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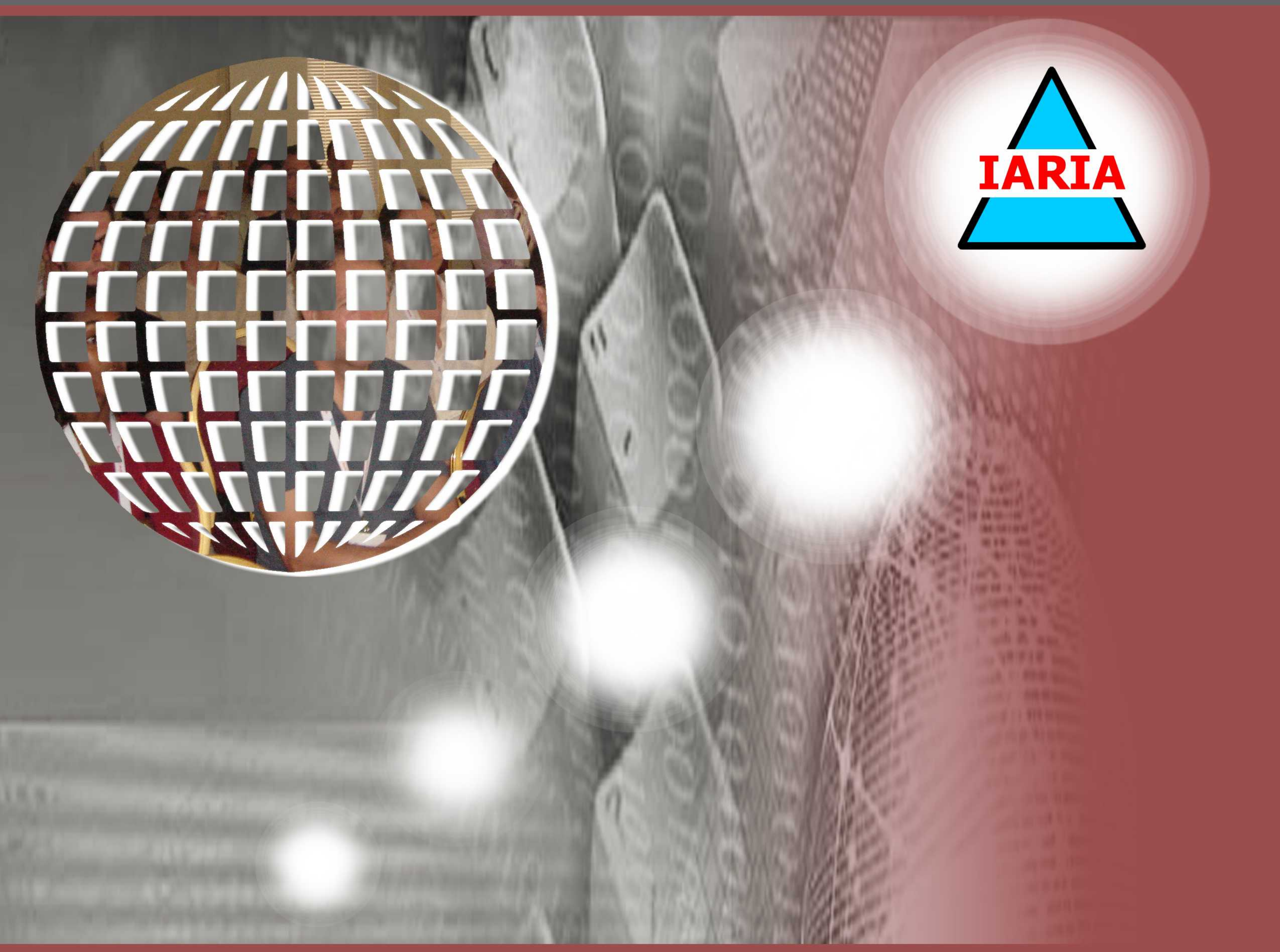

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CONTENTS

Vehicle Visible Light Communication at a Four-Legged Traffic Light Controlled Crossroad

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***Abstract*— A four-legged traffic lights controlled crossroad with Vehicular Visible Light Communication (V-VLC) is used for trajectory management, using request/response concept and relative pose estimation. The connected vehicles receive information from the network and interact with each other and with the infrastructure. An Intersection Manager (IM) coordinates traffic crossings and interacts with vehicles through temporal/space relative pose concepts. V-VLC is performed using the street lamps, the traffic signaling and the headlamps to broadcast the information. Data is encoded, modulated and converted into light signals emitted by the transmitters. As receivers and decoders, optical sensors with light filtering properties are used. Cooperative localization is realized in a distributed way with the incorporation of the indirect vehicle-to-vehicle relative pose estimation method. A phasing traffic flow is developed, as Proof of Concept (PoC) and a generic model of cooperative transmission is analysed. The results express that the vehicle's behavior (successive poses) is mainly influenced by the maneuver permission and presence of other vehicles.**

Keywords- Vehicular Communication; Light Fidelity; Visible Light Communication; white LEDs; SiC photodetectors; OOK modulation scheme; Traffic control.

I. INTRODUCTION

This paper is an extended version from the one presented in SENSORDEVICES 2021 [1].

High-end models of last generation vehicles nowadays are equipped with hundreds of embedded computers and sensors which allow them to perceive their surroundings, and interact with it in semi-autonomous, and eventually, fully-autonomous fashion. Although at a slower pace, the road infrastructure has evolved as well, with adaptive traffic lights. Next step in the evolution course of transportation systems is to adopt the concept of communication and enable information exchange between vehicles and with infrastructure (V2I) shifting the paradigm from autonomous driving to cooperative driving by taking advantage of Vehicle-to-Everything (V2X) communications [2] [3]. The objective is to increase the safety and throughput of traffic intersections using cooperative driving [4] [5].

Intersections, by their nature, easily become traffic bottlenecks and conflict areas. Two-way-two-way four-legged and split intersections are critical points of the road network either in terms of road safety, or at the level of operational conditions, because they usually cause considerable delays due to congestion problems. This specificity of intersections compels their careful study in order to achieve optimal road network operational conditions. They are distinguishable from each other by their geometric configuration, control conditions and technological requirements. Hence, it is necessary the existence of consistent selection criteria enabling one's choice for the best solution. The volume of traffic arriving at the intersection, i.e., its demand, remains the same. So, in the selection process it is fundamental to consider many other aspects such as road safety, performance, average delay per vehicle and functional and operational conditions in order to arrive at a best solution. The level of service at intersections can be improved by applying a split intersection. Here the conventional four-legged intersection can be replaced by two separate intersections. The main benefits of a split intersection are: improved safety, increased efficiency, a better synchronization and shorter wait times. Improved safety since it separates potential conflict points where vehicles, pedestrians, and bicyclists may cross paths. Increased efficiency since the separation of traffic flow on the major street allows the intersection to handle a greater volume of traffic and operate with less delay. A better synchronization, once corridor travel times are improved on both the major and side streets through synchronization of the two signalized intersections. Finally, shorter wait times because fewer vehicle traffic signal phases means less time stopping at the intersections.

Vehicular communication systems are a type of network in which vehicles and roadside units are the communicating nodes, providing each other with information, such as safety warnings and traffic information [6]. The Visible Light Communication (VLC) holds special importance when compared to existing forms of wireless communications [7] [8]. VLC is an emerging technology that enables data communication by modulating information on the intensity of the light emitted by LEDs. VLC is a precursor of optical communication for large scale-integration with other conventional communication technologies, and a strong candidate for next generation of indoor interconnection and networking, in parallel with radio communications. VLC finds application in many fields, namely: indoor navigation and localization services, safe communication at RF hazardous/undesirable places and V2X communications. Moving forward, an effort should be carried out to keep researching this topic, building synergies between the solid research work under VLC and RF technical areas. In fact, the self-configuration, self-optimization and self-healing (RF) use cases are progressing into VLC, and should be considered in future.

One of the main issues in a VLC system is the limited bandwidth of a few MHz for white light LEDs. There are several schemes for increasing the bandwidth of VLC, including equalization, multilevel modulation, parallel transmission, and Multiple Input Multiple Output (MIMO). MIMO is considered as a simple and effective technique, which divides a serial input data stream into multiple streams and concurrently transmits them to the multiple receivers. By doing so, the system capacity and the power efficiency are improved, compared to a conventional VLC system [9] [10] [11]. At the receiver, the original data can be recovered, if a full knowledge of the channel state information is available, which can be obtained by transmission of the pilot signals periodically.

The goal is to develop a cooperative system that supports guidance services. An edge/fog based architecture is proposed. Here, the streetlights and traffic lights, through VLC, report its geographical positions and specific information to the drivers and its infrastructure is reused to embed the edge/fog nodes in them. Using this architecture, an Intersection Manager (IM) can increase the throughput of the intersection by exchanging information and directing the incoming Connected Autonomous Vehicles [12] [13] [14] [15]. Cooperative localization is realized in a distributed way with the incorporation of the indirect Vehicle-to-Vehicle (V2V) relative pose estimation method. The vehicle gathers relevant data from neighboring vehicles and estimates the relative pose of them. In this paper a V2X traffic scenario is stablished and bidirectional communication between the infrastructure and the vehicles is tested, using the VLC request/response concept. Tetra-chromatic white sources are used to broadcasting the geolocation and traffic information. The receiver modules include a light controlled filter [16] recovering the transmitted information.

This paper is organized as follows. After the introduction, in Section 2, the V-VLC system is described and the scenario, architecture presented. The communication protocol, coding/decoding techniques are analyzed in Section 3. In Section 4, the experiential results are reported and the system evaluation performed. In Section 5, a phasing traffic flow diagram was developed, as a proof of concept, based on V-VLC, in order to control the arrival of vehicles at the intersection. Finally, in Section 6, the main conclusions are presented.

II. VEHICULAR VISIBLE LIGHT COMMUNICATION SYSTEM

A. Navigation Concepts

Navigation consists of vehicles laterally organized within lanes and needing to strictly drive within them. Two vehicles cannot occupy the same position in the same lane.

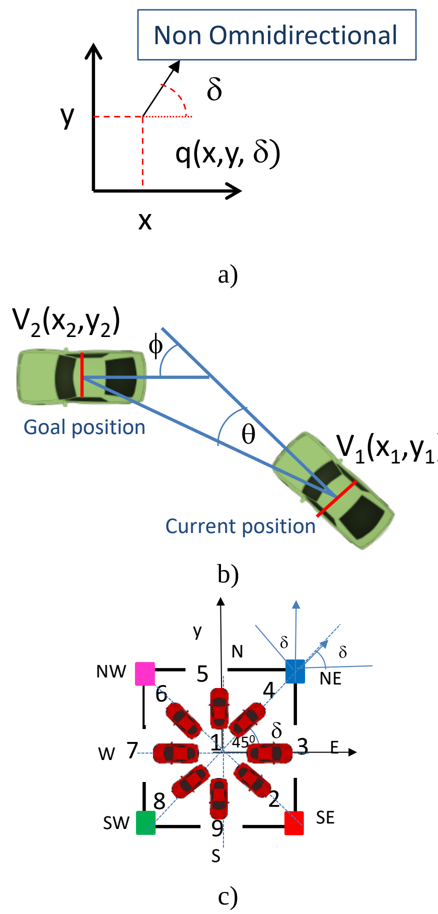


Figure 1. a) Pose: q=(x,y,δ). b) Ackermann steering principle. c) Pose orientations (N, S, E, W, NE, SE,SW, NW).

Self-localization is a fundamental issue since the vehicle must be able to estimate its position and orientation within a map of the environment it is navigating. The combined estimation of both position and orientation (pose estimation) are important to path definition. Consider a vehicle driving in a lane. Its non-omnidirectional configuration, in a two-dimensional coordinate systems is defined by position (x,y) and orientation angle δ, with respect to the coordinate axes. $q(t) = [x(t), y(t), \delta(t)]$ denotes its pose at time t, in a global reference frame. The triple $q=(x,y,\delta)$ is the mobile user pose, as displayed in Figure 1a.

The trajectory is a specification of both the path to take and the time information associated with the path, to be followed by the vehicle path consists of a set of points representing the positional coordinates of a particular route. Navigation to a goal location from a known starting location follows a basic principle. The vehicle decides which direction of travel to take at an intersection (e.g., turn right, turn left, or continue straight) by minimizing the difference in angle between the vehicle's heading and the direction to the goal, θ, as exemplified in Figure 1b. The concept of Ackermann steering principle [17] is summarized in Figure 1b. The principle took into account the angle, ϕ, required for the mobile receiver to steer from its current position to its intended position ($\theta = \phi/2$) [18] [19] [20]. Here, the pose of vehicle is grouped into eight orientations of viewpoint according to the cardinal points. The eight orientations are pointed out in Figure 1c (N, S, E, W, NE, SW, NW, SE). The pose of the vehicle in the same orientation will be varied to cover every angle. In this example, the vehicle navigates through a two-way-two-way intersection. The vehicle can detect the type of intersection that it is approaching (*e.g.* in Figure 1b.The principle, two-way-two-way intersection with the option to turn right, continue straight or left) using receivers measurements in real time. With this information, the angle between the vehicle's heading and the direction to the goal is determined for each possible route.

We denote q, q´, q´´ and q´´´ the vehicle pose estimation at the time t, t´, t´´ and t´´´(request, response, enter and exit times). To estimate these variables, it is possible to take advantage of what we call control inputs and which represent an estimation of the motion along the time. They come from receivers able to give the idea of the displacement. They help to build and improve the map and indirectly, to estimate the vehicle poses.

B. Communication modules

The Vehicular VLC (V-VLC) system makes use of outdoor light sources (street lamps and traffic lights) as the access points, which can serve for both lighting and communication purposes, providing drivers with outdoor wireless communications. The system is composed by two modules: the transmitter and the receiver located at the infrastructures and at the driving cars. The block diagram and the transmitter and receiver relative positions of the V-VLC system are presented in Figure 2a. Both communication modules (transmitter and receiver) are software defined, where modulation/ demodulation can be programed.

To realize both the communication and the street illumination, white light tetra-chromatic sources are used providing a different data channel for each chip. At each node, only one chip of the LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm), the Blue (B: 470 nm) or the Violet (V) while the others provide constant current for white perception.

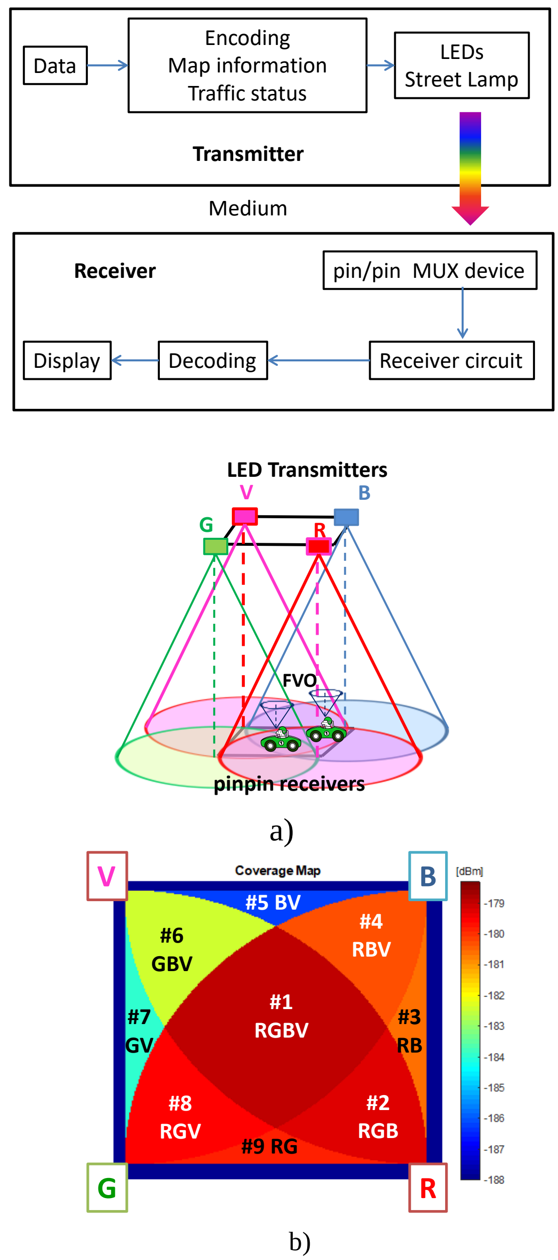


Figure 2. a) Block diagram of the VLC system.b) Illustration of the coverage map in a square unit cell.

Data is encoded, modulated and converted into light signals emitted by the transmitters. Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques. The signal is propagating through the optical channel and a VLC receiver, at the reception end of the communication link, is responsible to extract the data from the modulated light beam. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information.

The core element of a receiver is a Silicon-Carbon (SiC) photodetector. This component converts the optical power into electrical current. The VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n sandwiched between two conductive transparent contacts [16]. Due to its tandem structure, the device is an optical controlled filter able to identify the wavelengths and intensities of the impinging optical signals. Its quick response enables the possibility of high speed communications. The generated photocurrent is processed using a transimpedance circuit obtaining a proportional voltage. The obtained voltage is then processed until the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision [21] [22]).

To receive the information from several transmitters, the receiver must be positioned where the circles from each transmitter overlap, producing at the receiver, a multiplexed (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter. The grid size were chosen to avoid overlap in the receiver from adjacent grid points. The coverage map for a square unit cell is displayed in Figure 2b. Friis' transmission equation is frequently used to calculate the maximum range by which a wireless link can operate. The coverage map is obtained by calculating the link budget from the Friis Transmission Equation [23]. The Friis transmission equation relates the received power (P_R) to the transmitted power (P_E), path loss distance (L_R), and gains from the emitter (G_E) and receiver (G_R) in a free-space communication link:

$$P_{R\,[dBm]} = P_{E\,[dBm]} + G_{E\,[dB]} + G_{R\,[dB]} - L_{R\,[dB]} \qquad (1)$$

Taking into account Figure 3, the path loss distance and the emitter gain will be given by:

$$L_{R\,[dB]} = 22 + 20\ln\frac{d}{\lambda} \qquad (2)$$

$$G_{E\,[dB]} = \frac{(m+1)A}{2\pi d_{E-R}^2} I(\emptyset)\cos(\theta) \qquad (3)$$

With A the area of the photodetector and d_{E_R} the distance between each transmitter and every point on the receiver plane.

The receptors act as active filters [16]. Due to their filtering properties the gains are strongly dependent on the wavelength of the pulsed LEDs. Gains of 5, 4, 1.7 and 0.8 were used, respectively, for the R, G, B and V LEDs.

The coverage map, Figure 2b, was obtained by calculating the link budget using the Equation (3). The input parameters are displayed in Table 1. All the values were converted to decibel.

TABLE 1. LINK BUDGET INPUT.

Variable	**Value**			
	Red LED	**Green LED**	**Blue LED**	**Violet LED**
I_N(mcd)	730	650	800	900
G_E(dB)	Equation (5)			
G_R	5	4	1.7	0.8
L_R(dB)	Eq. (4)			

Users in different locations are served simultaneously by the same transmitter leading to a fine grained implementation. Due to the overlapping coverage area of adjacent nodes, joint transmission exists. In Table II the overlap regions (footprints) below each Access Point (AP) are displayed. Results show that the received power in each cell depends on the receiver position. Nine separated levels were found, in the square topology, and correspond to the nine possible combinations of the pulsed LEDs framed at corners of the unit cell (Figure 2b).

TABLE 2. FINE-GRAINED TOPOLOGIES: FOOTPRINT REGIONS.

Footprint regions	**Square topology**	**Hexagonal topology**
#1	RGBV	RGV
#2	RGB	GBV
#3	RB	RBV
#4	RBV	RGB
#5	BV	RGBV
#6	GBV	-
#7	GV	-
#8	RGV	-
#9	RG	-

Each node, $X_{i,j}$, carries its own color, X, (RGBV) as well as its ID position in the network (i,j). The overlap regions (footprints) are pointed out in Figure 2b and reported in Table 2. The device receives multiple signals, finds the centroid of the received coordinates and stores it as the reference point position (# in Figure 2b).

III. COOPERATIVE DRIVING

A. V2X Scenario and Architecture

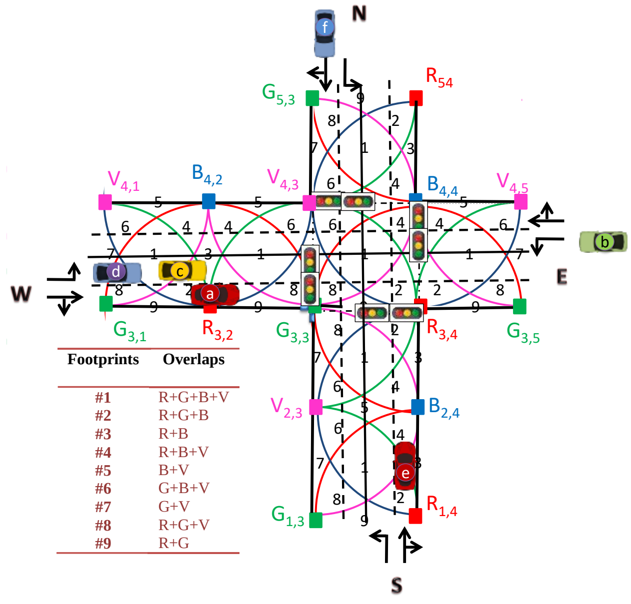
The typical single intersection (four-legged intersection) is attached to sixteen roads, eight incoming from and eight outgoing to North, West, South, and East neighbor crossroads' roads. A V2X communication link, in a traffic light controlled crossroad, was simulated. In Figure 3a the lighting plan and generated joint footprints in the crossroad region (LED array=RGBV modulated color spots) is displayed. An orthogonal topology was assumed.

Four traffic flows were considered (Figure 3a): One from West (W) with three vehicles (*a*,*c*,*d*) approaching the crossroad, Vehicle *a* with straight movement and Vehicle *c* and Vehicle *d* with left turn only. In the second flow, Vehicle *b* from East (E), approaches the intersection with left turn only. In the third flow, Vehicle *e*, oncoming from South (S), has e right-turn approach. Finally, in the fourth flow, Vehicle *f*, coming from North, goes straight.

It is proposed to build the I2V with a simplified cluster of unit square cells, in an orthogonal topology, that fills the entire service area [21] [24]. The grid size was chosen in order to avoid an overlap in the receiver from the data from adjacent grid points. The geometric scenario used in the experimental results uses a smaller size square grid**,** to improve its practicality. In the PoC, was assumed that the four-legged crossroad is located in the intersection of line 4 with column 3, and the emitters at the nodes (street lamps) along the roadside. To receive the I2V information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range (radial) of each transmitter. The nine possible overlaps, defined as fingerprint regions, are also displayed in Figure 3a for each unit cell. Thus, each LED sends a message that includes the synchronism, its physical ID and the traffic information. When a probe vehicle enters the streetlight´s capture range, the receiver replies to the light signal, and assigns an unique ID and the traffic message [22]. The received message, acts twofold: as a positioning system and as a data receiver. At each moment, *t*, the receiver identifies the footprint, finds it centroid and stores it as the reference point. All observations for a single section are jointly analyzed to produce an estimate of the occupied lane, direction and travel time along the considered section.

In Figure 3b we propose a draft of a mesh cellular hybrid structure to create a gateway-less system without any external gateways needed [25].

As shown, in this architecture, streetlights are equipped with one of two kinds of nodes: A "mesh" controller that connects with other nodes in its vicinity. Essentially, they are acting as routers in the network by forwarding messages to vehicles (I2V) in the mesh.



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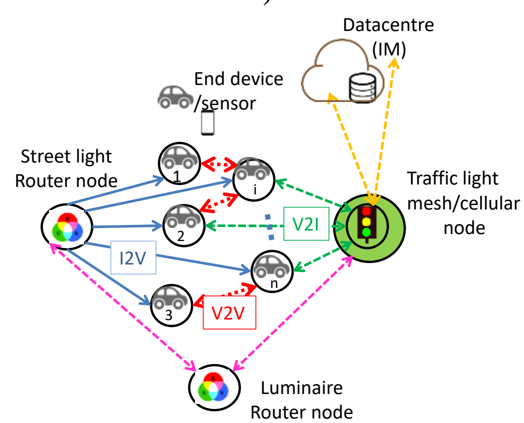

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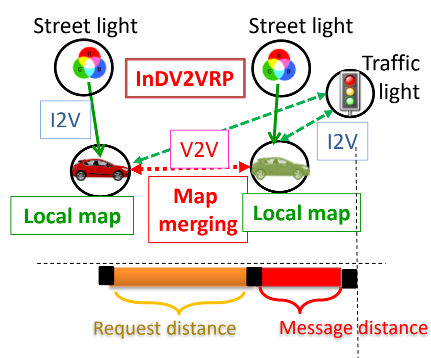


c)

Figure 3. a) V2X optical infrastructure and generated joint footprints in a crossroad (LED array=RGBV color spots).b) Mesh and cellular hybrid architecture. c) Graphical representation of the simultaneous localization and mapping problem.

The other one is the "mesh/cellular" hybrid controller that is also equipped with a modem provides IP base connectivity to the Intersection Manager (IM) services. These nodes act as border-router and can be used for edge computing. The proposed short-range mesh network enables edge computing and device-to-cloud communication, by ensuring a secure communication from a street light controller to the edge computer or datacenter, through a neighbor traffic light controller with an active cellular connection and enable peer-to-peer communication, to exchange information between V-VLC ready connected cars.

B. Multi-vehicle cooperative localization

A concept of request/response for multi-vehicle cooperative localization is used.

For the intersection manager crossing coordination the vehicle and the IM exchange information through two types of messages, "request" (V2I) and "response" (I2V). Each driver, approaching the intersection area from each side has previously selected and stays in the appropriate lane for their destination (left turn only or shared by right-turn and through movements). Inside the request distance, an approach "request" is sent, using as emitter the headlights as illustrated in Figure 3c.

To receive the "requests", two different receivers are located at the same traffic light, facing the cross roads (local controller of the traffic light). Concretely, when one head vehicle enters in the infrastructure´s capture range of one of the receivers (request distance) the request message is received and decoded by the receiver facing the lane which is interconnected to the Intersection Manager (V2I). The "request" contains all the information that is necessary for a vehicle's space-time reservation for its intersection crossing (speeds, and flow directions). Intersection manager uses this information to convert it in a sequence of timed rectangular spaces that each assigned vehicle needs to occupy the intersection. An intersection manager's acknowledge is sent from the traffic signal over the facing receiver to the in car application of the head vehicle. The response includes both the infrastructure and the vehicle identifications and the "confirmed vehicle" message. Once the response is received (message distance in Figure 3c), the vehicle is required to follow the provided occupancy trajectories (footprint regions, see Figure 2). If a request has any potential risk of collision with all other vehicles that have already been approved to cross the intersection, the control manager only sends back to the vehicle (V2I) the "response" after the risk of conflict is exceeded. A course is a typical path that is followed by a vehicle while approaching (request and message distances) and traversing the intersection.

Let's consider that $q_i(t,t')$ represents the pose of vehicle *i* at time *t´* relative to the pose of the same vehicle at time *t* and $q_{ij}(t)$ denotes the pose of vehicle *j* relative to the pose of vehicle *i* at time *t*. These three types of information $q_i(t)$, $q_i(t,t')$ and $q_{ij}(t)$ compose the basic elements of a pose graph for multi-vehicle cooperative localization [26].

From a digital map we automatically extract a set of attributes that characterize an intersection: the poses, $q_i(x, y, t)$, the courses and traffic rules (stop, give way).

The Indirect V2V Relative Pose Estimation (InDV2VRPE) method is exemplified in Figure 3c. Here, when two vehicles are in neighborhood, the geometric relationship between them can be indirectly inferred via a chain of geometric relationships among both vehicles positions and local maps. Let´s consider two neighboring vehicles. Both vehicles, having self-localization ability based on I2V street lamps communication perform local Simultaneous Localization and Mapping (SLAM). The follower vehicle can be localized by itself, as in single vehicle localization, $q_i(t)$, and can also be localized by combining the localization result of vehicle leader and the relative localization estimate between the two vehicles, $q_{ij}(t)$. For a vehicle with several neighboring vehicles, it uses the indirect V2V relative pose estimation method to estimate the relative pose of each neighboring vehicle one by one and takes advantage of the data of each neighboring vehicle.

C. Color phasing diagrams

The use of both navigation and lane control signs to communicate lane restrictions is demanding. Downstream from that location (request distance), lane restrictions should be obeyed.

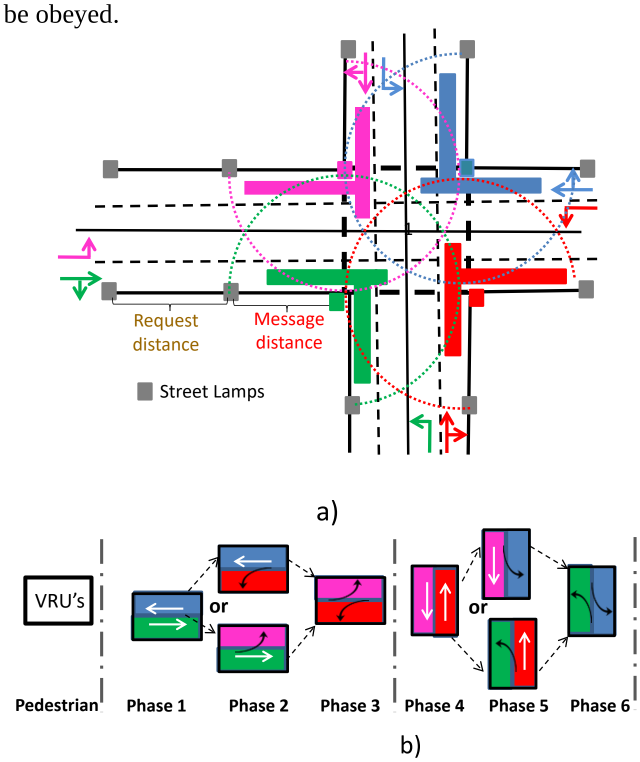


Figure 4. a) Physical area, color poses and channelization. b) Representation of a phasing diagram.

Vehicles may receive their intentions (*e.g.*, whether they will turn left or continue straight and turn right) or specifically the need to interact with a trafic controler at a nearby crossroad (message distance). In the sequence, a traffic message coming from a transmitter nearby the crossroad will inform the drivers of the location of their destination (*i.e.*, the intended intersection exit leg).

In the proposed architecture (Figure 3b), the major operational requirement of IM is the ability to register synchronized measurements in a common frame of reference. The effective solution is to maintain a buffer of time-stamped measurements and register them as a batch using a temporal sliding window.

The vehicles can use such techniques to find their "color poses" at regular time intervals. We have assumed four "color poses" linked with the radial range of the modulated light in the crossroad nodes. Based on Figure 4a, where the physical area and channelization are shown, the West straight, South left turn, and West right turn manoeuvres correspond to the "Green pose". "Red poses" have to do with manoeuvres like turning south straight, turning east left and turning south right. "Blue poses with East straight, North left turn and East right turn and finally "violet poses with North straight, West left turn and North right turn manoeuvres, In Figure 4b, a color phasing diagram is displayed. Since two movements can occur simultaneously without conflict, two of the timing functions are always controlled simultaneously.

IV. VLC Communication protocol and coding/decoding techniques

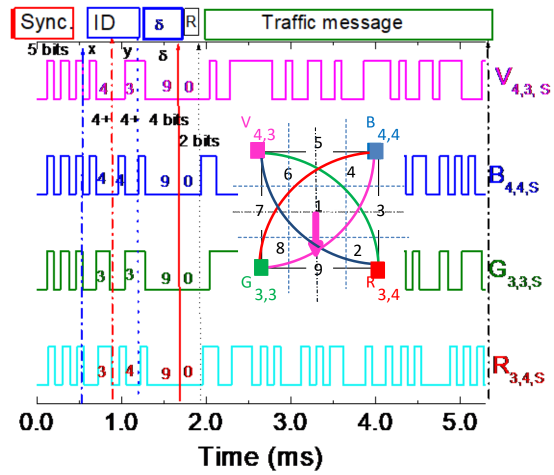
An on-off keying (OOK) modulation scheme was used to code the information. Synchronous transmissions based on a 64- bits data frame are analysed.

An example of the used codification to drive the headlamps LEDs of a vehicle, coming from N, located in in footprint #1 ($R_{3,4,}$ $G_{3,3,}$ $B_{4,4,}$ and V_{43}) moving to South is illustrated in Figure 5a.

Different control fields are used depending on the driver motivation. All messages, in a frame, start with the header labelled as Sync, a block of 5 bits. The same synchronization header [10101], in an ON-OFF pattern, is imposed simultaneously to all emitters. The next block (ID) gives the location (*x, y* coordinates) of the emitters inside the array ($X_{i,j,k}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. So, the next 8 bits are assigned, respectively, to the *x* and *y* coordinates (*i*, *j*) of the emitter in the array. If the message is diffused by the IM transmitter, a pattern [0000]) follows this identification, if it is a request (R) a pattern [00] is used. The steering angle (δ) completes the pose in a frame time. Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 1c) are possible from a start point to the next goal. The last block is used to transmit the traffic message. A stop bit is used at the end of each frame.

The decimal numbers assigned to each ID block are pointed out in the Figure 5a. Results show that, in network, $R_{3,4,S}$; $G_{3,3,S}$; $B_{4,4,S}$ and $V_{4,3,S}$ are the transmitted node packets, in a time slot, from the crossroad. In this location, the driver receives his request message [pose, and traffic needs] from the infrastructure. This allows its movement across the crossroad to South (violet code 9, δ=270º), directly from the current point (#1) to the goal point (#9).

The calibration of the receiver supplies an additional tool to enhance the decoding task. The calibration procedure is exemplified in Figure 5b. Here the MUX signal obtained at the receiver as well as the coded transmitted optical signals are displayed.



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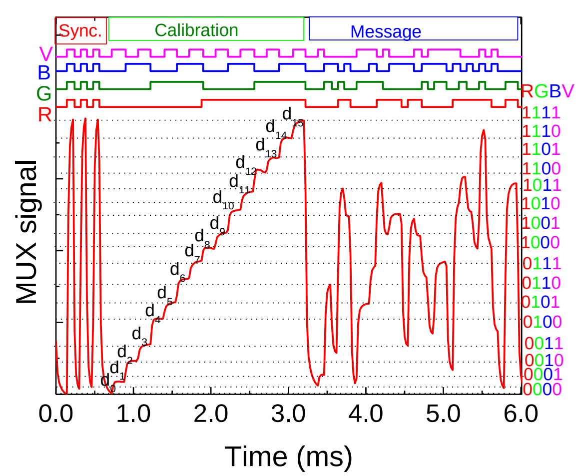

b)

Figure 5. a) Frame structure representation of a request message. b) MUX/DEMUX signal of the calibrated cell. In the same frame of time a random signal is superimposed.

The message, in the frame, starts with the header labelled as Sync, a block of 5 bits. In the second block, labelled as calibration, the joint transmission of four calibrated R, G, B and V optical signals is imposed. The bit sequence for this block was chosen to allow all the *on/off* sixteen possible combinations of the four RGBV input channels (2^4). Finally, a random message was transmitted. All the ordered levels (d_0-d_{15}) are pointed out at the correspondent levels and are displayed as horizontal dotted lines. In the right hand side the match between MUX levels and the [RGBV] binary code assigned to each level is shown. Comparing the calibrated levels (d_0-d_{15}) with the different assigned 4-digit binary [RGBV] codes, ascribed to each level, the decoding is straightforward and the message decoded. The footprint position comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off*. The pose of the mobile receiver (x,y, δ) in the network comes directly from the next 12 decoded bits. Finally, the received traffic message is decoded based on the last MUX levels.

V. SYSTEM EVALUATION

A. V2X Communication

Figure 6a displays the MUX signal associated with two IM response messages. The messages were received by Vehicle *a*, driving the right lane, that enters Cell $C_{4,2}$ by the enter #2 ($t'_{1,a}$, Phase1, green pose), goes straight to E to position #8 ($t'_{2,a}$; Phase1, green pose). Then, this vehicle enters the crossroad through #8 (t''_a) and leaves it in the exit #2 at t'''_a, keeping always the same direction (E).

In Figure 6b, vehicle *b* approaches the intersection after having asked permission to cross it and only receives authorization when the vehicle *a* has left the intersection (end of Phase 2). Then, Phase 3 begins with vehicle *b* heading to the intersection (W) (pose red) while vehicle *a* follows its destination towards E (pose green).

In Figure 6c, the movement of the cars is illustrated by their colorful poses (color arrows) and their spatial relative poses, q_{ac} (dot lines), as time develops.

According to the results, the received information patterns change as the receiver moves between generated point regions. The vehicle speed can be calculated by measuring the actual travelled distance overtime, using the ID´s transmitters tracking. Two measurements are required: distance and elapsed time. The distance is fixed while the elapsed time will be obtained through the instants where the number of received channels changes. The receivers compute the geographical position in the successive instants (path) and infer the vehicle's speed. In the following, this data will be transmitted to another leader vehicle through the V2V communication or to control manager (IM) at the traffic light through V2I. When two vehicles are in neighborhood and in different lanes, the geometric relationship between them can ($q_{i,j}$) (dotted lines in Figure 6c) can be inferred through local SLAM fusing their self-localizations via a chain of geometric relationships among the vehicles poses and the local maps.

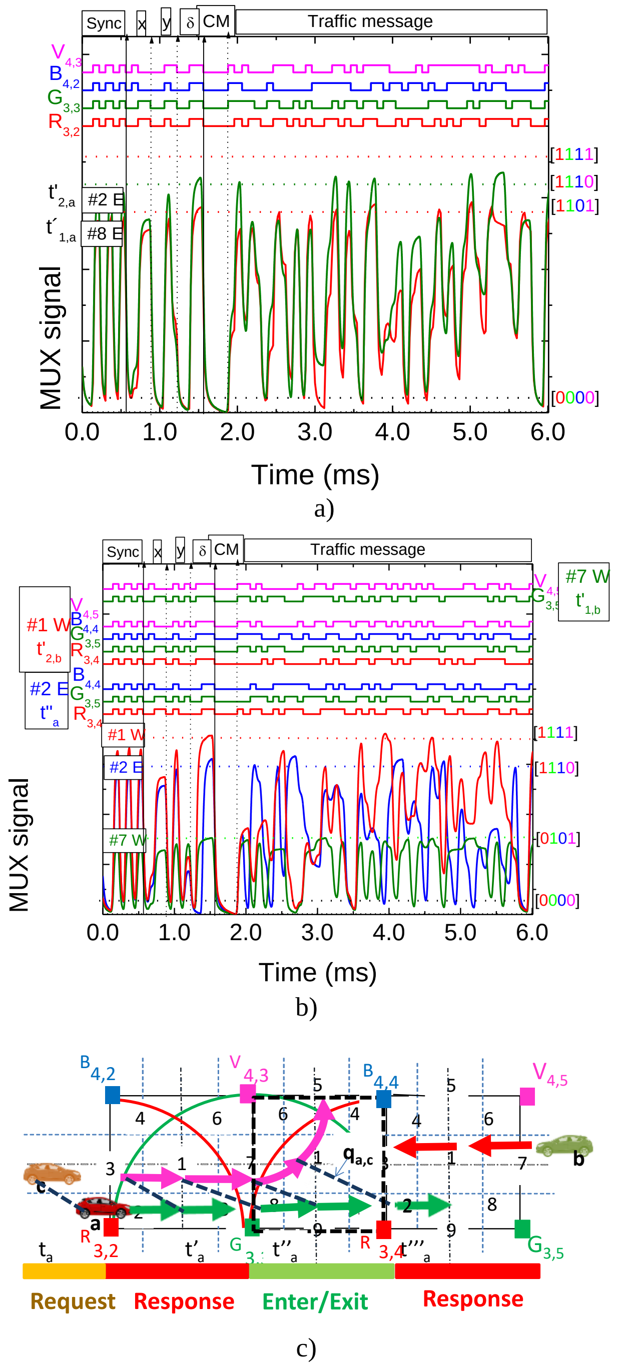

Figure 6. Normalized MUX signal responses and the assigned decoded messages at different response times. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Before the crossroad. b) After the cross road. c) Movement of the cars, in the successive moments, with their colorful poses (color arrows) and q_{ac} spatial relative poses (dot lines).

For a vehicle with several neighboring vehicles, the mesh node uses the indirect V2V relative pose estimations method taking advantage of the data of each neighboring vehicle.

B. *Traffic Signal Phasing: V2X Communication*

A phasing diagram was presented in Figure 4, for functional areas with two-way-two-way intersection. A traffic scenario was simulated (Figure 3a) using the new concept of VLC request/response messages. A brief look into the process of timing traffic signals is given in Figure 7.

To design traffic-actuated controls, we consider *a*, *b*, *c*, *d*, *e*, and *f* vehicles requesting and responding message information to determine phase durations appropriate to meet demand. Each driving vehicle is assigned an individualised time to request (*t*) and access (*t´*) the intersection. The exclusive pedestrian stage, "Walk" interval begins at the end of Phase 5 (Figure 4b).

A first-come-first-served approach could be accomplished by accelerating or decelerating the vehicles so that they arrive at intersections when gaps have been created between conflicting traffic flows and pedestrians. However, a one-by-one service policy at high vehicle arrival rates is inefficient. From the capacity point of view it is more efficient, if Vehicle *c* is given access at t'_c before Vehicle *b*, at t'_b to the intersection and Vehicle *d* is given access at t'_d before Vehicle *e*, at t'_e then, forming a west left turn of set of vehicles (platoon) before giving way to the fourth phase (north and south conflicting flows), as stated in Figure 7. The speed of Vehicle *e* was reduced, keeping a safe distance between Vehicle *e* and Vehicle *d*.

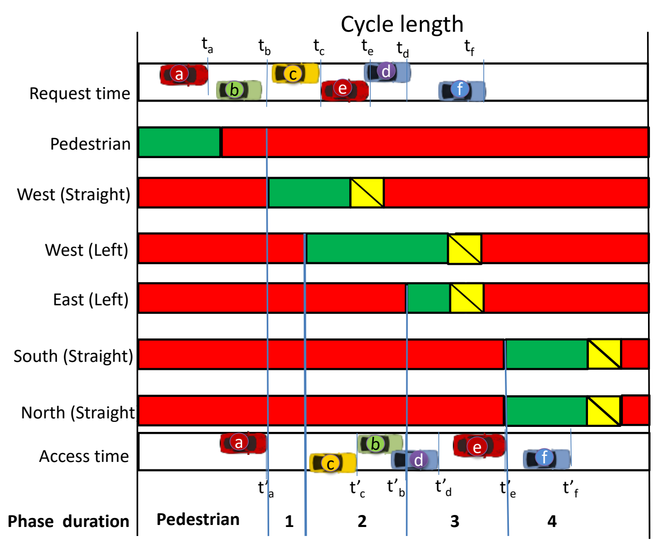

Figure 7. Requested phasing of traffic flows: pedestrian phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3(W and E left flows), Phase 4 (N and S straight flows). $t_{[x]}$ is the request time from the Vehicle *x* and $t'_{[X]}$ the correspondent response time from the manage controller.

As a final remark, traffic light coordination using the V-VLC request-response concept facilitates traffic circulation, promoting smooth movement along the network, forming platoons with efficient speeds, preventing the formation of queues, avoiding congestion and delays. This is also an effective way to reduce excessive fuel consumption and preserve the environment through minimal air pollution.

To evolve towards real implementation, the performance of V-VLC system still needs improvement, namely the distance between conflicting vehicles along with the trajectories of other opposing vehicles should also be monitored and optimized.

VI. Conclusions

This paper presents a new concept of request/response for the redesign and management of a trajectory in a two-way-two-way traffic lights controlled crossroad, using VLC between connected cars. The connected vehicles receive information from the network (I2V), interact with each other (V2V) and also with the infrastructure (V2I), using the request redesign distance concept. In parallel, a control manager coordinates the crossroad and interacts with the vehicles (I2V) using the response redesign distance concept. A simulated traffic scenario was presented and a generic model of cooperative transmission for vehicular communication services was established. As a PoC, a phasing of traffic flows is suggested. The simulated/experimental results confirmed that the proposed cooperative VLC architecture is suitable for the intended applications. The introduction of VLC between connected vehicles and the surrounding infrastructure allows the direct monitoring of relative speed thresholds and inter-vehicle spacing.

In order to evolve towards real implementation, the performance of such systems still needs improvement, namely the distance between conflicting vehicles along with the trajectories of other opposing vehicles should also be monitored and optimized. As further work, the research team plans to finalize the embedded application, for experimenting in several road configurations with either static or moving vehicles.

Acknowledgements

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A Survey on Application Layer Protocols for IoT Networks

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***Abstract*—Nowadays, all sectors utilize devices that are part of the Internet of Things (IoT) for the purpose of connecting and exchanging information with other devices and systems over the Internet. This increases the diversity of devices and their working environments, which, in turn, creates new challenges, such as real-time interaction, security, interoperability, performance, and robustness of IoT systems. To address these, many applications protocols were adopted and developed for devices with constrained resources. This paper surveys communication protocols divided according to their goals along with their merits, demerits, and suitability towards IoT applications. We summarize the challenges of communication protocols as well as some relevant solutions.**

Index Terms*—Internet of Things (IoT); Messaging Protocol; Device Management Protocol; Service Discovery Protocol; Constrained devices; Interoperability; Security; Quality of Service (QoS).

I. Introduction

The Internet of Things (IoT) [1], [2] refers to physical things that have been combined with sensors, actuators, and technologies in order to exchange data with other devices and systems on the network. The IoT is used to make people's lives and businesses easier in many areas. Generally speaking, there is no standard architecture for the Internet of Things systems, but what is certain is that all architectures are composed of several parts which interact and communicate with each other without human intervention. The Internet of Things connects the real world of things to the virtual world of networks and the Cloud.

Currently, there is no universally reference architecture for the IoT. There is a considerable amount of architectures available for IoT systems. The most widely architectures [3]–[6] used for IoT solutions are: 3-layer, Service-oriented Architecture (SoA) and 5-layer architectures. However, the 5-layer architecture, also called middle-ware architecture, presents the very common architecture in IoT. As shown in Figure 1, middle-ware architecture divides IoT systems into 5 layers: Perception, Network, Middle-ware, Application and Business. The Perception layer, or the device layer, represents the physical level objects, having as main function the gathering of useful information from the surroundings. Here, a number of sensors and actuators are used to monitor - control the physical objects. The Perception layer transmits then the gathered information to Middle-ware layer using the Network layer. The Network layer, or communication layer, connects Perception layer and Middle-ware layer by transporting data provided by Perception level to Middle-ware layer. The Network layer in IoT architecture does not present Network layer of the ISO/OSI model, that routes data within the network only along the best way. The Network layer of IoT 5 architecture includes all the technologies and protocols that make the connection possible between the Perception and Middle-ware layers. The Middle-ware provides some advanced functionalities, such as storage, processing, aggregation and filtering of data. The Application presents the collected and analyzed information to the end user. Lastly, the Business layer enables systems' administrators to manage and supervise the IoT platform's entire functionality.

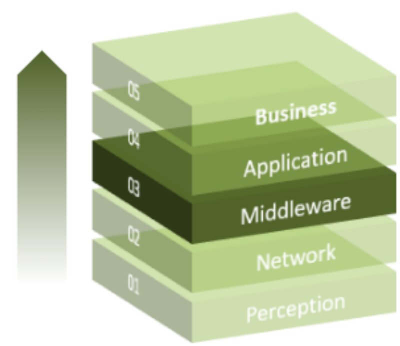

Figure 1: 5-Layer Architecture for IoT.

Figure 2 introduces a typical scenario of the IoT system where the interaction between the different parts is clearly presented. The IoT devices [7] are physical things. They are equipped with embedded sensors, actuators, and controllers to interact with the physical environments to collect information or to change the actual status. A device can exchange data either with other devices or with data-center, the Cloud, or other servers. The Gateway represents a physical entity that is composed of several electronic devices. The main purpose of the Gateway is to connect to different networks having different typologies. It contains software that translates the protocols to establish communication between the things and the network. The number of connected devices is expected to grow rapidly, with a predicted 75 billion devices worldwide expected to be connected to the Internet by 2025 [8]. This great number of connected devices is expected to generate unlimited data. As a result, an enormous amount of data to be stored, processed, and made available in a continuous, efficient, and easily interpretable manner is growing rapidly, which puts a lot of pressure on the Internet infrastructure. To solve this problem, companies combined the capabilities of IoT and cloud computing. The technology of cloud computing assists in alleviating the pressure on the Internet infrastructure by storing, processing, and transferring data to the Cloud instead of to the connected devices. Many platforms, called IoT Cloud Platforms, exploit Cloud Computing features to provide IoT services. For this purpose, a number of open sources and proprietary IoT platforms have been proposed and implemented to provide many efficient and easy IoT services, such as data collection, storage, analysis, monitoring, control, and management of connected things. Today, more than 300 IoT platforms are available on the market [9]. Mobile and Web applications make the IoT very user-friendly. A mobile application is a software application that is created to run on mobile devices especially those that are small and wireless. A Web application is a software application that is hosted on a server and accessible through a Web browser. Mobile and Web applications allow users to perform a set of specific functions and tasks on the Internet. These functions and tasks are summarized in the connection, monitoring, control, and management of connected objects.

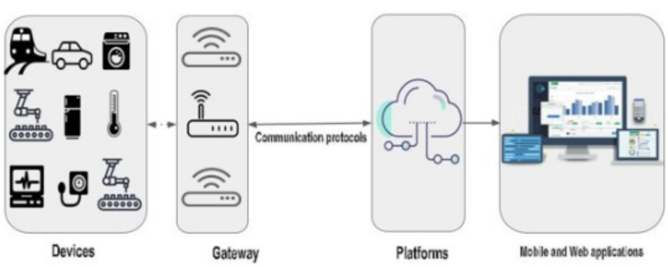

Figure 2: IoT Basic Scenario.

Communication Protocols are used to allow the connectivity for data exchange between physical or virtual entities, e.g, Devices and the Cloud, by defining rules and constraints where several requirements must be taken into account by these protocols when building IoT systems.

In this paper, we focus on communication protocols designed for IoT. Communication protocols are subdivided into three types, namely, (i) messaging (ii) device management, and (iii) service discovery.

The weaknesses of the current solutions have motivated the improvement of the existing protocols that seek to enhance the Internet of Things ecosystems' performance and avoid faults.

Thus, this work aims at presenting an extensive survey about the existent communications protocols that can be used in IoT applications. Different from the current existing surveys in the literature, this work does not only consider existing and well-known base protocols, but also all relevant solutions that have been introduced during recent years. The main contributions of this paper are summarized as follows:

- Classifies communication protocols into three groups, namely messaging, device management, and service discovery. Sequentially, we define each group.
- Surveys the most common messaging protocols used in IoT solution.
- Outlines the usage level of messaging protocols
- Overviews of device management and service discovery protocols.
- Identifies the problems most studied by the existing protocols in IoT scenarios.
- Reviews of the studied solutions that improve existing protocols.

The remainder of this paper is organized as follows: Section II introduces a taxonomy of communication protocols. Section III presents the messaging protocols used in IoT applications. Section IV outlines the usage level of the IoT messaging protocols and conclude the most used protocol. Section V lists the communication protocols for device management. Section VI sums up the communication protocols for service discovery. Section VII introduces the challenges for the communication protocols and surveys the recent approaches to the protocols enhancement. Section VIII concludes the paper.

II. TAXONOMY OF IOT APPLICATION PROTOCOLS

As introduced in section I, the Network layer of IoT architecture enables IoT devices to communicate with Middle-ware layer, by including several protocols. A protocol represents the rules and formats that IoT devices use to establish connections with Middle-ware layer. The Network layer's protocols are built on a stack of protocols [10]. Figure 3 shows a list of some of the most commonly used protocols, organized according to the TCP/IP paradigm.

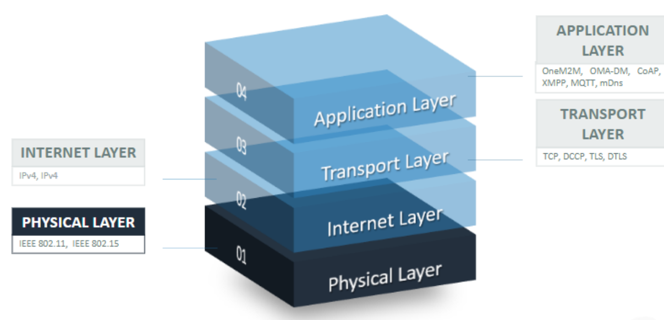

Figure 3: IoT Protocol Stack.

However, in this paper we focus on Application layer protocols of TCP/IP paradigm. The Application layer provides protocols that enable device to send and receive information, and should not be confused with the Application layer of the IoT 5-layer architecture. A few examples of Application layer protocols are: Message Queuing Telemetry Transport (MQTT) [11], [12], Constrained Application Protocol (CoAP) [13], [14], Data Distribution Service (DDS) [15]–[18].

As shown in Figure 4, those protocols can be classified into three different groups. Specifically, application protocols can be classified by their purpose: messaging protocols, device management protocols, or service discovery protocols.

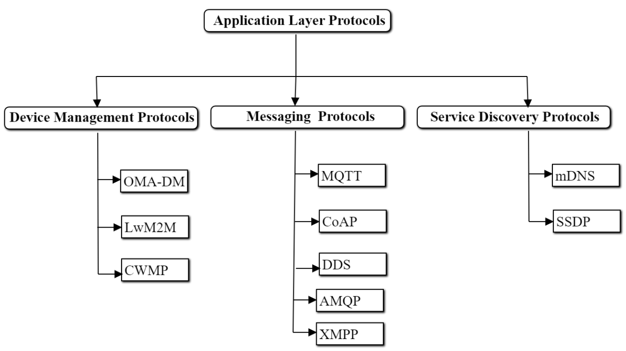

Figure 4: Taxonomy of Application Protocols for IoT.

a) Messaging Protocols: It define the formats, rules and functions for transferring messages between the components of a IoT system system. It is possible to build an IoT system with the typical messaging protocols based on classical HTTP Web requests even if they do not have certain requirements. However, they are no longer the right choice for Internet of Things. A IoT messaging should has important characteristics, namely speed (the amount of data that can be transmitted per second), latency (the amount of time needed to transmit a message), power consumption and security. New messaging protocols have been implemented, such as MQTT, CoAP, XMPP.

b) Device Management Protocols: A huge number of connected devices are deployed in remote, hostile and hard to reach places, which makes their configurations and maintenance difficult. Many solutions are proposed to provide device management necessity. For example, Perumal et al. [19] proposed a lightweight IoT device management framework for smart home services. Also, various protocols [20], called device management protocols, are proposed to ensure IoT network management. Here, a device management protocol [21] provides device location and status information to adapt the topology of IoT networks. A device management has advanced functionalities, such as disconnect and locate lost devices, modify security settings, delete device data.

c) Service Discovery Protocols: Mechanisms for discovery are important to use the services of the Internet of Things. Service discovery is a process of automatically locating the appropriate services. Ahmed et al. [22] proposed a secured service discovery technique for the Internet of Things. Several protocols [22] are proposed to handle service discovery. A service discovery protocol locates services across widely distributed and heterogeneous networks that are relevant to an entity of interest in the real world.

III. Messaging Protocols

IoT cannot rely on a single protocol for all needs [23]. Consequently, several of available messaging protocols are chosen for various types of requirements of the IoT system [24]. Thus, in the rest of this section, the most relevant protocols are cited with their descriptions.

a) Message Queuing Telemetry Transport (MQTT): It is a lightweight [11] [12] and flexible [25] messaging protocol. MQTT uses different approaches for routing mechanisms, such as one-to-one, one-to-many, or many-to-many, making the connection between IoT and Machine-to-Machine (M2M) to connected devices/applications possible [25]. M2M is used to provide communications between machines without human intervention. MQTT is designed as a publish-subscribe model [25], using TCP as transport layer protocol.

Figure 5 shows the process of message exchange in MQTT. MQTT consists of multiple clients connected to a central broker, which is a server running somewhere in the Internet network [26]. These clients can be a publishers or subscribers. A publisher is producer that publish messages on a particular topic [25]. However, a subscriber is a consumer that subscribes to receive published messages on a topic. Every time the MQTT Broker gets a new publish message to a specific topic, it broadcasts this message to the interested subscribers.

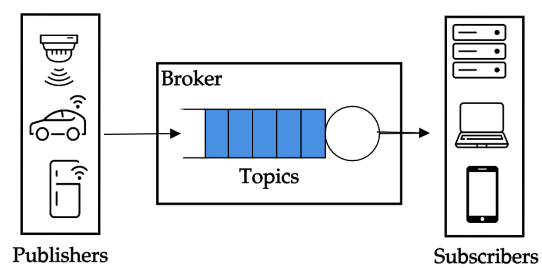

Figure 5: MQTT Architecture.

The MQTT protocol has several advantages [27], [28]. First, the messages may be sent/received at anytime, hence the communications are asynchronous. Second, the method of communication used is very simple. Third, MQTT provides the reliability of messages by providing 3 level of QoS [29] . Here, the publisher uses a QoS level for each published message to ensure that the data reaches its recipient. In the following, we present the QoS level supported by MQTT:

- QoS 0 (At most once): The receiver does not confirm the reception of messages, and the producer does not wait for such confirmations.
- QoS 1 (At least once): if the publisher uses the level 1 than it guarantees that the data is delivered at least one time to the receiver. For this purpose, the receiver confirms the delivery of data to the publisher, the publisher store the sent data to re-transmit it if necessary.

- QoS 2 (Exactly once): if the publisher uses the level 2 than it guarantees that the data is delivered at exactly one time to the receiver.

However, MQTT has some limitations. We will address some of them. The MQTT protocol is used between devices and Cloud, but it is not commonly used between devices. Another disadvantage is that MQTT uses TCP/IP and the use of TCP/IP requires more communication. The last drawback concerns the usage of a broker. A broker has restricted communication capabilities, and all nodes are connected to it. As a result, when the broker fails, the communication breaks down.

b) Constrained Application Protocol (CoAP): CoAP [13] [14] is mainly used in a constrained environment with constrained devices and constrained networks. As Figure 6 shows, CoAP environments use unicast and multi-cast request-response model for interaction between multiple clients and multiple servers by sending request and response messages using a URI with GET, POST, PUT and DELETE actions over UDP to keep things lightweight.

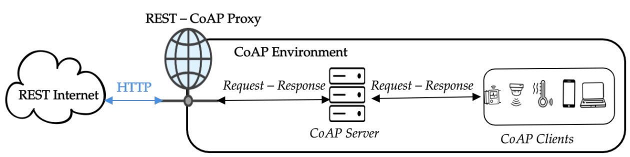

Figure 6: CoAP Architecture.

CoAP uses two modes of messages for request-response communication, namely piggyback and separate. The main difference between these two modes resides in the time and the way of responding [27], [28]. In direct communication between the client and server, piggyback means that the server sends its response message directly after receiving the request. In this case, the server response comes with an acknowledgment (ACK) message. While separate mode is used in indirect communication between client and server, the response is sent in a separate message from the ACK and may take some time for the server to provide it.

Also, CoAP provides two types of messages for the reliability and duplication of messages. The two types of messages are confirmable and non-confirmable. These two messages are used, respectively, for reliable and unreliable transmission. The use of the confirmable message requires the use of an ACK message to confirm the message's arrival, while the use of the non-confirmable message requires no use of an ACK message. The main merits of the CoAP protocol are that it can be used with constrained devices in interaction device-to-device, and that it allows fast communication since small packets are sent with the UDP layer. This protocol cannot be used in asynchronous communication because it does not support publisher-subscriber architecture. Also, it does not support broadcast. The clients cannot use a topic to send and respond to messages.

c) Data Distribution Service (DDS): [15]–[18] is used for real-time and industrial M2M communications, running over both TCP or UDP. DDS supports broker-less architecture where it uses a publish-subscribe model for interaction between entities without the use of a Broker. The tasks of a broker are handled by Data Writers (DW) and Data Readers (DR). The main advantages of DDS protocol are that the data usage is fundamentally anonymous, since the publishers do not enquire about who consumes their data, and the probability of system failure is limited (system more reliable) because there is no single point (no broker) of failure for the entire system [15]. The most remarkable disadvantage of DDS is that it is designed for Industrial application (IIoT) with considerable hardware resources. This makes the implementation for constrained devices that need a Lightweight protocol even harder. The other disadvantage is related to the increase of the communication workload by the publishing of data even if there are no interested subscribers [15].

d) Advanced Message Queuing Protocol (AMQP): AMQP [15], [16] is designed as a publish-subscribe model, which uses TCP as transport layer protocol. Mainly as described in Figure 7, it has three components, Publishers, Subscribers and, both parts of an AMQP Broker are Exchanges of Message queues. The Publisher creates a bare message and sends it to the Exchanges components that are used to forward the messages to appropriate message queues using the routing keys contained in messages. The latter can be stored into message queues before forwarding them to Subscribers. If there are more subscribers interested in a particular message, the broker can duplicate the messages and send their copies to multiple queues waiting for annotated messages from subscribers. The main advantage of the AMQP protocol is that it could be used in device-to-device, device-to-Cloud, and Cloud-to-Cloud interaction. But its main disadvantage is that the publishers and subscribers cannot publish and subscribe using the topic.

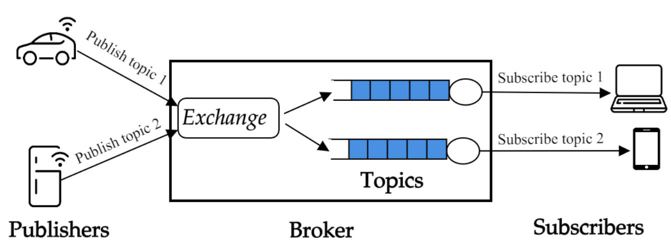

Figure 7: AMQP Architecture.

e) eXtensible Messaging and Presence Protocol (XMPP): As introduced in [30]–[32], XMPP, also known as Jabber, is a standard initially designed for instant messaging and exchange of messages between applications no matter which operating system they are using in IoT. It is designed to allow users to send messages in real-time and manage the presence of the user. XMPP supports Publish-Subscribe and Request-Response models with TCP transport protocol. To exchange messages between clients and servers XMPP uses streams of stanzas. XMPP is a text-based protocol where XMPP stanzas [30] [31] [32] are Extensible Markup Language (XML) messages exchanged between clients. The main advantage of the AMQP protocol is that could be used in device-to-device, device-to-Cloud interaction. As AMQP, DDS, and CoAP, topics are not used to publish and subscribe with XMPP.

The discussed IoT messaging protocols have similarities and differences among a number of features [33], [34].

However, all the cited protocols lack of IoT device management and service discovery procedures. When building an IoT system, it is important to think about the protocol's characteristics to ensure that it meets functional and operational needs. For that purpose, we provides a comparative analysis (see Table I), where the differences and similarities in the relationships between messaging protocols are clear. In the comparative analysis, we considered key features such as pattern, QoS, Payload's format and maximum size.

IV. Messaging Protocols Trends

This section investigates the level of use of IoT messaging protocols. First, we will analyse the results of the annual survey realized by the Eclipse Foundation [35] between 2016 and 2018. Then, we will be interested in the support of the messaging protocol by IoT Cloud Platforms.

Figure 8 adopts the evaluation of the use of the messaging protocols in IoT systems. According to the results of this survey [35], MQTT and HTTP are the two most used protocols. This survey confirms that MQTT is the choice for IoT solutions since it is the denominator by 62.61%. While HTTP usage is declining to 54.10 %, this could be due to the advantages of using the light-weight version of HTTP (HTTP/2). In addition, the AMQP protocol has significant traction in terms of its usage in 2018 compared to 2017 (18.24%). Furthermore, the use of the new WEBSOCKETS protocol shows a very high usage level of 34.95%.

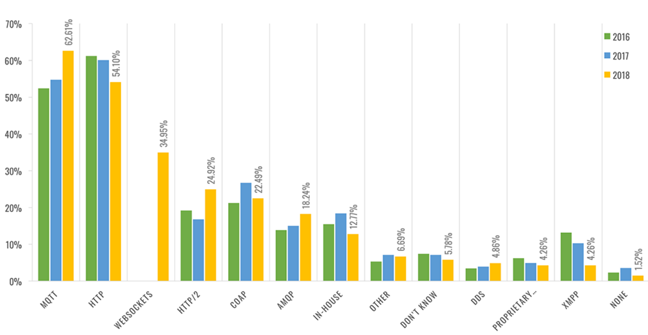

Figure 8: IoT Developer Survey Results Showing the Trend in the Usage of Messaging Protocols Between the Years 2016 and 2018 [35]

We will now examine the level of use of messaging protocols by examining how messaging protocols are supported on the IoT Cloud platforms.

Today, IoT networks transmit more data than they can handle effectively because of the amount of data generated and exchanged by devices. This behavior negatively affects the performance of IoT applications, such as increased response time and loss of network connectivity. On that basis, several cloud platforms were offered to improve IoT applications. Simply put, these platforms are designed to reduce network congestion. IoT communication protocols (messaging protocols) play an important role in IoT applications. Messaging protocols provide the ability to transfer data between devices and cloud platforms. However, not every messaging protocol can be used between devices and cloud platforms. Each IoT cloud platform supports its own specific messaging protocols. Here, and throughout the remainder of this section, we look at the support levels of the messaging protocols across the cloud platforms. But above all, we're going to outline three of the major existing IoT Cloud platforms.

Microsoft Azure IoT [36]–[38] Suite is a cloud computing PaaS that allows developers to publish web applications running on different frameworks and written in different programming languages, such as any. NET language, node. js, PHP, Python, and Java [1]. The IoT devices send the data to the cloud gateway directly or via a gateway, depending on the network capabilities of the IoT device. The Azure IoT Suite is used to build Internet of Things systems and applications by gathering, storing, processing, managing and analysing data. The processed data can later be delivered to other business and presentation applications.

IBM BlueMix [36], [39] is a Cloud-based PaaS developed by IBM for building, running, deploying and managing applications of all types such as web, mobile, new smart devices, and much more, runs on Soft-layer that is IBM's worldwide IaaS. BlueMix used to develop apps in many programming languages, including 1) JavaScript to develop mobile apps in iOS, Android, and HTML, 2) Node. js, Ruby, PHP, Java, Go, and Python and many more to develop web apps.

AWS IoT [36]–[38] is a Cloud-based PaaS developed by Amazon for facilitating security, services, and support. AWS IoT used to create apps in many languages, such as PHP, .Net, Node. js, Ruby, PHP, Java, Go, and Python and many more, to develop web apps or Docker containers that run on an application server with a database. The main services of this platform are: device management, rules and analytics, and data storage and integration, as well as security.

Table II presents the lists of the messaging protocols supported by the IoT Cloud platform for data transmission. Table II confirms that the MQTT protocol takes first place in the IoT market since it is supported by all the IoT cloud platforms. HTTP comes in second, followed by WebSockets.

Based on Figure 8 and Table II, our in-depth examination of messaging protocols leads us to the conclusion that MQTT is the messaging protocol with the greatest impact

Table I: Features of Messaging Protocols.

Feature	Messaging Protocols				
	MQTT	DDS	CoAP	AMQP	XMPP
Pattern	Publish-Subscribe	Publish-Subscribe	Client-Server Publish-Subscribe	Publish-Subscribe Publish-Subscribe	Publish-Subscribe Publish-Subscribe
Transport	TCP	TCP, [UDP]	UDP, [TCP]	TCP, [UDP]	TCP
Scope	Device-to-Cloud Cloud-to-Cloud	Device-to-device Device-to-Cloud Cloud-to-Cloud	Device-to-device	Device-to-device Device-to-Cloud Cloud-to-Cloud	Device-to-cloud Device-to-Cloud Cloud-to-Cloud
QoS Level	3	23	2	3	none
Addressing	Topic	Topic Key	URI	Queue Queue Routing key	Jabber Identification
Max Payload Size	256 MB	64 KB, 4 GB with block-wise transfer	40 B–1KB (without IP fragmentation), 1 MB–1GB with block-wise transfer	defined by end-points	defined by end-points (64 KB stanza size)
Payload Format	Arbitrary	Strongly defined types, Mixed	JSON,XML	-	XML

on the IoT. The MQTT protocol is the lightest, the most reliable, and the one that has the least overhead.

V. Device Management Protocols

A huge amount of heterogeneous devices, which are integrated into IoT, need to be (re)discovered, reconfigured, and maintained to fix security issues, deploy new features, or recover from their failures. It is possible to manage devices with the IoT messaging protocols by inventing new building blocks. It seems that these protocols are no longer the right choice for device management because of the high cost of development, where for every new management feature, a new block should be developed. To solve this problem, new protocols known as Device Management Protocols are proposed. A device management protocol enables the abstraction of an IoT/M2M device as a managed object to make the management of the device much easier [50].

Open Mobile Alliance Device Management standard [51] [52] [53] named as OMA-DM and designed by Open Mobile Alliance for device management, is used for Terminal M2M devices and Mobile terminal devices, e.g, Mobile phones, Smartphones, Tablets, laptops. Mobile network operators and enterprises use OMA-DM to manage mobile devices remotely. The main features of OMA-DM are: read and write configuration or monitoring nodes, read and set parameter keys and values, Firmware Update Management Object (FUMO), software components management object (SCMO) that means install, upgrade, or uninstall software elements. OMA-DM has several demerits. The OMA-DM protocol is designed only for no constrained and fixed devices. Another disadvantage is that OMA-DM cannot be used for industrial applications and cannot be built on top of the MQTT protocol. The disadvantage before the last is that it supports only XML serialization format and it does not support either Binary, Plain text, or TLV and JSON serialization format. The final disadvantage refers to the no support of interoperability.

Lightweight M2M [54] [55] (LwM2M) is a client-server standard developed by the Open Mobile Alliance (OMA). It is an OMA-DM successor. The LwM2M is a standard device and service management built on top of CoAP to ensure remote management and configuration of constrained and powerful devices. It can beneficiate from efficient communication in M2M and IoT environments over UDP and SMS bearers. So, SMS can be used for waking up the device or any GET, POST, and PUT request. The LwM2M main features are: device monitoring and configuration, server provisioning (bootstrapping) and firmware upgrades. There are numerous advantages of the LwM2M protocol. The most remarkable advantage of LwM2M is that it could be used with fixed and mobile-constrained devices. Another advantage refers to the support of the industrial application and interoperability. The most important disadvantages of LwM2M are: cannot support XML serialization format, cannot be built on top of MQTT and cannot be used in telecommunication applications.

The Broadband Forum defined CPE WAN management protocol (CWMP) that is used for remote management of home and business network devices, such as modems, gateways, routers, and VOIP phones (see Technical report 069 [56] [57] known as TR-069). The main capabilities of this protocol are firmware management, auto-configuration, dynamic service provisioning, software module management, status monitoring, performance monitoring, and diagnostics. The TR-069 uses SOAP (Simple Object Access Protocol)/HTTP protocol for communication between network devices called the Customer Premises Equipment (CPE) and central server called the Auto-Configuration Servers (ACS). The CPE and ACS present the main components of this protocol. TR-069 has the same disadvantages as OMA-DM.

IoT devices management protocols are not oriented for communication and service discovery features. Our depth study allows us to conclude that the device management protocol with the greatest impact on the IoT is the LwM2M. The overhead, footprint, and server load of the LwM2M are lighter than TR-069 and OMA-DM protocols, while the response time of LwM2M is faster than TR-069 and OMA-DM protocols.

Table II: Messaging protocols supported by existing IoT platform for data transmission.

IoT Platform	Messaging Protocols						
	MQTT	HTTP	WebSockets	HTTPS	CoAP	AMQP	XMPP
Microsoft Azure IoT [36]–[38]	✓	✓		✓		✓	
IBM BlueMix [36], [39]	✓	✓	✓	✓			
AWS IoT [36]–[38]	✓	✓		✓			
Kaa [37], [40]	✓	✓					
DeviceHive [41]	✓		✓				
ThingSpeak [42]–[44]	✓	✓	✓				
OpenMTC [45]	✓	✓					
SiteWhere	✓		✓		✓	✓	
Linksmart [40], [45], [46]	✓		✓	✓			
OpenRemote [45]	✓	✓	✓				
Zetta [39]			✓				
Google IoT Core [47]	✓	✓		✓			
Oracle IoT [48]	✓	✓	✓	✓	✓	✓	✓
Cisco Kinetic [49]	✓	✓	✓	✓		✓	
Eclipse Homo	✓	✓		✓	✓	✓	

VI. Services Discovery Protocols

Service Discovery Protocols (SDPs) are communication protocols that provide mechanisms to help clients to discover services available on the network. There are several SDPs for the IoT environment. This section focuses on the most known SDPs by introducing the following protocols: mDNS, SSDP. Multicast Domain Name System (mDNS) [58] [59] [60] is an open protocol defined by IETF, which requires minimal configuration, based on the Internet Protocol (IP) and the User Datagram Protocol (UDP). An mDNS client can discover a thing's endpoint by resolving its hostname to an IP address. An mDNS client has to send an IP multi-cast query message over the network. The message calls the host with that name to reply and identify. Once the host receives the message, it replies via a multi-cast message that contains its IP address. All nodes in the network receiving that multi-cast message update their mDNS caches accordingly. This protocol, coupled with DNS-based Service Discovery (DNS-SD), offers the flexibility required by environments where it is necessary to automatically integrate new devices and perform DNS-like operations without the presence of a conventional DNS server.

The Simple Service Discovery Protocol (SSDP) [58] [59] [60] is an open protocol, based on IP, UDP, and SOAP [58] [59] [60]. An SSDP client discovers SSDP services by multicasting a discovery request to the SSDP multicast channel and port. SSDP services listen on that channel until they receive a discovery request that matches the service they offer, then they respond using a unicast response. This protocol—included in the Universal Plug-and-Play (UPnP) architecture—makes it possible to transparently plug and play devices without the need for any manual configuration.

VII. Challenges and Enhancements of Communication Protocols

IoT protocols have limitations and drawbacks. Among these, we highlight communication protocols challenges:

- Real-time and industrial communication issues.
- Not suitable for constrained devices.
- Interoperability issues.
- Security issues.
- Quality of Service (QoS) issues.

Motivated by the presented issues, several new solutions have emerged recently. In this section, an overview of studies focusing on the improvement of existing and well-known base protocols are divided and presented according to their proposals. Table III summarizes the existing studies of some widely efficient and recently enhanced approaches for application layer protocols in IoT environment.

a) Real-Time and Industrial Communication: Several applications in IoT fields, such as medical, factory, and transportation are time-sensitive applications. Mostly, the delays of communications between the different parts of the IoT systems are in-bounded. Therefore, the real-time requirement is one of the challenges of communication protocols. Most IoT solutions involve time constraints to gather and process information, make decisions, and deliver actions that system components must perform. When time restrictions are present, the system is said to be real-time if at least one of the tasks is performed but it must be executed before a certain deadline.

XMPP and DDS protocols are designed for real-time communication. Even though the other protocols, such as MQTT and CoAP, have received a lot of attention due to their simplicity and scalability, none of them support real-time interactions.

To address this, many approaches are proposed to add enhancement to applications protocols without changing their simplicity and scalability. Kim et al. [61] propose to integrate MMS and MQTT protocol for Internet of Things industrial applications. Konieczek et al. [63] presented a lightweight Java implementation of the Constrained Application Protocol called jCoAP that enables CoAP-based communication for embedded devices with comparably small latencies (real-time interaction).

b) Constrained Devices: IoT devices are constrained. They have limited capabilities, memory, and energy. And the use of heavy communication protocols on these devices reduces the performance of IoT communication. i.e., shut down

Table III: Surveys on Communication Protocols Challenges and Enhancement.

Challenge	Focus	Protocol	References
Real-time communication	Industrial application	MQTT	[61]
	IoT based system	MQTT	[62]
	Embedded devices	CoAP	[63]
	Prototype Medical Instruments Applied to Neurodegenerative Disease Diagnosis	MQTT/AMQP	[64]
Constrained devices	Power saving	MQTT	[65], [66]
	Power saving	MQTT-SN	[67], [68]
	Power saving	CoAP	[69]
	Decrease the computational complexity of the clients	MQTT	[70]
Interoperability	Technical Interoperability	MQTT/HTTP	[71]
	Technical Interoperability	MQTT	[72]
	Syntactical interoperability	All protocols	[73]
	Semantic interoperability	MQTT	[74]
Security	Authentication	MQTT/MQTT-SN	[75]–[79]
	User authority to information access	MQTT	[80]
	User Registration	MQTT	[81]
	Denial-of-sleep attacks	CoAP	[82]
Quality of services	Control the traffic flow between the subscribers and publishers	MQTT	[83], [84]
	Maintain message order	MQTT	[85]
	Transit urgent message first	MQTT	[86]
	Reduce the delivery of unnecessary messages	MQTT	[87]
	Data Delivery in Mobile Scenarios	MQTT	[88]
	Network Congestion Control	CoAP	[89]
	Object Discovery	CoAP	[89]

the devices quickly, increase the delay of communication. Power consumption is one of the most constrained aspects of IoT devices, which makes the most powerful applications protocols not suitable for Internet of Things ecosystems.

Although MQTT is a lightweight protocol, it has its drawbacks for extreme environments. MQTT clients must support TCP and would normally keep an open connection to the broker at all times where packets loss and connection drop rates are high or computing resources are scarce. Moreover, topic names are often long ones, which make the header bigger and use significant bandwidth and power as well. To address this, many variations and enhancements are proposed. First, Query Telemetry Transport for Sensor Networks (MQTT-SN) was created [65], which runs over UDP. UDP is mainly used for sensor nodes and devices with low computing performance. MQTT-SN requires additional gateways to connect the clients to the MQTT broker over UDP, which can be suitable for devices with multicast support. A modification to MQTT-SN with additional security elements adopted from DTLS is proposed to replace the DTLS protocol to enable shorter lightweight packet headers [15].

Akintade et al. [66] proposed another architecture to facilitate the development of energy-efficient and low-cost IoT solutions, namely, the aMQTT architecture. The architecture is based on the existing MQTT architecture and the low cost ESP8266 IoT hardware platform. Second, many enhancement solutions were added to the MQTT-SN protocol to increase its performance especially in extremely lossy channels where re-transmission creates a huge overhead in terms of power consumption, delay, and processing. Alshantout et al. [67] created MQTT-SN with LT (MQTT-SN-LT). They aim to use Luby Transform Codes (LT) with the MQTT-SN-QoS1 protocol without changing the protocol itself. The authors [68] proposed to add Network Coding to an MQTT-SN network.

c) Security: Application protocols were not designed with security in mind [90]. They are based on common security solutions, such as DTLS and TLS which are not sufficient for optimal security as they reduce the performance of IoT systems. To go further, these solutions are very heavy for constrained devices. Added to that, certain attacks are no longer covered by these solutions which require the development of new standards to improve the security levels of each protocol. In the rest of this section, several attacks and problems are cited as well as their solutions. The flow of the distributed messages between the users of application protocol based on Publisher-Subscriber models is insecure. Wherein authentication layer authenticating credentials are sent in plain text and some form of encryption should be used. In authorization layer all users connected to the broker are listening to a Topic and receiving all the information.

For authentication layer several works are proposed such as the works [75], [77]–[79]. Blockchain is a distributed immutable time-stamped ledger. Today, researchers are combining the blockchain and the IoT together to increase the security level of IoT applications. In this context, new security schemes based on blockchain technology are proposed, for example [77]–[79], where M. Abubaker et al. [77] proposed a lightweight authentication schema for the MQTT protocol based on blockchain, and also F. Buccafurri et al. [78], [79] proposed a lightweight OTP(One-Time Password)-authentication schema based on blockchain for the MQTT protocol. ChaCha20- Poly1305 AEAD solution is proposed as a lightweight security scheme for MQTT/MQTT-SN communication in [75]. Since, in a MQTT environment, a user in the broker's access is authorized to access all information, after their connection to the broker the user is listening to a Topic and receiving all the information. A new solution of certified authority is opted for in [80] to generate two kinds of certificates, the first one for the client and the second one for the Topics. One of the most well-known types of attacks in network sensors is the Denial of Sleep (DoS) attack [91], [92]. DoS prevents the radio from reaching sleep mode, which would entirely consume the battery. In normal working conditions, sensors' energy consumption ratio consumes their batteries over months, however a denial of sleep attack drains them over days by keeping the radio transmitter system on the sensor nodes active. So, DoS attacks aim at depriving victims of devices entering low-power sleep mode. Since the CoAP protocol suffers from this type of attack where Internet-located attackers can force IoT devices that run CoAP servers to expend much energy by sending lots of CoAP messages to them, a new solution is proposed by adding a block to filter the CoAP messages en route before entering the network [82].

d) Interoperability: Interoperability is meant to make communication among heterogeneous devices and software applications from different vendors possible. Interoperability has four dimensions: technical, syntactical, semantic, and organizational interoperability [93]. There is no compatibility in inter-communication between application protocols. Messages are not supposed to be exchanged. Thus, we need new standards to convert communication protocols and to enlarge the protocol's capabilities for larger interoperability.

A new efficient application layer gateway that converts MQTT messages into HTTP is proposed in [71]. To address the problems of the interconnection of embedded systems in networks, the authors of [72] aim to dynamically model and create links between MQTT brokers based on multi-agent systems to establish the highest level of connectivity for brokers to ensure maximum transmission of messages to subscribing clients. Since there is no compatibility between the sensors, where each sensor for example has its own data display units, there is a need for common semantics for these sensors. To solve this problem, several standards have been developed to ensure that the precise meaning of exchanged information can be understood by any other application that was not initially developed for that purpose. A semantic data extraction implementation over MQTT for Internet of Things centric wireless sensor networks was introduced [74].

e) Quality of Service (QoS): The QoS characterizes the quality of communication links between nodes. Generally, it is the capacity to carry the traffic between nodes in the best condition, such as in terms of availability, packet loss rate, and throughput. So, to ensure good communication it is recommended to define clearly the quality metrics and to enhance the communication protocols accordingly. Quality of Service is the strength of application layer protocol, that represents the ability to configure the performance and reliability of the network. Some protocols do not define any QoS level which reduces their performance, while others, such as CoAP, MQTT, and DDS define different levels of QoS which address different requirements, such as message delivery, timing, loose coupling, and fault tolerance. As MQTT provides only three levels of QoS for different classes of traffic, so many drawbacks arise.

Firstly, the traffic flow between subscribers and publishers is not controlled since publishers send data to broker and broker forwards it to subscribers which could increase the number of packet losses and delays. A new flow control mechanism is designed to overcome the flow control problem of MQTT where the publisher can overwhelm the subscriber [83], [84].

Secondly, MQTT does not support the urgency of the message. Hence, normal and urgent messages are processed with the same priority. Many approaches are designed for this purpose. Hwang et al. [86] proposed a new method to expand the functions of the MQTT to transmit urgent messages first by creating a U-Mosquitto broker capable of processing urgent messages.

However, MQTT protocol has vulnerability to maintain order between messages, which is very important in some home automation, such as controlling gas valve. Hwang et al. [85] designed and implemented a reliable message transmission system using MQTT protocol to maintain messages order.

Also, the absence of a standard for controlling the number of messages received is such a serious problem where the subscriber devices are forced to receive all messages even if they do not need to receive them frequently. To solve this problem, reducing the delivery of unnecessary messages is the best solution. Hwang et al. [87] focused on the MQTT protocol that is currently used to deliver messages between IoT devices and proposed the concept of Reception Frequency Control (RFC), which is designed to control the frequency at which subscribers receive messages.

VIII. Conclusions

Application communication protocols in IoT ecosystems are used to successfully interact between IoT devices and servers / Clouds that process the information collected. Application protocols specific to IoT have been developed to meet the requirements of devices with limited resources, and those of networks with low bandwidth and high latency. However, establishing low-cost communications is not enough. These protocols must allow data to be exchanged and this data must be understood by the entities of different types which receive them. The interoperability of distributed applications is defined as the ability of success for the IoT thanks to a set of application protocols for users to communicate and exchange data and services, wherever they are in the world regardless of the origin of the equipment they use.

There several challenges in front of IoT application protocols. These challenges are related to the drawbacks of application protocols. Those challenges can be summarized in the following points: not suitable for real-time and industrial application, not suitable for constrained devices and lack of interoperability, security mechanisms and Quality of Service (QoS).

In this paper, we surveyed the most suitable communication protocols for the Internet of Things and related challenges of IoT issues by introducing relevant and recent approaches for improving the performance of application layer IoT systems.

The studied application protocols, in general, are based on MQTT, CoAP applications protocols. This is justified due to MQTT and CoAP being already the most suitable solutions in IoT since they are better suited to the application layer criteria: message size, overhead, power consumption, resource requirement, bandwidth, and reliability.

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