SimulateIoT: Domain Specific Language to Design, Code Generation and Execute IoT Simulation Environments

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ABSTRACT

Internet of Things (IoT) is widely applied in several areas such as smart-cities, home environments, agriculture, industry, etc. Developing, deploying and testing IoT projects require high investments on devices, fog nodes, cloud nodes, analytic nodes, hardware and software. New projects require high investments on devices, fog nodes, cloud nodes, analytic nodes, hardware and software before each system can be developed. In addition, the systems should be developed to test them, which implies time, effort and development costs. However, in order to decrease the cost associated to develop and test the system the IoT system can be simulated. Thus, simulating environments help to model the system, reasoning about it, and take advantage of the knowledge obtained to optimize it. Designing IoT simulation environments has been tackled focusing on low level aspects such as networks, motes and so on more than focusing on the high level concepts related to IoT environments. Additionally, the simulation users require high IoT knowledge and usually programming capabilities in order to implement the IoT environment simulation. The concepts to manage in an IoT simulation includes the common layers of an IoT environment including Edge, Fog and Cloud computing and heterogeneous technology. Model-driven development is an emerging software engineering area which aims to develop the software systems from domain models which capture at high level the domain concepts and relationships, generating from them the software artefacts by using code-generators. In this paper, a model-driven development approach has been developed to define, generate code and deploy IoT systems simulation. This approach makes it possible to design complex IoT simulation environments and deploy them without writing code. To do this, a domain metamodel, a graphical concrete syntax and a model to text transformation have been developed. The IoT simulation environment generated from each model includes the sensors, actuators, fog nodes, cloud nodes and analytical characteristics, which are deployed as microservices and Docker containers and where elements are connected by using publish-subscribe communication protocol. Additionally, two case studies, focused on smart building and agriculture IoT environments, are presented to show the simulation expressiveness.

INDEX TERMS

IoT systems, IoT simulation, fog computing, model-driven development, model to text transformation, data analysis.

I. INTRODUCTION

The Internet of Things (IoT) is widely applied in several areas such as smart-cities, home environments, agriculture, industry, intelligent buildings, etc. [46]. Usually, these IoT environments require using hundreds of sensors and actuators shared throughout these areas which are generating a vast amount of data. Data must be suitably stored, analysed and published using Big Data or Stream Processing techniques. Big Data or Stream Processing techniques must be applied
to conveniently store and analyse published data. Taking into account where data are processed and stored, the IoT environment architecture can be defined by several computing layers (Edge, Fog and Cloud computing (see Figure 1) [30]). Edge layer is defined closer to data generators, Fog layer resides on top of the edge and act as intermediary layer with limited storing and processing capabilities and Cloud layer is defined with full storing and processing capabilities. Thus, the development of IoT systems requires the management and integration of conveniently heterogeneous technologies such as devices, actuators, databases, communication protocols, stream processing engines, etc. As a consequence, in order to implement, deploy and test the IoT systems a high investment must be made in time, money and effort.

Simulating IoT environments is one way to decrease this initial investment because the users can measure and dimension the artefacts needed to deploy and interconnect the systems. Thus, these artefacts can include several kinds of devices from sensors or actuators to NoSQL databases, messaging brokers or stream processor engines. However, although there are several simulation environments for wireless sensor networks (WSN), there is a lack of IoT simulator tools for designing IoT environments at a high level that enable modeling this kind of systems by using the domain concepts and relationships. In addition, there is a lack of IoT simulation tools that makes it possible to deploy the IoT system on multiple nodes in order to test the communications among the system’s elements and where complex IoT components such as databases, complex event processing or message brokers can be suitable deployed and tested.

Currently, there is a lack of methodologies and tools to simulate IoT systems and allow users to properly describe the IoT environment. Currently, not only tools are needed but also methodologies to guide the simulation designing and simulation process of IoT environments. So, both methodologies and tools to simulate IoT systems are interesting research areas. should be developed. Thus, while methodologies would allow developers to describe the steps and the characteristics to simulate IoT systems, the tools would help to design and execute the IoT environment simulated in sandbox environments. These tools should take into account the main IoT characteristics including heterogeneous devices (sensors and actuators), heterogeneous communication mechanisms such as publish-subscribe communication protocol, analysis from information generated, storing of information, etc. However, an IoT environment is a broad and heterogeneous concept which involves heterogeneous technologies such as communication protocols such as publish-subscribe communication protocol, databases, analysis tools, etc. Not only should IoT methodologies and tools be designed and developed, but they should also be carried out using software engineering good practices.

Model-Driven Development is an emerging software engineering research area that aims to develop software guided by models based on Metamodeling technique. Metamodeling is defined by four model layers (see Figure 2). Thus, a Model (M1) is conform to a MetaModel (M2). Moreover, a Metamodel conforms to a MetaMetaModel (M3) which is reflexive [2]. The MetaMetaModel level is represented by well-known standards and specifications such as Meta-Object Facilities (MOF) [29], ECore in EMF [48] and so on. A MetaModel defines the domain concepts and relationships in a specific domain in order to model partial reality. A Model (M1) defines a concrete system conform to a Metamodel. Then, from these models it is possible to generate totally or partially the application code (M0 - code) by model-to-text transformations [44]. Thus, high level definition (models) can be mapped by model-to-text transformations to specific technologies (target technology). Consequently, the software code can be generated for a specific technological platform, improving the technological independence and decreasing error proneness.
So, Model-Driven Development (MDD) is proposed to tackle this heterogeneous technology (devices, actuators, complex event processing engines, notification technology, publish-subscribe communication protocol, etc.). Model-Driven Development [16], [20], [40], [43] increases the abstraction level where the software is implemented, focusing on the domain concepts and their relationships. These domain concepts (sensors, actuators, fog nodes, cloud nodes, etc.) and their relationships are defined by a model (M1), conform to a metamodel (M2), which can be analysed and validated using MDD techniques. Besides, the IoT environment code, including all the artefacts needed, can be generated from a model (M1) using model-to-text transformations, decreasing error proneness and increasing the user’s productivity.

The main contributions of this paper include:
- This work shows that using Model-Driven Development techniques are suitable to develop tools and languages to tackle successfully the complexity of heterogeneous technologies in the context of IoT simulation environments.
- A methodology called SimulateIoT to describe each step needed to define an IoT simulation environment and execute it.
- A Model-Driven solution that supports the methodology proposed. It facilitates the development of each methodology phase by defining a SimulateIoT metamodel (M2), a graphical concrete syntax (graphical editor) to define models (M1) and a model-to-text transformation towards the code generation for specific IoT simulation environment (M0 - code). It includes the code generation to execute the IoT simulation. Furthermore, the IoT system generated can be deployed.
- An IoT deployment process that makes it possible to deploy the simulation based on microservices which are deployed on Docker containers, including components such as databases, complex-event processing engines or message brokers.
- The application of SimulateIoT to two case studies focused on different kinds of IoT systems (Smart buildings and Agricultural environment).

The rest of the paper is structured as follows. In Section 2, we give an overview of existing IoT simulation approaches centered on both low level and high level IoT simulation environments. In Section 3, we present the SimulateIoT methodology. Section 4 describes SimulateIoT design and implementation phases including the SimulateIoT metamodel, the graphical editor and the model-to-text transformation developed. In Section 5 two case studies are presented. Finally, Section 6 elaborates on the limitations of the presented approach before Section 7 concludes the paper.

II. RELATED WORKS

IoT environments and IoT simulation environments have been developed using several strategies with different targets and distinct abstraction levels. The abstraction levels are not related to the different IoT Architecture levels (Edge, Fog or Cloud layers) but also the concepts and relationships used to design the simulation at the IoT architecture level. For instance, you could use concepts to low level such as memory, network capabilities and use tools to manage this kind of configuration or using high level concepts such as Fog Node, Cloud Node or Complex Event Processing, engines, NoSQL storage where low level concepts could be transparently managed. Additionally, using high level abstractions could be used to generate code for specific technological targets. In this sense, among other, the concepts analysed for each different related work include: the abstraction level used to define the IoT environment, Edge modeling capabilities, Fog modeling capabilities, Cloud modeling capabilities, Complex Event Processing, Big data support, and Code generation support. So, in the following subsections several IoT simulation approaches are reviewed that focus on the different abstraction levels used for their definitions. So, we are examining i) Low level IoT simulation environments; and ii) High level IoT simulations environments and IoT modeling based on model-driven development. The former are based on defining sensors and actuators close to hardware (Contiki-Cooja, OMNeT++, IoT-Lab), so these proposals foster the knowledge of hardware, networks or energy consumption characteristics. The latter (COMFIT, CupCarbon, IoTSim) focus on defining IoT context and environments at a level of high abstraction.

A. LOW LEVEL IoT SIMULATION ENVIRONMENTS

Contiki-Cooja [42] is a network simulator tool based on the Contiki operating system. It is implemented in Java and allows users to define large and small Contiki motes (a node in a sensor network) which can be deployed throughout the network. Relevant information about the network such as mote output or time-lines could be obtained after the simulation execution. Note that a mote can be defined ad-hoc using the motes templates. Obviously, these simulations are defined at a low level focusing on hardware and network issues more than IoT contexts or communication patterns such as publish-subscribe.

OMNeT++ [51] is a general network simulator adapted to simulate IoT networks. It offers a Domain Specific Language for modelling the IoT context including aspects related to routers, switches, routing protocols or network protocols (IPv4, IPv6, etc.). This is a powerful simulator focused on analysing low level aspects of network issues. It uses components and component-based compositions to define network simulations. This approach focuses on defining IoT environments at a low level of abstraction closed to hardware. So, it is not centered on describing the IoT environment and high-level component relationships. Therefore, simulating wide IoT environments could be tedious and error prone.

IoT-Lab [35] is a platform which allows deploying compiled WSN (Wireless Sensor Network)/IoT applications on a large WSN infrastructure. The applications can be installed on different types of sensors and can be developed on the
Contiki operating system, among others. Thus, the goal of the authors is showing how both local and global energy consumption can be precisely monitored.

Tossim [24] is a Wireless Sensor Network (WSN) simulator tool used over TinyOS. It can simulate thousands of nodes while it is able to capture the network behaviour with accuracy. It emulates the underlying raw hardware behaviour. Thus, the aim of this approach is simulating low level motes without defining communication patterns such as publish-subscribe or without using pattern data generations.

**B. HIGH LEVEL IoT MODEL-DRIVEN DEVELOPMENT AND SIMULATION ENVIRONMENTS**

This section includes both IoT development environments and IoT simulation environments which are based on graphical or textual domain concept descriptions, or model-driven technologies. There are several IoT metamodels [8], [36], [47] to model IoT systems, and usually the application code is partially generated from these models.

In [8] a Domain Specific Language has been defined to model IoT environments, taking into account several IoT concepts such as devices, and input and output properties. Its goal is modelling IoT environments and generating code for a specific platform such as KNX/EIB. Although it is not related to IoT simulation, it uses model-driven techniques in order to tackle designing IoT systems and it can be used for quick IoT system prototyping.

Another approach based on Model Driven Development [9] makes it possible to model complex event processing for near real-time open data. This approach is interesting because they present a methodology and a domain specific language to define models in order to model open-data sources, the processing nodes and the notifications agents. However, this approach does not focus on modeling and simulating IoT environments.

COMFIT [15] was a cloud environment to develop the Internet of Things system. It used model-driven techniques included in the Model-Driven Architecture (MDA) specification [18]. For instance, a model-to-text transformation towards code generation for specific operating system targets (for instance, Contiki or TinyOS operating systems) was implemented. It defined several UML Profiles such as PIM:UML Profile and PSM:UML Profile, a model to model transformation from PIM models to PSM models, and a model-to-text transformation. So, authors used well-known UML tools to model the IoT Systems, however they did not define an ad-hoc metamodel for IoT, but used UML diagrams such as detailed activity diagrams.

On the other hand, IoTSuite [36], [47] defined a high level domain specific language in order to model IoT environments including concepts such as regions, sensors, actuator, storage, request, action, etc. Thus, it joined computational services with spatial information related to regions such as buildings or floors. Several modelling languages were defined to model these kinds of systems: Srijan Vocabulary Language (SVL), Srijan Architecture Language (SAL) and Srijan Deployment Language (SDL). Then, a code generation process allows generating the application code. Although IoTSuite makes it possible to define IoT environments, it isn’t an IoT simulator.

In [39] a component-based approach for the Web of Things was presented. They defined a Model Driven Development process to model Web of Things (WoT) systems by using model-driven techniques such as meta-modelling and model transformations. Thus, they defined a metamodel for WoT which related Physical Entities such as Sensors or Actuators with Visual Entities such as components deployed on a system. These models can automatically turn into code skeletons. However, this metamodel does not allow defining specific domain concepts related to simulation or storage issues, among others.

Other approaches focus on simulating IoT systems proposing specific tools [4], [27], [45]. Thus, CupCarbon [27] defined an IoT Simulator environment which allows users to describe IoT contexts using a graphical editor. For instance, a mote could be added on a map like Google Maps, taking into account parameters such as action radio. It implements an ad-hoc language to manage the sensor’s communication and the business logic. It can execute simulations including the reactions to random events. So, although this approach allows describing IoT simulation issues, it does not allow describing the storage information or the complex communication protocols such as publish/subscribe using messages brokers.

IoTSim [53] is an extension of CloudSim [6] that focuses on simulating IoT applications in cloud environments. It supports and enables IoT big data processing using the MapReduce model in the cloud. However, in order to execute the IoT application to be simulated, users should implement the workflow that IoTSim proposes, including Datacenter configuration, IoTDataCenterBroker, JobTracker, etc. Obviously, this approach offers a framework to execute IoT applications on cloud, however it does not offer a designing tool to easily define the artefacts necessary to be deployed on the IoT-Sim. Additional extensions to CloudSim deal with the analysis and use of BigData. BigDataSDNSim [1] allows the simulation of the big data management system YARN, its related programming models MapReduce, and SDN-enabled networks in a cloud computing environment. On the other hand, IoTSim-Edge is another CloudSim extension specialised in EdgeComputing [22]. In this way, this simulator allows defining and simulating elements such as EdgeNodes (EdgeDevice, EdgeDataCenter, EdgeBroker), IoTDevices (sensors and actuators) and their characteristics such as battery consumption, mobility, communication protocol, etc. These simulators deal with relevant aspects of the IoT in detail, allowing the simulation of IoT environments or parts of these environments in a very realistic way. However, these works lack a high-level abstraction graphical interface to visualise and model the architecture of the environment. On the other hand, they lack a module capable of validating a configured environment before its simulation. Therefore, although these simulators are able to simulate an
IoT environment with high detail they need to define the configuration simulation environment using JSON files and Java code, which raise the learning curve. For instance, each sensor type needs to be implemented before being used on a configuration file. Finally, they do not model high concepts related to Complex Event Processing or they facilitate code-generation. Another important aspect is related with Simulation deployment which is carried out in the same machine without deploying a service-oriented architecture (common architecture where an IoT system is deployed), that is, all IoT aspects are simulated so code cannot be re-used for real implementation proposes.

Using the approach in [4] the developers can test their cloud and on premise MQTT (Message Queuing Telemetry Transport) [33] application for functional and load testing. So, it allows deploying IoT environments focused on using sensors, actuators and MQTT servers. This tool allows users to define sensors and actuators and publish/subscribe concepts to define the IoT environment. It defines a set of template sensors to be used in order to model the IoT environment. Besides, data generation can be defined by the users following several data patterns such as concrete value, range values, random set or based on time & client. However, the IoT environment does not make it possible to define stream rules to react to event patterns.

In [45] an IoT simulator was defined. It was written in Java and it allowed defining IoT simulations including agents, places and the context therein. The main steps to define a simulation included: i) defining the environment, ii) developing the behaviour and iii) packing and deploying it all together. The IoT system behaviour should be implemented ad-hoc using Java. So, this simulator required high expertise implementing Java agents. Furthermore, this approach did not resolve how to manage or analyse the device data.

Viptos [7] is an integrated graphical development and simulation environment for TinyOS-based [21] wireless sensor networks. Developers can model algorithms with the graphical framework included in Viptos and generate their code in nesC [17]. Besides, users can define environments to simulate the behaviour of these algorithms. These environments could have features such as communication channels, network topology (the nodes where the algorithms will be tested) and physical characteristics (low-level, such as OS interruptions) of the environment. In short, this framework allows application developers to easily transition between high-level simulation of algorithms to low-level implementation and simulation. However, due to the characteristics mentioned, this framework works with a low level of abstraction. For that reason, the application developers that use this framework need to know low level concepts about it and the domain which can simulate. In addition, modelling an extensive simulation could be complex and the use of simulators with a higher level of abstraction would be more suitable.

VisualSense [3] is a modelling and simulation framework for wireless sensor networks that builds on and leverages Ptolemy II [12]. This framework supports the modelling of sensor nodes, wireless communication channels, physical media such as acoustic channels, and wired subsystems among others characteristics. Besides, this framework supports the modelling of dynamic networks where nodes can change their connectivity in run-time. It’s worth mentioning that the communication between nodes is via events with timestamps [5]. Finally, the models can be simulated and visualised at run time. However, this simulator is focused on modeling networks at a low level of abstraction, without including high level concepts based on Cloud/Fog computing, publish-subscribe communication protocols and so on.

To sum up, although there is a wide literature focus on defining the IoT environment and IoT simulation environments at different abstraction levels, several issues should be additional treated including fog computing, cloud computing, storage data, communication protocols or data analysis (see Table 1. The following sections describe the SimulateIoT methodology and tools which are proposed to tackle the complexity of the description and execution of IoT simulation environments.

III. SimulateIoT METHODOLOGY

This section describes the Simulation Methodology which has two phases, simulation description and simulation execution, as shown in Figure 3.

First, simulation description includes the following steps:

1) Data and WSAN specification: Users should define the wireless sensors and actuator network (WSAN) to identify the device characteristics (including their data inputs and outputs) The wireless sensors and actuator network (WSAN) should be defined to identify the device characteristics (including their data inputs and outputs). It allows defining the edge computing layer formed by sensors and actuators;

2) Fog/Cloud computing spec includes defining devices with different process capacities. For instance, these nodes can define how and where data should be stored, including the database characteristics (SQL database, NoSQL database, etc.);

3) Processing data specification defines the communication schemas, that is, the communication protocols to connect the devices and nodes previously identified. In addition, this phase should make it possible to describe how data should be processed using multiple technologies such as big data or stream processors.

Next, Simulation execution phase includes aspects related to the hosts where the IoT devices and nodes should be deployed. So, it includes where databases, message brokers, stream processors, etc. should be deployed. As a consequence, these aspects allow the IoT to tailor the simulation, adapting it to real situations.

IV. SimulateIoT TOOLS

This section describes the tools designed to implement the SimulateIoT methodology (defined in Section III) which
include a Domain-Specific Language (DSL) named SimulateIoT for defining and deploying IoT simulation environments. For this, SimulateIoT uses model-driven development techniques to manage the IoT simulation environment definition using models. So, the models guide the system description and the code generation. Later on, the code generated can be deployed through several hosts.

In a Model-Driven Development approach like this the software development is guided through Models (M1) which conform to a MetaModel (M2). Moreover, a Metamodel conforms to a MetaMetaModel (M3) which is reflexive. The MetaMetaModel level is represented by well-known standards and specifications such as Meta-Object Facilities (MOF), ECore in EMF and so on. A MetaModel defines the concepts and relationships in a specific domain in order to model partial reality. Then these models are used to generate totally or partially the application code by model-to-text transformations. Thus, the software code can be generated for a specific technological platform, improving the technological independence and decreasing error proneness.
Figure 4 shows a mapping among the phases defined in the SimulateIoT methodology and the SimulateIoT design and implementation which defines a model-driven development process and the SimulateIoT deployment and execution phase. Thus, it shows the main elements needed to build the SimulateIoT Tools Execution Environment and includes: a Metamodel definition, a Graphical Concrete Syntax definition (Figure 4-1) and the model-to-text transformations (Figure 4-2) to generate the code artefacts needed to deploy, monitor and measure the IoT environment (Figure 4-3).

Thus, the Design and Implementation phase makes it possible to design the IoT models and generate the code which will be deployed and executed during the Deployment and Execution phase. Both the Design and Implementation phase and the Deployment and Execution phase together address users to design and implement the SimulateIoT methodology focusing on using well-known model driven software engineering practices such as metamodeling, validating, model transformations, etc. Using it improves the system development productivity and decreases the error proneness [43].

The main elements of the Design and Implementation phase such as the SimulateIoT Metamodel or the model-to-text transformations are described below.

**A. SimulateIoT DESIGN AND IMPLEMENTATION PHASE. SIMULATE IoT METAMODEL**

A MetaModel defines the concepts and relationships in a specific domain in order to model partially reality [43]. Then these models could be used to generate total or partially the application code. Thus, the software code could be generated for a specific technological platform, improving its technological independence and decreasing the error proneness.

Figure 5 defines the domain metamodel including concepts related to sensors, actuators, databases, fog and cloud nodes, data generation, communication protocols, stream processing, and deploying strategies, among others. The relevant elements are summarised below:

- **The Environment** element defines the global parameters of the IoT simulation environment, including simulationSpeed and the number of messages to be interchanged among the nodes (numberOfMessages). These attributes define global policies to manage simulation resources to be applied on all the Node elements defined.
- **Node** is an abstract concept to represent each node in the IoT simulation environment. It is extended by several concepts such as EdgeNode or ProcessNode in order to specialise each kind of node. A Node can publish and subscribe to a specific Topic. It defines publish or subscribe references towards a Topic in which it is interested. Note that, later on, each concrete kind of Node could be defined with specific constraints. Thus, the device position (Coordinates element) can be defined using latitude and longitude attributes. latitude and longitude attributes define the device position (Coordinates element). Furthermore, with the RaspBerryPi attribute, the generation of the node will be carried out for this kind of device.
- **The EdgeNode** element makes it possible to define simple physical devices such as a sensor or an actuator without process capacities. Moreover, with the attribute quantity, it is possible to define how many EdgeNodes of a type must be generated. Each EdgeNode could be linked with ProcessNode elements by Topic elements. Topic elements allow link each EdgeNode with ProcessNode elements. Moreover, each EdgeNode can be mapped with a physical device such as a temperature sensor, a humidity sensor, a turn on/off light device or an irrigation water flow device at the IoT environment.
- **A Sensor** element extends the EdgeNode element. It is the device that publishes the data that the IoT environment works with.
  - A Sensor element analyses a specific environment issue (temperature, humidity, people presence, people counter, etc.) and sends these data to be analysed later.
  - A Sensor element is able to publish on Topic elements which propagate data throughout the simulation nodes. To perform this data propagation, Sensors could integrate the element AdditionalConfiguration that, together with the element RedirectionConfiguration, can define a redirection route of ProcessNode through which their data can flow. Thus, Sensors are able to publish their data in Topics not accessible to them.
  - **An Actuator** element is a device in the IoT environment which can execute an action from a set of inputs. For instance, the inputs could determine that an actuator turn on or turn off a light; other actuators could require data input to define the light’s luminosity. In order to receive data, an Actuator element should be subscribed to topics.
  - **Topic** is a central element in this metamodel because it defines the information transmitted among any kind of Node elements. Thus, Topic elements are defined from CloudNode and FogNode elements, and help users to model a publish-subscribe communication model. Node elements should identify the target Topic for both publication or subscription. Consequently, the Topic element is a flexible concept to model how data should be interchanged.
  - **Data** element defines the simple data type to be generated (Boolean, short, integer, real, string). It has a DataSource element to model either the DataGeneration element or LoadFromFile element. The former (DataGeneration element) models how synthetic data are generated, for instance, using an Aleatory strategy among two values defined in a GenerationRange element. The latter (LoadFromFile element) models the path-file that contains the historic data, for instance, it could be defined by a CSVLoad element. In addition, external tools such as [11], [19] can be linked to increase the capabilities to offer additional data generation patterns.
  - **The ProcessNode** element defines an IoT node with process capability. For this, two subtype nodes could
be defined: CloudNode and FogNode. Essentially, both have the same properties and only differ in their process capability. Thus, in order to classify the ProcessNode capacity (the size attribute) related to batteries, CPU, memories, etc., a set of granularity values have been defined (XS, S, L, XL and XXL). They make it possible to define different kinds of nodes and apply different kinds of policies. Thus, Model-Driven Development helps to deal with the complexity of IoT systems and policies management by model abstractions and constraints.

Using labels (XS, S, L, XL and XXL) to define the node capacity simplifies the knowledge needed to model the IoT environment, overall in a changing environment such as IoT. Labels are used to simplify the reality taken into account the user’s knowledge and expertise. For instance, Scrum agile methodology [41] makes it possible to define the effort needed for a set of developers to develop a specific user history by using labels. Concretely they use the Planning Poker technique which uses Poker cards to estimate the effort needed to carry out a specific task summarising the developer’s knowledge and expertise, task complexity, context changing, and so on. In the same sense we estimate the node capacities using the labels defined. The resources that different users can associate to a specific label can change throughout the time or taking into account their knowledge and expertise.

This strategy allows specifying the ProcessNode element capacity and associating specific constraints. For example, in an XS ProcessNode a ProcessesEngine such as Complex Event Processing (CEP) engine cannot be deployed. Hence, granularity labels are used as in a Scrum project development to define task complexity. As mentioned, ProcessNode can define Topic elements, which can be referenced by any kind of Node elements. Besides, the redirectionTime attribute defines the frequency that stored data are flushed towards the next ProcessNode element defined by redirect references (redirection route defined in Sensors). The attribute BrokerType defines the message-oriented broker that currently is established by Mosquitto [32]. In addition, the ProcessNode element hides the complexity about how data should be gathered and processed. For instance, it defines how data will be stored, published or offered to be analysed by stream processing engines (SP) or complex event processing engines (CEP) by defining Component elements. Note that either the stream
FIGURE 5. SimulateIoT metamodel.
processing or the complex event processing capabilities help to define when an Actuator element should carry out an action.

- **FogNode** allows users to describe fog computing instances [6] which could manage and coordinate several devices or actuators. Thus, this concept focuses on aggregating data for a limited time or connection conditions that are released later on. Furthermore, a FogNode element can include persistent data storing and data processing.

- **CloudNode** extends ProcessNode and allows describing a special node deployed on a public or private cloud computing environment.

- The **ProcessEngine** element should be linked to a ProcessNode, to allow real-time data analysis defining coming from ProcessNode elements or EdgeNode elements. To do this, defining complete event patterns can be carried out by Rule elements. These patterns analyze Topic data in real time. Currently, the SimulateIoT environment works with WSO2 Stream Processor [37] and Esper CEP [13]. Usually, a CEP (Complex Event Processing) engine has a higher process capacity and lower latency than an ESP (Event Stream Processing) engine [25], [26].

- **Rule** elements are linked with the ProcessEngine elements defined at the ProcessNode element. Rule elements can be defined using the Event Processing Language (EPL) [14] defined for a concrete ProcessEngine kind. Note that the eventType attribute is used to name a rule.

- **Notification** elements make it possible to throw alerts by using several notification kinds: TopicNotification or eMailNotification. Obviously, Notification hierarchy could be extended in further metamodel versions. Mention that the Notifications are carried out by messages. Mention that messages carry out the Notifications. In this manner, the attribute message could define the notification message which will be notified.

**B. SimulateIoT DESIGN AND IMPLEMENTATION PHASE.**

**GRAPHICAL CONCRETE SYNTAX AND VALIDATOR**

The Design phase includes creating models conforming to the SimulateIoT metamodel. So, in order to do this, a Graphical Concrete Syntax (Graphical editor) has been generated using the Eugenia tool [23]. — So, in order to do this, the Eugenia tool [23] — makes it possible to generate a Graphical Concrete Syntax (Graphical editor). The Graphical Concrete Syntax generated from SimulateIoT metamodel is based on Eclipse GMF (Graphical Modeling Framework) and EMF (Eclipse Modeling Tools). Consequently, models (EMF and OCL (Object Constraint Language) [34] based) can be validated against the defined metamodel (EMF and OCL based). Note that OCL is a standard to define model constraints. Figure 6 shows an excerpt from this graphical editor. It helps users to improve their productivity allowing not only defining models conforming to the SimulateIoT metamodel, but also their validation using OCL constraints [34]. OCL rules have been defined as part of the SimulateIoT metamodel using OCL in Eclipse Tools (https://wiki.eclipse.org/OCL/OCLinEcore). Each OCL rule, defined as invariant, has its own context which is related to the class where it is established. Some of these OCL constraints are the following:

- An EdgeNode element can only send data to Topic elements defined in one FogNode:

```java
class EdgeNode {
   \ldots
   invariant send_data_to_one_node: self.publish-> forall (topic1, topic2 | topic1.oclContainer() = topic2.oclContainer());
   \ldots
}
```

- Each EdgeNode element should be connected (to publish or to subscribe) with a Topic:

```java
class Sensor {
   \ldots
   invariant sensor_publish: self.publish > 0
   \ldots
}
class Actuator {
   \ldots
   invariant actuator_subscribed: self.subscribed > 0
   \ldots
}
```

- **TopicNotification** generated by a Rule should be published on a Topic created by the FogNode which analyses data with this Rule:

```java
class ProcessNode {
   \ldots
   invariant TopicNotificationPublication: self.create_topic->includesAll(self.component->selectByKind(ProcessEngine).rule.generates_notification-> selectByKind(TopicNotification).publish_on_topic);
   \ldots
}
```

- **ProcessNode** could be a FogNode or a CloudNode, the main difference between these two kinds of node are their computation power, a characteristic defined by the ProcessNode attribute size which should be greater than L in the CloudNode element and smaller than or equal to L in the FogNode element:

```java
class CloudNode {
   \ldots
   invariant cloudSizeMajorThanL: self.size. toString() = 'XL' or self.size. toString() = 'XXL';
   \ldots
}
class FogNode {
   \ldots
   invariant fogSizeMinorThanXL: self.size. toString() <> 'XL' and self.size. toString() <> 'XXL';
   \ldots
}
```
The ProcessNode element has the ability to redirect data. To redirect data ProcessNode must have data persistence, be connected to another ProcessNode and its attribute redirectionTime must be greater than 0. If redirectionTime is equal to 0, ProcessNode won’t redirect the data and does not have to meet these requirements.

```java
class ProcessNode {
    \ldots
    invariant redirectionRequirements: self.
      redirectionTime = $0$ \or self.
      redirectionTime > $0$ \and self.
      component->selectByKind(DataBase) <>
      null \and self.redirect->size() > 0;
    \ldots
}
```

To sum up this subsection, the graphical concrete syntax (based on an Eclipse plugin) developed offers a suitable way to model the IoT environment by using the high-level concepts defined in the SimulateIoT metamodel. Later on, the graphical concrete syntax will be used to model and validate several case studies.

### C. SimulateIoT DESIGN AND IMPLEMENTATION PHASE. MODEL-TO-TEXT TRANSFORMATION

Once the models have been defined and validated conforming to the SimulateIoT metamodel, several artefacts can be generated using a model-to-text transformation defined using Acceleo. A model-to-text transformation defined using Acceleo [38] can generate several artefacts.

The generated software includes, MQTT messaging broker (based on MQTT protocol [33]), device infrastructure, databases, a graphical analysis platform, a stream processor engine, docker container, NoSQL database, MQTT broker, Monitoring using graphical visualisation and analysing characteristics labelled as Complex Event Processing (CEP).

### D. SimulateIoT DEPLOYMENT AND EXECUTION PHASE

The Execution phase involves deploying all the artefacts generated from the models. So, several software artefacts such as the MQTT messaging broker, device infrastructure, databases, graphical analysis platform, etc. can be configured and deployed.

Code is generated to allow users to package code, deploy and monitor the simulation. Thus, the simulation can be deployed through several hosts where each node should be deployed. Figure 7 shows an example of the IoT simulation deployed. It shows the different elements that can be deployed including a CloudNode or FogNode, Sensors and Actuators. Thus, each CloudNode and FogNode is implemented as a micro-service based on Thorntail [49] and it is deployed on a Docker container [28]. Besides, each node can be deployed on hardware with different characteristics such as Rasberry Pi, Jaguarboard, Orange Pi or Pine64. Note that these micro-computers run under several versions of Linux and Docker containers can be deployed on them.

Furthermore, each CloudNode/FogNode can define a Complex Event Processing Engine (e.g. Esper) or Event Stream Processing Engine (e.g. WSO2). Besides, it includes an MQTT broker (e.g Mosquitto), a No-SQL database (e.g. MongoDB) and a REST API. Likewise, as can be observed, all of these elements are inter-connected and are deployed on Docker containers. Finally, all Docker containers are orchestrated using Docker Swarm.
Moreover, each node deployed with storing characteristics includes a specific monitoring tool. Figure 8 shows an excerpt from the monitoring environment based on Compass [10]. So, users take over the monitoring tool including several kinds of graphical elements such as bar graphs, data lists and so on. The monitoring environment makes it possible to query the data stored.

Finally, an overview dashboard is generated to monitor the simulation execution. So, each node defined can be queried. For instance, the data stored on a specific ProcessNode can be queried in real-time. For instance, the user can query the data stored on a specific ProcessNode in real-time. So, during simulation execution the console of each ProcessNode shows the simulation execution log. Later on, the simulation logs and data stored in the ProcessNode with storage capacity are available to be queried.

The simulation execution process including the following steps: i) compiling and deploying the artefacts previously generated from a SimulateIoT model; ii) data generation to commence the simulation process, consequently the defined sensors start to generate data and send them towards the defined Topics; iii) data propagation, data analysis and actions are carried out taking into account the defined data flows; and iv) log simulation can be analysed both in real-time querying the databases or after simulation execution by querying the log simulation. For instance, the following characteristics can be analysed: the performance of each component (in real-time) including CPU or RAM usage, the total memory used for each component, the amount of data sent and received for each component over its network interface, etc.

Algorithm 1 shows a simplified simulation execution process. It focuses on the actions carried out in the Docker containers deployed to execute the simulation process. Note that each Docker container has its own behaviour depending on the simulation component deployed (Sensor,
Actuator, FogNode or CloudNode) as has been described previously.

The number of interactions in Algorithm 1 grows to \(O(N \times M)\) that is \(O(N^2)\), where \(N\) is the number of Node elements and where \(M\) the number of messages to be interchanged. Note that, each Node is deployed on a concrete Docker container where each Node should execute its behaviour \((O(N))\).

The generated IoT system defines a mesh topology network where sensors, actuators, fog nodes and cloud nodes could be interconnected following the model defined. The system modeller can use the Graphical Concrete Syntax that has been developed to describe the Node elements interactions.

V. CASE STUDIES

Next, two case studies have been defined using the SimulateIoT methodology and tools previously presented. The first one defines an IoT simulation on a smart building while the second one defines an IoT simulation in an agricultural environment.

Below is a synthesis of the methodology required to use SimulateIoT and the processes carried out by this tool to simulate these use cases in order to illustrate them more effectively.

1) Model definition: This step refers to the modelling of the IoT Environment that the user wants to deploy. This model corresponds to the DSL and therefore can contain all the elements defined in it. Two examples of IoT Environment models are shown in Figure 9 and in Figure 11.

2) Code generation and deployment: Once the model has been defined, the source code of all the elements involved can be generated from it. Sensors, Actuators, FogNodes, CloudNodes and all their sub-components and configuration files will be ready for the deployment phase. The deployment performs many steps for the correct deployment of all previously generated components.

A. CASE 01. SCHOOL OF TECHNOLOGY

Our first case study presents the simulation of a smart building, more specifically, we have modelled the School of Technology at the University of Extremadura. It has six buildings (Computer Science, Civil Works, Architecture, Telecommunications, Research and a Common Building). So, each building has its own environment with a set of sensors, actuators and analysis information processes.

1) CASE 01. MODEL DEFINITION

Figure 9 shows an excerpt from the School of Technology model. Note that Figure 9 also includes numerical references for each node which are then used to describe the use case. It is a design of an IoT system which includes several nodes shared throughout the different buildings. Each building takes over its own ProcessNode (Figure 9, references 1.1, 1.2, 2) which recovers all the information produced by the sensors (Figure 9, references 3.1, 3.2). Thus, these data are suitably stored on specific databases (Figure 9, references 6.1, 6.2, 6.3), analysed and monitored in ProcessNode elements. In this case study, a FogNode element is defined for each building (Figure 9, references 1.1, 1.2). For instance, Common_Building or Computer_Science are FogNode elements (Figure 9, references 1.2, 1.1). Furthermore, a CloudNode named SchoolTechnologyCloudNode (Figure 9, reference 2) is defined to store information gathered from the FogNode elements. Both FogNode and CloudNode elements define several Topic elements such as heating_temperature, presence, smoke-detection topics (Figure 9, references 5.1, 5.2, 5.3). These Topic elements communicate data among the Node elements defined in the IoT system (Figure 9, references 1.1, 1.2, 2, 3.1, 3.2, 3.3).

In order to model the School of Technology case study, several sensors such as heating_temperature_meter, presence_detector, smoke_detector (Figure 9, reference 3.1) and so on have been defined in Figure 9. Each of them publishes its own data on a specific Topic element (Figure 9, reference 5.1). As can be observed in Figure 9, the Sensor elements publish data to several FogNode through Topic elements. Note that Sensor elements are EdgeNode elements which generate data, so the data pattern generators should be defined (Figure 9, references 4.1, 4.2). For instance, in order to describe the synthetic data generated by a temperature sensor.
Algorithm 1: Deploying and Executing the IoT Simulation

1 begin
2
3 //Step 1)~Connections and configuration of each component
4
5 Compile and deploy each IoT component by using Docker Swarm
6
7 Subscribe each Node (Fog-CloudNode, Sensors, Actuators) to the Topics offered by MQTT Brokers
8
9 Subscribe each ProcessNode (FogNode and CloudNode) to the Topics on other Fog-CloudNode
10
11 Configure the CEP/SP Engine with their EPL rules
12
13 //Step 2)~Start the message flow, the~components start their processes
14
15 foreach Sensor do
16
17 start to publish data from it sources (.csv, syntheticDataGeneration(), etc.) to Topic
18
19 done
20
21 // Main process executed in parallel by each Node
22
23 while (data in Sensors is available) do
24
25 Nodes (FogNode, CloudNode, Actuator) subscribed to Topic receive the data
26
27 //each Node (FogNode, CloudNode or Actuator) process the data received
28
29 switch (NodeType n)
30
31 ProcesNode:
32
33 //2.1 CEP/SP Analysis
34
35 if (n has CEP/SP engine) then
36
37 foreach rule to apply to data do
38
39 ruleObserved=CEP-SP.applyRule(rule[i])
40
41 if ruleObserved == True then
42
43 CEP-SP.sendNotification(rule[i].notificationDestiny)
44
45 endif
46
47 endforeach
48
49 endif
50
51 // 2.2. Data Store
52
53 if (n has Persistence) then
54
55 n.saveData(MongoDB)
56
57 endif
58
59 // 2.3. Data redirection
60
61 if (n has redirection data) then
62
63 redirectionData = n.checkredirectionableData(MongoDB)
64
65 foreach redirectionData do
66
67 n.redirectData(redirectionData.Destiny)
68
69 endforeach
70
71 endif
72
73 Actuator:
74
75 n.doSomeAction(data)
76
77 endswitch
78
79 done
80
81 end

A .csv input file has been defined. It makes it possible to reuse historical data. Other sensors can define their synthetic data generators using a random pattern, incremental pattern, etc. So, the approach can consume synthetic data based on simple data, range data, a specific set of values, the values obtained from a .csv file, data obtained from a url source or data generated form the external tools such as [11], [19].

As mentioned, in Figure 9 each FogNode has its own characteristics about how data should be managed including storing, analysing or addressing. For instance, the ComputerScience FogNode element (Figure 9, reference 1.1) addresses the information every thirty seconds, storing the data obtained in a specific NoSQL database (Figure 9, reference 6.1). Then all data are flushed to the next node FogNode or CloudNode defined in the architecture and named in the example SchoolofTechnology_CloudNode. On the other hand, the Common_Building FogNode element (Figure 9, reference 1.2) defines a different behaviour in order to analyse the data and take advantage of being close to the devices that should carry out some action. For instance, the Common_Building FogNode defines a CEP engine component (Esper_CEP) and several Rule elements.
(Figure 9, reference 7), for example, the rule_heating analyses the data obtained from a specific Topic named heating_temperature to notify a specific action to another Topic named turn_on_heating which is subscribed by specific Actuator named heating. Thus, the rule_heating rule analyses the temperature sent to the heating_temperature Topic element from the heating_temperature_meter Sensor. Consequently, it is gathered and analysed by the CEP engine by means of the rule_heating Rule. Consequently, the CEP engine can gather data and analyse them by means of the rule_heating...
Rule. As a consequence, when the pattern defined is matched (for instance, \( \text{if (temperature < 20) then switch on heating} \)), the CEP engine generates an event to \text{turn\_on\_off\_heating} Topic. As a consequence, the CEP engine generates an event to \text{turn\_on\_off\_heating} Topic when the pattern defined is matched (for instance, \( \text{if (temperature < 20) then switch on heating} \)).

2) CASE 01. CODE GENERATION AND DEPLOYMENT

Once the model has been defined, the model-to-text transformation is applied with the following goals: i) to generate Java code which wraps each device behaviour; ii) to generate configuration code to deploy the message brokers necessary, including the topic configurations defined; iii) to generate the configuration files and scripts necessary to deploy the databases and stream processors defined; and finally, to generate the code necessary to query the databases where the data will be stored; iv) to generate for each ProcessNode and EdgeNode a Docker container which can be deployed throughout a network of nodes using Docker Swarm.

Figure 10 shows an excerpt from the School of Technology IoT model deployed and it includes the following: Each Node has been deployed on a Docker container using Docker Swarm technology. Each Docker container instance deploys...
the characteristics defined on the IoT model, including: where the nodes are deployed, and what the components included in each ProcessNode are.

Finally, executing the simulation modelled and later on deploying it, makes it possible to analyse the final IoT environment before it is implemented and deployed. Thus, each EdgeNode and ProcessNode element carries out its own functions such as sending messages, processing and storing messages, acting from messages, etc. Consequently, the code generated can be reused on the final system deployed. For instance, the EdgeNode elements can be replaced by physical devices (both sensors and actuators), and the Process Node can be deployed as Docker containers either on premise or on cloud. Not only is the simulation code generated, but also the final IoT system code is partially generated.

B. CASE 02. AGRICULTURAL ENVIRONMENT
This case study focuses on designing an IoT system for managing irrigation and weather data in order to improve crop production. So, the case study has been designed to simulate the sensors and actuators distributed over the countryside which can be monitored in real time. Nowadays, the agricultural domain has several requirements [50], [52]: i) Collection of weather, crop and soil information; ii) Monitoring of distributed land; iii) Multiple crops on a single piece of land; iv) Different fertilizer and water requirements for different pieces of uneven land; v) Diverse requirements of crops for different weather and soil conditions; vi) Proactive solutions rather than reactive solutions.

For instance, sensors such as temperature sensors, humidity sensors, irrigation sensors, PH sensors and actuators such as irrigation artefacts help to monitor and save water, optimising crop production.

This agricultural IoT environment has been designed over ten hectares of soil where tomatoes are being cultivated. So, for each hectare a set of sensors and fog nodes has been shared. So, using fog nodes decreases the communication requirements among them. The sensor network is built by temperature, humidity, irrigation and water pressure sensors. These sensors send data to a specific Topic element linked to a FogNode element which is gathering data and re-sending it, if it is needed. In addition, the irrigation actuators have been defined for controlling irrigation water. The notification events from the FogNode elements are sent to Actuator elements using Topic elements.

1) CASE 02. MODEL DEFINITION
In Figure 11 an excerpt from an IoT model conforming to the SimulateIoT metamodel is defined. It shows different Sensor elements such as ph_Hi, temperature_Hi, Humidity_Hi, etc. (Figure 11, reference 3.2) which generates data for simulation. Moreover, several fog computing nodes have been defined, although in Figure 11 (for the sake of simplicity) only two FogNode elements are shown (Figure 11, references 1.1, 1.2). They define several Topics such as Humidity, Temperature, pH, Water_pressure, etc (Figure 11, references 5.1, 5.2). In addition, each FogNode element defines a MongoDB database (Figure 11, references 6.1, 6.2) and an ESP engine (Figure 11, references 7.1, 7.2) by means of Component elements. Besides, several Rule elements (event pattern definitions) such as rule_Humidity or rule_PH have been defined to analyse the data gathered from Topic elements in real-time. Likewise, when an event pattern is matched, a Notification element such as Low_PH, High_PH, Low_Humidity, High_Humidity and so on is thrown. For instance, the Actuator element named Irrigator (Figure 11, references 3.1) activates when the Notification element named Low_Humidity is thrown.

2) CASE 02. CODE GENERATION AND DEPLOYMENT
Once the model has been completed and validated, a model-to-text transformation is carried out obtaining the simulation code, which can be deployed on a specific platform. Thus, the code generated includes several modules defined using several frameworks or programming languages. Thus, in order to define a scalable IoT environment, each deployable element (EdgeNode, CloudNode, FogNode, Actuators and ProcessEngine) is defined as a microservice, wrapping each Node element in a Docker container. Figure 12 shows an excerpt from the case study deployment architecture including the Docker containers defined and deployed. In Figure 12 the main characteristics of each node can be observed. For instance, each ProcessNode (Figure 12, references 1.1, 1.2, 2) defines a MongoDB database (Figure 12, references 8.1, 8.2, 8.3), a Mosquitto MQTT message broker (Figure 12, references 5.1, 5.2), and a WSO2 Stream Processor engine (Figure 12, references 6.1, 6.2). In addition, the Rule elements defined are processed through the WSO2 engine defined.

Each Docker container has its own characteristics:
- CloudNode (Figure 12, reference 2) is composed of a message-driven broker (Figure 12, reference 5.3) like Mosquitto [32] (that implements a MQTT communication protocol) and a NoSQL database like MongoDB [31] (Figure 12, reference 7.3). Besides, the MongoDB instance exposes the data stored using a REST API (Figure 12, reference 8.3). Moreover, the CloudNode deploys a Compass instance [10] to monitor the data gathered.
- Each FogNode (Figure 12, references 1.1, 1.2) is composed of a message-driven broker (Figure 12, references 5.1, 5.2) like Mosquitto [32] (that implements a MQTT communication protocol) and a NoSQL database like MongoDB [31] (Figure 12, references 7.1, 7.2). MongoDB stores the temporal data gathered by the FogNode instance. Currently, the main difference between a CloudNode and a FogNode is the process capability. Using the size attribute at FogNode element makes it possible to define the process capabilities of the node. Consequently, both CloudNode elements and FogNode elements are deployed as Docker containers on hardware nodes such as PC, VM or Raspberry Pi.
The ESP characteristic defined at ProcessNode deploys an event stream processor to process high amounts of messages in real-time. As can be observed in Figure 12 a WSO2 engine (Figure 12, references 6.1, 6.2) is deployed on each FogNode. The WSO2 engine processes the Rule elements associated with it.

The EdgeNode elements including sensors (Figure 12, references 4.1, 4.2) and actuators (Figure 12, references 9.1, 9.2) defined in the model are suitably deployed in Docker containers.

Later on, the execution information can be audited by querying the MongoDB database or using the monitoring tool available on each ProcessNode. Moreover, each Docker is generating log information during the IoT execution. Finally, the nodes deployed are accessible from a dashboard tool which gathers the available endpoints of each element, for example, to query a MongoDB database or to show information about a Mosquitto broker.

VI. DISCUSSION

Model-driven development can be used to model complex IoT environments using domain concepts. They could not be tied to specific technology, but rather a model-to-text transformation makes it possible to generate the code needed to deploy and simulate the systems. Besides, the system deployed is gathering continuous data which can be analysed later on.
Simulate IoT makes it possible to define models which could include a large amount of Node elements. Then, the code generated from models allows to create an scalable deployment based on well-known software architecture patterns such as publish-subscribe and Docker containers among others.

The technology used as a target, such as micro-services (Thorntail), containers (Dockers), message-oriented middleware and MQTT (Mosquitto broker) or a container orchestrator (Docker Swarm) can be quickly replaced by other suitable technology if needed. In order to change the target technology, a model-to-text transformation should be implemented. However, the domain concepts used to model the IoT environment are fixed. As a consequence, the models help users to understand the IoT system, their relationships and constraints. Besides, the code generated can be analysed later on.

On the other hand, the target users could be both: a) professional users and b) students. Professional users can use the methodology and tools presented in this work to define and analyse complex IoT environments where finally heterogeneous technology is used. Besides, our approach can be used for teaching purposes because it makes it possible for students to learn about IoT concepts and relationships. In addition, they can deploy the IoT simulation, and they can study the code generated to learn the technology used to deploy the IoT system. Thus, they can understand edge technology and integration patterns such as data patterns, IoT characteristics, publish-subscribe communication protocols, MQTT (Message Queuing Telemetry Transport) communication...
protocol, containers, NoSQL databases, distributed systems and so on.

An IoT environment where the nodes are moving throughout the system can be partially modelled. These kinds of nodes are needed to define more complex IoT simulation environments such as wearables, people on the move, etc. Modeling complex node behaviours could be managed by means of dynamic behaviours and self-adaptation characteristics which could be defined in order to offer additional mechanisms for simulation purposes. For example, currently we are working on Topics elements which could be discovered by using a service discovery or using an introspection mechanism over the MQTT broker. The node service discovery is a new service deployed on Fog and Cloud Node elements able to offer by an API information about the Topics available, making possible that the IoT Nodes can connect to, send to and receive data from not fixed IoT nodes.

The proposal that we are implementing to manage Node mobility includes the following aspects:

- It is possible to model a route generation, taking advantage of the geolocation that is already modelled. In this way, Node elements that require mobility to perform their functions can be moved through the IoT environment in such a way that the user who has modelled the environment requires it.

- The route generation solves the problem that arises from the need for mobility of devices in an environment. However, it is also necessary to define the coverage of the different Brokers in the environment, so that the different devices are able to make the decision to disconnect from one broker and connect to another. To solve this problem, it is proposed again the use of geolocation. In this way, the user who models the environment can define a radius of coverage of the different Brokers deployed, so that the devices, taking into account their own geolocation, can determine which Brokers are within reach and which are not. Thus, the different mobile devices in the environment can analyse which Brokers to connect to and which to disconnect from.

- The Topic Discovery Mechanism is a service that makes it possible to dynamically re-configure the Node elements in order to publish or subscribe on compatible Topics. To do this, Node elements publish a broadcast package to the network following Topic Services available and compatible with a concrete Topic. To answer the broadcast, each Node Processing element implements a Topic Discovery Node which answers it with the list of Topics available and compatible. Currently, the Topic compatibility is based on the Topic Data interchanged, Topic’s name or Topic’s Tags.

Initial results of this approach to manage node mobility show that IoT nodes can dynamically reconfigure their connections to send or receive data.

Finally, using the IoT simulation environment, users can propose and compare several policies before implementing them. Consequently, they can carry out several stress tests on the IoT architecture, obtaining valuable data. For instance, users can detect if a ProcessNode is running out of RAM. In addition, the bottlenecks in the IoT system could be detected by analysing the data gathered, producing valuable data that helps users to consider different IoT architectural alternatives.

A. LIMITATIONS

Although the domain-specific language and tools presented offer a wide expressiveness, they have several limitations to take into account:

- Node mobility has been partially developed following the approach that has been described before by defining the Topic Discovery Node (TDN). In this sense, on one hand, the route for nodes can be defined, and, on the other hand, the TDN makes it possible re-configuring dynamically the WSN deployed.

- This current version of our simulator IoT environment, for the sake of simplicity, allows defining connected nodes by TCP/IP, and we assume that connectivity is guaranteed.

- It is possible to simulate IoT environments defined using a high-level domain-specific language. However, the hardware simulation is only managed by the size attribute at ProcessNode which implies several constraints to avoid creating specific software elements (see Table 2). Obviously, it could be considered a simplistic approach to tackle this complex problem but in the end, it helps users to model the IoT environments thinking about the hardware restrictions.

VII. CONCLUSION

Model-driven development techniques are a suitable way to tackle the complexity of domains where heterogeneous technologies are integrated. Initially, they focus on modelling the domain by using the well-known four-layer architecture. Then, by using model-to-text transformations the code for specific technology could be generated. Thus, in this paper, we are tackling the IoT simulation domain allowing users to define and validate models conforming to the SimulateIoT metamodel. Then, a model-to-text transformation generates code to deploy the IoT simulation model defined.

The IoT simulation methodology and tools proposed in this work help users to think about the IoT system, to propose several IoT alternatives and policies in order to achieve a suitable IoT architecture. Finally, the IoT systems modelled can be deployed and analysed.

Future works include new concepts taking into account the role of connections among devices and brokers which could be simulated specifying the type of connection or distance among devices. Obviously, the SimulateIoT metamodel will be improved by applying these new concepts, although it will require that users define more accurately the IoT simulation model. Additionally, dynamic behaviours and self-adaptation characteristics could be defined in order to offer additional mechanisms for simulation purposes. For example, Topics
elements could be discovered by using a service discovery or using introspection mechanism over the MQTT broker. Finally, another interesting further work includes the definition and generation of new types of data generation patterns. Again, these model extensions will improve the IoT simulation.

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