Development of a Smart Traffic Light Control System with Real-Time Monitoring

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***Abstract*—From its emergence to the present day, traffic light control systems has been widely used to monitor and control the flow of vehicles. However, with the increasing number of public (bus) and private vehicles (car, motorcycle, and truck), urban centers are becoming more and more populous. Such phenomenon leads to traffic congestion and increases environmental and noise pollution. In order to stem the rise of such problems, large cities are adopting technological solutions, materializing the concept of smart cities. While observing traffic management systems themselves, several hardware and software solutions have been studied and implemented around the world. This paper aims to contribute to traffic signals improvement by developing a centralized traffic light control system, using a unique wireless communication network. In order to prove the system's effectiveness, the most common types of urban intersections were analyzed. Direct control routines were implemented for network traffic lights, providing a complete control system for extraordinary events, such as closing roads due to accidents or public events. Finally, safety routines were formulated to report the operating status of the traffic light system lamps to a central management. With the aid of a logic analyzer connected to the outputs for each focal group, it was possible to set up an operating stages timing diagram of each traffic light. Thus, the system validation was achieved based on theoretical and practical timing diagrams similarities.**

***Index Terms*—Smart traffic light, wireless communication, smart urban mobility, smart cities, internet of things.**

I. Introduction

About 68 % of the world's population will be living in urban areas by 2050, according to a projection of the world urbanization, undertaken by the United Nations (UN) in 2018 [1]. The urbanization area phenomenon, once predominantly rural, has completely changed human interaction with the environmental. This unplanned city growth has caused detriment to the population, such as increased vehicular traffic, congestion, increased in environmental and noise pollution, as well as many insecurity aspects [2, 3, 4, 5, 6].

To sort out problems generated by urban growth, several forms of high-tech electronic devices have emerged around the world, each proposing to solve a certain complication of everyday life. Such technological applications are fruits of the dissemination of the so-called Internet of Things (IoT) [7].

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Another key asset for the attainment of smart cities is the technologies relating to physical, electrical, and information and communication technologies (ICT) [8, 9, 10].

Figure 1 shows a simple and generic model of the composition of a smart city. One can notice the different areas of concentration that propose a specific solution to an urban problem.

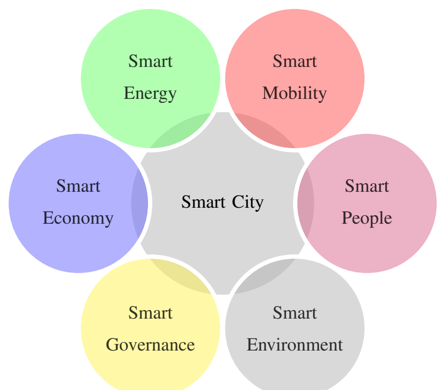

Figure 1. Smart city composition model.

Among the application areas in smart cities, the field of smart mobility stands out for its ability to propose technological solutions, which reduce traffic congestion, accidents, environmental and noise pollution. According to Schrank et al., in 2014, congestion costed North Americans about an additional 6.9 billion hours of travel, consuming around 3.1 billion liters of extra fuel, resulting in a bottling cost of 160 billion dollars [11].

To collaborate with traffic light system modernization and to improve living conditions in future urban centers, the present work has developed a traffic control system remotely operated using wireless communication technology.

The main improvements in traffic management would be: a) considering it is a wireless system, the installation of new traffic lights would be simpler, i.e, no communication cable installation would be necessary in intersections and throughout the city; b) Flexibility, i.e., with the proposed communication method, the system will operate not only at a crossing type, but also in several intersections types, from the simplest one (intersection with a single traffic light) to the more complex types (intersection with several traffic lights); c) real-time, i.e., since all traffic lights operating status are being carried out in real-time, traffic congestion situations caused by temporary traffic failure can be reduced, and a technical team can be immediately instructed to handle the traffic light faulty situation.

This paper has been split into nine sections. Section II provides definitions and functionality of existing traffic lights. Section III reports on similar existing work. Section IV describes the electronic device and wireless network utilized. Section V describes the main types of traffic light intersections. Section VI specifies modes of communication between wireless traffic lights of an intersection. Section VII relates the results obtained and practical tests. Section VIII discusses future research directions. Section IX reports final conclusions.

II. Traffic Light Systems

Originating in ancient Greece, the word *Semaphoros* is the union of *sema* ("sign") with *phoros* ("which leads"), that is, a signaling apparatus [12]. Created by John Peake Knight, the world's first traffic light was installed in 1868 at a crossroads in the city of London [13]. From its creation to the present day, its purpose has always been to control the circulation of vehicles. What has been changing is how traffic lights manage such flow.

A. Traditional Traffic Light

The traditional traffic light systems basically operate with their static time base, that is, manually configuring the time at which each lamp will be lit [14]. Its configuration can be either carried out by a professional operator or by a wired communication network, connecting each traffic light in the city to a single location, the so-called central management traffic light system. The advantages of conventional traffic lights are:

- Simplicity, for it is only a timed lamp drive circuit;
- When in possession of a centralized system, communication is done via cable, ensuring the connection between the traffic light and the management center.

However, its disadvantages consist of:

- Due to having a static time base, it does not consider current vehicle flow passing through the road. Therefore, it does not optimize the time at which each lamp is lit, leading to wasting time, inducing traffic jams, and increasing the emission of pollutant gases to the atmosphere;
- Despite the physical connection, via cable, ensuring the connection between the traffic light and the management center, when dealing with large urban centers, the length of these cables can reach thousands of kilometers [15]. According to the city of Sao Paulo's Engineering and Traffic Company (CET), a complete semaphore revitalization of the city would require 2520 km of electric cables [16]. About 11 % of occurrences that cause the city's signaling system to malfunction are due to wiring damage and humidity, and about 13 % to external agents such as cable theft and vandalism [15]. If the semaphore system communication is performed completely wirelessly, it would inhibit such occurrences.

B. Smart Traffic Light

To remedy the problems encountered in conventional traffic light systems, the concept of intelligent traffic lights has emerged. Smart traffic lights are electronic devices which perform traffic and pedestrian management dynamically. In order to perform such feature, they need to determine certain traffic characteristics at real-time. In general, the characteristics extracted are:

- Number of vehicles passing through the road;
- Speed of these vehicles.

The use of magnetic sensors [17], infra-red sensors [18] and cameras [3] allows for the gathering of traffic flow characteristics. By counting the vehicles that pass in each crossing, it becomes possible to establish priority scheduling algorithms [18]. By knowing the speed at which a car crosses the semaphore, it is also possible to calculate the time required to reach the next semaphore to find it open [19]. Figure 2 illustrates the various enhancements found in smart traffic lights.

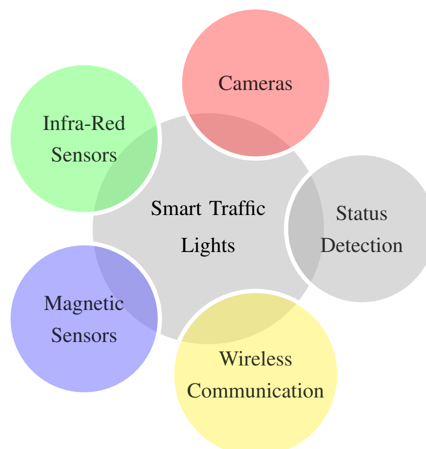

Figure 2. Composition of a smart traffic light.

The ability to report operating conditions (if the lamps are burnt, for instance) or whether failures are presented in the communication and/or control systems, allows for immediate action from the management center. To eliminate problems related to wired communication, the intelligent traffic lights seek to establish wireless communication with other traffic lights crossings, as well as with the management center [20, 21].

III. Related Works

The authors Megalingam et al. developed a traffic control system based on the information fed through a Wireless Sensor Network (WSN) nodes, not only to perform efficient traffic routing but also to track vehicles going at higher speed. However, in this case, the authors did not implement any real semaphore systems, only a system to exchanges data between WSN nodes and a Central Monitoring Station (CMS) [22]. Based on data found on WSN Rida et al. proposed a traffic light adaptive control method. Although the authors conclude the method reduces vehicle-waiting time, the system only operates in isolated intersections [23]. In their work designed to control multiple intersections, Zhou et al. developed a traffic light control based on the collection of many types of data through WSN [24]. Despite the work emphasizing the development of an algorithm capable of managing various intersections in real-time, the authors tested their method only for two-way (TW) intersections (both directions, that is, in TW/TW intersections). In the present work proposal, various intersections types of several intersection traffic lights would be simplified [24].

In many works proposed by Cunha [20, 25, 26, 27], a wireless communication system for traffic control and management have been presented. He has made use of ZigBee as the communication protocol information between the traffic lights. However, the communication between the intersections and management center was performed using a long-range communication protocol (LoRa technology). Silva have also used the ZigBee protocol in an intelligent traffic light system [21]. Although it presents several traffic light operational calculations, based on the number of vehicles circulating through the crossing, in his system, there were no vehicle detection sensors. Instead, he considered both random and deterministic values. His work addressed only one intersection type.

There are many research areas to come up with emergency systems for accident intersections, according to [3]. According to Qi et al., a control strategy based on Petri Nets (PN) and the traffic lights system can control other facilities, including magnetic loop detectors and warning lights. In [28, 29, 30], an electronic system was designed for traffic lights and emergency vehicles communication, allowing them to control the intersection to prioritize ambulances and police vehicles. Instead of building an infrastructure to remain positioned next to a traffic light and exchange information with vehicles, as in [28], the present work proposes that the traffic light itself be able to communicate over a wireless network with a management center. Sundar et al. have designed a system to count vehicles by using Radio Frequency Identification (RFID) to estimate green light required time. In this case, he used a ZigBee protocol to exchange information about the walking distance between the vehicles and the traffic lights, so police authorities could be activated in the case of a stolen vehicles detection [31]. Although the article details the RFID operation, Sundar et al. did not detail the communication system between traffic lights. Therefore, in the present work, despite direct intervention from the management center, specific safe routes could be created in case of a stolen vehicle detection culminated in a police chase.

IV. Traffic Light Electronic Circuit

In the topology adopted in this work, the traffic light is composed of a basic operating circuit and a wireless communication interface. A basic circuit means an electronic circuit capable of performing the following tasks:

- Switching Alternating current (AC) lamps;
- Switching Direct current (DC) lamps;
- Checking each lamp status;
- Entry for the pedestrian priority button;
- Network communication through the radio-frequency (RF) module.

The electronic system high-level architecture diagram can be seen in Figure 3. The system core is operated by an ARM Cortex-M3 32-bit architecture microcontroller, where all traffic light system programming will be done.

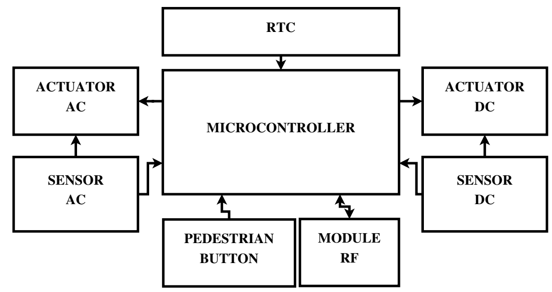

Figure 3. High-level architecture of the electronic circuit developed.

To perform the synchronization between several successive crossings, allowing the semaphore to operate in progression mode in real-time, a peripheral Real-Time Clock (RTC) was also used as the date source and as the reference clock of the traffic lights. The electronic circuit can be seen in Figure 4.

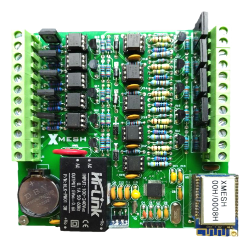

Figure 4. Electronic circuit developed.

The circuit allows for the control of a single traffic light, containing a vehicular focal group (green, yellow and red) and a pedestrian focus group (green and red), and has a priority button input (pedestrian button). More details on the actuator and sensor circuits design are described in [32]. In order to develop a low-cost technology, the total cost of the proposed prototype (considering the board manufacture, the components, and RF module), was about US$ 19.76. This calculation was performed for the construction of ten electronic boards, as presented in Figure 4, therefore, for large-scale production, the total cost will reduce. In addition, due to its small size, it can be placed together with the vehicle focus group, far from the ground, to reduce acts of vandalism.

A. XMesh Network and RF Module

Regarding the conduction of wireless communication between electronic devices, several technologies arise under certain operation circumstances. However, when the system requirements contain, for instance, large number of devices (more than 1000) within the same network, at certain distances and transfer rates, the horizon of choices are restricted. Several works have been utilizing the ZigBee communication protocol to create a mesh network [20, 21, 31, 17]. Mesh networks are ideal for the application to smart cities, since they can regenerate themselves in case of some device disconnection from the network. Thus, the system itself will look for another device within its range, planning another route path.

The present work uses recent technology still in the development phase (but is already operational for use, denominated XMesh), originally proposed in a doctoral research at Unicamp [33]. More specifically, as it can be seen in Figure 5, the XMesh network contains two innovative blocks to meet the needs of the smart city's requirements.

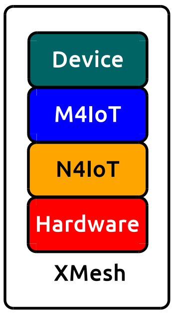

Figure 5. XMesh network model.

According [33], the blocks cited in Figure 5 are:

- Block N4IoT Network layer with mathematical modeling for routes;
- Block M4IoT - Protocol that allows for the creation of a Virtual Private Device Network (VPDN) and uses elliptic curves for security (encryption), having a very low packet payload when compared to other packet standards for mesh networks.

The XMesh network operates at 2.4 GHz Industrial, Scientific, and Medical (ISM) non-licensed frequency band, and can achieve a transfer rate up to 2 Mbps. It uses two output power options. For a maximum communication distance of 100 m, the output power is 0 dBm and for 1800 m the power output of 20 dBm is used. One way to get around the problem of the ISM band suffering disturbances and interference due to climatic conditions and other radio frequency signals at the location is to use the RF module at the maximum power allowed by local regulation. After being energized, the traffic lights only exchange messages with the other traffic lights at the intersection, at a short-distance. Another possibility to ensure receipt of warning messages for any loss situations messages would use another redundant network technology, used only in cases of data loss, as described in [20]. Optimized to improve latency, the data frame consists of 30 bytes, 20 bytes of header and 10 bytes for user data. Based on [34], several wireless network technologies were compared along with XMesh network data. The results are presented in Table I.

WSN communication protocols are a common research topic nowadays. Although many works define several package delivery methods, they do not implement a complete routing table, only partial [35, 36, 37, 38].

Table I
COMPARISON OF THE MOST COMMON WIRELESS TECHNOLOGIES AVAILABLE.

Tech.	Data Rate	Range	Power	Net. Size
ZigBee	250 kbps	60 m	Low	Very Large
Bluetooth	2.1 Mbps	100 m	Low	Small
Wi-Fi	1.3 Gbps	100 m	High	Medium
LoRa	100 kbps	5 km	Very Low	Medium Large
XMesh	2 Mbps	1800 m	Medium	Very Large

Unlike the ZigBee protocol, which is built on top of the IEEE 802.15.4 standard, the XMesh network is a completely new network, entirely independent of the limitations imposed by the IEEE 802.15.4 standard. A paper exclusively dedicated to detailing the functioning of all XMesh network building blocks is being prepared and will be published soon. The XMesh network develops its routes through mathematical modeling, enabling its use in low processing power devices, such as microcontrollers and embedded systems. It is a very important technology improvement, making countless network points possible. Besides, the XMesh network enables individual VPDN per device.

The development of a semaphore system whose communication is fully performed using a wireless network must not only operate synchronously, but also ensure a maximum robustness regarding possible data loss (RF signal), semaphore failures and WSN intrusions.

As presented in [39], sensors are used for vehicle flow detection whose data transmission is done by WSN could make the system vulnerable in terms of security. In this case, if a malicious hacker equipped with appropriate technological tool connects to the vehicle flow detector via WSN, they would be able to send manipulated data, misleading the semaphore system and causing possible traffic accidents. The XMesh network has three layers of encryption: hardware, software and protocol.

The M4IoT protocol implements, hardware level, 256-bit Advanced Encryption Standard (AES) encryption (algorithm with recommendations for government institutions and even military applications) and a 24-bit Elliptic Curve Cryptography (ECC), at software level (offers better security with smaller key size). The AES and ECC are a widely used encryption algorithm and are considered a secure and robust algorithm [40, 41]. Even if the attacker could decrypt the algorithms mentioned above, he would still have to find the correct protocol message in order to temper with the semaphore system.

Fortunately, the actuation commands provided by the M4IoT protocol are not the same for successive submissions, that is, the attacker would not find the sent data pattern to replicate them. In addition to the actuation commands not being constant, they are still valid for only one-time intervals, so any attempt to send command after this interval of time will automatically invalidate the message.

Regarding the network coordinator device (central management), even if it is turned off, all traffic lights continued to function normally, because the traffic lights only need to exchange information with the central management during ini-

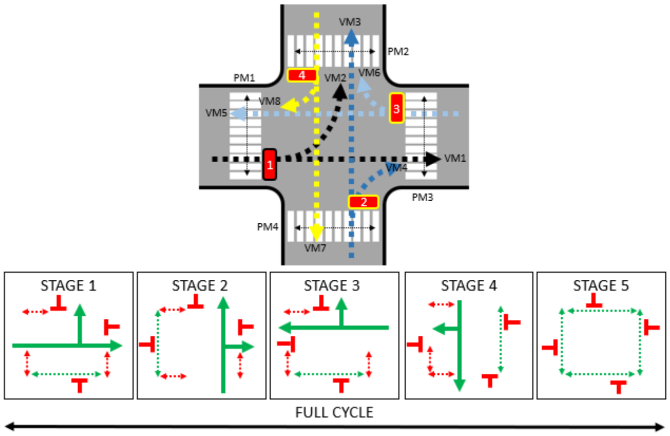

Figure 6. Model of an cross intersection TW/TW.

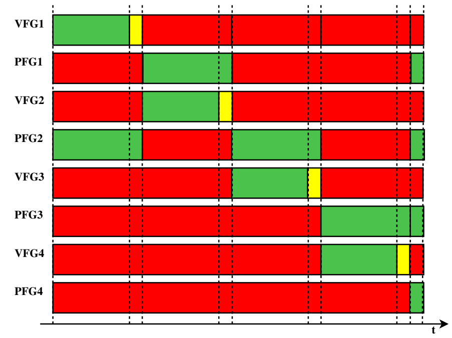

Figure 7. Temporal diagram of an cross intersection TW/TW.

tialization and traffic light failures moments. The management center does not need an internet connection, and therefore, the only way to invade the management center would be through its XMesh network, which has the protection mechanisms previously mentioned.

V. Urban Intersections

Regardless of whether a traffic light is intelligent or not, it has a certain operating cycle for each type of intersection. According to Martins (2013), the basic types of urban intersections are [42]:

- Intersections with 3 approximations, in "T";
- Intersections with 4 approximations, in "Cross";
- Intersections with multiple approximations.

Considering the number of approximations of an intersection, and if it has a one (OW) or two (TW) way street, its programming complexity increases. Given the existence of several combinations, the following intersections will be implemented throughout the work:

- Simple crossing of OW and TW;
- T Intersection OW/OW type 1, OW/OW type 2, OW/TW, TW/OW type 1, TW/OW type 2 and TW/TW;
- Cross Intersection OW/OW, OW/TW and TW/TW.

Figure 6 comprehensively shows a functioning TW/TW cross intersection, with a diagram of its respective stages.

Each stage represents a state (green, yellow or red respectively) for a certain semaphore. A complete operating cycle represents the execution of all stages of a semaphore.

The traffic lights are represented by enumerated red rectangles: master of the intersection (black border), slave with operation cycle different from that of the master (yellow) and slave with operation cycle equal to that of the master (turquoise). Finally, the rectangles represent traffic lights that have both Vehicular Focal Groups (VFG) and Pedestrian Focal Groups (PFG), represented by squares.

Figure 6 also shows the push-button operation, a device that detects the pedestrian request [43], represented by stage 5. The temporal diagram graph in Figure 7 represents all traffic lights states and stages and the cross intersection TW/TW.

VI. Communication Between Traffic Lights

The communication protocol utilized was based on the exchange of packets/messages between the "end device" and the "coordinator (gateway) network". It is considered as the "end device" the prototype presented in Section IV, and the "coordinator" the device that manages the messages exchanged with the prototype and the database, which contains information of all network traffic lights. The system coordinator uses a BeagleBone Black (development board) with Linux embedded. The operating system manages the queries in the local network database, as seen in Figure 8.

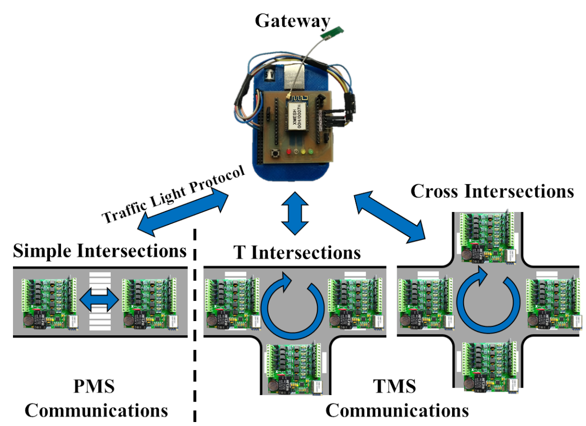

Figure 8. Network working scheme.

The system user can control all online traffic lights on the network through the gateway. All traffic light information registered on the network remains stored in a database form on the gateway, which periodically updates its data tables. Therefore, the user has access to all possible problems/warnings of all traffic lights. The proposed system intelligence is related to: a) self-configuration capacity of each semaphore, based on the data registered within the gateway (only requires its installation to the power grid), and b) the ability to detect the malfunctioning of traffic lights, alerting not only the management center, but also the crossing drivers (yellow light blinking for example).

All messages used during the communication between the traffic lights and the gateway can be seen in Figure 9. The data frame is limited to 10 bytes per packet.

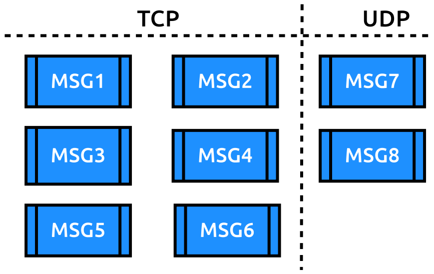

Figure 9. Traffic light protocol.

Thus, all the necessary commands for the traffic light system functionality were added to the M4IoT protocol, creating exclusive commands for the traffic light system [44], listed below:

- Each message definition that requires a response (Transmission Control Protocol (TCP) style) are:
  - Message 1 (*MSG1*): semaphore configuration request;
  - Message 2 (*MSG2*): response to the semaphore configuration request;
  - Message 3 (*MSG3*): trigger traffic light, which expects an MSG4 response;
  - Message 4 (*MSG4*): response to MSG3 traffic light;
  - Message 5 (*MSG5*): reading the semaphore, which awaits a MSG6 response;
  - Message 6 (*MSG6*): response to MSG5 traffic light.
- Message definition that do not require a response (User Datagram Protocol (UDP) style) are:
  - Message 7 (*MSG7*): sending data;
  - Message 8 (*MSG8*): semaphore failure.

The use of each message is specific to each analyzed situation and can be sent from the semaphore to the gateway, or vice versa. When studying the types of crossings to be implemented, it is possible to regard each semaphore component of a given intersection as master or slave, in which both have four states: green, yellow, red and pedestrian. The master semaphore defines the instant at which slaves must change state. The slave semaphore passes messages from the master to the other traffic lights at the intersection.

All these settings described above are performed the moment the semaphore receives its first response from the network coordinator. However, for security reasons, from the moment the semaphore is powered by the electric grid, it remains in alert mode, with the vehicular yellow and pedestrian red focus in alternating mode. The traffic light will only exit the alert routine if the process described in the following section is completed successfully.

A. Permanent Master-Slave Communication

The master-slave communication is used to alter the slave's state, which occurs together with the master's state change. The term "Permanent Master-Slave" (PMS) is defined for the simple crossings traffic lights, i.e.: simple crossing OW, simple crossing TW, T intersection OW/OW type 1 and TW/OW type 1. Therefore, the flowchart describing the initialization routine of such traffic lights can be seen in Figure 10. This flowchart also demonstrates a simple crossing traffic lights initialization procedure.

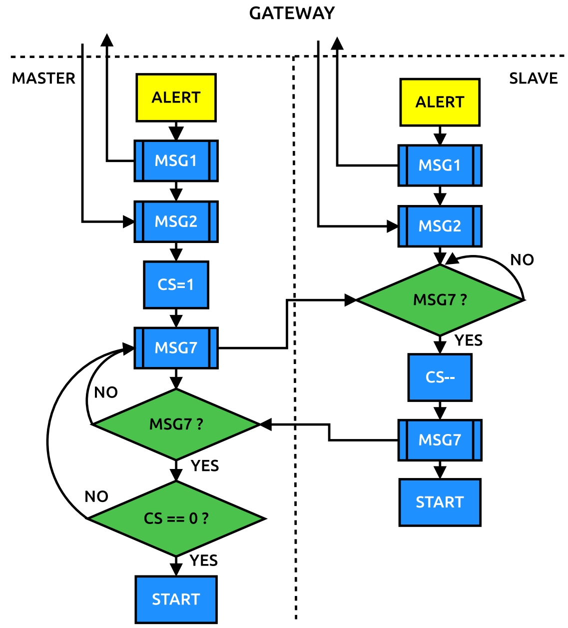

Figure 10. Routine communication between two traffic lights from the same intersection.

The operation procedures consist of:

- After both traffic lights are hooked up to the electric grid, they immediately enter in the alert routine;
- Next, they request a semaphore configuration (*MSG1*) to the network coordinator;
- After receiving the configuration from the coordinator (*MSG2*), such values are stored in their Random Access Memories (RAMs);
- If the semaphore is a master:
  - Value 1 is assigned for a traffic light count variable, *CS = 1*;
  - Through the *MSG7* message, variable *CS* is sent to the address of its slave;
  - It remains on hold by checking the receipt of messages and, at intervals, resubmits the *MSG7* message;
  - At the moment the master receives the return of the *MSG7* message containing the value of *CS = 0*, alert is ceased and the normal operating mode commences, that is, it performs the states changing routines according to green, yellow and red times provided by the coordinator. At the changing of each state, the master sends a new *MSG7* message to its slave.
- If the semaphore is a slave:
  - The slave awaits a *MSG7* messages, provided by his master;
  - After receiving the *MSG7* message, the traffic light count variable provided by *MSG7* is decremented and send back to its master;
  - The slave traffic light suspends alert mode and commences the normal operation mode, that is, it

will only change states if a new *MSG7* message is received, sent by the intersection's master.

Thus, the message will always make a complete turn at the intersection, always starting from the master, passing through the slaves and returning to the master again. This concept expands to the intersections in T OW/OW type 1 and TW/OW type 1, which have one master and two slaves. If the message does not reach the semaphore at the end of its current state, for more than 1 s, it will enter in the alert routine by sending a *MSG8* message to the gateway.

B. Temporary Master-Slave Communication

Akin to the PMS communication, the "Temporary Master-Slave" (TMS) communication also performs a full turn at the intersection. However, in this case, the slave changes its state in periods when there are no changes in the master's state. Thus, it is necessary to change the intersection arbitration, the master becomes a slave and vice versa.

In TMS mode, when the attention state changes to stop (the first loop ends), the master becomes a slave, handing over regency of the crossing. When finished, the loop is restarted to the original master of the intersection, Figure 11 exemplifies this situation.

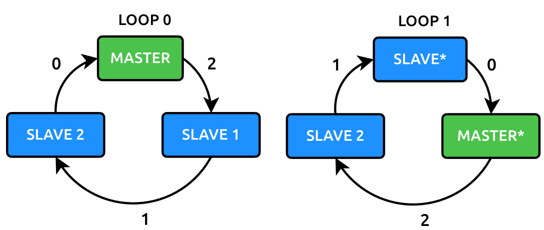

Figure 11. TMS communication routine of a crossing.

Figure 11 shows the specific case of an intersection with three traffic lights, with the semaphore counter decreasing from 2 to 0, just as PMS works. But when the master changes the state from yellow to red, instead of sending *CS = 2* to its slave, its sends 0 and automatically changes its condition from master to slave. The slave, when receiving the variable *CS = 0*, changes its slave condition to master.

VII. Results

The VFG and PFG states were measured on all semaphores of each intersection type. The measurements were obtained with the aid of a logic analyzer. However, as a logic analyzer used only eight digital channels, all signals of a traffic light were measured in five channels, and the vehicular green signal of the master traffic light was measured in the sixth channel.

Thus, the data measurement of all traffic lights was synchronized with its master. The synchronization of all semaphores was done by exporting the data from the software of the logic analyzer used to MatLab® software. To analyze the signals, we considered the vehicular green times of 10 s and vehicular yellow of 2 s.

The result of implementation on all types of intersections was successfully acquired. The practical operation cycle had the same time values as the theoretical one, as anticipated. Therefore, here will be presented only the results for the cross intersection TW/TW (the more complex approach). Figure 7 shows a temporal diagram of a cross intersection (theoretical) and Figure 12 presents the results of its measurements, both for TW/TW intersection.

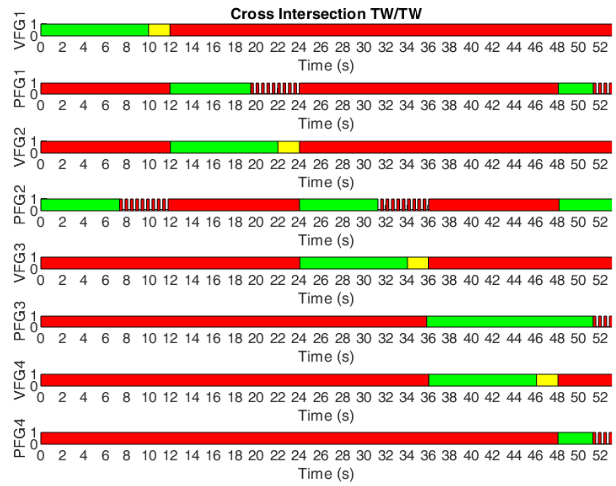

Figure 12. Measurement of all traffic lights of cross intersection TW/TW.

Both figures also exemplify the pedestrian button action (which adds an extra stage), where all VFGs remain red until the end-stage (after 5 s). The only discrepancy between them is that in the practical results the intermittent red routine for pedestrians was performed, signaling the time for pedestrians to cross is running out, a situation predicted in Brazilian Manual of Traffic Signs [43].

The blown bulbs detection routine was also verified, by disconnecting each lamp from the circuit of Figure 4. By using the *MSG5* message, it was possible to read the semaphore state in real-time. The task was able to detect the AC/DC lamps state correctly.

The action of *MSG3* messages was examined. The *MSG3* message was sent to a given semaphore to remain 30 s in the "stop" state. The same procedure was repeated for the "go" and "alert" states. In all cases, the semaphore remained in the state and time designated by the user. After this mode had finished, they returned to its normal operation.

An important system task to be analyzed concerns semaphore failures. Power outages in both master and slave traffic lights were considered, and the lack of communication between traffic lights were analyzed, as well. Figure 13 shows the time diagrams for a simple TW intersection the moment of semaphore failures due to power outages.

"Power Source 1" and "Power Source 2", seen in Figure 13, represent the power supplies for both traffic lights 1 and 2, respectively. Thus, the value "1" set the 127/220 V power supply for the semaphore and the value "0" represents no power supply.

By removing the power supply from the master traffic lights (*VFG1*), the traffic light system performs as presented in

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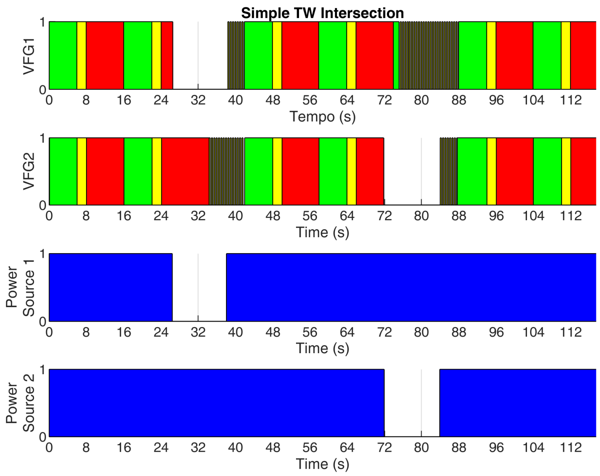

Figure 13. Measurement of all traffic lights of simple TW intersection, in first fail situation.

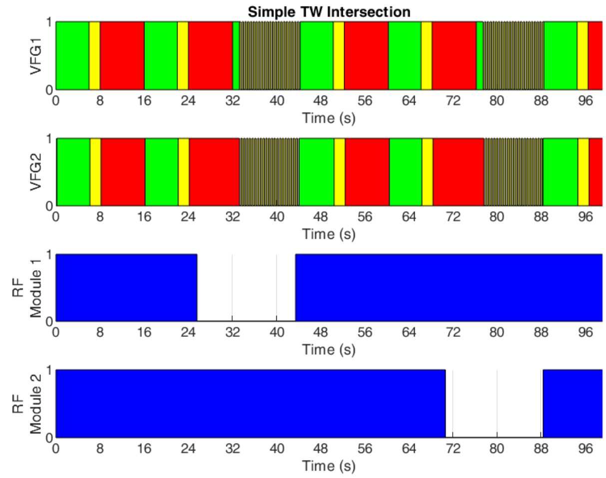

Figure 14. Measurement of all traffic lights of simple TW intersection, in second fail situation.

Figure 13. In this situation, the semaphore fault is reported to the network coordinator through the slave traffic lights located at the intersection where the fault occurred. Once more, when the power is restored, the traffic light immediately enters *ALERT* mode, and commences the normal operating mode. It is interesting to note that the timing between the intersection's traffic lights before switching off the power (activity observed happening under 24 s) was restored after they resumed their normal functioning (activity observed happening over 45 s). The same activity is observed when unplugging the power supply from the slave traffic light, that is, around 72 s. The slave traffic light was turned off, and since it does not receive a command *MSG7* at time no greater than or equal to the current state time plus one second, the master semaphore enters *ALERT* mode. By restoring the slave traffic light energy (around 85 s), the message *MSG7* (master) is sent by its slave, returning back to the master traffic light and, immediately, both traffic lights reestablish their normal operating cycles.

Finally, to establish wireless communication data loss between traffic lights, *VFG1* and *VFG2* were constantly connected to power sources. An electromechanical relay drive module was inserted to allow for switching on/off RF modules 5 V power supply only. Figure 14 shows the two traffic lights performance of a simple TW intersection, having 6 s of green light, 2 s of yellow light and 8 s of red light; a complete cycle of 16 s.

Signals with the words “RF Module 1” and “RF Module 2” when in “1” means that the RF module is working normally, but when in “0” it means is no wireless communication, corrupting and/or prohibiting communication between traffic lights. Therefore, when *VFG1* (intersection's master) loses communication with its slave, again there is no exchange of message *MSG7* between slave/master at a time no greater than or equal to the current state time plus one second, it immediately enters *ALERT* mode and, by not being able to communicate to its slave, the slave traffic lights also enters *ALERT* mode. It is only after the master resumes the communication again between other intersection traffic lights that they will return to normal operation. All the analysis is also valid in case a slave semaphore loses communication with others, according to the traffic light system activity for over 70 s.

VIII. Future Research Directions

The proposed system does not have sensors for the detection of vehicular flow nor an algorithm for adjusting the phase between traffic lights (commonly known as “green wave”), however it does allow the secure remote update of the times of each traffic light online in the network. Thus, as future research, we propose the development of an electronic sensor device capable of not only counting the vehicles traveling on an avenue, but also measuring the average speed of these vehicles. In this way, this device would use the same XMesh network as the traffic lights, but in another VPDN, to send such values to the traffic management center.

A interesting project would be the creation of an electronic device equipped with several sensors located in public vehicles, such as police vehicles and ambulances, so that in emergency situations, such vehicles would issue priority request messages to the management center, which in turn create exclusive routes for them.

Another great potential of using the wireless traffic light system is its use in conjunction with Intelligent Transport Systems (ITS). Through vehicle automation, the information exchange (technical conditions of the vehicle and the road) from vehicle-to-vehicle allows for a better perception of the environment surrounding it. The interaction between the traffic light system (such as an IoT platform) and the ITS, may (through the data exchange between the vehicle and the infrastructure) identify potential traffic jams and/or accidents and inform other vehicles traveling on the same route, enabling better decision making and improvement of navigation systems and location of automated vehicles.

Finally, another proposal for future work would be the creation of an algorithm (executed in the traffic light management center) that, based on the information sent by the vehicle flow sensors, is able to adjust the times of each traffic lights cycle of operation and the times for green wave coordination. With the development of the aforementioned applications, it will be possible to manage the flow of vehicles during peak hours and to synchronize traffic lights between successive intersections of an avenue (green wave) and thus determine which are the combinations of time adjustments that improve urban mobility for certain circumstances.

IX. Conclusion

According to the results described in Section VII, the traffic light system was fully operational. The communication between the crossing traffic lights and the network coordinating device was accomplished. All traffic light operation stages were configured remotely, and the safety routines enacted at the expected time (system initialization).

The action of the pedestrian buttons has entered the pedestrian stage correctly, i.e., at the end of its operating cycle. All routines presented in Section VI operated according to the project requirements.

The system can be fully configured. By sending commands through the gateway, the operation time can be set, as well as the intersection type and monitoring of the status of each lamp in the XMesh network. Despite being a low-cost solution, the ability to switch both AC/DC lamps allows for its employment in many real-world scenarios.

The results obtained in Section VII demonstrated the system's ability to perform all wireless communication tasks.

Data acquisition from other applications, as presented in Figure 2, such as the detection of official vehicles (police vehicles, fire engines and ambulances) or vehicle detection systems (cameras, infra-red and/or magnetic sensors) is also permitted. It enables the enhancement of traffic light management systems, blocking and creating alternative routes to not only avoid the traffic jams, but also preventing new accidents.

By making all information available from online traffic lights on the network, the proposed system can be used in different works to create algorithms to optimize the traffic light operation times, or synchronize successive intersections in real-time [23, 21, 31].

The wireless traffic light system here presented, in addition to a new way of managing urban traffic, enables the research and development of further technological devices associated with smart cities.

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