Abstract—This paper presents a methodology for simulating the Internet of Things (IoT) using multi-level simulation models. With respect to conventional simulators, this approach allows us to tune the level of detail of different parts of the model without compromising the scalability of the simulation. As a use case, we have developed a two-level simulator to study the deployment of smart services over rural territories. The higher level is based on a coarse-grained, agent-based adaptive parallel and distributed simulator. When needed, this simulator spawns OMNeT++ model instances to evaluate in more detail the issues concerned with wireless communications in restricted areas of the simulated world. The performance evaluation confirms the viability of multi-level simulations for IoT environments.

1. Introduction

The use of the Internet of Things (IoT) to create and deploy smart services at a large scale requires novel mechanisms to model things and understand how these can interact to create effective solutions for data retrieval, dissemination and computation [1], [2], [10]. A multitude of mobile terminals, sensors, RFID and other devices is being designed to accommodate an IoT -based applications at a large scale. Therefore, multi-level simulation is a viable tool to simulate IoT environments.

To address this challenge we propose a multi-level simulation approach for modeling large IoT environments that does not impose over-simplification of the model [8], [24]. Specifically, we use a “high level” simulator that provides a coarse-grained level of detail; this simulator coordinates the execution of a set of domain-specific “lower level” simulators that are spawned and executed where and when a finer-grained level of detail is needed. The simulators at both levels interact and synchronize their execution to compute correct state updates. The low level simulators continue their job until requested by the high level one. Then, the higher level simulator updates the state, based on the outcomes from the lower level and continues its computation. This means that the detailed simulation is performed only on a portion of the simulated area and only when needed.

As a use case, we study the development of smart services to be deployed over decentralized territories, which are not provided with a full wireless cellular network coverage [14]. In particular, we describe the implementation of a multi-level approach to simulate a large number of (static or mobile) entities that generate data that must be disseminated over the network using wireless broadcast protocols. We assume that the data being disseminated are enriched with tags, keys or metadata that allow nodes to filter such data. In this way it is possible to design viable publish-subscribe schemes that represent the substrate upon which proximity-based applications can be developed. For example, a user might decide to move toward a certain geographical area based on the received information, e.g., to reach a certain producer offering some peculiar product.

The above use case allows us to assess the ability of the proposed multi-level simulation approach to scale to large, highly intensive interacting IoT scenarios. Experimental evaluation shows that multi-level simulation provides better scalability with respect to a classic fine-grained simulation, while offering the same level of detail when needed. Therefore, multi-level simulation is a viable tool to simulate IoT-based applications at a large scale.

The remainder of this paper is organized as follows. Section 2 presents some related work. Section 3 briefly introduces issues concerned with multi-level simulation. In Section 4 we provide a discussion on the approach we propose to simulate large scale IoT environments using multi-level simulation. In Section 5 a performance evaluation is shown. Finally, concluding remarks are discussed in Section 6.
2. Related Work

It has been observed [7] that the simulation of the IoT can generate a huge amount of data, depending on the required level of detail. Low-level, detailed network simulators such as OMNeT++, ns-2 or ns-3, when used alone are quite often inadequate for that purpose [16] due to their lack of scalability.

Conversely, agent-based simulators (e.g., MASON [23], SUMO [21]) are the preferred choice when one needs to create models that mimic wide area (e.g., urban) systems in general. Agent-based simulators allow the user to select the time and spatial scales of the model [18]; therefore, these tools have been used to study intelligent traffic control systems, mobile applications and other similar systems [3], [19], [31], [32]. While agent-based models can typically scale with respect to the size of the system (e.g., number of network nodes, surface of the geographical area), they do not allow to easily select the level of details of different parts of the simulation, forcing the user to over-simplify the model. This is not always a good solution, especially when dealing with IoT, where networking issues may represent important local aspects to consider.

It is also worth noticing that discrete event simulation approaches are the common choice to simulate IoT [5], [17], [30], [20]. However, other kinds of simulation have been utilized in the literature. For example, MAMMotH is a software architecture based on emulation [22], while Monte Carlo methods are employed in [29]. Another proposed solution resorts to a model-driven simulation, according to which the standard SDL language is used to describe an IoT scenario [6]. Then, an automatic code generation transforms the description into an executable simulation model for ns-3.

Going back to discrete event simulation approaches, in [5] the authors propose to integrate the DEUS general-purpose discrete event simulation with the domain specific simulators Cooja and ns-3 for implementing large-scale IoT simulations. This solution offers a good scalability.

DPWSim uses models described through the OASIS standard “Devices Profile for Web Services” (DPWS) [17]. Its main goal is to provide a cross-platform and easy-to-use assessment of DPWS devices and protocols. Unfortunately, it is not designed for very large-scale setups.

The use of Cloud computing solutions enables large scale simulation settings. In this sense, our solution would benefit from the deployment of our simulator in a Cloud environment. As concerns other proposals, SimIoT exploits Cloud environments for back-end operations [30]; authors focus on a health monitoring system for emergency situations in which short range and wireless communication devices are used to monitor the health of patients.

Finally, in [20] a hybrid simulation environment is used where Cooja-based simulations (i.e., system level) are integrated with a domain specific network simulator (i.e., OMNeT++). In some sense, this approach resembles the idea of exploiting a multi-level simulation, since it tries to keep the best of the considered simulation approaches.

To sum up, it is evident that running a whole model representing a IoT scenario at the highest level of detail is unfeasible. A better approach is to bind different simulators together, each one running at its appropriate level of detail and with specific characteristics to be simulated (e.g., mobility models, wireless/wired communications). Our proposed approach, described in the next sections, follows this idea.

3. Multi-level Simulation Architecture

The rationale behind multi-level simulation is to take multiple models and glue them together into a hierarchical structure [7], [24], [9], where each simulator works at a different level of detail. A “high level” simulator starts the simulation and works at a coarse grained level of detail. When and where a more detailed model is needed, the high level simulator activates and coordinates the execution of one or more lower level simulators. Such coordination capabilities might be performed by the higher level simulator (this is the approach we will employ), or by some external coordinator module.

Figure 1 shows an example of a two-level simulation. Initially (timestep $t_2$ in the figure) the model is executed at a coarse level of detail by the top level (Level 0) simulator. However, at a certain point in time ($t_2$), part of the simulated scenario requires a finer level of detail. To achieve this, a Level 1 simulator is activated to handle that part of the model and all entities therein in more details – for example, using a shorter time step – while everything else is still managed by the Level 0 simulator. All the entities managed at Level 0 evolve using $t_2$-sized (coarse grained) timesteps and the others use $t_3$-sized (fine grained) timesteps. Timestep $t_2$ (that is the same of $t_1$ for Level 1) is the moment in which a part of the model components is transferred from the coarse grained simulator to the finer one. Then, the components at Level 0 will jump from $t_2$ to $t_3$ while the components simulated at Level 1 will be updated at $t_2′$, $t_3′$ and $t_4′$. When there is no more need for a finer level of detail, all the components simulated at Level 1 are transferred again to the Level 0 simulator.

This approach clearly requires the ability for the simulators to interoperate and synchronize. In the rest of the paper, we show how it is possible to let a coarse grained agent-based simulator interact with a discrete event simulator such as OMNeT++. It should be observed that the same ideas can be applied in order to use other available specific simulators, e.g., NS-3, Sumo, and so forth [5].

4. Multi-level Simulator for the IoT

In this section, we describe the implementation of a multi-level approach to simulate a general IoT scenario. The focus of this paper is on a tool that allows simulating IoT applications, rather than presenting a single application itself. Thus, in order to show an instance of a multi-level simulator, we describe a general use case with both static and mobile nodes immersed in a decentralized area where
no full cellular network coverage is available. Thus, other communication approaches might be exploited in order to offer smart services [14], [15]. Under some circumstances, a subset of nodes might generate a MANET-like overlay; in this case, from a simulation point of view it becomes mandatory considering all the details related to wireless communications.

4.1. Use Case

We consider a scenario to foster the development of novel, smart services in rural or decentralized territories [14], [15]. The aim is to provide means to support proximity-based applications, that is, applications where users can discover places of interest and ask to be guided there from their current position. A conventional realization of this service might be based on traditional client/server approaches, where a user connects to given Web service, looks for some point of interest, and then exploits a classic navigation tool to reach it. However, scenarios exist where such a typical scheme cannot be employed, because the user is located within an area with no full infrastructured wireless connectivity coverage. For instance, the user might be located indoor or in a rural area lacking 3G/4G connectivity. In this case, the use of an epidemic dissemination protocol, or a MANET-like solution, might be of help.

As a use case for demonstrating the viability of employing multi-level simulation for IoT environments, let us focus on a situation where communications occur through ad-hoc networks only [13]. In order to support the development of proximity-based applications, we need a middleware service that allows disseminating messages looking for users (located in the neighborhood) with specific interests.

A solution to build a data distribution service, in the absence of an infrastructured network offering a complete coverage, might be that of resorting to an unstructured, multi-hop relay based protocol (or better, we might consider the idea of analyzing the performance of such a kind of protocols, via multi-level simulation). Hence, we have a set of mobile and static nodes generating some content. We assume that these contents are treated as open data and are adequately enriched with some kind of tags, keys or metadata, that allow nodes filtering such data, upon reception. Nodes are allowed to relay and broadcast messages. On top of this dissemination strategy, it is possible to implement a publish/subscribe approach that filters information of interest for the applications. Through this cheap and simple dissemination strategy, producers are enabled to notify users that subscribed to some specific keywords.

Once a subscriber has received some data that is of interest for him, we can imagine that he moves towards a certain destination. During his path, he is dynamically guided to the exact location through local interactions with devices/sensors available in that area.

The simulation of such a wide scenario is not an easy task, since it involves several activities and different domains. This is a perfect example of a simulation scenario requiring different levels of granularity. Thus, it is necessary to employ multi-level simulation. This methodology is described in the next subsections.

4.2. Multi-Level Simulator

To simulate the use case presented above, we use a multi-level approach that combines a discrete-event simulation engine (Level 1) coupled with an agent-based model (Level 0). The coarse level (Level 0) simulates the whole IoT and related users, where different actors produce data, subscribe their interests, move towards different geographical areas. This has been implemented using an agent-based simulator equipped with parallel and distributed execution capabilities. The specific interactions within points of interest (e.g., a marketplace) impose more simulation details to consider wireless communication issues, fine-grained interactions and movements. Thus, a configurable OMNeT++ simulation model has been implemented (Level 1). In this case, each simulation step of the coarse grained simulation layer is decomposed into a set of events at the fine grained layer. Following this approach, Level 1 is able to notify Level 0 with its simulation advancements.

4.3. Level 0: agent-based simulator

The Smart Shire Simulator (S3) is a prototype simulator based on the GAIA/ARTIS simulation middle-
ware \cite{14}. ARTIS \cite{4} permits the seamless sequential/parallel/distributed execution of large scale simulation runs using different communication approaches (e.g. shared memory, TCP/IP, MPI) and synchronization methods (e.g. time-stepped, conservative, optimistic). The GAIA part \cite{12} of the software stack aims to ease the development of simulation models with high level application program interfaces. Furthermore, it implements communication and computational load-balancing strategies based on the adaptive partitioning of the simulation model.

According to this simulator, entities in the IoT can be static (e.g., sensors, traffic lights and road signs) or mobile entities (e.g., cars and smartphones), following specific mobility models. All these simulated things are equipped with a wireless interface card. The interaction among entities is based on a “Priority-based Broadcast” (PbB) strategy that implements a probabilistic broadcast approach \cite{27}. In PbB, every message that is generated by a node is broadcasted to all the nodes that are in proximity of the sender. The message contains a Time-To-Live (TTL) to limit its lifespan and the forwarding is based on two conditions. The first is a probabilistic evaluation (i.e., probabilistic broadcast) while the second is based on the distance between sender and receiver. In fact, to limit the number of forwarded messages, there is a message forward only if the distance between the nodes is larger than a given threshold. Under the implementation viewpoint, this can be done using a positioning system (e.g., GPS) if available. Otherwise, the network signal level associated to each received message is used. Finally, a message caching mechanism is employed to limit the presence of duplicated messages.

### 4.4. Level 1: OMNeT++ simulator

The finer grained simulator has been implemented using OMNeT++ v. 4.4.1, with the INET framework v. 2.3.0. It simulates a grid of fixed nodes (during the tests, a \(10 \times 10\) grid was used), representing a local subset of things/devices. Each device is equipped with WiFi technology. In the simulated scenario, no WiFi infrastructure was present, hence nodes organize themselves as a MANET exploiting DYMOUM \cite{11}, an implementation of the Dynamic MANET On-demand (DYMO) routing protocol \cite{26}.

A number \(N\) of mobile nodes, representing pedestrian users, is introduced by the higher Level 0 simulator. These \(N\) nodes are equipped with a mobile device with WiFi connectivity. Pedestrian users move at walking speed. The user application running on the mobile client broadcasts messages looking for the identifier of the specific location. In fact, we imagine that the user destination refers to a location (e.g., a point of interest, a seller within a crowded farmers’ market) where there is a device equipped with communication capabilities, that is communicating in the IoT. Thus, the device destination replies with his geographical position. All these messages are delivered through the mentioned MANET routing protocol. Based on the provided position, the mobile user moves towards his destination.

### 4.5. Interface between the two simulators

A TCP-based message-passing approach is utilized to let the two simulators communicate the inputs and outputs, as well as of triggering the “continue the simulation” or “end of simulation” commands sent, at the end of each Level 0 timestep, from Level 0 to Level 1. In particular, at the end of each Level 0 timestep, Level 1 sends a set of messages which describe its status and waits for a response. Level 0 receives the data sent by Level 1 and decides whether Level 1 must continue or end the lower level simulation.

This is a simple strategy that enables interaction, and synchronization, between the simulators without requiring a complete re-engineering of the simulators. The higher levels simulator must be able to freeze the simulation of certain parts of the scenario, waiting for updates from other sources. Moreover, lower level simulators should be enabled to obtain input from outside, and notify results outside. However, no knowledge on the external simulators are needed. This is an example demonstrating that existing products can be employed to create more complex multilevel simulations.

### 5. Performance Evaluation

The performance evaluation reported in this section refers to the multi-level simulator as composed of the Level 0 and the Level 1 simulators described above.

The results are obtained averaging the outcomes of multiple independent runs. The testbed used for the performance evaluation is based on a DELL R620 with 2 CPUs (Xeon E-2640v2, 2 GHz, 8 physical cores with Hyper-Threading). The software stack is composed of Ubuntu 14.04.5 LTS, GAIA/ARTIS version 2.1.0, OMNeT++ v. 4.4.1 with the INET framework v. 2.3.0.

As already mentioned, we implemented the simulation environment and the application running on top of it. However, we are more interested here on the effectiveness of the tool to simulate the considered scenario, rather than the application itself. Put in other words, we want to assess if this simulation strategy enables IoT developers to effectively build simulation scenarios and test them in a reasonable time, by considering large-scale IoT with high levels of details, when needed. For this reason, the main metrics of interest is the Wall Clock Time (WCT), i.e., the time needed to perform the simulation.

It is worth noting that, with the aim of comparing our solution with another simulator offering the same level of detail in the simulation, we built an OMNeT++ model comprising the whole simulation scenario (not only the limited regions simulated where and when necessary). Unfortunately, OMNeT++ was not able to scale up to the amount of simulated entities shown in the following results. In fact, simulations run with 1000 simulated entities lasted for approximately 10 hours each. For this reason, in the next charts and table we do not report results for that simulator.
5.1. Level 0 simulator

The Level 0 model is based on a bi-dimensional toroidal space without obstacles. The simulated area is populated by a given number of devices (in the following referred as Simulated Entities, SEs). A part of the SEs is static while the others implement the well known Random Way-Point (RWP) mobility model. In the simulated model, the communication is based on the proximity of SEs and the multi-hop data dissemination protocol (previously described) is implemented. Table 1 reports the main parameters of the Level 0 simulation model.

Each SE uses a caching mechanism to discard some of the duplicated messages generated by the PbB dissemination scheme. This caching system is based on a LRU (Least Recently Used) replacement algorithm.

| Model parameter | Description/Value |
|------------------|--------------------|
| Number of SEs    | [1000, 32000]      |
| Mobility of SEs  | 50% Random Way-point (RWP) |
| Speed of RWP     | Uniform in the range [1, 14] space-units/timestep |
| Sleep time of RWP| 0 (disabled)        |
| Interaction range| 250 spaceunits     |
| Density of SEs   | 1 node every 10000 spaceunits² |
| Forwarding range | > 200 spaceunits   |
| Simulated time   | 900 timeunits      |
| Simulation granularity | 1 timestep = 1 timeunit |
| Time-To-Live (TTL)| 4 hops             |
| Dissemination probability | 0.6                |
| Cache size       | 0 (disabled) or 256 |

TABLE 1: Level 0 model parameters.

5.2. Level 1 simulator

In this performance evaluation, the OMNeT++ simulation model described in Section 4.4 has been set up with a single SE transferred from the Level 0 simulator to Level 1. The SE is managed by the Level 1 for the length of a single Level 0 timestep. In other words, at the beginning of the Level 0 timestep where a Level 1 simulation is triggered, the Level 1 simulator is bootstrapped (including a warm-up phase) and at the end of the Level 0 timestep the Level 1 simulator is shutdown.

5.3. Scalability evaluation

First of all, we assess the scalability of the simulator in a sequential setup, that is, 1 CPU core is used. Figure 3 reports the Wall-Clock Time (WCT) to complete a single simulation, on average. The number of SEs has been set equal to 1000. In the graph, the horizontal axis reports the amount of Level 1 instances that are generated during a multi-level simulation; on the vertical axis we show the WCT. In particular, we report the average WCT required to complete the Level 0 simulation alone (cyan line), the average WCT required by a single instance at Level 1 to complete its own (partial) simulation (red line) and the average total WCT needed to perform the whole simulation (blue line). We observe that while each isolated simulation requires a given WTC, the combination of Level 0 and multiple Level 1 instances increases significantly the total WCT.

The results show execution times of the order of few minutes, that favorably compares to the several hours measured using a fine grained OMNeT++ model alone, the tests described above show that sequential simulations are unable to scale to the desired number of nodes and level of detail. As a consequence, due to the scale of IoT systems, the parallel setup of the multi-level simulator becomes of main importance. Thus, the set of SEs was partitioned among the CPU cores and a message passing scheme was used to deliver the interactions among SEs. In this case, the software component executed on each CPU core is called Logical Process (LP).

More in detail, we assume a configuration of the simulator with 4 LPs (run on 4 different CPU-cores) and in which, at given points in the simulated time, all the LPs spawn a Level 1 instance. In other words, multiple concurrent Level 1 instances are run at the same time.

Figure 3 shows the WCT of the multi-level simulator with an increasing number of concurrent instances when 4000 SEs are simulated. As expected the activation of Level 1 instances is costly but the scalability is still reasonable. Furthermore, if in the parallel/distributed execution architecture there are idle processor cores, then the execution of concurrent Level 1 instances is quite cheap. In fact, they can run in parallel with a negligible impact on the WCT of the multi-level simulator. Thus, these tests confirm that a good scalability can be achieved through the proposed multi-level simulator.

Finally, we measured the amount of system memory used by the multi-level simulator. Table 2 reports the peak resident set size (i.e., VmHWM) used by the multi-level simulator during the execution of a simulation run with an increasing number of SEs. The amount of LPs was 4 in which, as before, at given points in the simulated time, all the LPs spawn a Level 1 instance. It is worth noting that, in this case, each Level 1 instance manages a single SE. Clearly, in this setup, the presence of four concurrent Level 1 instances has a non-negligible impact on the total amount of used memory, but the overall consumption is quite limited and in line with our expectations. As a future work, both the Level 0 and Level 1 simulators will be optimized to reduce the memory consumption. In any case, also these measurements demonstrate that the use of multi-level simulation allows simulating large scale IoT scenarios with high levels of details in the simulation.

6. Conclusions

In this paper we have presented a case study on multi-level simulation of the Internet of Things (IoT). Our solution uses a two level simulation. An adaptive, parallel/distributed agent-based simulation technique is employed to model
the coarse level (Level 0), while an OMNeT++ simulation implements the finer level (Level 1).

The performance results confirm the viability of the proposal. The use of multi-level simulation allows scaling to a high numbers of SEs with respect to the use of a single fine-grained simulator that is able to capture the complexity and all the technical details of the interactions among SEs. In fact, with a high number of SEs, we observed a total execution times of the simulation of the order of few minutes, while the same simulations, built using a OMNeT++ model alone, required several hours that became days when the number of simulated entities increased. The proposed approach allows mimicking all the details only when needed. Hence, during the rest of the simulation the multi-level simulator behaves as a coarse-grained simulator. Nevertheless, the interaction and synchronization among active simulation levels guarantee a consistent and correct evolution of the simulation. To conclude, the presented approach represents a viable tool to simulate specific IoT-based applications at a large scale.

Figure 2: WCT of the parallel multi-level simulator, sequential setup, 1000 SEs, increasing number of sequential spawned Level 1 instances.

| #SEs | Level 0 (KB) | Level 1 (KB) per instance | Total (KB) |
|------|-------------|--------------------------|------------|
| 1000 | 132880      | 43916 (x4)               | 308544     |
| 2000 | 171728      | 43916 (x4)               | 347392     |
| 4000 | 263488      | 43916 (x4)               | 439152     |
| 8000 | 396416      | 43916 (x4)               | 572080     |
| 16000| 714720      | 43916 (x4)               | 890384     |
| 32000| 1351072     | 43916 (x4)               | 1526736    |

TABLE 2: Peak resident set size used by the multi-level simulator; parallel setup with 4 LPs.

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Figure 3: WCT of the parallel multi-level simulator with $\#LPs = 4$, 4000 SEs, increasing number of concurrent spawned Level 1 instances. For example, 2x4 means that all the LPs for 2 times during the simulation run trigger 4 concurrent Level 1 instances.

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