Remote Street Lighting Management System with Low-Rate Wireless Personal Area Networks

Francisco Domingo Pérez
Department of Computer Architecture, Electronics and Electronic Technology
University of Cordoba, Spain

***Abstract*—The project entitled "Remote Street Lighting Management System with Low-Rate Wireless Personal Area Networks" is an application of the new wireless communication technologies to the current street lighting system. The project goal is the implementation of a wireless prototype to be used in a remote management system. The prototype is able to control electronic ballasts in order to perform dimming in street lamps, it is also able to control any single light point individually and get some lamp parameters (like actual dimming level, power failures, etc.). The dimming functions allow us to save energy consumption, whereas the individual light point wireless monitorization and control allow us to save in installation and maintenance cost. When it comes to implementing the remote management system we needed a lighting control protocol and a communication protocol. The selected lighting control protocol has been DALI (IEC Standard 62386), since it is a very simple and easy to implement protocol (only two control wires) and it allows us to dim the lamps' light level and also to get a feedback from the lamps. As for the communication protocol we have chosen IEEE 802.15.4, since it is a well-standardized low-energy consuming wireless protocol. This paper shows how the two standards were applied to create the prototype.**

I. Introduction

We start from the fact that street lighting is one the most energy consuming services in a city, reaching heights between 5 – 60 %, in consonance with the city's size and the services the city's government is able to offer [1]. In accordance with several studies carried out by some agencies and companies [2], [3] there exists a huge potential to save energy consumption by investing in new technologies and switching the older lighting. On the other hand, as part of the electrical power grid, the new emerging Smart Grid paradigm not only requires a control, but also to monitor and perform a smart dimming according to demand and need of the end user. This last concept makes necessary the use of a two-way communication protocol, either full or half duplex, in order to know the current set dimming value and some other parameters about both ballast and lamp.

There are some traditional energy saving techniques like total or partial shutdown, but those techniques involve a reduction in the uniformity of light intensity and moreover, they have a very negative impact on lamp life expectancy, increasing maintenance and replacement costs.

As for achieving a reduction in the energy consumption there are some recommended measures [4]. Since street lighting is only active at night hours, one of the proposed measures is the adoption of special tariffs for the street lighting. Another measure is the application of a standardized classification of streets and roads which regulates the light level. In case of Spain, Spanish Order in Council 'RD 1890/2008' deals with energy efficiency in street lighting. More technical measures involve the lighting duration control, making use of photocell or astronomical time relays. The most innovative measure is the application of smart electronic dimming ballasts which are provided with a two-way communication lighting control protocol.

There also exist remote management systems which allow an individual remote control and monitoring of any single light point. As it was previously stated, for both monitoring and control it is necessary to use a bidirectional protocol. Toward the implementation of the remote management system only two elements are necessary, the lighting control protocol and the communication protocol.

Taking into consideration the previous comments, this paper focuses on the development of a wireless lighting control prototype to be used in a remote management system for street lighting. The following sections describe and justify the chosen standards (DALI and IEEE 802.15.4) for the lighting control and communication protocols. A description of the implemented prototype is also presented along with some comments about laboratory tests.

II. Standards Selection

A. *Lighting Control Protocol*

When it comes to selecting the lighting control protocol there are two mandatory requirements it must satisfy:

1) Dimming functions
2) Bidirectionality

Other interesting but not mandatory characteristics are the protocol standardization and the simplicity of the control implementation.

The main lighting control protocols are [5]:

- 0-10V
- X-10
- AC phase control dimming

- DMX512
- LonWorks
- BACnet
- DALI

0-10V protocol makes light output vary with control voltage; it is approved by ANSI as standard E1.3-2001. It is a one-way communication protocol, so ballasts cannot provide a feedback of the lamp. The standard has not been adopted by ballast manufacturers, so ballast's behavior among different manufacturers is not consistent.

X-10 uses power line wiring for signaling and control. It has been adopted by several manufacturers as a well-established standard. However, its lack of bidirectionality along with the reduced command set (it cannot even send a direct dim level) make it useless for our remote management system.

AC phase control dimming has not any specification or standard, it has the same disadvantages than 0-10V. It is not recommended to be used in a large installation due to power quality problems, since phase-cut technology involves power factor imbalance and harmonic distortion.

DMX512 is a standard for digital communication which is commonly used in theatrical lighting control systems. It is not supported by ballast manufacturers, since its control circuit is too much expensive to be included in the ballast design. In addition, it is a one-way communication protocol, so it cannot be used in a remote management system.

LonWorks is recognized as a global standard for building automation and it is supported by many control device manufacturers. However, its installation is very complex and it is very expensive for applications with a large number of points of control. Consequently, it has not been adopted by major ballasts suppliers.

BACNet is an open protocol, recognized as a global standard for home automation control devices. It was designed as a HVAC protocol, although lighting protocol attributes are going to be adopted into the standard. As LonWorks, it is very expensive for applications with a large number of nodes such as street lighting and its installation is not simple.

DALI stands for Digital Addressable Lighting Interface. It is a two-way communication protocol; ballasts can send operational parameters and some other information concerning both lamp and ballast, like ballast or lamp failures, status, etc. It also allows performing dimming, using direct level commands (in which the desired dimming level is sent) and indirect level commands (where a dim up or dim down command is sent and the ballast sets the lamp arc input power to the next or previous step). DALI control circuit is very easy and cheap to build, using a microcontroller we only need to design a voltage adapter circuit. These characteristics make DALI a suitable option for the street lighting control system.

DALI was defined in annex E.4 of standard IEC 60929 as control by digital signals of electronic control gears (controllable ballasts). The standard is only applied to electronic ballasts for tubular fluorescent lamps. It first version dates from 1990, after two amendments (1994 and 1996) digital signal control of electronic ballasts was introduced in 2003 [6].

This part of the standard was modified by IEC 62386 in 2009. The IEC 62386 series consist of two parts, the first part is the 62386-1xx (general requirements [7], [8]), which is divided in two parts:

- IEC 62386-101:2009: General requirements. System
- IEC 62386-102:2009: General requirements. Control gear.

The second part is composed of the IEC 62386-200 series, which are particular requirements for control gear, they are applied to fluorescent, incandescent, discharge, emergency, etc. lamps.

Section III explains how the DALI protocol is applied.

B. Communication Protocol

Our intention is to create a network in which any light point of the street lighting system is a node. Since lamp posts separation is only 20-30 m and we do not need to transmit large data packets we can use wireless personal area networks (WPANs). The main WPAN communication protocols are:

- Bluetooth (IEEE 802.15.1) [9]
- IEEE 802.15.4 [10]
  - ZigBee [11]
  - 6LoWPAN [12]

Bluetooth only uses a reduced number of network nodes and moreover, the energy consumption is bigger than IEEE 802.15.4. On the other hand, IEEE 802.15.4 deals with low-rate wireless personal area networks; its aim is the standardization of the two lower layers of OSI protocol stack (physical and MAC layers). As it does not define the network layer it does not include any routing mechanism, so the only available network topologies are star and peer-to-peer. This lack of routing mechanism becomes a problem in street lighting, since there is a big presence of obstacles like buildings and we need to cover a wide area with the network. ZigBee implements the network and application layers over the physical layer and medium access control (MAC) defined by IEEE 802.15.4. ZigBee enables IEEE 802.15.4 to form mesh, tree and cluster networks. On the other hand, 6LoWPAN defines encapsulation and header compression mechanisms that allow IPv6 packets to travel over IEEE 802.15.4 networks. Our street lighting application does not need to interface with IP devices and the packet size is very small. Taking into account these characteristics ZigBee can achieve better performance in such an application [13]. The main ZigBee disadvantage is that it is not an interoperable protocol among different manufacturers. As we needed at least a tree network topology we opted for the implementation of our own network layer based on ZigBee working with an IEEE 802.15.4 network. The development of our own ZigBee-based routing mechanism provides us with a proprietary network layer which can be implemented with IEEE 802.15.4-compliant devices from several manufacturers, achieving interoperability.

The next section describes the materials we used during the project and how the standards were applied.

III. System Components and Methodology

A. Components

The selected wireless module has been the DZ-ZB-Gx, manufactured by DiZiC [14]. The module integrates the STMicroelectronics STM32W108 system-on-chip, which integrates a 2.4 GHz, IEEE 802.15.4-compliant transceiver, an ARM Cortex-M3 microprocessor and other peripherals to design 802.15.4-based systems. Apart from being 802.15.4-compliant, DZ-ZB-Gx has been selected because it has a RF power amplifier, achieving a Tx power of +20 dBm (100 mW). We have taken this issue into consideration because the street lighting application may require a strong RF penetration, in order to transmit successfully inside a lamp post or through buildings.

As for the DALI ballast, we have chosen a high intensity discharge (HID) lamp ballast with DALI control interface. We have used HID lamps because most lamps used in street lighting are high pressure sodium (HPS) lamps. Ballasts used were OSRAM Powertronic® PTo DALI 70/220-240 3DIM with Philips SON 70W/220 I E27 1CT. Ballasts are able to perform dimming from 60 % to 100 % of the lamp input power.

B. Methods

Fig. 1 shows the block diagram of the remote management system. The operator controls the light points with a PC SCADA interface. A DZ-ZB-Gx is connected to the PC through the serial port acting as a PC-802.15.4 gateway. Using this gateway we can send data packets to the 802.15.4 transceivers which are mounted in every light point. The microcontroller unit (MCU) processes the data packet and sends the corresponding DALI command to the DALI ballast. The MCU can also receive a response from the ballast regarding the actual dimming level, lamp status, etc.

DALI is a master/slave protocol; the master (a DALI controller) sends messages to any slave device (DALI ballast) in the system. Those messages consist of an address field and a command field. Using the address field we can control any single ballast individually. A message sent by the master is called a forward frame; it consists of 19 bits at 1200 bps using a bi-phase encoding (Manchester Differential). The first bit is a start bit, the next 8 bits are the slave address and the next 8 are the command. There last two stop bits are not in Manchester code. There are query commands that makes the ballast enter into active mode and send a backward frame to the master, this is an 11 bits frame with the same characteristic than the forward frame, one start bit, 8 bits with the data response (ballast status, actual dimming level, etc.) and two stop bits. In the address byte of the forward frame only six bits are used for individual addressing. The address byte has the following structure (each letter represents a single bit): YAAAAAAS, where Y takes the value '0' when a short address is used and the value '1' for a group address or broadcast; A is the significant address bit and S is '0' when the command is a direct dim level command (a dimming value) or '1' when it is a DALI command. A master can only have 64 slaves as it can only address 64 directions (six A bits).

DALI is mainly used in home automation since it can only control 64 ballasts. It cannot be used the same way in street lighting due to that reason. Our approach consists of implementing the DALI master controller in an IEEE 802.15.4-based wireless network. We have the DALI ballasts as slaves and the nodes as masters. Nodes are controlled by the PAN coordinator, which is attached to a PC host with the SCADA interface. The coordinator controls any DALI ballast using the node MAC (EUI-64, 8 bytes) or network (2 bytes) addresses instead of the DALI slave device short address, expanding the number of connected devices. When the coordinator message reaches the addressed node the frame is sent from the node to the ballast, one node is only connected to one ballast, so the address byte of the forward frame can be let in broadcast mode (1111111S), allowing us to forget about DALI addresses and to overcome the 64 devices constraint.

A voltage adapter circuit from microcontroller to DALI has

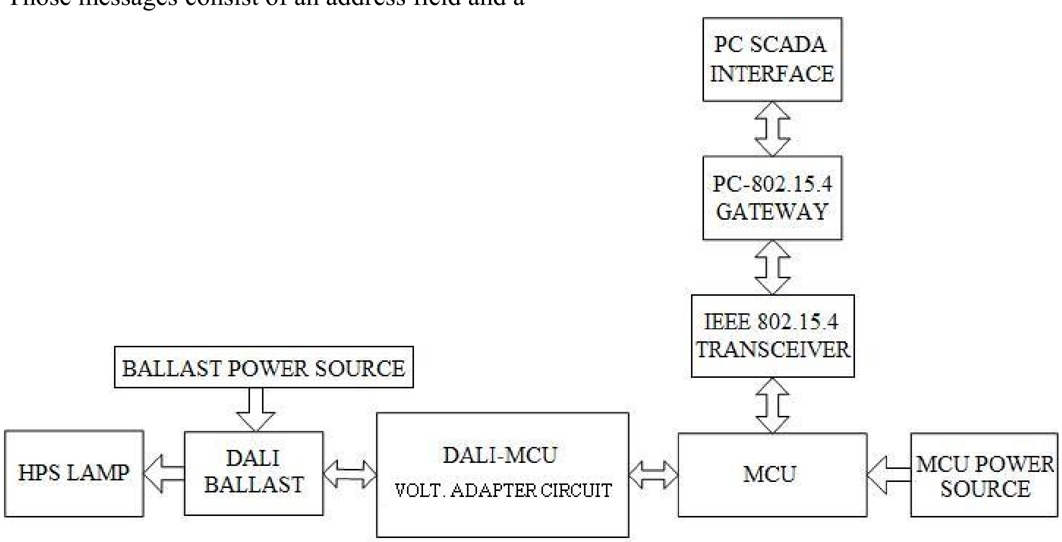


Fig. 1. Street lighting remote management system's block diagram

been built. A DALI control interface must consider a voltage between 9.5 V and 22.5 V a logical high signal, whereas a voltage in the ±6.5 V interval is taken as a logical low signal. As the microcontroller digital outputs are 0–3.3 V it is necessary to design a voltage adapter circuit to take the 3.3 V to the corresponding interval of a high signal. Fig. 2 shows this circuit. PC1 is set as an output, whereas PB0 is an input.

Optocoupler U1 deals with the transmission from the node to the ballast, whereas U2 is left in charge of receiving the backward frame when a query message has been sent. PC1 is put in high to transmit a high signal level, so the LED diode in U1 is not biased and its phototransistor is open, hence DALI terminals are in a high logical state. When PC1 is configured as a low level the LED is biased and the transistor is closed. After receiving a query frame the ballast enter into active mode and response with the backward frame, this time a high logical level from DALI terminals turns into a low level in the microcontroller digital input PB0. The microcontroller program is responsible of inverting this value when reckoning the ballast answer. An example of DALI command can be seen in Fig. 3. A query status command has been sent, the figure shows both forward and backward frames and it explains what any bit means.

The system is able to send any direct dim level and DALI command from 0 to 255, this command set includes indirect arc power level commands, query commands and configuration commands. Commands beyond 255 are not implemented, since they are used to generate DALI short addresses and we do not need them.

After developing the DALI master with wireless nodes we

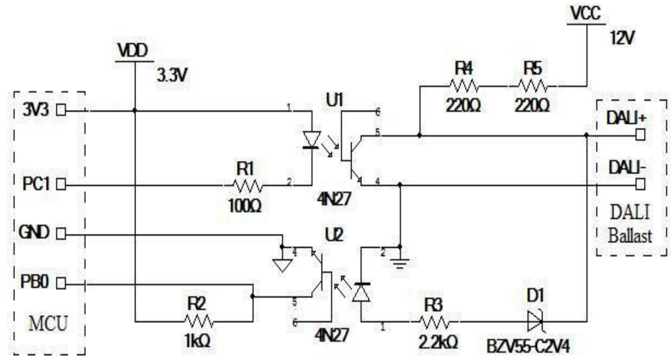
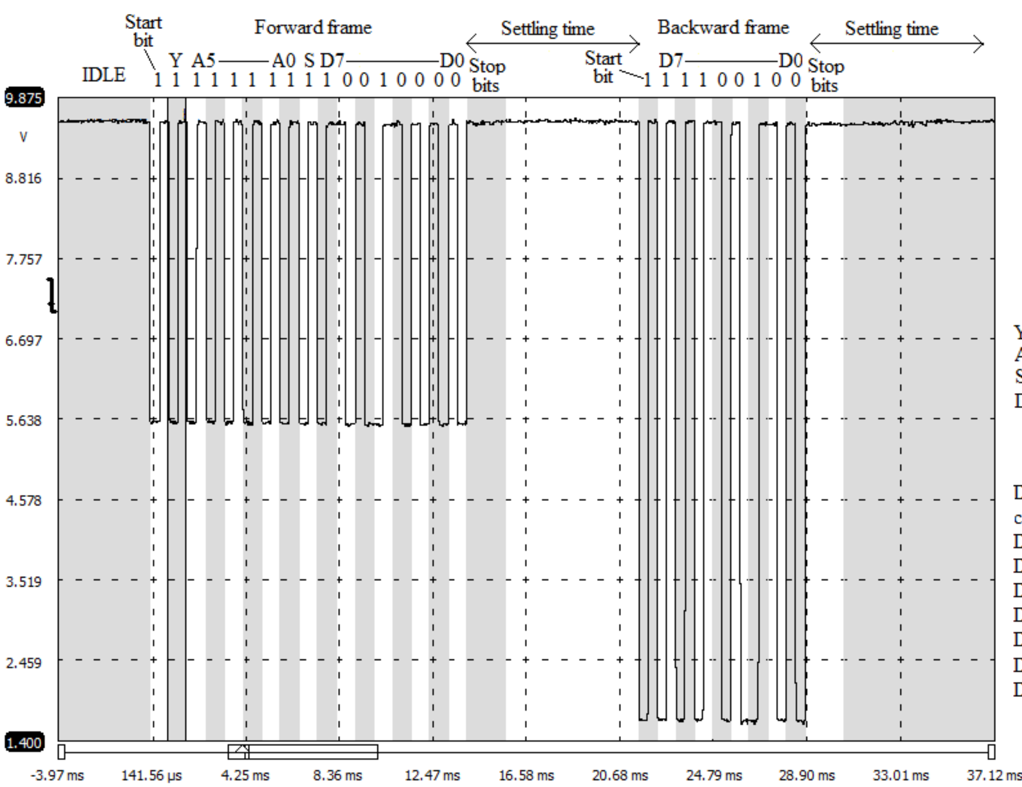


Fig. 2. Voltage adapter circuit

focused on the ZigBee-based network layer. In order to reach any light point we need a tree or mesh topology. As a tree topology is easier to design we chose this one. The coordinator, which is connected to the PC, is the root of the tree. The coordinator acts as a parent device and is associated to other devices in the network, called children. We have considered that any child can act as a router, i.e. it can act as a parent device too. The tree topology has been designed implementing ZigBee address allocation mechanism. This mechanism is called *default distributed address allocation*. We set the maximum length of the tree and the maximum number of children a parent can be directly associated. Address number 0 belongs to the coordinator, the address of the rest of the devices are determined with a function which uses the network maximum depth, the maximum number of children per parent and the depth of the device in the network. When this function becomes 0 we have reached the end of the



Domain	Time
Left cursor	767,291 µs
Right cursor	1,591 ms
Difference	833,334 µs
1/Difference	1.215 kHz

Forward frame
Y = 1 => Group / broadcast address
A(5:0) = '111111' => Broadcast
S = 1 => Command
D(7:0) = '10010000' = 144 => Query status

Backward frame
D7 = 1 => Any reset state or arc power command received since last power on
D6 = 1 => Missing short address
D5 = 1 => Control gear is in reset state
D4 = 0 => Fade is ready
D3 = 0 => No limit error
D2 = 1 => Lamp ON
D1 = 0 => No lamp failure
D0 = 0 => Control gear OK

Fig. 3. DALI *query status* command, forward and backward frames

network. Once the addresses are allocated, the network address of the selected node is reckoned with another function. This function only needs the origin address, the destination address and the previous function. References [15] and [16] explain this address allocation method and the mathematical functions.

Nodes' deployment is static and known, so we can use the MAC address (EUI 64) of any node to identify its position in the street lighting system. The coordinator, when it is discovering nodes and addressing the network addresses with the previous method, saves every MAC and its associated network address. The user only needs to know which MAC address corresponds to a light point, the software implemented in the microcontroller will do the rest and the packet will travel through the tree and reach its destination.

Finally, a SCADA interface (Fig. 4) has been implemented using LabVIEW. By using this interface the user is able to create the tree network and send a DALI command or direct dim level to the selected node. Direct dim levels set the lamp's arc input power and not the light intensity level. The interface only contemplates the more usual commands; scenes and so on are not included as they are not necessary in street lighting, but the developed microcontroller software is able to use them.

IV. Results

The system has been tested in laboratory. We have created a small tree network with only a coordinator and three children, forming a tree topology with a length of two depth levels. The coordinator is connected to one child which acts as a router, connected to the two other nodes. Using the SCADA interface it was possible to reach all the nodes and control their attached ballasts. Fig. 5 shows how the lamp input parameters (voltage, current and power) fulfills the expected results. The three graphs show the lower (a) and higher (c) dimming levels and they also show one of the middle levels (76 %, b). Maximum lamp's input power is 70 W, so the wireless network is able to dim as it was specified by the ballast manufacturer and DALI standard.

Another test was performed in order to know the maximum distance a node can reach. The test was performed in the university facilities, with the existence of Wi-Fi (IEEE 802.11) and Bluetooth networks. Both of them work in the same frequency as IEEE 802.15.4 (2,4 GHz), being an important interference source. This test proves that the system can coexist with Wi-Fi and Bluetooth networks. In this environment the nodes could reach a distance of more than 150 m. Separation between light poles is only 20-30 m, so the nodes are suitable for the application.

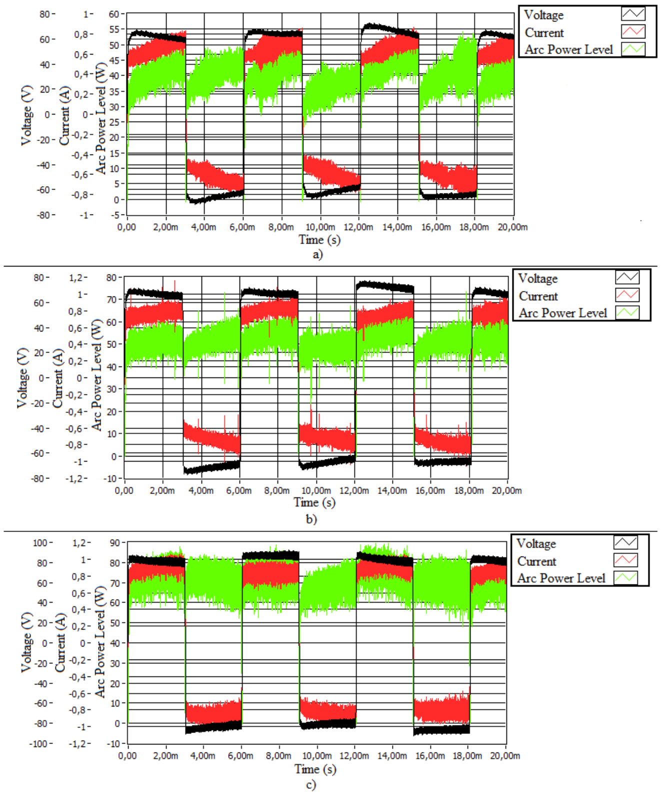


Fig. 5. Lamp input voltage; current and power (ballast output). a) 59,5 % ; b) 71,1 % ; c) 100 %

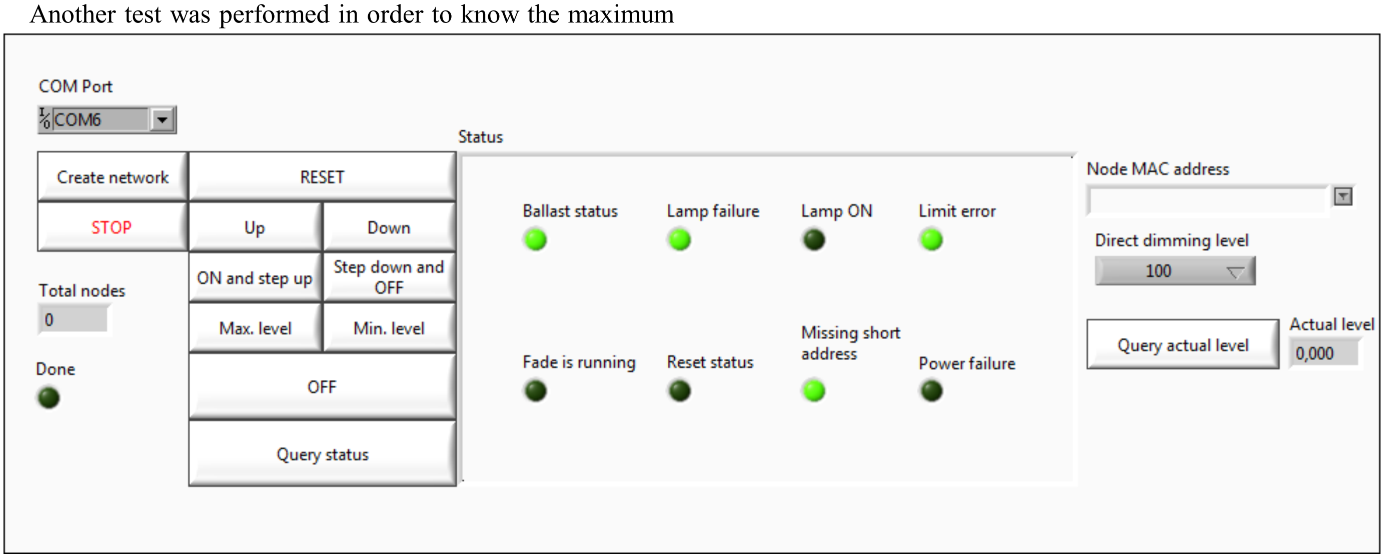


Fig. 4. SCADA interface

V. Conclusion

A new system for controlling IEC 62386 ballasts has been built using an IEEE 802.15.4-based wireless network. Any commercial ballast which has been built according to DALI standard should be controllable by the nodes. Not only is the system suitable for street lighting, but it also can be applied to indoor lighting and building automation.

Since we have created our own proprietary network layer (even though it is based on ZigBee) over IEEE 802.15.4 we can use any 2.4 GHz full 802.15.4-compliant device and implement the same network layer, whereas if we had used a ZigBee-based device we would have been bound to use that single device. Working over IEEE 802.15.4 physical and MAC layers assures interoperability among different manufacturers.

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