Analysis of IEEE 802.11g standard for communication in a traffic lights distributed control system

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Abstract—Several studies use wireless communication in different knowledge areas and for different purposes. Restrictions concerning the reliability of transmission may directly affect the good performance of wireless communication. In this work we analyze the wireless communication behavior, using the IEEE 802.11g standard as a basis and aiming at proposing a reliable communication model to a distributed control system of traffic lights. Moreover, analyzes were carried out, by simulations and experiments. Parameters such as distance, power and transmission rate were considered in the analysis and the validation of the results was performed by comparing the delay obtained in the experiments with the theoretical delay obtained in equations which consider the specifications of the IEEE 802.11 physical layer.

Keywords: IEEE 802.11g; Distributed control of traffic lights; modulation scheme; data rates; power transmission.

I. INTRODUCTION

Reliability is essential for the proper performance of any application which uses wireless communication for data transmission. Considering the constant evolution of wireless communication, which become increasingly used in several knowledge areas such as distributed control systems, it is observed which factors, such as the reliability of data delivery [1], the interference between the nodes or control system agents [2], and the frequency with which agents in a control system can update each other [3], are essential for good performance of control systems and also applies to another knowledge areas which uses wireless communication for data transmission.

Several works have been conducted in order to resolve problems presented on wireless communication. The majority of papers presented focused analysis on parameters defined by standard MAC layer IEEE 802.11, and the communication behavior is frequently analyzed in order to model delay and throughput limits of the network in which the major concern is the transmission of large amounts of data, due to the characteristics of the applications. There are few works related to parameters of the standard IEEE 802.11 physical layer [4] [5], such as the performance of modulation schemes, data transmission rates, and rates.

However, most works are based on simulations, which simplify the communication channel behavior, considering ideal conditions for the transmission and omitting, for instance, collisions. Besides that the major concern is the transmission of large amounts of data, thus the communication reliability is not considered by the analyses.

Considering which few studies evaluate aspects related to physical layer, focusing on the transmission of large amounts of data restricts the results to specific scenarios. This paper proposes the analysis of wireless communication of a distributed control system of traffic lights by performing simulations and experiments, considering aspects related to IEEE 802.11 physical layer and evaluating the performance of data rates, types of transmission and modulation schemes standard IEEE 802.11g [4].

In order to analyze the communication channel, it is proposed to investigate and validate the model presented in [7], which presents equations that define the theoretical values for the throughput and the delay of the transmission. Thereby, specifications - considering the IEEE 802.11 standard structure - for the use of wireless communication between nodes that make up the distributed system of traffic lights are established. Analysis of the IEEE 802.11 standard structure will be performed with testing for different configurations of networks and will be further validated by the model equations proposed in [7].

II. RELATED WORKS

There are few works related to parameters of the standard IEEE 802.11 physical layer, such as the performance of modulation schemes, data transmission rates, and range. The few studies which present these types of analyses use simulation results, often carried out in MATLAB [4] [5].

From the few studies that evaluate aspects related to standard IEEE 802.11 physical layer that use MATLAB to carry out research, [5] evaluates the performance of modulation techniques Quadrature Amplitude Modulation (QAM), Quadrature Phase-Shift Keying (QPSK) and Binary Phase-Shift Keying (BPSK), when subjected to a number users, noise and interference in the communication channel. The authors compare performances considering values of Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) for the modulation schemes. The studies conclude that modulation schemes that present high data transmission rates tend to have a higher error rate.

In [4] a performance analysis from QPSK and BPSK modulation schemes was conducted. Simulations were performed on MATLAB, considering the presence of noise...
in the communication channel. The authors describe that QPSK is better compared to BPSK because the number of symbols is doubled in the QPSK constellation with respect to BPSK, which enables the transmission of two bits simultaneously.

In the experimental tests carried out in this work we notice that, for the configurations used, higher rates have limited performance due to various parameters, such as the modulation scheme used, the transmission distance and also the overhead, which emphasizes the good performance of the lowest rates, as can be seen in [7]. In this work, it is pointed out that increasing the data rate without reducing the overhead limits communication performance.

The existence of a theoretical upper limit of throughput and a theoretical lower limit of delay to the IEEE 802.11 standard is emphasized in [4]. Results showed that performance with respect to delay and throughput is limited, which means that increasing the data rate only will imply improved performance until reaching the throughput limit. The authors emphasize that the reduction of overhead is essentially necessary for it to achieve higher throughput. To reach these results, the authors analyzed the fundamental method of access to the middle of the IEEE 802.11 Distributed Coordination Function (DCF).

It is notable the lack of research that present tests or experiments in real environments, besides the absence of analyses about the aspects related to the standard IEEE 802.11 physical layer, such as modulation / coding scheme. In this respect, this work intends to analyze the wireless communication behavior, using closest possible scenarios to reality.

III. PHYSICAL LAYER IEEE STANDARD 802.11

The physical layer selects the correct modulation scheme, considering the channel conditions, and provides the necessary bandwidth. The IEEE 802.11 standard defines four types of physical layers: infrared (IR), Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and Orthogonal Frequency Division Multiplexing (OFDM). This work only considers DSSS e OFDM modulation schemes for analysis.

A. Orthogonal frequency-division multiplexing (OFDM)

In OFDM, technique transmissions are performed at different frequencies simultaneously in sub-orthogonal carriers. The OFDM Physical Layer uses various subcarriers modulated in BPSK, QPSK, 16-QAM or 64-QAM for the parallel transmission of data [10]. The IEEE 802.11a IEEE 802.11g standard can reach 54 Mbps at maximum configuration using the OFDM modulation techniques QAM 64. The technique divides a single transmission of multiple signals with a lower spectral occupation, the modulation multi-carrier divides the signal band in parallel carriers that are called sub-carriers. The sub-carriers do not have overlapping frequency and thus do not interfere with each other. Figure 1 represents the operation of the OFDM technique.

B. Direct Sequence Spread Spectrum (DSSS)

DSSS also operates in the ISM band (Industrial Scientific and Medical) 2.4 GHz. Initially, the DSSS presents rates of 1 and 2 Mbps, and with the 802.11b standard specification have emerged 5.5 data rates and 11Mbps. The 1Mbps rate uses the modulation scheme Differential Binary Phase Shift Keying (DBPSK), and 2Mbps rate uses the Differential Quadrature Phase Shift Keying (DQPSK). The rates of 5.5 and 11 Mbps using Complementary Code Keying (CCK) as modulation scheme [11].

The DSSS technique uses a method known as the Barker sequence to spread the signal over a single channel without changing the frequencies. For each transmitted bit, a bit pattern called chip code is raised.

The code chip
- Allows signs that do not use the same standard to be filtered by the receivers, including noise and interference.
- Identifies the data in order to allow that the receiver recognizes them as belonging to a particular transmitter.
- Distributes the data over the available bandwidth.

Figure 2 illustrates the DSSS technique.

IV. IEEE 802.11G

The IEEE 802.11g has inherited some characteristics of previous standards, the IEEE 802.11a, and IEEE 802.11b. The ability to achieve high data rates can be compared to IEEE 802.11a and both can reach speeds of 54 Mbps. The
IEEE 802.11g operates in the frequency band of 2.4GHz which makes it compatible with IEEE 802.11b [6].

The IEEE 802.11g presents more possibilities of data rates. Using Orthogonal Frequency Division Multiplexing (OFDM) it is possible to traffic data in rates of 6, 9, 12, 18, 24, 36 and 54 Mbps to 5.5 data rates and 11Mbps the type of transmission used is Direct Sequence Spread (DSSS) code having complementary key (CCK) as modulation scheme, the DSSS is also used at lower rates, 1 and 2 Mbps BPSK and QPSK modulation schemes, [12]. Table 1 shows the types of transmission and modulation schemes used by IEEE 802.11g standard, [6].

<table>
<thead>
<tr>
<th>Data rate (Mbit/s)</th>
<th>Transmission Type</th>
<th>Modulation scheme/encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>OFDM</td>
<td>64 QAM</td>
</tr>
<tr>
<td>48</td>
<td>OFDM</td>
<td>64 QAM</td>
</tr>
<tr>
<td>36</td>
<td>OFDM</td>
<td>16 QAM</td>
</tr>
<tr>
<td>24</td>
<td>OFDM</td>
<td>16 QAM</td>
</tr>
<tr>
<td>18</td>
<td>OFDM</td>
<td>QPSK</td>
</tr>
<tr>
<td>12</td>
<td>OFDM</td>
<td>QPSK</td>
</tr>
<tr>
<td>11</td>
<td>DSSS</td>
<td>CCK</td>
</tr>
<tr>
<td>9</td>
<td>OFDM</td>
<td>BPSK</td>
</tr>
<tr>
<td>6</td>
<td>OFDM</td>
<td>BPSK</td>
</tr>
<tr>
<td>5.5</td>
<td>DSSS</td>
<td>CCK</td>
</tr>
<tr>
<td>2</td>
<td>DSSS</td>
<td>QPSK</td>
</tr>
<tr>
<td>1</td>
<td>DSSS</td>
<td>BPSK</td>
</tr>
</tbody>
</table>

Table 1. 802.11G Data rate, types of transmission and modulation schemes.

A. Characteristics and considerations IEEE 802.11g standard.

The IEEE 802.11g standard may be defined as the junction of standards 802.11b and 802.11a because it combines both settings [10]. The 802.11b and 802.11g standards operate on the same frequency band (2.4GHz). In addition to that, both of them have three channels that do not overlap. These factors contribute to the compatibility between these two patterns [6].

As observed in [6], similar to the 802.11a, the 802.11g uses the Orthogonal Frequency Division Multiplexing (OFDM) for transmitting data. The OFDM is a more efficient way of transmitting than Direct Sequence Spectrum (DSSS), which is used in 802.11b. When combined with various types of modulation, 802.11g (like 802.11a) is capable of supporting a much higher data rate than the 802.11b.

With respect to high data rates supported by 802.11g, there is an important factor which must be taken into consideration: the phenomenon known as Error Vector Magnitude (EVM), which shows that the increase in transmission power tends to decrease the device range at high data rates [6].

B. Delay and throughput limits.

According to their definition, the throughput upper limit (TUL) and delay lower limit (DLL) consider only the basic medium access mechanism, DFC without RTC / CTS. Two performance metrics needs to be considered to find the limits of delay and throughput. These are maximum achievable flow (MT) and lowest achievable delays (MD), as shown by equations (1) and (2).

\[
MT = \frac{BL_{DATA}}{TD_{DATA} + TD_{ACK} + 2\tau + T_{DIFS} + T_{SIFS} + CW}
\]  

(1)

\[
MD = TD_{DATA} + \tau + T_{DIFS} + \frac{CW_{min}T_{slot}}{2}
\]  

(2)

Therefore, by studying the logic operation of the basic mechanism to access the medium, DFC, it was possible to determine the existence of a throughput upper limit (TUL) and of a delay lower limit. For the basic access mechanism, the Throughput Upper Limit (TUL) and Delay Lower Limit (DLL) are independent of data rate, as shown in equations (3) and (4) [14].

\[
TUL = \frac{BL_{DATA}}{2\tau p + 2T_{PHY} + 2\tau + T_{DIFS} + T_{SIFS} + \frac{CW_{min}T_{slot}}{2}}
\]  

(3)

\[
DLL = T_{P} + T_{PHY} + \tau + T_{DIFS} + \frac{CW_{min}T_{slot}}{2}
\]  

(4)

In the equations, \(L_{DATA}\) is the payload size in bytes, \(T_{D\_DATA}\) is the delay of data transmission, \(T_{D\_ACK}\) is the delay of ACK transmission, \(\tau\) is the propagation delay, \(T_{DIFS}\) is the time of DIFS, \(T_{SIFS}\) is the time of SIFS, \(CW\) is the average time for "Backoff," \(T_{P}\) is the transmission time of the physical preamble, \(T_{PHY}\) is the transmission time of the physical header, \(CW_{min}\) is the minimum size of the "Backoff" window and \(T_{slot}\) is the time of a segment [14].

V. SIMULATIONS

The purpose of the simulations was to analyze the Wi-Fi communication behavior regarding aspects that influence delay, jitter and packet loss. The simulations were conducted in the NS2 simulator. The results presented in the simulations do not adequately represent the scenario of distributed traffic light control because the simulations consider the channel in ideal conditions for transmission. This way, there is no loss of data even if the size of packages is increased. The delay only increases when data packet size increases, and it was not possible to change parameters such as power and transmission distance. Thereby, we realized the need to carry out experimental tests. Graph 1 shows There is no data loss even if increase the size of the package in the simulations.
VI. EXPERIMENTAL TESTS

Communication performance tests were conducted based on the variation of parameters such as the transmitted signal power, transmission rate, and transmission distance. To perform communication between the stations and also reduce the number of variables that may interfere with communication, some measures have been adopted. The SSH protocol [15] and the emulator putty terminal [16] were used to establish the communication and set the configuration parameters of the tests.

The router firmware was changed in order to obtain different network configurations, enabling the setting of parameters such as transmission power and modulation scheme. The scenario consisted only of a notebook and an Access Point. The connection (between the router and setup terminal) was established via SSH by emulating the Putty terminal. The firmware used was TOMATO [17] and the parameters analyzed were the delay calculated by RTT (round trip time) and packet loss.

A. Settings / devices used in Indoor test scenario:
- Transmission power: 0 dBm.
- Transmission rates: 54, 48, 36, 24, 18, 12, 11, 9, 6, 5.5, 2 and 1Mbps.
- Linksys E-900.
- Protocol: ICMP.
- Package size: 50 bytes.
- Number of packages: 700 (10 transmissions of 70 packets).
- Distances: 1-25 m. Distance adopted for the tests: 25 m.

Graph 2 presents the relative values of the average and the standard deviation of the RTT for each transmission rate. The goal was to identify the limit of the relationship between data loss and different transmission rates. The RTT represents the time for a packet to be sent, plus the time of confirmation of receipt of the package.

The lowest rates of transmission, 1 and 2 Mbps, have a slightly better performance than higher rates, 48 and 54Mbps. This behavior is due to the phenomenon known as EVM (Error Vector Magnitude), in which the transmission power, mainly related to high data rates, tend to decrease the range of the receiver [6]. Furthermore, in QAM modulation the bit capacity per symbol of the constellation is high, which makes this technique subject to errors due to the noise caused by the symbols, which are closer to each other [5].

Graph 3 shows the rate of packet loss related to each data transmission rate

Graph 4 shows the signal power performance on the receiver in relation to increasing distance.
The receiver's power drops to as the distance increases, the traffic lights control distributed system specifies 200m distances for communication. The tests were performed with a device (router) without an antenna, the antenna has been removed in order to represent the device signal strength. The goal was to estimate the power at the transmitter to achieve the distance specified by the distributed control system of traffic lights, 200m.

Graph 5 shows the relationship between the theoretical minimum delay (red line) and minimum RTT obtained on experimental tests (blue line).

Data transfer rates of 1 at 54 Mbps and the packet size (50 bytes) were inserted into the equation in order to validate the proposed communication model. The communication behavior in both cases was similar as can be noticed in the graph. The lower transmission rates have higher transmission delays, however, it is possible to see some peaks in the theoretical delay that can be easily explained, rates of 11, 5.5, 2 and 1 Mbps consider the IEEE 802.11b standard for the calculation and the other rates include the IEEE 802.11g standard.

VII. DISCUSSIONS

The rate of 1mbps presents the ideal conditions to meet the specifications established by the distributed control system of traffic lights because: It has a low occurrence of data loss and low jitter. Therefore To validate the model, the RTT average rate of 1Mbps has been considered, because: The standard deviation for the average RTT of 16.3%, which means that 95% of transmissions RTT is between 70 and 98 but and even in the worst cases of RTT the results meet the specifications of the distributed control system.

The results show that the proposed specification for distributed control system of traffic lights is valid. The specification may be validated through the equations of the model proposed by [7] which showed a similar behavior to the test results. The low percentages of losses in lower transmission rates, together with the results observed for communication range reinforce the validation of wireless communication specification for distributed control system of traffic lights, showing that it is possible and get a more reliable communication through the adequacy of the network settings according to the needs of the project in question.

VIII. ANALYTICAL MODEL OF COMMUNICATION.

Validation of the test results was performed based on the model equation presented by [7], in which the minimum achievable delay for IEEE 802.11 is shown. The values specified for the distributed control system were inserted into the equation and the results of this equation may be compared with the test results. Below is the equation 2 used in the validation of the results,

$$ MT = \frac{B_{L\_DATA}}{T_{D\_DATA} + T_{D\_ACK} + 2\pi + T_{SIFS} + T_{SIFS} + CW} $$

Equation 1 shows the minimum delay achieved in the transmission. These values were compared to the minimum RTT media obtained in the tests and noted that the behavior of communication corresponds to the results shown by the model by replacing the values in the equation. In both cases, as the transmission rate decrease, the delay increases. The graphics 5 highlights this behavior, which reinforces the model’s validation with the results of equations.

With the test results and the model was able to prove that, for transmissions by settings made by distributed traffic light system, transmission of the lowest rates are the best options because the percentage of loss is low, as shown in graph 3 and the transmission delay has no significant difference from the higher rates, as can be noted in Figure 2.

Figure 3 is the wireless communication model built into the distributed signal control, in which the operating logic of nodes is presented, noting that each node representing an intersection, that is, the logic shown refers to a single node.
After studying the behavior of the IEEE 802.11 communication in diverse network configurations, the design of the communication model specification for distributed system of traffic lights was established. Delays in network represented as a consequence of delays. The parameters defining the theoretical minimum delay is represented in figure 4.

By replacing values of the test results in the diagram is obtained:
\[ T = \text{Network Delay} + \text{Controller} + \text{Semaphore} + \text{Sensors} + \text{Network Delay} \]
\[ T = 36 \text{ms} + 10 \text{ms} + 1 \text{ms} + 5 \text{ ms} + 36 \text{ ms}. \]
\[ T = 88 \text{ms}. \]

Worst case:
The worst time of transmission occurs in the maximum RTT values obtained in the transmission. The maximum time RTT obtained by the transmission was 321,566ms.

Then:
\[ T = \text{Network Delay} + \text{Controller} + \text{Semaphore} + \text{Sensors} + \text{Network Delay} \]
\[ T = 321,57 \text{ms} + 10 \text{ms} + 1 \text{ms} + 5 \text{ ms} + 321,57 \text{ ms}. \]
\[ T = 659,14 \text{ms}. \]

Therefore it is noticed that, even considering the worst case, the maximum RTT is shorter than the specified time for the distributed control of traffic lights, 1000ms. The average delay transmission obtained by the model was 88ms, which is well below the maximum specified delay to the distributed system of traffic lights, 1000ms. Thus, the model is valid and proposed specifications for the system meet the requirements.

IX. CONCLUSION
The main objective of this study was to analyze and validate the specifications of communication for a distributed control system of traffic lights. The analysis was performed by testing wireless communication with the IEEE 802.11 standard. The model was validated and a specification for the parameters of the IEEE 802.11 standard that meets the system requirements of distributed traffic lights control was obtained. As the average transmission time obtained by using the specification, 88ms, and also the worst case analyzed during transmissions, 659.14ms, were lower than the estimated time for the traffic light system, 1000ms, concludes that the specifications obtained by analysis of testing and validating the model equations are valid and meet the needs of control system distributed traffic lights. Thus, it is understood that the results