

# A Survey on Facilities for Experimental Internet of Things Research

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## ABSTRACT

The initial vision of the Internet of Things was of a world in which all physical objects are tagged and uniquely identified by RFID transponders. However, the concept has grown into multiple dimensions, encompassing sensor networks able to provide real-world intelligence and goal-oriented collaboration of distributed smart objects via local networks or global interconnections such as the Internet. Despite significant technological advances, difficulties associated with the evaluation of IoT solutions under realistic conditions in real-world experimental deployments still hamper their maturation and significant rollout. In this article we identify requirements for the next generation of IoT experimental facilities. While providing a taxonomy, we also survey currently available research testbeds, identify existing gaps, and suggest new directions based on experience from recent efforts in this field.

## INTRODUCTION

The Internet of Things (IoT) is a multidisciplinary domain that covers a large number of topics from purely technical issues (e.g., routing protocols, semantic queries), to a mix of technical and societal issues (security, privacy, usability), as well as social and business themes. IoT applications, both existing and potential, are equally diverse. If we are to summarize all of them into one, it is enabling the machine perception of the real world and seamless interactions with it. Environmental and personal health monitoring, monitoring and control of industrial processes including agriculture, smart spaces, and smart cities are just some of the examples of IoT applications.

Designing a system that can efficiently support such a large range of applications and be compliant with a plethora of often contradicting requirements as well as integrating all required components and technologies is a complex task. Simulations, as an important phase during this

process, are useful for developing further understanding of a system. However, they suffer from several imperfections [1] as they make artificial assumptions on radio propagation, traffic, failure patterns, and topologies. What makes it particularly difficult is the strong dependency of IoT systems on real-world processes that are often a result of complex systems-of-systems interactions and extremely difficult to model accurately.

To design robust applications, developers need appropriate tools and methods for testing and managing their applications on real hardware in large-scale deployments. In the early days of IoT research, the availability of smart devices was limited, and only recent advances in technology have increased their availability at lower costs. Although experiments were mainly small-scale and conducted in research laboratories, they allowed for an improvement in understanding the impact and limitations of real hardware on performance of protocols and design choices. However, the daunting logistical challenge of experimenting with thousands of small battery-powered nodes is the key factor that has greatly limited the development of this field.

Overcoming the technical challenges and socio-economic barriers of widescale IoT deployment in our daily lives requires a thorough, practical evaluation of IoT solutions using interdisciplinary, multitechnology, large-scale, and realistic testbeds. The ability to test IoT solutions on a larger scale and outside of research laboratories (i.e., in real environments and with real end users) has been considered only recently [2]. These new testbeds aim to design and deploy experimentation environments that will allow for:

- The technical evaluation of IoT solutions under realistic conditions
- The assessment of the social acceptance of new IoT solutions
- The quantification of service usability and performance with end users in the loop

This article identifies the main requirements for a next generation of experimental research

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facilities for the IoT, and provides a taxonomy and survey of existing testbeds that are currently available throughout the world. We identify the main features and capabilities of these testbeds, analyze how they fulfill the identified experimentation needs and challenges, and finally suggest research directions based on experience from recent efforts in this field.

## REQUIREMENTS AND CHALLENGES

Testbeds for wireless sensor network (WSN) research have provided a solid basis for experimentation with solutions to overcome the problems and challenges pertinent to the research domain. However, moving from islands of WSNs to a global networked infrastructure — as envisioned by the Internet of Things — opens up new challenges that demand new capabilities and features from suitable testbeds. In the following we briefly highlight the key challenges when moving from WSNs toward IoT. Based on those we motivate requirements for adequate facilities for research and experimentation with future IoT-based technologies.

### CHALLENGES FOR IOT EXPERIMENTATION

WSN research has primarily focused on advances within WSN islands, providing optimized solutions for the resource-constrained devices of which they are composed. In contrast, a major goal of IoT research is to integrate these island technologies into a globally interconnected infrastructure, moving from the currently existing *Intra-net* to a real *Inter-net* of Things [3]. A resulting challenge is an increase in *scale* with which the developed IoT solutions have to cope. Another challenge is an increasing *heterogeneity* of devices and device technologies. Both require new approaches to support interoperability at different layers of the communication stack for resource-constrained devices, which have to be adequately reflected in IoT experimentation environments. Increased heterogeneity and scale, however, also make *repeatability* of experiments on a testbed or across different testbeds more difficult. Finally, as the IoT is considered part of a larger future Internet, *federation* of IoT testbeds with other future Internet testbeds becomes more important for end-to-end experimentation and is a further challenge to be tackled.

Other key differences are the horizontalization of infrastructure and the pervasiveness of the IoT environment. While WSN research mainly focused on providing solutions optimized for a particular problem domain and application area, IoT research envisions supporting multiple application domains, possibly at the same time. A challenge is presented by the increased *concurrency* of access to the infrastructure, which has to be reflected by IoT testbeds as well. The experimentation space is not limited to interoperability at the communications layer, but also requires data layer solutions. As more real-world applications and services will rely on IoT infrastructures, the *realism of the environment for experimentation* becomes more important. With it comes support for realistic *mobility*. Finally, the pervasiveness of the infrastructure and the

potential social impact of IoT technologies call for human users to be included in the experimentation loop. A challenge is to design a mechanism that supports adequate *user involvement* during experimentation.

### REQUIREMENTS

The above identified challenges motivate requirements that adequate facilities have to support. In the following we provide a brief description of those.

**Scale** — As the IoT will become a globally interconnected infrastructure, supporting experimentation on an adequate scale is an important aspect contributing toward the realism of IoT experimentation. While smaller-scale testbeds in the range of tens up to hundreds of nodes were sufficient for most WSN experiments, many IoT experiments will demand an order of magnitude larger scale. In order to make experimentation with thousands of IoT nodes possible, techniques are required that minimize human intervention, maximize plug-and-play configuration, and automate fault management. As experimenters can easily lose an overview when experimenting with such large numbers of testbed resources, support mechanisms that ease the selection of adequate testbed resources and the composition of experiments are necessary.

**Heterogeneity** — The expected heterogeneity of devices and underlying solutions demands that experimental testbeds reflect this heterogeneity in terms of the hardware substrate and the nature of experiments supported on top of them. Furthermore, gateway devices, which have been previously considered only as sinks in WSN testbeds, should be an active part of the experimentation infrastructure. This requires tools allowing for an effective configuration and execution of experiments across heterogeneous testbed resources and the corresponding management of devices. A further requirement is providing support to ease programmability of heterogeneous devices, which often come with diverse execution environments.

**Repeatability** — There is an increasing trend in the scientific community to repeat experiments within and across different testbeds. Replayability goes even further by providing adequate packaging of experimentation specifications, traces, and results so they can be easily re-executed and compared across different testbeds. While contributing to scientific rigor, it will allow others to quickly build on other work, thus accelerating the scientific progress of the community. The heterogeneity and the wireless nature of IoT testbeds combined with ever changing ambient conditions make both features hard to implement. While a total replication of real-world conditions may be impossible, solutions supporting the monitoring of the radio environment during experimentation and benchmarking of different testbeds could partially overcome the associated issues by providing hints for the interpretation of experimental data. Replayability requires agreement on standards for the specification of experiments, collection of traces, and

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Handling such mobility and the associated system dynamics is thus a key requirement for future IoT solutions. Therefore, mechanisms to control and exploit realistic mobility of both IoT devices and real-world entities during experimentation are necessary.

packaging of experimental results across a variety of testbeds.

**Federation** — Federation with other testbeds is necessary to achieve scale or add capabilities for experimentation that are not locally available. Reasons for limited scale and diversity are hardware cost, space constraints, lack of expertise, or required management resources. Federation is a viable solution to create larger and more heterogeneous facilities out of specialized smaller-scale ones. From the management perspective, requirements on federation are a common framework for authentication, authorization, accounting, reservation, and experiment scheduling.

**Concurrency** — With an increased investment in infrastructure, supporting multiple concurrent users and experiments is a necessity for an economically viable operation, and larger-scale testbeds must support multiplexing of concurrent experiments. Unlike existing testbeds for Internet experimentation (e.g., PlanetLab), IoT devices are substantially resource-constrained, making virtualization at the hardware layer very difficult. Such “virtualization” is more feasible at the testbed level than on the node level, and will support the multiplexing of experiments in space and time. IoT testbeds require advanced mechanisms that allow selection of testbed resources to minimize interference of concurrently executing experiments (caused by colocated wireless transmissions, access to same hardware resources, etc.) while satisfying the requirements of the experiment.

**Experimental Environment** — IoT technologies heavily depend on ambient environmental conditions in which they are deployed; so does the service logic of the diverse IoT applications. Moving testbed deployments out of the laboratory and into the wild requires more robust techniques for realizing out-of-band management and control planes, as many of the currently wired solutions will have to be replaced by wireless ones. Increased robustness is also important due to the increased overhead of the maintenance of testbed equipment in such deployments, as ease of access is often traded off against the threat of physical tempering, deliberate damage, or theft.

**Mobility** — A key role of the IoT is to provide information on real-world entities and events or the interaction capabilities that influence them. Many such entities may move around in a real-world environment, thus making the IoT devices attached to them mobile. Handling such mobility and the associated system dynamics is thus a key requirement for future IoT solutions. Therefore, mechanisms to control and exploit realistic mobility of both IoT devices and real-world entities during experimentation are necessary.

**User Involvement and Impact** — Many IoT applications are centered on human users or require their active participation, which makes experimentation more difficult to control and may invalidate results. Experimental facilities

that involve users must offer mechanisms allowing for evaluating social impact and acceptance of IoT solutions and applications. This includes automated detection of situations when user behavior influences the validity of collected data, but also the provision of efficient multimodal mechanisms for user feedback.

## SURVEY OF EXISTING TESTBEDS

In the following section we provide a survey of the currently available testbeds for IoT experimentation and develop a taxonomy for evaluating the capabilities and features they offer. We concentrate our discussion on four main dimensions: the testbeds’ primary scope, underlying architecture and organization, hardware capabilities, and offered testbed services. We further discuss the extent to which the available testbeds fulfill the requirements for future IoT testbeds introduced in the previous section. For this article we restrict ourselves to testbeds publicly accessible and with notable use (Table 1). The table also contains references to other IoT-related testbeds that are not publicly available or are works in progress, but still provide interesting features.

### TESTBED SCOPES

When building an IoT testbed, one key consideration is its scope (Fig. 1). In terms of the technological scope, a testbed can be *single-domain* if it addresses only a particular type of IoT technology (e.g., WSN or RFID devices). Nearly all of the surveyed testbeds belong to this category [14]. A *multidomain* testbed is one that combines different IoT technologies into a common experimental facility. The latter type is increasingly important in addressing the IoT heterogeneity requirements [10]. Testbeds can be realized either *indoor* (Motelab) or *outdoor* (CitySense, Oulu smart city, SmartSantander), thereby influencing the choice of the underlying hardware architecture and software mechanisms. Indoor installations often provide easier access to power and cabling for the testbed control and management, making them easier to manage and more available. In contrast, outdoor testbeds often rely on wireless connections, requiring additional mechanisms in order to increase reliability. They also have to be protected against malicious physical access and other threats that do not occur as frequently in controlled environments. Furthermore, testbeds can be realized either as *permanent* installations that are constantly available or *portable* ones, usually temporarily deployed for measurement campaigns.

Testbeds can differ based on the *application domain* they are designed to investigate. *Generic testbeds* such as MoteLab, WISBED or SenseLab enable experimentation research of communication protocols at different levels of the protocol stack or application level algorithms that are mostly independent of a particular application or service. More recently, domain-specific testbeds have emerged that allow the evaluation of services and applications in a real environment and from the end-user perspective. Examples of these domains are smart city services (CitySense, Oulu Smart City, Friedrichshafen) or supply

Testbed	Scope	Nodes and locality	Noteworthy
MoteLab [4]	WSN	190 TelosB motes, indoor, spread across 3 floors of a laboratory building	One of the first and longest lasting testbeds. In-situ power measurements on some nodes. MoteLab testbed service framework used as a basis for various other testbeds, e.g. CCNY-CWSNET and INDRIYA
NetEye [5]	WSN	130 TelosB motes, indoor, 1 room, 15 wooden benches 1 feet apart	FCFS scheduling approach, static 3db attenuator to each mote antenna for realising multi-hop network and different power levels, to be integrated as part of the Kansai-Geni testbed
TutorNet [6]	WSN	104 motes (91 TelosB, 13 MicaZ), indoor, 1 room	The user indicates the start and end time for its reservation, as well as the list of motes it would like to reserve. The reservation will fail when attempting to exceed the allowed nodehours quota, where a nodehour represents a reservation unit corresponding to reserving one mote for one hour
MIRAGE/Intel [7]	WSN	100 MicaZ motes (currently only 58 available), indoor, laboratory environment	The reservation is based on an abstract resource specification language for resource discovery (only per-node attribute available) and by using the MIRAGE bidding language in order to reserve the discovered resources
VineLab [8]	WSN	48 TelosB motes, indoor, 1 floor inside a laboratory	unlike other testbeds provides only very basic experimental user support via Python scripts, utilisable for research on smart in-door environments
Kansei [9]	Mesh, WSN	210 XSM motes, 210 Stargate gateways, 50 Trio motes, indoor	One of the most advanced surveyed testbeds with various testbed service functions, co-simulation support, mobility support using mobile robots, event injection possible both at GW and mote level
WISEBED [10]	WSN	750 motes (200 iSense, 143 TelosB, 108 G-Node, 100 MSB-A2, 44 SunSPOT, 60 pacemate, 24 Tnode), in- and outdoor, 9 different locations in Europe	Federation architecture, co-simulation support, topology virtualization, in-situ power measurements on some nodes, mobility support using 40 mobile robots
FRONTS [11]	WSN	21 iSense motes, indoor, laboratory environment	In-situ power measurements on some nodes, purely wireless in-band management
DES-Testbed [12]	Mesh, WSN	95 MSB-A2, 95 Linux nodes, in- and outdoor	Mobility planned, currently one prototype robot available
w-iLab.t Testbed [13]	Mesh, WSN	200 TMoteSky motes, indoor, laboratory environment	Measurement and battery emulation, repeatable mobility support
Senslab [14]	WSN	1024 WSN430 (521 with 802.15.4 MAC, 512 with free MAC layer), indoor, 4 different sites in France	Energy measurement supported for every node, repeatable mobility via electric toy trains
KanseiGeni [15]	Mesh, WSN	576 motes (96 XSM, 384 TelosB, 96 iMote2) attached to Stargate gateways, indoor, laboratory environment	Based on Kansei and Neteye, federation with other GENI envisioned, heterogeneous mote platforms
TWIST [16]	WSN	204 motes (102 TelosB, 102 eyesIFX)	Forms the basis for a variety of other testbeds such as WUSTL

**Table 1a.** Active and publicly available testbeds.

commissioning and stock management (METRO real, SAP Future Retail Centre).

### ARCHITECTURE

The architecture is another key dimension of IoT testbeds, as it inherently determines their properties. We distinguish between three important features, as shown in Fig. 1. The structure of a testbed refers to the organization of the testbed hardware components. Most testbeds either follow a *two-tier* structure with a server tier and directly attached IoT device tier or a

*three-tier* structure that introduces an intermediate gateway (GW) device tier (Fig. 2).

Smaller testbeds (hundreds of nodes) often follow a two-tier structure, in which IoT devices are organized in a flat tier and directly connected or attached to a server tier. These interconnections can be wired (e.g., via USB or Ethernet) or wireless (e.g., via WiFi). The initial realization of *Motelab*, one of the first publicly accessible testbeds, was based on a two-tier architecture, in which sensor motes with an attached Ethernet interface were connected via a LAN to a testbed



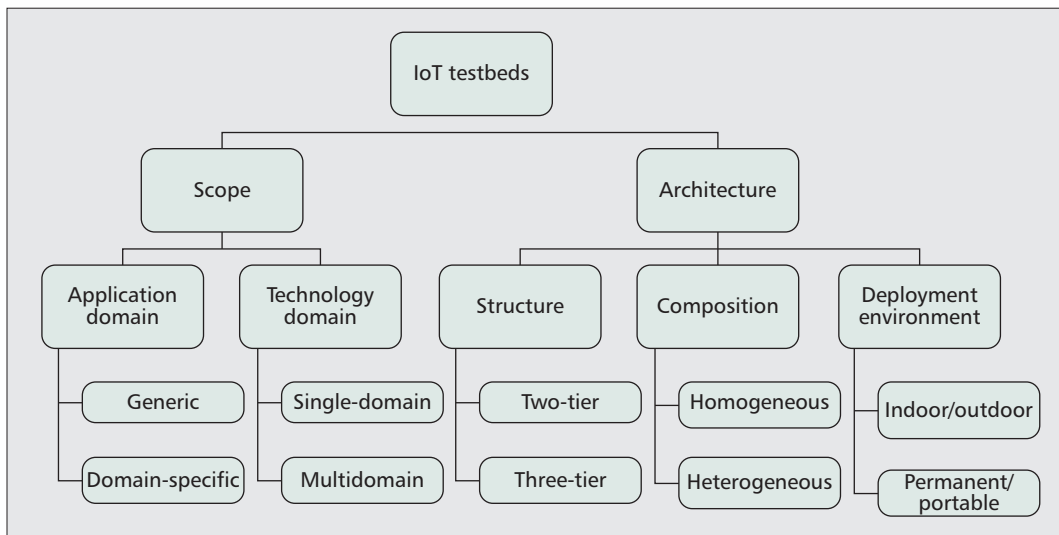
Testbed	Scope	Notes
CitySense [17]	Mesh	City-scale deployment on light poles and private or public buildings. Nodes comprise of an embedded PC, 802.11a/b/g interface, and various sensors for monitoring weather conditions and air pollutants. Envisioned scale is around 100 nodes. Two features make this testbed particularly interesting: its realism and domain specificity provided by a permanent out door installation in an urban environment and the realization of the control and management plane based solely on wireless links.
Oulu Smart City [18]	WSN	Smart City project to study urban computing, or the interaction between urban spaces, human, information technology and information. IEEE 802.15.4 technology on the 868 MHz band
Friedrichshafen [19]	Multiple	Smart City project (comprising PDAs, Sensors, Smartphones, etc.) to evaluate prototypical services such as e-Learning, Smart Metering, e-Health, e-Tourism, etc.
Motescope [20]	WSN	WSN testbed for energy metering at UCB. Large smart metering deployment that will comprise more than 500 heterogeneous sensor nodes with the aim of providing building energy consumption profiling and a platform for protocol experimentation
FlockLab [21]	WSN	Wireless sensor network deployment based on a new board (observer) providing advanced features such as energy consumption monitoring of the mote and emulation of radio behavior. Using particular adapter, the board results compliant with different off-the-shelf motes.
METRO real,- Future Store [22]	RFID	RFID Innovation Center, Test lab area of 2000 sqm., Covering various areas of RFID application in retail such as supply commissining, stock management, warehouse, instore and consumer household.
SAP Future Retail Centre [23]	RFID, WSN	The main purpose is the experimentation with IoT technology and services to improve the customer experience while optimizing in-store processes by enabling complete visibility and traceability of handling units along the supply chain. The centre covers three experimentation scenarios: retail, retail management and logistics.
CITC testbed	RFID	The main purpose is to experiment within a typical environment combined with specific frequencies in order to study the RFID effectiveness in a given environment (metal, liquids, etc). More information available at <a href="http://www.citc-eurarfid.com">http://www.citc-eurarfid.com</a> .
RFIT Lab	RFID	The testbed allows experimentation with RFID devices in a given environment and an evaluation of electromagnetic compatibility. More information available at <a href="http://rftlab.grenoble-inp.fr">http://rftlab.grenoble-inp.fr</a> .
VizBee	RFID	The main purpose of this testbed is to integrate RFID receivers, tags, exciters and repeaters. More information available at <a href="http://www.vizbee-rfid.com/technology.asp?ID=2">http://www.vizbee-rfid.com/technology.asp?ID=2</a> .

**Table 1b.** Testbeds with interesting features.

server. Examples of other two-tier testbeds with a wired backbone are *MIRAGE* or *Vinelab*, the latter using USB cables for interconnections to a server. Many RFID-based testbed environments follow a two-tier architecture, where RFID readers are attached via wired backbones to middleware servers [22]. *CitySense* and *FRONTS* are two-tier testbeds that have connections to the server via wireless links. *FRONTS* implements the testbed management in-band over wireless links. In contrast, *CitySense* nodes make use of two separate WiFi radio interfaces, in order to separate the experimentation and testbed management planes, which are interconnected via multihop links. While two-tier testbeds are easy to set up, they become more complicated to manage once they start growing in size. Furthermore, experimentation capabilities are limited to the IoT device tier only, thereby constraining experimentation with tiered network architectures and protocols for internetworking with other networks.

Larger testbeds typically exhibit a three-tier architecture, in which one or up to dozens of IoT devices are connected via wired connections to an intermediate GW device. This reduces the

need for each individual IoT device to provide a possibly costly network interface card, in order to enable communications with remotely located testbed servers. The *TWIST* testbed as well as the latest version of *Motelab* and *INDRIYA* make use of low-cost USB-to-Ethernet devices as intermediate aggregation nodes to which various motes are attached via cheap USB cables and hubs, implicitly providing power to the motes. GW nodes are realized by different types of hardware such as laptop computers (*NetEye*), embedded Linux servers (*Kansei*, *KanseiGeni*), or custom-built hardware (*FlockLab*). Most of the surveyed three-tier testbeds in this article utilize the GW tier as an utility, providing only connectivity aggregation and passive experimentation support. Only a few testbeds, such as *Kansei*/*KanseiGeni*, allow the GW devices to be programmed with experimentation code to become an active participant in experimentation. This allows the realization of more complex IoT experimentation scenarios with protocols for a larger-scale interconnection of IoT islands, which are crucial when moving from the Intra- to the Internet of Things technologies [3]. An example of this is end-to-end 6LoWPAN experi-



**Figure 1.** Scope and architecture of testbeds.

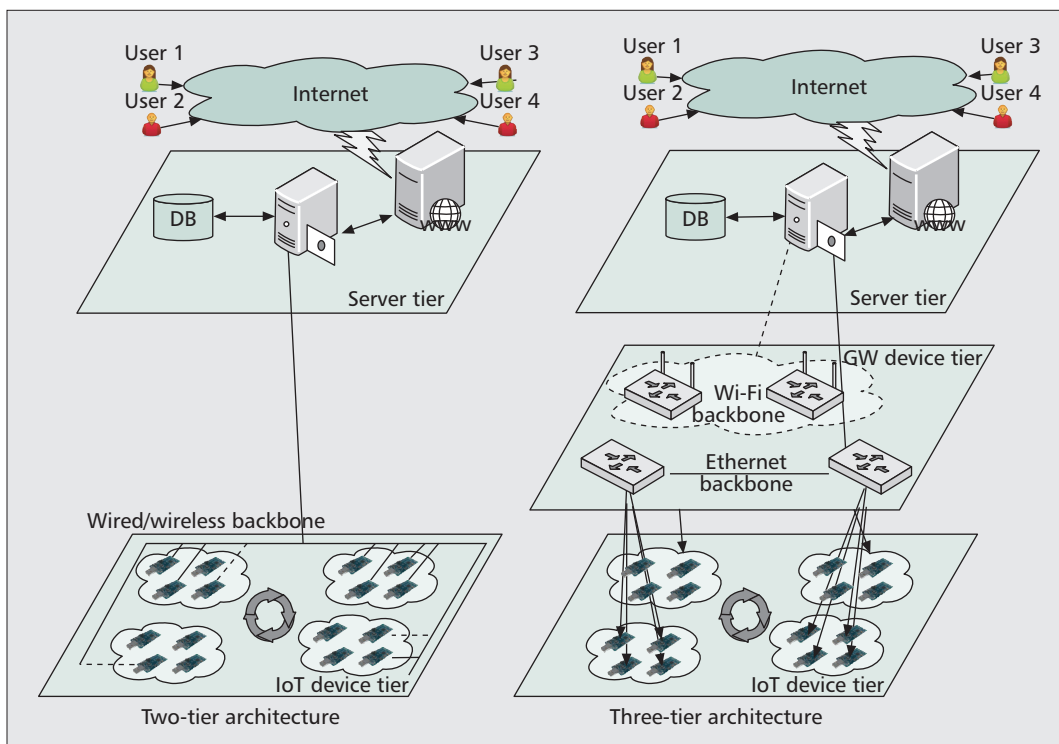
mentation, which require not only the deployment of 6LoWPAN stacks on IoT nodes, but also IPv6 routers on the GW tier to support interaction with applications on the server tier.

Within each tier, many testbeds comprise the same type of testbed hardware (e.g., Motelab or Neteye). We consider the composition of such testbeds *homogeneous*. Some recent testbeds such as KanseiGeni and *WISEBED* are *heterogeneous* within a tier and are realized by different device platforms, thereby providing an experimenter with more choices and increased realism, at the cost of the increased complexity in handling experimentation and testbed management.

Finally, the physical deployment architecture or, *testbed topology*, has a strong influence on the

possibilities of direct radio links between the nodes and determines what types of experimental scenarios can be realized within the testbed. Most of the testbeds are permanent and indoor, spanning one or more floors of a given building. Examples of 3D testbeds are INDRIYA and Motelab, where in both cases three different floors are covered by sensors. The Kansei testbed provides a large grid-like structure of motes evenly distributed on tables within a warehouse. All of the testbeds usually span an area large enough to obtain a natural multihop network topology. Topology control for experimentation is mainly done by selecting a set of nodes for experiments based on their geographic properties (e.g., distances) and by adequate configura-

While two-tier testbeds are easy to set up, they become more complicated to manage once they start growing in size. Furthermore, experimentation capabilities are limited to the IoT device tier only, thereby constraining experimentation with tiered network architectures and protocols for internetworking with other networks.



**Figure 2.** Typical IoT testbed architectures.

Sensor nodes are equipped with basic temperature, humidity, and light sensors. More sophisticated testbeds provide a selection of other sensors such as magnetometers, microphones, and pressure sensors. Apart from LEDs, actuators can rarely be found.

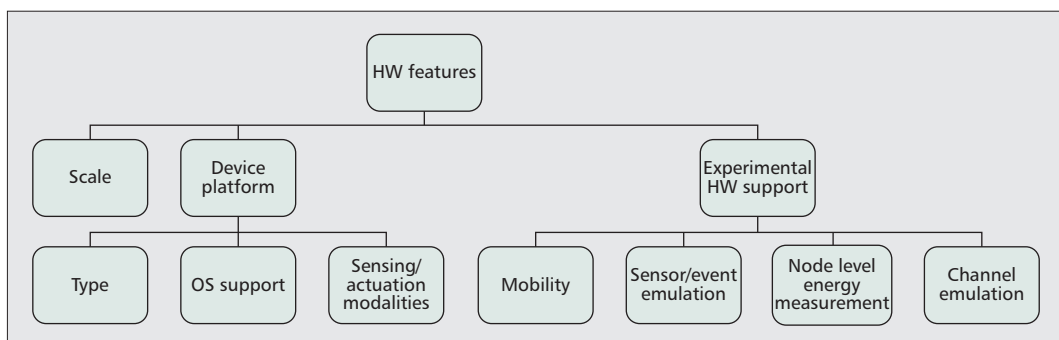


Figure 3. Classification of hardware features.

tion of transmission power levels. In order to constrain the physical topology in dense indoor deployments, attenuators are often attached to the antennas of the IoT nodes (e.g., NetEye). Topology changes during experimentation can be achieved by turning on/off motes. This is supported in TWIST and INDRIYA by toggling the power on ports of the USB hubs to which the motes are attached. WISEBED provides increased flexibility for topology configuration even across remote IoT islands using *virtual links* [24].

### HARDWARE FEATURES

This section examines the hardware features provided by different testbeds. As shown in Fig. 3, many existing testbeds vary in the type of underlying *device platforms*. At the IoT tier, most publicly available testbeds focus on WSNs, which utilize off-the-shelf mote platforms, although in some cases custom-built solutions can be found (Senslab). RFID-based testbeds realize this tier with typical off-the-shelf readers and tags. The GW tier is mostly based on more powerful devices, such as embedded servers.

For WSN testbeds, operating system (OS) support depends largely on the mote platforms used in the IoT tier. Commonly found OSs are TinyOS, Contiki, Sunspot, iSense, or MoteRunner. While in principle most mote platforms support one or more OSs, a few testbeds are limited to a particular OS (Motelab, TWIST, Vinelab). A notable example on the other end of the spectrum is the WISEBED testbed, which offers seven different hardware platforms and thus a variety of OS choices. Currently, the majority of mote platforms use a standard medium access control (MAC) layer (IEEE 802.15.4), which inhibits research on custom MAC layer protocols; only a few testbeds (Senslab, DES-Testbed) provide the flexibility of replacing the MAC layer. Some testbeds (Kansei, DES-testbed, w-iLab.t, FlockLab) provide additional, more powerful hardware such as embedded Linux computers.

Sensor nodes (TelosB/TmoteSky testbeds) are equipped with basic temperature, humidity and light sensors. More sophisticated testbeds (MicaZ and iSense platforms) provide a selection of other sensors such as magnetometers, microphones, and pressure sensors. Apart from LEDs, actuators can rarely be found.

Another important metric is the *scale* of testbeds. The majority of single-location testbeds

feature a limited number of nodes (a few dozen up to 200 nodes, except KanseiGeni, which has over 600 nodes) due to cost and space constraints. A promising approach is the federation of individual testbeds interconnected over the Internet, as in the cases of Senslab and WISEBED. Here, an important aspect is to allow the distributed testbeds to appear as a single one at the application layer by using an approach like virtual links [24].

Some testbeds allow realization of more complex experimentation scenarios, thereby increasing the flexibility and control possibilities. An example is the introduction of node mobility. Devices are attached to movable objects with controllable trajectory like robots (WISEBED) or electronic toy trains (Senslab), allowing repeatable mobility patterns during experimentation.

Another important feature is the *emulation of sensor events* by attaching digital-to-analog (D/A) converters to the IoT platforms, from which arbitrary sensor events can be generated during experimentation. For example, the w-iLab.t testbed provides *environmental emulators*, which trigger sensor readings on the individual sensor nodes that correspond to emulated environmental events. This also allows replaying of sensor events obtained from a real-world environment on the testbed. Some testbeds (FlockLab, Senslab) are able to *emulate channel characteristics* between IoT nodes. Lastly, a useful feature is the ability to measure energy consumption of nodes by means of dedicated onboard hardware (iSense) or connected GWs (FlockLab, Senslab), or perhaps with the use of battery emulators (w-iLab.t, TWIST).

### TESTBED SERVICES

Testbed services enable efficient execution of experiments throughout the complete life cycle of an experiment (Fig. 4).

In most testbeds (Motelab, Senslab, TWIST, NetEye, Kansei, WISEBED), *experiment specification* is done via web interfaces where users define the number and type of resources needed, the programs to upload, and the metrics to be collected.<sup>1</sup> Other platforms, such as TUTORNET, Vinelab, and Motescope, provide script-based tools only. WISEBED defines a set of web service application programming interfaces (APIs) that compatible testbeds must implement. Clients (e.g., a web interface or script) invoke these services to run experiments and

<sup>1</sup> A similar framework for assisting users in the complete life cycle of an experiment with wireless/wired devices is represented by the OMF tools [25], developed within the OneLab project. An Experiment Description Language assisting users in deploying experiments is provided along with a control Measurement Library (OML), useful for instrumenting the experiment in order to produce logging and analysis information.

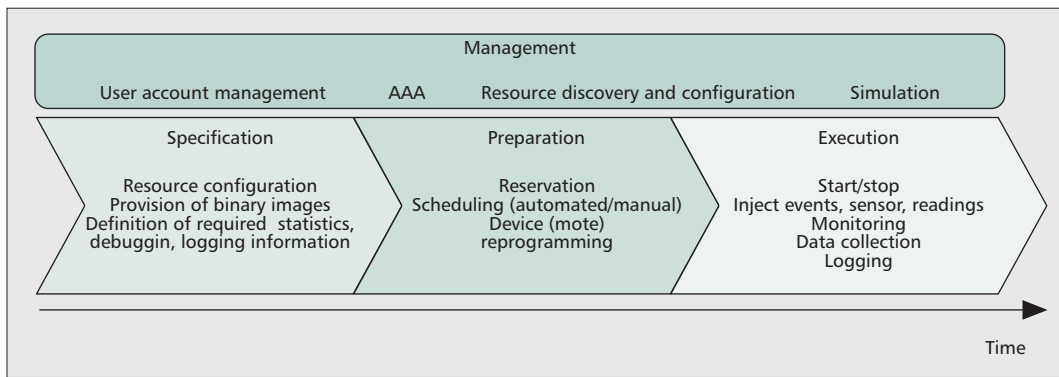


Figure 4. Experiment execution workflow and corresponding testbed services.

interact with the testbed. WISEBED also provides a generic XML-based language (WiseML) for experiment description, configuration, and storage of results.

Testbeds like NetEye (in its basic implementation) use a priority-based approach for *reservation* and *scheduling* in which only experiments requiring available resources at any given time take place, and the resource allocation is prioritized based on the start time of each submitted experiment. Motelab allows for the reservation of specific radio channels. Other approaches enable resource reservation using calendar applications. Examples are Motelab (using a custom calendar application), FRONTS (Google Calendar), and WISEBED (extensible database-backed Google Calendar or in-memory storage). To avoid long-term blocking of resources, some testbeds have daily user quotas (e.g., TUTORNET). Others calculate optimal schedules based on reservation requests (e.g., Senslab's OAR server or MIRAGES micro-economic processes).

Before an experiment is executed, the devices are reprogrammed. Typically, *reprogramming* uses a wired infrastructure, while only a few testbeds use wireless reprogramming techniques (e.g., FRONTS). *Execution control* allows influencing of the experimentation flow (e.g., by injecting events or sensor readings (w-iLab.t and FlockLab). Some testbeds offer access to ongoing experiments through web interfaces, via SSH (CitySense), cURL tool (TWIST), or web services (WISEBED) to adjust parameters, including aspects of *monitoring and data collection*. The monitoring and collection of statistics during experimentation allows users to debug experiments, follow the progress of the execution, or store performance indicators/statistics for later analysis. However, such processes can interfere with the experiment. Motelab and similar testbeds let users download such data only after an experiment. Other testbeds use out-of-band mechanisms or efficient logging schemes [26] that collect statistics and debug information during periods of node inactivity in order to allow real-time access to messages and metrics (Senslab, WISEBED, and FRONTS) and the transmission of control messages to nodes (WISEBED).

Implementations of *management services* are mostly proprietary (FRONTS, TWIST), although some testbeds use standards such as Shibboleth

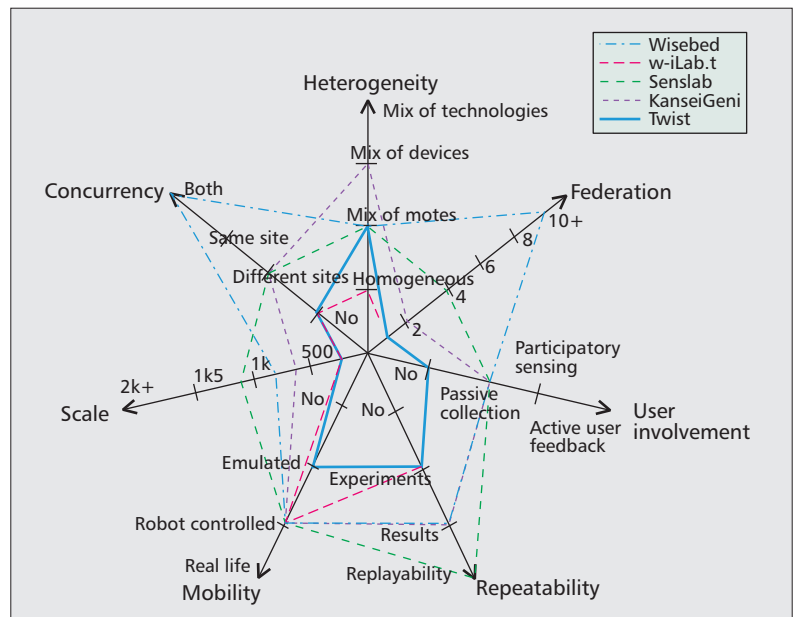


Figure 5. Mapping of features of current testbeds to identified requirements.

(WISEBED) to realize a subset of functionality (e.g., access control). *Resource discovery and configuration services* ensure that the connected testbed resources are discovered and properly configured to operate as expected for experimentation. With increasing scale, autonomous operation of these services becomes more important. Most of the surveyed testbeds require manual configuration of resources or at least a manual initiation process. One exception is Kansei, which features tools for node configuration and plug-and-play registration of resources. The same applies to *fault management tools*, responsible for hardware and service recovery after failures. In current deployments, this is manually initiated by testbed administrators when *performance monitoring* tools report misbehaving elements. This is often realized by pinging the nodes to obtain their status (NetEye) or using controllable cameras to provide ground truth during experimentation, especially in the presence of node mobility (Kansei and Senslab).

*Co-simulation* tools, if offered, permit the scaling of experiments beyond the available testbed hardware using simulated nodes, or allow the injection of real data into a simulator



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to make simulations more realistic (Kansei and WISEBED). With the same aim of extending existing testbed capabilities and to introduce heterogeneity, a recent trend in testbeds is *federation*, which allows experiments to span multiple physical testbeds (WISEBED and KanseiGeni).

## TOWARD A NEW GENERATION OF IOT EXPERIMENTATION FACILITIES

We have analyzed a range of publicly available IoT testbeds, evaluated their scopes, architectures, and features, and identified the requirements for future IoT experimentation. While many of these testbeds provide interesting and useful features, this survey has demonstrated that there are still gaps in fully addressing the requirements as illustrated in Fig. 5 for the most promising testbeds.

An attempt towards closing these gaps represents the SmartSantander project, which aims at the creation of a city-scale environment for IoT research and experimentation. In order to support experimentation at realistic scale the project aims to deploy 20,000 heterogeneous IoT devices and gateway nodes in urban and indoor environments (attached to lamp posts, buried in the asphalt, attached to buildings and mounted to vehicles), mainly on the streets of Santander, but also at federated sites at Guildford, Lübeck, Belgrade, and Melbourne.

To achieve the required heterogeneity we plan to utilize a large variety of IoT technologies for experimentation. Examples are different sensor platforms (e.g., Waspmotes, iSense, Telos, and SunSpots) equipped with a large diversity of sensors (e.g., temperature, humidity, noise level, parking occupancy, light intensity, and air pollution), utilizing various wireless technologies to connect to the system (e.g., IEEE 802.15.4, WiFi, and 3G/GPRS) and allowing a variety of communication stacks (e.g., Zigbee, 6LoWPAN/CoAP) to be configured on top of it for experimentation. The testbed will also integrate other types of IoT devices such as actuators, RFID readers, and tags, NFC enabled mobile phones (used as participatory and opportunistic sensing platforms) as well heterogeneous gateway platforms.

The testbed is composed of a three-tier architecture, in which devices of every tier can be freely configured and programmed for experimentation needs and that utilizes WISEBED testbed services to provide the core management functionality. Due to deployment constraints in the urban environment, many of the deployed nodes cannot be attached via wired links to a backbone infrastructure. Therefore, a reliable wireless management plane has been realized, which allows out of band data collection and monitoring and multi-hop over the air reprogramming utilizing a secondary wireless transceiver at each of the nodes.

In order to deal with the challenges of heterogeneity and scale, our testbed services rely on semantic technologies. Testbed resources are semantically described, allowing tools to easily select and query testbed resources, and compose larger-scale experiments based on declaratively

expressed user requirements.<sup>2</sup> This will allow more optimized testbed resource allocation and contribute toward concurrent execution of experiments. Furthermore, testbed traces and results will be made available though machine readable and inter-linkable formats, making a comparison of experiments across different testbeds easier.

A service platform<sup>3</sup> will complement the above described infrastructure, with the ability to develop and experiment with smart urban services and applications on top of the infrastructure. Primary users of these services will be the city authorities and its citizens. User feedback about usefulness of services or after IoT intervention will be collected using participatory sensing mechanisms provided by the testbed through the mobile phones of the users and installed terminal devices in the city.

We hope that this new generation facility for experimental IoT research will accelerate IoT research and global deployment by providing an adequate experimentation environment that fulfills the needs not only of IoT researchers, but also service providers and ultimately us citizens who will be the primary beneficiary of this technology.

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<sup>2</sup> This functionality exploits parts of the rendezvous infrastructure (resource directory, semantic query resolver) developed by the SENSEI project, <http://www.sensei.eu>.

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