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# Federation of Internet of Things Testbeds for the Realization of a Semantically-Enabled Multi-Domain Data Marketplace

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**Abstract:** The Internet of Things (IoT) concept has attracted a lot of attention from the research and innovation community for a number of years already. One of the key drivers for this hype towards the IoT is its applicability to a plethora of different application domains. However, infrastructures enabling experimental assessment of IoT solutions are scarce. Being able to test and assess the behavior and the performance of any piece of technology (i.e. protocol, algorithm, application, service, etc.) under real-world circumstances is of utmost importance to increase the acceptance and reduce the time to market of these innovative developments. This paper describes the federation of eleven IoT deployments from heterogeneous application domains (e.g. smart cities, maritime, smart building, crowd-sensing, smart grid, etc.) with over 10,000 IoT devices overall which produce hundreds of thousands of observations per day. The paper summarizes the resources that are made available through a cloud-based platform. The main contributions from this paper are twofold. In the one hand, the insightful summary of the federated data resources are relevant to the experimenters that might be seeking for an experimental infrastructure to assess their innovations. On the other hand, the identification of the challenges met during the testbed integration process, as well as the mitigation strategies that have been implemented to face them, are of interest for testbed providers that can be considering to join the federation.

**Keywords:** Data Marketplace; Federation; Internet of Things; Testbeds; Platform;

## 44 1. Introduction

45 It goes without saying that experimentation is one of the basis for technological advances [1].  
46 Being able to test and assess the behavior and the performance of any piece of technology (i.e.  
47 protocol, algorithm, application, service, etc.) under real-world circumstances is of utmost  
48 importance to increase the acceptance and reduce the time to market of these innovative  
49 developments. However, despite the attention that the Internet of Things (IoT) has attracted [2]  
50 thanks to the large number of application domains where it can play a game changer role [3–7], there  
51 is still a lack of real, large-scale testbeds where all these innovations can be actually assessed. In this  
52 respect, real-life experimentation should play a major role in these developments. It would be  
53 necessary to deploy, maintain and open to the research community this kind of infrastructures so  
54 that their research can have tangible results from real-world deployments [8,9].

55 Interestingly, there are initiatives that, in order to improve these solutions' maturation and  
56 significant rollout, try to support the evaluation of IoT solutions under realistic conditions in real  
57 world experimental deployments [10–12]. However, still they tend to lack the necessary scale or they  
58 fail to fulfil some key indicators [13,14]. Nonetheless, large-scale infrastructures enabling the  
59 assessment of developed solutions under real-world circumstances are scarce and are not always  
60 available for those willing to test their innovations. Moreover, such infrastructures are typically  
61 bound to a specific application domain, thus, not facilitating the testing of solutions with a horizontal  
62 approach (i.e. fulfilling requirements from different application domains). Finally, even when,  
63 through the combination of different testbeds, the requirements from an experimenter were fulfilled,  
64 it is necessary to deal with interoperability issues resulting from the different interfaces and models  
65 used by the different testbeds.

66 This paper describes the federation of testbeds that have been created within the framework of  
67 the H2020 FIESTA-IoT project [15]. The platform designed in the project provides the tools and  
68 techniques for building applications that horizontally integrate silo platforms and applications. The  
69 semantic interoperability of the diverse sensor clusters and IoT networks federated is based on the  
70 virtualization of sensors in the cloud. At the heart of these virtualization mechanisms is the modelling  
71 of heterogeneous IoT devices according to a common ontology. However, the detailed description of  
72 the platform design principles and building blocks is out of the scope of this paper. Specific insights  
73 about the EaaS IoT Platform designed and implemented in the FIESTA-IoT Project can be found at  
74 [16].

75 The main aim of this paper is to present the actual federation of testbeds on top of a running  
76 instance of this platform. This federation aggregates and ensures the interoperability of data streams  
77 stemming from eleven different IoT deployments. The paper summarizes the resources that are made  
78 available from eleven IoT deployments from heterogeneous application domains (smart cities,  
79 maritime environment monitoring, smart building, crowd-sensing, smart grid, smart agriculture)  
80 with over 10,000 IoT devices overall which produce hundreds of thousands of observations per day.  
81 Detailed information is provided on the amount of sensors and observations that are made available  
82 to the interested experimenters.

83 The main contributions from this paper are twofold. On the one hand, the paper provides an  
84 insightful summary of the federated data resources. While some informational details about the  
85 papers is publicly available<sup>1</sup>, the review presented in this paper provide the necessary insights to  
86 fully understand the experimentation possibilities raised by having access to all the federated  
87 resources. This detailed and precise overview is particularly relevant to the experimenters that might  
88 be seeking for an experimental infrastructure to assess their innovations. In this sense, to the best of  
89 our knowledge, there is no single or federated IoT experimentation infrastructure currently offering  
90 the amount of data resources described in this paper. On the other hand, the paper discusses over the  
91 most relevant challenges that have been met during the testbed integration process, as well as the  
92 mitigation strategies that have been implemented to face them. This discussion summarizes the

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<sup>1</sup> The FIESTA-IoT Testbeds. <http://fiesta-iot.eu/index.php/fiesta-testbeds/> [Online 13<sup>th</sup> August 2018]

93 technical solutions adopted to provide semantic and functional interoperability among the  
94 heterogeneous underlying IoT infrastructures and should be of particular interest for testbed  
95 providers that can be considering to join the federation. Thus, the paper goes beyond the plain  
96 description of data offerings but also presents practical insights on how the main technical challenges  
97 involved in the semantically-enabled federation of IoT platforms have been tackled. In this sense, it  
98 is important to highlight that the technical discussion presented in the paper recaps on lessons learnt  
99 from actual deployment and development experience.

100 The remaining of the paper is organized as follows. Section 2 briefly reviews existing related  
101 work. A high-level overview of how the testbeds have been federated and the requirements imposed  
102 by the underlying FIESTA-IoT Platform for allowing new testbeds to federate are introduced in  
103 Section 3. Section 4 presents the summary of the testbeds' federation as well as the key details of each  
104 of the testbeds within the federation. Lessons learnt during the federation process and some  
105 discussions about the testbeds' federation concept are sketched in Section 5. Finally, Section 6  
106 concludes the paper.

## 107 2. Related Work

108 This section reviews on the key aspects and technologies that are behind the developments  
109 described in the paper to position the research and contributions of the paper in context and to  
110 validate its relevance by establishing the similarities and highlighting its differentiating features with  
111 currently existing approaches.

112 **Experimental Infrastructures.** The required effort and cost for creating realistic environments  
113 over which new IoT solutions and technologies could be tested has led to the creation of experimental  
114 testbeds open to the research and innovation community. Wisebed [17], FIT IoT-Lab [11], Fed4FIRE  
115 [18], BonFIRE [19] and GENI [20] are all testbeds that support wireless sensor network  
116 experimentation. They allow testing of new communication protocols and wireless communications  
117 that underpin the IoT domain. However, these experimental infrastructures are technology specific  
118 and mainly focused on Wireless Sensor Networks rather than on IoT as a whole. As a consequence,  
119 they do not support experimentation of new IoT applications and services. In response,  
120 SmartSantander [10] provides a large-scale, geographically distributed range of real-world sensors to  
121 test new innovative IoT services; LiveLab [21] offers a facility to evaluate human-usage of the  
122 technologies; and [22] presents a Mobile Sensing testbed of smart phones to support field-testing of  
123 new crowd-sourcing applications. Even if the usefulness of these experimental infrastructures in their  
124 own right is out of any doubt, these higher-layer testbeds are all domain specific. Thus, they do not  
125 consider an important aspect that is currently at stake within the research community. Achieving  
126 interoperability across domain silos and heterogeneous technologies is the next frontier that has to  
127 be overcome to unleash the IoT foreseen potential. The FIESTA-IoT facility is technology and domain  
128 agnostic (federating multiple smart city, smart home, crowd-sensing testbeds) to allow experiments  
129 that demonstrate IoT interoperability across highly heterogeneous IoT environments.

130 **Experimentation-as-a-Service.** Experimentation-as-a-Service (EaaS) model can be seen as an  
131 instance of the general Everything-as-a-Service paradigm [23] introduced and developed by  
132 leveraging the advances in cloud computing. EaaS enables stakeholders belonging to the research  
133 community or industrial sector to promote and accelerate innovation by testing and verifying new  
134 technologies supported by realistic and specialized experimental testbeds, through the use of a cloud  
135 environment. In [24] a platform for assessing the performance and reliability of commercial mobile  
136 broadband networks is presented, where authenticated users are able to orchestrate network  
137 experiments following an EaaS paradigm. FLAME project [25] is developing an EaaS architecture for  
138 exploring the viability of Future Media Internet platforms in smart-city deployments. The  
139 experiments aim to highlight the benefits of a software-enabled communication infrastructure for the  
140 optimal information distribution and control. While the FLAME project is not related with IoT, it  
141 develops an EaaS architecture for content distribution aimed at the support of experimentation and  
142 innovation on top of open platforms. This platform is similar to the FIESTA-IoT platform on top of  
143 the testbed federation presented in the paper does.

144 The EaaS model applied to the IoT domain stands out as an upgrade to the Sensing-as-a-Service  
145 [26] model; EaaS services are not confined to a number of virtualized sensor queries but implement  
146 and execute complex experimental workflows “in the wild” by orchestrating various devices and  
147 diverse testbeds. Thus, it is possible to widen the scope and complexity of the IoT applications  
148 supported as well as reuse the infrastructures and data streams provided and maximize their  
149 utilization. The SmartCampus facility [27] offers a testbed based on a three-tier architecture for  
150 executing user-centric experiments in an office environment, set up by external stakeholders.  
151 Although adopting the EaaS paradigm, the facility is highly domain specific in stark contrast to the  
152 FIESTA-IoT platform. A federation of experimentation platforms is presented in [28], where users are  
153 able to rapidly deploy reproducible experiments related to several smart city domains, by on-demand  
154 access to virtual reusable resources. Organicity [29] provides a facility for federating different smart  
155 city platforms and assessing the crowd-sensing problem by encouraging different stakeholders to  
156 identify urban challenges and tackle them by co-creating suitable experiments. These platforms bear  
157 a number of similarities with the one presented in this work. They offer virtualized access to IoT data  
158 produced by real-world IoT infrastructure. Datasets available span over a number of different  
159 application domains. They allow experimentation through web-based APIs. Some of them have  
160 aggregated data from IoT infrastructures which are managed by different providers. Nevertheless,  
161 they neither enjoy the diversity of testbeds described here nor employ semantic web technologies for  
162 facilitating the semantic interoperability between deployed IoT infrastructures.

163 **Semantic Interoperability.** Semantic web technologies to query and manage information within  
164 federated cyber-infrastructures [30–32] are being used as a promising approach to guarantee the  
165 necessary consistency among IoT infrastructures. However, they usually only define the framework  
166 and assess the meta-directory service using their own ontologies [33,34]. Thus, they fail in taking  
167 into account the needs from IoT infrastructures that are already deployed. Moreover, the definition  
168 of the procedures to extend their deployments by integrating already existing ones is also missing.  
169 Additionally, some of them are still only proposed as theoretical solutions [35] which have not been  
170 implemented nor assessed. Finally, those that present some kind of assessment of their solutions’  
171 implementation, while supporting the potential of the solution, exhibit a lack of exposure to real-life  
172 situations and actual heterogeneous testbeds, including large-scale IoT experimental infrastructures,  
173 which would show the true scalability and flexibility of the solutions. Only recently, the semantic  
174 interoperability have been explored in standardization fora [36] defining some base ontology and  
175 data catalogues that can be adopted by a large community, both already existing and forthcoming.  
176 The approach followed, mainly by oneM2M base ontology, is similar to the one followed within the  
177 FIESTA-IoT project for defining the FIESTA-IoT ontology [37]. The main reason for defining our own  
178 ontology was that at the time of initiating our work, the oneM2M standard was not available.  
179 However, the same that it has been possible to federate one oneM2M-based testbed, it is possible to  
180 define and implement the adaptations in the opposite direction.

181 **IoT data marketplaces.** The data generated by IoT devices is mostly owned by device owners  
182 and is often private in nature. There are however third parties that could benefit from using that data,  
183 and the challenge is in allowing them to access it under the conditions that data owners find  
184 acceptable. The concept of data marketplace has been introduced already some years ago [38].  
185 However, although data management was clearly identified as one of the key challenges for IoT [39],  
186 solutions proposed until recently focused on creating the backend storage solutions plus the indexing  
187 mechanisms to discover the relevant pieces of information among the massive amount of data that  
188 IoT infrastructures can generate [40–42]. Nevertheless, there is an important requirement that has to  
189 be fulfilled. Developers who want to use existing platforms need to negotiate access individually and  
190 adapt to the platform-specific API and information models. Having to perform these actions for each  
191 platform often limits the applicability of the developed applications as they have to be tailored to the  
192 different platforms. This fragmentation of the IoT and the missing interoperability result in high entry  
193 barriers for developers and prevent the emergence of broadly accepted IoT ecosystems. Only recently  
194 some initiatives have appeared defining not only the data management platforms that support the  
195 marketplace but also the interoperability mechanisms that make the proposed solutions prepared to

196 integrate a potentially endless amount of IoT heterogeneous infrastructures [43–46]. Although these  
197 approaches have multiple commonalities with the federation of IoT testbeds that is described in this  
198 paper, to the best of our knowledge, none of them shows the diversity and scale of the one presented  
199 in this paper.

200 **Sensor Web Enablement and Web of Things.** The Sensor Web Enablement (SWE) initiative  
201 (<http://www.ogcnetwork.net/swe>) has developed a suite of standards that can be used as building  
202 blocks for a Sensor Web. SWE defines the term Sensor Web as “Web accessible sensor networks and  
203 archived sensor data that can be discovered and accessed using standard protocols and application  
204 programming interfaces” [47]. To achieve this, SWE incorporates models for describing sensor  
205 resources and sensor observations. Further, it defines web service interfaces leveraging the models  
206 and encodings to allow accessing sensor data, tasking of sensors, and alerting based on gathered  
207 sensor observations. Leveraging the SWE concepts, the Web of Things (WoT) emerges from applying  
208 web technologies to the IoT to access information and services of physical objects. In WoT, each  
209 physical object possesses a digital counterpart. These objects are built according to Representational  
210 state transfer (REST) architecture and accessed with HTTP protocol via RESTful API. A Web Thing  
211 can have an HTML or JSON representation, REST API to access its properties and actions, and an  
212 OWL-based semantic description.

213 W3C has recently launched the Web of Things Working Group [48] to develop initial standards  
214 for the Web of Things. Its main aim is “to counter the fragmentation of the IoT”. They are still working  
215 on defining the WoT architecture and the description of the WoT Thing, which should define a model  
216 and representation for describing the metadata and interfaces of Things, where a Thing is the  
217 virtualization of a physical entity that provides interactions to and participates in the WoT.

218 In parallel to this standardization efforts, several projects and platforms have been developed  
219 targeting the support of service provision based on the SWE and WoT paradigms. In [49], authors  
220 present their WoT-based platform for the development and provision of smart city services. Precision  
221 agriculture is the application domain which benefits from the platform described in [34]. While they  
222 provide some of the solutions promised by the WoT, still do not address the IoT fragmentation as  
223 they rely on proprietary modelling. In the works presented in [50–52], semantic technologies are  
224 employed to fulfil the extendable modelling requirement. As we are proposing in this paper, we  
225 believe that this is the necessary combination in order to fully develop the WoT concept into a  
226 running system. The key novelty from the work presented in this paper is that, most of the existing  
227 previous works have not been implemented and proven over real-world scenarios with federation of  
228 heterogeneous IoT infrastructures, as it is the case of the platform presented in this paper. Some well-  
229 known implemented Sensor Webs [53–55], which have actually put SWE and WoT standards and  
230 paradigms in practice, have not faced the necessary heterogeneity to actually face the interoperability  
231 challenge.

232 **Semantic Web and Semantic annotation of sensor data.** In semantic web, there exists standards  
233 such as SSN ontology [56] that are widely accepted and used by different testbeds. A new version of  
234 SSN ontology [57] covers mainly concepts that are common to most of the domains (horizontal  
235 concepts). SSN ontology defines concepts such as Sensor, Observation, Samples and Actuators that  
236 form core concepts within the Domain and Information Models defined in the IoT Architecture  
237 Reference model (ARM) [58]. However, in more abstract terms, definitions of such concepts are  
238 provided in another widely promoted oneM2M ontology [59]. There are several other ontologies such  
239 as Smart Appliance REference (SAREF) [60] that are standardized but are context-based and only  
240 focus on one domain (vertical concepts). Efforts have been made to unify concepts defined vertically  
241 and horizontally so that federation and interoperability can be achieved. One such effort is that of  
242 lightweight FIESTA-IoT ontology [37] that reuses concepts to focuses on competency based questions  
243 [61] across different domains. It mainly targets concepts that are necessary to answer: who is the  
244 provider of the information, under what conditions observations are collected, when and where are  
245 the observations made and how collected information is exposed. In FIESTA-IoT ontology the core  
246 concepts are borrowed from SSN and IoT-lite ontology [62], a lighter version of the IoT-A ontology

247 [63], to conform with IoT ARM's Domain and Information Models. These core concepts relate to  
 248 defining:

- 249 • A Resource which is a "Computational element that gives access to information about or  
 250 actuation capabilities on a Physical Entity" [58].
- 251 • An IoT service which is a "Software component enabling interaction with IoT resources  
 252 through a well-defined interface." [58].
- 253 • An Observation is an "Act of carrying out a procedure to estimate or calculate a value of a  
 254 property of a feature of interest" [64].

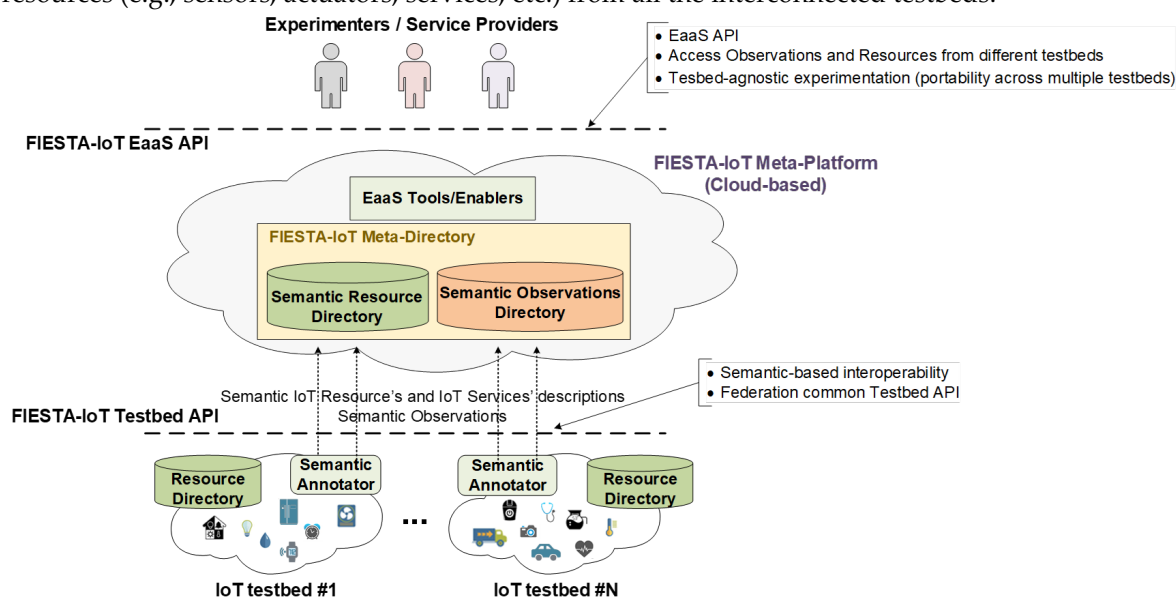
255 Further many related concepts to abovementioned core concepts have been reused in FIESTA-  
 256 IoT ontology. As it has been already said, the FIESTA-IoT ontology is defined to be as lightweight as  
 257 possible precisely to cope with this requirement of easing the integration process. To keep it  
 258 lightweight, on top of the core concepts FIESTA-IoT ontology reuses some of the already defined  
 259 concepts and relationships between the concepts. To name a few, these are: Platform defined via SSN,  
 260 Instant defined via Time [65], QuantityKind and Unit defined through the M3-Lite taxonomy [66],  
 261 Point defined through WGS84 [67], Metadata defined using IoT-lite, hasDataValue defined using  
 262 DUL [68], hasDomainOfInterest defined using M3-lite taxonomy and location defined using WGS84.

### 263 3. Testbed Federation Concept and Conditions

264 The main aim of the FIESTA-IoT federation is to enable an EaaS paradigm for IoT experiments.  
 265 However, instead of deploying yet another physical IoT infrastructure it enables experimenters to  
 266 use a single EaaS API for executing experiments over multiple existing IoT testbeds that are federated  
 267 in a testbed agnostic way [16]. Testbed agnostic implies in this case the ability to expose a single  
 268 testbed that virtualizes the access to the underlying physical IoT testbeds. Experimenters learn once  
 269 and accordingly use the EaaS API to access data from any of the underlying testbeds.

270 To this end, the testbeds that aim to participate in the federation have to implement the common  
 271 standardized semantics and interfaces that have been defined within the FIESTA-IoT project. This  
 272 enables the FIESTA-IoT meta-platform to access the data that their devices produce as well as the  
 273 descriptions of their devices and the services that these devices might expose.

274 Figure 1 presents the abstract EaaS and testbed federation concepts overview for the of the  
 275 FIESTA-IoT meta-platform. Its central component is a directory service (so-called FIESTA-IoT meta-  
 276 directory), where sensors (or IoT resources) from multiple testbeds are registered along with the  
 277 observations produced by them. This directory enables the dynamic discovery and use of IoT  
 278 resources (e.g., sensors, actuators, services, etc.) from all the interconnected testbeds.



279  
 280

Figure 1. FIESTA-IoT Platform abstract EaaS and testbed federation concepts overview

281 The key concept behind the federation of IoT testbeds is the specification of a common Testbed  
282 API that defines the interfaces to carry out the registration of the testbed resources as well as pushing  
283 of the observations to the meta-directory. Besides the actual technologies used for implementing  
284 these interfaces, the main feature that underlies the FIESTA-IoT Testbed API is the fact that the  
285 information is exchanged in a semantically annotated format.

286 In this sense, the main design decision is the use of semantic technologies to support the  
287 interoperability between heterogeneous IoT platforms and testbeds. The FIESTA-IoT ontology [37,69]  
288 makes it possible to seamlessly deal with data from different sources. The phenomena and units of  
289 measurement related concepts have been incorporated to the FIESTA-IoT ontology through the M3-  
290 Lite taxonomy. This taxonomy has been created by integrating and aligning already existing  
291 ontologies in order to homogenize the existing scattered environment in which a quite large number  
292 of similar ontologies define the same concepts in an overlapping manner.

293 Federated testbeds have to implement their own Semantic Annotators to transform the data they  
294 handle internally to the common semantic ontology defined by FIESTA-IoT. Different RDF  
295 representation formats (e.g. RDF/XML, JSON-LD, Turtle, etc.) are supported as long as the common  
296 ontology is used.

297 The FIESTA-IoT Platform takes as reference the IoT ARM as defined in the IoT-A project [58].  
298 ARM consists of Domain and Information model that also form a base for data that is being stored  
299 in. Although, the model defines Resources [58] and IoT-Services [58], it misses to define the  
300 observations [64] collected by the IoT-devices. FIESTA-IoT ontology considers all such aspects (see  
301 Section 2) and thus enables the FIESTA-IoT architecture to be based on a canonical set of concepts  
302 that all IoT platforms can easily adopt.

303 The adoption of these essential concepts only requires, from the underlying testbeds, a  
304 straightforward tuning of the models that they handle internally. In this sense, independently of  
305 which internal model the testbeds uses, whether it is proprietary or based on existing standards  
306 [70,71], the Testbed Provider (TP) should be able to find in a quite straightforward manner how to  
307 map the internal modelling to the canonical concepts managed within the FIESTA-IoT ontology. The  
308 aforementioned tuning of models basically consist on mapping the internal structure of information  
309 to the one that uses the FIESTA-IoT ontology as a basis. The less number of concepts to map and the  
310 more fundamental these concepts are, the less the chances to have a TP that is unable to perform the  
311 mapping between her internal data model and the interoperable model used within the FIESTA-IoT  
312 Platform that is based in the FIESTA-IoT ontology.

313 The complete description of the FIESTA-IoT ontology is out of the scope of this paper. A  
314 complete specification of the FIESTA-IoT ontology is defined in [37]. It is important to emphasize that  
315 this ontology is the baseline for the interoperability of the heterogeneous testbeds and IoT platforms  
316 that have been already federated and those that will be joining the FIESTA-IoT meta-platform in the  
317 future. The different testbeds have to converge for participating in the federation and they use this  
318 ontology as the reference for this convergence. Precisely this is the main reason why the ontology has  
319 been kept simple as a design decision.

320 Since a testbed may internally use various standard and/or proprietary interfaces, in addition to  
321 the semantic model that underpins the interaction between each of the testbeds and the FIESTA-IoT  
322 Platform, a list of services (so-called Testbed Provider Interface – TPI) has been specified. A testbed  
323 has to expose, at least, a subset of them in order to enable different connection methods to the  
324 platform.

325 The TPI is a set of RESTful web services that spans across two different realms [16]. The first is  
326 the FIESTA-IoT Platform side with the TPI Configuration & Management layer that controls the  
327 functionality of the TPI. The second is the testbed side with the Testbed Provider Services (TPS) where  
328 the TP has to implement a set of services that enables the management and manipulation of the  
329 offered data. These services can be grouped into two types according to the relation established  
330 between the testbed and the FIESTA-IoT Platform, namely get-based and push-based. For the Get  
331 case, the services should respond with the latest observations from a list of sensors. For the Push case,  
332 the services correspondingly initiate a stream at the testbed side that pushes the observations from a



333 list of sensors. In both cases, the list of sensors from whom the observations are retrieved or have to  
 334 be pushed is the input parameter. The TPs can choose which of these two options fit better in their  
 335 platforms and decide to either let the platform control the schedule (get-like option) or control the  
 336 schedule of when to push the data (push-like option).

#### 337 4. Federated Testbeds

338 This section summarizes the main characteristics and datasets available through the FIESTA-IoT  
 339 Platform<sup>2</sup> after the integration, until the time of writing this paper, of eleven different IoT  
 340 infrastructures.

##### 341 4.1. Criteria for Testbed Federation

342 The federation initially started with five testbeds being integrated with the platform to serve as  
 343 reference implementations for testbed integration [72]. These were SmartSantander, SmartICS,  
 344 SoundCity, Grasse Smart Territory and CABIN. In order to enlarge the value of the offer and also to  
 345 proof the adequacy of the solutions designed to enable interoperability among heterogeneous IoT  
 346 platforms, two open calls for testbed integration were conducted. As a result of these Calls, six more  
 347 testbeds were selected.

348 The main aim of federating more IoT testbeds and not restricting it to the original four ones is to  
 349 challenge the platform design. This way tuning of that design can be made by following the lessons  
 350 learnt and best practices that can only be elicited from actual implementation. Moreover, addition of  
 351 more application domains also brings further challenges that were not initially considered as they  
 352 were not present in the initial set of testbeds. This selection was based on the following criteria:

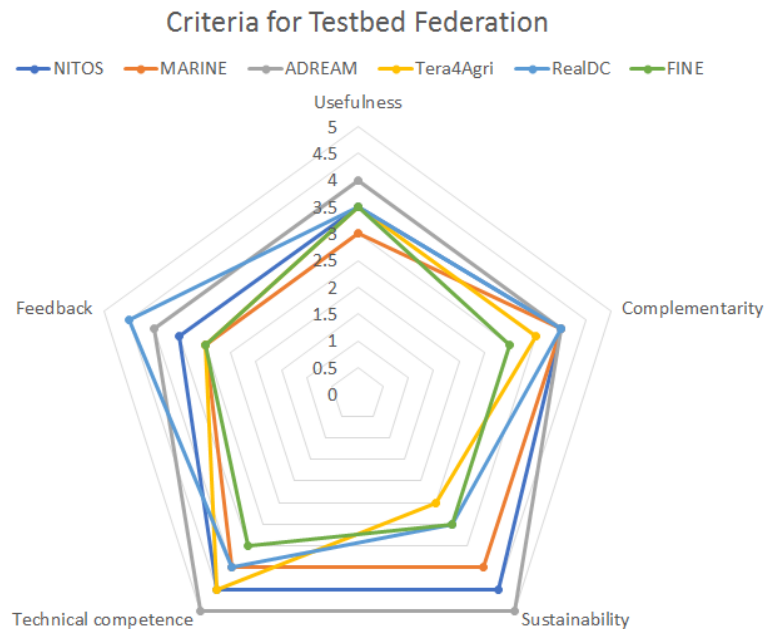
- 353 • **Usefulness:** the degree of expected future use of the extension, which takes into account the  
 354 amplitude (number and variety) of the testbed IoT resources, their nature (i.e. real or virtual  
 355 resources), the testbed availability and the accessibility to the testbed resources for platform  
 356 users during the whole project duration and beyond.
- 357 • **Complementarity:** the degree at which the testbed will provide new datasets and data  
 358 streams, whereby it contributes to enlarge the critical mass of the existing experimentation  
 359 support capacity offered by the 4 integrated testbeds, as well as to probe the interoperability  
 360 solutions developed within the project, by providing additional datasets and data-streams  
 361 on the domains of interest of the existing ones. Else, it can offer extra scenarios (smart  
 362 agriculture, smart factory, crowd-sensing, underwater, etc.) with a high potential impact in  
 363 terms of the real-world innovation enabled through the offered infrastructure and its  
 364 associated datasets and data-streams.
- 365 • **Sustainability:** The guarantee of availability of the services offered by the extension in  
 366 absence of future funding. This is linked with the history of the infrastructure and its  
 367 demonstrable ability to support experimentation.
- 368 • **Technical competence:** The testbed provider should exhibit prior testbed management  
 369 experience and the necessary qualifications to integrate their testbeds within the FIESTA-IoT  
 370 federation.
- 371 • **Feedback:** The potential for providing feedback regarding the platform and the process of  
 372 integrating new testbeds within the federation. Testbed providers must demonstrate value  
 373 of the FIESTA-IoT federation procedures and/or motivate added-value extensions. Also, the  
 374 business impact for joining the federation was considered.

375 Figure 2 illustrates the assessment of the testbeds based on the criteria set out in the Calls  
 376 processes. As it has been previously mentioned, the six testbeds whose key features are assessed in  
 377 Figure 2 are those that were selected during the Open Calls process. The remaining five testbeds were  
 378 the founding members of the federation.

---

<sup>2</sup> FIESTA-IoT Platform. <https://platform.fiesta-iot.eu>. [Online 3<sup>rd</sup> September 2018]

379 The overall marks of the different testbeds are remarkable and interestingly high in  
 380 Complementarity. This provides good insight on the heterogeneity that, in general, is exhibited by  
 381 the compound offering of the federation of testbeds. This conclusion is also supported by the above  
 382 average marks that all the testbeds received in the Feedback criterion. On the one hand it shows that  
 383 the integration of these testbeds can generate valuable lessons learnt, which could not be elicited  
 384 otherwise, and, on the other hand, it indicates, together with the respective Usefulness marks, the  
 385 added-value of integrating the offerings from these testbeds.



386  
 387

**Figure 2.** Assessment of the six testbeds that joined the federation through Open Calls process

388 Another criterion with several excellent marks is the Sustainability. While this is not related to  
 389 the technical challenges brought forward by the inclusion of this testbed, it certainly demonstrates  
 390 that the federated testbeds have a long track of previous and future IoT experimentation support.

#### 391 4.2. Overall Federation Summary and Data Marketplace Offering

392 For almost all the cases, the IoT devices are actually located around the TP premises. However,  
 393 since the SoundCity testbed is based on data stemming from smartphones, its actual coverage is not  
 394 limited to Paris.

395 Table 1 provides a summary of the eleven testbeds and highlights roughly the application  
 396 domain and the IoT devices that are part of each of the deployments. Further, the Table 2 presents  
 397 categorization of the eleven testbed in different application domain.

398 **Table 1.** FIESTA-IoT testbeds summary

Testbed	Short description	Deployed devices
<i>SmartSantander</i> [73]	Large-scale Smart City deployment.	Thousands of fixed and mobile sensors (environment, parking, transportation, etc.).
<i>SmartICS</i> [74]	Smart Environment based on an indoor deployment of sensor nodes.	Hundreds of indoor environment sensors.
<i>SoundCity</i> [75]	Crowdsensing testbed using mobile phones	Variable number of phone-based sensors measuring noise pollution and proximity.

<i>CABIN</i> <sup>3</sup>	Indoor and outdoor environment smart building deployment with outdoor sensors.	Hundreds of indoor environmental sensors with tens of outdoor parking sensors.
<i>NITOS</i> [76]	Heterogeneous Lora and Wireless Sensor Network.	20 LoRa and 60 Zigbee indoor environmental and presence sensors.
<i>MARINE</i> <sup>4</sup>	Seawater and Air quality monitoring testbed.	4 floating seawater quality monitoring buoys and 5 fixed air quality monitoring stations (17 different sensor types).
<i>RealDC</i>	Live data center testbed for monitoring DC operations.	100 sensors for power consumption and weather station producing over 2000 observations.
<i>Tera4Agri</i>	Outdoor testbed for Smart Agriculture.	More than 10 sensors for environmental, soil and tree monitoring.
<i>FINE</i>	Smart City, smart building and home automation testbed.	40 outdoor environmental monitoring and 6 indoor automation sensors and actuators.
<i>Grasse Smart Territory</i>	Smart City testbed open to local developer community who bring their own sensors	5 sensor boxes with each containing multi environmental sensors.
<i>ADREAM</i>	Large-scale smart building testbed	6500 sensors for lighting, electricity, HVAC, solar panels, etc.

399

400

Most of these testbeds are internally using proprietary platforms which does not follow any

specific standard or largely adopted IoT platform. CABIN testbed is based on oneM2M standard.

However, it only implements the functional specifications and not the semantic ontology that has

been recently defined by the ETSI oneM2M standard. ADREAM testbed uses a proprietary ontology

[77] which is certainly aligned with the oneM2M base ontology but still is not part of any standard.

Finally, SmartSantander testbed is based on FIWARE<sup>5</sup> generic enablers and follows the data

catalogues. All in all, the heterogeneity is, significantly, the main feature that can be derived from

406

407

408

409

**Table 2.** Categorization of Testbeds in different Application domain

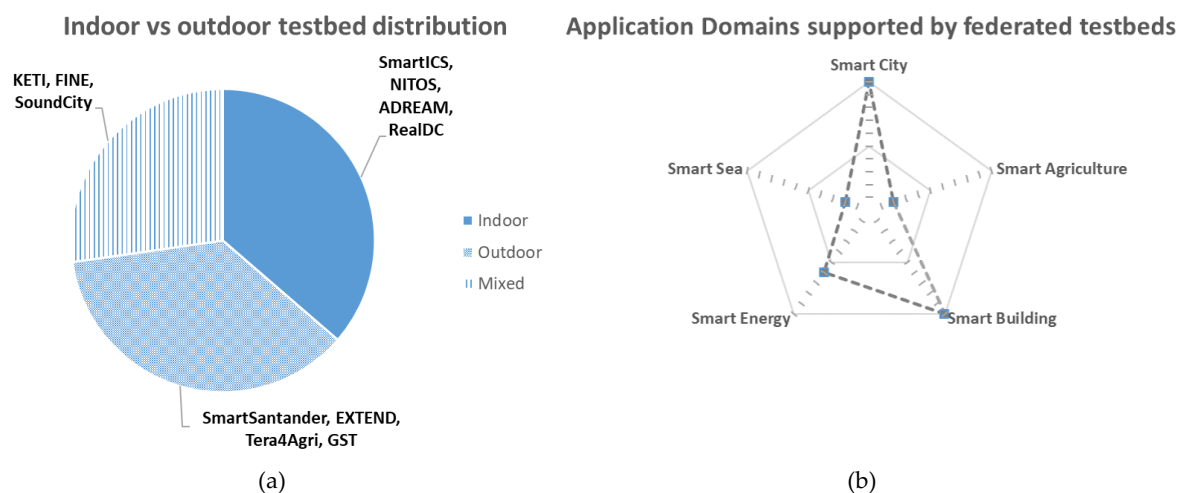
<b>Application Domain</b>	<b>Testbeds</b>
Smart City	SmartSantander, SoundCity, CABIN, FINE, Grasse Territory
Smart Agriculture	Tera4Agri
Smart Buildings	SmartICS, CABIN, NITOS, FINE, ADREAM
Smart Energy	SmartICS, RealDC, ADREAM
Smart Sea	MARINE

<sup>3</sup> CABIN testbed. <http://developers.iotocean.org> [Online 13<sup>th</sup> August 2018]

<sup>4</sup> GRIDNET. <http://gridnet.gr/MARINE/> [Online 13<sup>th</sup> August 2018]

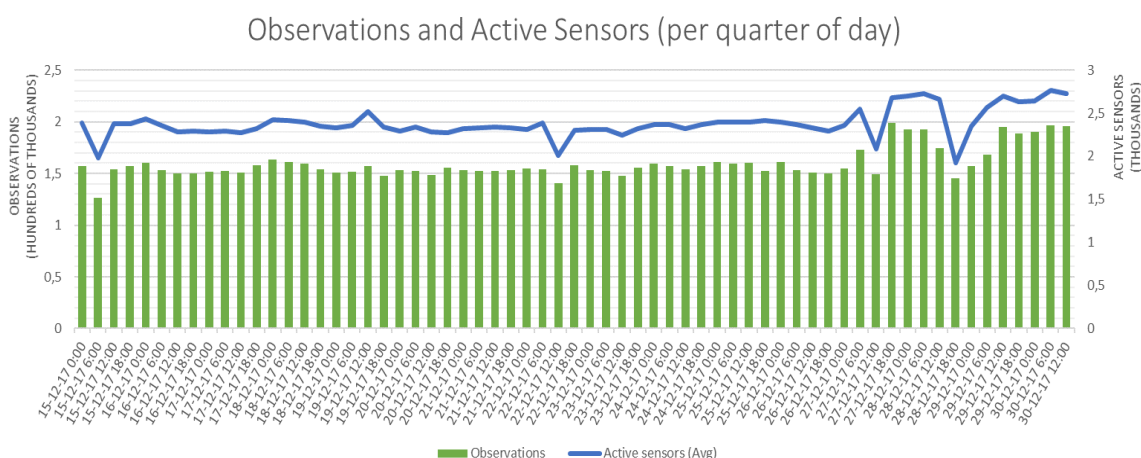
<sup>5</sup> FIWARE. <https://www.fiware.org/> [Online 3<sup>rd</sup> September 2018]

410 Overall, there is a reasonable balance between indoor and outdoor sensors (cf. Figure 3a)  
 411 covering five wide application domains (cf. Figure 3b), namely smart city, smart building, smart  
 412 energy, smart agriculture and smart sea). The spider graph in Figure 3b roughly represents the depth  
 413 in which each of the application domains are covered attending to how many of the federated  
 414 testbeds cover that particular domain. This creates a quite varied offering able to cope with the needs  
 415 of a good number of potential IoT researchers and innovators which would like to assess their  
 416 developments in a scenario excerpted from the combined offering.



417 **Figure 3.** Application domains of the integrated sensors

418 In addition to the general details, it is important to highlight the raw figures that the federation  
 419 of testbeds is continuously providing in terms of active sensors and amount of observations  
 420 generated. In this sense, Figure 4 shows these two key parameters evolution during second half of  
 421 December 2017.



422 **Figure 4.** Active sensors and generated observations during Dec' 17

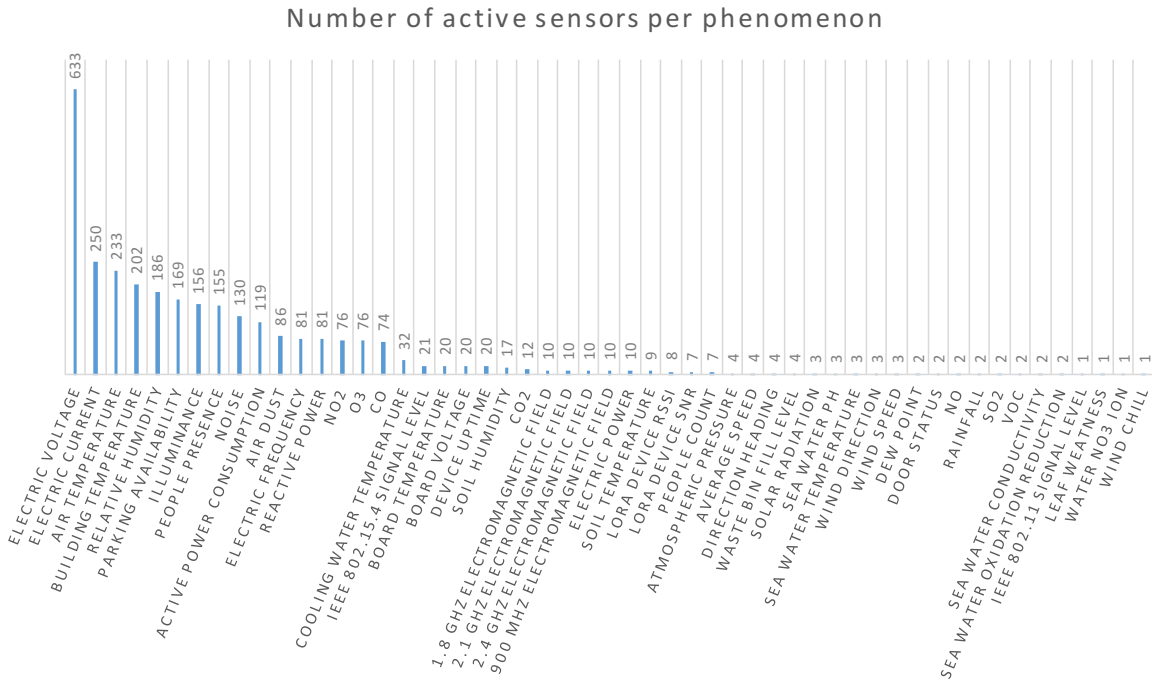
424 More or less constantly, every 6 hours (time scale in X-axis is set to quarter of day for the sake of  
 425 clarity), the testbeds' federation is generating around 150,000 observations. These observations are  
 426 coming, on average, from 2,000 active sensors that are continuously capturing events in its  
 427 environment and reporting them to the platform.

428 Appendix A. FIESTA-IoT testbeds detailed offering  
 429 Table 3 (in Appendix A) and Figure 5 present the detailed analysis of the offerings from each of  
 430 the FIESTA-IoT testbeds. In contrast with information available on-line [78], the figures summarized  
 431 in Appendix A. FIESTA-IoT testbeds detailed offering

432 Table 3 have been extracted from the actual FIESTA-IoT Platform, thus, presenting the actually  
 433 available number of active sensors and their observations' generation frequency and not the textual  
 description of testbeds that indicates the deployed devices but not the ones regularly producing

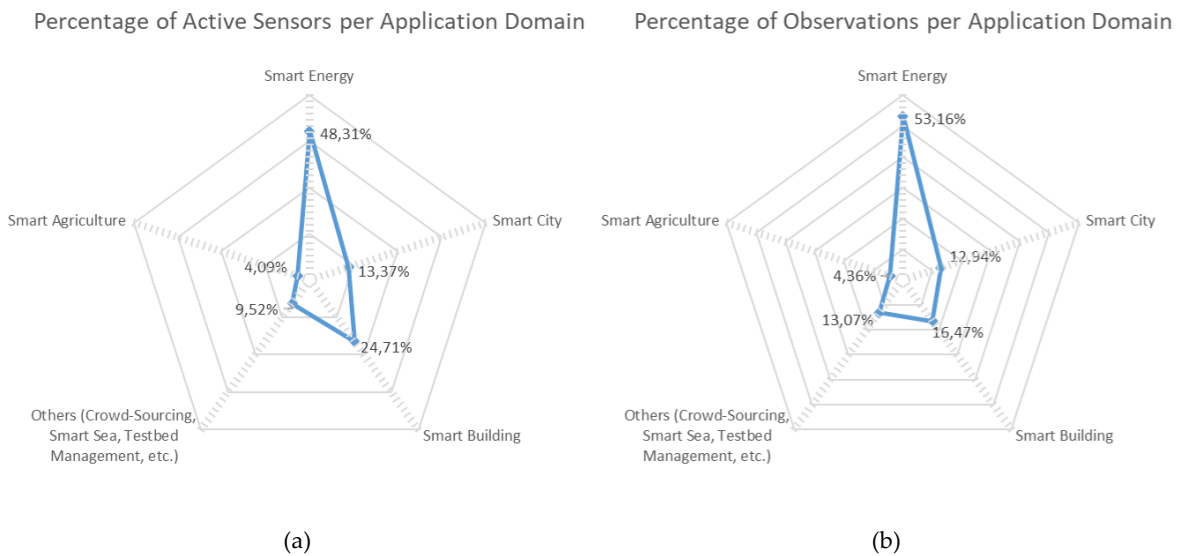
434 observations, which is the most relevant information for the experimenters willing to carry out their  
 435 experiments on top of the FIESTA-IoT Platform. The key details presented in Appendix A. FIESTA-  
 436 IoT testbeds detailed offering

437 Table 3, apart from the actual amount of devices producing data from each testbed, are the  
 438 Phenomenon, which stands for the physical parameter observed, and the Quantity Kind, which  
 439 stands for the Internationalized Resource Identifier (IRI) assigned in the FIESTA-IoT ontology to the  
 440 respective physical phenomenon. This latter parameter is particularly important as it is the one that  
 441 has to be used within the FIESTA-IoT Platform when looking for the corresponding phenomenon.



442  
 443 **Figure 5.** Amount of active sensors per phenomenon

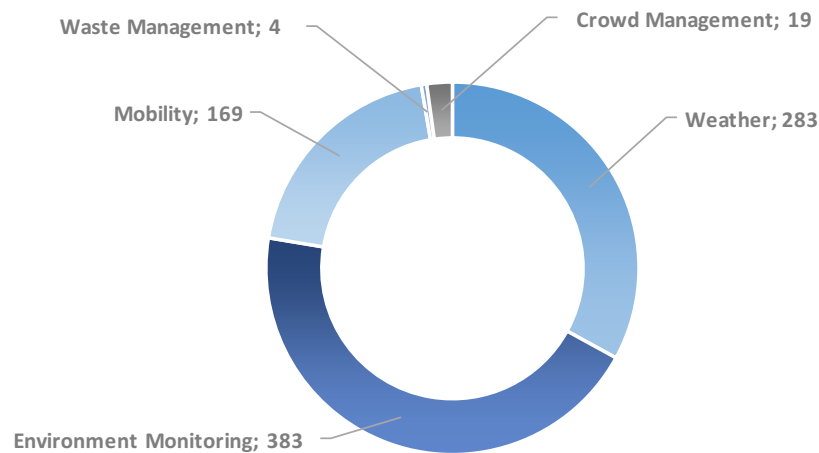
444 In terms of the covered application domains, the Smart Energy domain is the one that has both  
 445 more active sensors and more generated observations. In this respect, the RealDC, SmartICS and  
 446 ADREAM testbeds have a large set of IoT devices measuring the power consumption at its Data  
 447 Centre, offices’ desks and buildings respectively, which produce observations quite often.



448 **Figure 6.** Distribution of active sensors (a) and observations (b) per application domain

449 Following, the Smart City deployments from the SmartSantander and FINE testbeds also  
 450 contribute with a significant amount of observations and active sensors to the federation offering.  
 451 Testbeds, such as CABIN and NITOS, characterized under Smart Building accounts for the sensors  
 452 that are deployment at indoor environments measuring environmental conditions at the different  
 453 buildings at which some of the federated testbeds are deployed. Last but not least, Smart Agriculture  
 454 deployments (Tera4Agri) has a smaller but still relevant share of the available offering. Finally, there  
 455 are several sensors made available by various testbeds that can be catalogued under other application  
 456 domains (such as CrowdSensing - SoundCity, Smart Sea - MARINE, Testbed Management or  
 457 Wireless Network Status - Grasse Territory) as well and still can be discovered by a researcher and/or  
 458 innovator willing to experiment with them. More yet brief description about the testbeds is provided  
 459 in Section 4.3.

### Active sensors for Smart City application domains

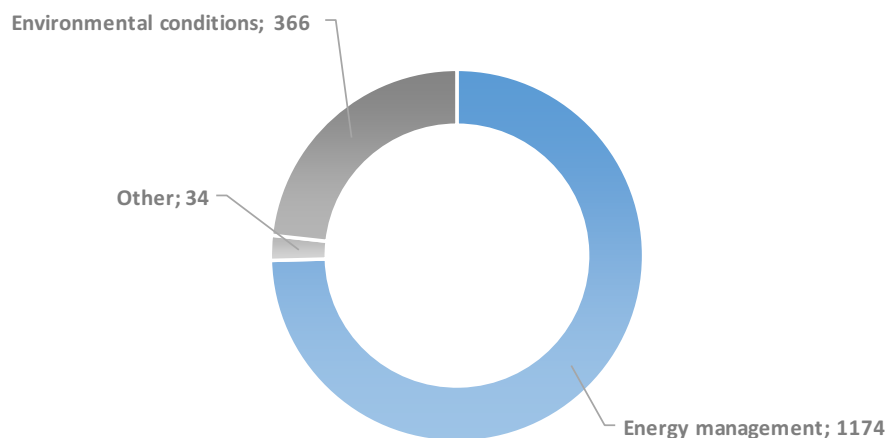


460

461 **Figure 7.** Distribution of active sensors per application sub-domain within the Smart City domain

462 Interestingly, for the Smart City domain, several sub-domains (cf. Figure 7) are covered by the  
 463 combined deployments. While SmartSantander deployment accounts for most of these active  
 464 sensors, there are other testbeds like FINE or SoundCity that contribute with several environment  
 465 monitoring sensors or CABIN that includes parking availability sensors, thus, enabling experiments  
 466 that can be transparently applied to different cities.

### Active sensors for Smart Building application domains



467

468 **Figure 8.** Distribution of active sensors per application sub-domain within the Smart Building domain



469 The other two large domains, in terms of available active sensors, are the Smart Energy and  
470 Smart Building. They can be combined into one since they are actually building energy management  
471 sensors the ones coming mainly from RealDC and ADREAM testbeds. For this combined domain,  
472 also some internal categorization can be made as presented in Figure 8. The other testbeds related to  
473 this category, like SmartICS, NITOS and CABIN contribute to the other big sub-domain, namely,  
474 building environmental conditions.

#### 475 4.3. Federated testbeds overview

476 One of the largest testbed within FIESTA-IoT federation is the SmartSantander testbed. It is an  
477 experimental test facility for the research and experimentation of architectures, key enabling  
478 technologies, services and applications for the IoT in the context of a city. The infrastructure made up  
479 of 12,000 deployed diverse IoT devices covers a wide area of the city of Santander, located in the  
480 north of Spain. This testbed goes beyond the experimental validation of novel IoT technologies. It  
481 also aims at supporting the assessment of the socio-economical acceptance of new IoT solutions and  
482 the quantification of service usability and performance with end users in the loop.

483 SmartICS focuses on the domain of smart buildings and is deployed in the Institute of  
484 Communication Systems at the University of Surrey. It provides a facility for IoT experimentation  
485 using a variety of sensor devices deployed within the building. These sensor devices are mainly  
486 installed on office desks in the building and are used to capture a number of quantity kinds relating  
487 to air quality, ambient environment, energy consumption and desk occupancy. Observations from  
488 the devices are reported to a proprietary testbed server every minute. The proprietary testbed server  
489 keeps a register of all reporting sensor devices, and a data repository for each sensor device.  
490 Experimenters can interact with the testbed through a proprietary RESTful API, whereby sensors are  
491 exposed as dereferenceable web resources.

492 SoundCity testbed leverages the Ambiciti<sup>6</sup> mobile application and the sensors within the  
493 smartphone to collect ambient noise measurements. On top of collecting such participatory data on  
494 a large scale, the Ambiciti mobile application provides its users with the ability to form groups and  
495 contribute to that specific group. The SoundCity testbed leverages such grouping feature and only  
496 federates data within the “FIESTA-IoT” group in the FIESTA-IoT platform.

497 CABIN (Context Aware smart BuildINg) is located on the KETI headquarter premises in  
498 Seongnam city, South Korea. This testbed is deployed using OCEAN<sup>3</sup> open source software that  
499 implement oneM2M IoT platform global standard. The main purpose for the deployed infrastructure  
500 is to study building energy optimization considering human behavior. In addition to the indoor  
501 sensors, parking sensors are also deployed outside the building. The benefit of having the CABIN  
502 testbed is to ensure oneM2M TPS replicability for future oneM2M and FIESTA-IoT enabled testbeds.

503 NITOS Future Internet Facility is an integrated facility with heterogeneous testbeds that focuses  
504 on supporting experimentation-based research in wired networks, wireless networks and IoT in  
505 general. NITOS is remotely accessible and open to the research community 24/7 and supports  
506 evaluation of protocols and applications under real world settings. The testbed is based on open-  
507 source software that allows the design and implementation of new algorithms, enabling new  
508 functionalities on the existing hardware. NITOS WSN testbed is part of the overall facility and offers  
509 several NITOS Wireless Sensor Motes developed in house by NITlab<sup>7</sup> and deployed in an office  
510 environment. NITOS WSN is a smart building testbed, capable of measuring environmental  
511 parameters with the purpose of providing the infrastructure upon which an experimenter can build  
512 own applications.

513 MARINE testbed has been deployed by GRIDNET<sup>4</sup> for testing the performance of own prototype  
514 communication hardware enabling IoT applications in the marine and city environments. Testbed  
515 nodes are equipped with a wide variety of heterogeneous communication technologies, ranging from

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<sup>6</sup> Ambiciti. <http://ambiciti.io> [Online 13<sup>th</sup> August 2018]

<sup>7</sup> NITLab. <https://nitlab.inf.uth.gr/> [Online 13<sup>th</sup> August 2018]

516 IoT related standards (ZigBee, LoRa) to the widely adopted Wi-Fi and LTE protocols, along with a  
 517 unique real-time power monitoring framework for monitoring consumption of wireless interfaces.  
 518 Moreover, the nodes feature a wide set of environmental sensors (17 different sensor types), suitable  
 519 for application scenarios such as monitoring of water and air quality and detection of potential  
 520 dangers for inhabitants of the area. The facility currently consists of 8 fixed air quality monitoring  
 521 stations deployed in the city of Volos, Greece and 4 floating seawater quality monitoring buoys  
 522 deployed in a bathing and recreation coastal area, close to the city.

523 RealDC provides live Data Centre environmental information into the FIESTA-IoT ecosystem.  
 524 This integration comes in the form of power consumption, cooling and ambient weather. The data is  
 525 captured at five-minute intervals.

526 Tera4agri Testbed comprises of data collected from the monitoring of environment, soil and  
 527 trees. Thereby enabling the implementation of innovative experiments in the agriculture domain. The  
 528 testbed is located in Minervino Murge (Italy) in the Tormaresca - "Bocca di Lupo" (one of Italy's top  
 529 wineries) estate. The testbed collects data from the sensors using the Tera s.r.l.'s Internet of Everything  
 530 Gateway.

531 FINE facility provides an experimental testbed that is able to support innovative IoT applications  
 532 in the smart city domain. It utilizes RERUM architecture [79] for enabling the interconnectivity of a  
 533 large number of heterogeneous IoT devices based on the concept of security, privacy and reliability  
 534 by design. The testbed comprises several indoor and outdoor deployments in the city of Heraklion  
 535 in Crete, Greece, operating on 6LoWPAN and LoRaWAN communication technologies to aid  
 536 applications such as environmental monitoring, comfort quality and energy management and smart  
 537 parking.

538 The Grasse Smart Territory Testbed is an experimental testbed for Smart City applications for  
 539 the urban, suburb and rural areas of the City of Grasse. The main purpose of the testbed is to provide  
 540 experimental digital facilities and applications to the citizens to make life greener and more efficient  
 541 using state-of-the-art IoT technologies, and to make public authorities' managers understand the way  
 542 IoT technologies can benefit to citizens. It is developed with the collaboration of the local authorities  
 543 and other local associations and companies. The privileges are given to the use of LoRa technology  
 544 for the connectivity of devices, which can significantly extend the battery life on the field devices.  
 545 Several environmental sensors, i.e. CO<sub>2</sub>, pollen, humidity, are being deployed and tested to be  
 546 connected to the testbed.

547 The ADREAM building is a living lab providing a horizontal platform to foster research projects,  
 548 either focused on one aspect of the building or cross-domain. The building is meant to have as little  
 549 energy footprint as possible and is thus equipped with a large range of sensors to analyze its energy  
 550 consumption, as well as its production based on solar panels.

## 551 5. Federation Process Discussion

552 Interoperability is at the core of many IoT applications [80]. That is what the FIESTA-IoT  
 553 platform, with its unified interface and vocabulary enabling access to testbeds data, adds value to  
 554 said data by improving its interoperability. However, the original value remains within the data  
 555 itself, collected by each testbed individually and unified by the platform. Therefore, the value is  
 556 created by the testbeds, and improved by the platform. This section of the paper aims at describing  
 557 the scientific and technical challenges met during the integration of the currently federated testbeds,  
 558 in order to pave the way for future testbeds and ease their integration.

559 The integration of a testbed within the platform is a well-defined process, constituted of a series  
 560 of steps [16]:

- 561 • The testbed's data model is aligned to the FIESTA-IoT taxonomy;
- 562 • The testbed provider develops an annotator to enrich the data, and a TPS to expose it;
- 563 • The compliance of the annotated data and of the TPS are examined, and the testbed is  
 564 certified;
- 565 • The testbed and its resources (sensors) are registered on the platform;
- 566 • The testbed provider configures the data collection process.



567 Data arriving to the FIESTA-IoT Platform from the testbeds has to be semantically annotated  
568 using the FIESTA-IoT Ontology. So, for the first step TPs can either develop the annotator themselves  
569 or use the AaaS API provided by the FIESTA-IoT platform. After successfully generating the testbed's  
570 annotator, the TP should decide on how the captured observations are going to be provided and  
571 develop the TPS accordingly. The two possibilities are to instruct FIESTA-IoT Platform to periodically  
572 poll the testbed for the observations generated or to directly push observations into the FIESTA-IoT  
573 Platform as they are generated. In order to facilitate the TP with the TPS development, FIESTA-IoT  
574 provides a skeleton component in Java<sup>8</sup> implementing all the services required by the FIESTA-IoT  
575 Platform. From this skeleton, the TP would only need to develop the testbed's internal data access  
576 and annotator integration. Once the TPS implementation is completed, the next step would be to  
577 validate the implemented TPS and annotator. The FIESTA-IoT Platform includes a Certification  
578 Portal that can be used by the TP to get FIESTA-IoT certified. Moreover, the tools available on this  
579 Certification Portal can help the TP in the previous two steps. The next step would be to register the  
580 available testbeds and resources to the FIESTA-IoT Platform. The TP can make use of the tools at the  
581 FIESTA-IoT Platform Portal UI for this process. Finally, the TP should instantiate and schedule the  
582 data pushing (testbed controls the scheduling) or retrieval (platform polls periodically).

583 In the remainder of this section, the challenges met at each step of this integration process are  
584 described, as well as the mitigation strategies that have been implemented to face them. Indeed,  
585 model alignment, data transformation or massive data publication are not trivial topics, present in  
586 many IoT deployments [81] beyond the FIESTA-IoT platform. The description of these challenges  
587 and their mitigations is followed by a discussion on the benefits for the TPs who joined the federation.

## 588 5.1. Technical Requirements Discussion

589 This section discusses the key lessons learnt and best practices that the experience of integrating  
590 the previously described testbeds within the FIESTA-IoT Platform has allowed us to extract.

### 591 5.1.1 Preparing the integration

592 The testbeds are completely independent of each other, and the architectures they deploy are  
593 highly heterogeneous. The purpose of the integration process described in this section is to lead these  
594 initially unrelated data providers into compliance with the FIESTA-IoT platform interface, so that the  
595 produced data is seamlessly consumable by the experimenters. At the end of the process, the testbed  
596 is certified and is integrated into the federation.

#### 597 5.1.1.1 Data model alignment

598 The data within FIESTA-IoT platform is annotated with a single vocabulary, described using  
599 M3-lite taxonomy [66]. Initially, as there is no constraint whatsoever on the testbeds internals, the  
600 data model used by the testbeds are very diverse, and range from relational databases to datasets  
601 semantically annotated with an ad-hoc vocabulary. The first step to providing interoperability over  
602 the testbed data is to align its idiosyncratic data model to the common vocabulary.

603 Challenges and mitigation: One of the challenges met at this point in the federation is that some  
604 subjective modelling choices do not allow a straightforward one to one equivalence mapping  
605 between a testbed model and the target vocabulary (especially when a testbed has its own  
606 vocabulary). Some elements implicit on the testbed side had to be made explicit to be compliant with  
607 the platform, and knowledge that was stored in a several separate knowledge bases had to be  
608 gathered in a single repository. As one of the mitigation strategies, FIESTA-IoT platform provides a  
609 dedicated workflow for testbeds to propose updates to the vocabulary with the needed concepts.

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<sup>8</sup> Java Software Development Kit: <http://www.oracle.com/technetwork/java/index.html> [Online 13<sup>th</sup> August 2018]

610 Specific technical details: As it has been already described, the FIESTA-IoT ontology has been  
611 designed for the basic modelling of any IoT system. This has been proven correct since all the 11  
612 testbeds were able to accommodate to this basic modelling. However, while the core of the ontology  
613 has remained stable, the addition of testbeds to the federation has resulted in extensions to the  
614 ontology in terms of *QuantityKind* and *Unit*. These two classes are the parent classes used for  
615 describing the physical phenomenon observed and the unit of measurement used respectively. These  
616 classes are key both for describing the sensors and actuators that conform an IoT deployment as well  
617 as the observations that they generate. In this sense, while the core ontology uses the parent classes  
618 (i.e. *QuantityKind* and *Unit*), any sub-class from them can be used for describing IoT devices and  
619 observations. The workflow used to progressively update the FIESTA-IoT ontology basically  
620 consisted in requesting the TPs to make an initial study of the FIESTA-IoT ontology and only if none  
621 of the already existing sub-classes of *QuantityKind* and *Unit* met some of their needs, this is, one of  
622 their IoT devices observes a physical phenomenon not yet covered, they could make an argued  
623 request for addition. The requests for additions coming from the TPs were subsequently analyzed by  
624 the FIESTA-IoT ontology maintainers and incorporated if they were necessary. This process was  
625 straightforward in most of the cases. Only some iterations were necessary when the arguments  
626 incorporated to the request for addition were not clear enough. Most of the times the TPs seamlessly  
627 found the appropriate *QuantityKind* and *Unit* sub-classes that their testbeds needed.

#### 628 5.1.1.2 Building a resource description

629 The FIESTA-IoT platform hosts the description of the devices that are associated to a testbed.  
630 Once the data model is aligned it is essential that resources are described in the needed format and  
631 are registered to the FIESTA-IoT platform. The FIESTA-IoT platform provides a tool to generate said  
632 descriptions in compliance with the vocabulary with a capability to register one device at a time or  
633 perform bulk upload if the annotations are already available.

634 Challenges and mitigation: As said in the previous section, testbeds that use semantics internally  
635 to store data have to comply with the unified FIESTA-IoT model. The generation of such mapping  
636 could be time consuming effort. For testbeds that already have a semantic description of their devices,  
637 the approach proposed by [82] allows the translation of the source description into the target using  
638 the alignment between data models. Moreover, for testbeds that do not have semantic descriptions  
639 at hand, using AaaS tool, a testbed can generate annotation of the resource description and can use  
640 them to register the resources. The services therein have capability to provide annotated descriptions  
641 to both resources and observations based on information that is provided to it post the data model  
642 alignment phase. On top of AaaS tool, FIESTA-IoT also provides best practices that a testbed should  
643 follow while producing annotations to harmonize and ease out building annotations.

644 Specific technical details: The AaaS tool leverages the baseline structure of the FIESTA-IoT  
645 ontology and the design criteria followed during its definition. In this sense, for generating the  
646 annotated version of their IoT devices, the TPs could directly take the FIESTA-IoT ontology and the  
647 examples provided in the handbook<sup>9</sup> provided as training material, which provides best practices  
648 for producing valid annotations. However, it is highly recommended to make use of the AaaS tool.  
649 Not only because, it eases the process but also because it guarantees validity and certification of the  
650 testbed. In terms of IoT devices descriptions, the AaaS tool followed the cardinality included into the  
651 FIESTA-IoT ontology and defined through a JSON schema the mandatory attributes that must be  
652 included by the TPs for requesting the annotated description of one of their sensors. Basically, it  
653 requested a valid unique identifier, and its sensing and/or actuating capabilities. This latter aspect  
654 included the type of sensor and the physical phenomenon observed (or actuated upon). TPs were  
655 asked to provide the corresponding *SensingDevice*, *QuantityKind* and *Unit* sub-class from the FIESTA-  
656 IoT ontology. Additionally, the TPs had to include their testbed unique identifier in order to

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<sup>9</sup> FIESTA-IoT Handbook. <http://moodle.fiesta->

[iot.eu/pluginfile.php/711/mod\\_resource/content/6/FIESTA-IoT\\_Handbook4ThirdParties\\_v4.3.pdf](http://moodle.fiesta-iot.eu/pluginfile.php/711/mod_resource/content/6/FIESTA-IoT_Handbook4ThirdParties_v4.3.pdf)

657 internally link their devices to their testbeds. Apart from the mandatory fields, the TPs could enrich  
658 the descriptions of their devices with additional optional attributes. For example, the device location,  
659 which was not mandatory to support mobile devices, or some metadata about the device sensing  
660 capacities (e.g. its accuracy, frequency, etc.). The AaaS tool compiled the information provided by the  
661 TP through a JSON document, posted to the RESTful AaaS' API, and generated the corresponding  
662 RDF document. The AaaS allowed to generate the description of many devices at once.

#### 663 5.1.1.3 Annotating observation data

664 Providing a unified access to resource observations requires said observations to be annotated  
665 with the common vocabulary. This annotation can either be performed by the testbed if it has  
666 semantic capabilities, or by the FIESTA-IoT platform using the AaaS tool mentioned in the previous  
667 section.

668 Challenges and mitigation: As stated before, within FIESTA-IoT, there are different testbeds that  
669 are associated with different application domains of IoT. Some testbeds such as SoundCity, SmartICS,  
670 and ADREAM face privacy challenges when it comes to publishing data to open platforms such as  
671 FIESTA-IoT. In order to publish data, such testbeds have to first get consent of users before the user  
672 specific data can be published. Further, testbeds have to anonymize the data so that there is enough  
673 noise when correlation of the published data sample to a particular user is performed. Privacy also  
674 pose challenge when data attributes are not reported due to privacy concerns. This make it hard for  
675 testbeds to comply with the FIESTA-IoT ontology causing annotations to fail the validation step. To  
676 mitigate this problem, testbeds should set default value for the data attributes that are not reported.

677 Specific technical details: Similarly to the case of annotating the description of the testbed  
678 resources, the AaaS tool offered the possibility to produce valid RDF documents for the observations  
679 generated by that IoT devices. In this case, the mandatory fields, according to the concept's  
680 cardinality defined by the FIESTA-IoT ontology, were, apart from the observation value, the  
681 observation location, its timestamp, the identifier of the sensor that produced it and the physical  
682 phenomenon observed, together with the unit of measurement. As it happened with the device  
683 descriptions, these mandatory fields were available for all the testbeds so the integration was  
684 seamless. It is important to highlight that this is only possible because of the appropriate design of  
685 the FIESTA-IoT ontology, which has demonstrated its flexibility and scalability to accommodate the  
686 integration of the eleven testbeds.

687 While the use of the AaaS for the generation of annotated resource descriptions is a process that  
688 would not be so frequent (only at the initial testbed integration and when new IoT devices are  
689 deployed at the testbed), its use for generating valid RDF-formatted observations had important  
690 delay restrictions. The frequency with which a testbed produces an observation can be really big.  
691 Thus, the AaaS should not increase the processing time too much. The implementation of the AaaS  
692 kept the annotated observation generation time in the range of some milliseconds.

#### 693 5.1.1.4 Implementing the TPS

694 The platform endpoint is publicly known, but each testbed has its own domain name and public  
695 interfaces. To make it possible for the platform to collect data from the multiple testbeds, each testbed  
696 has to implement on of the services from its TPS. From an architectural standpoint, the TPS is an  
697 interworking proxy, hiding the internal specificities of each testbed under a common interface. Using  
698 the TPS, the FIESTA-IoT platform is able to either actively collect data (pull-based approach) or to  
699 subscribe for push-based publication initiated by the testbed. Implementing the former or the latter  
700 is up to the testbed provider, depending on which is more convenient considering its own workflow.

701 Challenges and mitigation: In order to enable communication between the testbed and the  
702 platform, access credentials have to be provided and right HTTP certificates have to be set. While  
703 different identification methods are supported by the FIESTA-IoT Platform, the integrated testbeds  
704 only used two of them: API Key over HTTPS connection and IP filtering. Indeed, only the first one  
705 impose some requirements on FIESTA-IoT Platform while the second is transparently handled at the

706 testbed side. Being able to identify the issuer of a request to the testbed is a security issue, as it  
707 prevents malicious requests to be processed.

708 Specific technical details: After successfully generating the testbed's annotator the TPs had to  
709 functionally integrate the two domains at hand, this is, their testbeds and the FIESTA-IoT Platform.  
710 For this functional integration, the TPI specification considers the main functionalities and properties  
711 that should be exposed by IoT testbeds in order to enable their integration within the EaaS Platform  
712 for the purposes of testbed-agnostic experimentation. The TPI spans across two different realms. On  
713 the one side, the testbed side, the TPS API have to expose a set of services that enables the  
714 management and manipulation of the offered data. At the other side, the FIESTA-IoT Platform side,  
715 the behavior of the TPS methods is controlled from a set of services so-called TPI Data Management  
716 Services (DMS). They enable the TPs to consume and control the TPS services that their testbeds  
717 expose either by identifying a specific schedule or by enabling a data stream connection. The TPs  
718 should decide on how the captured observations are going to be provided, this means if the "Get" or  
719 the "Push" methodology is going to be used, and develop the TPS accordingly. In order to facilitate  
720 the TP with the TPS development a skeleton component implementing all the required services has  
721 been provided. This skeleton only requires the testbed's internal data access and annotator  
722 integration.

#### 723 5.1.1.5 Obtaining a certification

724 At this point, all the functionalities required for the testbed to be integrated to the federation are  
725 implemented. To validate this implementation, the testbed must go through a certification process  
726 available on the platform where the compliance of both resources and observations description are  
727 evaluated along with the conformance of the TPS behavior with the specification.

728 Challenges and mitigation: Generally this step was not imposing any challenge in the process.  
729 Indeed, as TPs are able to access the tools available on the Certification Portal<sup>10</sup> as many times as  
730 necessary, these tools were used for the tuning and polishing of their annotators and TPS  
731 implementations. The key aspect that was necessary to highlight to the TPs was precisely that they  
732 should use the certification process for their benefit instead of thinking that it is a hurdle to be  
733 overcome.

734 Specific technical details: Before the TPs are provided with credentials to register their testbeds  
735 at the FIESTA-IoT Platform, they have to obtain a certificate that the previous steps have been  
736 accomplished correctly. The Certification Portal basically offers a set of tools for validating the  
737 annotations and the TPS interfaces that the underlying testbed is offering. It is important to highlight  
738 that it is recommended, as a best practice for the TPs, to exploit the tools available at the Certification  
739 Portal during the development of their TPS interfaces and annotators and not restrict its use to the  
740 pure certification. In this sense, TPs have an unlimited number of attempts at the Certification Portal  
741 and it provides assessment reports on each attempt. Thus, the TPs are able to progressively fine tune  
742 the annotations and TPS implementation according to the reports obtained.

743 For the validation of the annotators, the Certification Portal provided a generic semantic  
744 validator that assessed both the syntactic (i.e. literals, URI and namespaces validation) and semantic  
745 (i.e. predicate and class validation and semantic errors) analysis of the RDF documents provided.

746 For the TPS validation, the Portal had an interoperability testing tool which included tests for all  
747 the possible TPS interfaces. TPs can provide the details of their TPS (endpoints, sensor identifiers,  
748 API Key, etc.) and check if they behave as the FIESTA-IoT Platform expects.

#### 749 5.1.2 Integrating the testbed

750 Once the testbed is certified, it is now ready to be integrated to the FIESTA-IoT platform.

751 As it has been described before, the testbed integration process consists on a number of steps  
752 which requires actual interaction with FIESTA-IoT Platform interfaces. All the steps have been

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<sup>10</sup> FIESTA-IoT Certification Portal. <https://certificate.fiesta-iot.eu>

753 streamlined to make then user-friendly. However, there are still best practices and lessons to be learnt  
754 that can only be acquired through actually taking the aforementioned steps. In this sense, all the steps  
755 have been briefly introduced at the beginning of this section and for each of them there is a specific  
756 aspect that, from the experience that we have acquired, must be carefully addressed. Thus, during  
757 the registration of testbed and devices, which is made through a graphical user interface, the testbed  
758 provider must take care of the correct alignment of testbed and resources description as the linked  
759 data paradigm is used within the FIESTA-IoT Platform and consistent information is critical in order  
760 to exploit the potential of this paradigm. For the configuration of the TPS, even when functional  
761 interoperability of interfaces had been previously certified, finding the most suited schedule is not  
762 always straightforward. Finally, confirming that the integration has been properly carried out and it  
763 is properly maintained in time (testbed integration is a continuous process) requires the execution of  
764 a number of tests that qualify this integration.

765 Challenges and mitigation: In order to allow the testbed providers to try out their deployment  
766 and fix issues incrementally, the FIESTA-IoT platform provides a controlled test environment. The  
767 challenges described in this section were tackled within the test environment, and had no impact on  
768 the experimenters, who interact with the actual production environment where the testbeds are only  
769 deployed when stable. The entire integration process is first performed in this test environment  
770 before being made public.

#### 771 5.1.2.1 Registering the testbed and its resources

772 The first step to the testbed deployment is its registration, where some information about the  
773 testbed as a whole are provided, and in particular the endpoint of its TPS. Once the testbed is  
774 declared, its resources can be registered as it is described above. At this point, the resources of the  
775 testbed can be discovered by the experimenters, but no observation data has still been published.

776 Challenges and mitigation: Creating the annotated descriptions of the testbed devices can be a  
777 tough and complicated task mostly for providers that have little or no expertise with semantics and  
778 its peculiarities. Moreover, some of the testbeds had a large number of devices which could make  
779 this process time-consuming. The AaaS tool that was provided to the testbeds transforms this  
780 potentially complex step into a more user-friendly process in which testbed providers simply creates  
781 plain JSON documents from a simple template and through a single API call they can generate the  
782 descriptions from all the resources in their testbeds.

#### 783 5.1.2.2 Configuring the TPS

784 The platform implements a tool to configure its behavior regarding the TPS. If the data is pushed  
785 by the TPS, the platform declares the resources it is interested in, and the TPS pushes data observed  
786 by these sensors as soon as it is available. Otherwise, the platform collects data from the platform at  
787 fixed intervals.

788 Challenges and mitigation: While configuring the TPS one challenge that occurs is that not all  
789 resources can be scheduled at a single time. This usually happens when a testbed has thousands of  
790 resources. To schedule all the resources it is advised that resources should be grouped in different  
791 chunks where each chunk has a different schedule to reduce the load of each individual push.  
792 Another issue is the impossibility to edit a schedule once it is registered. This makes it tedious for  
793 large testbed if some resources are not reliable, and require to be removed from the platform schedule  
794 individually.

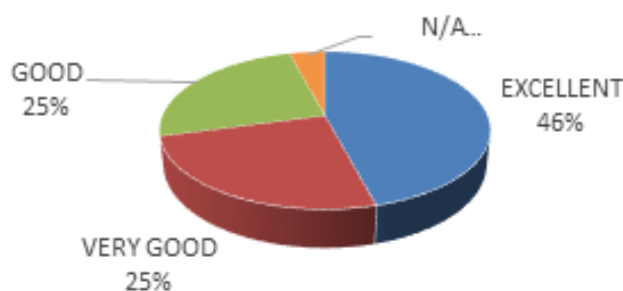
#### 795 5.1.3 Running the TPS and publishing data to the platform

796 At this point in the integration process, the testbed is compliant in every aspects with the  
797 FIESTA-IoT specification, and the data it generates can be consumed by the experimenters. The  
798 FIESTA-IoT platform acts as a data broker: there is no direct communication between the data  
799 producers and consumers, they only communicate with the platform through standardized  
800 interfaces.

801 Challenges and mitigation: Some challenges are faced when the TPS is running, especially in the  
 802 virtual environment. One of the issues is the size of the bulk loads: the data that is transferred via  
 803 TPS to the platform as RDF/XML. This data can be quite verbose leading to documents that are  
 804 sometimes too large to be reliably transferred over the network. In order to keep the platform side as  
 805 generic as possible, the mitigation strategies for this issue have to be implemented by the testbeds. In  
 806 order to limit overload, the publications of data to the platform must be paced, and a 5-seconds break  
 807 between the pushes ensures that the pushed data has been completely processed before publishing  
 808 new data. Moreover, the datasets can be split into smaller subsets before being pushed to the  
 809 platform. Once integrated to the knowledge graph on the platform's side, this bursting at publication  
 810 type has not impact on the experimentations. Another issue is the lack of synchronism between the  
 811 data collection and publication: depending on the testbeds inner configuration, data can only be  
 812 published sometime after having been collected. This interval can be of several hours, up to days.

#### 813 5.1.4 Technical integration concluding remarks

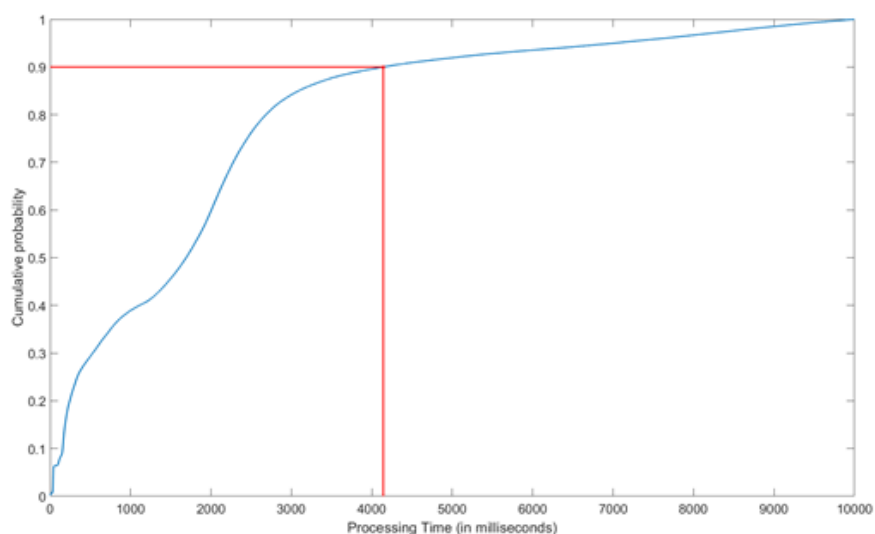
814 The evaluation of the testbed integration process was twofold. On the one hand, it was based on  
 815 feedback provided by the Testbed Providers. The feedback focused on the assessment of the  
 816 requirements, and the effort to address them, (like annotation process, certification of their testbeds,  
 817 and interfaces implementation) in order to complete the testbed integration. As it is shown in Figure  
 818 9, most of them agreed that the ease of deployment was above satisfactory and they did not  
 819 experience any significant degradation in terms of performance within their testbeds. This was  
 820 expected as the integration process, as it has been presented above does not alter any of the internal  
 821 procedures of the testbeds.



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823 **Figure 9.** Evaluation of the testbed integration. Assessment of ease of setting up and deployment

824 On the other hand, a non-functional evaluation was carried out focusing on the response times  
 825 that the platform offered to the underlying testbeds upon they sent their observations for its storage  
 826 into the FIESTA-IoT Platform.

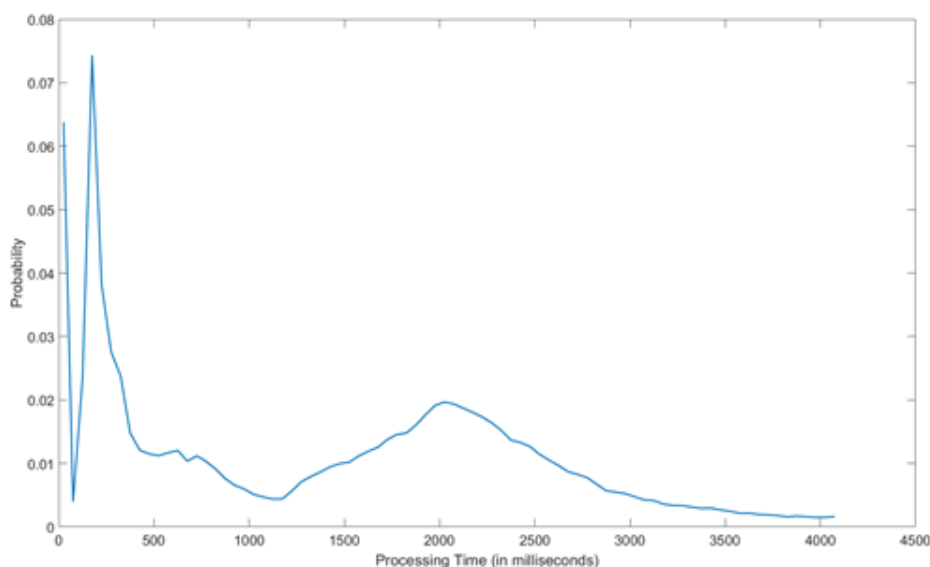


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**Figure 10.** Cumulative Distribution Function of processing times for observations' writings

829 Figure 10 and Figure 11 shows the results from the performance analysis made. As it can be seen,  
 830 90% of the queries are handled in less than 4.1 seconds while the amount of queries taking more than  
 831 8 seconds is negligible. Moreover, it is interesting to highlight that more than half of the queries were  
 832 responded in less than 2 seconds. In that sense, we can notice that the distribution is not completely  
 833 exponential, and most probable processing times are around 10, 200 and 2000 milliseconds. In this  
 834 respect it is important to remind that testbeds were asked not to push individual observations but to  
 835 digest a number of them into each query. The amount of observations per query were dependent on  
 836 the size of the testbed and the nature of the observations. In this sense, smaller testbeds typically  
 837 digested all its observations (up to a couple of tens of them) in each query, while larger ones used a  
 838 digest size of 100 observations per query. Thus, the response times show this heterogeneity as it can  
 839 be clearly seen in Figure 11. However, even in the case of this larger batches of observations the  
 840 response time of the system was rather good. Note that in its semantic representation every  
 841 observation is composed of 7 objects.



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**Figure 11.** Probability Density Function of processing times for observations' writings

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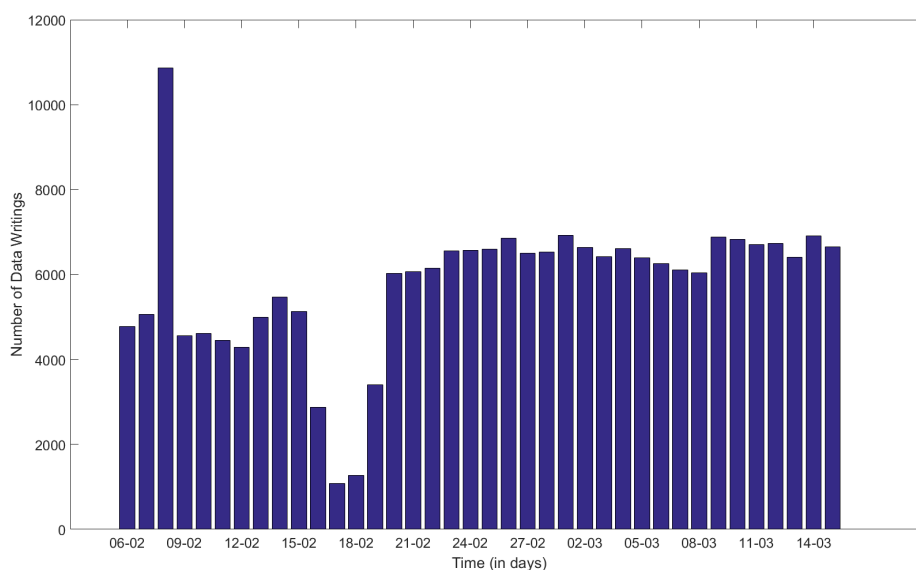
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It is important to highlight that these results have been obtained under heavy load in terms of the demand that the system was experiencing. As it is presented in [16], the performance evaluation was carried out between 6<sup>th</sup> February 2018 and 15<sup>th</sup> March 2018. At that time, the amount of queries that the FIESTA-IoT platform received each day was, in average, around 13,000 queries per day, which is equivalent to 9 queries per minute. The FIESTA-IoT platform was not only storing the observations coming from the 11 testbeds but also serving the experimenters' demands at the same time. From the total amount of queries, Figure 12 presents the number of data writings (i.e. the amount of queries for storing observations) coming from the underlying testbeds.



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**Figure 12.** Observations' writings per day during the analyzed period

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As it can be seen, there were a massive and continuous flow of observations coming from the 11 testbeds towards the FIESTA-IoT Platform.

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### 5.2. Federation Exploitation Discussion

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The FIESTA-IoT federation has been currently joined by eleven heterogeneous IoT facilities spanning a wide range of application domains. In this section, we discuss the motivation behind joining the testbed federation, both for the testbeds and the affiliated organizations.

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The key offering of FIESTA-IoT platform is a common set of Testbed tools and APIs enabling collection of data from any of the federated testbeds. The unified approach of instrumenting experiments and collecting data through a single point of access and set of tools offers unique ease of experimentation over the wide variety of supported testbeds. Developers who want to use existing platforms need to negotiate access individually and adapt to the platform-specific API and information models. Having to perform these actions for each platform often limits the applicability of the developed applications as they have to be tailored to the different platforms. This fragmentation of the IoT and the missing interoperability result in high entry barriers for developers. Considering the complex case of experimenters interested in simultaneously accessing data stemming from multiple testbeds, we understand the advantage of employing the federation that inherently supports such scenarios, through the orchestration of a single experimental description.

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The federation driven ease of use and ability to offer open data access generate direct advantages for connected testbeds, such as the expanded user base and platform visibility. In addition, the accumulated access of external users through the common platform portal has the potential to introduce users to new interesting testbeds and resources and further increase the individual testbed community. The federation also attracts totally new types of users that are not directly interested in the underlying facilities, but specifically in the applied semantic technologies, potentially searching for semantic interoperability with their data or application. The increased platform visibility offers also the potential for creating synergies between academic experimenters and industrial developers.

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At the heart of the federation-enabling mechanisms lies the common semantic ontology, which serves as means for linking related data streams and ensuring interoperability of data stemming from totally heterogeneous resources. The federation includes testbeds like CABIN and ADREAM that had previously incorporated semantic technologies in their platform operation, which had to work towards aligning their existing taxonomy and vocabulary with the FIESTA-IoT ontology. On the other hand, facilities like MARINE and RealDC had their first experience in implementing common standardized semantics, by joining the federation. Such developments directly benefited the testbeds adopting semantic technologies to query their resources more effectively and layer sophisticated



887 analytics on top of collected data. In addition, the adoption of M3-Lite taxonomy by the FIESTA-IoT  
888 ontology has offered semantic interoperability with other testbeds too. Summing up, we remark that  
889 all federated testbeds gained significant experience in working with semantically annotated data and  
890 applying semantic technologies in-field, which can be beneficial for future projects as well.

891 Moreover, there are also other important benefits that must not be neglected. Firstly, the great  
892 dissemination opportunities, stemming from the overall project's promotion and marketing  
893 activities, which offer increased visibility to all federated testbeds and affiliated organizations.  
894 Secondly, the ability of all participating members to directly strengthen their position in the IoT and  
895 testbed experimentation communities, resulting in increased qualification for attracting additional  
896 funding through relevant research initiatives (EU research calls, etc.) or through potential  
897 organizations interested in using the testbed resources and offered measurements.

898 Last but not least, FIESTA-IoT Platform has proven successful in realizing the open data concept  
899 that FIESTA-IoT/EU is supporting in order to democratize the access to data. Not just in the sense of  
900 simply opening the data but increasing the meaningfulness of this data as the datasets are upgraded  
901 through the interoperability feature that the FIESTA-IoT Platform Error! Bookmark not defined. design and  
902 implementation intrinsically conveys.

## 903 6. Conclusions

904 Supporting real-world experimentation is undoubtedly part of the innovation cycle for any  
905 technological advance. In view of the attention that the IoT is attracting, several IoT open  
906 infrastructures have been deployed all around the world. Even if the usefulness of these experimental  
907 infrastructures in their own right is out of any doubt, the ecosystem that they have created is scattered  
908 and domain specific. It is deemed necessary to offer a homogeneous and interoperable framework  
909 that can actually fulfil the requirements from IoT research and innovation communities. These  
910 communities are in need of an IoT data marketplace that can serve them with cross-domain,  
911 interoperable, real-world data and environments.

912 In this paper, we have described the instantiation of such an environment stemming through  
913 the federation of eleven different IoT deployments. The resulting environment offers, to the best of  
914 our knowledge, the highest level of diversity and scale available through any single or federated IoT  
915 experimentation infrastructure, integrating totally heterogeneous application domains (e.g. smart  
916 cities, maritime, smart building, crowd-sensing, smart grid, etc.) and offering over 10,000 IoT devices.  
917 The paper briefly introduces, for the sake of completeness, the high-level architecture and key  
918 technologies employed for the realization of this unique federation of heterogeneous IoT  
919 infrastructures. In addition, the key paper contribution is presented through the analysis of the  
920 insightful summary of the actual data offerings and key characteristics of all the testbeds that are  
921 currently federated. For the community of IoT-based innovators and developers it is of utmost  
922 importance to be acquainted with the real offerings stemming from the unparalleled ecosystem for  
923 IoT experimentation that the interoperable federation of testbeds described in the paper is making  
924 available [83].

925 Moreover, the paper summarizes first hand experiences, lessons learnt and best practices that  
926 have been elicited during the integration of the testbeds. The description of the challenges faced  
927 during the integration process and their mitigations is followed by a discussion on the benefits for  
928 the TPs who joined the federation. The discussion included in the paper condenses the views of the  
929 different testbed providers and, apart from describing the techniques employed to fulfil the technical  
930 challenges associated with the federation of heterogeneous IoT platforms, it should be extremely  
931 valuable for other infrastructure owners that might consider joining the current federation of  
932 testbeds.

933 In order to highlight the value of the contributions of this paper, it is important to mention that  
934 the platform design represents the necessary condition for supporting IoT experimentation, as it  
935 enables the dynamic discovery of resources and their data. However, it is only through the actual  
936 federation of testbeds described in the paper that the sufficient condition is met. Thus, we remark the  
937 significant value of our work for the IoT research community, since it is essentially the federation of

938 testbeds the one that tangibly (i.e. not as an academic exercise but in the real-world) enables the  
 939 dynamic on-demand formulation of cloud-based IoT services over a virtualized Data Marketplace.

940 The contributions of the paper are the description of the resulting federation of testbeds and the  
 941 lessons learnt during the process of federating one testbed. Details of the actual platform and insights  
 942 about the technical details about the platform that supports the federation are out of the scope of the  
 943 paper. However, the semantically-enabled multi-domain data marketplace can be accessed on-line.  
 944 In this sense, the testbed federation itself is, implicitly, the proof for the realization of this concept.  
 945 Through the tools available from the FIESTA-IoT Platform<sup>2</sup>, the experimenters can discover and  
 946 access the whole variety of datasets and develop their research or innovative applications. The  
 947 experimenters are able to discover the offerings from the data marketplace independently of the  
 948 origin of the data. They only have to follow the FIESTA-IoT ontology while browsing and consuming  
 949 the data that the underlying testbeds have previously pushed.

950 Future lines of development will include the development of cross-domain data analytics.  
 951 Having the ability to apply data mining or machine learning techniques on top of the federation  
 952 presented in this paper will have a twofold benefit. On the one hand, analytics developers benefit  
 953 from the homogeneous access to heterogeneous datasets, thus, maximizing the re-utilization of the  
 954 developed algorithms and minimizing the burden of having access to information that nowadays are  
 955 part of different vertical. On the other hand, re-use of the techniques and services (like dashboards,  
 956 KPIs derivation) developed for any of the testbeds federated boosts the attractiveness of the  
 957 federation itself. In particular, data quality and infrastructure performance insights should be of great  
 958 interest to IoT infrastructure providers who, in the majority of the cases, are experts in managing the  
 959 physical infrastructure but does not have the know-how to effectively manage and curate the data  
 960 that the infrastructure is producing and, more important, their customers consuming.

961

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 967 Work and Overall Federation Summary and Data Marketplace Offering sections. J. Lanza described and  
 968 integrated the SmartSantander testbed; J.R. Santana performed the performance analysis of the testbed  
 969 federation; R. Agarwal and P. G. Raverdy contributed with the description and integration of SoundCity testbed;  
 970 correspondingly T. Elsaleh and Y. Fathy provide input related to the SmartICS testbed; S. Jeong described  
 971 CABIN testbed; A. Dadoukis and T. Korakis provided the content related to NITOS testbed; S. Keranidis lead  
 972 the edition and contributions to section 5.2 in addition to the integration and description of MARINE testbed; P.  
 973 O'Brien and J. Horgan contributed with the RealDC testbed sketch; A. Sacchetti and G. Mastandrea worked on  
 974 the integration of Tera4Agri testbed; A. Fragkiadakis and P. Charalampidis integrated and described FINE  
 975 testbed; N. Seydoux lead the edition and contributions to section 5.1 in addition to the description and  
 976 integration of ADREAM testbed, which was also carried out by C. Ecrepont; Finally, M. Zhao authored the  
 977 content related to the Grasse Smart Territory testbed. J. Lanza, L. Sanchez, R. Agarwal, T. Elsaleh and M. Zhao  
 978 have lead the design, implementation and integration of many components of the FIESTA-IoT Platform which  
 979 underlies the testbed integration described in this paper.

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Table 3. FIESTA-IoT testbeds detailed offering

Testbed	Phenomenon	FIESTA-IoT Quantiy Kind	Avg. number of active sensors	Avg. number of observation per hour (aprox.)
SmartSantander	Parking Availability	m3-lite#PresenceStateParking	150	n/a
	Air Temperature	m3-lite#AirTemperature	144	12
	Air Dust	m3-lite#ChemicalAgentAtmosphericConcentrationAirParticles	74	50
	CO	m3-lite#ChemicalAgentAtmosphericConcentrationCO	74	50
	NO <sub>2</sub>	m3-lite#ChemicalAgentAtmosphericConcentrationNO2	74	50
	O <sub>3</sub>	m3-lite#ChemicalAgentAtmosphericConcentrationO3	74	50
	Relative Humidity	m3-lite#RelativeHumidity	17	12
	Noise	m3-lite#SoundPressureLevelAmbient	11	12
	2.4 GHz Electromagnetic Field	m3-lite#ElectricField2400MHz	10	12
	2.1 GHz Electromagnetic Field	m3-lite#ElectricField2100MHz	10	12
	1.8 GHz Electromagnetic Field	m3-lite#ElectricField1800MHz	10	12
	900 MHz Electromagnetic Field	m3-lite#ElectricField900MHz	10	12
	Soil Humidity	m3-lite#SoilMoistureTension	8	12
	Soil Temperature	m3-lite#SoilTemperature	8	12
	People Count	m3-lite#CountPeople	7	6
	Waste Bin Fill Level	m3-lite#FillLevelWasteContainer	4	6
	Atmospheric Pressure	m3-lite#AtmosphericPressure	1	12
	Solar Radiation	m3-lite#SolarRadiation	1	12
	Wind Speed	m3-lite# WindSpeed	1	12
Wind Direction	m3-lite# WindDirection	1	12	
SmartICS	Building Temperature	m3-lite#Temperature and m3-lite#RoomTemperature	104	6
	Relative Humidity	m3-lite#Humidity	104	6



	Noise	m3-lite#Sound	103	6
	Illuminance	m3-lite#Illuminance	103	6
	People Presence	m3-lite#Distance	98	6
	Active Power Consumption	m3-lite#Power	29	6
<i>SoundCity</i>	Noise	m3-lite#Sound	4	n/a
	Direction Heading	m3-lite#DirectionHeading	4	n/a
	Presence	m3-lite#Proximity	4	n/a
	Average Speed	m3-lite#SpeedAverage	4	n/a
<i>CABIN</i>	People Presence	m3-lite#PresenceStatePeople	49	n/a
	Building Temperature	m3-lite#BuildingTemperature	41	6
	Relative Humidity	m3-lite#RelativeHumidity	41	6
	Illuminance	m3-lite#Illuminance	39	6
	Parking Availability	m3-lite#PresenceStateParking	19	n/a
	CO <sub>2</sub>	m3-lite#CO2	10	6
	Active Power Consumption	m3-lite#Power	9	6
<i>NITOS</i>	People Presence	m3-lite#PresenceStatePeople	4	3
	Building Temperature	m3-lite#AirTemperature	3	3
	Relative Humidity	m3-lite#Humidity	3	3
	Illuminance	m3-lite#WeatherLuminosity	3	3
	Noise	m3-lite#SoundPressureLevel	2	3
	Door Status	m3-lite#DoorStatus	2	3
	Radiation	m3-lite#IonisingRadiation	1	3
<i>MARINE</i>	Sea Water PH	m3-lite#PH	3	4
	Sea Water Temperature	m3-lite#WaterTemperature	3	4
	Sea Water Conductivity	m3-lite#Conductivity	2	4
	Sea Water Oxidation Reduction	m3-lite#Voltage	2	4
	Atmospheric Pressure	m3-lite#AtmosphericPressure	2	6
	Air Temperature	m3-lite#AirTemperature	2	6

	Relative Humidity	m3-lite#Humidity	2	6
	Water NO <sub>3</sub> Ion	m3-lite#ChemicalAgentWaterConcentrationNO3Ion	1	4
	IEEE 802.15.4 Signal Level	m3-lite#Power	1	6
	IEEE 802.11 Signal Level	m3-lite#Power	1	6
	LoRa Device RSSI	m3-lite#Power	1	6
<i>RealDC</i>	Electric Voltage	m3-lite#Voltage	486	4
	Electric Current	m3-lite#ElectricCurrent	243	4
	Active Power Consumption	m3-lite#ActivePower	81	4
	Reactive Power	m3-lite#ReactivePower	81	4
	Electric Frequency	m3-lite#Frequency	81	4
	Air Temperature	m3-lite#AirTemperature	33	3
	Cooling Water Temperature	m3-lite#WaterTemperature	32	3
	Atmospheric Pressure	m3-lite#AtmosphericPressure	1	4
	Dew Point	m3-lite#DewPointTemperature	1	4
	Relative Humidity	m3-lite#RelativeHumidity	1	4
	Rainfall	m3-lite#Rainfall	1	4
	Wind Chill	m3-lite#WindChill	1	4
	Wind Speed	m3-lite# WindSpeed	1	4
	Wind Direction	m3-lite# WindDirection	1	4
<i>Tera4Agri</i>	Soil Humidity	m3-lite#SoilHumidity	9	2
	Soil Temperature	m3-lite#SoilTemperature	1	2
	Air Temperature	m3-lite#AirTemperature	1	2
	Dew Point	m3-lite#DewPoint	1	2
	Leaf Wetness	m3-lite#LeafWetness	1	2
	Rainfall	m3-lite#Precipitation	1	2
	Relative Humidity	m3-lite#RelativeHumidity	1	2
	Solar Radiation	m3-lite#SolarRadiation	1	2
	Wind Speed	m3-lite#WindSpeed	1	2

	Wind Direction	m3-lite#WindDirection	1	2
<i>FINE</i>	Board Temperature	m3-lite#BoardTemperature	20	6
	Board Voltage	m3-lite#Voltage	20	6
	Device Uptime	m3-lite#DeviceUptime	20	6
	IEEE 802.15.4 Signal Level	m3-lite#Power	20	6
	Air Temperature	m3-lite#AirTemperature	17	6
	Relative Humidity	m3-lite#RelativeHumidity	17	6
	Air Dust	m3-lite#ChemicalAgentAtmosphericConcentrationAirParticles	12	6
	Illuminance	m3-lite#Illuminance	11	6
	Noise	m3-lite#SoundPressureLevelAmbient	10	6
	Electric Current	m3-lite#ElectricCurrent	7	6
	Electric Voltage	m3-lite#Voltage	2	6
	NO	m3-lite#ChemicalAgentAtmosphericConcentrationNO	2	6
	NO <sub>2</sub>	m3-lite#ChemicalAgentAtmosphericConcentrationNO2	2	6
	CO <sub>2</sub>	m3-lite#CO2	2	6
	O <sub>3</sub>	m3-lite#ChemicalAgentAtmosphericConcentrationO3	2	6
	SO <sub>2</sub>	m3-lite#ChemicalAgentAtmosphericConcentrationSO2	2	6
	VOC	m3-lite#ChemicalAgentAtmosphericConcentrationVOC	2	6
<i>Grasse Smart Territory</i>	Lora Device SNR	m3-lite#SNR	7	10
	Lora Device RSSI	m3-lite#RSSI	7	10
<i>ADREAM</i>	Electric Voltage	m3-lite#Voltage	145	8
	Building Temperature	m3-lite#Temperature	54	3
	Air Temperature	m3-lite#AirTemperature	36	2
	Electric Power	m3-lite#Energy	10	10