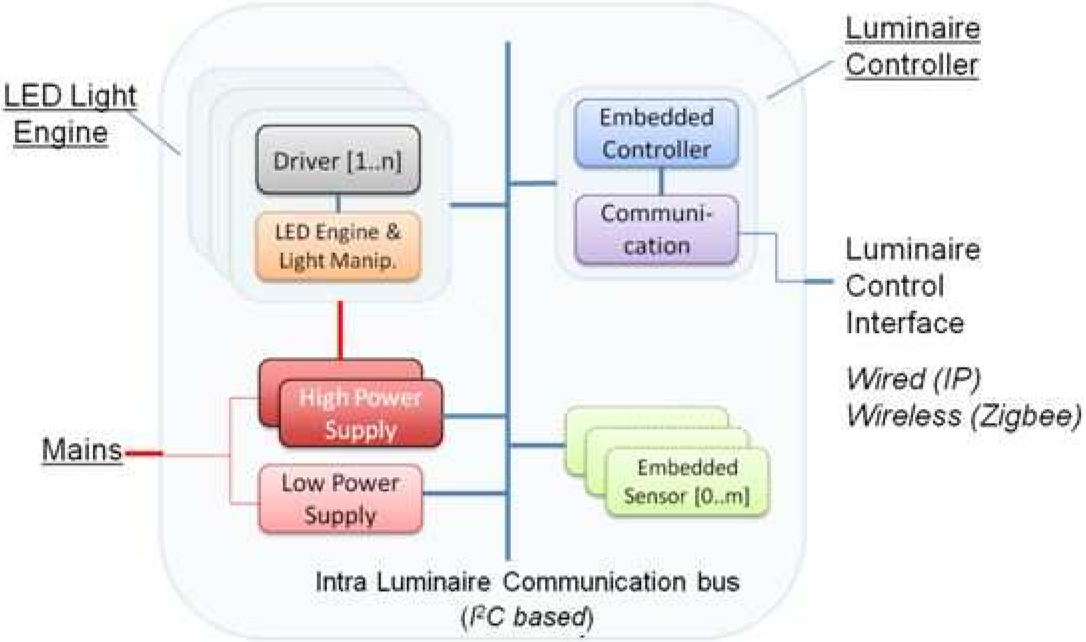


Figure 6: Intra-Luminaire Bus ILB (functional view)

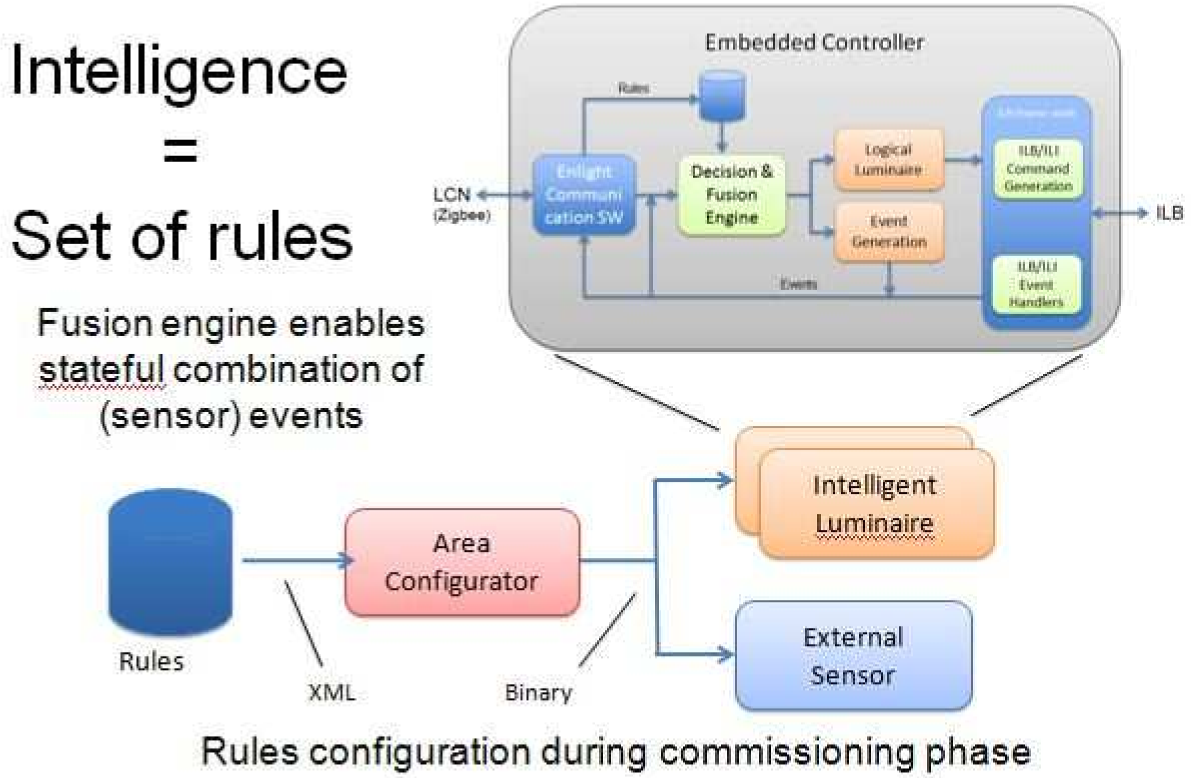


Figure 7: Embedded controller, fusion engine and rules mechanism

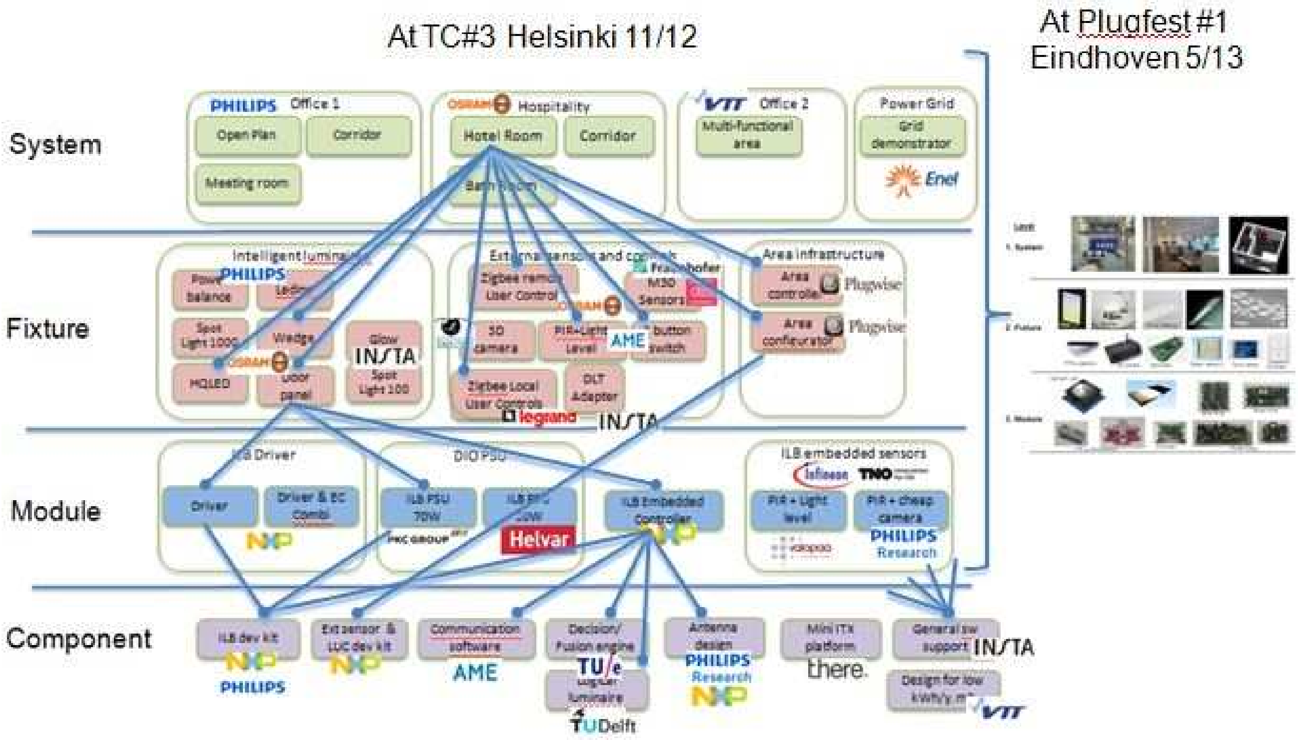


Figure 8: EnLight building blocks as defined during TC#3, Helsinki in 11/12 (left side) and dto, as available during Plugfest #1, Eindhoven in 5/13 (right side)
The arrows indicate the “Shopping list” for setup of the hotel room in demo hospitality.

Figure 9: Sketch of Demo Hospitality in hotel room

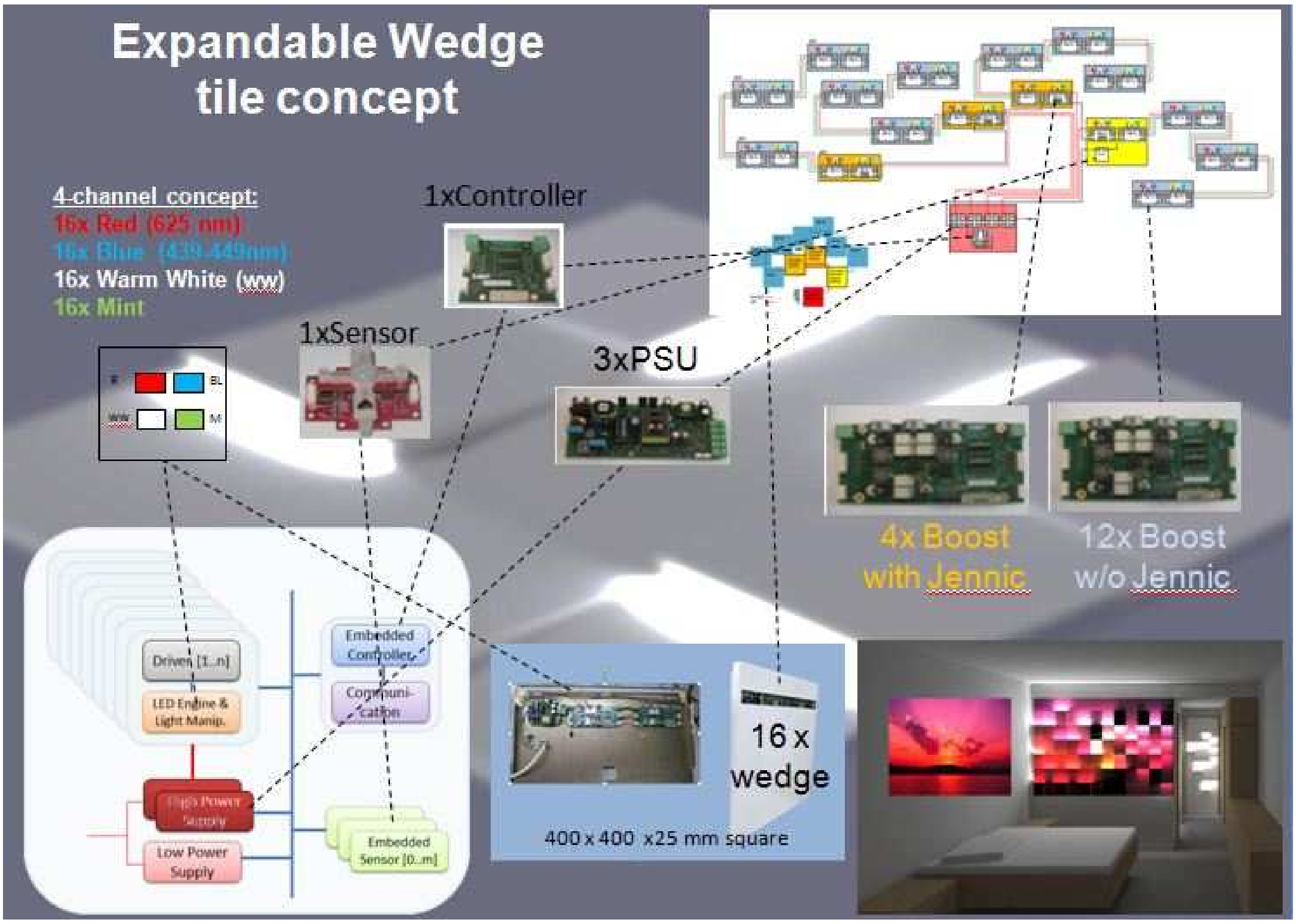


Figure 10: “Cooking recipe” for flexible wedge tile concept

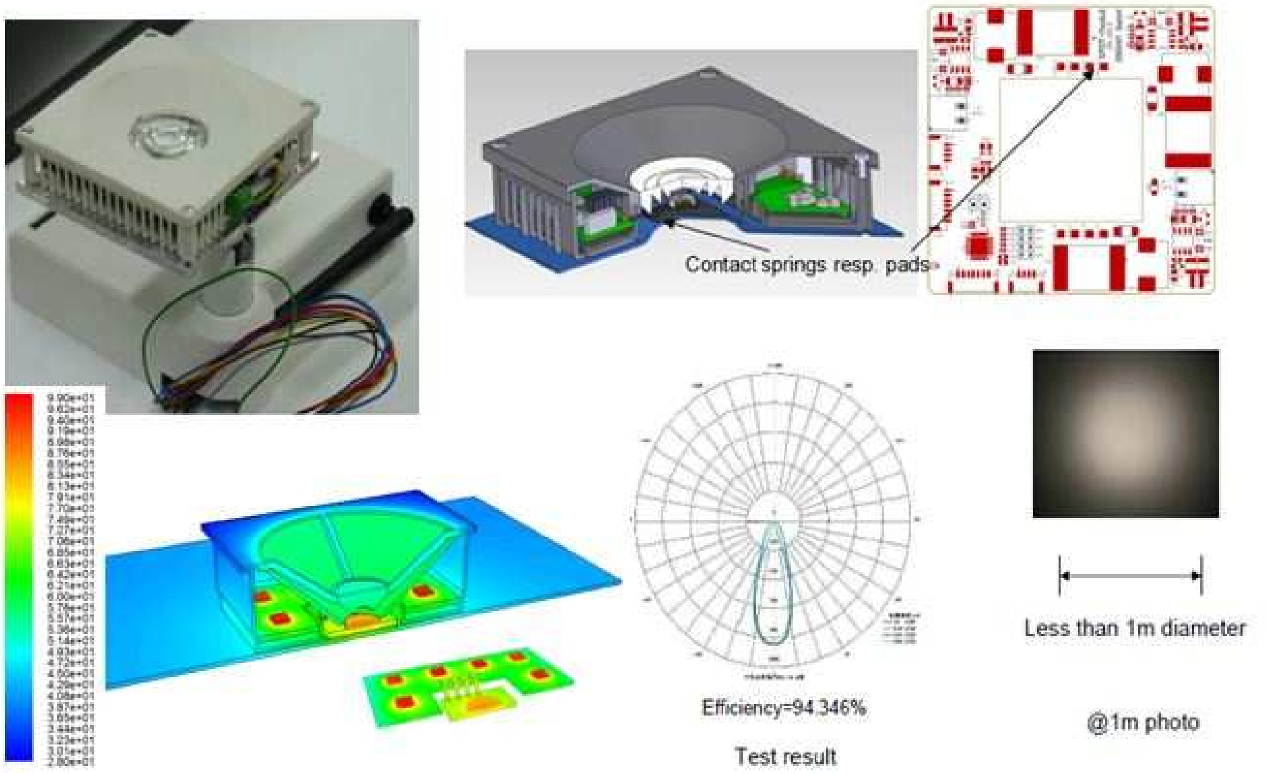
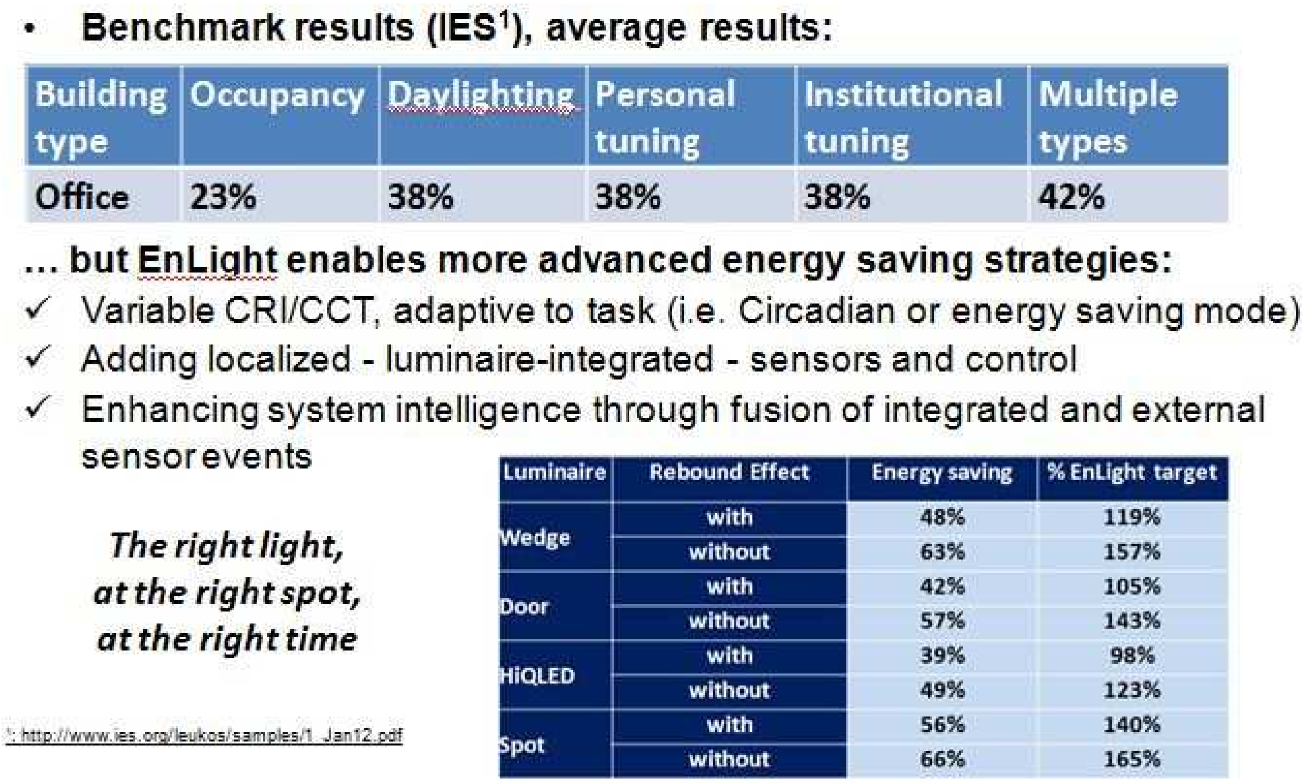


Figure 11: Concept and advantages of spot module



- **Benchmark results (IES[1]), average results:**

Building type	Occupancy	Daylighting	Personal tuning	Institutional tuning	Multiple types
Office	23%	38%	38%	38%	42%

… but EnLight enables more advanced energy saving strategies:

- ✓ Variable CRI/CCT, adaptive to task (i.e. Circadian or energy saving mode)
- ✓ Adding localized - luminaire-integrated - sensors and control
- ✓ Enhancing system intelligence through fusion of integrated and external sensor events

Luminaire	Rebound Effect	Energy saving	% EnLight target
Wedge	with	48%	119%
	without	63%	157%
Door	with	42%	105%
	without	57%	143%
HiQLED	with	39%	98%
	without	49%	123%
Spot	with	56%	140%
	without	66%	165%

The right light,
at the right spot,
at the right time

[1]: http://www.ies.org/leukos/samples/1_Jan12.pdf

Figure 12: Benchmark results and estimated energy saving potential of OSRAM luminaires with and w/o "Rebound Effect" [ST13]