The Building Blocks for Intelligent Future Luminaires

The EnLight consortium came to the conclusion that to provide cost effective solid-state lighting products there are several aspects in which a modular approach seems to be advantageous. Tim Böttcher and Lucie Chandernagor from NXP, Philippe Maugars from PMC, Hannu Vihinen from Helvar, Mark Coopmans from Philips Lighting, Olli-Pekka Jokitalo from PKC Electronics, Raimo Ontero from Valopaa, Christian Paul from Infineon, and Rafael Jordan from Fraunhofer IZM explain how the new approach works.

The EnLight Lighting System design was based on a modular hardware approach, which was founded on a Plug-and-Play hardware bus and distributed intelligence of the individual communicating luminaires. This modular approach allowed realizing the required large variety of luminaires with a limited set of hardware, even coming from different partners. The functionality of the individual luminaire was then only realized in software and no hardware change was required. An example of the variety of building blocks inside one luminaire is illustrated in figure 1.

In order to give as much freedom to the luminaire design as possible, it was intended to have very compact and energy efficient modules. Besides the small size, this allowed the heat sinks to be reduced in size or to use parts of the luminaire housing as heat sink.

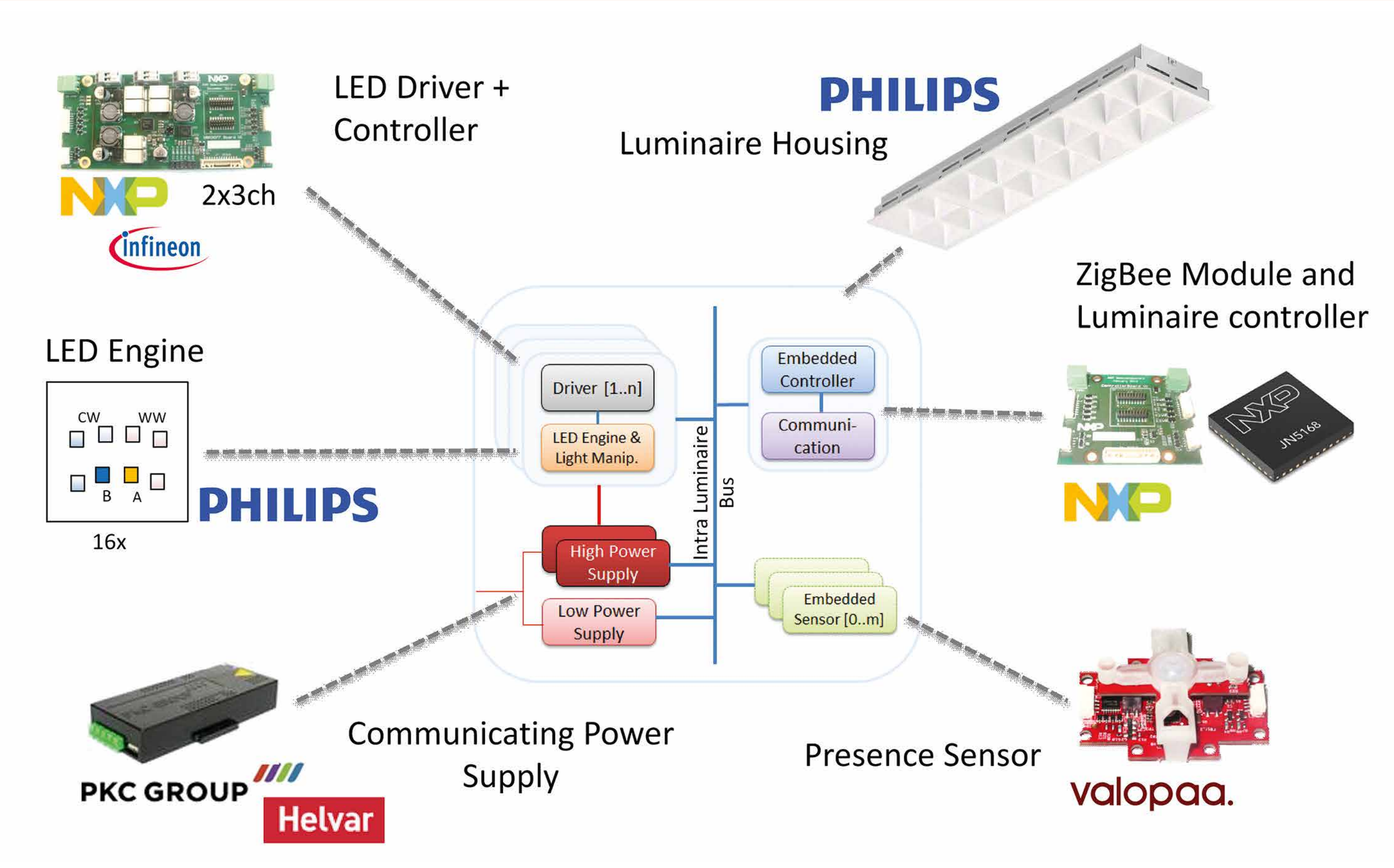


Figure 1: Set of four different luminaire types build on the same set of hardware

Diversity Management

In order to connect all the individual modules, a novel bus system was developed. Since several partners contributed to the hardware platform, the bus system was required to be highly flexible and simple to adapt to the actual hardware requirements. In the following section the hardware and the software parts are illustrated.

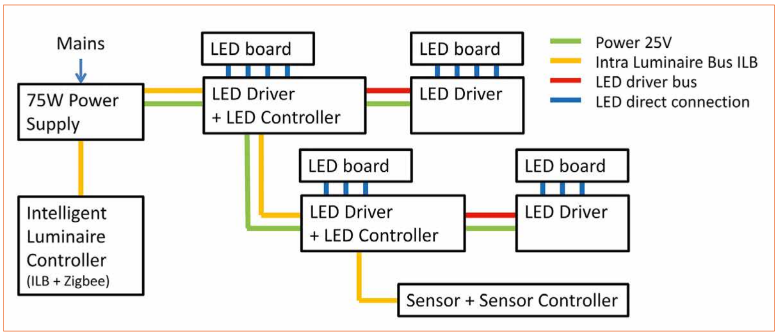


Figure 2: Bus system inside an intelligent EnLight luminaire, connecting LED driver and sensor boards

ILB hardware bus system

The EnLight luminaires were based on LED driver and communication modules, which were connected through a standard I²C bus. The bus driver was modified in such a way, that the plug-and-play operation of modules is possible. Within one luminaire, one distinguishes the Intra Luminaire Bus (ILB) and the LED driver bus. The ILB bus system is connecting the individual modules on hardware basis to an intelligent luminaire controller. The LED driver bus purely operated in master-slave mode in order to distribute commands to the PWM generator on the LED driver board. All modules and boards were designed to allow the daisy chain connection of boards, thereby simplifying the wiring in total. An example of such a luminaire configuration is shown in figure 2.

The decision engine was placed in the intelligent controller module, which was commonly connected to the ZigBee or area network. Based on the programmed rule set in use, the controller translated the rules into module commands on the ILB network. The behavior of the luminaire as a whole was then only defined by the rule set programmed into the intelligent controller. Accordingly, it was possible to use standardized and small LED driver modules to operate the LED strings, which were connected on the ILB bus in order to build luminaires of all sizes.

ILB software bus system

The main concepts behind the Intra Luminaire Bus (ILB) are to introduce modularity, yet allow an easy integration if required for BOM. As illustrated in figure 3, the ILB framework forms a platform for functions that need to communicate to one another, where a function (e.g. presence sensing) typically consists of a hardware part and a software part. In ILB the software part is referred to as an application.

Technical features of ILB are:

- Reusable and exchangeable building blocks
- Abstraction from implementation technology (e.g. PIR vs. Ultrasound for motion detection)
- Application software integration into combined hardware execution platform
- Multi-master mode enabling low standby power
- Plug and Play
- Portability to different physical communication layers (e.g. I²C, RS485)

When partitioning the system in hardware modules, a function may migrate from one hardware module to another, depending on the most appropriate implementation for that system. To support such a migration, the ILB framework abstracts the physical location and routes messages between modules as applicable.

The ILB framework is a shared software component that:

- Provides address resolution and physical communication between hardware modules
- Provides an interface for applications to exchange messages
- Associates an application with the appropriate hardware module
- Provides a managed message set

One of the applications is a controller implementing the intelligence in the form of a decision engine, which takes input from sensor applications and drives lamp applications.

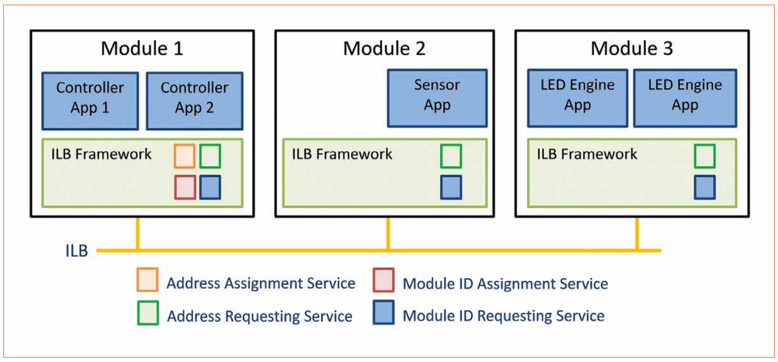
During power up, an address requesting service queries the address assignment service for a unique I²C hardware address to be assigned. Similarly for the module ID service after a hardware module was assigned a hardware address. The controller is the only module that is found on a fixed hardware address. All other modules are assigned a hardware address (and also module ID) dynamically.

Hardware Modules

The implementation of the actual hardware was guided by the luminaire requirements, which, in particular constrained the possible volume and the heat management of the modules. Here, the key modules are described by example.

Power supply units

The Power Supply Units (PSUs) were AC/DC converters designed for this new architecture. Each PSU contained two separate power supplies: high power supply (HPS) for LED drivers and low power supply (LPS) for ILB devices. To address all luminaire needs, two different PSU versions with a power of 75 W and 20 W were developed. The main criteria for the PSUs were high power factor, high power conversion efficiency and low stand-by power. The power factor corrector was based on a boost topology with quasi-resonant control, which results in a power factor of up to 0.97.



Figures 3: The ILB framework as platform for communicating applications

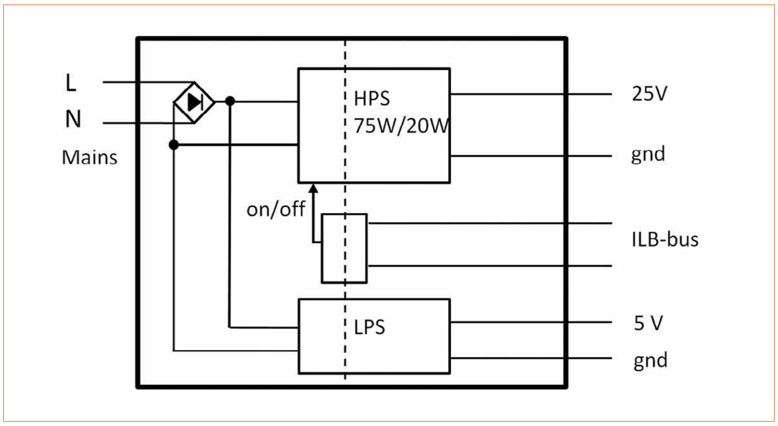


Figure 4: The block diagram of the power supplies

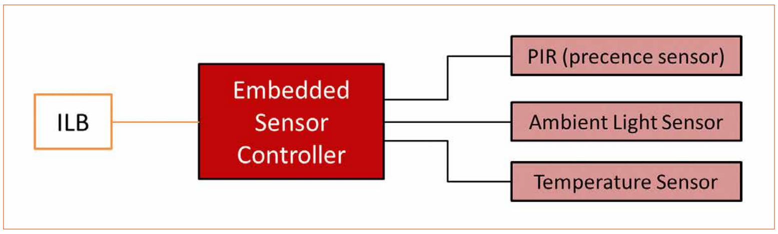


Figure 5: Embedded sensor block diagram

The 75 W HPS used a LLC resonant topology with synchronous secondary side rectification (NXP SSL4120T). The 20 W HPS was driven by a quasi-resonant flyback controller (NXP TEA1755T) with synchronous secondary side rectification. The LPSs of both PSUs were based on a flyback converter that enters the burst mode at low load to ensure low losses. The functional block diagram of the units is presented in figure 4.

Also, up to 4 pieces of the PSUs can be combined to form high power luminaires. When the LED load was switched off completely, the main power supply was switched off as well via the ILB-bus.

Embedded ambient sensor

Embedded sensor boards were designed to provide luminaire level information on movement of people, prevailing ambient light level and temperature inside the sensor. The sensor boards accommodated sensor controller, PIR sensor, and ambient light sensor and temperature sensor. They were powered from 5 V DC supply, delivered via ILB bus connector and from which power consumption below 10 mW is achievable. The functional block diagram is presented in figure 5. The sensor boards were designed in two form factors to fit into different luminaires.

LED driver boards

The LED driver boards were designed to operate autonomously once a defined setting is programmed through the ILB. This was achieved through a pulse width modulation (PWM) expander (NXP PCA9685), which had an I^2C interface to the LED driver controller. As illustrated in figure 6, the setting from the intelligent luminaire controller was translated by the LED driver controller into a set of required PWM signals. The related commands are then given to the PWM expander, which independently generates the PWM signals for the DCDC converter at the LED strings.

One DCDC LED driver for short strings was designed for an average LED current up to 0.7 A (Infineon ILD6070). Switching and conduction losses of the IC were minimized to achieve a high efficiency. LED driver switching frequencies up to 1 MHz enable the use of low inductance inductors keeping the board size small while achieving high slew rates of the LED current. The high slew rate together with the short PWM delay time of the IC allowed high contrast ratios in each LED string. For long LED strings, boost DCDC LED driver boards were designed accordingly.

Intelligent controller and ZigBee communication

A combined CPU and ZigBee transceiver for all EnLight building blocks was chosen (NXP JN5168). On most of the modules, a connection slot was reserved so to be able to plug a standard CPU / ZigBee module flashed with the relevant firmware when necessary. Although the communication function was not needed in all modules, the same controller chip was chosen so as to have full flexibility for reuse of the embedded SW blocks without any redesign.

The dynamic smart lighting requirements from EnLight require a major extension of the hardware and software capabilities. A new ZigBee stack was developed, enabling up to 250 nodes in a single network. The radio receiver, optimized for better efficiency allowed lowering the standby consumption below 100 mW, thus meeting the future targets. The chip will feature a full Multi Master I^2C bus that improved the performances of the ILB bus described above. A full function JTAG debugger allowed easier and faster real time software development, and a larger flash memory will enable seamless over the air re-flashing. The block diagram of the new chip is displayed in figure 7.

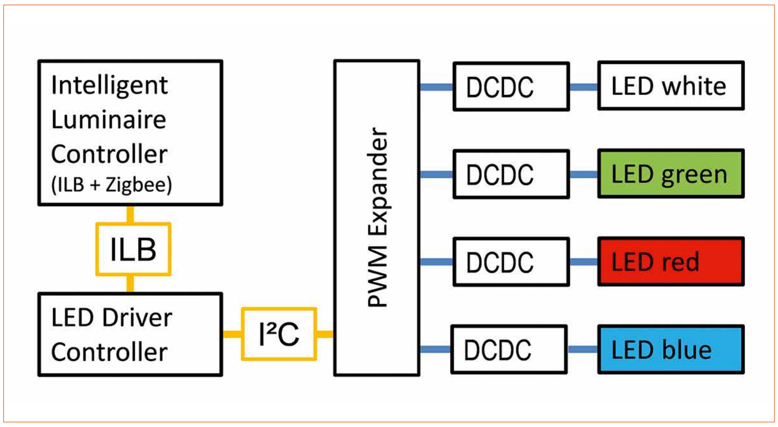


Figure 6:
Hardware bus system inside one LED driver board connected to the ILB

Miniaturization

To go beyond the given size constraints from the chosen EnLight luminaires form factor, the miniaturization of modules was evaluated further. Here, different aspects such as board design and LED design were addressed.

Compact single stage PSU for simple luminaires

Most EnLight luminaires featured several LED strings, or even several LED Light Engines; therefore, the two-stage topology with central PSU previously described, was chosen. However, for some simple luminaires a single stage approach is more appropriate, since this allowed a more compact electronic module and lower standby power consumption.

Such an application was developed, tested and demonstrated (NXP SSL5511). Figure 8 shows the mains interface, the manual switch, the Jennic module with printed antenna and the connections to the LED module. The compact size (10 x 7 x 2 cm) allowed the integration of the module in the foot of the lamp, which was not possible with the two-stage design.

Integrated LED light engine with hermetic package

Another component for the modular luminaire was a spotlight with about 1000 lm out of a 20 mm^2 package surface. As the project partners always focused on forward looking solutions, this module had to be hermetically sealed to withstand humidity as well as harmful gases and other harsh environments. To achieve this goal, a completely new approach was launched, starting from thermal and thermo-mechanical simulations, developing a complete 8” wafer level packaging process and assembly of prototypes. The packages were designed for flexible configurations with pure white LEDs, RGB-LEDs or even additional sensors. The footprint is compatible with standard board technologies and the thermal pad was insulated from the electrical connections, illustrated in figure 9.

The assembly process of the packages was chosen in a way that no step would re-melt prior interconnections and that the final package would withstand process temperatures up to 270°C. Known and new technologies like eutectic bonding, anodic bonding, transient liquid phase bonding and more were chosen the way that no polymeric or other permeable interfaces are built. Therefore, the package is completely hermetic and highly reliable.

Energy Efficiency

The project achieved the energy efficiency targets, in particular, through intelligent control of the illumination on the basis of highly efficient modules in the system electronics. Examples of this work are illustrated in the following,

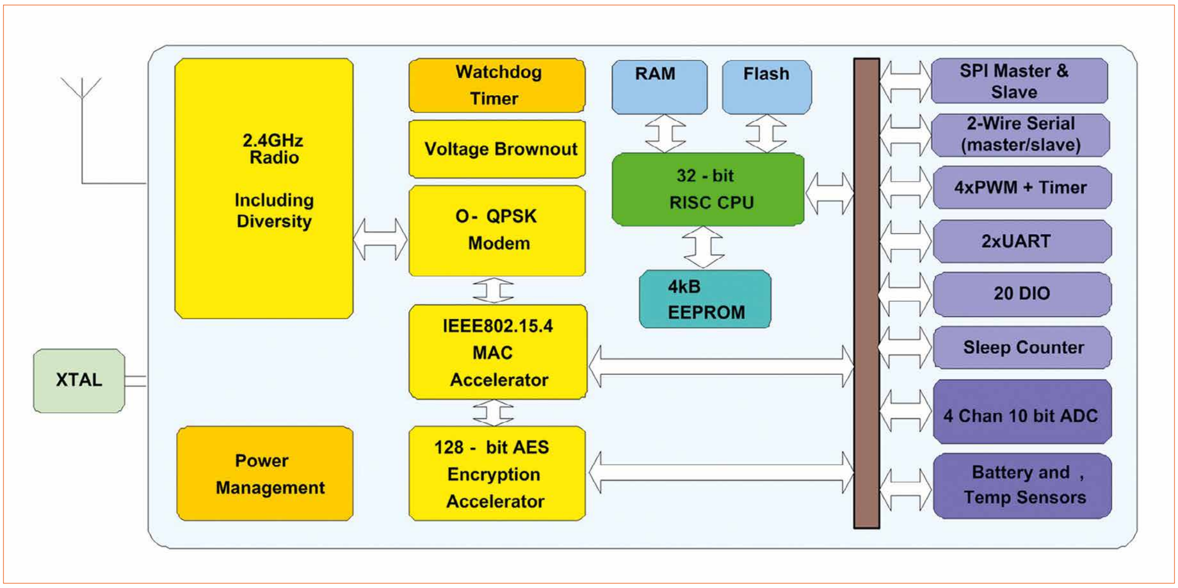
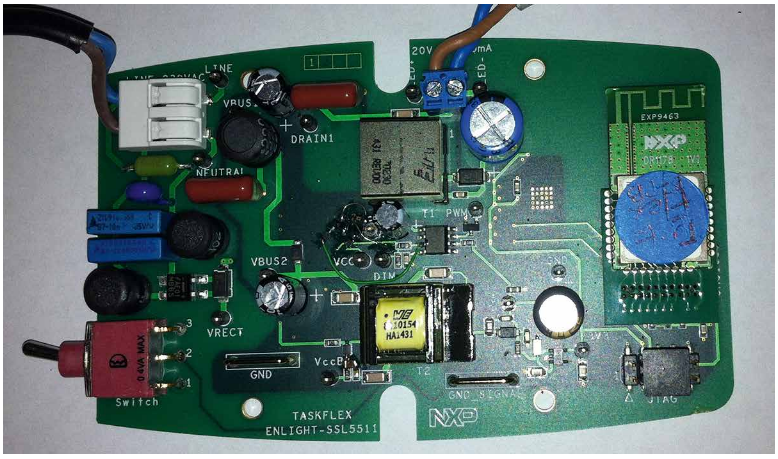
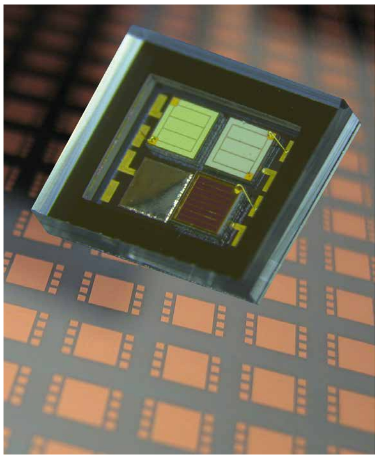


Figure 7:
Block diagram of the JN5169, a CPU / ZigBee chip based on the project findings





Figures 8 & 9:
Compact Supply/ Driver/Communication module (left).
A hermetic package housing red, green and blue LEDs. The background shows the wafer on which the LED light engine was manufactured (right)

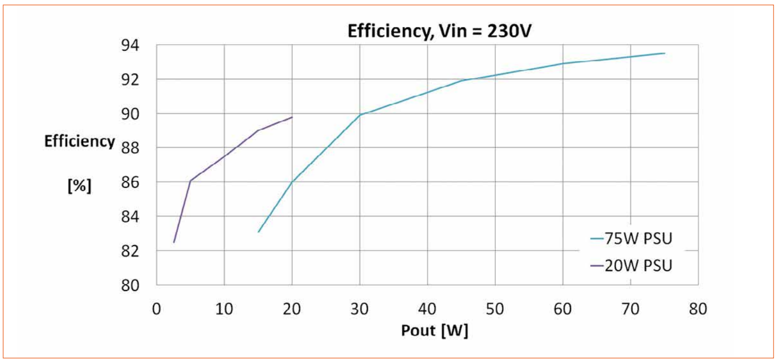


Figure 10:
The efficiencies of the PSUs as a function of the output power

where components designed for the specific requirements of intelligent lighting are described.

PSU and LED driver efficiency

The efficiencies of the PSUs at full load were about 93.5% (75 W PSU) and 90% (20 W PSU). However, even more important is the good efficiency throughout the entire load range in a system where the energy consumption is minimized by dimming or shutting down the LEDs. In figure 10 the efficiencies are plotted as a function of the output power, showing the efficiency above 82% even at the lowest load.

The 75 W PSU was able to receive commands on the ILB bus, such that the high power output can be switched on/off in order to optimize load and losses. The standby power loss was then down to 160 mW. However, the standby losses depended on the quantity of devices connected to the ILB-bus. The low power output is always on and it provided the power to the control circuitry of the system.

The complete LED driver in an EnLight luminaire with 25 V DC supply voltage (including losses of inductor, current sense resistor and Schottky diode) achieved efficiencies above 95% driving 6 LEDs at the rated current of the IC. In PWM dimming down to 1% duty cycle the efficiency of the LED driver was better than 81% due to the low power consumption of the IC, which is a prerequisite for intelligent lighting with its intense usage of dimming and color control.

Wake up radio

Even if the ILB cuts off the main power supply, the receiver still drains power on the order of 100 mW. The wake-up radio is an additional receiver only in charge of the activation of the application (Figure 11). As a net result, the standby power use of the whole application was reduced to the power consumption of the wake-up radio. This consumed only 100 µW, i.e. a thousandth of the standby power consumption. Setting a lower operation rate at the cost of a higher latency time can reduce this consumption further.

The wake-up radio was designed in CMOS technology and operates on its own supply source at 3.3 V. In standby mode there is no power drain on the main supply.

When a user presses the command switch, an activation message at 433.92 MHz is emitted. This wake-up message is Manchester encoded at 25 kbit/s. The 24 bits address it contains is programmable by SPI bus. If the expected code is received, the wake-up radio provides a pulse that drives an electrical relay connecting the main supply to the application. This pulse is delivered with a maximum latency time of 125 ms. The wake-up radio achieves a - 55 dBm sensitivity that allows for a 10 m range in indoor conditions when using a standards regulation compliant 10 dBm emitter.

The wake-up receiver is compatible with a ZigBee transceiver. Indeed, it is therefore suitable for use at 868 MHz or 2.45 GHz. ZigBee transceivers are able to generate the wake-up message subject to software modifications.

DCDC choice of the flyback diode in the LED driver

In the chosen low cost non-synchronous LED driver architectures, Schottky diodes were used due to their low forward voltage during conduction and the fast switching. However, choosing an optimal diode for the application was not straightforward due to the loss contributions arising from forward conductance,

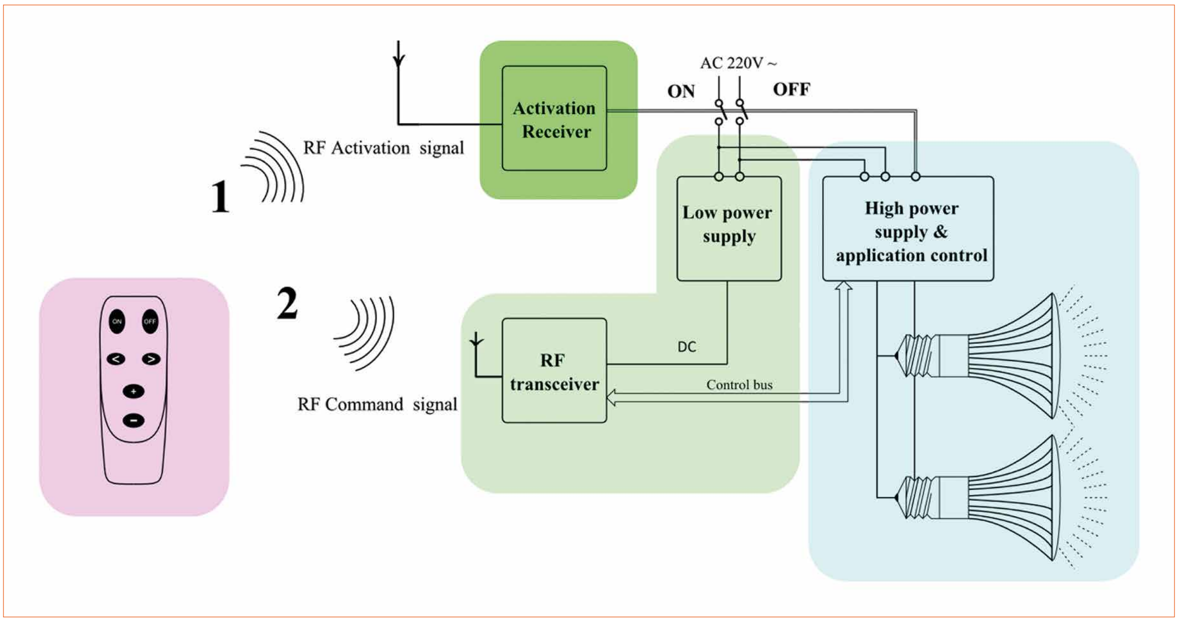


Figure 11: Schematic diagram of the wake up radio application

leakage current and switching. The peak efficiency of the buck DC-DC converter exceeded 95%, and by choosing the correct Schottky diode the efficiency can be increased to 96%. At low load conditions, the efficiency improvement can even be as high as 5%. This does not seem impressive, but it translates to a reduction of the losses by more than 20%, easing the requirements on the thermal design.

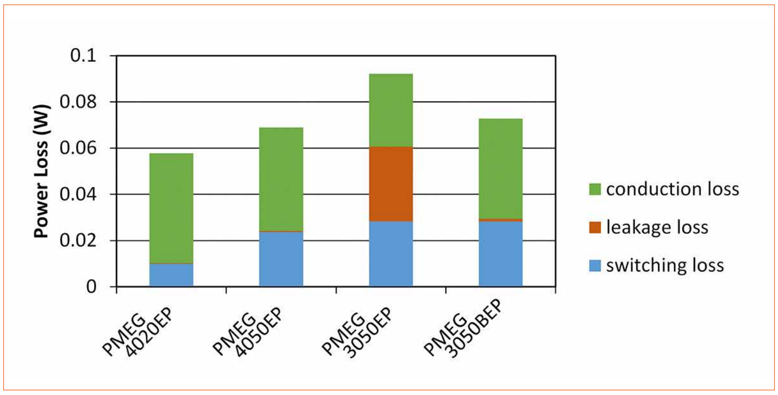


Figure 12: Power loss contributions in the flyback diode of the DCDC LED driver

One might think that a Schottky diode with lower forward voltage drop VF would always result in better efficiency. This is based on the assumption that the losses due to the leakage current and the switching are negligible. It is valid as long as the conversion frequency is not too high. Once the board operates in the range above 100 kHz as for the EnLight design, the switching losses become relevant for the system.
Figure 12 shows details of the loss contributions for an LED driver with 6 LEDs, operating at 300 kHz. Except for the ultra-low VF PMEG3050EP that has a very high leakage current, loss due to reverse leakage is negligible as compared to the switching loss and the forward conduction loss. Interestingly, the smallest diode with the highest forward voltage PMEG4020EP gives the highest efficiency due to the smaller switching loss.

Since the I-V and C-V characteristics of Schottky diodes could be well described by SPICE models, it was possible to evaluate the total loss of the Schottky diode in this application in the design phase and even to predict the operating temperature.

Conclusion

This Chapter detailed the design of the modules inside the intelligent and energy efficient EnLight architecture. It was shown that it is possible to build a large variety of luminaires on the basis of few hardware modules from different suppliers, which are seamlessly integrated via the smart usage of reusable software on top of I^{2}C bus architecture. This Intra Luminaire Bus is fully plug-and-play from a hardware and software perspective, enabling the easy and secure replacement of modules inside one luminaire. The application of intelligent lighting with its intense usage of deep dimming and color control is supported by the power electronics, which were designed to deliver high efficiency at full and partial load. Embedded sensors and the distributed presence of controller modules enable the intelligent control.

To conclude, the modular architecture supports future lighting system upgrades facilitating the shift of the current linear economy to a more sustainable circular economy. Easy exchangeable (modular) lighting systems, as opposed to "sealed-for-life" systems, are required to realize this circular economy.