Chapter 16

Street Lighting System Based on Wireless Sensor Networks

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1. Introduction

An urban network, according to the document RFC 5548 (2009) - Routing Requirements for Urban Low-Power and Lossy Networks, is defined as:

"Sensing and actuating nodes placed outdoors in urban environments so as to improve people's living conditions as well as to monitor compliance with increasingly strict environmental laws. These field nodes are expected to measure and report a wide gamut of data (for example, the data required by applications that perform smart-metering or that monitor meteorological, pollution, and allergy conditions). The majority of these nodes are expected to communicate wirelessly over a variety of links such as IEEE 802.15.4, low-power IEEE 802.11, or IEEE 802.15.1 (Bluetooth), which given the limited radio range and the large number of nodes requires the use of suitable routing protocols".

According to Gungor et al. (2010), low-range WSNs are being widely recognized as a promising technology due to results obtained for smart metering, in particular the IEEE 802.15.4 standard, standardized by IEEE (Institute of Electrical and Electronics Engineers) in 2006 (IEEE 802.15.4), for its robustness, financial costs, low power consumption and simplicity.

Furthermore, there are two task groups that foresee the extension of IEEE 802.15.4 protocol in order to suit the requirements from smart grids. One of them (IEEE 802.15 WPAN TASK GROUP 4G, 2011) is preparing a protocol to support large networks, geographically diverse, with minimal infrastructure and millions of nodes; the other (IEEE 802.15 WPAN TASK GROUP 4E, 2011) is including characteristics extracted from CWPAN (Chinese WPAN standard – Chinese Wireless Personal Area Network), which specify power-saving methods for networks with high latency tolerance.

This paper presents an application for urban networks using the IEEE 802.15.4 standard, which is used for monitoring and control electric variables in a public lighting scenario.

This application consists of an urban network, where sensors (nodes) are coupled to the lamp posts or lighting points in order to control the control the lighting for these points, and capture important information from diagnostics, operation and failures.

This type of application is expected to improve quality in public lighting service and rationalize power consumption through smart sensors and supervision screens. The next section describes specific aspects involving the quality of public lighting service and the current stage of its structure in Brazil. Section 3 describes the system requirements, which its understanding is fundamental to develop the control and monitoring application and routing protocols. In section 4 the solutions regarding the control and monitoring application are detailed. Section 5 is presented the routing protocols strategies. In the last section, the conclusions are indicates the conclusions.

2. Specific aspects for the application in Brazil

An application for public lighting involves some specific aspects that should be highlighted. Economic aspects and aspects of sustainability are relevant to a public lighting system. The current public lighting system in Brazil needs to be modernized and must rely on sustainable energy sources and energy rationing.

Moreover, by automating the lighting system, it is possible to provide the population with a better service in resolving problems. According to Elektro (2011), the concessionaire responsible for the public lighting has no means to obtain the information related to problems, such as a lighting point that is out of operation (either because of a problem with the lamp or the device). Currently, a public lighting failure is usually reported to the concessionaire by a customer complaining on the phone or at the concessionaire's web page, as indicated at the Cemig web site (ATENDIMENTO CEMIG, 2011). Another way to detect a problem is patrolling the structure, which is made without a defined logistic. For this reason, it is desirable that the system to be developed is able to report the status of the devices installed on public streets, and also provide emergency alarms.

This work aligns with the work that began in 2009 in the USA: a comprehensive program in which electricity distribution companies, device manufactures, telecommunication companies and Information Technology companies have joined the Department of Energy (DOE) and the National Institute of Standards and Technology (NIST, U.S. agency for standardization) to define standards for smart grids and assure interoperability for protocols and devices in various areas, such as telecommunications, Information Technology and energy. That work has produced a document (NIST, 2009), which contains a survey of more than 80 standards, including some directly related to this project: transmitting messages over wireless networks, using networks based on IP (Internet Protocol), ZigBee (ZIGBEE, 2007), using the standard specification of GPS signals (Global Positioning System) (GPS NAVSTAR, 1995) and W3C Simple Object Protocol (SOAP, Web Services standard).

Looking at the work developed in the U.S., in June 2010, the Brazilian government, through the Brazilian Electricity Regulatory Agency (ANEEL), opened a public hearing for strategic projects on the “Brazilian Smart Grid Program" (ANEEL, 2010a). This program focuses on presenting project proposals in order to join efforts to coordinate and generate new technological knowledge of great relevance for the Brazilian electricity sector. More specifically, in accordance with the document generated by the mentioned public hearing (ANEEL, 2010a), this study contributes to the research of “telecommunication infrastructure”.

In addition, the regulatory resolution nº 414, of September 9, 2010 (ANEEL, 2010b) from ANEEL establishes changes to the maintenance policy for the Brazilian public lighting structure. This document states that, from September 2012, municipal governments shall be responsible for maintaining the public lighting structure, instead of the concessionaires, which shall be responsible only for power supplying.

Finally, control and monitoring public lighting, through lamps or dimming ballasts, decreases light pollution, caused by poor adjustment of luminosity and number of lamps lit in specific directions, depending on the angle, intensity, etc (Figure 1). Besides, light pollution should be studied aiming to improve roads, streets and avenues conditions, in order to provide better maneuverability for drivers, and brightness for unsafe places, such as alleys and public squares (MIZON, 2001) (SCHWARZ, 2003).

Figure 1. Light Pollution

The current public lighting structure in Brazil consists of a set of lighting points arranged in a certain manner. Each point has a housing with a device called photocell relay, which is responsible for turning the lights on or off according to a brightness sensor. Then, at nightfall, the relay turns the light on at the lighting point. This limited structure may compromise consumption efficiency, quality of service to the community, and other factors, for example, problems in the lamp, power supply, the photocell relay, etc.

To solve the problems mentioned above in an automatic way, allowing fast and efficient preventive and corrective maintenance, an automation system may be applied. The basis for such a system is implementing the communication between parts involved, like devices, computer software, among others. Therefore, the photocell relay mechanism can be attached to an Information Technology structure, through device and sensor networks, supervision workstations and applications.

The stage of development of public lighting projects in Brazil is restricted to rationing energy and improving lighting efficiency, by replacing sodium or mercury lamps by LED lamps, installing photovoltaic panels for sustainable lighting, powered by solar energy, and, finally, luminaires to reduce lighting focus dispersion (CPFL CAMPINAS, 2011).

LED lamps offer better color reproduction; they do not emit ultraviolet and infrared rays, they propagate less heat, and they attract fewer insects. They also show good efficiency and longer life, estimated at approximately 50,000 hours of operation. Sodium vapor lamps, most commonly used today, last up to 32,000 hours; mercury vapor lamps may last 12,000 hours, and metal halide lamps, commonly used in facades of buildings, 10,000 hours.

The Companhia Energética de Minas Gerais (Cemig), an electric energy utility company in the State of Minas Gerais, Brazil, together with the municipal government of Belo Horizonte, began testing LED lamps. Some luminaires have been already installed on poles near San Francisco Church (CEMIG, 2009). Cemig provides annual reports and sustainability reports that can be accesses at the company's website (CEMIG, 2011).

In addition, driven by the investments for the World Cup 2014, Cemig's project "Minas Solar 2014" seeks to install photovoltaic panels to power public lighting, aiming to improve public infrastructure and soccer stadiums (CHIARETTI, 2011).

Cemig signed a cooperation agreement with the U.S. government, through the U.S. Trade and Development Agency (USTDA), to fund their smart grid project. The U.S. agency will provide US$ 710,000 for the Brazilian company, to be applied on the study that analyzes the feasibility of implementing smart grids, which has been developed by the company together with Light (SMART ENERGY ONLINE, 2011).

CPFL Energia, an electric energy utility company in Brazil, together with the Development Foundation from the University of Campinas (FUNCAMP), the Foundation for Research and Advisory Service to the Industry from the Federal University of Itajubá (UNIFEI), HYTRON Hydrogen technology, FUSION, and the AQUA GENESIS Institute for Studies and Projects on Energy, Hydrogen and Environment, is currently investing in a project of a solar photovoltaic and/or wind hybrid system to generate electricity, which can operate connected to the distribution network or isolated, and the goal is to evaluate the integration of distributed generation at low voltage, with and without energy storage. Considering the increasing use of local alternative sources of energy generation, low power systems, renewable energy sources, and technological availability that allow immediate applications, utilization of solar photovoltaic and wind energy, with and without energy storage, stands out above other options (PORTAL INOVAÇÃO CPFL, 2011a).

A project that involves communication, however not between sensors (PORTAL DE INOVAÇÃO CPFL, 2011b), called "failure diagnostic system for public lighting points", is being developed by CPFL in partnership with companies MATRIX and PLAYMUSIC. The development stage is restricted to alterations in the master part device, aiming to determine more appropriate, and also less vulnerable to transportation, means to perform maintenance on lighting points. Maintenance concerns handling from the field team, to make it practical to use. Furthermore, the project involves adapting the device to industrial production.

Closer to the project proposed in this work, which involves sensors communication in a system, the Smart Substation project from CPFL, in partnership with the Foundation for the Technological Development in Engineering (MUSP – FDTE) and CONTREL, proposes a smart system by adapting or inserting monitored devices with built-in intelligence in maintenance, security, qualimetry and control, connecting to the respective remote management centers. Nowadays, relays, sensors, qualimeters, and other digital devices operate underutilized, less integrated and do not repay their high costs. Back office processes (operation, planning, security, qualimetry, maintenance, etc.) are still detached and without intelligence (PORTAL INOVAÇÃO CPFL, 2011c).

Information for this project was provided by Elektro and the Eldorado Institute, in order to modernize the infrastructure of public lighting through WSN communication and control and monitoring workstations, which allow rationing energy, sustainability, automated detection of physical or logical fails, alarms related to emergencies, supervision of lighting points, and controlling actions (turning the lamp on or off and adjusting brightness, for example) for lighting points.

3. System requirements

The recent document proposed by IETF (RFC 5548, 2009), which describes requirements for routing on urban networks, also affirms that these networks must attend convergent traffic, where one node (usually a gateway or sink) receives messages from several low frequency meters (a maximum of one measurement per hour, and a minimum of one measurement per day). The number of nodes must be in the order of 10^2 to 10^7, distributed in areas varying from hundreds of meters to one square kilometer, considering that nodes are commissioned in groups, and the battery shelf life is usually in the order of 10 to 15 years. The frequency band must be ISM (Industrial, Scientific and Medical), and the nodes will probably have from 5 to 10 immediate neighbors to communicate. The routing protocol must enable the network to be autonomous and organize itself, requiring a minimum energetic cost for maintenance functions. The protocol must also ensure that any diagnostic or failure information from the nodes is communicated without interfering on the network operational mode, respecting the time limits.

The project of a Wireless Sensor Network depends on the application where the network will be used, and it should be based on functional and non-functional requirements. Functional requirements for this type of project are:

- Points supervision: node status, whether it is connected to the network or not; battery power; lifetime estimation for battery and lamp; and LEDs luminosity level;
- Control: switch on/off the luminosity level lamp; switch on/off a lamp post, a selected segment, a street, neighborhood, city, etc;

- Automatic programmed actions: for example, the city lights should be turned on at 7 PM;
- Actuate the nodes through a remote tool: besides the automatic actions, the operator should be able to select a region through a remote tool to actuate;
- Diagnostic and alarms: trigger an event when a network, hardware or lamp failure occurs;
- Automation of information storage: mechanisms automating the storage process of related street lighting information (geodesic coordinates supplied for electrical companies) should be applied to simplify and streamline the process.

To meet the functional requirements, a control and monitoring application is required to report system information to the user (Figure 2). This application is able to monitor operating conditions, for example, notifying the user about the end of life of a lamp if it exceeds a particular limit of hours, and graphically displaying city maps on a supervision screen, with the lighting points in operation. Figure 2 shows an example of status of lighting points, which are represented in different colors: lighting points in yellow indicate lit points; lighting points in blue indicate unlit points; lighting points in red indicate the boundaries of a specific region in which the application must act. Regarding control, the application sends commands to activate or deactivate lighting points as pre-programmed or when there is a request from the system operator.

As non-functional requirements, portability and robustness are considered essential factors in the application project. For more information, section 4 covers the details about the application project.

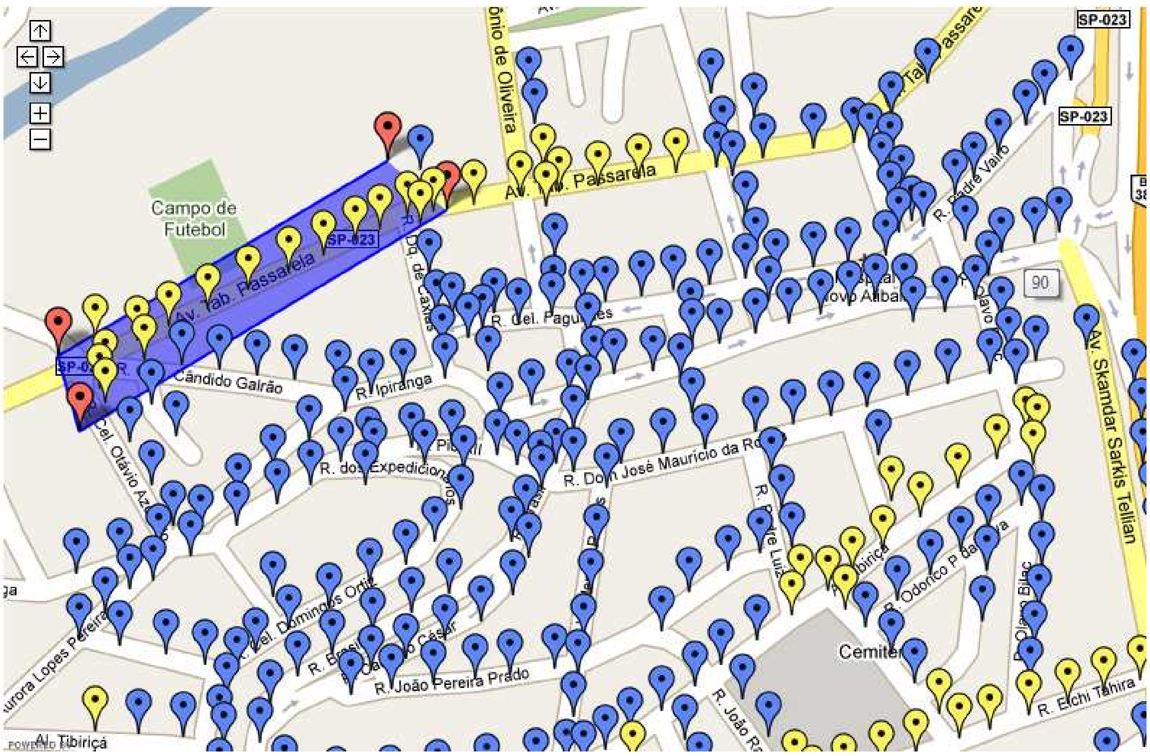

Figure 2. Control and Monitoring Tool Display

To understand the non-functional requirements, the list below briefly describes parameters relevant to the application, in order of importance (KHALIFA et al., 2011):

- Scalability: when proposing an approach to sensor networks, it is important to consider that the project should apply to small (up to 25 nodes), medium (25 to 10^3 nodes), or large networks (10^2 to 10^7 nodes);
- Fault tolerance: depending on the physical conditions, it may be necessary to adopt sensor nodes with special characteristics. In addition, due to difficult accessibility in some environments, it may be unmanageable to replace damaged nodes or batteries. Therefore, it is necessary to provide sensor nodes with adaptive capacities to deal with unstable environments. In the type of application described in this work, nodes must support high temperatures and heavy rain. Considering the failures related to sensor nodes, the routing algorithm proposed in this work must be fault-tolerant because the messages must find a reliable path to reach the destination;
- Delivery Guarantee: regarding the unstable wireless communication nature, because of external interference and/or electronic noise, it is necessary to create a point-to-point acknowledgment mechanism, which is a consensus among researches in the wireless network area. End-to-end confirmation messages are implemented in higher layers, preferably in the transport layer (TCP);
- Lifetime: sensor nodes depend on batteries, which require the use of efficient protocols in energetic terms. However, for this project, most sensor nodes are powered by energy cables that are already used in current street lighting structures. Avoiding the use of batteries is an ecological issue, because devices' maintenance involves a considerable amount of trash. Batteries would be used only in areas where there is no energy cable structure, such as rural areas. Therefore, the lifetime estimation should be medium to high, but it should not be prioritized in detriment of other requirements, especially not to compromise the delivery rate;
- Latency: this parameter reflects the time interval the network has to inform the observer about a specific phenomenon. Some applications can be sensible to latency, therefore it is necessary to respond in a short time interval (equal or less than one second), for example, in control process supervision. On the other hand, other applications do not depend on a quick response time (for example, monitoring bridge stabilization). In relation to street lighting application, the acceptable latency should be on a time interval in the order of tens of seconds.

Routing protocols are used in two types of package traffic in Wireless Sensor Networks: the first type directs packages from the sink node to the network nodes (i); the second type directs packages from the network nodes to the sink node (ii). Different terminologies may be used for these two traffic types: Tian and Georganas [1] and She et. al [2] use the terms *downstream traffic* for (i) and *upstream traffic* for (ii); Watteyne et al. [3] use the terms *divergent traffic* for (i) and *convergent traffic* for (ii); in other works, such as [4], authors name (i) as *gradient-descendent traffic* and (ii) as *gradient-descent traffic*, if routing is based on gradient. This works uses the terms *divergent traffic* for (i) and *convergent traffic* for (ii).

Figure 3 represents the two types of package traffic, differing by the communication flow in relation to the sink node.

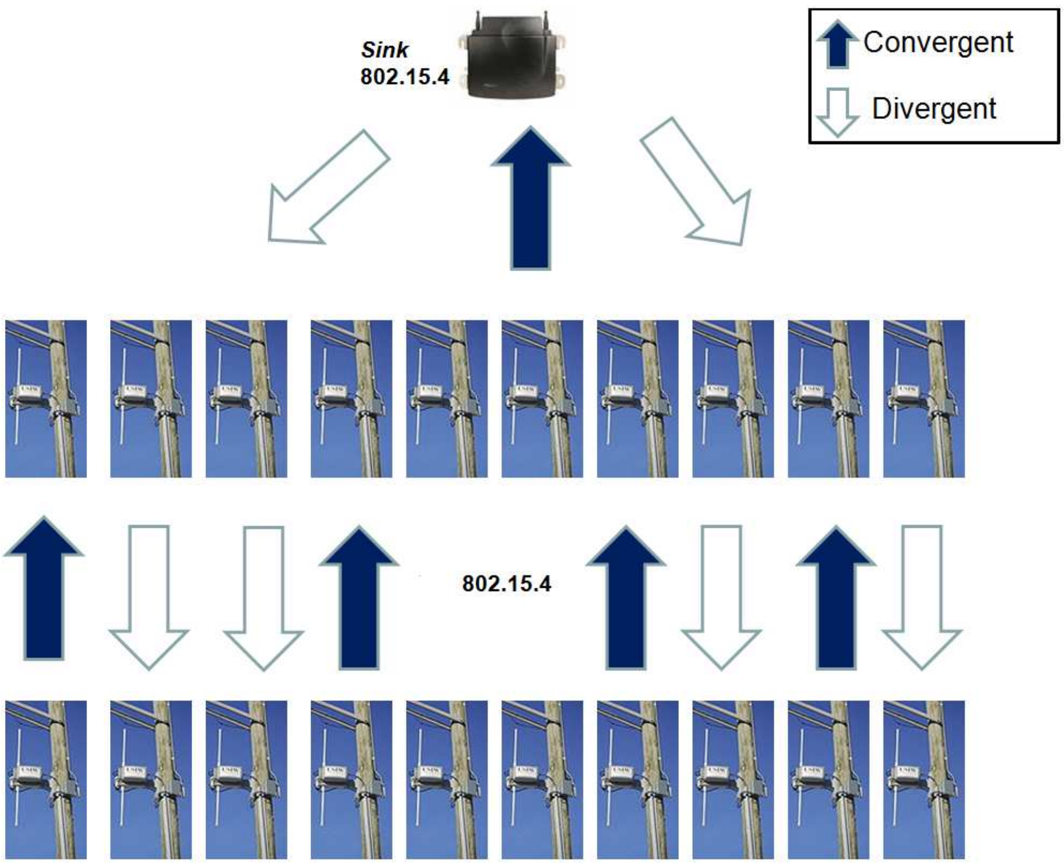

Figure 3. Typical WSN simplified architecture

In order to control and monitor public lighting systems, which is the goal of this work, the following message types based on RFC 5548 are needed, according to the mentioned requirements, subdivided in convergent and divergent traffic.

Convergent traffic:

- Message to notify the system about failures (which can occur on a lamp, hardware, etc);
- Message to update the system about status (on/off) and other information. Periodicity is a maximum of one message per hour, and each node has its own cycle or clock;
- Message to notify the system that some neighboring node is out of radio range;
- Specific diagnostic response (battery power, LEDs luminosity level, battery lifetime estimation, and lamp lifetime estimation).

Divergent traffic:

- Actuate the nodes luminosity (activation, dimerization, etc);
- Specific diagnostic request (battery power, LEDs luminosity level, battery lifetime estimation, and lamp lifetime estimation, etc).

4. Control and monitoring application

The proposed architecture is based on the cell model. The cell should provide access to supervision and control of a number of sensor nodes for the management applications. By definition, the sensor node is the device coupled to the lighting point, which is able to communicate via a wireless network.

A cell is composed by a compartment, an industrial computer, a GPS antenna, a communication controller, and sensor nodes. Numerous cells can be formed to completely cover an urban center.

The industrial computer is installed inside the compartment and it is connected to a communication controller, communicating via a serial protocol, while the communication controller communicates to the sensor nodes via wireless network.

The GPS (Global Positioning System) antenna is considered the only time basis among several cells, and then alarms that occurred in different cells can be ordered. Management applications (Configuration/Topology, remote operation server and monitoring) are installed on the Operation computer and they communicate to the cells via Ethernet network.

Remote access is done through an Internet browser from the remote operation application computer to the remote operation server. The Google Maps library (GOOGLE MAPS FAMILY, 2011) is used to plot the lighting points on the maps (Figure 4).

Figure 4. Screen obtained with Google Maps library

Figure 5 shows the system architecture and illustrates cell 01, which is responsible for grouping some sensors, and also shows the capability of adding new cells until all lighting points from the city are mapped.

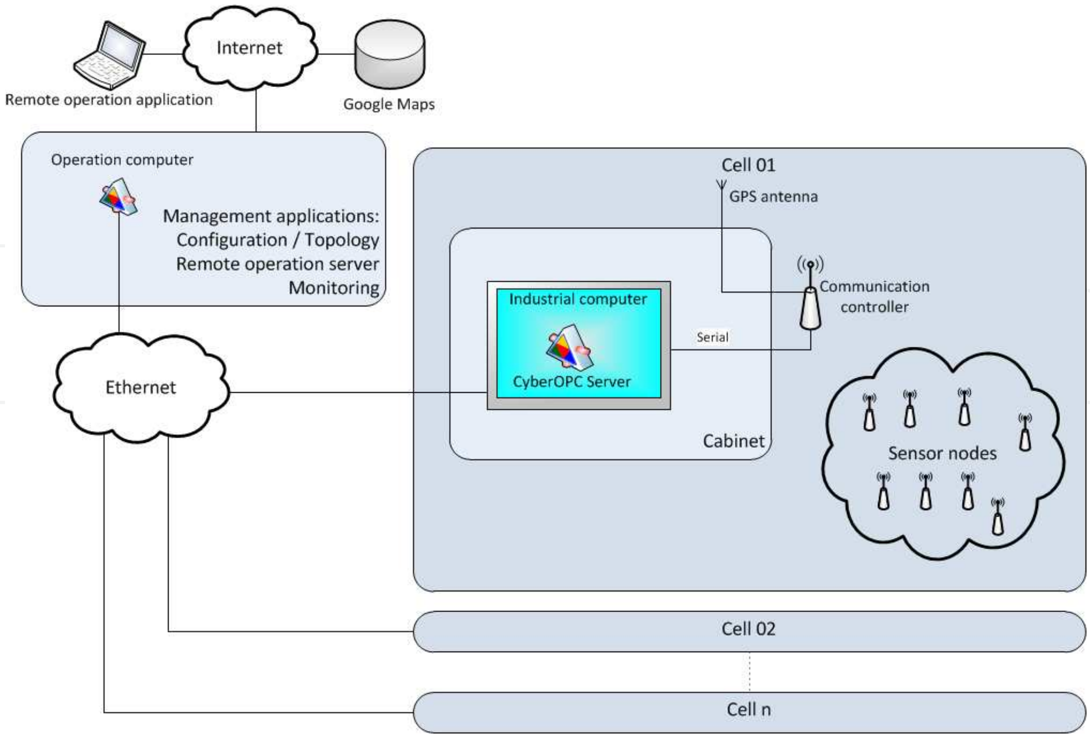

Figure 5. Application Architecture

The communication standard adopted between the operation and the industrial computer is CyberOPC. CyberOPC is an academic research project that proposes an open communication system, based on HTTP (Hyper Text Transfer Protocol), specially developed for remote control and supervision of industrial systems over public IP (Internet Protocol) networks (TORRISI, 2011).

Communication works as follows: management applications installed on the Operation computer request control and supervision data via the Ethernet network to the industrial computer installed on the compartment. The message is received by the computer and transferred to the communication controller connected to the serial port.

The communication controller transmits the message via the wireless network, identifying the request. The sensor nodes receive the notifications, process the request and transmit the response to the controller via the wireless network. The response is received by the controller via the wireless network, and retransmitted to the computer via the serial port. The industrial computer sends the response to the operation computer via the Ethernet network.

For detailed information about this control and monitoring application, refer to Fonseca (2011).

5. Routing protocols

Due to the robustness, low cost, low power consumption and simplicity, this work is based on the IEEE 802.15.4 standard. For the devices to form large scales networks, as described in

RFC 5548 (2009), the protocol from this standard must operate on a mesh-type topology, so that the devices communicate in multiple hops, based on the low range communication (around 100 meters) with distributed routing to transmit information to their final destinations.

However, the large number of nodes and the peculiar nature of operation of wireless sensors urban networks require the project of routing and medium access control (MAC) protocols to be specifically developed.

Protocols that use only global disseminations to communicate, through broadcast messages (known as flooding protocols), may cause high package traffic, which can lead to a high number of collisions and, thus, reduce the delivery rate. In addition, they demand high energy consumption to exchange information.

On the other hand, *unicast* protocols should be stateless, which means that packages cannot store information about the route taken to avoid loops or package delivering problems. This is due to a limitation of information that the package of lower layers from the IEEE 802.15.4 standard has. Moreover, protocols must considerer the minimum energy consumption and a satisfactory delivery rate.

The public lighting concessionaire has the geodesic coordinates of the lighting points in their digital maps, which help in the structure management and maintenance. The routing protocols can then implement mechanisms that use such information.

Furthermore, devices must have mechanisms that minimize energy consumption, such as periodically switching the radio off, since devices would be idle most of the time.

This section intends to only cite the proposed protocols. They were divided according to two different types of traffic (divergent and convergent), and evaluated to demonstrate which are more suitable for the mentioned urban network.

5.1. Divergent traffic

The proposed protocol for divergent traffic consists of four parts: it is based on the GPSR protocol (KARP and KUNG, 2000), which has two modes, greedy and perimeter (i); the second part is that when it reaches a particular target region, indicated by the geodesic coordinates, it spread the message, thus operating in *geocast* mode (ii); the third part is that it is able to reverse the direction of the perimeter mode, in order to go around blank spaces competently (iii); finally, the last part consists of retransmitting to different neighbors in case a fail occurs, using the original GPSR criterion to chose neighbors (iv). Originally, GPSR uses the right-hand rule to define the node to retransmit the package, choosing the neighbor by the smaller angle. Then, to reverse the direction, the logic was reversed, using the left-hand rule. Figure 6 shows the mode of operation of the protocol for divergent traffic.

For detailed information about the protocol used for divergent traffic, including flowcharts and analyses, refer to Pantoni and Brandão (2011).

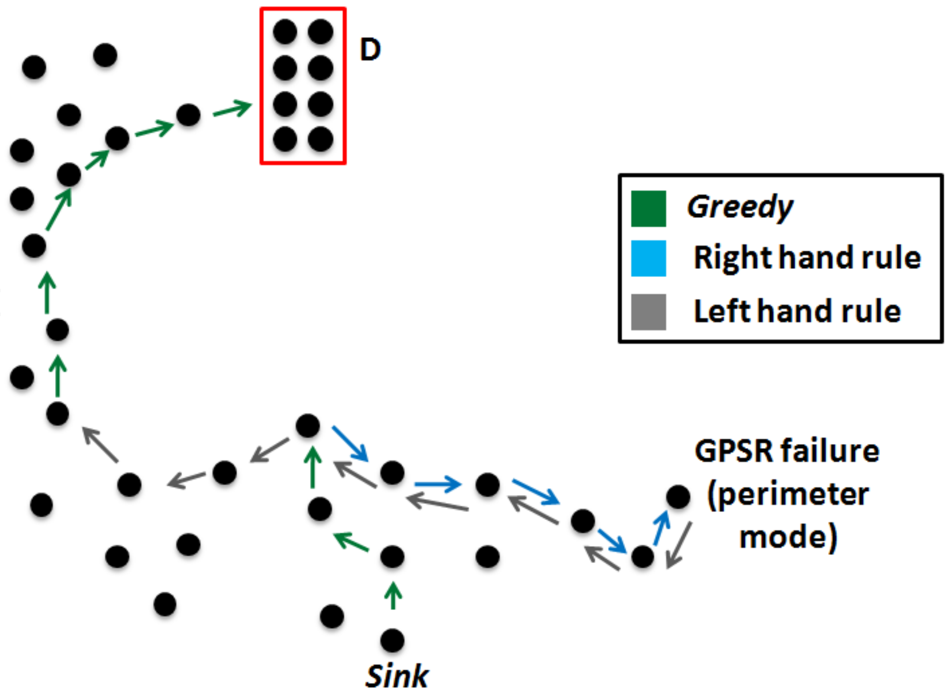

Figure 6. Operation of the routing protocol for divergent traffic

5.2. Convergent traffic

The main idea of the routing algorithm based on gradient is to forward the package towards the sink node choosing the neighbors with the lowest height, where height represents the number of hops over nodes in relation to the sink node.

In order to enable the routing process, the sink node broadcasts a message with its height equals to zero (H=0) in the initialization phase. The nodes that receive the "gradient initialization" package assign the incremented value to their height variable and, later on, broadcast the message to other nodes on the network, in order to assign heights to all network nodes, creating height levels (H) on the network, as indicated in Figure 7.

The logic of the protocol consists of transmitting a package to only one neighbor, according to the lowest height. The proposed protocol differs from the previous works because it considers other aspects to forward the package in case the neighbors have identical heights. In addition, in case acknowledgment messages identify a failure in transmission, the package is retransmitted to other neighbors, and the retransmissions are limited to only one transmitter node per data flow.

The protocol is based on choosing the neighbors for retransmitting the message according to the number of attempts made. The next hop is selected based on a list that is sorted in descending order by the longest distance and populated with all neighbors, except the neighbor from the last hop. On the first transmission, among the neighbors with the lowest heights, the most distant node from the current node will be chosen; in other words, the first element from the list. If it is the first retransmission, the second most distant element will be chosen, and so on. If no nodes with the same lowest height are chosen, the next group to be

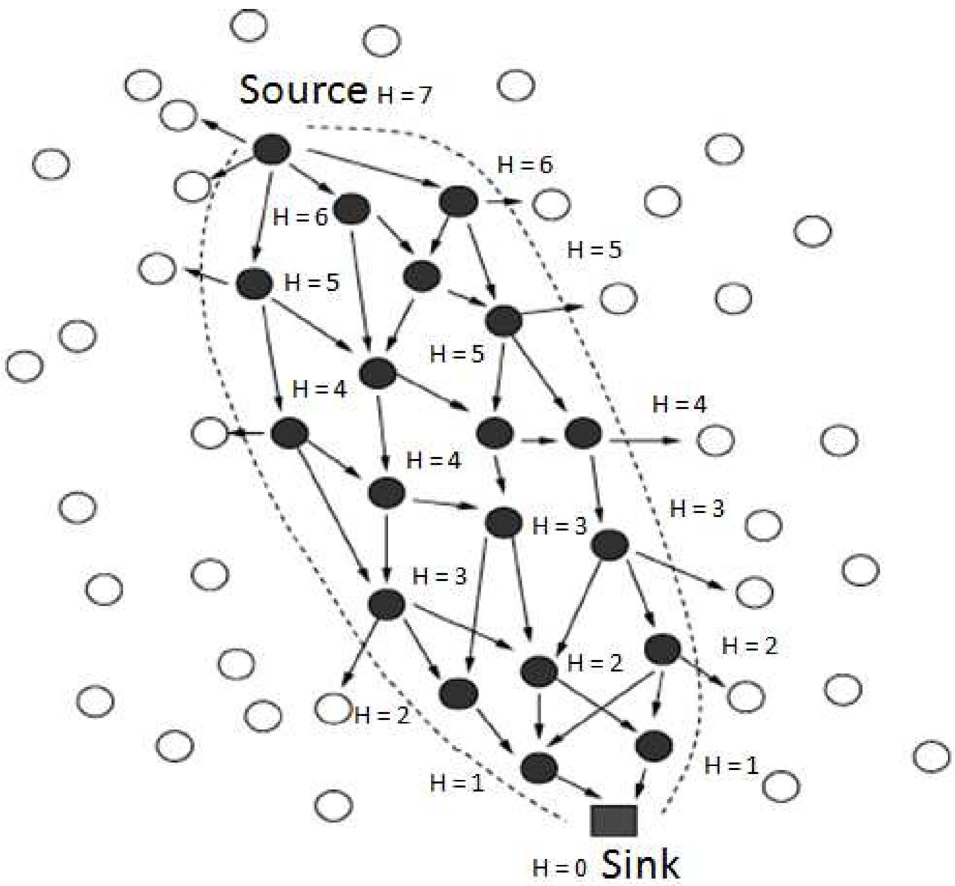

Figure 7. Height mapping for gradient routing protocol. Source: Ye et al. (2005)

sorted according to the distance will be selected based on the succeeding lowest height among the neighbors.

For detailed information about the protocol used for convergent traffic, including flowcharts and analyses, refer to Pantoni and Brandão (2012).

6. Conclusions

The public lighting system provides automation for control process, diagnostics and alarms from possible failures in the structure. Therefore, an improvement in public lighting service is expected, plus a rationalization of energy consumption.

The two task forces related to the IEEE 802.15.4 standard (IEEE 802.15 WPAN TASK GROUP 4G, 2011; IEEE 802.15 WPAN TASK GROUP 4E, 2011) assure a protocol extension to the lower layers in order to increasingly meet urban networks requirements, as well as smart grid applications.

Although this work comprises a specific application for public lighting, it can also be applied to other applications, such as monitoring energy and water consumption meters, measurement of climatic factors in order to implement weather forecast systems, with humidity sensors, temperature sensors, etc.

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