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# LEDWIRE: A Versatile Networking Platform for Smart LED Lighting Applications using LIN-Bus and WSNs

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**Abstract:** In this paper, the architecture of a versatile networking and control platform for Light-Emitting Diode (LED) lighting applications is presented, based on embedded wireless and wired networking technologies. All the possible power and control signals distribution topologies of the lighting fixtures are examined with particular focus on dynamic lighting applications with design metrics as the cost, the required wiring installation expenses and maintenance complexity. The proposed platform is optimized for applications where the grouping of LED-based lighting fictures clusters is essential, as well as their synchronization. With such an approach, the distributed control and synchronization of LED lighting fixtures' clusters is performed through a versatile network that uses the single wire Local Interconnect Network (LIN) bus. The proposed networking platform is presented in terms of its physical layer architecture, its data protocol configuration, and its functionality for smart control. As a proof of concept, the design of a LED lighting fixture together with a LIN-to-IEEE802.15.4/ZigBee data gateway is presented. *Copyright © 2016 IFSA Publishing, S. L.*

**Keywords:** LED lighting, Solid-state lighting, Local interconnect network (LIN), DMX512, Wireless sensor networks (WSN), Architectural lighting, Greenhouse lighting.

## 1. Introduction

Light-Emitting Diode-based Solid-State Lighting (SSL) has been considered as the dominant technology for lighting world-wide. Compared to other existing lighting technologies, LED lighting has several advantages, regarding their luminous efficacy, their life-time of operation, and their dynamic response [1, 2]. Until recently, lighting control was traditionally based on permanent wires between predetermined switches and the lighting fixtures. However, during the last decade, Building Management System (BMS) technologies have been introduced for enhanced building operation, based on buses like EIB (European Installation Bus), or LON (Local Operation Network) for the physical layer [3, 4]. Furthermore, the KNX is a standard that relies on the communication stack of EIB and is an open (EN 50090, ISO/IEC 14543), OSI-based, networking and communication protocol, that covers all of the aspects of Building Automation (BA). The main disadvantage of the aforementioned BMS solutions is the high wiring cost. For this reason wireless protocols, such as the KNX-RF, have been proposed, and they are used as BMS extensions. Alternatively, power line networking solutions, such as the X10, or the KNX power line extensions, which utilize the existing electric power wiring infrastructure for control, have been also introduced. All these BMS extensions have been extensively used for lighting applications where the synchronization between the lighting fixtures (LFs) is not important (simple on/off applications), as for example, in the industry sector, in professional buildings like hotels, in trade centers and sport stadiums. These extensions have been designed without mechanisms for lighting fixtures synchronization and therefore they are not suitable for this specific category of lighting applications.

Modern networking approaches, that support timing synchronization mechanisms, have been applied for lighting control and are based on embedded networking technologies using the Ethernet or Internet Protocol, embedded WiFi implementations [5] and Wireless Sensor Networking techniques [6]. However, all these approaches require the networking of every single LED Lighting Fixture (LLF), resulting to increased cost and management complexity concerning the continuous and secure connectivity.

Finally, the DMX512 wired protocol is used for lighting control, which is based on the EIA-485 standard for the physical layer, enabling the control of 512 lighting fixtures (channels) [7]. The EIA-485 bus standard enables the direct addressing of 32 up to 256 Lighting Fixtures (LFs) in a bus topology, while splitters are used for controlling a large number of LFs. Extensions of the DMX protocol based on Ethernet and IP networks have been recently proposed for lighting control with implementations of DMX over IP, such as Art-Net [8]. However, these DMX extensions have disadvantages due to the increased maintenance, installation cost, and the increased complexity, especially for Ethernet connectivity where the number of wires must be at least six (four signal plus two power cables).

For many lighting applications, the grouping of LEDs in clusters, as well as their timing synchronization, becomes a very important issue raising special control requirements. Applications of this type are those found in studios, theaters, decorative flood lighting, entertainment, landscape architecture, smart horticulture, etc., where strict requirements are imposed from the dynamic response of human vision. However the direct application of BMS technologies (or of extensions that can be integrated, e.g. Digital Addressable Lighting Interface-DALI), is not suitable, mainly due to the required dynamic response, the installation cost and the management complexity. For LED clusters control, the necessity of a solution that can integrate the simplicity of a low-cost wired bus, like DMX-512 for full-duplex communication, is more than obvious.

In this paper, a versatile single-wire networking platform is proposed for the distributed control of LFs that are based on clusters of LLFs. This platform has been designed in an optimal way for improved dynamic response, which is mandatory for the implementation of lighting scenarios with high synchronization needs. Moreover, an efficient topology for the distribution of power and control signals is proposed, utilizing the minimum number of cables. The modular architecture followed enables the future extension of this platform in a scalable way using Wireless Sensor Network (WSN) technology [9] or embedded WiFi technology. In what follows, a complete description of the LED lighting fixtures clustering topology is given and different alternatives for the distribution of power supply and control signals for the LLFs are presented, utilizing the proposed networking platform, namely the LEDWIRE platform.

## 2. LED Lighting Clusters, Topologies and Control Networks

In general, an LLF is comprised of the parts shown in Fig. 1. In particular, a printed-circuit board (PCB) is usually designed where the LEDs are soldered and referenced as the *LED Engine* (LE). At the top of the fixture normally lenses are integrated and which have been selected according to the lighting application's needs (e.g. lighting angles and light distribution shape). These additional lenses, called as the *secondary optics*, may be either positioned onto the LED engine or in the frame of the fixture.

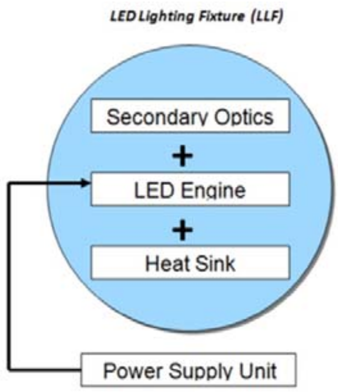


**Fig. 1.** The main parts of a LLF.

The heat sink is always placed at the bottom of the fixture. The heat sink must be in close contact with the PCB of the LED engine in order to release the temperature generated by the operation of the LEDs.

The power supply unit can be implemented either externally or onto the LED engine's PCB. The choice of the power supply implementation approach imposes particular implications regarding the power distribution topologies, as it is presented in the following paragraphs.

### 2.1. LED Lighting Clusters (LLCs)

The grouping of LED lighting fixtures in clusters is of substantial importance, especially for cost reduction and maintenance of the lighting fixtures' network [10]. For example, in office lighting applications where we encounter a unified space with many top (ceiling located) lighting fixtures that must provide a uniform light, it is normal to have the fixtures connected in clusters and controlled through one or two wall switches. Another application example, where clustering can be advantageous, is in architectural lighting of buildings and landscapes. In particular, for indoor or outdoor lighting of large wall surfaces, bars of LEDs are normally placed near the floor, in RGB or monochrome combinations. This type of lighting is also referred to as *wall washing*.

All these lighting applications impose strict synchronization of the lighting fixtures dimming level and mixture of colors for the successful implementation of the selected lighting scenario. In other applications that require linear illumination, the use of a single lighting fixture with a very lengthy linear LED array is not practical and, therefore, a cluster of interconnected lighting fixtures is normally selected. Furthermore, for LED lighting applications like in fountains and pools, the use of LED clusters which are placed under water and are controlled with various topologies, remains the best solution.

Additionally, the use of the clustering approach is very important to the agricultural domain. In greenhouses, the plants (e.g. flowers and vegetables) are organized in raws (clusters). As it has been reported in several studies, the control of the lighting inside the greenhouse can positively influence the growth of the plants [11-13]. Particularly, the aim is to provide supplemental lighting, at top or inter-lighting [1]topologies, controlling its period and spectrum.

### 2.2. LED Lighting Cluster Membership Attributes

The topologies which are applied for the distribution of power and control signaling to the LED lighting fixtures (LLFs) affect the way that grouping of LLFs in clusters is performed, as well as the network architectures that are utilized for remote control. The main advantages and disadvantages of the most commonly used topologies will be discussed in more detail in the next sub-section.

The procedure of the lighting fixtures' clustering relies on the similarities in the characteristics' profile of the class members of the particular cluster. According to particular applications specifications and requirements, all the cluster members must have similar characteristics. Among such characteristics are the luminance, the color, the color temperature, and, the time response. Obviously, all of the cluster members must have the same “On” or “Off” state. Other LLFs characteristics, such as the secondary optics (additional optical lenses), the physical dimensions, the power consumption level, and the power supply unit topology, are considered as non-critical for the cluster’s performance. Thus, regarding to the non-critical characteristics, each of the cluster members can have the same or different options compared to other members. The critical and non-critical attributes of the cluster members are presented in Table 1.

**Table 1.** Critical and non-critical attributes of the LLFs cluster members.

| Attribute Name | Critical Attibute |
|---|---|
| Luminance | Yes |
| Color | Yes |
| Color Temperature | Yes |
| Time Response | Yes |
| On/Off State | Yes |
| Secondary Optics | No |
| Physical Dimensions | No |
| Energy Consumption | No |
| Common Power Supply Unit | No |

### 2.3. Power and Control Distribution Topologies for LLFs

LED-based lighting designs impose strict requirements for a high-performance DC power supply, small form factor and low cost. In particular, when the LED engines are grouped in clusters, the distribution of the power supply and control signals must be implemented in an efficient way in terms of controllability and cabling.

Two schemes of DC power supply are commonly used for LLFs, based either on constant voltage (CV), or on constant current (CC). On the other hand, from the LLF PCB perspective, two topologies for power supply distribution are usually applied. In the first topology, the LLFs are designed without any power circuits onboard (just the LEDs are soldered onto the printed-circuit board) as it is depicted in Fig. 2, where the LLF must be powered by external constant current supply units. According to this approach, a string of LLFs can be supported with a constant current single power supply unit. However, all the LLFs must have identical power supply requirements. In the most of the cases, this design constraint entails limitations in the LLFs selection, i.e. the lighting fixtures must be of the same type, or even of the same manufacturer.

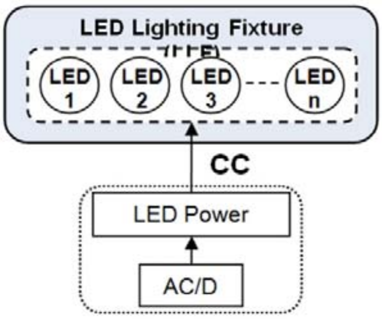


**Fig. 2.** LED lighting fixture (LLF) powered from an external constant current power supply unit.

In the second topology, the LLFs have embedded current LED drivers onboard (LDoB- LED Driver onboard), as it is depicted in Fig. 3. In this case, the embedded current drivers follow buck, boost, or buck-boost converting topologies, so as to ensure that the appropriate amount of current is provided using a relatively wide range of external DC input voltage. The aforementioned topology imposes increased cost for the LLF unit as well as decreased energy efficiency. However, it is confirmed in practice that it is the best solution for medium to large-scale lighting applications and especially for LLF networking. Furthermore, the retrofit concept for the home ligting, according to which, a LED engine with the AC-to-DC power unit integrated into the same lighting bulb, is directly placed in the existing AC-powered bulb holdings. So, the lighting industry seems to be attracted by the approach of the LDoB.

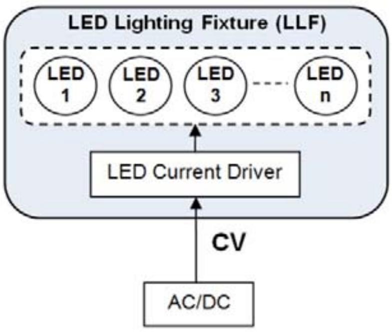


**Fig. 3.** LED lighting fixture (LLF) with LED power driver onboard (LDoB architecture) and external constant voltage power supply unit.

Another distinct advantage of the LDoB architecture is its inherent ability for LLF self-protection against over-heating and power problems such as broken, as well as, short circuits. Recent advances on solid-state lighting standardization [14] put a priority on the selection of the LDoB topology from the world-wide lighting industry in order to provide the necessary flexibility in power supply.

Based on our experience, gained from extensive LED lighting fixtures design for the last ten years, for small-scale lighting applications (e.g. installations with less than 10 LLFs), it is better to use external constant current supply units and LED engines without LDoB. For medium to large-scale lighting applications, it is more cost effective to use constant voltage supply units with LDoB. The cost reduction in this case is up to 20 %. The application-level cost also decreases by following a string power supply connection scheme, that is, the replacement of several separated standalone LLF power supply units by just one with higher power capability. In Fig. 4, the utilization of constant voltage power supply units connected to LLFs with LDoB is illustrated, following both dedicated and string power distribution topologies [15].

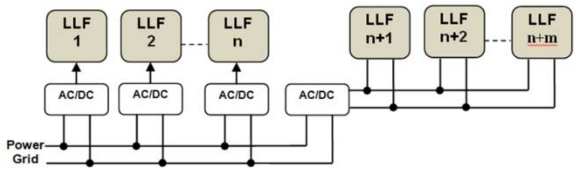


**Fig. 4.** Constant voltage power supply in dedicated and string power distribution topologies.

For color Red-Green-Blue (RGB) lighting applications, three additional control channels are used, for mixing the primary colors in every LLF. Therefore, for these applications the installation complexity and cost increase, while the flexibility is reduced. Fig. 5 depicts the power supply topology for the case of an RGB LLF. As it is shown in Fig. 5, a discrete power supply unit is used for every one of the three colors.

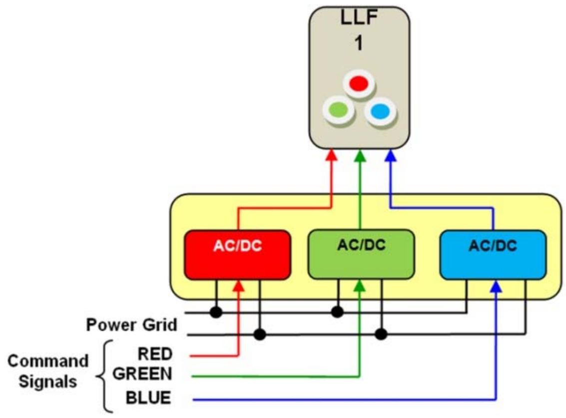


**Fig. 5.** The power supply topology for a RGB LLF.

In the cases where the RGB channels are directly controlled from the external power supply units, through the incorporation of various power electronics switching circuits, long cables with significant current tolerance have to be used. Apart the increased cost of such cables, this topology suffers also from high electromagnetic interference (EMI). Additionally, any future modification is limited due to the cabling inflexibility [16]. Regarding the clustering of RGB LLFs, Fig. 6 shows the power distribution topology. The power cables per color are routed to every LLF. The color mixing commands are given through discrete command signals at each one of the three power supply units. For medium to large-scale applications such a clustering topology impose certain limitations regarding the flexibility, the cost, and the maintenance of the lighting system.

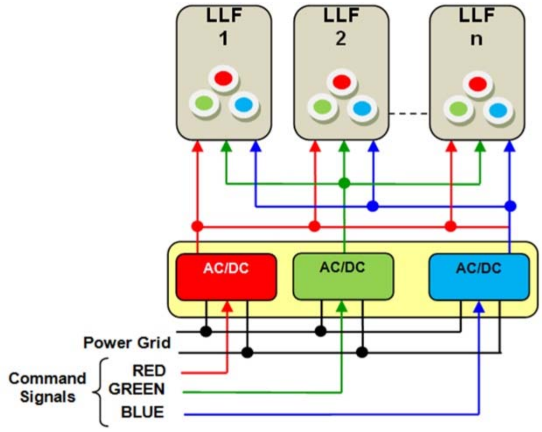


**Fig. 6.** RGB LED lighting fixtures (LLFs) clustered according to the drive of each particular color.

As an alternative to the above traditional approach, a bus architecture for color control is proposed by many engineers. According to this, the LLFs should facilitate the networking function guided by a local microcontroller unit (MCU), through which they can get the color mixing commands (see Fig. 7).

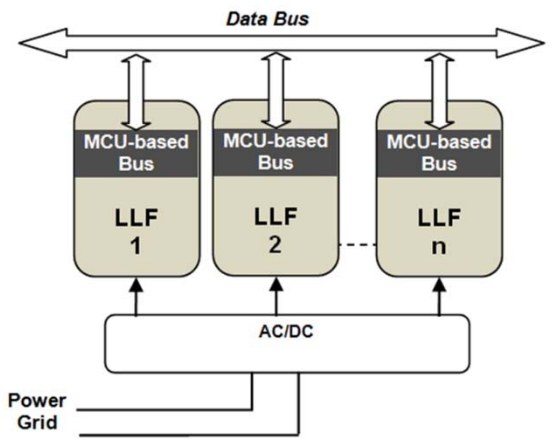


**Fig. 7.** RGB color control topology for a cluster of LLFs based on the bus topology.

Regarding the power supply topology, any of the CV and CC topologies presented above can be incorporated. According to the bus approach, the large number of RGB high power signal cables is replaced by two bus signal lines (low power cables). For realizing this topology, a microcontroller must be embedded in every LLF that integrates the necessary networking technology and processes the lighting commands for the generation of the appropriate RGB control signals for the LED engines. As it has already mentioned, BMS extensions, like DALI and DMX512, can be utilized for such applications, enabling the digital control of the RGB channels for each LLF. However, these extensions rely on communication standards like EIA-485 for the physical layer, which use differential signaling for long ranges resulting to a large number of bus cables.

## 3. LEDWIRE Networking Platform for Lighting Applications

In this section we present the proposed LEDWIRE networking plaform. The most significant novelties of this proposition lies firstly on the adoption of the Local Interconnect Network (LIN) as the bus through which a cluster of LLFs can be controlled, and secondly, on the ability of bridging the LIN-based LLFs with other wireless or wired networking protocols. Based on these contributions, we provide a flexible, reliable and long-life maintainable solution for lighting applications where there is the need either for demanding time synchronization, or for convenient and low cost in clustering. In the following subsections, we describe the details of foundation of the LEDWIRE, i.e. the physical layer of the bus, the facilitation of LLFs clustering, and the proposed data protocol structure, etc.

### 3.1. The Physical Layer of the Bus

In lighting applications where the need for bidirectional communication and control is of substantial importance, the LLFs must have an embedded microcontroller supporting a variety of serial bus communication protocols. As it has already mentioned, several wired communication protocols have been used for lighting control like DMX512, DALI, and EIB-KNX at the application level [17]. In particular, the DMX512 protocol has extensively been used for entertainment applications, with most realizations presenting difficulties in programming, limitations in communication and networking capabilities. Moreover, such realizations are normally based on proprietary solutions and are utilizing a large number of cables. The LEDWIRE platform has been designed as a low-cost lighting control network that allows for the simplicity of the concept of the DMX512 protocol but, on the other hand, ensures two-way communication and, at the same time, with less power and communication cables. An optimal bus topology for distributing power and RGB control signals in a LLF cluster can be realized using the

LDoB approach and a wired communication bus. For the implementation of the associated wired bus, the CAN and LIN wired bus standards, which are used in automotive applications, have been considered respectively. The CAN bus is more complex and more expensive than the LIN bus, and it is more appropriate for higher bandwidth applications [18, 19]. For these reasons the LIN bus is ultimately selected. Its simplicity and its low cost of implementation, are mandatory issues for medium to large-scale LLF deployments. The LIN standard specification covers the definition of the protocol and the physical layer, as well as the interfaces for the development tools and the application software [20]. Its widespread adoption from the automotive industry has resulted to the manufacturing of extremely low cost LIN drivers for LIN master and slave devices in form of integrated circuits. The communication protocol is based upon the Universal Asynchronous Receiver/Transmitter (UART) data format that implements a single-master/multiple-slaves communication interface topology. The main characteristics of the LIN bus can be summarized as follows:

- Low-cost single wire implementation;
- Single master;
- Self-synchronization without a quartz or ceramic resonator in the slave nodes;
- Deterministic signal transmission with signal propagation time computable in advance.

An additional advantage of the LIN bus is the extended range of power supply input with single polarity, instead of the more complex power supply distribution of the EIA-485 standard. In Table 2, the key parameters are presented for the EIA-485 and the LIN buses [21].

**Table 2.** Comparison between EIA-485 and LIN protocols.

| Parameter | EIA-485 | LIN |
|---|---|---|
| Bus Length (m) | 1200 | 40 |
| Number of Bus Wires | 2 for half duplex<br>4<br>4 for full duplex | 1 |
| Voltage Levels (V) | -7 to +12 | -27 to 40 |
| Max. Number of Nodes | 32 | 16 |
| Cost | Low | Very Low |
| Driver Supply Voltage | +3.3 V up to +5 V | Up to +27 V |
| DC/DC converter | No | Yes |
| Baud Rate | > 10 Mbit/sec | 20 kbits/sec |
| ESD/EMI immunity | Normal | High |
| Under-Voltage Protection | No | Yes |
| Over-Temperature Control | No | Yes |
| Short-Circuit Protection | Yes | Yes |
| Installation/Wiring | Difficult | Easy |
| Special Wires | Twisted Pairs | No |

We have compared the LIN bus with the EIA-485 standard, since the latter is the physical layer of the DMX512 and other traditional protocols for lighting. Accordingly, a number of advantages for the LIN bus over EIA-485 are evident from Table 2, such as the simplicity, the integration of a DC/DC converter in the LIN driver, the wide range for the supply voltage and the extremely low cost. It is clear that LIN bus is fully compatible with all the 12 VDC or 24 VDC power operated commercially available lighting fixtures. This means, that the voltage level of the bus data signal can be easily tied at the existing power supply signal, e.g. at 12 VDC. Hence, there is no need to have a secondary power supply units for driving the bus as it is happening in the case of using any pf the EIA-485-based protocols. For these reason the LIN bus was chosen to be used as the physical layer of the LEDWIRE networking platform.

### 3.2. LED Lighting Fixtures' Clustering Based on LEDWIRE

In the proposed platform, the wired control of remote LED lighting fixtures is based on the LIN bus. More specifically, the platform comprises a LIN master module with gateway capability, namely the LEDWIRE Master, and a maximum of 15 individual addressable LLFs acting as LIN slaves, namely the LEDWIRE Slaves. Each LLF can be implemented with a LED engine of various topologies (string, parallel or combined). The master module communicates with the LLF slaves using appropriate messages through the local LIN bus (see Fig. 8).

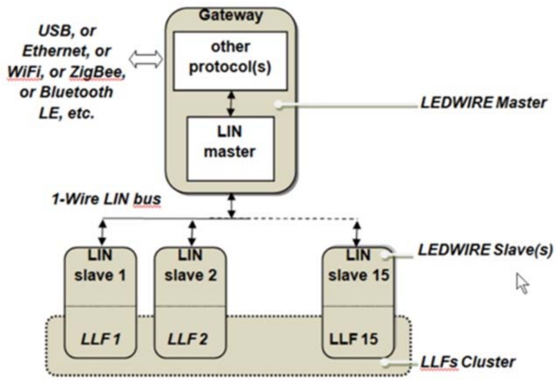


**Fig. 8.** LIN master communication with LLFs LIN slave.

The LEDWIRE Master module specifies certain LED engine parameters in the slave modules, as the state (on/off), the desired lighting level (dimming), as well as the required color mixing. For each LEDWIRE Slave, the lighting parameters are transmitted as commands over the control bus and are translated to specific timer values for the generation of appropriate pulsed-width modulated (PWM) waveforms. Four

PWM waveforms (for the Red, Green, Blue and White channels) control the individual LED engines for the required lighting level and color mixing scenario. It is also worth noticed that the termination time is not affected from the transmission of control messages in the LIN bus, since it has deterministic behavior and the delays added can be estimated in advance. This is very significant for cases of lighting fixture extension using strings of LLFs, which are commonly controlled by sharing the same LIN address and which must be perfectly synchronized for the particular lighting scenario realized (i.e. negligible jitter for the execution of the lighting scenario).

### 3.3. Data Protocol Structure Performance Considerations

In a typical lighting application, the **master** of the LEDWIRE network always initiates the communication by transmitting the associated commands to the members of the lighting cluster. For the message based API (Application Programming Interface) that we have implemented, it has been decided that the minimum information content for lighting applications must include data fields for the *Red*, *Green*, *Blue* and *White* channels, as well as data for lighting intensity operations as *Fade* (FADE In/FADE Out for intensity control) and *Scen* (Scenario). Therefore, we have allocated one byte for each of the aforementioned command data fields, thus enabling true-color (24-bit color depth) lighting applications and white light saturation (if White LEDs exist on LED engine). The LEDWIRE Master transmits the command data to all the LEDWIRE Slaves. The transmission to all the LEDWIRE slaves is called Global Command according to the LIN standard ver. 2.1 (Fig. 9a). In the LEDWIRE platform, it is used for the realization of a LIN broadcast scheme, that is, for sending a frame from the LIN master to all LIN slaves. The Global Command is very important for lighting applications, since, through it, the synchronization of all members of a lighting cluster can easily be assured.

With respect to the Global Command, the LEDWIRE Master realizes a specific frame structure, which starts with a *Break* field followed by a *stop* bit, a *Synch* field, a *Protected Identifier* field *(PID)*, the *data* field (six bytes payload for the LEDWIRE network plus two null fields reserved for future use), and, finally, one byte for the *Checksum* field (CS). Except for the *Break* field, all the other fields have 10 bits each (one start bit plus eight data bits plus one stop bit). The structure of the Global command is given in Fig. 9a, where the *Break* and *Synch* fields, with which each frame starts and ends, are not depicted. The *Break* field is a low-level state signal with duration of thirteen (13) bit periods and is terminated with a Stop bit, while the *Synch* field has duration of ten (10) bit periods. The structure of the *Protected Identification* field (PID) is given in Fig. 9b.

The *PID* field carries addressing information for the LIN bus. The *ID0-ID3* bits define the identity of the slave addressed by the master. Address $0000_b$ is reserved for the Global Command, while the remaining combinations are used for independently addressing up to fifteen (15) LIN slaves of LLF cluster. The bits *ID4* and *ID5* determine the number of the data bytes in the transmitted frame, while bits *P0* and *P1* are parity bits

In the developed message-based API, a LLF Status Command was realized, on the basis of which the LEDWIRE Master can acquire the status of a LLF in a lighting cluster. When the LIN master executes this command, it transmits through the LIN bus the appropriate data, which comprise a *Break* field, a *Synch* field and a *PID* field with the identity of the slave that must be addressed. Subsequently, the addressed slave node responds by sending the LLF Status data, that comprise, as it is illustrated in Fig. 9c, the *TEMP* field for the temperature, the *LIGHT* field for the brightness level measured, the *MOTION* field that contains motion data from an embedded occupancy sensor and the *STATUS* field that contains information about the LED engine's embedded microcontroller operation parameters (e.g. firmware version number, total hours of operation, errors report codes, etc.). In cases where there is no occupancy, light and/or temperature sensors onto the LED engine, then the relevant status fields are filled with zero values. The *CS* field is the checksum with which the slave's response is terminated.

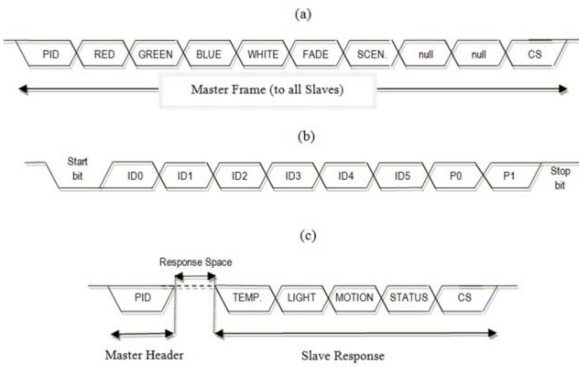


**Fig. 9.** The Global Command (a), the Protected Identifier (PID) field (b), and the Status Command followed by a Slave's response (c).

The status information acquired from the LLFs can be exploited to reach energy reduction in lighting applications in a building environment [22, 23]. Thus, the LEDWIRE network can enable the development of intelligent ambient applications in buildings [24].

Concerning the LIN bus activity in the LEDWIRE platform, the LIN master initiates a command session by sending a lighting application command in the LIN bus. With the LEDWIRE platform can be achieved can be achieved the maximum time synchronization following the Global Command. The LIN specification standard determines a maximum baud rate of 20 kbps. Accordingly, we have selected a baud-rate of 19.2 kbps, which is supported from the UART serial peripheral of the microcontroller used. This data rate, combined with the light-weight data format structure, ensures that the dynamic response of the LLFs will be always faster than the 100 Hz that is the limit of the human visual perception.

## 4. Implementation of a LEDWIRE Network Platform

LEDWIRE Master and Slave nodes can be implemented using either microcontrollers with an integrated LIN driver, or separated microcontroller and LIN driver integrated chips. The final choice depends on the requirements imposed by particular applications for the physical dimensions of the control and communication boards. We selected the second choice because it allows for greater flexibility in terms of power supply distribution. In order to limit the form factor of the nodes we used low pin-count microcontrollers, and electronic components of surface-mounted technology (SMT). For the microcontrollers we adopted the Programmable-System-on-Chip technology (PSoC). In particular, we used the 8-bit PSoC microcontroller CY8C21123 from Cypress Inc. This is an eight pin reconfigurable device (two pins for power supply and six input/output pins). Its six I/O pins can be configured to function as digital or analog inputs and outputs, timers, comparators, pulse width modulation channels, as well as serial communication buses as $I^2C$, SPI and UART, respectively. This microcontroller implements up to two different UART peripherals and due to this fact is suitable to support the design of both the master and slave nodes. Fig. 10 demonstrates the simplicity of the proposed implementation. In the LEDWIRE Slave node case, the microcontroller is configured to have one UART peripheral for interfacing with the LIN driver, and four distinct 8-bit PWM channels for controlling the color mixing of RGBW LED engines (Fig. 10a). Similarly, in the LEDWIRE Master mode implementation, the microcontroller has been configured to have one UART peripheral for the LIN driver interface, and another serial interface for the communication with various communication protocols' embedded modules.

As a proof of concept of the implementation of a gateway in the LEDWIRE Master device, we choose to implement the communication with a IEEE802.15.4/ZigBee module for wireless sensor networking applications (Fig. 10 b).

The AT6625 LIN driver from Atmel Inc. has been adopted for use in both the master and slave nodes. Fig. 11 illustrates the LED engine we designed and implemented for our experiments. It is based on the XLamp MC-E Color LED from CREE Inc. This is a four-core, common lens, Red-Green-Blue-White (RGBW) power LED device.

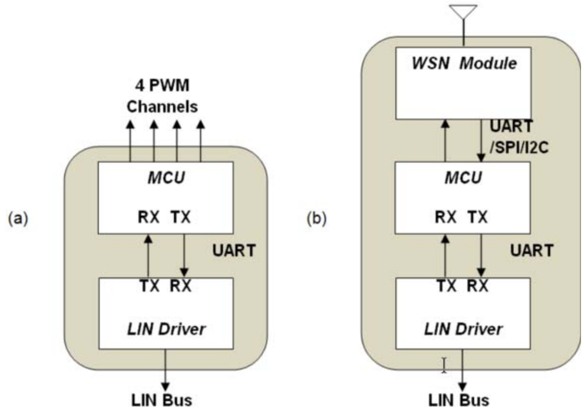


**Fig. 10.** (a)The LEDWIRE Slave node, (b) the LEDWIRE Master node.

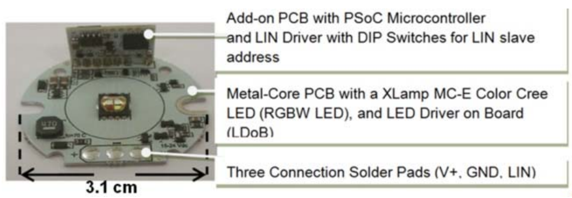


**Fig. 11.** The LEDWIRE Slave implementation onto a LED engine.

In Fig. 12 the LEDWIRE Master node is depicted. It is a small form factor printed circuit board with LIN bus driver, a 8-pin PSoC microcontroller, and a ZigBit IEEE802.15.4/ZigBee module from Atmel, Inc. operating at the frequency band of 2.4 GHz. Each LEDWIRE Master can control a cluster of up to 15 different LLFs. Each LLF may consist of several LED engines. Instead of ZigBee wireless communication protocol, other wireless protocols, such as the WiFi and Bluetooth, or wired protocols such as Ethernet, could also be used by the LEDWIRE Master gateway device. With this versatile architecture, wide LLF clusters network can be easily implemented and managed.

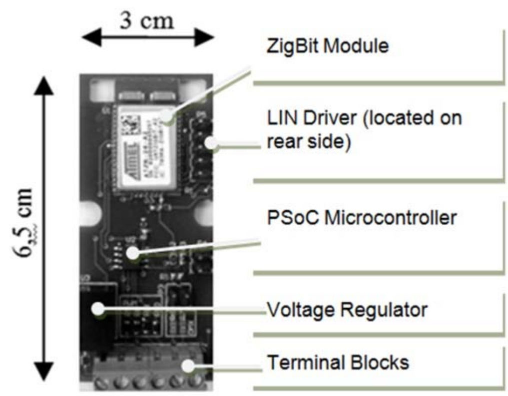


**Fig. 12.** The front side of the LEDWIRE Master node with ZigBee gateway capability.

Additionally, a suitable software GUI (Graphical User Interface) based on LabVIEW, depicted in Fig. 13, has been developed for testing the LEDWIRE network. By this software GUI, up to six different LLF clusters can be controlled. For the interface with the personal computer at which the GUI is running, a LEDWIRE Master node has been used. Specifically, the UART port of the LEDWIRE Master node is routed to a UART-to-USB converter dongle.

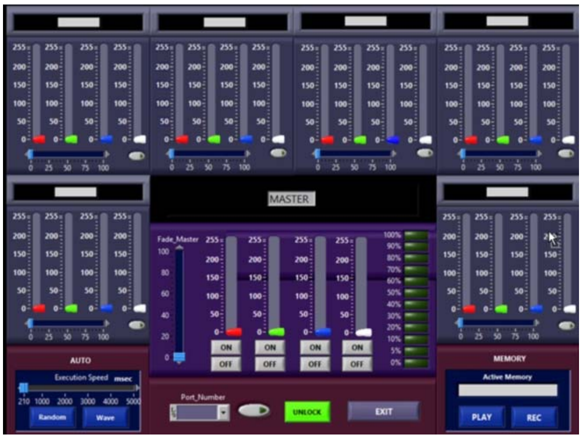


**Fig. 13.** The LabVIEW-based software GUI for LEDWIRE network platform testing.

## 5. Conclusions

A modular platform has been reported for the networked control in LED lighting applications, where the clustering of lighting fixtures is important and the synchronization between the LED engines imposes strict requirements for data communication delays. The proposed platform is a complete solution for the control of LED lighting clusters and constitutes a unified approach for the distribution of power supply and control signals of the LED engines using the minimum number of cables. Moreover, the requested lighting scenarios are executed in a simple manner in the LED engines, by using the embedded microcontroller and its networking capabilities. The high level commands at the application layer are transmitted through the LEDWIRE network to the LFs; embedded microcontrollers, wherein they are translated and the requested scenario is executed at each particular LED engine. Following this approach, the data traffic is kept to the minimum. Regarding the LIN-based embedded wired network, the minimum latencies for the reception and execution of lighting scenarios from the LED engines are achieved. These latencies are always below the minimum threshold imposed by the human vision persistence time for a successful lighting application. Concluding, the proposed approach of the LEDWIRE network allows for bidirectional communication, control and synchronization in a cluster of LLFs. Also, the LEDWIRE supports lower complexity than Ethernet networking or DMX solutions, and it ensures lower cost of implementation, compared to WiFi or WSN "full topology" implementations where each LLF must integrate its own wireless networking platform capability.

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ADVANCES IN SENSORS: REVIEWS 1

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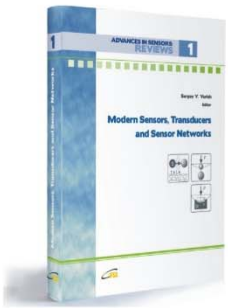

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