Wireless Communication System for Traffic Management and Control

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Abstract

Urban vehicle fleets are constantly expanding, with traffic blocks as an unwanted consequence. As the conventional traffic light systems have not kept up with the quality of life improvements in large urban centers, the expansion of vehicles and the unwanted traffic jams has motivated the need to study other solutions to improve these systems.

Conventional traffic light systems currently incorporate signal acquisition devices (sensors) with control algorithms and communication methods that are inadequate in comparison to the technological developments registered in the last decade.

The SmartCity concept is spreading more and more, and with it come some benefits to cities, with traffic control becoming all-important to their quality of life.

Traffic light systems have always been dependent of complex networks of cabling and servers.

In this dissertation a solution is presented which has the objective to improve the control capacities and minimize the costs that the systems currently hold. The diverse prototypes are presented and characterized. Tests to replicate limit situations, verify the signal range of the prototypes and assure the network communication were projected and realized.

This study was made with concerns with network security in mind and proposes a security system for the same.

Keywords: Traffic Lights, Wireless Sensor Networks, Smart Cities, Internet of Things (IoT).

1. Introduction

Every major city has a large part of the population travelling by car or by public transportation, and traffic jams are a frequent problem [1]. Better public transportation is the sustainable long-term solution to road traffic jams but a nearer term solution is also required. The most obvious solution is to build new roads but, in urban areas, this is generally not feasible, due to a lack of suitable land or insufficient funds [2]. Hence, the traffic density is increasing at an alarming rate in developing countries which calls for intelligent traffic lights control to replace the conventional manual and time based ones [3].

Today, ways of thinking the cities are different. The quality of life in the cities is now the main goal of the cities’ strategic planning.

New traffic systems have been developed to provide answers to these strategies [4]. The new traffic system areas, namely, the intelligent transportation system (ITS), combine the existing technology with artificial intelligence and wireless communication technologies (WCT) that, in the limit, would truly think for themselves [5]. An ITS has to capture many environmental measurements in order to improve traffic. Using suitable protocols, WCT are also able to acquire real-time data in a reliable way. Accurate and reliable real-time traffic data monitoring systems are essential for the efficient and successful execution of all ITS systems [6,3]. For example, a traffic lights network of a whole city can use weather and climate (air pollution) values to choose sequences of time to alternate traffic lights, in addition to the collected real-time data concerning vehicles (speed or queue length) [7,8].

The strategic works that have been carried out belong to a wider field of cities management, the so called Smart Cities. Smart Cities go far beyond traffic management to include energy, water, and waste management among...
many other managing aspects of the Cities. However the use of WCT in cities remains relatively limited. Regarding traffic control, solutions exist for connecting traffic lights using the Global System for Mobile Communications (GSM) network operators. They rely on an unique GSM operator and, at the local level, some solutions exist for acquiring data from sensors (bellow the pavement) and wirelessly transmit their information to the local controller [9].

The WCT have been developed but one in particular has received a lot of attention: ZigBee. This is a low power wireless networking standard designed for controlling and monitoring applications. The ZigBee standard was prepared by an industry consortium: the ZigBee alliance [10]. Using WCT, it becomes easier adapt to fluctuations, as the number and type of sensors may be largely increased. Wireless sensors can be installed almost everywhere and provide important additional information to optimize traffic management.

In local area solutions, data acquired in a certain location is used there to know what road to open, decided by any pre-programmed or pre-defined algorithm or local sensors. In wider area solutions for traffic control, the system processes the data acquired in the various locations with devices capable of doing so. They send information to all the local controllers not only to improve the traffic flow in that intersection but also in the neighbor intersections. This type of system also allows tracking of priority vehicles, like ambulances, to accommodate easier and quicker transportation of critical patients and public transportation priority roads. The reaction capability of the system is limited to the central data analysis and there are no proactive capabilities aiming to prevent possible and, eventually, foreseeable events [11,12,13].

A functioning and applicable solution to a traffic control system has to be robust. The malfunction of any modules at any time is a possibility, so the choice of the communications topology has to be done to effectively deal with this issues. Point-to-point and Star-type networks were ruled out because solutions based on networks in which the communications in the grid depend from the functioning of one module have to be avoided. A mesh-like grid is a type of network that is not dependent from only one point at any time. Moreover, several paths are available for the same communication, which allows the prototype to carry its purpose successfully even if there are missing or malfunctioning modules.

This main contribution of this paper is the definition and performance analysis of a reliable communications infrastructure to maintain and continuously refresh the real time database of sensors and actuators that support the optimization methods for the intelligent traffic management, and ascertain that the existing traffic control systems can be improved by the use of wireless technologies [14]. Wireless technologies present advantages and drawbacks but the trade-off between them seems in favor of their use for traffic sensing and control.

2. Communications

With the current technological evolution, there are many innovations created in the universe of low-energy consumption wireless networks. Of all the existent communication technologies today some are of note, like WiMAX, WiFi, Bluetooth, NFC, RFID, ZigBee, LoRa (Long Range), SigFox, UWB, GSM, among others. Some of these technologies work alongside other radio-frequencies (RF) in widths of free use, while others are more restricted at regional level. The various technologies allow adaptation to different uses and can, in most cases, be used simultaneously, allowing the developed network to benefit from the qualities of different technologies. With clearly defined objectives, it becomes necessary to find a protocol and a communication network that allows high network flexibility and can, at the same time, have a large range so signal breaks in local communications don’t exist. To transmit the information between intersections and direct it to the Control Central a technology with a higher transmission range is required, allowing for the flexibility of the network to be lessened. Different frequencies in the free use bandwidth were also used. In the following topic the different technologies and frequencies chosen will be analyzed, in turn, explaining the points for and against their choice and the best place in the network for their use.

2.1. Zigbee

For the more local level of the network, a technology easily adaptable to new modules was necessary, that is to say, that allowed for high network flexibility. By modules it’s meant every point that requires control, be it traffic regulating stoplights, peon or cycling way stoplights or any sensor necessary to collect information about the road or the existing traffic.

Of all the technologies mentioned in the previous topic, the Zigbee modules were the ones elected due to it’s autoconfiguration abilities and regeneration/adaptation of the weave to the inclusion of new modules. Zigbee is a reliable, low power, low cost and efficient technology for the creation of information networks. [15] The most desirable features of the ZigBee protocol are the ability to create the data network topology, the self-healing capabilities and security bringing versatility to the network [16,17–19].
With ZigBee, every time we need to add a new module to the network all it takes is load the necessary firmware, do a few brief configurations to incorporate in the network and supply the current. As it is fed, the module will automatically incorporate the previously constructed network and adapt to the mesh according to its type of firmware. Since it’s a low consumption network, it’s one of its strengths, with the protocol allowing as well for the modules to enter a state of standby, turning on only when they have to transmit messages. Another important detail is the type of antenna chosen. The multiple type of antennas makes ZigBee the most versatile, easily adaptable module.

However, available material only featured the Wire, Chip or internal PCB antennas. There were no ZigBee with only the connector. As such, only the ones available were analyzed to determine which show the best results.

The characteristics of the communication modules ZigBee S2, PRO S2 and PRO S2B are presented in Table 1.

### Table 1 – Characteristics of the Zigbee communication modules

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>S2</th>
<th>PRO S2</th>
<th>PRO S2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>Wire</td>
<td>Chip</td>
<td>PCB</td>
</tr>
<tr>
<td>Tension</td>
<td>3.3 V</td>
<td>3.3 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Estimated Energy Consumption</td>
<td>40 mA</td>
<td>295 mA</td>
<td>295 mA</td>
</tr>
<tr>
<td>Output Power</td>
<td>2 mW</td>
<td>50 mW</td>
<td>63 mW</td>
</tr>
<tr>
<td>Speed</td>
<td>250 kbps</td>
<td>250 kbps</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Estimated Range</td>
<td>122 m</td>
<td>1600 m</td>
<td>1600 m</td>
</tr>
<tr>
<td>Frequency</td>
<td>2,4 GHz</td>
<td>2,4 GHz</td>
<td>2,4 GHz</td>
</tr>
<tr>
<td>Encryption</td>
<td>128-bit</td>
<td>128-bit</td>
<td>128-bit</td>
</tr>
<tr>
<td>Network Topology</td>
<td>Mesh</td>
<td>Mesh</td>
<td>Mesh</td>
</tr>
</tbody>
</table>

#### 2.2. Moteino

Another technology used were the RFM69HW modules created by HopeRF, utilized jointly in the Moteino MEGA developmental plaques. The main differences of these modules are the frequency utilized in the transmission and the protocol utilized. Contrary to the ZigBee presented in the previous subtopic, these modules have a lower communication frequency, in the 868-915 MHz range, and so trying for the lower frequency to translate into a larger communication range between modules. This larger range would allow communication between the existing local control points at each nexus. The fact that in this technology the communication has to be programmed from ground up and it doesn’t have the flexibility to adapt easily to inclusion of new modules, as well as being unable to generate a weave consulting the surrounding devices makes a possible adoption to focus only on non-local use, creating then a network that would use two different technologies.

Moteinos are small microcontrollers that may come together with communication modules that communicate in one of the following frequencies: 315 MHz, 433 MHz, 868 MHz, or 915 MHz. These bandwidths belong to the free use bandwidth internationally licensed for industrial, scientific or medical use (ISM, Industrial, Scientific and Medical).

For better understanding of which are the differentiating characteristics and to make possible the analysis of which were the factors that most weighed on the choice of this communication module, the main differences of these devices were compiled, and their strengths and weaknesses identified. The characteristics of the RFM69 communication modules are presented on Table 2.
Of the various chips available to integrate Moteinos within the RFM69 family there were still some who had a 13 dBm communication power, lower relative to 20 dBm of the chosen chip. Despite all manage to perform communications within 3 bands available and has already been ruled out of the 433 MHz to be used with other modules that support LoRa, the decisive factor was therefore the output power.

### 2.3. LoRa

Finally, the RFM96WLoRa modules were used, also manufactured by HopeRF used in conjunction with the Arduino development boards. These modules have the Lora technology that allows the construction of LoRaWAN networks (LoRa Wide Area Network), which in turn are part of the list of low-energy networks (LPWAN, Low Power Wide Area Network).

The characteristics of the RFM9x communication modules are presented on Table 3.

### 3. Prototype

#### 3.1. Zigbee Prototype

A mobile prototype, with access to a Bluetooth GPS in order to provide the precise position of each test was planned. Readings were also acquired with the XCTU program and were recorded together with the geographical coordinates. The Zigbee static prototype is shown in Figure 1.

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### Table 2 – Characteristics of RFM69 communication modules

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>RFM69CW</th>
<th>RFM69W</th>
<th>RFM69HW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>External</td>
<td>External</td>
<td>External</td>
</tr>
<tr>
<td>Tension</td>
<td>3.3 V</td>
<td>3.3 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Estimated Energy Consumption</td>
<td>45 mA</td>
<td>45 mA</td>
<td>130 mA</td>
</tr>
<tr>
<td>Output Power</td>
<td>+13 dBm</td>
<td>+13 dBm</td>
<td>+20 dBm</td>
</tr>
<tr>
<td>Speed</td>
<td>300 kbps</td>
<td>300 kbps</td>
<td>300 kbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>315 MHz / 433 MHz / 868 MHz / 915 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encryption</td>
<td>AES-128 / CRC-16 / 66-byte FIFO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Network Topology</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>

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### Table 3 - Characteristics of RFM9xWLoRa communication modules

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>RFM95WLoRa</th>
<th>RFM96WLoRa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>Adjustable</td>
<td>Adjustable</td>
</tr>
<tr>
<td>Tension</td>
<td>3.3 V</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Estimated Energy Consumption</td>
<td>10.3 mA</td>
<td>10.3 mA</td>
</tr>
<tr>
<td>Output Power</td>
<td>100 mW</td>
<td>100 mW</td>
</tr>
<tr>
<td>Speed</td>
<td>37.5 kbps</td>
<td>37.5 kbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>868 MHz / 915 MHz</td>
<td>433 MHz</td>
</tr>
<tr>
<td>Encryption</td>
<td>CRC-16 e 64-byte FIFO</td>
<td>CRC-16 e 64-byte FIFO</td>
</tr>
<tr>
<td>Network Topology</td>
<td>Star</td>
<td>Star</td>
</tr>
</tbody>
</table>

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Figure 1 - Zigbee static prototype.
3.2. LoRa Prototype

The LoRa communications module was required more time for planning and assembly. As indicated in the previous chapter to integrate this prototype took two communications modules RFM96WLoRa. The LoRa prototype is shown in Figure 2.

![Figure 2 - LoRa prototype.](image)

3.3. Traffic Light Prototype

To give some realism to the final prototype was also developed a traffic light prototype. Using LED strips in the colors required 3 blocks were cut with 50 mm for each color.

3.4. Final Prototype

The final prototype, is the junction of three small prototypes of the preceding subtopics. The final prototype with all the intermediate prototypes assembled is shown in Figure 3.

![Figure 3 - Final prototype with all the intermediate prototypes assembled.](image)
3.5. Network Topology

For the intelligent traffic lights control, the type of the communications grid used is vital for the success of the system. The communication grid is composed by several nodes, arranged in a grid that can communicate with each other allowing messages to flow from any module to another throughout the others. The configuration of the traffic lights prototype can be extrapolated to a real case. The Zigbee mesh with all the possible modules is shown in Figure 4. The RFM69 and the RFM9xLoRa modules have a star network topology but it’s adjustable with some code changes.

3.6. Protocol Developed

The communication protocol is one of the most sensible aspects about any communication system, not to mention the safety and privacy. At this phase of building the prototype it was important to focus not only on the communication and message delivery in the system but also receiving feedback from each module, to acknowledge the success of the transmission. An encrypted password is used to protect any relevant information [11,18]. The protocol to communicate between every pair of modules in the grid was hence developed. At this phase no special protocol message size optimization was carried out to keep the messages readiness. The validation of liveness and absence of deadlocks will be needed in a more complete version of the protocol developed. The hash symbol was used as a general separator, and SMSTART as a message starter. The final protocol format is given by:

```
STARTER#INTERSECTION#TRAFFICLIGHT#OPERATION MODE#ORDER#PASSWORD#CRC
```

If the coordinator needed to send a specific red light manual order to the third traffic light in the intersection number 23, the message sent, according to this protocol, given by:

```
SMSTART#023#3#MANUAL#RED#PASSWORD#CRC
```

If the coordinator needed the intersection to start the self-management automatic mode the message is given by:

```
SMSTART#023#ALL#AUTO#ON#PASSWORD#CRC
```

The coordinator sends the information to different modules through a broadcast message. Each module interprets the message and checks if the message is assigned to it or not. This was the implementation for the prototype. A real wider case would require a unicast to the specific device and avoid the intensive use of multicasts.

4. Performance Tests

4.1. Limit Range Situations

As a simulation of possible range or connection related issues five tests were done in five different situations. Measurements were taken in the same place and same distances. The following cases were considered to check the Packet Reception Ratio (PRR):

Case 1: All the modules within the communications range; Case 2: One module disconnected. The other is located in the limit range; Case 3: All modules connected but one in the limit range; Case 4: One module out of the range of the coordinator but in the range of other modules; Case 5: Same as Case 4, all devices kept the same position except the device closer to the coordinator that is moved to the limit range of the coordinator. All the cases are shown in Figure 5.

Figure 5 - Case 1, Case 2, Case 3, Case 4 and Case 5, respectively from left to right.
To evaluate the ratio between the sent and received packets, the routers were programmed to send an ASCII character with a number incrementing from 0 for each packet sent, with a five second delay. Based on the serial sent by each router, through MATLAB it was possible to evaluate offline the packet reception ratio given by

\[
PRR = \frac{pr}{ps} = \frac{pr}{pr + pnr}
\]  

where \( pr \) is the packets received, \( ps \) the packets sent, \( pnr \) the packets not received.

For a better overview, the mean, maximum, minimum time per packet and packet reception ratio (PRR) obtained are shown in Table 4:

Table 4 – Mean, maximum, minimum time per packet and packet reception ratio (PRR) obtained

<table>
<thead>
<tr>
<th>Cases</th>
<th>Source</th>
<th>Mean time per packet (s)</th>
<th>Maximum time per packet (s)</th>
<th>Minimum time per packet (s)</th>
<th>Packet reception ratio (PRR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Router 1</td>
<td>5.0068</td>
<td>5.0340</td>
<td>4.9730</td>
<td>97.33</td>
</tr>
<tr>
<td></td>
<td>Router 2</td>
<td>5.0047</td>
<td>5.0380</td>
<td>4.9460</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Router 1 (OFF)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Case 2</td>
<td>Router 2</td>
<td>6.1841</td>
<td>26.4100</td>
<td>0.7650</td>
<td>79.80</td>
</tr>
<tr>
<td></td>
<td>Router 1</td>
<td>5.0083</td>
<td>5.1250</td>
<td>4.8730</td>
<td>96.34</td>
</tr>
<tr>
<td></td>
<td>Router 2</td>
<td>5.3491</td>
<td>31.1570</td>
<td>4.6940</td>
<td>92.68</td>
</tr>
<tr>
<td>Case 3</td>
<td>Router 1</td>
<td>5.0059</td>
<td>6.5560</td>
<td>3.4710</td>
<td>97.65</td>
</tr>
<tr>
<td></td>
<td>Router 2</td>
<td>5.0003</td>
<td>6.6680</td>
<td>3.3680</td>
<td>95.35</td>
</tr>
<tr>
<td>Case 4</td>
<td>Router 2</td>
<td>6.6024</td>
<td>20.1980</td>
<td>2.0120</td>
<td>74.75</td>
</tr>
<tr>
<td></td>
<td>Router 2</td>
<td>10.8373</td>
<td>127.3110</td>
<td>1.7620</td>
<td>44.33</td>
</tr>
</tbody>
</table>

For better comparison all cases described, the results were plotted together to determine if it corresponds to the best value of the PRR. The proximity of the coordinator with the repeaters positively influences the performance of transmission, resulting in a lower packet loss and increase in quality between the different modules. The Packet Reception Ratio of the different cases is shown in Figure 6.

Figure 6 - Packet Reception Ratio of the different cases.

4.2. Range Tests – Linear and Urban Situations

Range tests are an essential point in this work, as it ensures that all communications were properly established and establish the network communication limits. They were planned two different tests to put to the test the communication divided as follows: open field tests (line-of-sight) and urban environment (near wireless networks and buildings between modules).

To improve signal reception conditions was prepared an open field test in order to test connections in line-of-sight. In these tests were used three different communications modules and the location chosen for the realization of
those was between the Central Pavilion of the IST and the top of the Fonte Luminosa. The location of the linear tests is shown in Figure 7.

The tests were performed in an urban environment in the vicinity of the Instituto Superior Técnico, trying to get the signal transmitted between different intersections separated by office buildings, which may influence the signal quality. The location of the urban tests is shown in Figure 8.

4.3. Architecture Tests

After careful analysis of the results of the three tests, it is possible to briefly draw some conclusions of which can highlight the good adaptation of the network topology and high receptivity to new sensors and modules using the ZigBee protocol, good communication when the antennas are in line-of-sight and the difficulties on pass through a building when using low frequency LoRa transmissions. With the data obtained is possible to structure a possible architecture to be used in the control network.

For a regional communication between junctions a long-range communication is required. From the results it can be concluded that it is impossible to easily implement this communication between intersections without resorting to another form of communication present in all the places and, therefore, dependent on external operators, such as GSM.

All the different levels of the architecture presented are shown in Figure 9.
To test if it was possible to give an order through the global LoRa network and this is understood by the local system Zigbee was broadcast globally to all network modules the RSSI value of the connection of the first LoRa module being showed in the last Zigbee module. With the cadence of each transmission the destination Zigbee could acquire the RSSI value of the first LoRa module. The communication between the two wireless communication technologies using different operating frequencies was established.

5. Conclusion

Prototypes built and the tests realized were able to prove that all the presented system is functional. Limit situations tests showed that the local network Zigbee allows easy addition of new modules. It allows, for example, the addition of new sensors to some intersections without having to replan and reconfigure the whole network. More points of traffic detection, among other sensors may integrate the existing traffic control network. Signal range tests concluded that when the modules are in line-of-sight range is higher and the network can be expanded more easily. But in urban centers where there is a large cluster of obstacles it is important to place more repeaters. Architecture tests performed allowed to test the entire network, allowing interaction between all wireless communication technologies chosen for the prototype presented.

References


