Evaluating a Development Framework for Engineering Internet of Things Applications

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Abstract

Application development in the Internet of Things (IoT) is challenging because it involves dealing with a wide range of related issues such as lack of separation of concerns in multiple layers and lack of high-level abstractions to address both the large scale and heterogeneity. Moreover, stakeholders involved in the application development have to address issues spanning to multiple life-cycles. Therefore, a critical challenge is to enable IoT application development with minimal effort from various stakeholders involved in the development process.

Several approaches to tackling this challenge have been proposed in the fields of wireless sensor networks and ubiquitous and pervasive computing, regarded as precursors to the modern day of IoT. However, although existing approaches provide a wide range of features, stakeholders have specific application development requirements and choosing an appropriate approach requires thorough evaluations on different aspects. To date, this aspect has been investigated to a limited extend. In view of this, this paper provides an extensive set of evaluations based on our previous work on IoT. Specifically, we evaluate our approach in terms of (1) development effort: the effort required to create a new application, (2) reusability: the extend to which software artifacts can be reused during application development, (3) expressiveness: the characteristics of IoT applications that can be modeled using our approach, (4) memory metrics: the amount of memory and storage a device needs to consume in order to run an application under our framework, and (5) comparison of our approach with state of the art in IoT application development on various dimensions, which does not only provide a comprehensive view of state of the art, but also guides developers in selecting an approach given application requirements in hand. We believe that the above different aspects provide the research community with insight into evaluating, selecting, and developing useful IoT frameworks and applications.

Keywords Internet of Things, Development Framework, Development Life-cycle, Domain-specific Languages, Empirical Evaluation

1. Introduction

The Internet of Things [10, p. 6] applications will involve interactions among extremely large numbers of heterogeneous devices, many of them directly interacting with their physical surroundings. Therefore, a critical challenge is to enable IoT application development with minimal effort from various stakeholders involved in the development process. Similar challenges have already been addressed in the closely related fields of Wireless Sensor Networks (WSNs) [35, p. 11] and ubiquitous and pervasive computing [35, p. 7], regarded as precursors to the modern day IoT. While the main challenge in the former is the large scale – hundreds to thousands of largely similar devices, the primary concern in the latter has been the heterogeneity of devices and the major role that the user’s own interaction with these devices plays in these systems (cf. the classic “smart home” scenario where a user controls lights and receives notifications from his refrigerator and toaster.). It is the goal of our work to enable the development of such applications. In the following, we discuss one of such applications.

1.1 Application example

To illustrate the characteristics of IoT applications, we consider the building automation domain [35, p. 361]. This building system might consist of several buildings, with each building in turn consisting of one or more floors, each with several rooms that have a large number of heterogeneous devices equipped with sensors, actuators, storage, and user interfaces. Figure 1 describes such a building automation system. Many applications can be developed using the in-built devices, one of which we discuss below.

Personalized HVAC application. This application aims to regulate temperature for workers’ productivity and personal comfort. To accommodate the workers’ preference in the room, a database is used to keep the profile of each worker, including his preferred temperature level. A badge reader in the room detects the worker’s entry event and queries the database for the worker’s preference. Based on this, the thresholds used by the room’s devices are updated. To reduce electricity waste when a person leaves the room, detected by badge disappeared event, heating is automatically set to the lowest level or according to the building’s energy target.

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1.3 Contributions

As evident above, an important challenge that needs to be addressed in the IoT is to enable the IoT application development with minimal effort by the various stakeholders. To address this challenge, many approaches have been proposed. Although existing approaches provide a wide range of features, stakeholders have specific application development requirements and choosing an appropriate approach requires thorough evaluations on different aspects. To date, this aspect has been investigated to a limited extent for IoT applications, given heterogeneity at different life-cycle phases. Largely, the metric used to assess the stakeholders’ productivity in existing approaches is the number of lines of code [17, p. 45] [22, p. 22] and it provides a little guidance to stakeholders to select an appropriate approach given application requirements in hand. In view of these, this paper provides an extensive set of evaluations based on previous work [21, 23, 24] on IoT application development framework, we call it as IoTSuite. We believe that the following reported assessments not only be helpful for our research, but might provide the research community with insights into evaluating, selecting, and developing useful IoT frameworks and applications.

- Development effort: In order to measure effort to develop an application using our approach, we evaluate a percentage of a total number of lines of code generated by our approach (Section 3.1). Moreover, we measure development effort for an application that involves a large number of devices (Section 3.2). The results of both these experiments conclude that there is a drastic reduction in development effort.

- Reusability: We evaluate reuse of specifications and implementations across applications using our approach. We consider different scenarios and demonstrate the development effort using our approach to handle them. The results of these experiments conclude that there is a drastic reduction in development effort for subsequent application development (Section 3.3).

- Expressiveness: We evaluate the scope of our approach. More specifically, we answer the question: What are the characteristics of IoT applications that can be modeled by our approach? We presents various characteristics of IoT applications. Then, we map the representative IoT applications into identified characteristics using our approach (Section 3.4). Such an explicit evaluation may not only be helpful as a framework for discussing coordinated research (e.g., avoiding duplicate work) in the IoT field, but may provide a basis for the development of software framework to meet different IoT application requirements.

- Memory metrics: We measure the code size and memory consumption of device-specific code that is deployed on devices. These two metrics are important because they give approximate indication of the amount of memory a device need to run an application (Section 3.5).

- Comparison with state of the art: We begin by various dimensions that characterize IoT application development approaches. Then, we map existing approaches back to the dimensions, which does not only provide a comprehensive view of state of the art, but also guides developers in selecting an approach given application requirements in hand (Section 3.6).

Outline. The remainder of this paper is organized as follows: Section 2 summarizes our IoT application development process. This includes a brief on modeling languages and automation techniques. Section 3 evaluates the development framework in a quantitative manner. Section 4 concludes this paper.

2 An open source version, targeting on Android- and JavaSE-enabled devices and MQTT middleware, is available on: https://github.com/pankeshlinux/IoTSuite/wiki
2. IoT application development process

To provide the reader necessary background, this section summarizes our IoT application development process (a complete tour is available in our previous publication [21]), illustrated in Figure 2. It separates IoT application development into different concerns and integrates a set of high-level languages to specify them. It is supported by compiler, mapper, and linker modules at various phases of IoT application development process to provide automation. Stakeholders carry out the following steps in order to develop an IoT application using our approach.

2.1 Domain concern

This concern is related to concepts that are specific to a domain (e.g., building automation, transport) of an IoT application. It consists of the following steps:

Specifying domain vocabulary. The domain expert specifies a domain vocabulary (step 1 in Figure 2) using vocabulary language (VL). The vocabulary specification includes concepts specific to a target application domain. For example, the building automation domain is reasoned in terms of rooms and floors, while the transport domain is expressed in terms of highway sectors. Furthermore, the vocabulary includes specification of resources, which are responsible for interacting with entities of interest (EoI). This includes sensors (sense EoI), actuators (control EoI), and storage (store information about EoI).

Compiling vocabulary specification. Leveraging the vocabulary, the development framework generates (step 2 in Figure 2) a vocabulary framework to aid the device developer, (2) a customized architecture grammar according to the vocabulary to aid the software designer, and (3) a customized deployment grammar according to the vocabulary to aid the network manager. The key advantage of this customization is that domain-specific concepts defined in the vocabulary are made available to other stakeholders and can be reused across applications of the same application domain.

2.2 Functional concern

This concern is related to concepts that are specific to functionality of an IoT application. An example of a functionality is to open a window when an average temperature value of a room is greater than 30°C. It consists of the following steps:

Specifying application architecture. Using a customized architecture grammar, the software designer specifies an application architecture (step 3 in Figure 2) using architecture language (AL). He specifies computational services and interactions with other components. Computational services are fueled by sensors and storage (defined in the vocabulary). They process inputs data and take appropriate decisions by triggering actuators (defined in the vocabulary specification).

Compiling architecture specification. The development framework leverages an architecture specification to support the application developer (step 4 in Figure 2). To describe the application logic of each computational service, the application developer is provided an architecture framework, pre-configured according to the architecture specification of an application, an approach similar to the one discussed in [8,9].

Implementing application logic. To describe the application logic of each computational service, the application developer leverages a generated architecture framework (step 5 in Figure 2). It contains abstract classes 3 corresponding to each computational service, that hide interaction details with other software components and allow the application developer to focus only on application logic. The application developer implements only the abstract methods of generated abstract classes.

2.3 Deployment concern

The concepts that fall into this concern describe information about device and its properties, placed in deployment scenario. It consists of the following steps:

Specifying target deployment. Using a customized deployment grammar, the network manager describes a deployment specification (step 6 in Figure 2) using deployment language (DL). The deployment specification includes the details of each device, including its regions (in terms of values of the regions defined in the vocabulary), resources hosted by devices (a subset of those defined in the vocabulary), and the type of the device. Ideally, the same IoT application could be deployed on different target deployments (e.g., the same inventory tracking application can be deployed in different warehouses). This requirement is dictated separating a deployment specification from other specifications.

Mapping. The mapper produces a mapping from a set of computational services to a set of devices (step 7 in Figure 2). It takes as input a set of placement rules of computational services from an architecture specification and a set of devices defined in a deployment specification. The mapper decides where each computational service will be deployed. The current version of algorithm [20] selects devices randomly and allocates computational services to the selected devices. A mapping algorithm aware of heterogeneity, associated with devices of a target deployment, is a part of our future work.

2.4 Platform concern

This concern specifies the concepts that fall into this are computer programs that act as a (operating system-specific) translator between a hardware device and an application. It consists of the following steps:

Implementing device drivers. Leveraging the vocabulary, IoT-Suite generate a vocabulary framework to aid the device developer (step 8 in Figure 2). The vocabulary framework contains a set of interfaces and concrete classes corresponding to resources defined in the vocabulary. The concrete classes contain

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3 We assume that the application developer uses an object-oriented language.
concrete methods for interacting with other software components and platform-specific device drivers. We have integrated existing open-source sensing frameworks for Android devices. So, the device developer has to only implement interfaces, connecting integrated sensing framework and generated vocabulary framework.

2.5 Linking

The linker combines and packs code generated by various stages into packages that can be deployed on devices (step 9 in Figure 2).

This stage supports the application deployment phase by producing device-specific code to result in a distributed software system collaboratively hosted by individual devices, thus providing automation at the deployment phase.

The final output after linking is composed of three parts: (1) a runtime-system runs on each individual device and provides a support for executing distributed tasks, (2) a device specific code generated by the linker module, and (3) a wrapper separates generated code from the linker module and underlying runtime system by implementing interfaces. The main advantage of separating wrapper and runtime system is that developers have to implement given interfaces, discussed in [31], in order to integrate a new runtime system. The current implementation of development framework implements the MQTT and iBICOOP runtime system, which enables interactions among Android devices and JavaSE enabled devices.

2.6 Evolution

Evolution is an important aspect in IoT application development where sensors, actuators, and computational services are added, removed, or extended. To deal with these changes, we separate IoT application development into different concerns and allow an iterative development for these concerns. This iterative development requires only a change in evolved specification and reusing dependent specifications/implementation in compilation process, thus reducing effort to handle evolution, similar to the work in [9].

3. Evaluation

The goal of this section is to describe how well the proposed approach addresses our aim. Unfortunately, quality measures are not well-defined and they do not provide a clear procedural method to evaluate development approaches in general. We established a set of measures and metrics that are vital for the productivity of stakeholders. The set of measures is non-exhaustive. However, they reflect principal quantitative advantages that our approach provides to stakeholders involved in IoT application development. We evaluate our approach in terms of development effort, reusability, expressiveness, memory metrics, and comparison with state of the art.

3.1 Development effort

In order to measure effort to develop an application using our approach, we evaluate a percentage of a total number of lines of code generated by our approach. This section is organized as follows: Section 3.1.1 describes two applications to evaluate the development effort. Section 3.1.2 shows results we obtained that indicates the effort required to create these two applications.

3.1.1 Applications for evaluating development effort

To evaluate development effort using our approach, we consider representative IoT applications. Figure 3 describes the building automation domain with various devices. Many applications can be developed using these devices. We describes two applications:

(1) a personalized HVAC application (discussed in Section 3.1.1) and (2) a fire detection application. It aims to detect fire by analyzing data from smoke and temperature sensors. Figure 4 shows a layered architecture of both applications. In the fire detection application, a fire state is computed based on a current average temperature value and smoke presence. Finally, the fire controller decides whether alarms should be activated or not.


Figure 4: Layered architecture of (a) personalized HVAC and (b) fire detection application.
We measured the lines of code using Eclipse EclEmma 2.2.1 plug-in.\footnote{http://www.eclEmma.org/} This tool counts actual Java statement as lines of code and does not consider blank lines or lines with comments. Our measurements reveal that the percentage of handwritten lines of code, produced by stakeholders, is very low in both applications (see Figure 5). The measure of lines of code is only useful if the generated code is actually executed. We measured code coverage of the generated programming frameworks (i.e., mapping framework, vocabulary framework, architecture framework) of two applications (see Figure 5) using the EclEmma Eclipse plug-in. Our measures show that more than 80% of generated code is actually executed, the other portion being error-handling code for errors that did not happen during the experiment and/or unused features such as getter and setter. This high value indicates that most of the execution is spent in generated code and that, indeed, our approach reduces development effort by generating useful code.

Figure 5: Percentage of lines of code in (a) personalized HVAC and (b) fire detection application.

3.2 Development effort for a large number of devices

The experiments, described in the previous sections, was conducted for a small number of devices. It does not demonstrate development effort for a large number of devices. Therefore, the primary aim of this section is to evaluate effort to develop an IoT application involving a large number of devices.

In order to achieve the above aim, we have developed the road traffic monitoring & control application\footnote{Figure 6 Road traffic & monitoring application scenario (Image credit to [18]).}, depicted in Figure 6, that aims to maximize the flow of vehicles on the road. This kind of system is divided in disjoint sectors. Each sector is controlled depending on the current status of the sector. In each sector, data is first collected from speed sensors and presence sensors and measurements such as average speed of vehicles and average queue length on a ramp are derived. The aggregated information is fed to an algorithm to determine the best actions to achieve the system objective – maximize the flow of vehicles on the highway in each sector. The actions are then communicated to the ramp signals.

The application is developed on a set of simulated devices, running real MQTT middleware, on a single PC. The assessments were conducted over an increasing number of devices. The first development effort assessment was conducted on 6 devices instrumented with sensors and actuators. In the next subsequent assessments, we kept increasing the number of devices equipped with sensors and actuators. In each assessment, we have measured lines of code to specify vocabulary, architecture, and deployment, application logic, and device drivers. Figure 7 illustrates the assessment results containing a number of devices involved in the experiment and hand-written lines of code to develop the road traffic & monitoring application.

In Figure 7, we have noted the following two observations and their reasons:

- As the number of devices increases, lines of code for vocabulary and architecture specification, device drivers, and application logic remain constant, even for a deployment consisting a large number of devices. The reason is that our approach provides the ability to specify an application at a global level rather than individual nodes. It means one entity description for many implementations and instances. Thus, development effort does not depend on the number entities.

- As the number of devices increases, lines of code for a deployment specification increase. The reason is that the network manager specifies each device individually in the deployment specification. This is a limitation of deployment language. Our future work will be to investigate how a deployment specification can be expressed in a concise and flexible way for a network with a large number of devices. We believe that the use of regular expressions is a possible technique to address this problem.

3.3 Reusability

This section demonstrates the reusability of software artifacts using our approach. We consider two scenarios to demonstrate it: (1) evolving deployment (detailed in Section 3.3.1). (2) evolving functionality (detailed in Section 3.3.2). The results of these experiments conclude that there is a drastic reduction in development effort for subsequent applications.
### 3.3.1 Evolving deployment

This scenario demonstrates the reusability of specifications and implementations when the same application is deployed to different deployment scenarios. To illustrate it, we consider the home scenario shown in Figure[3] and take the fire detection application (discussed in Section 3.1.1). The application is initially deployed in the bedroom. Latter for the safety reason, it is decided to deploy the same application in the kitchen and meeting room. Figure[3] shows both the kitchen and meeting room have all necessary sensors and actuators to deploy the fire detection application. To measure the effort for developing the same fire management application for different deployment scenarios, we have simulated it on a set of simulated devices, running MQTT middleware that simulates network, on a single PC. Initially, when the application is developed using our approach in the bedroom, we have written the vocabulary, deployment, and architecture specification, device drivers, and application logic from scratch. Table[1] shows the lines of code for developing the fire detection application in the bedroom. However, the reusability of specifications and implementations becomes apparent when we deploy it in the kitchen and meeting room. To develop subsequent applications, we only need to specify deployment specification and can reuse other software artifacts. Table[1] shows the drastic reduction in development effort for the kitchen and meeting room. We conclude that the primary reason of drastic reduction of deployment effort in the next two deployment scenarios using our approach is separation of concerns. Our approach separates the IoT application development into well-defined concerns. Therefore, stakeholders achieve high reusability of specifications and implementations across applications of a same application domain. Thus, it reduces the development effort.

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<td>49</td>
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<td>60</td>
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<tr>
<td>Fire detection (in kitchen)</td>
<td>0</td>
<td>0</td>
<td>49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fire detection (in meeting room)</td>
<td>0</td>
<td>0</td>
<td>49</td>
<td>0</td>
<td>0</td>
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</table>

Table 1: The lines of code to develop the fire detection application. Initially, it was deployed in the bedroom and latter it was deployed to the kitchen and meeting room.

### 3.3.2 Evolving functionality

This section demonstrates the reusability of specifications and implementations when functionality is evolved. To illustrate this scenario, we consider the home scenario shown in Figure[3]. Apart from two applications, described in Section 3.1.1, we consider a scenario of implementing the following two new functionality:

- **Safety in kitchen** raises an alarm if the stove is switched on and when nobody in the kitchen. Figure[8] shows a layered architecture of it. The motion sensor detects the presence of moving objects. The smart stove senses if it is turned on or off. Based on these inputs, the system takes appropriate decisions.

- **Heating control system** regulates the temperature in the meeting room depending on the room occupancy. Figure[8] shows a layered architecture of it. The system receives motion detection events to detect the occupancy. Thus, if a person enters into the meeting room and the average temperature is below the certain threshold, the heating control system automatically controls the temperature.

![Figure 8: Layered architecture of (a) safety in kitchen application and (b) heating control system](image)

We have simulated the above applications on a set of simulated devices, running iBICOOP that simulates network, on a single PC. Initially, when the personalized HVAC, fire detection, safety in kitchen applications are developed using our approach, we have written vocabulary specification, architecture specification, deployment specification, application logic, and device driver. The labels (a1), (b1), (c1) in Figure[9] show the lines of code for developing these three applications and the corresponding labels (a2), (b2), and (c2) describe the components specified in the vocabulary specification.

The reusability of previously written components becomes apparent when we develop the heating control application. The components specified in the previous three applications are reused to write vocabulary specification and the device driver. The label (d2) in Figure[9] indicates the reusability of the previously written temperature sensor, heater, and motion sensor components with similar patterns and colors. The (d1) in Figure[9] shows the drastic reduction in the lines of code for the heating control application. More specifically, the lines of code for the vocabulary specification and device driver remains zero. We conclude that the primary reason of drastic reduction of development effort for the heating control system using our approach is separation of concerns. Since, our approach separates the IoT application development into well-defined concerns. Therefore, stakeholders achieve high reusability of specifications and implementations across applications. Thus, it reduces the development effort.

### 3.4 Expressiveness

This section evaluates the scope of our approach. More specifically, it answers the question: **What are the characteristics of IoT applications that can be modeled by our approach?** In order to answer this question, we map the IoT applications (discussed in Section 3.1.1.3.2) into identified characteristics using our approach. Table[2] indicates the subset of IoT application characteristics that can be modeled using our development framework. It notes the following observations about our approach.

**Heterogeneous components.** An IoT application may execute on a network consisting of different types of components. For exam-
Figure 9: The labels (a1), (b1), (c1), and (d1) show the lines of code for developing the personalized HVAC, fire detection, safety kitchen, and heating control system applications and the corresponding labels (a2), (b2), (c2), and (d2) describe the components specified in the vocabulary specification.

ple, the smart building application consists of components, including sensing (e.g., temperature sensor, badge reader), actuating (e.g., heater, light), storage (e.g., profile storage on different database systems such as MySQL or MongoDB). As indicated in Table 2, our approach supports components commonly found in IoT applications.

**Heterogeneous platforms.** An IoT application may execute on a network with heterogeneous platforms. These platforms are operating system-specific. For instance, a device could be running Android mobile OS, Java SE on laptops, or a server OS such as GNU/Linux etc. Table 2 shows the supported platforms in the current version. It generates code for JavaSE and Android platforms. However, our approach is flexible to generate code for different platforms, as discussed in our previous work [31].

**Heterogeneous runtime system.** An IoT application may consist of devices, running heterogeneous runtime system that are responsible for a distributed execution of an application. Table 2 shows the supported runtime systems in the current version. It implements the MQTT and iBICOOP runtime system. However, the framework does not restrict the stakeholders to a specific runtime systems and it is flexible to integrate different runtime systems, as discussed in our previous work [31].

**Heterogeneous interaction modes.** The devices could be different in terms of how data can be accessed from them. Table 2 shows four interactions modes supported by our approach, largely found in the IoT applications: periodic [17], publish/subscribe [12], request/response [4], command [11].

**Topology.** It indicates whether an application is characterized by static or dynamic topology. In static topology, devices do not move once they are deployed. In dynamic topology, devices (e.g., smartphone) move autonomously. Table 2 shows that applications with static topology is supported. Our immediate future work will be to provide mobility support in our framework.

**Network size.** It indicates a number of devices participating in an application [27]. The participating devices could be sensing, actuating, computational, and/or user interface devices. Table 2 shows our approach can cover an application from a small to large number of devices.

**Behaviors in IoT applications.** To guide us our efforts in creating a development framework for the IoT, we survey various applications present in the research literature as well as commercial product proposals. Our early study came to the conclusion that the IoT brings the following behaviors to the mix (refer our previous work [22] for more detail). Table 2 shows the behaviors of IoT applications that are covered by the development framework.

- **Intermittent sensing.** This behavior comes from the early definition of the IoT, which was centered around RFID technology, and is found mostly in applications where things have an information shadow [34] on the Internet. The reader (e.g. RFID reader, barcode reader) observes an ID of a tag and sends it to a service on the Internet, which fetches data associated with the ID from the storage and returns it to the application.

- **Regular data collection.** This behavior is seen in the class of IoT applications where (smart) things interact with users by stating information about themselves periodically or event-based. Actual objects are observed by sensors, and then the observed information is sent for various purposes to users. One of classic examples could be found in the building automation domain. One of ways to save energy is to engage the residents of the building. A system can generate situation awareness by displaying general information about the building such as cur-
rent temperature or energy usage of the building on dashboard placed on a central location of a building.

- **Sense-Compute-Actuate loops.** This behavior is seen in applications where smart things interact with each other at either the local level or through the Internet, and provide information that can be used as new knowledge. They may also take corrective actions with no human originator, recipient, or intermediary, and may notify or prompt users as required.

### 3.5 Memory metrics

Increasing stakeholders productivity often comes at a cost. To precisely evaluate this aspect, we measure the average **code size** and **memory consumption** of device-specific packages that are deployed on devices. These two metrics are important because they give approximate indication of the amount of memory a device needs to run an application. A device with less memory is not able to run the application implementation.

**Code size.** IoT devices possess the limited amount of program memory. So, the code size is an important metric to measure for IoT applications [19].

**Memory consumption.** RAM is a severely limited resource in devices. So, it is important to be known memory consumption of a device. We measure the average amount of heap space used by device-specific packages using VisualVM, a tool that reports the heap allocated of running application. To get precise results, we separately asess the virtual machine with each package code loaded and when the whole application running.

Table 3 shows an average code size and heap allocated for the applications. These results give not very precise, but approximate, indicate the amount of memory a device needs to run an application, thus guiding stakeholders to choose an appropriate device run to device-specific code generated as final package using our approach.

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<th>Application</th>
<th>Average code size (in MBs)</th>
<th>Average memory consumption (in MBs)</th>
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<td>Personalized HVAC</td>
<td>18.58</td>
<td>16.95</td>
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<tr>
<td>Fire detection</td>
<td>18.40</td>
<td>16.91</td>
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</table>

Table 3: Average code size and memory consumptions of a device-specific code

### 3.6 Comparison with state of the art

This section takes a snapshot of the current approaches available for the IoT application development and compares them with our approach. We begin by presenting various dimensions that characterize application development approaches. Then, we map existing approaches back to the dimensions in Table 4, therefore providing not only a complete view of the state of the art with respect to our approach, but also useful insights for selecting the most appropriate approach given an application requirement at hand. Table 4 shows the comparative analysis with our approach. Due to similarity, we pick one representative system in some cases. For instance, TinyDB and Cougar have adopted SQL-based interface for collecting data. So, we take only TinyDB as a representative example.

**Classification.** We see application development approaches for the IoT are classified into four broad categories: node-centric programming, database approach, macro-programming, and model-driven approach. For detail descriptions with pros and cons, readers are referred to our work [20] p. 9.

**Systematization of the development process.** It defines a precise sequence of steps to be followed to develop IoT applications, as well as identifies roles of each stakeholder and separates them according to their skills. The clear identification of expectations and specialized skills of each type of stakeholders helps them to play their part effectively. Hence, this separation of roles smoothen the application development process.

**Technological change support.** It indicates the support provided by an approach to integrate runtime systems and programming languages. The key advantage of this feature it gives a flexibility to extend an approach with a new supported communication technologies and new programming language.

**Programming interface.** It indicates interface provided by an approach to programmer in order to specify an application. An approach largely provides Domain-specific Language (DSL), General-purpose Programming Language (GPL), or combinations of both. DSL could be graphical/textual. Examples of graphical DSL are drag and drop blocks or UML notations. Examples of GPL are Java, C, etc.

**Open source.** It indicates whether an approach is open source or not. Given the usefulness of open source, it aims to provide an opportunity of sharing of novel software engineering tools and technologies.

**Integrated Development Environment (IDE) Support.** It indicates an IDE is provided by an approach or not. An IDE is a software application that provides comprehensive facilities for software development. It normally consists of editors, which facilitate syntax coloring and error reporting, and automation tools to reduce application development effort.

**Deployment state.** It represents maturity of an approach. Whether it is just a prototype or it has been released as product.

### 4. Conclusion

An important challenge that needs to be addressed in the IoT is to enable the IoT application development with minimal effort by the various stakeholders. To address this challenge, many approaches have been proposed. Although existing approaches provide a wide range of features, stakeholders have specific application development requirements and choosing an appropriate approach requires thorough evaluations on different aspects.

This paper is an attempt to address the above issue partially. It presents a set of evaluations based on our previous work on IoT application development framework. This paper evaluate our approach in terms of development effort, reusability, expressiveness, memory metrics, and comparison with the state of the art in IoT application development one various dimensions. The set of measures is non-exhaustive. However, they reflect principal quantitative advantages that our approach provides to stakeholders. Moreover, these measures provide the research community with insight into evaluating, selecting, and developing useful IoT frameworks and applications.

### References


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<th>Runtime System</th>
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<th>Topology</th>
<th>Network size</th>
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**Table 2: Expressiveness of our approach**

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