UNIVERSITY OF LATVIA
FACULTY OF COMPUTING

ENABLING WIRELESS SENSOR NETWORK TESTBEDS FOR HIGH TRL RESEARCH

DOCTORAL THESIS

Author: **Jānis Judvaitis**

Supervisor: Prof., Dr. Sc. Comp. Leo Seļāvo

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ANOTĀCIJA

Promocijas darba mērķis ir sniegt skaidru priekšstatu par bezvadu sensoru tīklu testgultnes platformu izmantošanu un funkcionalitāti, analizēt, kādi testgultnes platformu uzlabojumi ir nepieciešami lai atbalstītu bezvadu sensoru tīklu pētniecību un izstrādi līdz 7. tehnoloģiju gatavības līmenim, kā arī izstrādāt un novērtēt identificētos uzlabojumus.

Promocijas darbā tiek definēts termins ”testgultnes platforma” un pamatota šī termina nepieciešamība.

Disertācijā ir iekļauti divi autora veikto sistemātisko literatūras pārskatu rezultāti par: (i) faktiskajiem sensoru tīklu izvietojumiem piecu gadu periodā un (ii) eksistējošām testgultnes platformām desmit gadu periodā, atklājot testgultnes platformu jomas piedāvājumu un pieprasījumu, kas tiek aprakstīts piecu novērojumu veidā par šo tematu. Šie novērojumi tiek izmantoti, lai pamatotu nepieciešamību pēc četriem atšķirīgiem testgultnes platformas uzlabojumiem, kas disertācijā tiek aprakstīti. Viens no identificētajiem uzlabojumiem – pielāgojama izvietošanas iespēja, ir patentēts Latvijā.

Uzlabojumi ir izstrādāti EDI TestBed testgultnes platformai un novērtēti pamatojoties uz pieciem pabeigtiem un diviem vēl notiekošiem reāliem izmantošanas gadījumiem, diapazonā no 3. līdz 7. tehnoloģiju gatavības līmenim, pierādot uzlabotās EDI TestBed testgultnes platformas pielietojamību bezvadu sensoru tīklu pētniecības un izstrādes atbalstam līdz 7. tehnoloģiju gatavības līmenim. Katram uzlabojumam tiek sniegtas vadlīnijas un prasības, lai to varētu iekļaut jebkurā saderīgā testgultnes platformā.

Promocijas darba rezultāti ir publicēti divpadsmit zinātniskajās publikācijās, kas sastāv no četriem konferenču referātiem, septiņiem žurnālu rakstiem un vienas grāmatas nodaļas. Desmit publikācijas ir indeksētas Scopus datubāzē, un vēl divas ir publicētas Europe Open Research publicēšanas platformā.

Autors ir piedalījies vai joprojām piedalās trīs nacionālajos un piecos starptautiskajos Eiropas Savienības programmu Apvārsnis2020 un Apvārsnis Eiropa pētniecības projektos, kas ir tieši vai netieši veicinājuši šajā promocijas darbā sasniegtos un aprakstītos rezultātus un to aprobāciju.

Atslēgvārdi: Testgultne, lietu internets, bezvadu sensoru tīkli

ABSTRACT

The aim of this thesis is to provide a clear view of the usage and functionality of testbed facilities for wireless sensor networks, to analyze what improvements to testbed facilities are needed to support research and development of wireless sensor networks up to Technology Readiness Level 7 and to develop and evaluate the identified improvements.

The thesis defines the term ”testbed facility” and justifies the need for this term.

The thesis includes the results of two systematic literature reviews carried out by the author on (i) actual sensor network deployments over a five-year period and (ii) existing testbed facilities over a ten-year period, revealing the supply and demand in the field of testbed facilities, which is described in the form of five observations on the subject. These observations are used to justify the need for the four different testbed facility improvements described in the thesis. One of the identified improvements, the flexible deployment option, has been patented in Latvia.

The improvements have been developed for the EDI TestBed facility and evaluated on the basis of five completed and two ongoing real use cases, ranging from Technology Readiness Level 3 to Technology Readiness Level 7, demonstrating the applicability of the improved EDI TestBed facility to support research and development of wireless sensor networks up to Technology Readiness Level 7. Guidelines and requirements are provided for each improvement so that it can be incorporated into any compatible testbed facility.

The results of the thesis have been published in twelve scientific publications, consisting of four conference papers, seven journal articles, and one book chapter. Ten of the publications have been indexed in the Scopus database and two more have been published in the Europe Open Research publishing platform.

The author has participated or is still participating in three national and five international research projects of the Horizon2020 and Horizon Europe programmes of the European Union, which have directly or indirectly contributed to the results achieved and described in this thesis and to their validation.

Keywords: Testbed facilities, Wireless sensor networks, Internet of Things

To my close family:

parents Ainars and Līga, brother Toms,

wife Una, and children Liene, Līva, and Jēkabs.

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I am eternally grateful to my loving parents Ainars and Līga, and brother Toms, for supporting me throughout not only the preparation of this thesis but my whole life with advice when needed and constant motivation to keep moving forward. I am very lucky to be a part of this great family.

My immeasurable gratitude goes to my supervisor Leo Seļāvo, who introduced me to the exciting nature of research and the fascinating world of wireless sensor networks when I was but a green student in my 3rd year of Bachelor studies.

I would also like to thank the management of the Institute of Electronics and Computer Science, namely the director Modris Greitāns, and the deputy director of development Kaspars Ozols, for the opportunities and trust placed on me throughout my career.

Last, but not least, I would not have done this without the best colleagues at the Cyber-Physical Systems Laboratory, who provided well-formulated criticism and suggestions during the thesis-related research period of my life. Namely, my fellow PhD candidates Rihards Balašs, Juris Ormanis, and Krišjānis Nesenbergs.

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GLOSSARY

Adapter EDI TestBed Adapter. 17, 67–79, 81, 82, 87, 99, 112, 115

CLI command line interface. 47, 53, 65, 102, 103, 105, 113, 118, 120

DUT Device Under Test. 39, 40, 42–45, 47–59, 62, 63, 67, 69–75, 78, 79, 81, 87, 90, 91, 100–103, 106–108, 110–112, 115, 117–119

EDI TestBed EDI TestBed facility. 16, 17, 19, 45–47, 57–59, 64–73, 76, 78, 81, 82, 84, 86–88, 90, 91, 93, 95, 98, 99, 102–122, 124, 125, 127

GUI graphical user interface (UI). 47, 53

HPED High Performance Embedded Devices. 48–51

IMU inertial measurement unit. 49–51

Innovation Action Innovation Action projects in Horizon Europe research framework. 15

IoT Internet of Things. 14, 18–20, 41, 46, 47, 51, 61, 63, 65, 66, 93–95, 98, 99, 105–107, 111, 114, 117, 118, 120, 121, 126

LPED Low Performance Embedded Devices. 48–51

Manager EDI TestBed Workstation Manager. 69–73, 75–77, 80

MD Mobile Devices. 49–51

NB-IoT Narrow Band IoT. 14, 95, 98

Research and Innovation Action Research and Innovation Action projects in Horizon Europe research framework. 15

SBC Single Board Computers. 49–51

testbed facility Wireless Sensor Networks (WSN) testbed facility. 14–16, 19, 20, 26, 31, 40–50, 52–68, 78, 86, 91–93, 101–109, 112, 124–127

TRL Technology Readiness Level. 15, 16, 23, 26, 27, 32–34, 57, 62–64, 86, 109, 111, 112, 114, 116, 118–122, 124–126

UI user interface. 52–54, 92, 102–105, 114, 126

Workstation EDI TestBed Workstation. 17, 68–72, 86–93, 95, 98, 99, 101, 103, 108–110, 112, 114–121

WSN Wireless Sensor Networks. 14–17, 20, 38–41, 46, 47, 51, 53–56, 58–62, 64–67, 84, 86, 87, 90, 91, 93, 105–107, 109, 111, 113, 114, 118, 121–127

INTRODUCTION

Leading into the 3rd decade of the 21st century the digitalization trends in transportation [Noussan et al., 2020; Noussan and Tagliapietra, 2020], intralogistics [Winkler and Zinsmeister, 2019], education [Dorofeeva and Nyurenberger, 2019; Li et al., 2019], agriculture [Kosareva et al., 2019], banking [Rodin et al., 2019; Evdokimova et al., 2019] etc. are providing new and engaging ways for technology to improve our daily lives. To facilitate these improvements an interaction from digitalized systems in the form of sensing or altering the physical world is necessary. As one of the solutions gaining a lot of popularity is IoT, as identified by their growing popularity, as Grand View Research predicts that the Narrow Band IoT (NB-IoT) market size will reach more than $6 Billion by 2025 [Sherry, 2019] and IoT market size is expected to reach more than $555 Billion by 2030 [Grand View Research, 2023]. Although this work primarily focuses on WSNs, [Manrique et al., 2016] identified that researchers are starting to recognize WSN as a technology integrated into the IoT ecosystem.

WSNs are typically composed of small, low-cost sensor nodes equipped with sensing, processing, and wireless communication capabilities, enabling them to collaboratively gather and transmit data from the physical world to a central location. These networks have revolutionized the way we collect and analyze data, facilitating real-time monitoring, decision-making, and control in various domains. The distinctive characteristics of WSNs, such as scalability and adaptability, make them an ideal choice for applications requiring large-scale deployment in challenging and dynamic environments. However, the design and implementation of efficient WSNs pose several significant challenges due to the inherent resource constraints of the sensor nodes, including limited energy, processing power, memory, and communication bandwidth.

As in the domain of WSN and IoT the prototyping of a new solution can be time-consuming and expensive, a solution to address this has emerged - testbed. The term testbed can refer to many things and is too ambiguous. The majority of research literature uses the term testbed to describe a test bench or deployment created and used to evaluate a single scenario or experiment. Yet the term is also used to refer to purposefully built testing facilities capable of supporting different testing scenarios, providing assistive tools, experiment repeatability, and a significant degree of flexibility to be used in a generic WSN development. In this dissertation the author uses the term ”testbed facility” as a facility providing remote access to the embedded WSN hardware and software environment which can be used freely without any restrictions regarding the usability or functionality, more detailed explanation is provided in the Section 1.2.

The main idea of a testbed facility is to provide the necessary equipment and software environment to speed up development and reduce the costs of purchasing new equipment or software. Yet the majority of researchers still use simulation tools to validate their theories [Lima et al., 2019] and refrain from using actual device deployments or publicly available testbed facilities.

An established approach for the evaluation of the development stage for technology is Technology Readiness Level (TRL), whose extensive history and formulation of the meaning used today is thoroughly described by [Héder, 2017]. The main research framework in Europe at the time of writing, Horizon Europe, differentiates between two research project types, Research and Innovation Action and Innovation Action, with expected outcomes to be in the range of TRL 5 to 6 and TRL 6 to 8 respectively [APRE, 2023]. The expected outcomes of Research and Innovation Action and Innovation Action should be taken into consideration when discussing the future of tools, such as testbed facilities, aiming to provide valuable assistance to the research community.

Theses

Taking into consideration the ambiguous terminology of the term testbed and the expected outcomes of the Horizon Europe research projects the following theses are put forward in this work:

1. **Thesis 1**: A testbed facility whose functionality contains at least a flexible deployment option, current measurement system, scriptable interface, and user manual supports WSN research and development up to TRL7.

2. **Thesis 2**: The usage of the term testbed in the research literature indicates ambiguity, therefore a more precise definition of testbed facility is needed and is provided in this work.

Research objective

The research objective of this thesis is to analyze what improvements are crucial for testbed facilities in order to support WSN research and development up to TRL7 and to develop the identified improvements:

1. Flexible deployment option – the possibility to deploy the testbed facility sensor nodes in any reasonable location;
2. Current measurement system – a system capable of providing the current measurements of the connected sensor node;
3. Scriptable interface – an interface intended to be integrated into an automated control sequence;
4. User manual – an instruction and information set providing the user with the needed knowledge to use the testbed facility.

Brief description of materials and methods used

In order to compile this thesis author has concluded two systematic reviews: (i) on sensor network deployments during the five-year time period from 2013 to 2017, and (ii) a systematic review of existing testbed facilities during the ten-year period from 2011 to 2020. The outcome of the sensor network deployment systematic review identified and codified 3059 sensor network deployments. The results of testbed facility systematic review identified and codified 32 testbed facilities. By combining the findings from both systematic reviews five observations were made about the supply and demand in testbed facility domain and as a result, four improvements of testbed facilities were identified. In the experimental part of this thesis, the identified improvements of testbed facilities were developed for the existing EDI TestBed, where the improvements were validated and evaluated. The guidelines for the development of the improvements are also provided.

Author’s contribution

The author was one of the few leading researchers working on both systematic reviews, but overall they are a great team effort. Many people were involved in the development of EDI TestBed, in the initial stage, the author’s contribution was mostly related to the implementation of EDI TestBed Adapter firmware. The author was closely involved in the development of EDI TestBed from the year 2015 and in the latter years was the person responsible for maintaining, developing, and improving the EDI TestBed.

The developed improvements and evaluation were conceptualized and implemented in a team effort as follows:

- Flexible deployment enabled EDI TestBed Workstation was conceptualized by the author, Arnis Salmins, Rihards Balass, and Krisjanis Nesenbergs. The implementation and evaluation was done by the author, Arnis Salmins, and Rihards Balass.
- The improved current measurement system was conceptualized by the author, Rihards Balass, Juris Ormanis, Armands Ancans, Andris Ivars Mackus, and Krisjanis Nesenbergs. The implementation and evaluation were led by the author with the help of Rihards Balass and Andris Ivars Mackus.
- The improvement of EDI TestBed user interface and manual was conceptualized by the author. The implementation and evaluation were done together with Andris Ivars Mackus.

The observations and the following reasoning extracted by analyzing and evaluating the results of both systematic reviews together have been researched and developed by the author alone.

The described seven use cases were implemented in a team effort, and the author’s contribution was as follows:

- Practical implementation in three use cases: (i) Wireless Sensor Networks university course, (ii) Mobility point, and (iii) Intelligent Transport System.
- Leading the implementation in three use cases: (i) Sensor network deployment replication, (ii) Rapid hardware development, prototyping, testing, and evaluation, and (iii) One step open digital building logbook.
- Consultative role in communication technology comparison use case.

Approbation

During the development of this thesis, the author has or still is participating in several research projects which have directly or indirectly contributed to and approbated the results achieved and described in this work:

1. Latvian National research program SOPHIS: ”Cyber-physical systems, ontologies and biophotonics for safe&smart city and society”, grant agreement Nr.10-4/VPP-4/11;
2. European Union’s Horizon 2020 research and innovation programme project ENACT: ”Development, Operation, and Quality Assurance of Trustworthy Smart IoT Systems”, grant agreement No 780351;
3. ERDF Specific Objective 1.1.1 “Improve research and innovation capacity and the ability of Latvian research institutions to attract external funding, by investing in human capital and infrastructure”, 1.1.1.1. measure “Support for applied research” project “iTrEMP: Intelligent transport and emergency management platform”, grand agreement No 1.1.1.1/18/A/183;
4. European Union’s Horizon 2020 research and innovation programme ECSEL project Arrowhead-Tools: ”Arrowhead-Tools for Engineering of Digitalisation Solutions”, grant agreement No 826452;
5. European Union’s Horizon 2020 research and innovation programme project TRINITY: ”Digital Technologies, Advanced Robotics and increased Cyber-security for Agile Production in Future European Manufacturing Ecosystems”, grant agreement No 825196;
6. European Union’s Horizon Europe research and innovation programme project OpenDBL: ”One Step Open DBL solution”, grant agreement No 101092161;
7. European Union’s Horizon Europe research and innovation programme KDT project EdgeAI: ”Edge AI Technologies for Optimised Performance Embedded Processing”, grant agreement No 101097300;
8. Latvian National research program MOTE: “Smart Materials, Photonics, Technologies, and Engineering Ecosystem”, grant agreement No VPP-EM-FOTONIKA-2022/1-0001.

Thesis outline

This dissertation consists of four body sections and a conclusion section.

Section 1 describes the results of sensor network deployment systematic review and systematic review of existing testbed facilities. Overall results obtained from the two systematic reviews about the usage and applicability of the testbed facilities in the IoT era are provided.

Section 2 provides the description of original EDI TestBed laying the foundation upon which the experimental work described in this thesis was implemented.

Section 3 describes the implemented testbed facility improvements and evaluation on EDI TestBed and provides guidelines for implementation in any testbed facility. This Section also lists the possible testbed facility improvements the author deems noteworthy.

Section 4 describes seven use cases of the improved EDI TestBed and evaluates the usefulness of the described improvements in the implementation of the use case.

Section 5 describes the main results of this thesis alongside the conclusions about testbed facility relevance and applicability together with the author's relevant publication list.

1 TESTBED FACILITY USAGE AND APPLICABILITY

Since the majority of researchers still use simulation tools to validate their theories [Lima et al., 2019] there must be a reason for the under-usage of testbed facilities. To understand this reason two separate systematic reviews were concluded on: (i) actual sensor network deployments and (ii) available testbed facilities. This section uses materials from the author's publications [Judvaitis et al., 2020, 2022b,a, 2023].

1.1 Systematic review of sensor network deployments

In order to better understand the applicability of testbeds a systematic review of sensor network deployments was carried out. The research on sensor network deployments would provide not only a clearer view of the usability of testbed facilities but also of the testbed facility necessity in the form of sensor network deployment requirements.

For more than seven decades, the research community has been working on sensor networks [Zedalis, 1978]. Sensor network research output truly took off in the 1980s, when DARPA launched its distributed sensor network program [Morf et al., 1979], and with the emergence of Wireless Sensor Networks (WSN) and the Internet of Things (IoT), more than a million sensor network research articles have been published, with the number expanding by the day. Because of its magnitude, it is nearly impossible for new researchers focusing on sensor networks to have a comprehensive understanding of the existing state-of-the-art and application domains. Existing sensor network-related evaluations concentrate on specific sub-fields, for example, oceanic monitoring [Albaladejo et al., 2010], monitoring of coal mines [Muduli et al., 2018], etc., or cover a small number of current papers, usually less than 100. This results in redundant research and a complicated path to the future of sensor network development.

The aim of this research was to understand what kind of actual deployed sensor networks academics are working on and how this trend develops over time, especially now that we are entering the IoT era [Taivalsaari and Mikkonen, 2017; Aksu et al., 2018]. The first step of the systematic review was gathering and classification of actual sensor network deployments in research studies from 2013 to 2017 published as a data set [Judvaitis et al., 2020]. The scope was defined as gathering and codifying all scientific peer-reviewed publications describing original practical sensor network deployments for a 5-year period, ending with the last full year at the time of the beginning of this research. A total number of 15010 unique articles were selected from indexing databases SCOPUS and Web of Science, for both databases a query with the same information was prepared and executed on the 12th of June, 2018:

- **SCOPUS:** KEY(sensor network OR sensor networks) AND TITLE-ABS-KEY(test* OR experiment* OR deploy*) AND NOT TITLE-ABS-KEY(review) AND NOT TITLE-ABS-KEY(simulat*) AND (LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013))
- **Web of Science:** TS = (”sensor network” OR ”sensor networks”) AND TS = (test* OR experiment* OR deploy*) NOT TI=”review” NOT TS=simulat* **with additional parameters:** Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC Timespan=2013-2017

For practical purposes, there were some limitations placed on the articles to qualify for inclusion in the resulting sensor network deployment data set:

- Only publications in the English language were considered;
- Only publications that could be accessed by the research team without the use of additional funds were considered;
- To be considered a network, the deployment had to have at least two actually deployed sensor devices;
- Devices didn’t have to be wireless, to be considered sensor network - also wired, acoustic or other networks were considered;
- Only research doing the deployment themselves was considered - no use of ready data sets from other deployments was included;
- No simulated experiments were included;
- The time frame was selected as 2013 - 2017, because the data acquisition was started in the middle of 2018, and only full years were chosen for comparability;
- To avoid duplicates only original deployments were included instead of review articles.

An overview of the systematic review methodology including 15010 unique articles and the results for each phase is given in Figure 1.1.

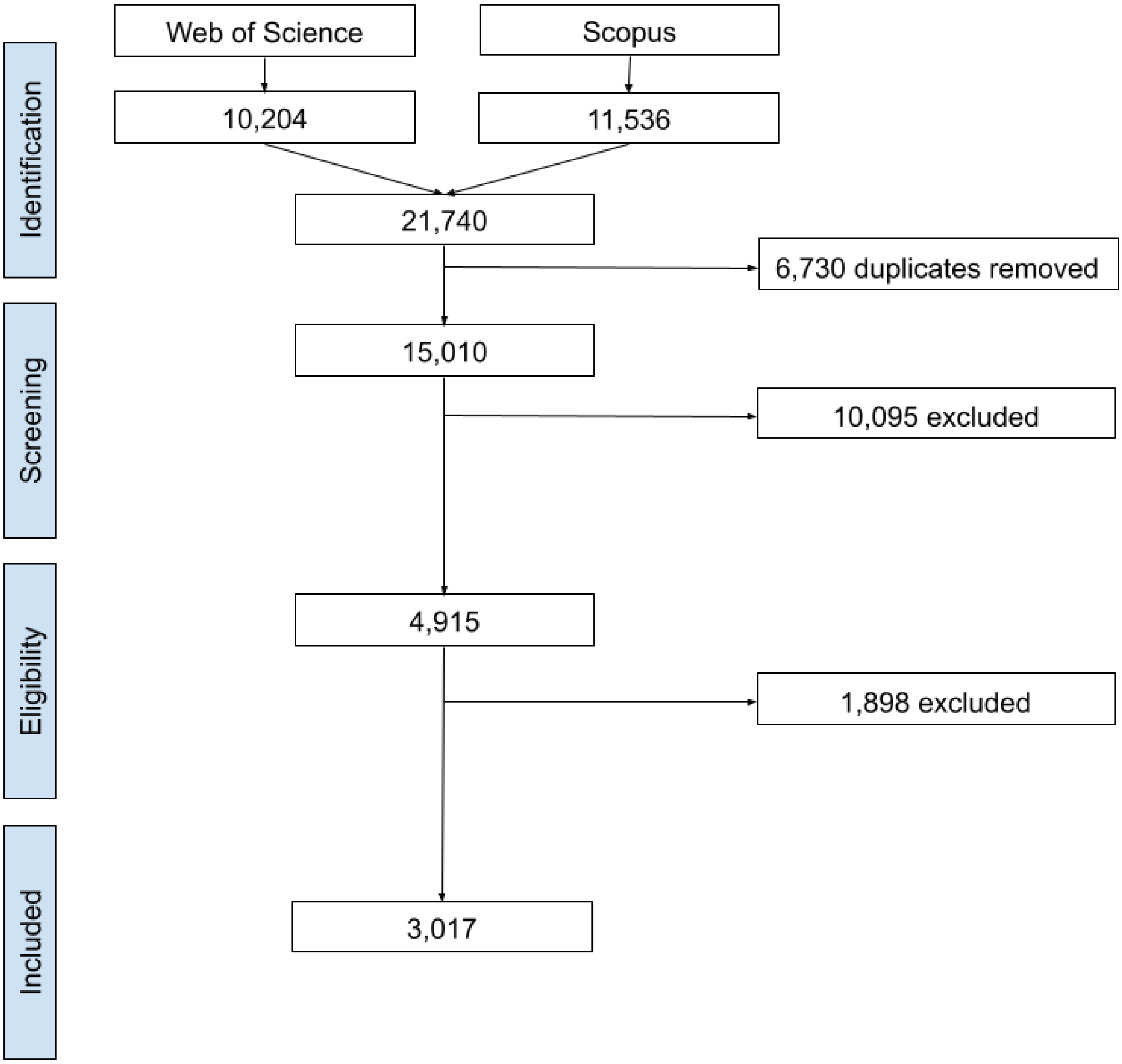


Figure 1.1: An overview of the systematic review methodology and the results for each phase.

This research resulted in 3017 articles describing 3059 actual sensor network deployments identified after two iterations of screening. The whole screening and classification process lasted from June 2018 to July 2020 involving a team of 12 volunteer researchers. For each of the identified 3059 sensor network deployments a total of 15 metrics were extracted, after excluding the metadata concerning the screening and classification process itself, only 12 relevant metrics remain:

- **Year** - year, when the article containing the deployment was published, possible values are: *2013, 2014, 2015, 2016 or 2017*;

- **Node connection** - a type of connection between sensor nodes, possible values are: *wireless, wired, hybrid (using both types) or not defined*;
- **Node mobility** - mobility type of sensor nodes, possible values are: *static only, mobile only, mixed (some static and some mobile) or not defined*;
- **Rich nodes** - which sensor nodes are "rich" devices instead of ordinary sensor nodes, possible values are: *none, only base station, all, mixed (some simple and some rich nodes) or not defined*;
- **Tool or subject** - whether the deployment in the article is used as a tool in the research described, or is the subject of the research itself, possible values are: *tool or subject*;
- **Testbed** - whether a sensor network testbed is used for the described sensor network deployment, possible values are: *used, not used, part of (whether the sensor network itself is part of a testbed)*;
- **Deployment TRL** - the Technology Readiness Level of the deployment, possible values are:
  - *TRL3* - tested concept;
  - *TRL4* - validated in laboratory;
  - *TRL5* - tested in artificial environment/testbed;
  - *TRL6* - demonstrated on close-to-real environment;
  - *TRL7* - demonstrated in real environment;
  - *TRL8* - final system in real environment;
- **Has goal network** - weather deployment is made with goal application in mind instead of just technology focused, possible values are: *Yes or No*. If the goal application was described in the article the following metrics about it were extracted:
  - **Field** - the target field of the application, possible values are:
    * *Health and well-being* - including patient, frail, and elderly monitoring systems, sports performance, and general health and well-being of both body and mind;
    * *Entertainment* - including computer games, AR/VR systems, broadcasting, sporting and public events, gambling, and other entertainment;

    * *Safety* - including anti-theft, security, privacy-enhancing, reliability improving, emergency response, and military applications and tracking people and objects for these applications;
    * *Agriculture* including systems related to farming, crop growing, farm and domesticated animal monitoring, and precision agriculture;
    * *Environment* - monitoring of environment both in wildlife and city, including weather, pollution, wildlife, forest fires, aquatic life, volcanic activity, flooding, earthquakes, etc.;
    * *Communications* - general communications like power lines, water and gas pipes, energy consumption monitoring, internet, telephony, radio, etc.;
    * *Transport* - including intelligent transport systems (ITS), smart mobility, logistics and goods tracking, smart road infrastructure, etc.;
    * *Infrastructure* - general infrastructure, such as tunnels, bridges, dams, ports, smart homes and buildings, etc.;
    * *Industry* - anything related to industrial processes, production, and business in general like coal mine monitoring, production automation, quality control, process monitoring, etc.;
    * *Research* - not related to other fields, but to support future research (better research tools and protocols), testbeds, etc.;
    * *Multiple* - the deployed network will serve multiple of the previously described fields;
  – **Scale** - the target deployment scale of the sensor network with one of the following values, possible values from smallest to largest scale are:
    * *Single actor* - such single entities as a person (e.g. body area network), animal, vehicle, or robot;
    * *Room* - such relatively small territories as rooms, garages, small yards;
    * *Building* - larger areas with separate zones, like houses, private gardens, shops, hospitals;
    * *Property* - even larger zones capable of containing multiple buildings, like city blocks, farms, small private forests or orchards;

    * *Region* - areas of city or self-government scale like a rural area, forest, lake, river, city, or suburbs;
    * *Country* - objects of scale relative to countries, like national road grid, large agricultural or forest areas, smaller seas;
    * *Global* - networks of scale not limited to a single country, such as oceans, jungle, or space;
    * *None* - no scale information of target deployment provided or it is not clearly defined;
- **Subject** - the main target subject meant to be monitored by the goal network, possible values are:
    * *Environment* - all types of environmental phenomena, like weather, forests, bodies of water, habitats, etc.;
    * *Equipment* - all types of inanimate objects, including industrial equipment, buildings, vehicles or robots as systems not actors in the environment, dams, walls, etc.;
    * *Opposing actor* - all types of actors in the environment, which do not want to be monitored, thus including security and spying applications, tracking and monitoring of perpetrators or military opponents, pest control, etc.;
    * *Friendly actor* - actors that do not mind being tracked or monitored for some purpose, like domestic or wild animals (tagging), elderly or frail, people in general if compliant;
    * *Self* - cases where the sensor network monitors itself (location of nodes, communication quality, etc.);
    * *Mixed* - target deployments with multiple subjects from the previously stated values;
- **Interactivity** - the interactivity of the goal sensor network, possible values are:
    * *Passive* - passive monitoring nodes and data gathering for decision-making outside the system or for general statistical purposes;
    * *Interactive* - sensor networks providing some kind of feedback, control, or interactivity within the loop or confines of the system, like automated irrigation systems, real-time alarms, etc.;

* *None* - no specific interactivity is provided or clearly defined in the article;

Here is a brief overview of the results obtained from the sensor network deployment systematic review to provide an overview of available data for this study. This data was thoroughly analyzed, to provide an overview of the trends in sensor network deployments described in published research and gain a better understanding of possible future testbed facility requirements. The complete analysis is published as a systematic review of actual sensor network deployments [Judvaitis et al., 2022b].

The distribution of sensor network deployments between the processed 5 consecutive years as shown in Table 1.1 is consistent - the difference between the most (2017) and least productive year (2016) is only 26 deployments or 0.85%, this means that the field is mature.

Year	Records	Percentage
2013	619	20.24%
2014	616	20.14%
2015	606	19.81%
2016	596	19.48%
2017	622	20.33%

Table 1.1: Sensor network deployment distribution by year

The distribution between TRLs displayed in Figure 1.2 shows specifics of a particular domain. Logically there aren't any deployments related to TRL1 and TRL2 because basic technology research typically does not result in deployments and TRL9 is not related to research. Only a small amount of deployments are related to TRL3 (3.37%) and TRL8 (2.65%) - deployments are seldom employed in these scenarios, and the outcomes of associated utilization are rarely published. The data, in general, follows a normal distribution, with the exception of an outlier at TRL6, which could be due to confusing codification differences between TRL6 and TRL7 leading to spillover from TRL6 to TRL7. Complete data about sensor network deployment distribution by TRLs is given in Table 1.2.

It isn't surprising that only a rather small amount of sensor network deployments assume usage of testbed as visible in Table 1.3, with 82.25% of sensor deployments having no relation to testbed at all. On the other side, this aspect leads to the conclusion that there are tempting

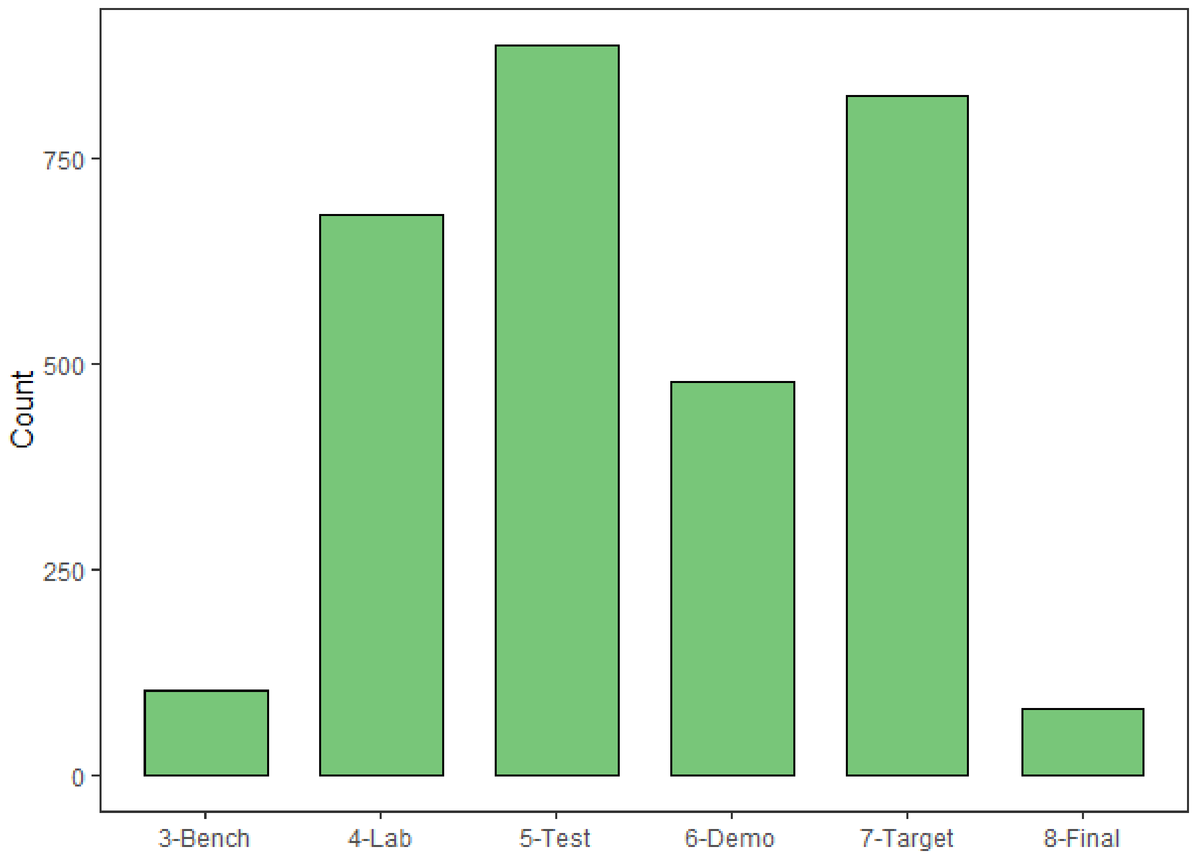


Figure 1.2: Sensor network deployment distribution by Technology Readiness Level

possibilities for further improvements due to increased usage of testbeds, there is a lot more room to grow.

TRL	Records	Percentage
3-Bench	103	3.37%
4-Lab	682	22.29%
5-Test	888	29.03%
6-Demo	479	15.66%
7-Target	826	27.00%
8-Final	81	2.65%

Table 1.2: Sensor network deployment distribution by Technology Readiness Level

Testbed	Records	Percentage
Not used	2516	82.25%
Used	478	15.63%
Part of	65	2.12%

Table 1.3: Sensor network deployment distribution by the usage of testbeds

As shown in Table 1.4 there is quite even distribution between deployments for research on sensor networks themselves and deployments for solution of problems in other domains. Therefore we can conclude that sensor networks still are in their further developmental phase and are not only a technical tool for other domains.

Deployed as	Records	Percentage
Subject	1441	47.11%
Tool	1618	52.89%

Table 1.4: Sensor network deployment distribution by deployment type

Table 1.5 shows that generally (77.61%) sensor network deployments are based on simple devices, in some cases (13.60%) more sophisticated devices are used in the role of base stations. Only a small amount of deployments (7.39%) are completely based on advanced devices.

Rich nodes	Records	Percentage
None	2374	77.61%
Base stations	416	13.60%
All	226	7.39%
Mixed	27	0.88%
Unknown	16	0.52%

Table 1.5: Sensor network deployment distribution by node type

Most of the sensor network deployments are realized using static nodes as shown in Table 1.6. Only 18.96% of deployments are based on mobile nodes and usage of both mentioned approaches together is very untypical. Therefore increase in mobile sensor networks could give additional benefits due to the need for fewer sensor nodes for equivalent geographical areas.

Mobile nodes	Records	Percentage
Static	2286	74.73%
Mobile	580	18.96%
Mixed	140	4.58%
None	53	1.73%

Table 1.6: Sensor network deployment distribution by node mobility

Table 1.7 shows that almost all (93.49%) of sensor network deployments are indeed wireless. Only a small amount is hybrid or entirely relies on wired connections. Probably, there are specific reasons such as increased reliability, an environment not appropriate for wireless communication, or the need for silence in the entire electromagnetic spectrum.

Node connectivity	Records	Percentage
Wireless	2860	93.49%
Wired	94	3.07%
Hybrid	89	2.91%
None	16	0.52%

Table 1.7: Sensor network deployment distribution by node connectivity

The distribution of sensor network deployments depending on whether or not they target a specific goal network is shown in Table 1.8. Most of the sensor deployments (59.66%) tend to have a specific goal network, but for the rest goal network is not defined and it is assumed that the deployment is created for internal research purposes only.

Goal network	Records	Percentage
True	1825	59.66%
False	1234	40.34%

Table 1.8: Sensor network deployment distribution by having a goal network

The most popular fields of the goal network are Infrastructure (22.63%), followed by Health & wellbeing (19.12%), Environment (16.27%), and Agriculture (12.55%) as shown in

Table 1.9. Less common are deployments in the fields of Safety (8.93%), Industry (7.84%), and Transport (6.74%), other fields together form only 5.92%. Such fields with a small amount of deployments could be tempting for new researchers.

Field	Records	Percentage
Infrastructure	413	22.63%
Health & wellbeing	349	19.12%
Environment	297	16.27%
Agriculture	229	12.55%
Safety	163	8.93%
Industry	143	7.84%
Transport	123	6.74%
Communications	51	2.79%
Research	20	1.10%
Education	10	0.55%
Entertainment	17	0.55%
Multiple	10	0.55%
Total	1825	

Table 1.9: Sensor network deployment distribution by field of goal network

Table 1.10 shows that more than half of sensor network deployments tend to scale up to Buildings (29.04%) or Properties (24.49%), less common are larger scales like Country (1.48%) and Global (1.32%).

Scale	Records	Percentage
Building	530	29.04%
Property	447	24.49%
Single actor	345	18.90%
Region	317	17.37%
Room	131	7.18%
Country	27	1.48%
Global	24	1.32%
None	4	0.22%
Total	1825	

Table 1.10: Sensor network deployment distribution by the scale of goal network

Table 1.11 reveals that most real-world deployments are dedicated to monitoring only three distinct subjects: Environment (39.89%), Equipment (27.29%), and Friendly actors (24.99%). Due to domain specifics monitoring of opposing actors is less widespread or it is less used for publications.

Subject	Records	Percentage
Environment	728	39.89%
Equipment	498	27.29%
Friendly actor	456	24.99%
Opposing actor	126	6.90%
Mixed	16	0.88%
SELF	1	0.05%
Total	1825	

Table 1.11: Sensor network deployment distribution by the subject of goal network

Typical deployment only senses and stores and/or sends data, visible in Table 1.12. Only a small amount of deployments (20.55%) are equipped with actuators and can react to any events, this might suggest that there is still an open research area here.

Interactivity	Records	Percentage
Passive	1448	79.34%
Interactive	375	20.55%
None	2	0.11%
Total	1285	

Table 1.12: Sensor network deployment distribution by the interactivity of goal network

In the context of this thesis, the most important metric extracted is related to the usage of testbeds. Unfortunately, at the stage of designing this systematic review the term testbed facility was not yet conceptualized by the author, therefore the extracted data is not testbed facility specific but refers to a wider usage of the term testbed. More explanation about the terminology and differences is given in Section 1.2.

The obtained results were not a surprise at all, only 478 (15.63%) deployments used any

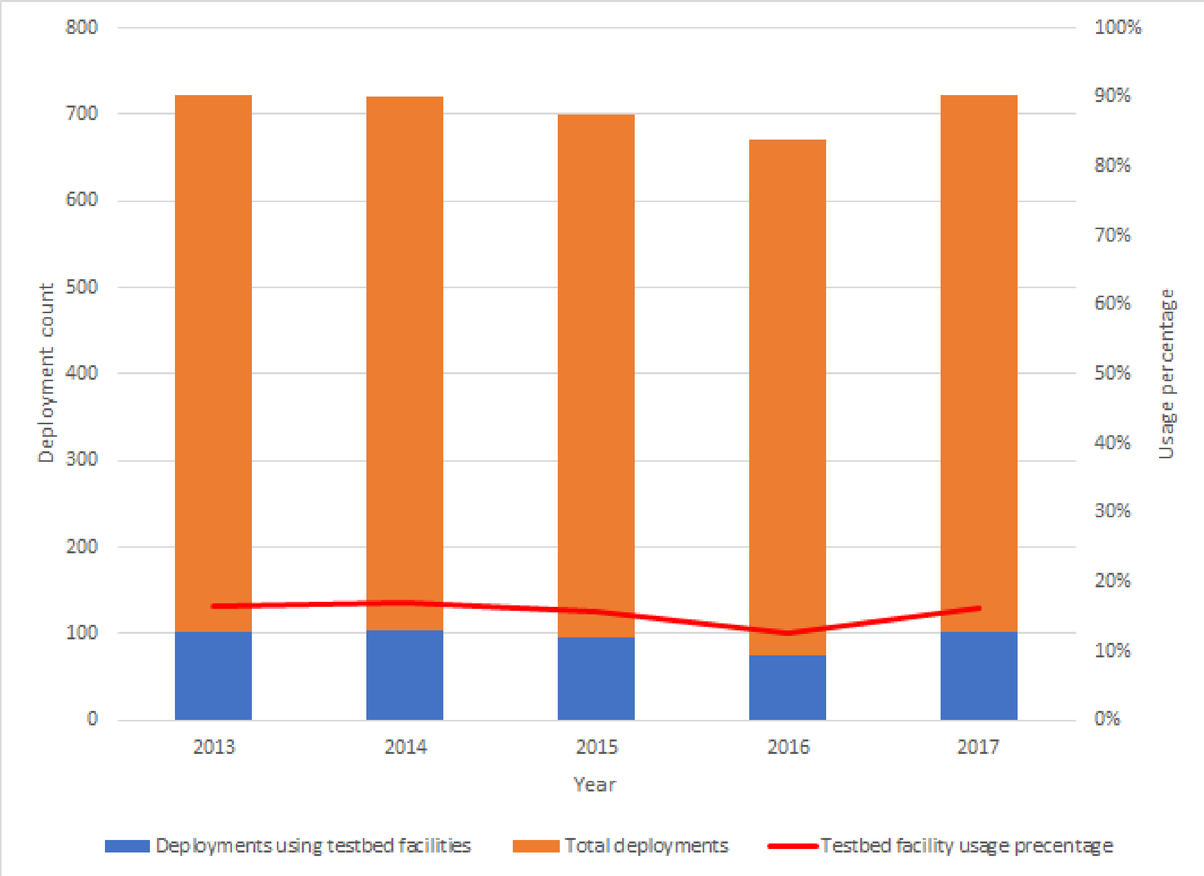


Figure 1.3: Usage of testbeds in actual sensor network deployments per year

testbed. The usage of testbeds by year is shown in Table 1.13 and Figure 1.3, on the first look the usage of testbeds has not changed significantly. But looking at the rolling average for a three-year period 2013 - 2015 (16.40% per year), 2014 - 2016 (15.06% per year) and 2015 - 2017 (14.83% per year), the usage of testbeds is slowly declining.

Year	Deployments using testbed	Deployments total
2013	103(16.6%)	619
2014	104(16.9%)	616
2015	95(15.7%)	606
2016	75(12.6%)	596
2017	101(16.2%)	622
Total	478(15.63%)	3059

Table 1.13: Usage of testbeds in actual sensor network deployments by year

Table 1.14 shows the sensor deployment TRL for the deployments using testbed, most

TRL	Deployments using testbed	Deployments total
TRL3	3(2.9%)	103
TRL4	26(3.8%)	682
TRL5	346(38.9%)	888
TRL6	54(11.3%)	479
TRL7	44(5.3%)	826
TRL8	5(6.2%)	81
Total	478(15.63%)	3059

Table 1.14: Usage of testbeds in actual sensor network deployments by Technology Readiness Level

deployments used testbed when the deployment is targeting TRL5 (38.9%), this is because TRL5 means that the ”technology has been validated in the relevant environment” [Héder, 2017] and testbed can be regarded as a relevant environment because usually it is not located directly at the lab, but next to it.

To investigate this further, more data about the usage characteristics of the testbeds were extracted. With regards to the goal application, it was identified that 354 (74.1%) of the sensor network deployments using a testbed are technology-focused instead of a use case with the specific goal application. Next, the testbed usage with regards to TRL depending on the goal application was observed, the results are shown in Table 1.15. In this data a noticeable difference can be observed, which is better shown in Figure 1.4, the sensor network deployments with the goal network tend to target higher TRL when using a testbed compared to the deployments without a goal network targeted on development and research for specific technology and such differentiation is not observable if we remove the usage of testbed from the equation, as shown on the Figure 1.5.

TRL	With goal application		Without goal application		Using testbeds
TRL3	0	0%	3	100%	3
TRL4	4	15.4%	22	84.6%	26
TRL5	71	20.5%	275	79.5%	346
TRL6	18	33.3%	36	66.7%	54
TRL7	26	59.1%	18	40.9%	44
TRL8	5	100%	0	0%	5
Total	124	25.9%	354	74.1%	478

Table 1.15: Usage of testbeds in actual sensor network deployments by Technology Readiness Level and goal network usage

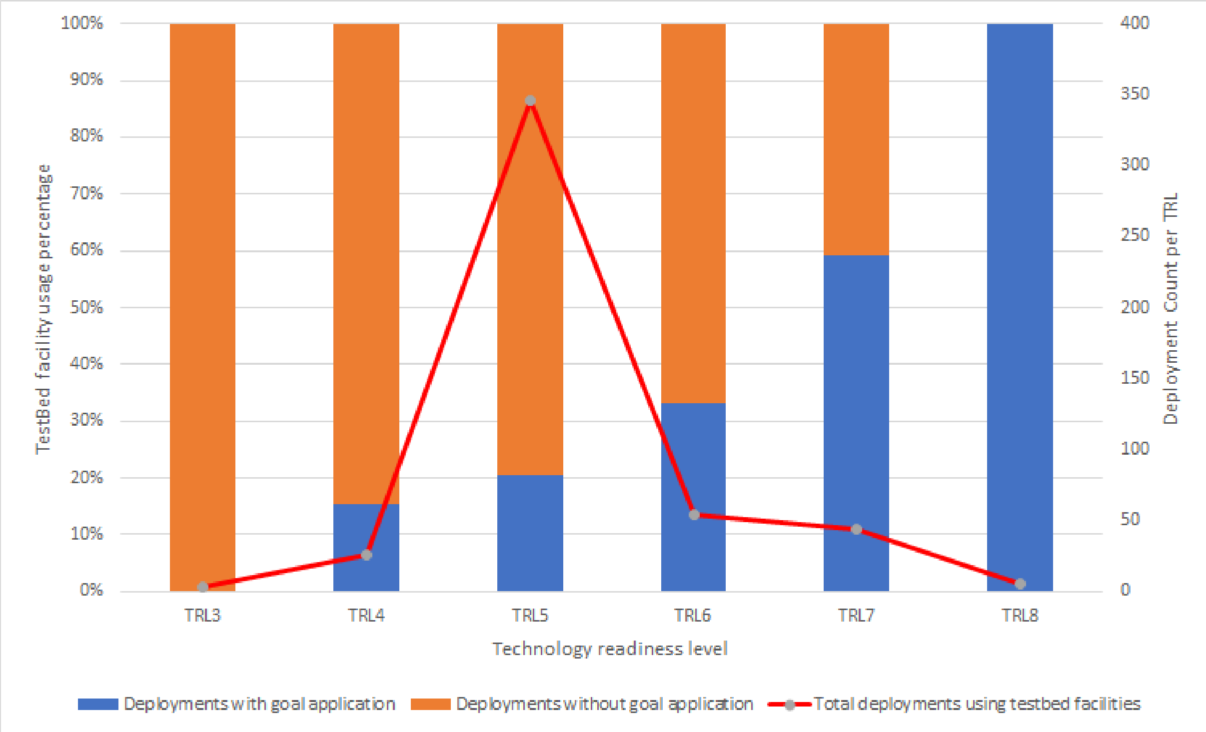


Figure 1.4: Usage of testbeds in actual sensor network deployments per technology readiness level depending on goal network usage

Figure 1.5: Goal network usage statistics in actual sensor network deployments per Technology Readiness Level

Figure 1.6 shows that when the testbed is used the deployment is more likely to be used as a tool to perform research on the sensor network itself rather than for research in another domain. This also conforms with the previously stated conclusions that the testbeds are more used for technology testing when the deployment is a subject of research and thus suggests that there

Field	Used testbed	Total deployments
Research	2(10.0%)	20
Multiple	1(10.0%)	10
Infrastructure	37(8.9%)	413
Transport	11(8.9%)	123
Environment	23(6.6%)	297
Communications	3(5.9%)	51
Entertainment	1(5.9%)	17
Health and well-being	20(5.7%)	349
Industry	8(5.6%)	143
Safety	9(5.5%)	163
Agriculture	9(3.9%)	229
Education	0	10
None	354(28.7%)	1234

Table 1.16: Usage of testbeds in actual sensor network deployments by field

is a possible niche for testbeds - provisioning the development of deployments targeting other research domains and helping with the increased complexity the sensor networks are facing in the real world compared to laboratory environments.

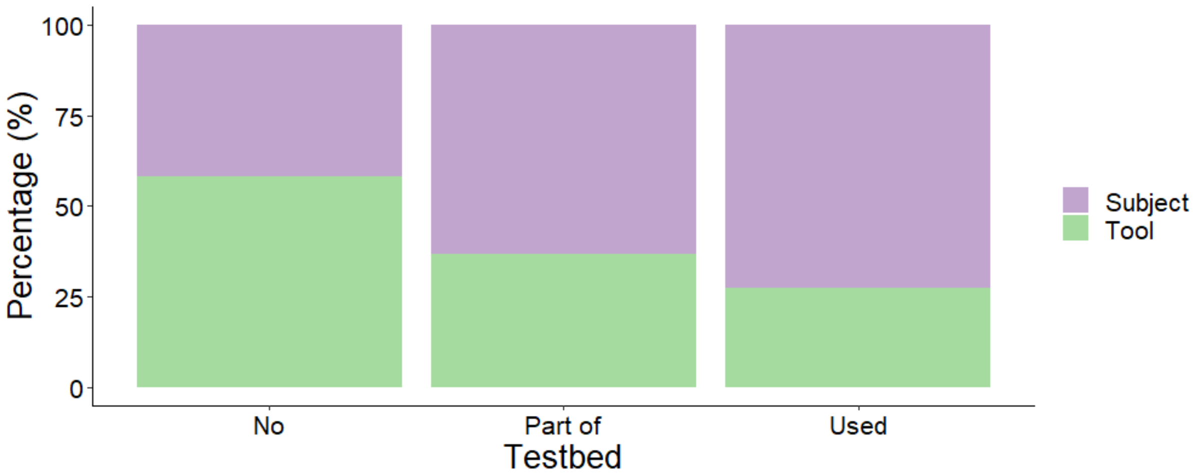


Figure 1.6: Deployment distribution between usage of testbed and deployment type

When considering the fields of usage where the testbeds have been used, shown in Table 1.16, it is noticeable that there are no significant differences in deployment count using testbeds between fields, with the three exceptions: (i) Infrastructure with 37 (8.9%) deployments, (ii) Environment with 23 (6.6%) deployments, and (iii) Health and well-being with 20 (5.7%) deployments. But since the relative usage between even those fields is insignificant, there is nothing that can be extracted from this data.

Sensor network deployments using testbeds are typically on a medium scale (Room, Building, or Property), as seen in Figure 1.7, this could be explained by the scale of testbeds, they seldom focus on a Single actor or cover a Region or Country. Since the testbeds typically only allow medium-scale deployments, the question arises is it worth it for a testbed to support a Single actor or Countrywide deployments? The answer is yes. For the scale of a Single actor, it represents 18.9% of sensor network deployments with a goal network, so the testbeds should expand in this direction. As for the Region and Country scale, such deployments are very difficult to deploy and maintain, in this regard, testbeds could foster the emergence of such large-scale deployments.

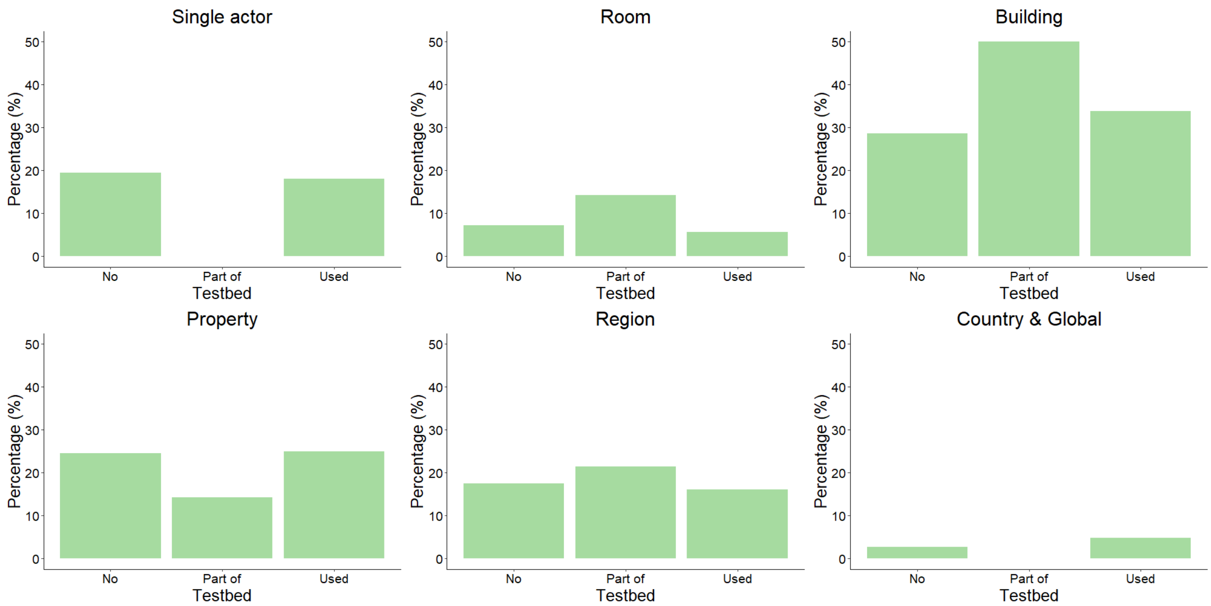


Figure 1.7: Deployment distribution between usage of testbeds and deployment scale

Typically a testbed is created to solve some specific problems such as communication, time synchronization, network optimization, etc., without any specific goal networks in mind, as shown in Figure 1.8. Yet, it would be beneficial to employ some specific testbeds for specific purpose sensor networks such as urban, rural, underwater, or industrial environments providing the circumstances that are not reproducible in the laboratory.

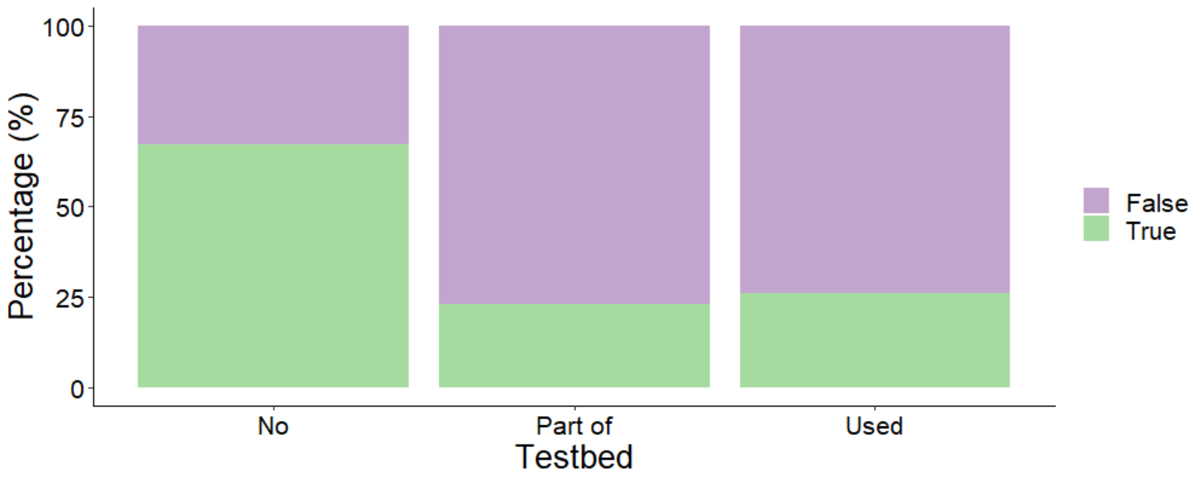


Figure 1.8: Deployment distribution between usage of testbeds and the existence of goal network

1.2 Testbeds and testbed facility definition

The main focus of any testbed is to provide testing grounds to the researchers and engineers for easier and faster prototyping of the solution. An overview of the existing reviews and surveys about the Wireless Sensor Networks (WSN) testbeds are provided with the aim of outlining the testbed domain and complementing a definition of a testbed to narrow the scope of this dissertation. A total of 9 survey articles ranging from years 2008 to 2018 are investigated.

A technical survey of WSN platforms was published in 2008 by [Omiyi et al., 2008] with the aim of summarizing the state of the art about available WSN hardware and testbeds to develop a new testbed for Airbus/ESPRC Active Aircraft Project. Six at the time popular sensor nodes were compared and seven testbeds were discussed, five of them were located in the US and two in Europe. The testbeds were outlined in terms of their scope, size, key functions, architecture, and wireless technology used. There is no mention of the definition of the testbed or any information about the methodology used to choose the included testbeds. As an appendix the survey provides technical requirements for the planned testbed in two categories: (i) design and implementation and (ii) experimenting and validation, mostly focused on the task of developing the Airbus sensor and actuator network for real aircraft deployments with deep integration of the developed testbed and tested devices.

A survey about Simulators, Emulators, and Testbeds for WSNs was published in 2010 by [Imran et al., 2010] focusing on performance evaluation tools of WSNs. The tools were selected based on their popularity, support for WSNs, active maintenance, and the help available, but no indication of how these metrics were evaluated nor their values are given. The article provides a brief overview of 7 evaluated testbeds, yet no definition or requirements for a testbed are given.

A survey of WSN testbeds was published in 2011 by [Steyn and Hancke, 2011] shortly describing 18 testbeds published from the year 2005 to 2010, 5 additional testbed-related improvements, and 3 deployments. No definition or criteria for inclusion of testbeds are given, but testbeds are classified into the following groups, with a number of testbeds in each of them: Central server (4), Single PC (3), Hybrid (4), Multi-site (2), In-band Management (1), Specialized hardware (2) and Industrial application (2). The article also features a comparison table with the testbed name, hardware summary, and a list of extra features.

A survey of Wireless Multimedia Sensor Networks and testbeds was published in 2014 by [Farooq and Kunz, 2014] summarizing the state of the art in wireless multimedia sensor nodes capable of capturing, processing, and transmitting audio and video data. 5 testbeds are evaluated based on the following metrics: number of deployed nodes, software and hardware heterogeneity, availability, and deployment scale. No definition or criteria for the inclusion of testbeds are given.

A survey on testbeds and experimentation environments for WSNs was published in 2014 by [Horneber and Hergenröder, 2014] with the main purpose of discussing the design decisions taken during the process of testbed development. The article provides a description of the testbed as a special environment, designed for experimentation, and limits the scope of the survey to testbeds that are providing ”multiple interconnected hardware sensor nodes”, meaning that there needs to be at least two sensor nodes capable of communicating with one another. The article provides a summary table and research focus of 40 testbeds developed from year 2003 to 2011 together with requirements and architectural aspects common to all WSN testbeds. Also, possible future research directions in WSN testbeds are given suggesting the following trends: wireless backbones, nomadic testbeds, mobile nodes, energy measurement, repeatable experiments, management software, powerful data evaluation tools and interconnection of testbeds.

A survey on mobile WSN experimentation testbeds was published in 2014 by [Tonneau et al., 2014] and extended into a guide on how to choose an experimentation platform for WSNs in 2015 by [Tonneau et al., 2015]. The authors surveyed 10 stationary testbeds and 6 mobile testbeds. The surveys describe the requirements and challenges for testbeds and place great emphasis on mobile testbeds featuring Device Under Test capable of moving around while the experiment is ongoing. Although the surveys claim of providing the basic requirements for a testbed, it is provided as a list of optional features or functionality against which the observed testbeds are compared.

A survey on experimental research testbeds for large-scale WSNs from the architectural perspective was published in 2014 by [Kim et al., 2015] and provides a taxonomy of testbeds that are represented as the architectural design approaches. The survey defines three core requirements for testbeds: scalability, flexibility, and efficiency, but again they are described as optional features or functionality, not really requirements.

A survey of recent achievements for WSN testbeds was published in 2017 by [Ma et al., 2017] providing challenges and evaluating 8 testbeds divided into 4 categories: (i) high precision testbeds, (ii) testbeds for environmental adaption evaluation, (iii) mobility testbeds, and (iv) large-scale testbeds with federated features. No definition or criteria for the inclusion of testbeds are given.

Merriam-Webster glossary [Merriam-Webster.com Dictionary, 2020] explains ”test bed” as ”broadly: any device, facility, or means for testing something in development”, although multiple surveys on WSN testbeds are published, as described in Section 1.2, nor they, nor any other scientific literature known to the author provides a clear definition of what is considered a testbed and what differentiates a test bench from a testbed. The term testbed is widely used and the full-fledged testbed facilities intended to be used in general experimentation needs to be differentiated from devices used for validation on a single instance of tests or any other possible meanings of the word testbed, therefore the author proposes and in this work uses the term ”testbed facility” in accordance with **Thesis 2**, which is defined as:

> ”a facility providing remote access to the embedded hardware and software environment which can be used freely without any restrictions regarding the usability or functionality”.

In addition to this definition, in order to explicitly describe a fully functional testbed facility, the following criteria should be met by the testbed facility:

- Designed to run a variety of different experiments, where the Devices Under Test are completely controlled by the user. This excludes the test bench where only certain parameters or configurations can be changed by the user;
- Users do not need physical access to the hardware, reprogramming or any other interaction with the hardware and software can be performed remotely;
- Provide a user interface specifically designed for testbed facility purposes. This excludes the Secure Shell Protocol (SSH) or Virtual Private Network (VPN) access and similar solutions, where the user is burdened with a lot of overhead in order to run the experiments;
- Access to the testbed facility can be restricted and is not a necessity for it to qualify in regards to the author’s narrative;

The relation between testbeds and testbed facilities, as used in this dissertation, can be visualized by the Venn diagram shown in Figure 1.9: all testbed facilities are also testbeds, but not all testbeds are testbed facilities.

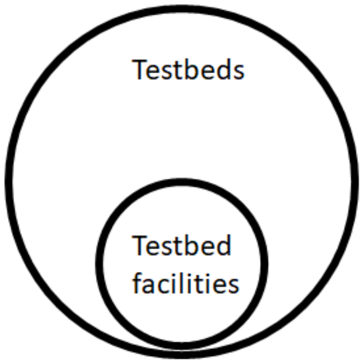


Figure 1.9: Relationship between sets of testbed and sets of testbed facilities

1.3 Systematic review of testbed facilities

With the described minimal viable testbed facility definition a team of researchers led by the author completed a systematic review of testbed facilities. This review was commenced with the goal of providing a comprehensive overview of current Wireless Sensor Networks and Internet of Things testbed facilities available for scientific and commercial use, as well as identifying potential gaps that future testbed facility developments could fill. The first step of the systematic review was gathering and classification of testbed facilities in research studies from 2011 to 2020 published as a data set [Judvaitis et al., 2022a]. The scope was defined as gathering and codifying all scientific peer-reviewed publications describing testbed facility deployments and updates for a 10-year period, ending with the last full year at the time of the beginning of this research. A total number of 359 unique articles were extracted from indexing databases SCOPUS and Web of Science, for both databases a query with the same information was prepared and executed on the 21st of July, 2021:

- **SCOPUS:** TITLE (testbed) AND TITLE-ABS-KEY (wsn OR iot OR ”sensor network*” OR ”internet of thing*”) AND SUBJAREA (comp) AND PUBYEAR < 2021 AND PUBYEAR > 2010;
- **Web of Science:** TI = (”testbed”) AND (AB = (wsn OR iot OR ”sensor network*” OR ”internet of thing*”) or AK= (wsn OR iot OR ”sensor network*” OR ”internet of thing*”)) and SU=”Computer Science” and py = (2011-2020)) **with additional parameters:** Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

For practical purposes, there were some limitations placed on the articles to qualify for inclusion in the resulting testbed facility data set:

- Only publications in the English language were considered;
- Only publications that could be accessed by the research team without the use of additional funds were considered;
- To be considered a testbed facility it needs to correspond to the criteria mentioned in Section 1.2;
- The time frame was selected as 2011 - 2020, because the data acquisition was started in the middle of 2021, and only full years were chosen for comparability;
- To avoid duplicates only original testbed facility articles were included instead of review articles.

An overview of the systematic review methodology including 359 unique articles and the results for each phase is given in Figure 1.10.

To determine the availability and geographical location of the testbed facilities a systematic approach was undertaken. The following possible data sources were examined for any reference to the testbed facility, its availability, and location: any links provided within the articles; search on the internet using the testbed facility name; official websites of relevant organizations and institutions; web pages of funding projects, if specified in the article; address listed in the affiliation of the first author of the main article. If the above-mentioned steps did not yield any information regarding the availability of the testbed facility, it was marked as 'not available' (NA), and for the location the most accurate location extracted was used.

This research resulted in 45 articles describing 32 testbed facilities identified after three iterations of screening. The whole screening and classification process lasted from July 2021 to November 2022 involving a team of 9 volunteer researchers. For each of the identified testbed facilities, a total of 23 metrics were extracted, after excluding the metadata concerning the screening and classification process itself, only 18 relevant metrics remain:

- **Year** - the year when the main article describing the testbed facility was published;
- **DUT** - what devices are available for experiments;

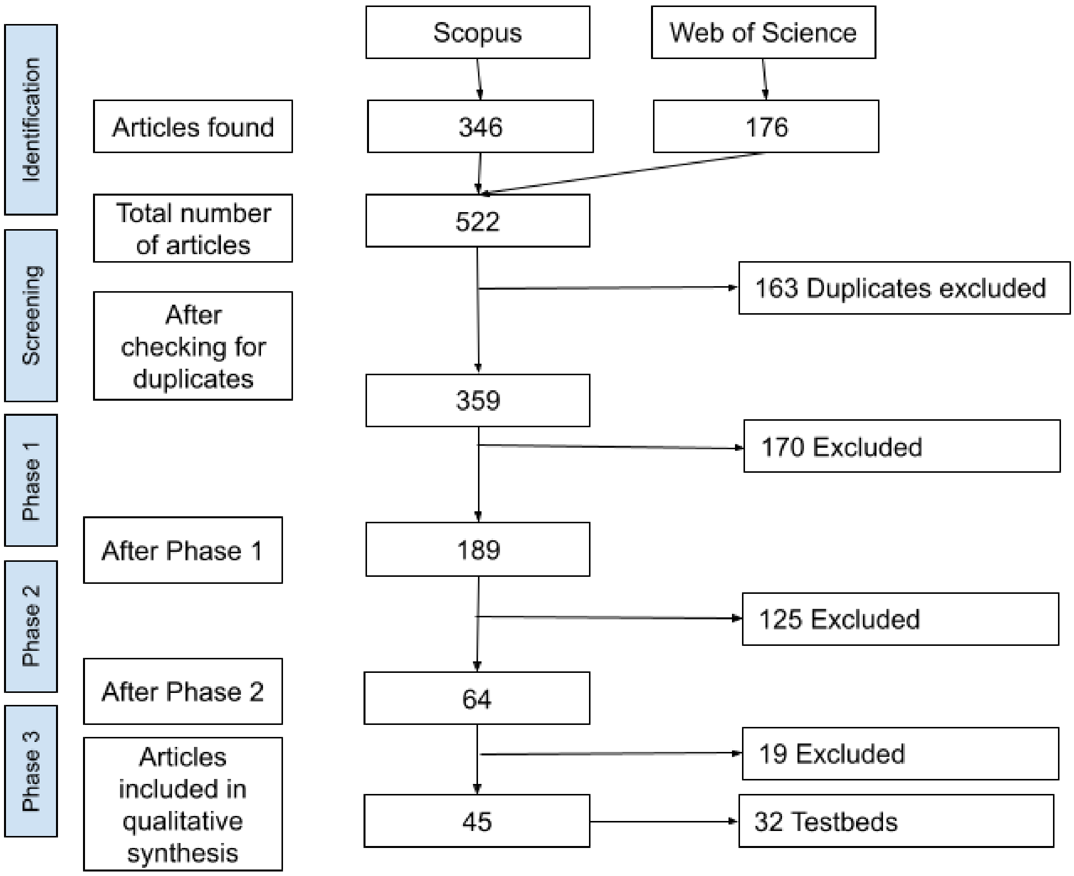


Figure 1.10: An overview of the systematic review methodology and the results for each phase.

- **Sensors** - what type of sensors are available for experiments;
- **Location** - generic description of the place where the DUTs are located;
- **DUT location accuracy** - what is the precision to which the user knows the DUTs location;
- **DUT connection and interaction interfaces** - physical connections available to the DUT;
- **Mobility** - can the DUTs physically move while the experiment is ongoing;
- **Workstations** - what devices, if any, are used as workstations. Workstation is a DUT-to-server relay, typically a Linux-capable device that forwards the data and commands between the server and DUTs;
- **Deployment options** - what deployment options the testbed facility supports.
- **Facility count** - there might be more than one facility;

- **Access level** - what is the level of user control;
- **Assistive tools** - any tools designed to facilitate or improve the user experience;
- **Functionality** - the features that the testbed facility provides to users;
- **Architecture** - the internal design of the testbed facility;
- **Open Source** - whether the testbed facility is available as Open Source;
- **Implementation cost** - what is the investment to build this testbed facility;
- **Availability** - is the testbed facility available at the moment of writing;
- **Location** - what is the geographic location of this testbed facility;

Because the data describing testbed facilities contains data entries that are not machine-readable, the nature of the initial data set did not allow processing using programming tools such as Python or Jupyter Notebooks, it only provided a textual compilation of different metrics about the evaluated testbed facilities. To address this issue, a subset of all extracted data was compiled in JSON format, unifying and simplifying the extracted values to make them more usable. The unifying process and actions taken were discussed with team members in order to obtain a unified vision of the process, but the process itself was completed by the author in order to minimize the risks of interpretation differences. Following this, the team members examined the unified data set. Since similar values were merged for improved readability, the JSON data set includes less information overall, but it can be read and analyzed by any modern programming language script or data analytic application and this data set was used for further analysis.

Here is a brief overview of the results obtained from the testbed facility systematic review to provide an overview of available data for this study. This data was thoroughly analyzed, to provide an overview of the trends in testbed facility development described in published research and to gain a better understanding of possible future testbed facility requirements. The complete analysis is published as a systematic review of the testbed facilities [Judvaitis et al., 2023].

The following metrics contain only one value per testbed facility: Year, Access level, Architecture, Cost of implementation, Open Source, Facility count, and DUT count. The remaining metrics can contain more than one value per testbed facility depending on the context, for example, multiple DUT deployments, etc., leading to a total amount that is larger than the total amount of testbed facilities observed in this systematic review. Also, there are testbed facilities for whom some of the metrics could not be extracted, this results in the totals for some metrics being less than the total amount of evaluated testbed facilities. Any such deviations are also noted in the appropriate place in the text.

An overview of the identified testbed facilities along with the corresponding article references is given in Table 1.17. Most (22) of the testbed facilities have only a single article about them, while among those testbed facilities that have more than one article, there are seven articles with updates, five articles with demonstrations, and one abstract. The testbed facility with the most articles is EDI TestBed by [Ruskuls et al., 2015], which has a main article and four follow-up articles.

Table 1.18 lists the reviewed testbed facilities ordered by provided DUT count and includes the following information: (i) the name of the testbed facility, (ii) main article publication year, (iii) DUT count, (iv) whether the testbed facility is active and (v) brief information about what makes the testbed facility stand out. For testbed facilities City of Things by [Latre et al., 2016], FIST by [Guo et al., 2012], Dandelion by [Wang et al., 2019], and Open CLORO by [Portaluri et al., 2019] the DUT count is ”NA”, this is because the available DUT count was not mentioned in the articles. There are also several testbed facilities described who provide a concept implementation with minimal DUT count with the aim to only evaluate the proposed approach and not continue to provide the services of a testbed facility.

Testbed facility name by the main article, additional references
Dandelion by [Wang et al., 2019]
Open CLORO by [Portaluri et al., 2019]
FIST by [Guo et al., 2012]
City of Things by [Latre et al., 2016]
AssIUTIoT by [AbdelHafeez and AbdelRaheem, 2018], update by [AbdelHafeez et al., 2020]
TWECIS by [Pötsch et al., 2014], abstract by [Potsch, 2016]
Rover by [Brodard et al., 2016]
Ocean-TUNE UCONN testbed by [Peng et al., 2014]
Multidimensional Internet of Things Testbed System by [Alsukayti, 2020]
WaIT by [Brunisholz et al., 2016]
ASNTbed by [Dludla et al., 2013]
EASITEST by [Zhao et al., 2010]
Fully reconfigurable plug-and-play Wireless Sensor Networks testbed by [Bekan et al., 2015]
MobiLab by [Wen et al., 2017]
MOTEL by [Förster et al., 2015]
Integrated Testbed for Cooperative Perception by [Jiménez-González et al., 2011]
CaBIUs by [Alvanou et al., 2020]
SDNWisebed by [Schaerer et al., 2019]
I3ASensorBed by [Olivares et al., 2013]
OpenTestBed by [Munoz et al., 2019]
FlockLab by [Lim et al., 2013], demo by [Trüb et al., 2019]
EDI TestBed by [Ruskuls et al., 2015], updates by [Salmins et al., 2015; Judvaitis et al., 2019; Salmins et al., 2017; Judvaitis et al., 2016]
RT Lab by [Pradeep et al., 2015]
Indriya by [Doddavenkatappa et al., 2012]
NetEye by [Ju et al., 2012]
USN testbed by [Mir et al., 2012]
LinkLab by [Gao et al., 2020]
SmartCampus by [Nati et al., 2013], demo by [Nati et al., 2017]
PhyNetLab by [Venkatapathy et al., 2015], update by [Falkenberg et al., 2017]
SensLab by [Burin des Rosiers et al., 2012], demo by [des Roziers et al., 2011]
FIT IoT-LAB by [Adjih et al., 2015], demo by [Harter et al., 2015]
SmartSantander by [Sanchez et al., 2014], update by [Lanza et al., 2015], demo by [Jara et al., 2015]

Table 1.17: Identified testbed facilities

Testbed facility name	Year	DUTs	Active	What makes it different
Dandelion	2019	NA	Yes	Indoor and outdoor DUTs, sub-GHz LoRa DUTs
Open CLORO	2019	NA	No	DUTs include moving robot, Android app for robot movement control
FIST	2012	NA	No	Wirelessly managed DUTs, the same radio channel for control and experimentation, tree topology
City of Things	2016	NA	Yes	Urban deployment, integrated big data analysis, includes wearables, data visualization
AssIUT IoT	2018	4	No	DUTs supporting LoRa, WiFi, ZigBee and Cellular communication, web interface
TWECIS	2014	4	No	GPIO event timestamping, support of gdb, network-wide power monitoring
Rover	2016	8	No	Open source, cheap to implement
Ocean-TUNE UCONN testbed	2014	10	No	Testbed facility for underwater WSN, Multiple configurable acoustic modems, web interface
Multidimensional Internet of Things Testbed System	2020	12	No	DUTs supporting LoRaWAN, 6LoWPAN, ZigBee and BLE communication, power monitoring
WaIT	2016	12	Yes	Reproducible platform, DUT OS image management, automated topology discovery, cheap, open source
ASNTbed	2013	16	No	Dedicated base station node
EASITEST	2011	20	No	Multi-radio DUTs, web interface
Fully reconfigurable plug-and-play Wireless Sensor Networks testbed	2015	20	Yes	Configurable wireless transceivers, CoAP handlers for interaction
MobiLab	2017	21	No	Mobile DUTs, robot movement control, CLI
MOTEL	2015	23	No	DUTs include two different moving robots and a camera, robot movement control
Integrated Testbed for Cooperative Perception	2011	27	Yes	Mobile and static DUTs, a large variety of sensors, time synchronization, indoor positioning, robot movement control
CaBIUs	2020	30	No	Custom designed programming language, web interface
SDNWisebed	2019	40	No	SDN networking support, traffic statistics for DUTs
I3ASensorBed	2013	46	No	Wide range of sensors, including CO2, presence, smoke, etc.
OpenTestBed	2019	80	Yes	Fully open source
FlockLab	2013	106	Yes	GPIO tracing and actuation, power monitoring, time synchronization
EDI TestBed	2015	110	Yes	GPIO interaction, power monitoring, ADC and DAC interaction, flexible deployment options, CLI
RT Lab	2015	115	Yes	Indoor and outdoor DUTs, online code editing, parametrized control, power monitoring
Indriya	2012	127	Yes	Small maintenance costs, distributed in three floors
NetEye	2012	130	Yes	Topology control, health monitoring, policy-based scheduling
USN testbed	2020	142	No	Indoor and outdoor DUTs, management GUI
LinkLab	2020	155	Yes	Web interface, online compilation, self-inspection module
SmartCampus	2013	240	Yes	DUTs include Smartphones, public display infrastructure for user interaction, topology explorer
PhyNetLab	2015	350	Yes	Deployed in materials handling facility, time synchronization, data visualization, OTA reprogramming, energy consumption accounting
SensLab	2012	1024	No	4 interconnected locations, mobile DUTs, pre-made virtual machines for development
FIT IoT-LAB	2015	2845	Yes	Mobile robot nodes, 6 facilities, 5 hardware platforms, open source visualization, and interaction tools
SmartSantander	2014	3530	Yes	Urban deployment, multi-tier mobile and static DUTs, end-user involvement

Table 1.18: Identified testbed facilities

Figure 1.11 summarizes the main article publication years for testbed facilities, as visible, there are no major trends in the evaluated ten-year period, except for the peak around 2015 and 2016 and following dip in 2017 and 2018, but after that, for two consecutive years, the publication of articles about new testbed facilities continues on a steady pace.

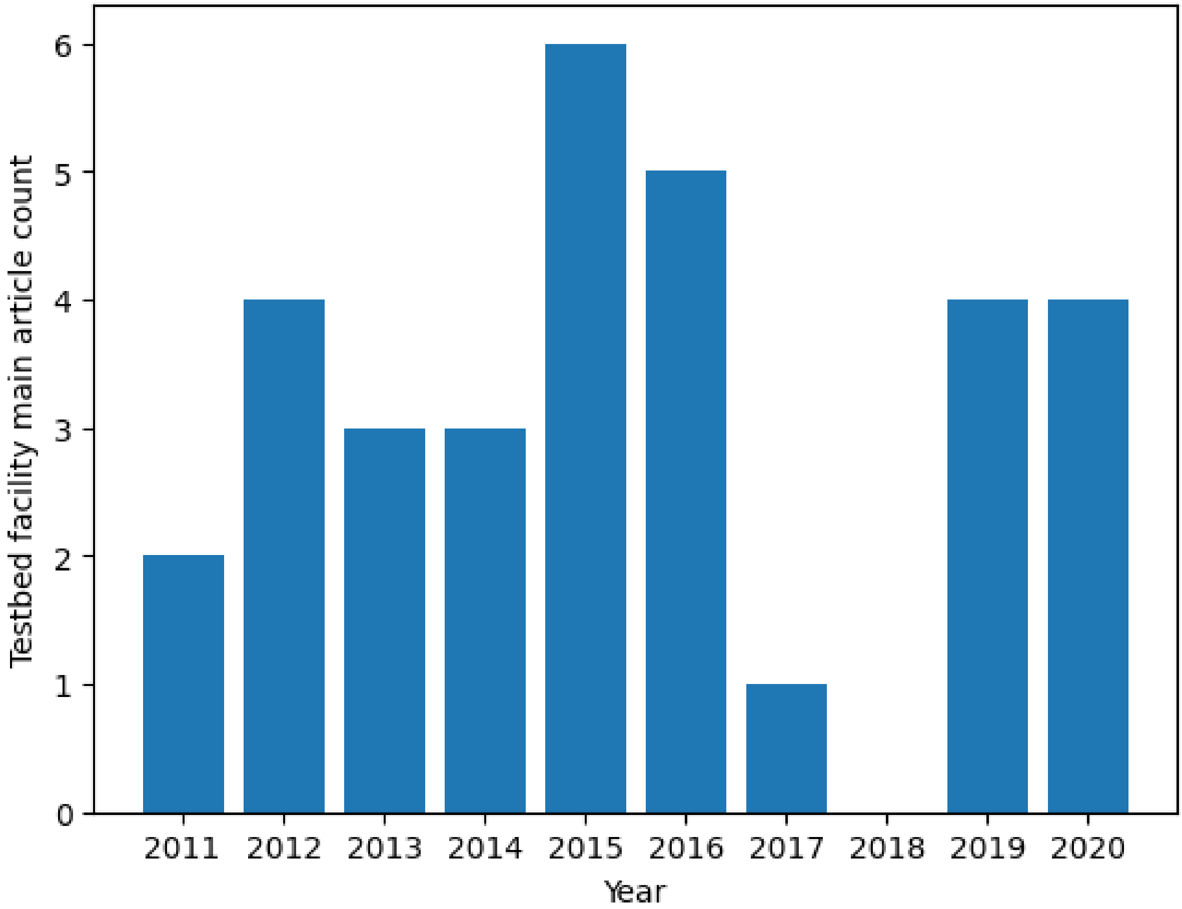


Figure 1.11: Testbed facility main articles by year

The overview of the available DUTs and sensors is shown in Table 1.19. The following assumptions should be kept in mind while reading the table:

- Any DUT that can not be commercially purchased or whose type is not stated in the article is considered as *Custom*;
- *Low Performance Embedded Devices (LPED)*: MSP430-based and similar devices mainly intended for battery-powered deployments;
- *High Performance Embedded Devices (HPED)*: ARM A8, M3, M4 and similar DUTs with considerable computational power;

- *Mobile Devices (MD)*: DUTs that are located on a mobile platform or are a mobile platform themselves;
- *Single Board Computers (SBC)*: devices like Raspberry Pi and similar, tablets and smartphones;
- For sensors and actuators the following categories were used:
  - *Inertial measurement unit (IMU)*: accelerometers, gyroscopes, and magnetometers;
  - *Acoustic*: acoustic and noise sensors;
  - *Air quality*: CO, CO2, dust, gas, smoke, etc.;
  - *Presence*: presence or proximity of an object or event, for example, door and window state, fire detection, car presence, etc.;
  - *Location*: GPS, line followers, hall encoders, etc.;
  - *Environment*: temperature, humidity, light, weather station, etc.;
  - *Energy*: energy consumption measurements of any third device;
  - *Actuators*: interaction with the real world in any perceived way;
- Not available (NA) means that there is no information about the count of the devices or sensors, but the article mentions that the testbed facility provides them.

An example of how to interpret the data from Table 1.19 for FIT IoT-LAB by [Adjih et al., 2015] would be the following:

- Devices Under Test:
  - 96 Custom, referred to in the article as generic host nodes;
  - 1144 LPED, referred to in the article as WSN430 open nodes;
  - 1488 HPED, referred to in the article as 938 M3 open nodes and 550 A8 open nodes;
  - 117 MD, referred to in the article as 85 Turtlebots and 32 Wifibots;
- Sensors and actuators:
  - 1488 IMU sensors, referred to in the article as:
    * 938 3-axis(gyro, accel, magnetometer) attached to M3 open nodes, 1 per node;

    * 550 3-axis(gyro, accel, magnetometer) attached to A8 open nodes, 1 per node;

- 1023 Presence sensors, referred to in the article as:
    * 938 Pressure sensors attached to M3 open nodes, 1 per node;
    * 85 Microsoft Kinect sensors attached to Turtlebot, 1 per node;
- 381 Location sensors, referred to in the article as:
    * 232 GPS sensors attached to M3 open nodes, not all nodes have this;
    * 85 odometers attached to Turtlebot, 1 per node;
    * 32 cameras attached to Wifibot, 1 per node;
    * 32 hall encoders attached to Wifibot, 1 per node;
- 4164 Environment sensors, referred to in the article as:
    * 1144 Temperature sensors attached to WSN430 open nodes, 1 per node;
    * 938 Temperature sensors attached to M3 open nodes, 1 per node;
    * 1144 Light sensors attached to WSN430 open nodes, 1 per node;
    * 938 Light sensors attached to M3 open nodes, 1 per node.

The most popular type of DUT amounting to more than half of available devices in testbed facilities is Custom (56.8%), considering that the development of a testbed facility itself is not a simple endeavor, developing custom DUT only adds to the total complexity. LPED (23.3%) and HPED (18.0%) are similarly represented and a relatively small amount of DUT types are MD (1.3%) and SBC (0.6%). The latter might be an unexplored opportunity for future testbed facilities.

Similarly as with the type of DUTs, the most dominant type of available sensors are Environmental (65.3%), followed by IMU (12.1%), Presence (8.7%), Acoustic (8.6%), Location (2.6%), Air quality (1.4%) and Energy (1.4%). The amount of actuators is quite low at only 2.2% of the total amount of sensors available.

	Device Under Test					Sensors and actuators							
Name	Custom	LPED	HPED	MD	SBC	IMU	Acoustic	Air quality	Presence	Location	Environment	Energy	Actuators
Dandelion	NA												
Open CLORO		NA							NA	NA			
FIST		NA								NA			
City of Things	NA							NA					
AssIuT AIoT		4									8		
TWECIS	4	NA											
Rover			8										
Ocean-TUNE UCONN testbed	10										6		
Multidimensional Internet of Things Testbed System					12		12	36			36		
WaIT			12										
ASNTbed		16							16		48		
EASITEST		20									40		
Fully reconfigurable plug-and-play Wireless Sensor Networks testbed	20												
MobiLab		20		1							60		
MOTEL		23									46		
Integrated Testbed for Cooperative Perception	21			6							21		
CaBIUs		30				30					90		
SDNWisebed		40									120		
I3ASensorBed		46						184	138		92	46	
OpenTestBed			80								160		
FlockLab	56	26	24							78			
EDI TestBed		110									330		
RT Lab		115											
Indriya		127				254	127				508		
NetEye		130									130		
USN Testbed	142	1				1	141			1	562		
LinkLab		100	50		5	45					235		45
SmartCampus		200			40		200				800	200	
PhyNetLab	350					350					1050		350
SensLab	1024						1024				2048		
FIT IoT-LAB	96	1144	1488	117		1488			1023	381	4164		
SmartSantander	3530						50	30	390		1176		
Total	**5253**	**2152**	**1662**	**124**	**57**	**2168**	**1554**	**250**	**1567**	**460**	**11730**	**246**	**395**

Table 1.19: Provided DUTs, sensors, and actuators

Exactly half of the testbed facilities (16) reviewed were found to be available, meaning that the approach described in Section 1.3 yielded some results regarding the testbed facility and it can be deemed still available, exact information about the availability of each testbed facility can be seen in Table 1.18. The data seems to suggest that there is a correlation between the size of the testbed facility expressed in provided DUT count and whether the testbed facility is available, with the larger testbed facilities more likely being available. Figure 1.12 shows the availability of the testbed facility against the rank of testbed facility by available DUT count, meaning that the smallest testbed facilities, with ranking starting from 1, are located to the left on the x-axis and largest testbed facility SmartSantander by [Sanchez et al., 2014] with the rank of 32, is the last on the right side.

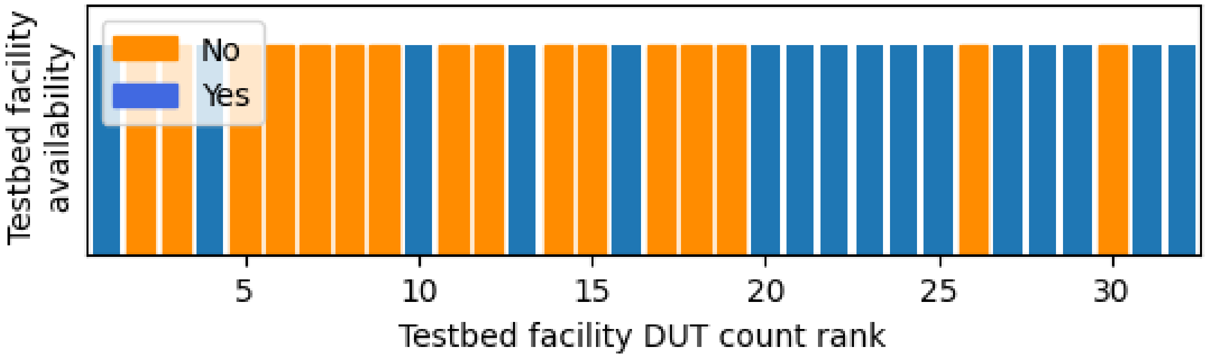


Figure 1.12: Testbed facility availability by DUT count ranking

Access level is the type of interface provided to the user, for 32 testbed facilities 39 data points were extracted about the access level as the testbed facility may provide multiple access levels.

The most popular access level for testbed facilities accounting for 69.2% was a dedicated user interface specifically developed for this purpose, which is expected. A considerable number of testbed facilities (20.5%) also provide API-based access, which would allow for automated and scripted interactions promoting repeatability and providing an easier way of running a large number of experiments for the scientific soundness of the research.

The SSH access is used by 3 (7.3%) testbed facilities and only one of them relies solely on an SSH connection. FIT IoT-LAB by [Adjih et al., 2015] has a dedicated UI, but as an added benefit provides SSH access to the most powerful sensor node in this testbed facility equipped with a Cortex-A8 processor capable of running Linux or Android operating system, this direct connection enables wider control over the hardware and is used for hardware-specific purposes and not general interaction with the testbed facility. ASNTbed by [Dludla et al., 2013] uses

SSH connection as a temporary access model while the web-based UI is being developed, as the provision of SSH access is easy and fast to set up. SensLab by [Burin des Rosiers et al., 2012] is the only testbed facility to use SSH as the primary and only planned access method, as it provides access to a remote virtual machine pre-configured with all the necessary tools needed for the user to interact with the testbed facility. To sum up, SSH access is not widespread for testbed facilities as it generally poses too many security risks, yet it is still tempting because of the ability to provide complete control over the DUT with minimal effort.

The only testbed facility where a VPN connection is used in conjunction with a GUI is Integrated Testbed for Cooperative Perception by [Jiménez-González et al., 2011] - a testbed facility for cooperative experiments involving mobile robots and WSNs. The VPN connection is used to secure communications and prevent potential uncontrolled and malicious remote access, as the additional layer of security provided by the VPN access is introduced because of the ability of testbed facility users to control several robot motion control functionalities such as low-level velocity control, local position control, trajectory following, etc.

The extracted data set provides 41 data points about the provided UI as the testbed facility may provide multiple UIs. The most popular UI, accounting for 39.0% (16), among testbed facilities is a GUI, followed by a web interface with 29.3% (12). This suggests that these testbed facilities are more tended toward non-expert users preferring easy-to-use and more intuitive interfaces. The usage of the CLI for user interaction is supported by 26.8% (11) testbed facilities, this is a trade-off between the ease of usage and intuitiveness to non-expert users and ease of usage for professional use cases where the interaction with the testbed facility must be seamless and easy to integrate into an existing workflow and/or automation. An exception to this would be a testbed facility providing both, a graphical or web based UI alongside an API access level or a CLI.

The only testbed facility to provide the UI with a mobile app is the smart city testbed facility SmartSantander by [Sanchez et al., 2014] and it is used to provide the users with the ability to subscribe to the data streams and alerts relevant to their proximity. SmartSantander also provides a Participatory Sensing mobile app that enables the users to become part of the testbed facility by providing sensed physical measurements along with any users' observations transmitted as text, images, or video. Along with the mobile application, the SmartSantander testbed facility also provides traditional user interaction possibilities by means of CLI and a web-based interface.

An unusual outlier is Fully reconfigurable plug-and-play Wireless Sensor Networks testbed by [Bekan et al., 2015] using RESTful API as a UI, it is used in a proof of concept reference implementation with the idea that when the proposed architecture is implemented into a fully-fledged testbed facility the approach for the UI is improved.

The extracted data set provides 32 data points about provided assistive tools, but this does not mean 1 to 1 correlation with testbed facility count as only 18 testbed facilities have any sort of assistive tools, as a single testbed facility may provide multiple assistive tools. The fact that only a small amount of testbed facilities provide a tutorial (6) or manual (4) means that the rest of the testbed facilities are not intent on actively attracting new users or alleviating the learning curve. There are a total of 7 distinct testbed facilities with some supportive material available, 3 of which contain both a tutorial and a manual.

To facilitate a deeper integration between the user code and the provided capabilities, 5 testbed facilities provide libraries for such integration. For example, FIT IoT-LAB by [Adjih et al., 2015] provides wireless communication libraries with simple and useful APIs for MAC protocol implementations.

Only two testbed facilities provide drivers as assistive tools to the users. FIT IoT-LAB by [Adjih et al., 2015] has developed and is maintaining OS-independent drivers to give access through an API to all hardware modules on the DUT. This is particularly useful for testing the envisioned system on a set of heterogeneous devices because, in theory, the users do not need to worry about device-specific implementations of their code provisioning a faster implementation path with the trade-off of code portability, as it will only work on the hardware supported by the FIT IoT-LAB team. SensLab by [Burin des Rosiers et al., 2012] also mentions the existence of drivers ready to be used with the SensLab testbed facility, unfortunately, no additional details about this integration are given in the articles.

For almost half of the testbed facilities (15) the articles do not mention what kind of backend architecture for interconnection of internal components is used. The same amount (15) testbed facility articles refer to the Star topology as the used architecture, where there is one central Server with multiple Workstations connected to it directly or through aggregators.

The only testbed facility to use mesh as architecture is SmartSantander by [Sanchez et al., 2014], where the used DUTs are provisioned to provide two separate communication channels, one is used for the experimentation by the users and the other provides the data channel for management and service functionality. The management and service communication channel use both single-hop and multi-hop to transfer data to the gateway and server via Digimesh (`https://www.digi.com/products/browse/digimesh`) enabled radio interface.

The only testbed facility to use a tree topology for the backend communications is the flexible and low-cost testbed testbed facility FIST by [Guo et al., 2012], it relies solely on the wireless connections provided by the TelosB DUTs and manages to use the same radio channel for the control of the sensor nodes as well as the needs of the experiment itself. This is achieved by dividing the software into two separate parts: Testbed Program Space and User Experimental Program Space, both of which coexist in the same device.

Only two testbed facility articles have provided the cost for the workstation and DUT, respectively 158 EUR for Indriya by [Doddavenkatappa et al., 2012] and 476 EUR for OpenTestBed by [Munoz et al., 2019]. The OpenTestBed has also provided a cost for the total implementation of the testbed facility which amounts to 9480 EUR. Overall the extracted data about the implementation cost is insufficient to provide any meaningful insight into the associated cost of developing a testbed facility.

The cost of implementation alone provides little value for trying to build a testbed facility, it needs to be accompanied by documentation and possibly open-source implementation details for software and hardware allowing to reproduce the testbed facility. From the aforementioned testbed facilities, only the Indriya implementation is fully open source, while OpenTestBed only published the hardware implementation. Altogether only 9 testbed facilities have provided their implementation as open source and previously mentioned OpenTestBed has published their hardware implementation as well. 23 testbed facilities do not provide any implementation details thus making it impossible to reproduce their work. If this could be addressed, it potentially would give a positive benefit to the testbed facility ecosystem allowing for a faster and more diverse expansion of testbed facilities based on previous knowledge and resources.

The only testbed facility with more than one facility location is SensLab by [Burin des Rosiers et al., 2012] which is composed of four WSNs distributed across France and interconnected by the Internet, with a total of 1024 sensor nodes.

JTAG is the most popular and powerful connection used for the debugging of the embedded software, but only 3 testbed facilities provide a JTAG connection interface to the DUT, this indicates that most of the testbed facilities are not focused on this kind of activities.

On the other hand, the most typical DUT connection interface used is USB, which is found on 22 testbed facilities.

PhyNetLab by [Venkatapathy et al., 2015] provides a custom 8-pin connection interface to integrate on the board together with the management platform, which is connected to the testbed facility backend by using a ZigBee connection. This approach was chosen in order to make the implementation effective and allow for precise current measurements and support for energy harvesting capabilities but limits any usage of other DUTs because they must admit to the custom 8-pin interface.

EASITEST by [Zhao et al., 2010] uses Ethernet or WiFi for the DUT connection as the used hardware is capable of providing this connection type for management purposes. This is quite unusual because typically testbed facilities use IP stack capable devices as gateways for less powerful devices to be used asDUTs. There are two different types of devices used as DUTs in EASITEST: a more powerful one with full Linux support and an MSP430-based device with an attached WiFi module.

Open CLORO by [Portaluri et al., 2019] uses a custom-made I2C communication over the RJ2 type connection to control a LEGO Mindstorms Platform which is used because of the limited connection capabilities of the chosen DUT.

Two distinct outliers who use low-rate wireless personal area network IEEE 802.15.4 for the connection interface for the DUT are the flexible and low-cost testbed facility FIST by [Guo et al., 2012] and a Fully reconfigurable plug-and-play Wireless Sensor Networks testbed by [Bekan et al., 2015]. They both are providing a wireless management channel, although each is using a somewhat different approach, as the first one is using two MAC stacks on top of the same physical layer and the second one is using two radio modules on the same sensor node. Both of the solutions claim that the approach has no effect on the user space of the wireless communication used in the experiments.

The only testbed facility to use Power over Ethernet (PoE) for the DUT connection interface is the USN testbed by [Mir et al., 2012]. The PoE provides a more capable and direct communication channel connection but noticeably limits the possible kinds of DUTs in the sensor network domain because PoE connection is not available on most of the devices.

Another exotic DUT connection interface is the RF link used in the Ocean-TUNE UCONN testbed by [Peng et al., 2014] because this testbed facility is located below buoys underwater and thus can not feasibly provide any wired connection. The testbed facility is aimed toward acoustic communication channel testing.

The extracted data set provides 17 data points about provided DUT interaction interfaces. Only 3 testbed facilities provide GPIO interaction capabilities for the DUT while the majority (13) use the standardized UART-to-USB interface for any interactions mainly by using bi-directional serial communication. The issue with providing more than the standard USB interaction interface is the necessity to manually connect the interface for each sensor node and possibly for each experiment, depending on the interface type.

There is one noteworthy distinction with the EDI TestBed by [Ruskuls et al., 2015], which provides a controllable 8-channel ADC and DAC to interact with the DUT, this is implemented in workstation hardware, which allows the user to use ADC to send analog signals to, and DAC to read signals from DUT. This feature allows for sensor data infusion into the embedded software for external sensor simulation, etc. or extraction of raw voltage data for verification purposes, etc.

The extracted data set provides 60 data points about DUT deployment locations as a single testbed facility can have multiple deployment locations, which all count. Most (45) of the DUTs deployments are located in the office environment. This directly corresponds to stepping away from the laboratory environment and usually corresponds to TRL5. The second popular deployment location with 14 deployments is outdoors in a city which allows for outdoor testing adding a new set of complexities for a sensor network to cope with. The only noteworthy exceptions are (i) PhyNetLab by [Venkatapathy et al., 2015], which is located in a materials handling research facility, and sensor nodes are attached to smart shipping containers thus it provides an ideal place to emulate sorting and picking applications typical to material handling facilities up TRL7 and (ii) Ocean-TUNE UCONN testbed by [Peng et al., 2014]providing a testing environment for underwater sensor networks. The DUT location accuracy with which the user knows where the DUT is located ranked high to low with corresponding testbed facility counts is as follows: Precise (5), Room (9), Building (9), Premises (5), Not specified (4).

The DUT deployment flexibility is the ability to place the deployment anywhere where it might be necessary, this does not include the ability to create the whole testbed facility in any location. The idea is that the testbed facility is capable of providing the infrastructure to allow temporary deployments in any reasonable location, excluding exotic and harmful environments such as underwater, outer space, etc. There are only 3 testbed facilities providing deployment flexibility, two of them, OpenTestBed by [Munoz et al., 2019] and Fully reconfigurable plug-and-play Wireless Sensor Networks testbed by [Bekan et al., 2015], are designed to provide deployments everywhere with the available power grid, but they do not provide a functioning testbed facility, as the articles are descriptions of testbed facilities providing reference implementations. Only EDI TestBed by [Ruskuls et al., 2015], with the additions described in this work, provides the workstations capable of supporting battery-powered temporary deployments in any location. This deployment requires a wired or wireless internet connection, but as the articles mention, it can be provided by a mobile hotspot.

A significant number of testbed facilities did not provide sufficient information regarding their geographic location or accessibility. Information about 16 testbed facilities was available online, indicating that there is an available angle of approach for users to get access. For 19 testbed facilities the exact location was determined, as shown in the map in Figure 1.13. There is a noticeable concentration of testbed facilities located in Europe.

Note: Blue markers - the exact location, red markers - the city of the location, and orange markers - the country of the location.

Figure 1.13: Map of all located testbed facilities.

Energy efficiency is one of the important aspects of WSN development, yet only 6 testbed facilities are providing current consumption measuring functionality: TWECIS by [Pötsch et al., 2014], FlockLab by [Lim et al., 2013], EDI TestBed by [Ruskuls et al., 2015], RT Lab by [Pradeep et al., 2015], SensLab by [Burin des Rosiers et al., 2012] and FIT IoT-LAB by [Adjih et al., 2015]. As shown in the overview in Table 1.20, the parameters differ and in some cases are not mentioned in the articles about testbed facilities. Another functionality related to current consumption is the adjustable voltage provided to the DUT, this is available only on FlockLab by [Lim et al., 2013] and EDI TestBed by [Ruskuls et al., 2015] allowing the simulation of battery discharge and observing the functionality of DUT with a decreasing voltage supply values significantly increasing the possible range of validation scenarios.

Testbed facility	Resolution	Frequency	Range
FIT IoT LAB	-	-	-
FlockLab	10nA	56kHz	-
SensLAB	10µA	1kHz	-
EDI TestBed	100µA	100kHz	0.1mA - 100mA
TWECIS	-	-	1µA - 100mA
RT Lab	-	-	-

Table 1.20: Testbed facilities with current consumption functionality

Summarizing the systematic review 32 testbed facilities multiple discussion-worthy challenges and considerations for the future ecosystem of WSN testbed facilities emerge.

The review highlights a challenge regarding the limited ability to replicate and reuse published testbed facilities for research purposes. To address this, the suggestion is to make the testbed facilities open source, provide cost estimates, and encourage other researchers to implement similar facilities. Connecting these testbed facilities could create a larger, shared testing environment. Only one such example, SensLab by [Burin des Rosiers et al., 2012] is distributed across multiple locations in France. Out of the examined testbed facilities, only 9 were open source, and just 8 offered sufficient supporting documentation like manuals and tutorials. Addressing these issues in futuretestbed facility designs is crucial to ensure their longevity, meaningful contributions, and active engagement within the community.

A significant challenge in WSN development is acquiring reliable ground truth data, particularly for measurements, communication, and location aspects. Ground truth represents precise and accurate measurements or determinations of specific parameters in a system, serving as the reference for other evaluations. Though certain testbed facilities offer ground truth data to some extent, many do not. It is advisable for future testbed facilities to consider incorporating reliable ground truth data as a crucial element. The accuracy and precision of sensors within WSNs can differ due to factors like cost, design, and calibration, causing notable measurement discrepancies. This challenges the establishment of reliable ground truth, but a testbed facility that offers verified environmental measurements through a side channel could aid inquiries about sensor calibration, optimal measurement frequency, and ensuring accurate measurements in a constrained environment. Furthermore, communication among sensor nodes in a network can be disrupted by various elements like interference, noise, and signal weakening. These issues can lead to data loss, corruption, or delays, adding to the challenge of establishing ground truth, but a testbed facility could furnish statistics on actual communication attempts, offer insights into the communication environment's attributes, or potentially simulate and replicate the communication environment's noise and related factors during testing. Lastly, sensor positioning, particularly in mobile sensor networks, presents another obstacle to establishing ground truth. Localization methods and timing can introduce errors, resulting in unreliable or partial details about sensor locations and their gathered data. A testbed facility could assist in overseeing and assessing the accuracy of estimated application-derived positions in relation to ground truth.

Among the examined testbed facilities deployments, the majority (48) were situated indoors, often simulating office building conditions, while a smaller portion (14) were located outdoors. Notably, only a single testbed facility, Ocean-TUNE UCONN testbed by [Peng et al., 2014] offered a unique environment specifically designed for underwater sensor networks. Diversifying the environments offered by testbed facilities brings numerous advantages. The location of a testbed facility significantly influences the range of possible experiments, including factors like temperature, pressure, altitude, and air quality, which vary across different geographic locations. While researchers might be eager to test their work in unconventional environments such as oceans, volcanoes, or even space, logistical and resource constraints might hinder their access to such environments. Enabling testing and validation in demanding environments holds value for the community due to its potential for more authentic real-world deployment scenarios and addressing challenges related to cost and accessibility. As a result, an increase in testbed facility offerings featuring diverse and challenging locations would be both encouraging and captivating.

Reflecting on the reviewed testbed facilities prompts the question: what constitutes an ideal ecosystem for WSN testbed facility? This ecosystem would facilitate the development and availability of testbed facilities to cater to the global research community's needs. Presently, the utilization of testbed facilities seems limited, as indicated by infrequent references to them in scientific publications. A related question emerges: what attributes define a testbed facility as a valuable and sought-after tool? This answer could revolve around factors such as hardware and software resources, research and development initiatives, and robust community support. Regarding hardware and software resources, an effective ecosystem for WSN testbed facility would encompass a wide range of devices, sensors, and networking equipment offering various communication channels and protocols. However, due to limitations, it's not feasible to incorporate all these elements into a single testbed facility. Thus, an optimal ecosystem would consist of a well-balanced and coordinated assortment of testbed facilities, each emphasizing specific aspects of hardware or software environments. Furthermore, if multiple testbed facilities support similar or compatible hardware, the ecosystem should facilitate their integration, enabling the creation of distributed testbed facility rather than focusing solely on individual sites.

In addition to hardware and software elements, a thriving and engaged community is crucial for an effective ecosystem for WSN testbed facility. This support fosters the growth and utilization of existing testbed facilities, facilitates networking and collaborative opportunities, provides access to training and educational resources, and backs events and conferences focused on testbed facilities. Such a community would also encourage research and development initiatives aimed at advancing testbed facilities. This might include support for open-source hardware and software projects, collaborations with industry stakeholders, and financing for research projects.

Although numerous testbed reviews exist, a centralized information hub (`https://www.fed4fire.eu/testbeds`) also offers comprehensive details about available testbeds across various domains not only limited to WSN and IoT. However, only SmartSantander by [Sanchez et al., 2014] among the 32 testbed facilities identified in this review is integrated into this hub, thus being accessible to a broader community. The exclusion from hubs like these can result in many testbed facilities being underutilized, supporting only a few projects and remaining inactive for extended periods.

1.4 Supply and demand of testbed facilities

The combination of the results of both systematic reviews about sensor network deployments described in Section 1.1 and WSN testbed facilities described in Section 1.2 give an opportunity to examine both the supply and demand in the WSN domain related to the testbed facilities. As a result, five observations are put forward.

Observation I - there is a demand for flexible deployment options, but not enough supply. Comparing the provided deployment locations of testbed facilities with the total amount of sensor network deployments it is visible that TRL5 is the most popular level (38.9%) for sensor network deployment taking advantage of testbeds and testbed facilities tend to provide TRL5 comparable deployment locations the most, as 75% are located in an office environment. Since TRL3 and below as well as TRL8 and above are not really the target for testbed facilities we need to examine what is necessary from testbed facilities to foster usage at TRL6 and TRL7. As TRL7 means ”system prototype demonstrated in the operational environment” as defined by the European Commission [Héder, 2017], the testbed facilities need to support deployments in any location to support TRL7. This can be achieved by providing flexible deployment options allowing the testbed facility workstations to be deployed independently with only minimal or no requirements from surrounding infrastructure.

Observation II - the demand for low-performance embedded devices in sensor network deployments is high, but supply from testbed facilities is lacking. According to the testbed facility review, only 23% of available DUTs are low-performance embedded devices, they are comparable to the simple devices described in the sensor network deployment review and are used exclusively in more than 77% of all deployments and for 13.6% more only base station was not a low power embedded device. This gap needs to be minimized in order to facilitate the usage of WSN testbed facilities.

Observation III - the supply of current consumption measurement functionality is low, but the demand is high. More than 93% of sensor network deployments are wireless and thus it is likely they most of them rely on batteries or energy harvesting technologies. The growing importance of the reduction of carbon emissions in the 21st century also implies that energy consumption should be optimized even if the source is the power grid. The combination of the aforementioned implies that the data about the current consumption is an important factor not only in the scale of a single device but in the WSN as a whole in order to push through to

TRL7 and beyond. Yet only 6 (18.75%) of the testbed facilities provide any means of current consumption measurements and the ones who do either do not provide related specifications or are not up to the task to measure the current consumption of the latest low-power IoT devices, as described in Section 3.2 in conjunction with the **Observation II**.

Observation IV - there is a large supply of custom devices in testbed facilities, but not enough demand. When comparing the provided DUTs by the testbed facilities and sensor nodes used in actual sensor network deployments, it is visible that more than 56% of nodes provided by the testbed facilities are custom-made, meaning that they can not be purchased off the shelf. Unfortunately, the sensor network deployment analysis does not provide information about the usage of custom devices. But one could argue that very few are willing to experiment on custom hardware provided by the third party because the custom platform: (i) may require a steep learning curve, (ii) is unlikely to be mature and bug-free, (iii) has very limited support, and (iv) is difficult to scale beyond the testbed facility, as reproduction is not as simple as ordering from the store.

Observation V - the potential demand for ease of usage is likely to rise, but the supply is very low. One of the possible ways to check the actual state of some technology is the Gartner hype cycle graph by [Linden and Fenn, 2003]. Taking into account the more than seven decades of the sensor network era and the selected period of five years for sensor network deployment review, the deployment distribution by years indicates that these five years match the phase #5—Plateau of Productivity. Expecting that the addressing of previously mentioned observations increases the usage of testbed facilities, they still possess some crucial flaws in order to facilitate the growth, namely the steep learning curve as indicated by the poor availability of assistive tools among testbed facilities and lack of integration options, as only 17 testbed facilities have a scriptable interface.

As shown by the sensor network deployment systematic review about the TRLs in Section 1.1, the most popular TRLs are from TRL4 to TRL7, therefore it only makes sense for testbed facilities to focus on research and development up to TRL7. TRL1 to TRL3 are not excluded because in order to achieve higher TRLs, the lower ones also need to be achieved. For TRL1 (basic principles observed) and TRL2 (technology concept formulated) typically only analytical studies are required, therefore no usage of testbed facility is necessary.

For TRL3 (experimental proof of concept) and TRL4 (technology validated in the laboratory) the testbed facilities should address the **Observation III** by providing a current measurement system. It is necessary to accurately assess the needed precision and range of the provided current measurement systems because as stated by the **Observation II**, low-performance embedded devices are widely used and one of the advantages they provide is the low current consumption allowing for extended deployments on battery power. A detailed investigation of this is provided in Section 3.2.

For TRL5 (technology validated in relevant environment), TRL6 (technology demonstrated in relevant environment), and TRL7 (system prototype demonstrated in operational environment) it is crucial for testbed facilities to address **Observation I** by providing flexible deployment options. Even if the testbed facility deployment can be considered a relevant environment in the scope of TRL5 and TRL6, it can not fulfill the role of the operational environment for general WSN deployment. **Observation IV** should be considered in order to avoid abstinence from the usage of testbed facility for the reason of manufacturer lock-in in the form of custom sensor nodes provided by the testbed facility.

In order to facilitate faster movement through the TRLs the testbed facilities should address the **Observation V** by providing: (i) a scriptable interface for automated execution of tests and the possibility to integrate into existing workflows and (ii) a user manual or tutorial, preferably both, to alleviate the initial learning curve of starting to use testbed facility.

To summarize, if a functionality set of a testbed facility contains at least a current measurement system, flexible deployment option, scriptable interface, and user manual, then the testbed facility supports WSN research and development up to TRL7. Table 1.21 provides information about the identified functionality between the testbed facilities from the systematic review described in Section 1.3. EDI TestBed is listed twice, as it is compared before the improvements described in Section 3 and after. For the user interface of a testbed facility to be scriptable it needs to support a command line interface or provide an API, then it is possible to write simple scripts for automated and repeated operations and integrate the interaction with the testbed facility in the existing workflow or integrated development environment of user's choice. In order for a testbed facility to provide assistance to the user it must contain a user manual or tutorial, or both. Investigation of the reviewed testbed facilities shows that none of them contains all of the identified functionality to support WSN research and development up to TRL7.

Testbed facility	Flexible deployment	Power consumption	Scriptable	User manual	Feature count
Dandelion					0
Open CLORO					0
FIST			CLI		1
City of Things testbed			API		1
Twecis		Provided	API		2
AssIuT-IoT			CLI	Tutorial	2
Rover					0
Ocean-TUNE UCONN			CLI		1
Multidimensional Internet of Things Testbed System			API		1
WaIT			CLI		1
ASNTbed			CLI		1
Estitest					0
Fully reconfigurable plug-and-play Wireless Sensor Networks testbed	Limited by power grid		API		2
MotiLab			CLI		1
MOTEL					0
Integrated Testbed for Cooperative Perception					0
CaBIUs					0
SDNWisebed					0
I3ASensorBed					0
OpenTestBed	Limited by power grid		CLI		2
FlockLab		Provided		Manual, Tutorial	2
EDI TestBed before this work		Provided			1
EDI TestBed after this work	**Unlimited**	**Provided**	**CLI, API**	**Manual, Tutorial**	**4**
RT Lab		Provided		Manual, Tutorial	2
Indriya				Manual	1
NetEye					0
USN Testbed					0
LinkLab			API		1
SmartCampus				Manual, Tutorial	1
PhyNetLab			API		1
SensLab		Provided	CLI	Tutorial	3
FIT IoT-LAB		Provided	CLI, API	Tutorial	3
SmartSantander			CLI		1

Table 1.21: Comparison of testbed facilities

2 EDI TESTBED FACILITY

As the baseline of this dissertation, the EDI WSN and IoT testbed facility (referred to as EDI TestBed in the text) have been used and improved to evaluate and approbate the proposed ideas. This section describes the initial idea and implementation of EDI TestBed (referred to as the original EDI TestBed in the text) as well as describes the basic structure and inner workings of the original EDI TestBed and the reasoning behind it. The author bears no contribution to the creation of the original idea of EDI TestBed and thus is not among the authors of the publication describing it [Ruskuls et al., 2015], but shortly after that, the author contributed to the implementation and development of the EDI TestBed, which is described in [Judvaitis et al., 2016; Lapsa et al., 2017]. This section uses materials from the author's publications [Judvaitis et al., 2016; Lapsa et al., 2017] and descriptions partly based on [Ruskuls et al., 2015].

2.1 Introduction

The beginning of EDI TestBed goes as far back as the year 2010 when [Ruskuls and Selavo, 2010] developed the prototyping test bench called EdiMote shown in Figure 2.1, a tool providing flexibility of prototyping, performance monitoring, and hardware and software

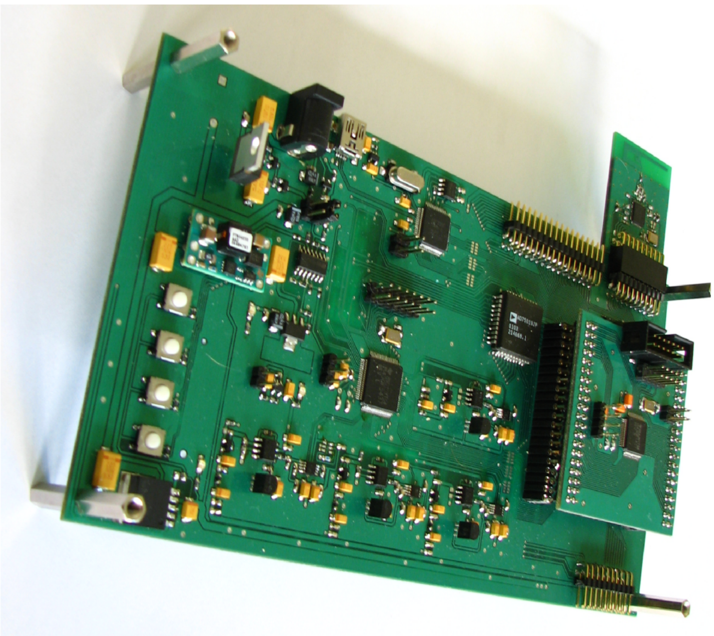


Figure 2.1: EdiMote prototyping and profiling board

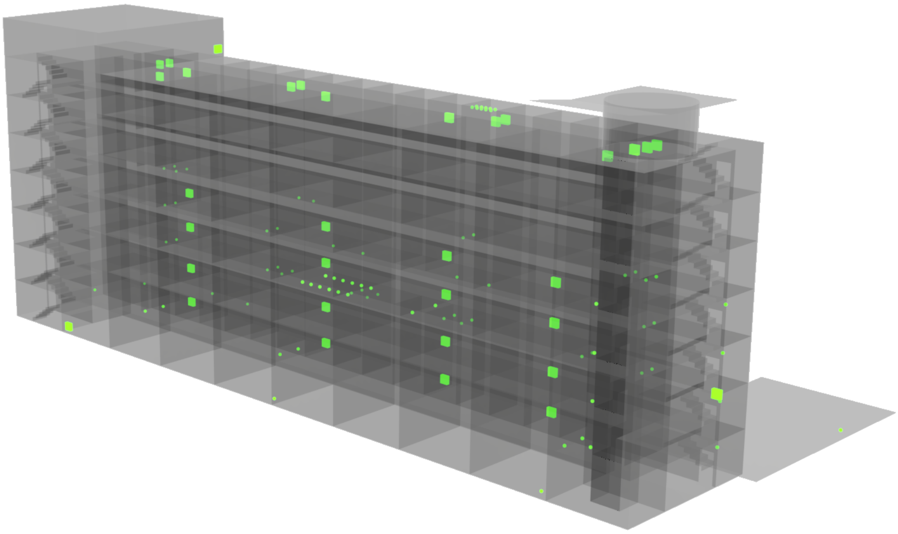


Figure 2.2: EDI TestBed sensor node locations at the EDI building

debugging assistance. Over the years the idea of EdiMote transformed and so the EDI TestBed was conceptualized, developed, and described by the same author [Ruskuls et al., 2015]. The initial goal of EDI TestBed was to address all the problems regarding the WSN design creating a universal WSN testbed facility.

The original EDI TestBed is a 100-sensor node testing facility, with 90 of the sensor nodes located in the premises of the EDI building across the 7 floors and 10 of the sensor nodes located outside in the territory adjacent to the EDI building in Riga, Latvia. The sensor node placement is shown in Figure 2.2.

2.2 Features

EDI TestBed provides a basic feature set of testbed facility as well as some niche features designed to ease the WSN prototyping. As one of the most important functionalities for a testbed facility the remote simultaneous reprogramming of all 100 connected DUTs is possible, as well as remote reading and writing to serial port and data logging. The outstanding functionality is provided by the developed Adapter which allows users to evaluate designed WSN system performance by providing additional information such as current consumption measurements and battery discharge simulation for up to two devices per Adapter, sensor data emulation, and signal logging and debugging.

The EDI TestBed contains 100 DUTs available without any additional hustle, described in Section 2.5, as well as the possibility for a user to connect any other USB compliant embedded device by using the provided connectors. For advanced users with specific needs, the modularity of the developed Adapter allows for the development of task-specific Adapter module which can be integrated into the existing EDI TestBed for added functionality.

2.3 Implementation

As the basis of EDI TestBed is the architecture proposed by the TKN Wireless Indoor Sensor network Testbed (TWIST) by [Handziski et al., 2006] was used with some modifications. The TWIST architecture as shown in the Figure 2.3 consists of four hierarchically ordered entities: (i) Sensor node, (ii) Super Node, (iii) Server, and (iv) Control Station, using Ethernet and USB connections. The main EDI TestBed differences from TWIST architecture are the extensive usage of Power-over-Ethernet over the USB connections and USB hubs and the aggregation of Server and Control Station tasks into the same entity.

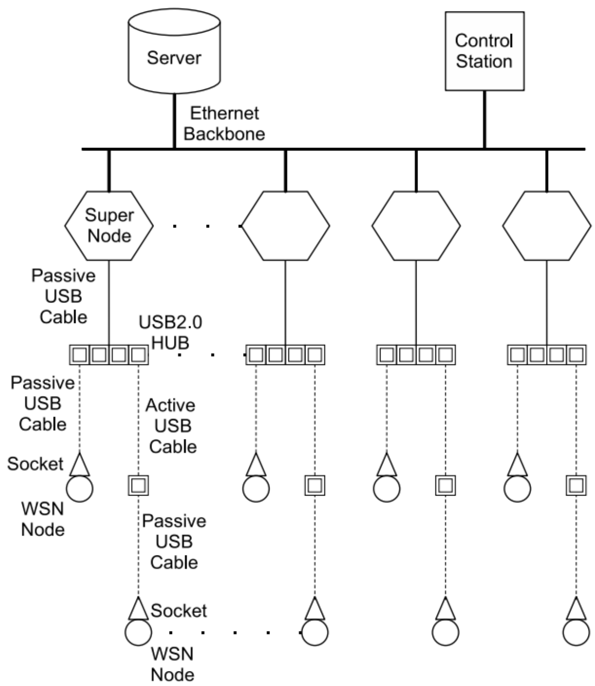


Figure 2.3: Hardware architecture of the TWIST testbed facility

The hardware architecture of EDI TestBed is shown in Figure 2.4. It consists of a single central server and a scalable count of Workstation, which are connected to the server by using Power-over-Ethernet switches in between them, this limits the maximum power consumption of a single EDI TestBed Workstation to 15.4W, consequently, this somewhat limits the hardware choices for the Workstations. The Power-over-Ethernet switches are placed in convenient locations to connect the Workstations in the corresponding floors to the EDI TestBed backend.

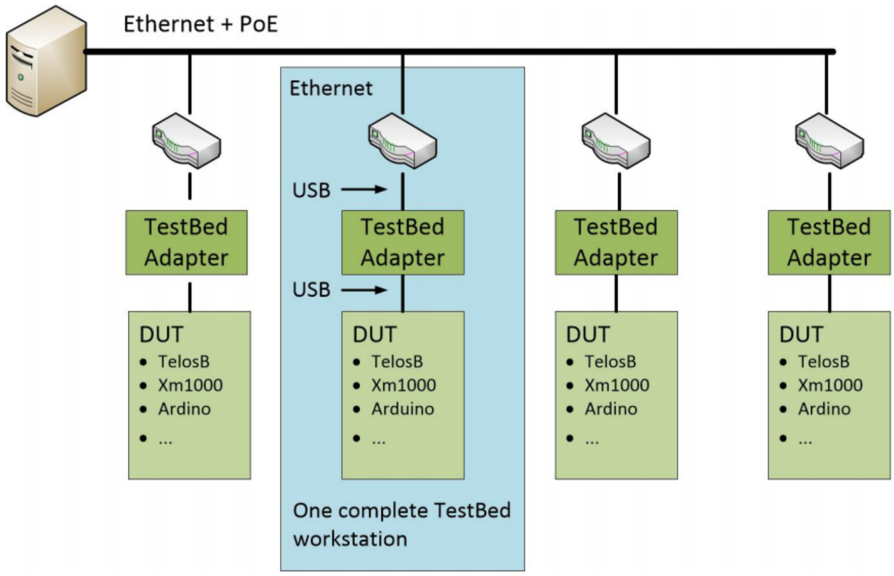


Figure 2.4: Hardware architecture of the EDI TestBed

EDI TestBed backend is controlled by a single server acting as a central point of the EDI TestBed backend network and it is the only gateway for any outside interactions with the Workstations.

EDI TestBed Workstation as shown in Figure 2.5 consists of three separate devices: (i) Manager, (ii) Adapter and (iii) DUT.

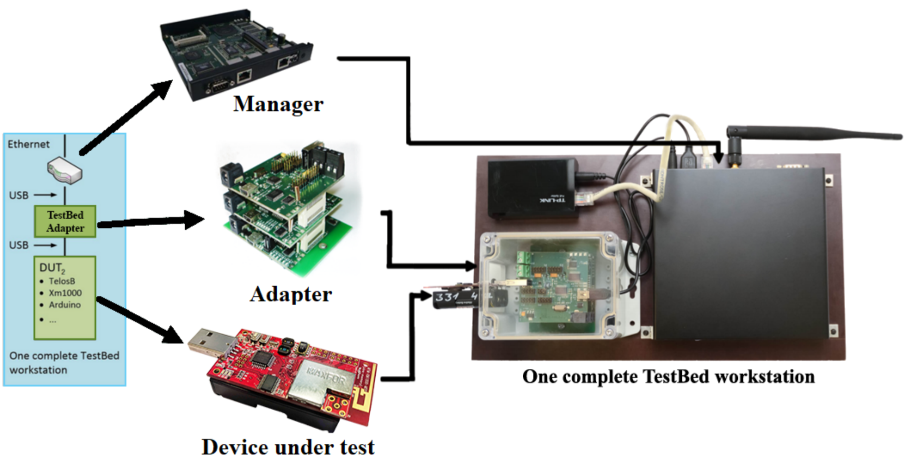


Figure 2.5: EDI TestBed Workstation

The **Manager** device serves as an end device of the EDI TestBed backend Ethernet network and manages the Workstation-specific tasks, it is capable of running Linux. Two types of devices were used in the original EDI TestBed implementation: (i) Alix2d2 router, consuming a maximum of 4W at Linux idle state and peaking at 10W, and (ii) Carambola2 router, consuming a maximum of 0.5W at Linux idle state and peaking at 3W. USB connection is used to connect the Adapter and DUT to the Manager.

The **Adapter** is a custom-made modular device initially made up of three modules but designed with the possibility to add more modules providing new functionality in the future. The three modules initially developed are named (i) Communication, (ii) Power Metering, and (iii) Data Acquisition modules. Due to the design choices only one of the modules located on the Adapter can use communication capabilities with the Manager at the same time, the reason for this is that they are all sharing the same USB connection, but they can still operate simultaneously and independently.

The **Communication module** is located at the top of the Adapter and contains (i) a USB hub to which DUT and Adapter are internally connected and (ii) all the pin headers required for Adapter and included modules. It can control the communication channels between Manager and other modules on the Adapter, as well as enable or disable power and data lines going to the DUT.

The **Power Metering module** is located in the middle of the Adapter and it contains the hardware necessary for the current consumption measurements and battery discharge simulation and an internal SD card connector for local data storage. To simulate the battery discharge for the DUT a low drop-out voltage regulator and digital potentiometer are used. The current consumption measurement range and accuracy are $0.1mA$–$100mA(+/-0.5\%/1.2nA)$. Voltage regulator range and accuracy is $0.47V$–$4.7V(+/-0.046\%/6mV)$. The sampling rate is approximately 12kHz and the burden voltage is about 70 mV.

The **Data Acquisition module** is located at the bottom of the Adapter and it contains 8 channel 12-bit analog-to-digital converter, 8 channel 12-bit digital-to-analog converter, and an internal SD card connector for local data storage.

As for the power consumption limitations, due to the limit imposed by the Power-over-Ethernet of 15.4W, the Workstations equipped with Alix2d2 routers can only support up to two USB devices, because the router itself can consume up to 10W of power and a USB 2.0 device can consume up to 2.5W of power. This means that the Alix2d2-based Workstations are already at the maximum capacity of possible DUTs because Adapter also counts as a USB device. The Workstations equipped with the Carambola2 routers can theoretically support up to 4 USB devices because the peak consumption of 3W leaves 12.4W for DUTs.

The software architecture of EDI TestBed is concentrated around the central server, but it aims to load balance the system so that in the case of scaling central server does not become a bottleneck. There are 5 software components: (i) Adapter software, (ii) Manager software, (iii) Backend software, (iv) Database, and (v) Web interface.

The **Adapter software** was written using MansOS by [Strazdins et al., 2010] and provides all the necessary functionality exposed by the modules located on the Adapter, as well as the module switching logic.

The **Manager software** was written using python2 and it (i) manages the data forwarding from Adapter modules and DUTs to the Database, this includes monitoring and management of USB ports as well as periodic Workstation status reports, and (ii) manages the execution of commands received from the Backend, such as reprogramming DUT, sending and receiving serial communication with Adapter and DUT and configuration of Adapter modules.

The **Backend software** was written using python2 and it serves as a control point of the whole EDI TestBed system. The design goal was to keep as much of the computational load away from Backend and move it to the Manager and Database for improved scaling capabilities. The tasks performed by the Backend are mostly data forwarding, user management, and system status related.

The **Database** was based on PostgreSQL, it stores all the active Workstation, user, and experiment information as well as log files from the performed experiments.

The **Web interface** was written using python2 and it serves as the gateway for the user to interact with the data stored in the Database and DUTs and Adapter located in the Workstations through the Backend. The design of the Web interface is shown in Figure 2.6, it provides easy to use interface for development and experiment control, including the following functionality:

- Code editor with code highlighting, code folding, and auto-complete embedded in the browser;
- Code compilation for different microcontroller architectures such as MSP430, XM1000, Atmel, and others;

- Monitoring of data streams from Workstations or system, for example, compilation logs;
- Simultaneous reprogramming of DUTs, with the possibility to provide different applications for specific DUTs;
- Accessing the functionality provided by the Adapter on each Workstation;
- Asynchronous communication with the DUTs through the Serial connection;
- Long-term logging of ongoing experiments and past log file downloads.

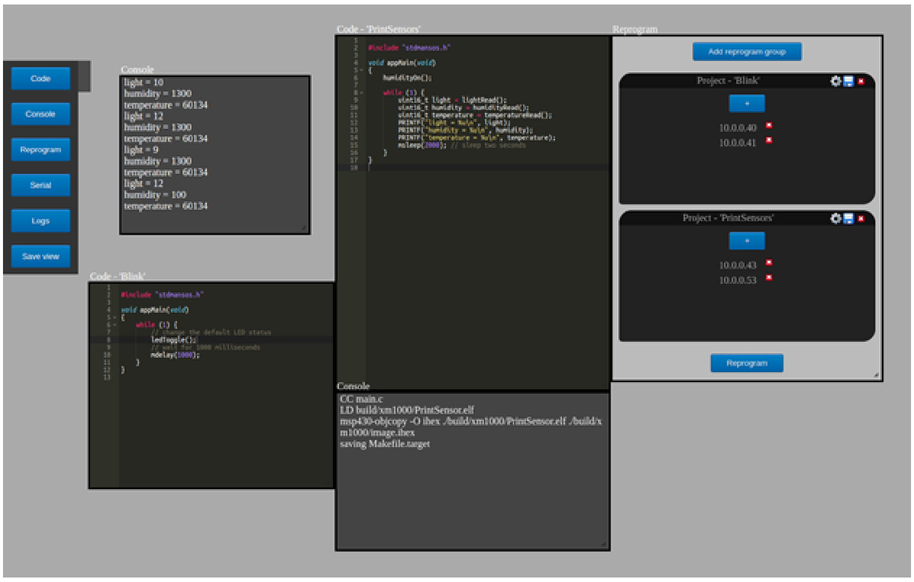


Figure 2.6: EDI TestBed Web interface

The data management task is divided into five logical steps that directly correspond to the EDI TestBed data flow architecture:

1. Data generation on Adapter and DUT;
2. Data gathering on Manager;
3. Data processing on Manager;
4. Data representation on the web interface.

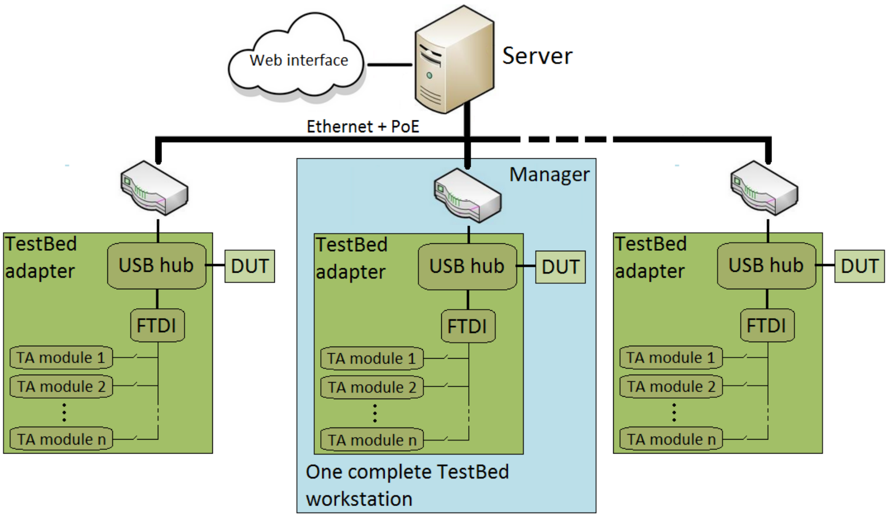


Figure 2.7: EDI TestBed data flow architecture

All of the interesting data is generated or acquired at the DUT or Adapter, both of which are connected to the Manager via USB cable. As you can see in Figure 2.7, technically DUT is connected to Adapter, but since Adapter includes a USB hub, the DUT can be accessed as a different USB port from the Manager, so the data can be gathered from DUT and Adapter simultaneously.

To access Adapter modules it is needed to switch between them since Manager has only one USB connection to the Adapter itself, but multiple modules are located on the Adapter. To solve this Adapter contains software controllable switches on UART lines after the FTDI chip, allowing to enable or disable communication to each Adapter module individually, but because modules are sharing the same USB connection to the Manager only one module can be active at any given time.

To make the communication protocol between Manager and Adapter modules robust and scalable High-Level Data Link Control (ISO 13239) style packets are used, the packet format for both directions is shown in Table 2.1.

1 byte	1 byte	1 byte	n bytes	2 bytes	1 byte
Start flag	Length	Command	Payload	CRC	End flag

Table 2.1: Data packet structure for Manager and Adapter module communication

The total length of the data packet not counting the flags is length + 4 bytes. 2-byte Cyclic Redundancy Check (CRC) is used to ensure that received data are valid. Field *command* defines what kind of command/data is transmitted and field *payload* contains data transmitted or command parameters depending on the command.

Not all modules have the same requirements regarding data flow, understanding where the most of generated data comes from helps to understand how to build an optimal Adapter data management life-cycle.

The Communication module contains only a few switches controllable by software for the DUT control and serves as the controller for UART line switching e.g. enabling or disabling communication for other Adapter modules and thus it needs negligible bandwidth.

The Power Metering module contains an analog-to-digital converter for the DUT current consumption estimation and a digital potentiometer for battery discharge simulation. Battery discharge simulation is controlled by providing the discharge rate throughout the experiment or providing a constant battery voltage at certain experiment points, it requires negligible bandwidth to operate. The analog-to-digital converter on the Power Metering module has 1 channel with 16-bit resolution and it can operate with frequencies up to 500 kHz, which means that the maximum theoretical bandwidth it can produce is 1 MB/s. When performing the tests on the actual Power Metering module the maximum data bandwidth achieved was 600.2 KB/s, this is due to the bottle-necking of the chosen microcontroller *MSP430F247*, which lacks the performance to forward data from analog-to-digital converter to the UART line.

The Data Acquisition module is responsible for external signal generation and capturing with regards to DUT operation. Analog-to-digital converter located on this module has 8 channels, each channel has 12 bit resolution and it can operate with frequencies up to 1 MHz, which means that the maximum theoretical bandwidth each channel can produce is 1.5 MB/s, leading to total maximum theoretical bandwidth of 12 MB/s. When performing the tests on the actual analog-to-digital converter located on the Data Acquisition module by reading all 8 channels sequentially the maximum data bandwidth achieved was 187.8 KB/s, this again is due to the bottle-necking same as seen on the Power Metering module. Digital-to-analog converter located on this module has 8 channels, each channel has a 12-bit resolution and it can be controlled by setting the output value pattern for each channel or controlling each channel during the course of the experiment, either way, the bandwidth necessary is negligible. The Data Acquisition module differs from other modules since it has two FTDI chips, so it basically consists of two logical modules on a single physical module, meaning that for the aforementioned UART line switching between the modules, these are two separate modules referred in the text as *ADC* and *DAC* modules respectively.

Because of the separate USB connections to Adapter and DUT, it is possible to read data from both of them simultaneously. Handling data acquisition from Adapter modules is not trivial because there is only one USB connection, but 4 logical modules providing data and accepting configuration messages. This can be solved by using the UART line switch and communicating with each Adapter module in turns. This means, that it is not possible for Adapter modules to send data whenever they have anything to send and expect the Manager to receive the data, because it is not possible to assure that the UART lines are connected. It is necessary to develop a communication protocol where Manager asks for data to Adapter modules and Adapter modules respond only when asked, forming a master-slave communication protocol.

To ensure that no data is lost the communication protocol is implemented in such a way that after the request for data has been sent to the Adapter module, Manager waits for a response, and if no response is received in some defined time, Manager retries the request up to 3 times. If there is no response after 3 retries it is assumed that the current Adapter module has malfunctioned, there are two possible scenarios after such an event. If the experiment supervisor has allowed restarting of malfunctioning Adapter modules, the restart command is sent to the malfunctioning Adapter module and after that, the experiment continues as planned. But sometimes there might be some very important data saved on the Adapter module and it is possible that the malfunctioning Adapter is continuing to work and only the communication part has failed, so the experiment supervisor has forbidden to restart the Adapter modules and after the end of the experiment, SD card of the Adapter module can be manually examined to understand what exactly caused the malfunction and scavenge any usable data the malfunctioning module may have saved.

To evaluate the bandwidth between the Manager and Adapter multiple tests were performed using different test scenarios and payload sizes, from 5 to 255 bytes with the step of 5 bytes. The results are shown in Figure 2.8. Testing was done using constant data stored in the Adapter module microcontroller memory, before every message sent by Manager the target Adapter module was switched to ensure that the correct module is selected, this is also applied to tests where only one Adapter module was used. Each test with a different payload size was continued until at least 10 KB of data was transferred. These tests were performed for each Adapter module except the Communication module. A mixed test was also performed, where a random Adapter module was chosen for each message, for example, when using a payload size of 100 bytes, it is needed to send 100 messages to send a total of 10 KB of data, so for each of those 100 messages a random target Adapter module was used.

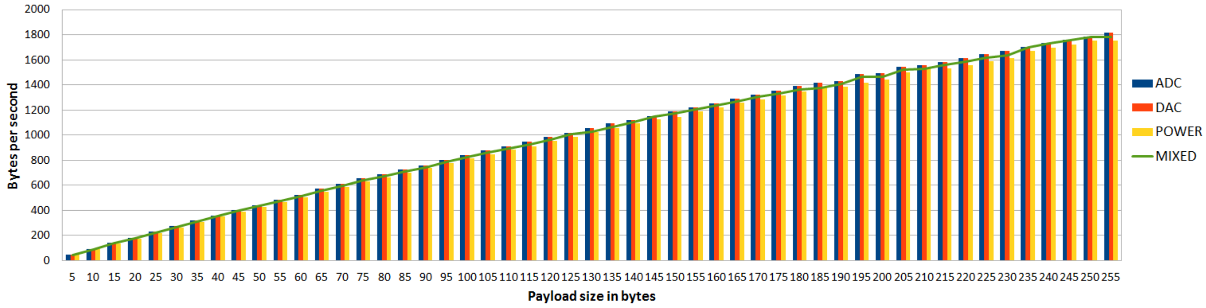


Figure 2.8: Bandwidth measurements between Manager and Adapter

The results show that there is no noticeable bandwidth difference between Adapter modules. Also, it is clear that when using mixed data sending, it does not affect bandwidth, so it is not needed to worry about very careful scheduling of module switching. As expected, at larger payload sizes the bandwidth increases because the ratio between payload and overhead increases. When using a payload of 255 bytes, it is possible to achieve a bandwidth of approximately 1.8 KB/s, which is way less than the bandwidth theoretically produced by Adapter modules, as described in Section 2.3. This means that in order not to lose gathered data some form of processing is necessary before the data are sent to Manager, for example, it would be possible to send some average values over time or send only the relative differences when they occur.

Every message received by the Manager must be parsed in order to structure and save necessary data. The Manager also adds timestamps to every received message. Parsing is not very performance heavy but it can cause problems if carried out on a great scale on a single central server, especially if the data to be parsed are made up of a relatively big argument list, for example, a large vector or matrix. To tackle this problem and introduce more scalability to the EDI TestBed a decision was made to perform all necessary data parsing and structuring on Manager devices and since all the data are parsed and structured, the Manager connects directly to the database and calls save query on parsed data every time new data is available. This way not only some load is taken off from the central server, but independent connectivity provides easier network expansion and better device health monitoring because the Manager automatically adds itself to the database as connected and the state of the device can be monitored. This solution allows for the distribution of computational load and reduced data flow in the network.

Data parsing speed on Manager devices is so effective that it is challenging to generate data sets that would create a noticeable lag. Roughly one millisecond of processing time is needed for 1000 elements with 3 arguments each. In a real-life scenario, the connected devices can not generate data sets of that size in such a short time. The only time when incoming data can grow larger than 1000 elements is when the Adapter returns gathered data sets from a long period of time - energy consumption, etc. But because it happens over a large time span it is not even close enough for a system slowdown and thus growth of the task queue is not likely to happen. Writing to the database directly from Manager takes about 9 to 10 ms, depending on the data set size. By structuring the data path in this manner Manager device becomes independent from the central server and keeps open the possibility of multiple central servers in the future.

Every data set stored in the database can be visualized in the web interface. When the call for data visualization is made, a query is sent to the database and the received data is drawn in the necessary format and it is also refreshed dynamically. Gathered data is streamed to the user web interface session in near real-time. It is done by requesting the data from the central server by sending AJAX requests for changes in the data set every 300 ms, this kind of solution does generate overhead which can be avoided by using web socket technology, but it would put more computational pressure on the central server and heavily increase the overall system complexity.

Data representation can be divided into two time-consuming actions: (i) loading and visualizing already existing data from the database, and (ii) refreshing the data set while it is being viewed by the user. For both actions elapsed time consists of an initial AJAX call, reading from the database, data parsing, and callback execution. Tests were carried out on a local network with an initial data set of 1000 elements and 3 new elements added every second. AJAX requests and callbacks tend to run in a time frame between 30 to 50 ms, but, of course, it is heavily dependent on network speed and data set size. Database read speed is about one millisecond for 10 elements and is also almost identical in both actions. Data parsing happens in an instant - one millisecond for 1000 elements. As mentioned before, data is only requested from the central server once every 300ms which is the main slowdown in data refreshing.

2.4 Current consumption measurement system

One of the main distinctive functionalities offered by EDI TestBed differentiating it from the rest of available testbed facilities at the time was the current consumption measurement capability and it was heavily emphasized. EDI TestBed Adapter power meter circuitry uses the shunt ammeter measuring method, compared to other techniques [Handbook, 2004; Forghani-Zadeh and Rincon-Mora, 2002], this was a cost-effective and most applicable solution. The calculations of the system performance characteristics confirmed that it is fully adequate to the set requirements. The goal was to measure both the current of the DUT in active mode up to 100mA and the current in the microprocessor's sleep mode. Block diagram of the experimental power supply and current consumption measuring unit is shown in Figure 2.9, it can be divided into four parts:

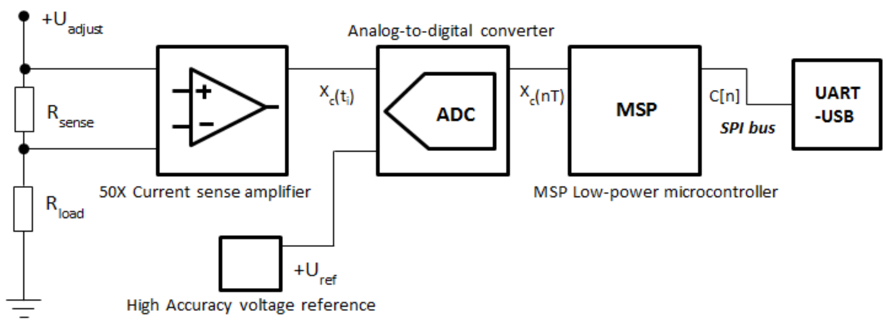


Figure 2.9: Basic block diagram of current measurement circuit

- Power supply system;
- Low voltage sensing and analog amplification system;
- Analog to digital converter;
- Digital data processing and broadcasting;

The Adapter can be powered by stabilized DC voltage $+5V$ in two ways: (i) from any external source $+5V_{ext}$ or (ii) from USB connection $+5V_{USB}$ across the switch, controlled from USB UART type $FT232R$. Both voltage inputs have been separated by diodes, so the output voltage is $+U_0 = +4.5V$, connected to the input of an adjustable stabilizer A_3 and to the supply input of an electronic potentiometer A_4. Electronic potentiometer A_4 serves as one of the feedback divider resistors for stabilizer A_3 and the value of A_4 resistance can be controlled by software from the main micro-controller across the I2C interface. This provides the possibility to choose stabilizer A_3 output voltage $U_{adj.out}$, which is the supply voltage for all DUTs, in the range from $+0.78V$ to $+4.7V$. This supply voltage $A_{adj.out}$ must be switched on by signal $TestPowEN$ from the main micro-controller and connected to two identical current consumption measuring channels in supply circuits of two DUTs. The electric schematic is represented in Figure 2.10. The adjustable voltage functionality allows for battery discharge simulation by artificially lowering the supply voltage passed to the DUT.

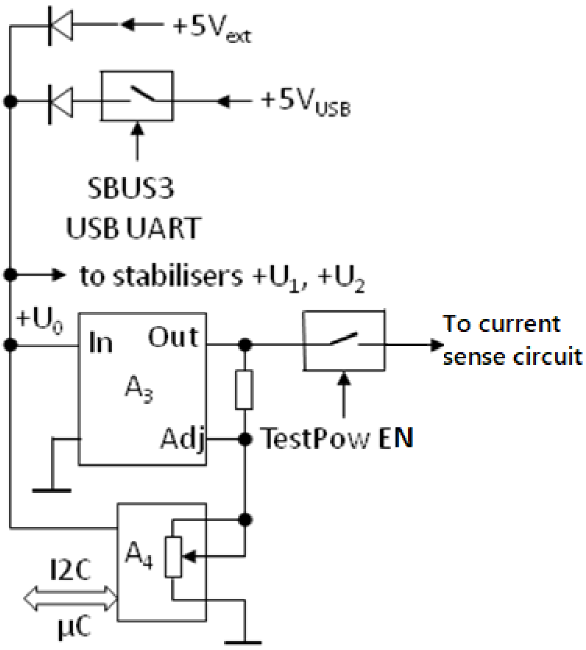


Figure 2.10: Adapter power supply unit for Power Metering module

From the left side in Figure 2.9 the low voltage sensing and amplification circuitry is depicted. More specific details of the circuitry are presented in Figure 2.11, where each of the current consumption measurement channels consists of logic inverter A_1, two precise resistors $R_1 = 10\Omega$ and $R_2 = 0.82\Omega$ and differential amplifier A_2 with a constant gain of 50. One end of the resistors R_1 and R_2 is connected to the voltage $+U_{adj.out}$ and to the positive input of the amplifier A_2. The other end of resistors R_1 and R_2 connected together across the two reed relays, to the negative input of amplifier A_2 and to the positive supply voltage input of the DUT in the relevant channel. The output of inverter A_1 is connected to the control input of the switch in circuit R_1, but digital control signal $PWRCHx_{res.sel}$ is connected to the input of inverter A_1 and to control input of the switch in circuit R_2. Two different values of measurement resistor are necessary for having more wide range of measured currents, the current setup allows for the measured current to be in the range from $0.1mA$ to $100mA$.

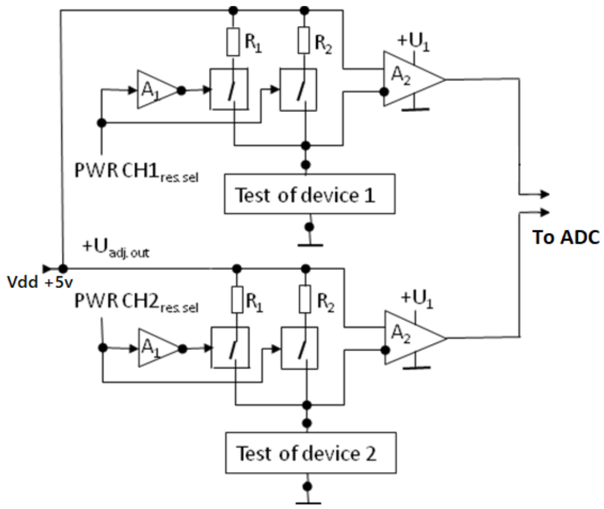


Figure 2.11: Current sense amplifier schematic

The voltage drop across the shunt resistor R_{sense} is the actual value that is amplified by the current sense amplifier and used to calculate the current flow in the load circuit. The circuit diagram is presented in Equation 1. Labels of equations are related to the Figure 2.9, where Q is the number of quantization bits, $C[n]$ is a continuous-time signal, $X_c(t_i)$ is a binary formed data, but during measuring process, this value has been changed, $X_c(nT) = X_c[n]$ as data samples with a specific frequency. $X_c(t)$ is an analog value of the line received by the analog-to-digital converter.

$$I_{sense} = (X_c[n] \cdot Q) \cdot \frac{1}{50} \cdot \frac{1}{R_{sense}} \tag{1}$$

Analog-to-digital converter schematic is shown in Figure 2.12. Amplifier A_2 outputs from both test channels are connected to the positive analog input of an analog-to-digital converter ADC type across the internal multiplexer MUX. The negative analog input of ADC is connected to the ground and positive reference voltage $U_{ref} = +4,096V$ from voltage standard type is connected to the relevant input of ADC. The analog part of ADC is supplied by the voltage $U_1 = +4,3V$, but digital control and output part by voltage $U_2 = +3.3V$. Both voltages U_1 and U_2 are stabilized on separate stabilizers from voltage $+U_0$. All digital control signals and ADC digital output signals are connected to the main micro-controller by SPI interface where the data are processed and transferred to the Manager or stored in an external SD card.

The quantization bit value is estimated by Equation 2, based on [Ott, 1988; Johansson, 2013] and on the second part of the circuit shown in Figure 2.12, where the analog-to-digital converter process involves systematic error known as quantization error. U_{ref} is reference voltage provided to ADC and powered by the value of analog-to-digital converter bit resolution number.

$$Q = \frac{U_{ref}}{2^{bit}} \tag{2}$$

To detect and calculate the error of precise current flowing in the main circuit, Agilent DMM was used by connecting it in series with the Power Meter module and the load for which a resistor was used. To validate that the measured current consumption value is obtained as precisely as needed, a lot of experiments were carried out with the XM1000 sensor node acting as an active load. Comparison is shown in Table 2.2, but EDI TestBed Adapter has many other parameters that can't be directly compared to the other units, like the modular structure of the Adapter and multi-functionality of debugging DUTs. The Adapter was specially designed to access all necessary parameters of the DUT to ease the debugging of hardware and software and to improve the operating efficiency.

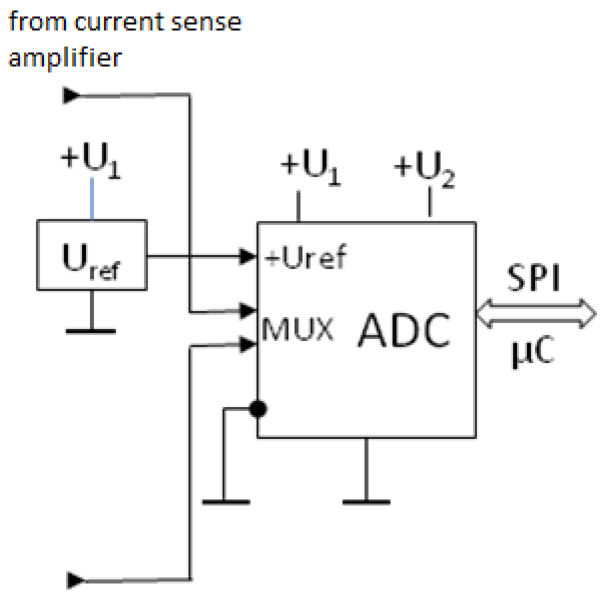


Figure 2.12: Analog to digital converter schematic

	TestBed Adapter		Agilent 34460A		RocketLogger	
Voltage dynamic range/accuracy	1.2mV - 5V	0.046% +0.006V	100mV - 1000V with 1nV res	0.004% + 0.006V	6uV - 5.5V	0.02% + 13uV
Current dynamic range/accuracy	0.1uA - 100mA	0.5% + 1.2nA	100uA - 3A with 1 nA res	0.01% + 0.02A	1nA - 500mA	0.09% + 4nA
Sampling rate	∼12.75kHz		1kHz		64kSPS	
Input resistance			10MΩ or >10GΩ		∼1TΩ	
Burden voltage	∼70mV		0.011V - 2V		∼53mV	
Form factor	Portable and stationary		Stationary laboratory device		Portable	
Power supply	PoE connection required		Wall plug required		Battery powered	
Remote measurement	Full control		Full control		Acquisition management and control	
Environmental logging	DUT data logging		Temperature only		Digital sensor bus	
Extendable	Closed, proprietary		Closed, proprietary		Linux compatible	
Cost range (estimated per channel)	∼100$		4000-7000$		∼50$	

Table 2.2: EDI TestBed Adapter compared to existing current consumption logging alternatives in this field.

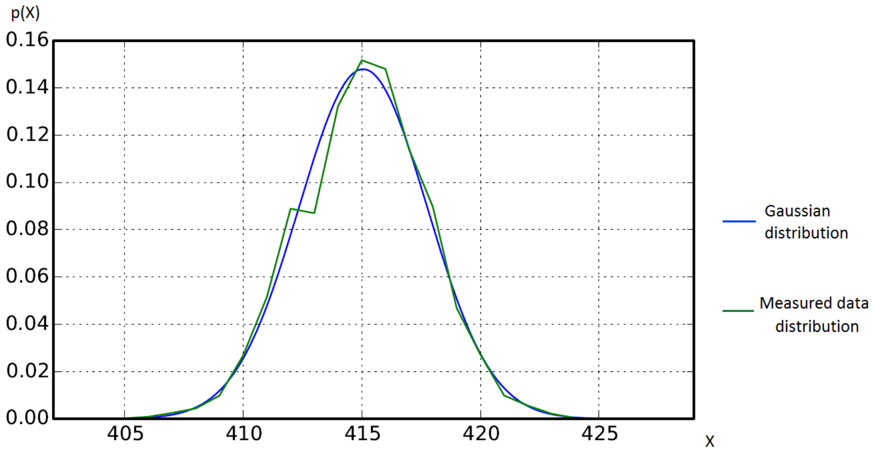
In experiments with different loads, to evaluate the accuracy of the Power Meter module, an error was constant 0.4% of signal, using high accuracy current measuring unit in the circuit. A simple example is shown in Table 2.3, where I_{ref} is the measured value with high accuracy current measuring unit, but $I_{measured}$ is the mean value from the data stream. Relative error was calculated using Equation 3.

Average ADC value	I_{ref}	$I_{measured}$	Error
126.0	0.0000157	0.0000158	0.376%
162.8	0.0000203	0.0000204	0.381%
403.3	0.0000502	0.0000504	0.384%
1036.1	0.0001290	0.0001295	0.403%

Table 2.3: Examples of measurement results

$$Error = \frac{I_{ref} - I_{measured}}{I_{measured}} \tag{3}$$

In the calculation of the systematic error of the measured signal, the direct component caused by the current sense circuit in the analog part of the circuit must be accounted for. To get this value measurements with an open circuit in the current-sense part must be made without any load. After the measurements, the aforementioned direct component must be subtracted from the $mean(X_i)$ value.



Note: Measured probability density function - green line. Gaussian distribution for measured dispersion σ and mean value $\bar{X}$ - blue line.

Figure 2.13: Measured probability density function vs calculated Gaussian distribution for measured dispersion

Even after this calculation eliminates the systematic error, this value still contains noise and electrical disturbance. It is easy to calculate and compare the data after using the formula from Equation 4, but to determine the nature of the error, the most common solution is processing data with a Gaussian distribution and standard deviation functions. In Figure 2.13 two lines are shown, the blue line is calculated using the Gaussian distribution function, but the green line presents a measured data probability density function.

$$X_c(t_i) = mean(X_i) = \frac{1}{N}\sum_{i=1}^{n} X_i \tag{4}$$

When measuring very small current, wire length in a circuit is important [Handbook, 2004]. It involves noise from electromagnetic fields around the room or even from the PCB traces. Reference voltage steadiness is also important, otherwise, it introduces more noise into the system. A simple method how to detect the error of reference voltage is to add a voltage divider from the reference source to the analog-to-digital converter input, this will show the behavior of the reference voltage.

To improve the accuracy and quality of the measured data and acquire the relevant values, it is essential to apply post-processing techniques when a large collection of data is processed. Usually, the actual value is not in the individual numbers, but rather in certain descriptive quantities such as the average or the median. Power meter module measuring system results are obtained using averaging and the Gaussian distribution functions as explained in more detail in the material by [Ott, 1988].

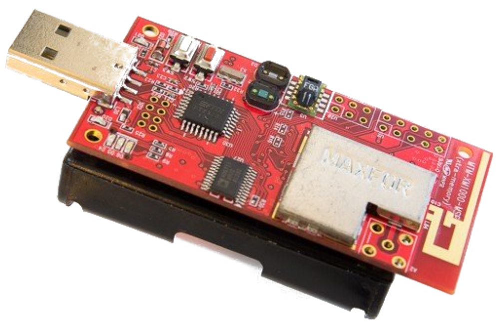
2.5 Devices Under Test

Theoretically, any embedded device supporting a USB connection can be used with EDI TestBed, but as the default devices to perform experiments on two different devices are available: (i) Advanticsys XM1000 [Environmental Expert, 2021] sensor node and (ii) Zolertia Z1 [Zolertia, 2010] sensor node, with no additional attachments. Both of the provided sensor nodes are based on the popular TelosB platform [Polastre et al., 2005] which is a typical representation of value-based choice for WSN experiments during the decade after its publication in the year 2005 and provide similar features, the only major distinction is in the included on-board sensors.

Advanticsys XM1000 sensor node shown in Figure 2.14 is equipped with Texas Instruments MSP430F2618 microcontroller, 116 KB flash, 8KB RAM, 1MB external flash memory for storage, a 12bit analog to digital converter with 8 separate channels, IEEE 802.15.4 compliant Texas Instruments CC2420 radio chip operating on 2.4GHz frequency band and 3 sensors:

- Light sensor Hamamatsu S1087 for visible light range measurements;
- Light sensor Hamamatsu S1087-01 for visible and infrared light range;
- Temperature and humidity sensor Sensirion SHT11.

Zolertia Z1 sensor node shown in Figure 2.15 is equipped with a Texas Instruments MSP430F2617 microcontroller, 92KB flash, 8KB RAM, 2MB external flash memory for

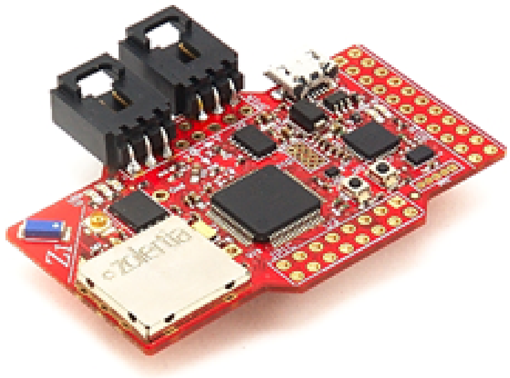


Source: [The TRINITY network, 2023]

Figure 2.14: Advanticsys XM1000 sensor node

storage, IEEE 802.15.4 compliant Texas Instruments CC2420 radio chip operating on 2.4GHz frequency band and 2 sensors:

- Accelerometer Analog devices ADXL345 for gravity, motion, and shock measurements;
- Temperature sensor Texas Instruments TMP102.



Source: [Zolertia, 2010]

Figure 2.15: Zolertia Z1 sensor node

3 IMPROVEMENTS AND RECOMMENDATIONS FOR TESTBED FACILITIES

In order to enable the testbed facilities to support WSN research and development up to TRL7 the author set out to introduce multiple improvements of testbed facilities related to the observations provided in Section 1.4. The improvements are implemented as updates to the previously in Section 2 described testbed facility EDI TestBed by [Ruskuls et al., 2015] and for each of them the guidelines and necessary information is provided in order to facilitate these additions to any other testbed facility.

3.1 Flexible deployment options

Along with the digitalization of the 21st century wireless and mobile applications are growing rapidly, for example, global mobile data traffic grew 17-fold over the five-year period of years 2012 to 2017 [Forecast, 2019] and is expected to grow 7-fold more over the next five year period. The ever-changing complexity of the outside world can be difficult to tame for the embedded system being developed resolving to tasks filled with daunting manual labor due to factors such as battery lifetime, environmental factors, radio coverage accompanied with manual reprogramming, configuring, etc. Therefore the testbed facilities should provide a way of introducing the real world complexity into the possible test scenarios allowing for the solution to be pushed faster through the Technology Readiness Level above TRL5 as identified by the **Observation I** in Section 1.4.

To solve the aforementioned problems tools and infrastructure on top of the existing EDI TestBed described in Section 2 were developed to enable flexible deployment of Workstations, referred to as **flexible deployment option**. This would allow to speed up the development and enable testing of the developed solutions in a real-world environment. The author believes that this sort of approach enables developers to move their product through Technology Readiness Level faster, more comfortably, and with more confidence in the quality of the end product. Another benefit of Workstations with flexible deployment option is the possibility to provide Workstations for industrial and other applications as Infrastructure as a Service, for initial validation of digitalization possibilities with negligible initial cost. This section uses materials from the author's publication [Salmins et al., 2017] and the described solution was also patented in Latvia under Application number: P-17-69.

EDI TestBed backend is made up of two parts: (i) Central server and (ii) Workstations. The server is responsible for storing the data, providing a user interface in the form of a web page therefore it is accessible from any device with a browser capable of processing JavaScript. Workstations consist of three parts: (i) Device Under Test, (ii) Adapter - which includes functions such as current consumption monitoring, power supplying for DUT in addition to battery discharge simulation and any digital or analog signal monitoring and (ii) Router - providing the connection to Central server, temporary data storage and all the functionality control regarding the Adapter and DUT. To enable flexible deployment options to the Workstation several changes and improvements were necessary to both parts of the EDI TestBed backend. From now on we distinguish between stationary Workstations connected to the EDI TestBed backend using Power over Ethernet and flexible deployment-enabled Workstations not limited by the aforementioned wired connection.

A flexible deployment-enabled Workstation, the same as the stationary Workstation consists of a Router, Adapter, and a DUT. The only hardware addition is a battery and a sealed enclosure for the Workstation itself. Flexible deployment-enabled Workstation, as shown in Figure 3.1, is supplied with a 5200mAh battery with an integrated solar panel for extended battery life during outdoor deployments. When the Workstation is powered on without the DUT, the current consumption is approximately 300mA which indicates an approximate battery life of about 18 hours, though real-life tests proved that the realistic maximum is about 13 hours. To ensure that the Workstation is not damaged in outdoor experiments IP65 enclosure is used. Software solution for flexible deployment-enabled Workstations is the same as software on stationary Workstations with the upgrade to add an application-level message queue to hold messages until the connection to the EDI TestBed backend is available to receive or send data. Router RAM is used for temporary data storage, current Router models in use have a total of 64MB RAM, half of which is mapped as a drive allowing for 32MB of temporary data storage. It is enough for most WSN solutions, taking into account the approximate 13-hour battery life of Workstation it can save a stream of 700 B/s without sending data to the server at all. This amount is enough for streaming 16-bit accelerometer and gyroscope data at 350Hz for the whole flexible deployment-enabled Workstation battery life.

Figure 3.1: Flexible deployment-enabled Workstation

It is necessary to distinguish between a flexible deployment-enabled Workstation located on the main premises of the EDI TestBed and deployed somewhere else due to how the connection to the Central server is established.

A flexible deployment-enabled Workstation located on the EDI TestBed premises uses a WiFi network hosted by stationary Workstations to connect to the Central server. If the current connection is lost the Router connects to the next WiFi access point - a stationary Workstation, with the strongest signal. The network is set up in such a way that all WiFi access point clients use the same address space and the same DHCP server, this way a flexible deployment-enabled Workstation will have the same static IP address no matter from where the connection is made. Multiple access point infrastructure also provides an approximate location discovery feature for future implementation.

To allow for flexible deployment-enabled Workstation to be deployed outside of the EDI TestBed the Workstation needs to connect to EDI TestBed internal network via a VPN connection. Every Workstation has its own certificate for identification and legitimacy. External flexible deployment-enabled Workstations also has static addressing and message queues in case of connectivity loss similar to local flexible deployment-enabled Workstations. Multiple target WiFi networks can be defined to use for connecting to the internet, this way even free public WiFi can be used to facilitate the deployment.

To evaluate the flexible deployment-enabled Workstation approach multiple outdoor tests were performed. 10 external flexible deployment-enabled Workstations were placed in an orchid at the Institute of Horticulture in Dobele, Latvia, to: (i) test the new functionality, and (ii) gather the data about light intensity, temperature, and humidity. As seen in Figure 3.2 the gateway (WiFi access point) was located in the center of the Workstation to provide different paths to

Figure 3.2: Flexible deployment-enabled Workstation arrangement in the orchid

test flexible deployment-enabled Workstations, for example, Workstation 71 was in direct line of sight, but Workstation 77 was put next to the cherry tree roots and has other trees in the path to the gateway. Despite the obstacles in the way and the fact that WiFi routers didn't have external antennas connected, a strong connection to the gateway from Workstations that was located approximately 40m - 70m away was observed.

Flexible deployment-enabled Workstations were gathering data for approximately 2 hours, and each Workstation generated about 5Kb of sensor data transmitted to the EDI TestBed backend per minute. During the outdoor test DUT radio transmit power and duty cycle were configured for optimal radio coverage and current consumption ratio. It was done using reprogramming and current consumption measuring functionality, iteratively arriving at adequate parameters for autonomous WSN functioning. An excerpt of current consumption measurements from one of the iterations can be observed in Figure 3.3.

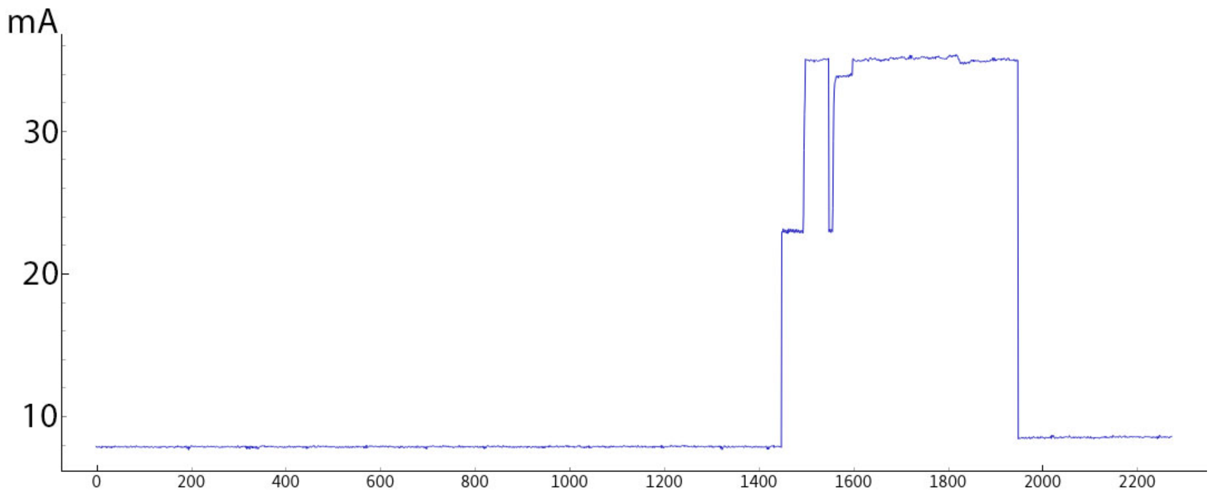


Figure 3.3: Radio send current consumption measurements for XM1000 DUT

In urban conditions, near the EDI building in Riga, Latvia, a strong signal could be observed at a gateway from Workstations that was about 100m away, taking into account that Workstations were in the line of sight and the flexible deployment-enabled Workstations didn't have external antennas.

On the communication side, there are two possible improvements: (i) a dedicated GSM modem that would provide the necessary internet connection to the deployed Workstations where a mobile internet connection is the only possible option, and (ii) external antennas would drastically increase the distance in which the Workstations can be deployed, as the chip-antennas were the main reason for the small transmission distance from Workstations to the gateway.

From the hardware perspective, three possible improvements were identified: (i) a higher capacity battery, (ii) IP67 enclosure, and (iii) non-volatile memory for Router. Flexible deployment-enabled Workstations are constantly connected to the internet and send the gathered data to the EDI TestBed backend, providing the options to read serial output or reprogram the DUT. In these circumstances the lifetime provided by the battery decreases quickly, therefor a higher capacity battery would increase the possible duration of the deployments. For the prototype, a basic electrical junction box was used for the enclosure. To improve the applicability in outdoor environments a custom-made enclosure with at least an IP67 rating should be used for the ability to test sensor networks in changing weather conditions. To minimize outdoor exposure, the battery should be integrated inside of the enclosure. If the Router unexpectedly turns off or loses power the locally collected data is lost, therefor a non-volatile memory unit should be added to the Router for data storage during long-running deployments without internet connectivity or in case of a loss of internet connectivity.

Since the flexible deployment-enabled Workstations can technically be deployed anywhere, they have the potential to be exploited as Infrastructure as a Service, providing not only the testing capabilities for WSN research, prototyping, and testing but also for minimizing the cost for validation of solution in exactly the place where it will be deployed. A potential scenario - in a factory not yet digitalized, the complexity and cost of undergoing the digitalization process are quite cumbersome. Traditionally, this requires the acquirement of new equipment supporting the digitalized features leading to high costs in equipment purchase, human resource re-training with the new equipment, and lost revenue due to downtime of the factory while the upgrade process is undergoing.

By using flexible deployment-enabled Workstations as Infrastructure as a Service the testbed facility can, for example, provide an alternative route of introducing digitalization in the factory while still running the original equipment thus completely avoiding all the previously mentioned downsides of the factory digitalization process. The proposed solution can bring digitalization to the factory while reducing costs and minimizing factory downtime while doing so. The cost reduction is achieved by using Infrastructure as a Service instead of acquiring the infrastructure and that also leads to reduced development time meaning fewer engineering hours are needed. Infrastructure as a Service enables faster time to prototype by providing the bare bone of the necessary technical implementation and allowing more focus on business logic implementation.

This approach allows for faster implementation times, reduced cost, and some flexibility of experimentation with the digitalized solution validation and fine-tuning. Ultimately increasing the confidence of the investor before the decision to make an investment and purchase the digitalized solution for the factory is made.

To add the flexible deployment-enabled Workstation functionality to an existing testbed facility the following prerequisites should be met:

- Workstations capable of:
  - Internet connection through WiFi, GSM, or other wireless means;
  - Connecting to a virtual private network;
  - Being powered by a battery;
- Internal addressing of Workstation does not change if the connection type changes and is sustained between different connection sessions;
- A backend system capable of hosting a virtual private network server;
- Access to the user interface is not restricted to geographic location;

To facilitate the addition of flexible deployment-enabled Workstations it is required to add: (i) a battery suitable to the Workstation and (ii) a fitting enclosure; As for the software, general changes include the addition of a virtual private network and internet connectivity, as well as local message queue on the Workstations.

Flexible deployment-enabled Workstations provides a lot more usability for testbed facility in terms of different use case testing, for example (i) inertial sensors in a close to a real-world environment, (ii) dynamic routing algorithms concerning node positioning and virtually any algorithm related to position or movement, or (iii) battery discharging process monitoring in locations with different outdoor conditions, to understand how the battery coupes with seasonal weather. Using this feature multiple Workstation deployments in different locations can be controlled simultaneously allowing evaluation and debugging on stationary and flexible deployment-enabled Workstations at the same time providing almost unlimited possibilities for testing in terms of node geographic location. Deployments can span across large areas with multiple Workstations presenting gateway to the internet. All of the testbed facility functionality is available allowing the user to test their solution in a real-world environment with all the debugging and control tools provided by the testbed facility.

3.2 Current consumption measurement system

As the global usage of lightweight IoT devices is increasing, the evermore open issue is the lifespan of said devices, which heavily depends on the current consumption of the device in question. Therefore the testbed facility relevant for WSN and IoT should provide the users with the current consumption metrics of the device as identified by the **Observation III** in Section 1.4. The original EDI TestBed already provides the possibility of current consumption measurements, but as it will be shown in Section 3.2, the provided technical specifications do not cover the needs of IoT devices relevant in the 3rd decade of the 21st century and an improved version is described, referred to as **improved current consumption measurement system**. This section uses materials from the author's publication [Balass et al., 2023].

The original EDI TestBed provides the possibility to measure the current consumption as described in Section 2.4. But the system was designed in 2015 and the requirements and specifications should be reassessed from today's perspective. In this Section, the capabilities of the original EDI TestBed current consumption measurement system are evaluated against the hardware relevant at the time of its development and nowadays. A practical example of a current consumption measurement experiment is also provided.

The original EDI TestBed current consumption measurement system was designed with the Telos platform by [Polastre et al., 2005] in mind, targeting sensor nodes like tmote sky [Moteiv Corporation, 2006], XM1000 [Environmental Expert, 2021], Zolertia Z1 [Zolertia, 2010] and similar. The description of the Telos platform also provides the measured current consumption and operational characteristics of a Telos sensor node, which is shown in Table 3.1. By comparing the original EDI TestBed current measurement system characteristics with the Telos platform characteristics it is observable that for the most part, the original current measurement system satisfies the requirements to fully observe the Telos platform-compatible sensor node. The only exception is the timing of the MCU wakeup which can not be monitored with the theoretical maximum of 12.75 KHz, which leads to approximately 78 µs between each measurement.

Operation	Telos platform
Minimum voltage	1.8V
Standby with RTC on	5.1 µA
MCU idle, DCO on	54.5 µA
MCU active	1.8 mA
MCU and Radio RX	21.8 mA
MCU and Radio TX at 0dBm	19.5 mA
MCU and Flash read	4.1 mA
MCU and Flash write	15.1 mA
MCU wakeup	6 µs
Radio wakeup	580 µs

Source: [Polastre et al., 2005]

Table 3.1: Measured current consumption and operational characteristics of Telos platform

Taking a further look into the current consumption of telos platform, [Croce et al., 2008] provides a detailed tmote sky current consumption table during the operation of the Radio module as shown in Table 3.2. The values are comparable to the ones provided by the [Polastre et al., 2005], the main difference can be observed in reduced radio wakeup time from 580 µs to 470 µs. The most relevant entry in the context of the current consumption measurement system is the time necessary to receive or transmit a single byte, which is 32 µs, this leads to approximately 4 µs per bit. The original current consumption measurement system can not differentiate between transmitted or received bytes, as it can make a measurement approximately per 2.5 bytes, this can potentially even lead to it not detecting the transmission if it is less than 2.5 bytes long.

An overview of IoT hardware development platforms is given by [Singh et al., 2020] in the year 2020, it lists the following IoT Hardware platforms: (i) ESP8266 , (ii) Arduino , (iii) Raspberry PI , (iv) Particle, (v) Samsung's Artik, (vi) Intel IoT development boards, and (vii)

Operation	Time	Consumption
Initialize radio	470 µs	14 mA
Turn on radio	1.42 ms	1 mA
Switch to Rx/Tx	212 µs	14 mA
Time to sample radio	288 µs	21 mA
Evaluate radio sample	197 µs	14 mA
Receive one byte	32 µs	19.7 mA
Transmit one byte	32 µs	17.4 mA

Source: [Croce et al., 2008]

Table 3.2: Time and current consumption of tmote sky

Adafruit IoT development boards. A total of 16 different IoT development boards are compared in the final comparison table and the relevant information for the power supply system is about the input voltage of the specified boards which ranges from 3.3V up to 15V.

The empirical research by [Michelinakis et al., 2020] describes the current consumption of Narrow Band IoT devices Quectel-BC95 [Quectel Wireless Solutions, 2020] and SARA-N211 [u blox, 2021]. When the devices are in a power-saving mode with the radio turned off, the current consumption is 10.61 µW and 9.35 µW respectively, this translates to 2.95 µA for the Quectel-BC95 and 2.6 µA for the SARA-N211 device, both devices typically operate at 3.6 V. This corresponds to the device data sheets, both providing 3 µA as typical current consumption during the power saving mode, which is consequentially also the lowest possible current consumption when these devices are powered on. While at the most demanding state of the system - data transmission, typically the Quectel-BC95 can achieve the current consumption of up to 280 mA and SARA-N211 up to 220 mA.

The other popular IoT hardware solution states even lower current consumption in their data sheets, for example, 30nA for STM32L476xx microcontroller [STMicroelectronics, 2019], 0.7 µA for nRF52832 Bluetooth 5.2 SoC [Nordic Semiconductor, 2021], and 0.03 µA for STM32WLE5x LoRa enabled SoC [STMicroelectronics, 2021].

To validate the current consumption measurement system of the original EDI TestBed, an experiment was concluded in which the current consumption of a prototype which led to the development of Swamp Radio [Smite and Smits, 2018] was measured to estimate the battery life of the proposed sensor node. The developed prototype is shown in Figure 3.4 and the hardware specification can be seen in Table 3.3. Besides the sensors listed in Table, the Swamp Radio prototype sensor node also collected swamp battery voltage data, which was acquired by reading the ADC channel connected to the swamp battery. The sensor node acquired 10 swamp battery voltage measurements and one measurement of all other sensors in each duty cycle.

The current consumption of the Swamp Radio prototype sensor node was measured using EDI TestBed Workstation. The experiment was run without using a serial interface, with swamp battery reading delta set to 100ms resulting in about 1s between each radio message, to reduce the current consumption data. In actual usage, only the sleep cycles will be longer. The total time of the taken measurement was 3 seconds, as shown in Figure 3.5, resulting in a total of 26625 data points. This leads to an average of 8,875 kHz sampling rate, or approximately 0.112 ms per reading.

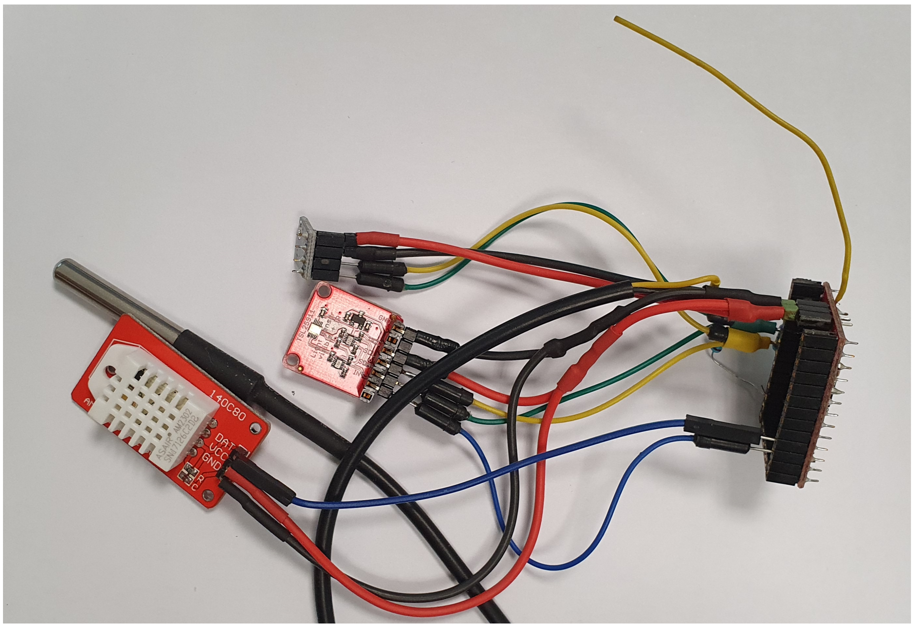


Figure 3.4: Swamp Radio prototype

In Figure 3.6 it is visible that the sensor node wakes every 100ms to read swamp battery voltage, this can be seen on 3 short peaks near 600 µA. The consumption in between these peaks averages at about 80 µA, this value corresponds to the sleep state of the MCU with all peripheral devices put into sleep mode or disabled.

Figure 3.7 shows the sensor node current consumption during a radio transmission, which can be divided into four phases. The first phase at around 8500 µA(8.5 mA) is sensor reading and lasts for about 700ms. The second phase at around 9700 µA(9.7 mA) is radio initialization

Component	**Name**	**Info**
Platform	Moteino	4Mbit Flash
MCU	ATmega328p	
Radio	RMF69	LoRaWAN enabled
Temperature and relative humidity sensor	Geekcreit AM2302 DHT22	
Temperature sensor	DS18B20	Waterproof
Visible and infrared light sensor	TSL25911	
Barometric pressure sensor	BMP180	
USB-TTL bridge	CP2102	
Battery	LiIon 3.7V, 6600mAh	

Table 3.3: Swamp Radio prototype components

and lasts for 450ms. The third phase peaks over 100 mA which is the saturation point of the hardware used, so the real consumption is higher. This should be a radio transmission and it lasts for about 100ms. Forth phase at around 1500 µA(1.5 mA) is radio going to sleep mode and lasts for about 300ms.

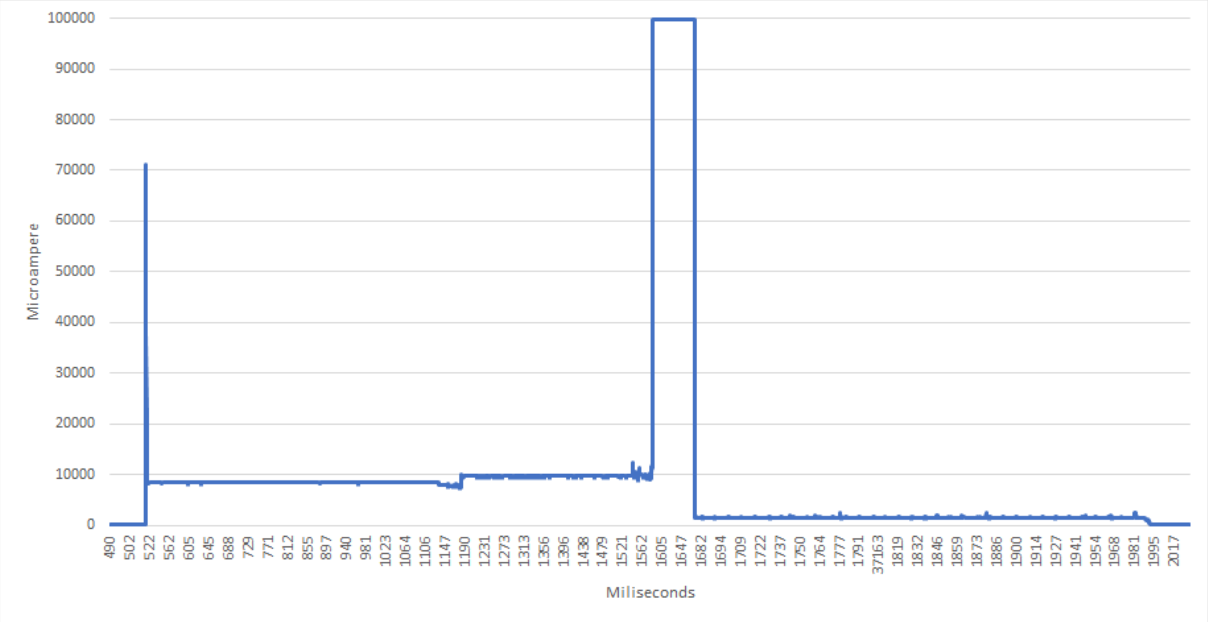


Figure 3.7: Swamp Radio prototype current consumption during radio transmit

The Swamp Radio prototype sensor node spends 0.26% of its time reading sensors and sending data when the swamp battery reading interval is set to 10 min(1.55s active, 598.45s

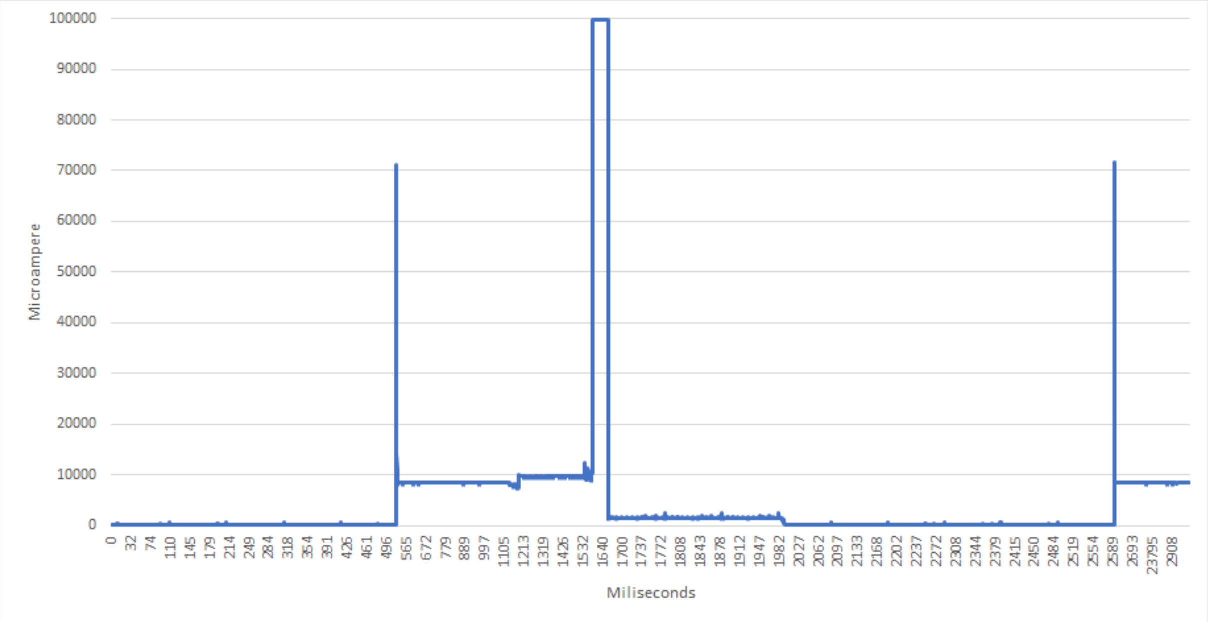


Figure 3.5: Swamp Radio prototype current consumption

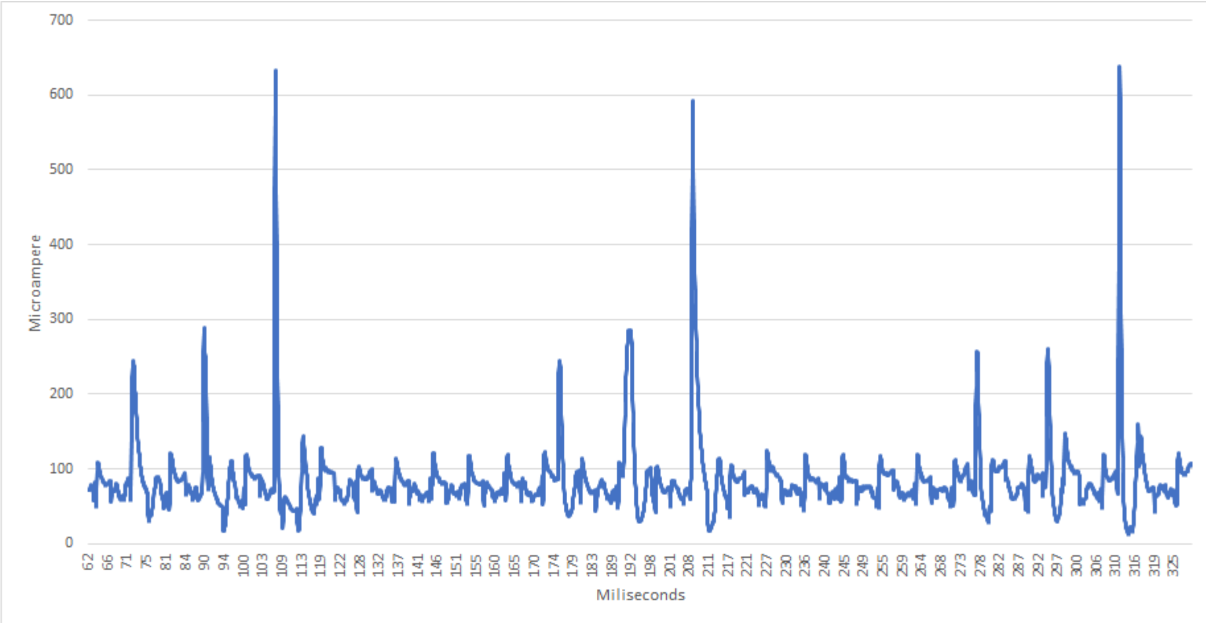


Figure 3.6: Swamp Radio prototype current consumption during sensor reading

sleeping). The following assumptions were made for battery life estimation: (i) the sleep consumption is 100 µA, (ii) awake consumption is 100 mA, and (iii) the typical Li-ion battery self-discharge is about 600 µA.

$$0.0026 \times 100000 + 0.9974 \times 600 = 858.44 \quad (5)$$

The Equation 5 shows that the Swamp Radio prototype sensor node on average consumes 860 µA including self-discharge, which theoretically would yield about 320 days of running on battery, of course, this is an estimate not assuming many factors such as temperature, actual battery discharge rate, etc.

From a theoretical point of view the requirements related to the current consumption measurement of IoT devices have increased, the most demanding hardware can achieve as low as 0.03 µA current consumption in the most aggressive current saving mode. On the other hand, the NB-IoT devices can consume up to 280 mA. This exceeds the possibilities of the EDI TestBed Workstation current consumption measurement system to both the minimum and maximum of the measurable current consumption. The voltage of some of the mentioned IoT devices can go from 3.3 V up to as high as 15 V, but the original current consumption measurement system can only provide up to 5 V.

From a practical point of view, the EDI TestBed Workstation current consumption measurement system performed well. The sampling rate provides the ability to notice distinct sensor measurement events, even when they are as simple as reading an ADC value. The accuracy at a low range proves to be enough for the used ATmega328p MCU combined with the previously mentioned peripherals reading around 80 μA and providing the ability to validate sleep mode efficiency. The only downfall observed in this test is during the radio transmit phase, where the current consumption of the sensor node exceeds 100 mA which is the practical limitation of the EDI TestBed Workstation current consumption system due to the choice of the shunt resistor specification.

The requirements for IoT-relevant current consumption measurement system are summarized in Table 3.4, which acts as a guide towards the specification of the developed system.

The specification of the improved version of EDI TestBed current consumption measurement system compared to the original EDI TestBed can be seen in Table 3.5. The aim is to improve accuracy by using better-suited hardware and 32bit 1 Msps ADC for current measurement and 16bit 3.6 Msps ADC for voltage measurements. The improved current consumption measurement system is developed as a replacement of the Adapter in the existing Workstation, it also includes multiple interface and quality-of-life improvements, which are out of the scope of this dissertation.

	Original system	New system
Output voltage range	1.2 V – 5 V	0 V – 34 V
Current measurement range	0.1 μA – 100 mA	2 nA – 3A
Current measurement accuracy	4 nA	100 pA
Maximum output current range	500 mA	1 A
Current measurement frequency	12.75 KHz	1 MHz

Table 3.5: Current consumption measurement system comparison

Metric	Minimal	Maximal
Supply Voltage	3.3 V	15 V
Current consumption	0.03 μA	280 mA

Table 3.4: IoT relevant current consumption system requirements

The theoretical maximum data throughput coming from the improved current consumption measurement system consists of 1 Msps 32bit ADC outputting 32 Mbps and 3.6 Msps 16bit ADC outputting 57.6 Mbps. The total theoretical bandwidth necessary is 89.6 Mbps or 11.2 MB/s.

The shunt ammeter circuit is used for high current range measurements as shown in Figure 3.8. This method measures gained voltage across a shunt resistor and the current (I) measurement is obtained by dividing the voltage drop measurement (V_{DROP}) with the known value of the resistor (R_{S}).

$$I = V_{DROP}/R_S \tag{6}$$

R_{S} is connected in series with a DUT that introduces a voltage drop error to the circuit if R_{S} is too high compared with a load impedance. This indicates that the shunt resistance should be as low as possible, to reduce voltage drop across it. For the implementation a 50 mΩ resistor as a shunt resistor is used as it will create only a 150 mV drop if there is 3 A load thru the measuring circuit, this is specified as the upper limit of the current measurement range. Also 50 mΩ resistor provides the capability to theoretically measure current form 1 nA up to 3 A using 32bit ADC.

A feedback ammeter technique is used for low current range measurement as shown in Figure 3.9. The feedback ammeter provides a smaller voltage drop (V_{DROP}) allowing to measurement of smaller current changes with a decreased error rate. The current (I) measurement is obtained by dividing output voltage (V_{O}) with known shunt resistance (R_{S})

$$I = V_O/R_S \tag{7}$$

The utilization of an operational amplifier provides readings faster than shunt ammeter measuring due to the nature of voltage settling across the resistor because the capacitance from wiring significantly increases the settling time for circuits designed to measure small current amounts with a shunt ammeter.

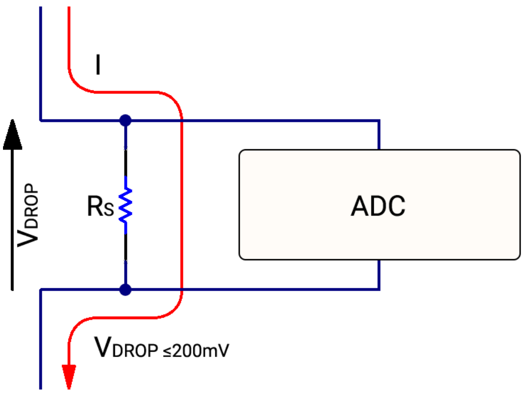


Figure 3.8: Shunt ammeter scheme

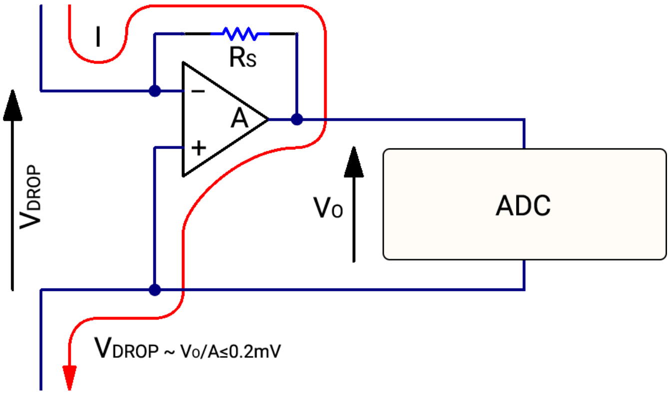


Figure 3.9: Feedback ammeter scheme

In order to validate the chosen approach multiple tests were conducted using the LTC2500-32 [Analog Devices, 2022] ADC module supporting single channel 32bit precision filtered output, 1 MHz data acquisition, and 100 MHz SPI data transfer frequency. A test bench on a breakout board with additional components as described in the datasheet and wiring for communication and data acquisition was designed. DSLogic U3Pro16 logic analyzer [DSLogic, 2023] was used to acquire the data for proof of concept current consumption measurements during the boot stage of AdvanticSYS XM100 [Environmental Expert, 2021] sensor node.

Evaluation of the new current consumption measurement system is not possible, because the system is not yet implemented due to delays caused by the global chip shortage. For the usage in use cases described in Section 4 the original version of the current consumption measurement system is used.

In order to add the described current consumption measurement system to the existing testbed facility the following prerequisites should be met:

- Workstations capable of:
  - Free port for 100 Mbps Ethernet or USB 2.0;
  - Power supply, capable of providing up to 34W;
  - Processing capabilities to store and/or forward 11.2 MB/s of data;
  - DUT interface capable of integrating current consumption measurement device, as it needs to be in the chain of power supply;
- Internal network capable of supporting data rates up to 11.2 MB/s for each workstation;

- A backend system capable of receiving, processing, and storing 11.2 MB/s of incoming data;

A modern, precise, fast, and reliable current consumption measurement system can improve the usability of the testbed facility by allowing for more in-depth experimentation usually only reserved for a test bench with a single DUT. The ability to easily validate the current consumption across a large fleet of devices increases the overall trust in the end product quality as well as allows for more enhanced current consumption fine-tuning across the whole network by developing more current consumption-aware algorithms. The resulting products can obtain better battery lifespan and increased quality assurance.

3.3 User interface and assistive tools

The possibilities of testbed facilities, when analyzed, can consist of quite a large set of functionality, as described in Section 1.2, thus the usability of UI should be considered as a major factor in the designing phase and also later, since it needs to be friendly to new users and also easy to include in the existing workflows as identified by the **Observation V** in Section 1.4

The user interface for the original EDI TestBed was based on a web interface, but this turned out to not work as well as expected. The drawbacks of a web-based interface were the limited connectivity, the need to support multiple web browsers, limited computing capabilities, the effort required for implementation and maintenance, and no straightforward way of integrating into the existing workflow. Taking this into consideration it was decided to create a new UI for EDI TestBed based on a simple command line interface, referred to as **simple CLI**. It can be easily integrated into different types of interfaces by separating the command execution from user interaction, allowing the UI to become much simpler in terms of implementation and leaving the CLI as a backbone. Different UIs on top of a command line-based interface can be implemented:

- Web-based interface by creating a local web server;
- Graphical interface by creating a separate application for user interactions;
- Integration into existing integrated development environments like VS Code, Eclipse, Atom, Sublime Text, etc., by means of scripting;

Command	Explanation
connect	Connect to EDI TestBed
disconnect	Disconnect from EDI TestBed
quick	Provides a way to quickly test a program on EDI TestBed
project	Create and interact with the project
upload	Upload the specified program file to the project
assign	Assign the uploaded program to the specified target
config	Read or set project-specific configuration
start	Start the experiment as defined by the selected project
stop	Stop the ongoing experiment
status	Print info about the selected project
read	Start reading the UART output of Device Under Test
write	Write the provided input to the UART input of Device Under Test
download	Download all the logs recorded during the specified experiment

Table 3.6: EDI TestBed command line interface commands

The decision was made to build the CLI as a standalone UI while keeping the possibility to integrate into another type of UI in the future. To provide testbed facility users with ease of usage, it was decided that the CLI should support both (i) single command execution, for scripting support and (ii) shell-like experience without the need to repeatedly call the executable. For the implementation Python 3 programming language was chosen, since most of the EDI TestBed infrastructure already runs on Python 3, and the Cmd framework by [The Python Software Foundation, 2020] was used for a single call and shell mode compatibility.

The user flow of the CLI was designed around the concept of projects and experiments based on those projects. The aim of such an approach is to promote the experiment's repeatability for the user and also in the future to enable project sharing and thus experiment sharing among the users. Once the project has been created and all the data about the necessary input files and targeted Workstations and DUTs has been filled, the experiment itself can be executed multiple times.

In the first iteration the commands available to the user were limited to the most crucial ones, the complete list along with brief explanations can be seen in Table 3.6.

Reflecting on the data provided in Section 1.3 about the provided Assistive Tools by the existing testbed facilities the author believes that two of the most important ones are manual and tutorials, referred to as **user guide**. But they are underrepresented in the existing testbed facilities, with only 4 manuals and 6 tutorials available in 7 of 32 testbed facilities. Since the EDI TestBed was also "guilty" of not providing any manual or tutorial to the user, the author chose to develop and describe the contents for such tools. In the following paragraphs, the guidelines for the creation of a manual and tutorial are given, as created by the author for EDI TestBed.

The manual was created describing the following topics:

- Obtaining access - this is the first thing a manual should present, allowing anyone to understand what are the restrictions and procedures for user account creation. Also, the expected timeline for this needs to be mentioned, if the application is approved manually;
- Architecture concept - a brief explanation of how the user can interact with the testbed facility and the naming scheme used for the devices and services relevant to the user. This section should refrain from diving too deep into technical questions or explanations of the inner workings of the testbed facility;
- User interface concepts - once the new user knows how to access and understands the general concepts of the testbed facility, he needs the knowledge of how to actually interact with it. An overview of how the UI works needs to be given connecting the structure of the UI with previously explained services and interaction with devices to understand the possible interaction scenarios;
- Workflow description - understanding how to use a testbed facility can be challenging at first, so a simple high-level workflow guide describing: (i) how to acquire the necessary software, (ii) log in, and (iii) first startup helps to get started quickly. To keep the new users going the workflow guide should also include a description of how to plan for experiments, what are the necessary prerequisites and what the user can expect as an output from the testbed facility;
- Simple experiment - this section contains a description of a ”hello world” like experiment for a testbed facility, guiding the user through the described workflow but minimizing the complexity without the introduction of advanced features and functionality. If the experiment requires any additional inputs such as code or configuration file, it should be provided;
- Advanced experiment - in this section a more advanced experiment is described showcasing the full potential of the testbed facility with detailed explanations of different features and their inner workings. If the experiment requires any additional inputs such as code or configuration file, it should be provided;

- User interface description - finally, a full description of the available functionality of the testbed facility should be given in the form of a manual for the chosen UI.

In order to provide a quick reference guide the complete UI description together with a quick ”cheat sheet” describing the most frequently used commands or workflows for the UI should be provided in a wiki format for easy access and distribution.

The preferred form of tutorials nowadays is videos, as an optimum at least 3 videos should be presented with the following topics: (i) an introduction covering the topics from the manual about obtaining access, architecture, and UI concepts and workflow, (ii) simple experiment, and (iii) advanced experiment. As the minimum author would suggest at least one video with a brief introduction to the concepts and a simple experiment showcase.

The CLI, manual, and tutorial does not rely on any existing infrastructure or service, as long as the testbed facility provides any way of user interaction, the author believes that it can be adjusted to use a CLI. Therefore there are no requirements necessary for the addition of CLI and assistive tools to any existing testbed facility.

The addition of command line interface improves the usability of the testbed facility by providing a way to integrate the usage of testbed facility into an existing workflow, this allows for automated, controlled experiments in a repeatable fashion. The addition of assistive tools in the form of manuals and tutorials helps new users as well as experienced users to interact efficiently with the testbed facility thus increasing its applicability. On a related note, the author believes that the provision of an already configured environment in the form of a docker container would be beneficial as well allowing for an even faster initial setup alleviating any setup-related issues.

3.4 Other possible improvements

While being involved with the development of EDI TestBed and working on WSN, embedded hardware, IoT, and other related solutions in the Faculty of Computing at the University of Latvia (LU DF) and Institute of Electronics and Computer Science (EDI), and also in the time spent conducting research and development for this thesis, the author has noticed and conceptualized multiple different improvements which could result in increased usage and applicability of testbed facilities, but these improvements are not investigated further, yet :] The following paragraphs contain some initial thoughts about the possible benefits of such improvements.

Since the investment in developing a large testbed facility is quite steep the gains should outweigh the costs. This is a problem if the testbed facility is not widely used or become popular yet. One of the possibilities for improving the usability of testbed facilities is to ”spread the word”, this should come in the form of a public relations plan aimed to improve the recognition. The possible target audience is students, fellow researchers, and to some extent also the representatives of industry. Another possibility is to use the hardware already deployed at the testbed facility while it is not being used actively for experiments. A typical testbed facilities DUT contains some sort of sensors, for example, the default DUT for EDI TestBed, the XM1000 sensor node [Environmental Expert, 2021] contains light, humidity, visible light and infrared light sensors. The data gathered by these sensors about the environment can be gathered, stored, and made available for public use.

The concepts and practices nowadays used for embedded development vastly differ from the ones used in traditional application development creating quite a steep learning curve for newcomers, be they professional desktop or cloud application developers or completely new to programming. Therefore the testbed facilities should strive to flatten the learning curve as much as possible since they already provide an easy way of accessing non-general consumer hardware. The getting started tutorials are a must-have, but the extension into a full Massive Online Open Course would bring a big benefit to the recognition and usage of the testbed facility.

The widespread availability of different WSN and IoT embedded devices we are experiencing nowadays do play an important role in the design of a testbed facility because the usually limited resources for development forbids one to have all the devices needed to satisfy the needs of every experimenter. Some sort of survey or research about how to make a good composition of DUTs provided by a testbed facility should be made to (i) follow the trends of IoT evolution and (ii) cover the most popular use case scenarios. This partly correlates with the research described in Section 1.1, **Observation II** and **Observation IV** described in Section 1.4, but more focused research in this direction would be needed in order to answer these questions.

A lot of research done in the WSN and IoT fields lack the proper evaluation of the results, as shortly described in Section 4.1, leading to somewhat doubtful or even misleading results. Therefore the testbed facilities should incorporate a way of providing a full and transparent way of experiment repeatability and sharing. This should come in the form of easy to reproduce setup of experiments, similar to verification and validation tests used in general programming. The idea behind this is to implement the experiment storage on a version control platform allowing anyone, with the permission of the author of course, to download, validate, and execute the original experiment themselves without the need of additional configuration steps. This can be achieved if the testbed facility supports experiment data export and import in a standardized format.

The latest development paradigms in desktop and cloud application development tend to adapt the DevOps practices, and the embedded development seems to also adopt this trend as described by [Ferry et al., 2018] and [Ferry et al., 2021]. Therefore testbed facilities should look into the future and assess the usage of DevOps practices in WSN and IoT and adapt the necessary functionality to promote this movement. Some initial work towards this is described by the author in [Judvaitis et al., 2019].

The concept of remote hardware that the testbed facilities offer also means that the user needs to send their code or compiled application to the testbed facility, which in some cases can be a problem of Intellectual Property safety. Testbed facilities should implement strict access control to the user data and the executed code should not be on the DUTs for longer than absolutely necessary, this means that when the experiment is not running an idle application which does nothing or gathers sensor or any other useful information, as described in Section 3.4, should be employed, to lower the possibility of malicious actors acquiring the physical access to DUT being able to extract any useful or valuable information.

Once the data from the experiment on the testbed facility is gathered, users need to process this data and there can be quite a lot of data, for example:

- As described in Section 2.3 the original EDI TestBed theoretically produces up to 13 MB/s, although the practically achieved maximum bandwidth was approximately 788 KB/s.
- As described in Section 3.2 the improved version of EDI TestBed current measurement system can deliver data with speeds up to 11.2 MB/s.

When taking into consideration the possible data generated by DUT itself, the user can easily be overwhelmed with the data flow, so the testbed facilities could provide an integrated way of data processing and some automatic result highlighting depending on certain scenarios. There is also a possibility to make use of Artificial Intelligence or Machine learning algorithms for automated smart experiment result syntheses.

The first step of data analysis for testbed facilities could include an automated comparison between different runs of the same experiment and highlighting the differences observed.

The debugging of embedded devices is complicated enough, but when the debugged device becomes a remote debugged device, this adds a whole new level of complexity to deal with, so this needs to be addressed with the extended debugging capabilities of testbed facilities. It could be a simple web camera showing the LEDs on DUT or an advanced debugging tool connected, there should be a way of interacting with the DUT apart from the serial connection used to transfer data.

The possibility of interacting with the testbed facility from the user-controlled DUT could provide meaningful tools to help accelerate the development itself as well as the debugging process. The interaction examples could be a request to start current consumption measurement, provide a precise timestamp, etc. To increase development speed and ease the implementation the communication protocol to use between DUT and Workstation could be given as an open source library implemented in easy-to-port style with implementations provided in the most popular programming languages for the given DUT.

3.5 Summary

During the development of this dissertation, four improvements to testbed facilities were implemented in the EDI TestBed according to the **Thesis 1** and related to the observations put forward in the Section 1.4: (i) flexible deployment options described in Section 3.1, (ii) current consumption measurement system described in Section 3.2, (iii) scriptable interface described in Section 3.3, and (iv) user guide described in Section 3.3. The improvement description was provided together with the rationale for the chosen solution and presented in a manner to facilitate the replication in any other testbed facility together with considerations and requirements necessary for implementation.

The author also provided a list of possible improvements to the testbed facilities along with some initial thoughts and rationale behind them, but they haven't been investigated further and this is left as a future work in the context of this dissertation.

4 TESTBED FACILITY USE CASES

This section provides a description of use cases that were developed on or used EDI TestBed, detailing the usage and actual testbed facility functionality necessary for the use case. For each use case, a TRL is provided for evaluation of developed improvements in relation to **Thesis 1**: WSN research and development up to TRL7.

4.1 Sensor network deployment replication use case

With all the developments made to improve the EDI TestBed described in Section 3 there was an idea to practically test the usability of EDI TestBed by replicating existing research in the sensor network domain. To do this a colleague with minimal experience with sensor network development and surface-level knowledge of EDI TestBed implementation was tasked to provide the replicated implementation and evaluate the impact of EDI TestBed for this task. To evaluate the usefulness of the improved EDI TestBed a random sensor network deployment from the sensor network deployment review described in Section 1.1 was chosen to be replicated using the EDI TestBed. This section uses materials from [Elkenawy and Judvaitis, 2022].

The task in this use case consisted of three parts: (i) replicate the sensor network deployment for a tunable transmission power to improve the 2D RSSI-based localization algorithm described by [Polese et al., 2015], (ii) validate the obtained results in the previous research through a detailed experiment executed on the EDI TestBed, and (iii) assess the impact of using EDI TestBed.

An RSSI range-based indoor localization system typically consists of two distinctive hardware components: (i) static anchor nodes, and (ii) a single mobile target node.

For the static anchor nodes, four EDI TestBed Workstations with connected AdvanticSysXM1000 [Environmental Expert, 2021] sensor nodes were attached to the ceiling of a $5.8m \times 5.6m \times 2.7m$ office room at the height of $2.7m$, as shown in Figure 4.1. Locations of anchor nodes are chosen to be at the corners, which is the case for 3 nodes, whereas the fourth node is near the midpoint of the ceiling, being away from any wall and aimed to give more uniform wave propagation toward the target node. The anchor nodes were programmed to constantly transmit data with the node ID to be received by the mobile target node and all possible values of transmit power for the used CC2420 radio transceiver [Texas Intruments, 2013] were tested.

As the mobile target node Texas Instrument LaunchPad CC1352R1 [Texas Instruments, 2018] was used instead of a flexible deployment-enabled Workstation because EDI TestBed could not provide an external antenna for the connected DUT. CC1352R1 was connected directly to the development PC because this device is not supported by the EDI TestBed, it forwarded the received messages from the anchor nodes directly to the PC for analysis. The mobile node is equipped with an external omnidirectional antenna to boost the gain of RF power and add some uniformity to the wave's radiation pattern, which should eventually increase the probability of receiving packets successfully.

The challenging part of this sensor network deployment replication turned out to be fine-tuning the localization algorithm described by [Polese et al., 2015], which did not contain all

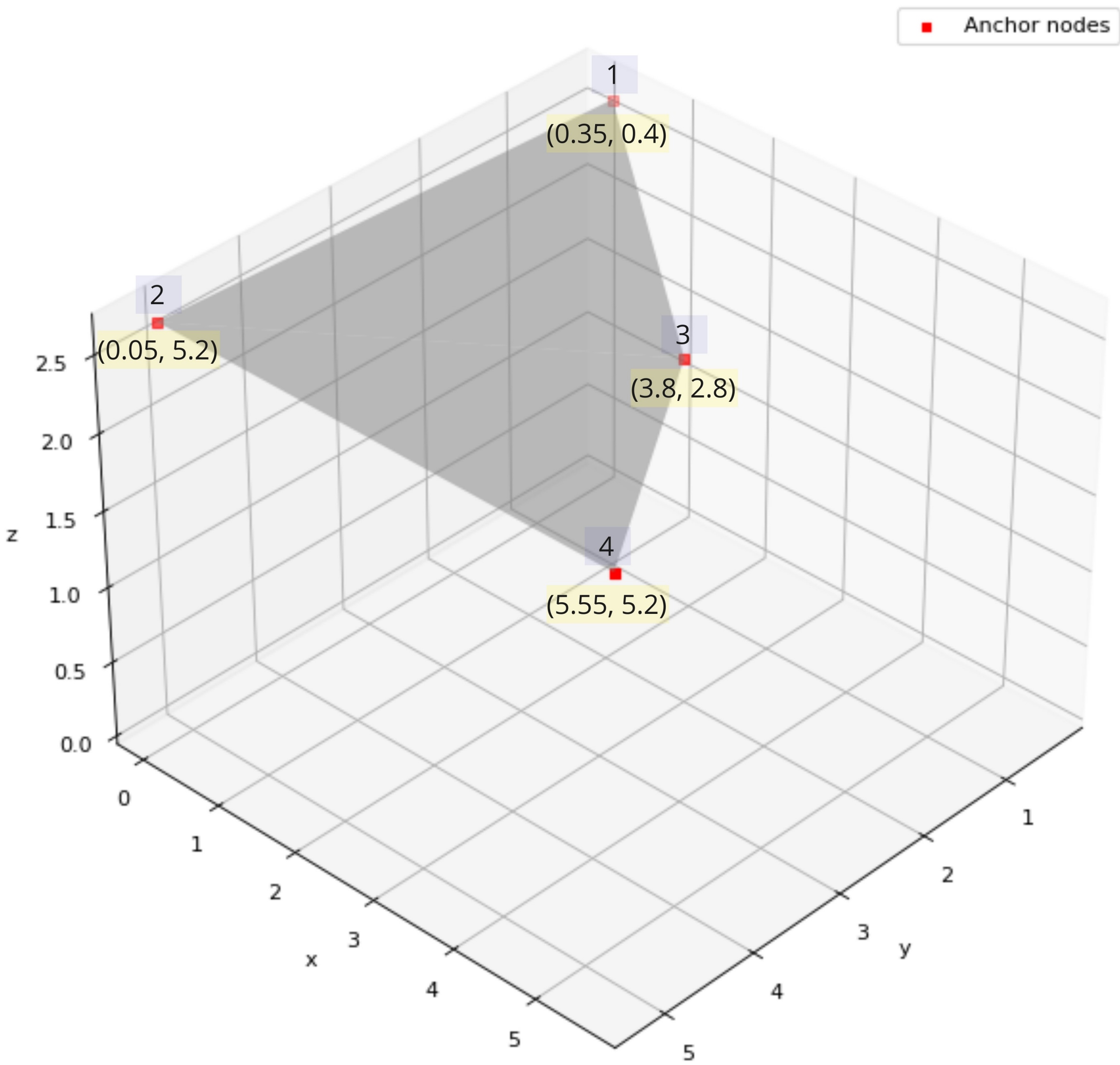


Figure 4.1: Locations of anchor nodes in the room.

the necessary details for straightforward replication, as described by [Elkenawy and Judvaitis, 2022].

The sensor network deployment replication use case achieved TRL4 - technology validated in the laboratory, as the test setup was made to test the principles of operation, but no tests were made outside of the laboratory. In the process of replicating the sensor network deployment from already described research, it was identified, that the user guide described in Section 3.3 provided enough information for a developer relatively new to the WSN domain to achieve the functionality necessary for the research, this also is in line with the conclusions from the use case with university students described in Section 4.3. To develop the application for the anchor nodes scriptable interface described in Section 3.3 was used. As the main drawback, the lack of an external antenna for the provided DUT - AdvanticSys XM1000 was identified, this is partly in line with the **Observation II** identified in the Section 1.4.

4.2 Communication technology comparison use case

As WSNs and IoT usage is gaining popularity the available communication technology range is also expanding, and recently this includes not only communication through the typical environment, such as air, water, or solid objects but also some more exotic use cases, for example, communication through the human body, as described by [Ormanis and Elsts, 2020]. Due to the difference in TRLs of the different communication technologies and protocols, it is difficult to evaluate the performance of a new communication technology or protocol. For example, a comparison of full stack Bluetooth solution and TRL4 prototypes for previously mentioned communication through the human body in terms of energy efficiency, latency, etc., where the used communication protocols and communication mediums are different, but both technologies can be viable for Body Area Network solution. In order to accordingly compare the communication technologies and protocols, possibly targeting different communication mediums, with regards to their physical (PHY) level a methodology for such comparison needs to be developed.

During the development of the mentioned methodology tests with Bluetooth and TRL4 prototype for human body communication will be carried out with the help of EDI TestBed inside an anechoic chamber.

The task was to provide EDI TestBed functionality inside an anechoic chamber for two

Workstations.

The Anechoic chamber in which the functionality of EDI TestBed will be necessary is custom-made. It has an outer size of 1 cubic meter, it provides 100 dB attenuation from 150 kHz to 10 GHz, has 4 optically decoupled USB 3 connectors and a power socket that supplies filtered 220V 16A current and it is made from stainless steel with foam pyramid absorbers.

Since the electromagnetic interference should be kept as low as possible on the inside of the anechoic chamber, it was decided to split the Workstation and only place the Adapter in the chamber and keeping the Router outside, connecting them with the optically decoupled USB connection. This solution allows to keep all the EDI TestBed functionality for the DUT placed inside the anechoic chamber.

For the Bluetooth test two nrf52840 dongles will be used running a bridge application, the first dongle forwards everything received from the UART through Bluetooth to the other dongle, which in turn forwards the received data from Bluetooth to the UART. The test was designed in this way in order to provide a controlled and repeatable data input, validate that the data is transmitted, and measure the latency and current consumption of the dongles.

For the TRL4 prototype for communication through the human body a similar approach will be taken, with the only difference being that the prototype can not be reprogrammed from the EDI TestBed, as the platform is not supported.

The communication technology comparison use case will achieve TRL4 - technology validated in the laboratory, as the test setup will be made to test the principles of operation, but no tests are planned outside of the laboratory. The usage of EDI TestBed will allow to provision of identical input data for both tested communication technologies, validate that the data was successfully transferred, and measure the current consumption and latency.

The communication technology comparison use case will take advantage of all four testbed facility improvements described in this dissertation. The flexible deployment options described in Section 3.1 will be used to bring EDI TestBed functionality inside an anechoic chamber allowing for remote interaction with tested devices. The current consumption measurement system described in Section 3.2 will be used to measure the consumption of tested devices for comparison of watts per bit between the tested communication technologies. scriptable interface described in Section 3.3will allow for the preparation of a batch of experiments and run them in an automated and repeatable fashion. With regards to the user guide described in Section 3.3 it will be tested if it provides enough information for researchers to get the experimental setup running and if there will be no substantial issues or delays related to the usage of EDI TestBed.

4.3 Wireless sensor networks university course use case

The university courses requiring any specialized equipment tend to place a limitation on the time the students can have hands-on experience. The issue arises because typically the equipment is costly and universities do not provide students with access to it outside of lectures and practical lessons. In order to mitigate the situation for the Wireless Sensor Networks bachelor and master level courses in the University of Latvia, Faculty of Computing, an agreement was made with the Institute of Electronics and Computer Science about the usage of EDI TestBed in said courses.

The task was to provide the students with the possibility to learn and experiment with real sensor nodes outside of the in-person lectures provided by the university.

In this use case, the challenge was related to the training of new users who also have little to no experience with the programming of sensor nodes. To provide a smoother learning curve the manual and tutorial for EDI TestBed were developed, as well as an introductory lecture was held where the main concepts and usage was explained with a practical example. Over the years EDI TestBed switched from web interface to scriptable interface described in Section 3.3, and the observations made by the author suggest that although the initial getting up to speed seems to be easier using the web interface, the CLI provided an easier way of reporting and replicating problems and also simplified the providing of assistance, which in turn simplified the user experience and eased the user support on the EDI TestBed team side.

Starting from the year 2016 the EDI TestBed has been used by the University of Latvia, Faculty of Computing Wireless Sensor Networks course students as the only possibility to experiment with an actual sensor node outside the university laboratory if they do not outright purchase the devices themselves. The usage of EDI TestBed provides the students with an additional angle of learning, being able to simultaneously work with multiple devices and monitor the outcome in real-time as well as later by downloading the experiment logs. It was identified, that the user guide described in Section 3.3 provided enough information for a with no experience with the WSNs to independently develop and test sensor node applications. In this use case, the scriptable interface described in Section 3.3could be directly compared to the previously used web interface in terms of usability, and the observations suggest that although initial getting up to speed was hampered, once the users become familiar with the UI there were no issues related to it.

The WSN university course use case is not a typical one in terms of TRL because each student develops his own WSN, but in general, they all should at least achieve TRL3 - experimental proof of concept.

As an additional benefit, multiple students have chosen to develop and successfully completed their bachelor's thesis or qualification work in relation to WSNs by using EDI TestBed under the supervision of the author.

4.4 Mobility point use case

During the summer of 2020 an innovation movement VEFRESH together with Riga Energy Agency and Ie.La opened the first prototype of a mobility point in Latvia `https://www.vefresh.com/infrastructure#anchor-1`. Mobility point provides simple access to micro-mobility while connecting various modes of transportation. The aim is to offer alternatives for completing the intended journey in a sustainable, environmentally friendly, and smart manner without the use of a private vehicle.

The mobility point consists of three different installments located in close proximity to each other in order to achieve its goals:

- Mobility inventory consisting of safe parking options for cyclists, electrical scooter rental points, and free WiFi and phone charging facilities;
- Cyclist and pedestrian counter providing information to every passerby about the daily and yearly statistics;
- IoT testing station consisting of specialized hardware accessible to businesses and students allowing for experimentation in the urban environment with IoT and machine vision solutions.

A collaboration with EDI resulted in a flexible deployment-enabled EDI TestBed Workstation to be deployed as part of the IoT testing station for experimentation and data gathering.

The task was to prepare the EDI TestBed Workstation for long-term deployment in an urban environment.

As the target deployment location was outdoors and exposed to all kinds of weather conditions, as visible in Figure 4.2, it was decided to use an IP68 enclosure for the Router of the Workstation as well as Adapter and DUT. The enclosure for Adapter and DUT was specifically modified to be able to withstand the outside conditions and still provide reasonable estimation about the temperature, humidity, photosynthetically active, and total solar radiation.

Figure 4.2: Deployed flexible deployment-enabled EDI TestBed Workstation

The resulting modified enclosure, visible in Figure 4.3 had a 32mm fan blowing the air out in order to keep the internal environment as close as possible to the outer environment and still keep the electronics safe from moisture. The fan was powered from the Adapter and the speed can be changed by software using the adjustable supply voltage functionality.

The connection to the power grid and internet connection was provided by the VEFRESH team and the EDI TestBed Workstation was set up to provide experimentation possibilities. While the Workstation was not used, it was running a default application that

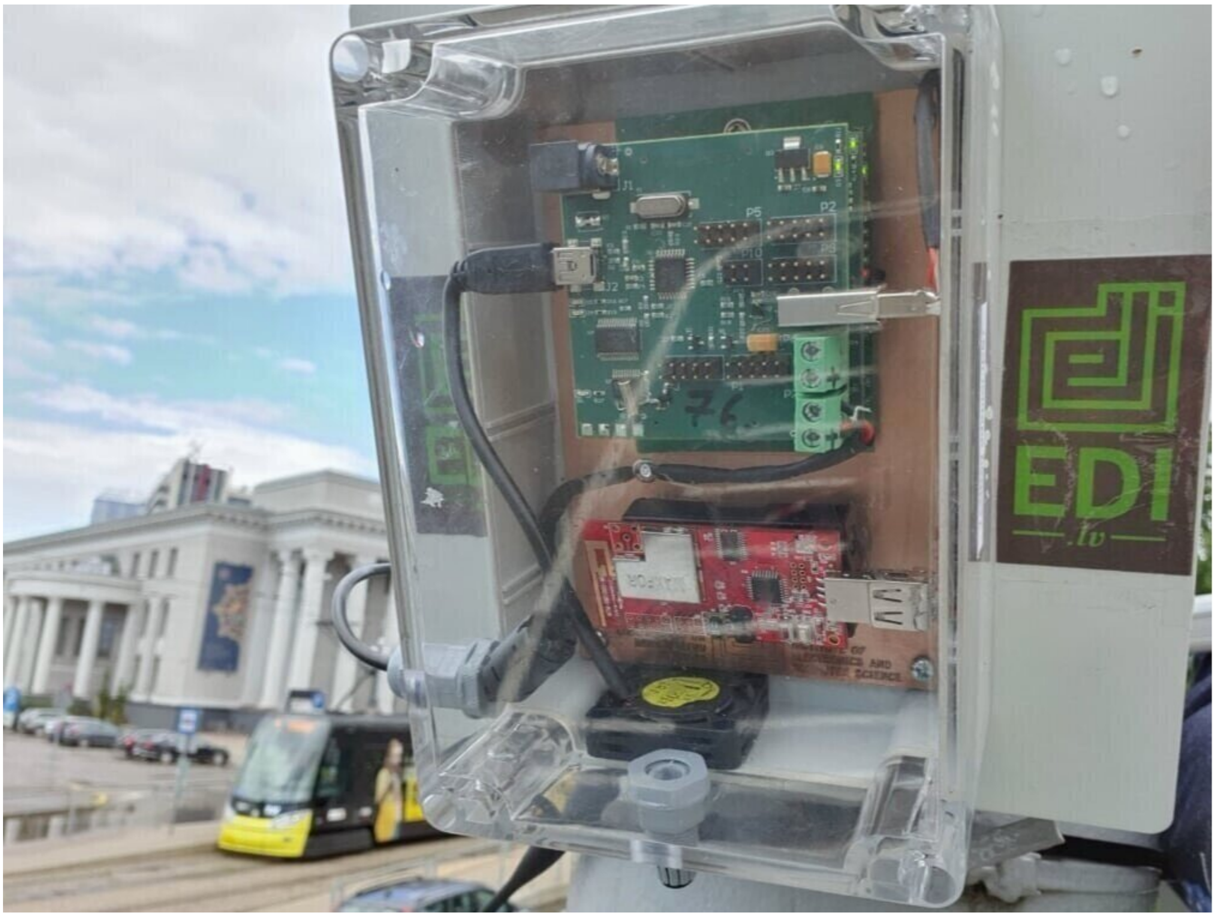


Figure 4.3: EDI TestBed Workstation with modified enclosure

gathered sensor data about the temperature, humidity, and visible and infrared light every 30s. The resulting data set was made available publicly under the CC BY 4.0 license through the REST API in JSON and CSV formats, as it was supplemented with new data regularly. The guideline for data acquisition together with a short description in Latvian is available at `www.vefresh.com/dati-vef/edi`.

The mobility point use case achieved TRL7 - system prototype demonstration in an operational environment, as the target of this use case was the monitoring of the urban environment for which a prototype was built and demonstrated. The deployed Workstation is still operational in the spring of 2023, but there are issues with the internet connection resulting from the poor quality of used WiFi access point hardware. The Workstation is available when the internet connection is active and proves to be reliable in the device stability aspect. The possibilities of providing an internet connection integrated into the flexible deployment-enabled Workstations need to be investigated, but in the meantime, the provision of data is disabled since they are a lot of gaps created by the lack of internet connection. This use case relied on flexible deployment options described in Section 3.1 of EDI TestBed Workstations as any stationary Workstation would not be suited for the placement outside the EDI main building because the power supply and connectivity to the stationary Workstations are provided using Power over Ethernet, which is not available at the mobility point.

4.5 Intelligent Transport System use case

EDI TestBed was used during the European Union Horizon2020 project ENACT: ”Development, Operation, and Quality Assurance of Trustworthy Smart IoT Systems” (`https://www.enact-project.eu/`) described in more detail by [Ferry et al., 2021]. The aim of ENACT project was to enable DevOps practices in the realm of trustworthy smart IoT systems and facilitate the smooth integration to leverage DevOps for existing and new IoT platforms and approaches, by enriching it with novel concepts for end-to-end security and privacy, resilience, and robustness strengthening trustworthiness, taking into account the challenges related to ”collaborative” actuation and actuation conflicts.

During the project, an Intelligent Transport System use case was developed as described in the book chapter by [Parrilla et al., 2021], to which the author has also contributed. The use case included three sensor nodes, which theoretically would be located on a rolling stock wagon, transmitting sensor data once every 250 ms with a high emphasis on data integrity and overall system stability. This use case served as a base for testing and validation of the multiple technology enablers developed during the project. The implementation of the early prototype for the Intelligent Transport System use case used EDI TestBed Workstation and DUTs, the second iteration moved away from the usage of EDI TestBed because of the need for specific sensors and communication capabilities. This Section uses materials from the author’s publication [Judvaitis et al., 2021].

In this use case, the task related to the usage of EDI TestBed was to provide an initial mock-up implementation of the envisioned system in order to test core services and align data formats.

The Intelligent Transport System consisted of on-board and on-track infrastructure, each having a sensor network and edge layers, but for early prototypes only on-board infrastructure was developed. On-board sensor network infrastructure layer consists of a base station sensor node located in from of the rolling stock on the locomotive and ordinary sensor nodes located on the wagons, one per wagon. The use case proposed three different sensor data from each of the sensor nodes: (i) GNSS data, (ii) Accelerometer data, and (iii) RSSI value from the base station, in order to calculate the rolling stock integrity. A mock-up implementation of on-board WSN provided dummy data in the correct format for GNSS and accelerometer, but real RSSI values were used as sensor nodes transmitted the data to the base station which forwarded it to the Router of EDI TestBed Workstation. On-board edge layer consists of a single board computer performing data processing and forwarding implemented on EDI TestBed Workstation. From the received sensor data a rolling stock integrity is calculated and forwarded to the cloud layer together with raw data through the MQTT protocol.

The Intelligent Transport System use case relied on EDI TestBed to achieve TRL3 - experimental proof of concept. This use case relied on the ability to transmit wireless data between DUTs and the fact that EDI TestBed is built upon the MQTT protocol, which was used as a communication protocol for the Intelligent Transport System use case. It is worth noting, that the use case could only be implemented by obtaining higher than user-level access to the EDI TestBed because the standard users have no direct access to the MQTT broker used by the EDI TestBed. At the time this use case was implemented EDI TestBed did not have a fully functional CLI developed. With the usage of scriptable interface described in Section 3.3 this use case could be implemented without privileged access by using the read function and forwarding it to the Edge layer application running elsewhere.

4.6 Rapid hardware development, prototyping, testing, and evaluation use case

EDI TestBed was used during the European Union Horizon2020 ECSEL project Arrowhead-Tools: ”Arrowhead-Tools for Engineering of Digitalisation Solutions” (`https://tools.arrowhead.eu/home/`) described in more detail by [Paniagua and Delsing, 2020]. The Arrowhead-Tools project aimed to close the gaps that hinder IT/OT integration by introducing new technologies in an open-source platform for the design and run-time engineering of IoT and System of Systems in the European industry. The project provides engineering processes, integration platforms, tools, and toolchains for the cost-efficient development of digitalization, connectivity, and automation system solutions in various fields of application.

During the project, a Rapid hardware development, prototyping, testing, and evaluation use case was developed showcasing an engineering toolchain that can reduce the overall system development time by up to 40%. The toolchain consists of two parts: (i) a portable power supply electrical testing and verification tool, and (ii) a portable large-scale wireless communication testing and verification tool - EDI TestBed. The time necessary for hardware design and approval process for power supply production can be reduced by 20-25% with the combination of both tools into one toolchain, while the time to market for developers can be reduced by 20-30% by using EDI TestBed. The overall system development time can be reduced by up to 40% when both improvements are used together. The use case was demonstrated on a production line in the Arcelik factory in Istanbul, Turkey, and moved the Technology Readiness Level of the used tools from TRL5 to TRL7.

The task in this use case was to integrate EDI TestBed Workstation with the portable power supply electrical testing and verification tool to be used at the Arcelik power supply factory in Istanbul, Turkey to provide Arrowhead Tools framework-compatible toolchain. The resulting toolchain allows automatic remote control of the power supply test bench located in the factory, a complete overview of the use case is shown in Figure 4.4.

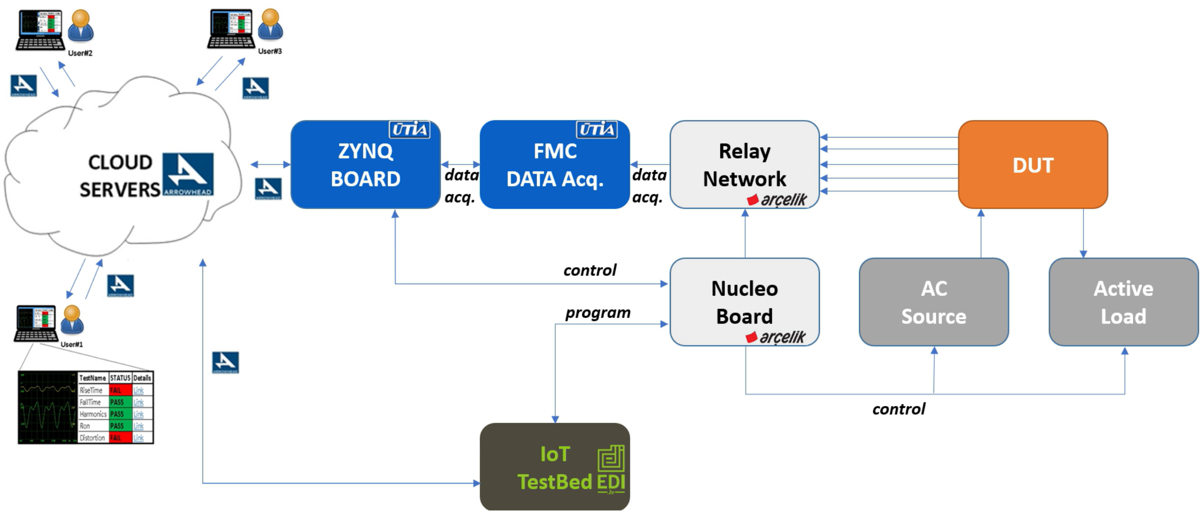


Figure 4.4: Rapid hardware development, prototyping, testing, and evaluation use case overview

The interaction with the portable power supply electrical testing and verification tool was done through the ST Nucleo STM32H753 board, which was connected to the EDI TestBed Workstation as DUT allowing for remote control and reprogramming. An update to EDI TestBed was developed to support ST Nucleo devices and integrate part with Arrowhead Tools framework. Single flexible deployment-enabled Workstation together with attached ST Nucleo board was shipped to Arcelik factory for use case evaluation and validation showcasing that the developed solution allows the remote control of the power supply bench in the factory. During the remote deployment of the Workstation, an issue regarding the used VPN connection was observed, the target WiFi network firewall was configured to block any outgoing VPN connections. This was an unforeseen issue that could not be solved from the EDI TestBed side and the partners had to provide an alternative WiFi with the VPN blocking disabled.

The rapid hardware development, prototyping, testing, and evaluation use case achieved TRL7 - system prototype demonstration in an operational environment, as the prototype was deployed and demonstrated in the Arcelik power supply factory. This use case relied on the following three described EDI TestBed improvements: (i) flexible deployment options described in Section 3.1 to provide all range of EDI TestBed functionality outside of the stationary deployment at EDI building, (ii) scriptable interface described in Section 3.3 to allow for automated interaction with the ST Nucleo board for the use case partners, and (iii) user guide described in Section 3.3to lessen the learning curve and allow for reduced development time when using the EDI TestBed, yet it was noticed that the possibility to execute the CLI as a single command and in a shell experience created confusion in the users and that this aspect should be better explained in the documentation.

4.7 One step open digital building logbook use case

Starting from the 1st January of the year 2023 a European Union Horizon Europe project OpenDBL: ”One Step Open DBL solution” (`https://www.opendbl.eu/`) is implemented. OpenDBL intends to integrate multidisciplinary know-how to solve the issues of the current situation Architecture, Engineering, Construction, and Operation (AECO) industry by providing an open digital building logbook (DBL). The challenge of the project is to allow, through the development of openAPI, the exploitation of openDBL in a unique standardized platform and create useful content, to simplify the workload of the AECO industry.

During the project 3 pilot deployments of the IoT platform are planned in three different European countries: Italy, Greece, and Spain. The IoT platform is intended to collect big data, such as energy consumption, external and internal temperature, number of people, etc., from the building with the ultimate target to derive behaviors, and patterns and provide suggestions on how to reduce energy impacts. The developed IoT platform will be scalable and capable to handle up to 100 sensor measurements per building. To achieve this goal it is planned to use the EDI TestBed allowing rapid integration of selected sensors, selection of the most appropriate communication network, and protocols, as well as pre-processing and processing units for energy-efficient and secure data collection.

The task in this use case is to use the EDI TestBed in the development of a large-scale IoT platform intended for data collection about the building and its environment with the ultimate goal of providing a pre-commercial system to be commercialized after the project for the use in building monitoring solutions.

The initial test deployment before the 3 pilot deployments mentioned before is planned to start in the autumn of 2023 in a kinder garden in Ruvo di Puglia, Italy. This will function as an early test for project partners to better understand the usability of sensors in the building and how it correlates with the DBL solution, allowing them to better prepare for the 3 pilot deployments of large-scale IoT platform. This initial deployment will consist of 20 sensor nodes all deployed together with EDI TestBed Workstations in order to test, develop, and integrate the envisioned WSN in its target environment. The sensor nodes will contain the sensors for the following parameters: temperature, humidity, pressure, CO2 equivalent, total volatile organic compounds, and 9-axis inertial measurements. One of the biggest challenges for the developed IoT system will be the thickness of walls in the historical building where the deployment will take place limiting the efficiency of wireless communication, therefore it is planned to use LoRa radio communication technique and adjust the transmission power accordingly. The current consumption measurements provided by the Workstation will allow for fine-tuning of the duty cycle for data transmission in order to provide decent battery life and ensure reasonable data delivery speed.

It is planned that the one step open DBL use case will achieve TRL7 - system prototype demonstration in an operational environment, as it is planned to deploy a sensor network in 3 different locations across Europe. This use case will rely on the following three EDI TestBed improvements: (i) flexible deployment options described in Section 3.1to facilitate the initial test deployment and allow for experimentation while the deployment is located in the target location, (ii) scriptable interface described in Section 3.3for simplified remote development, and (iii) current consumption measurement system described in Section 3.2for fine-tuning of radio transmission duty cycle versus the battery lifetime. During this project, it is also planned to evaluate the usage of EDI TestBed and add any functionality necessary.

4.8 Summary

A total of seven use cases were described for the usage of the EDI TestBed with the improvements described in Section 3, two of them are under development at the time of writing this dissertation. The use cases can be categorized into three different categories:

- Research related:
  - Sensor network deployment replication use case described in Section 4.1;
  - Communication protocol comparison use case described in Section 4.2;
  - Intelligent Transport System use case described in Section 4.5 related to European Union Horizon2020 project;
  - Rapid hardware development, prototyping, testing, and evaluation use case described in Section 4.6 related to European Union Horizon2020 project;
  - One step open digital building logbook use case described in Section 4.7 related to European Union Horizon Europe project;
- Education related:
  - Wireless Sensor Networks university course use case described in Section 4.3;
- Publicity related:
  - Mobility point use case described in Section 4.4.

The usage of provided improvements between the use cases is shown in Table 4.1, scriptable interface described in Section 3.3 was used by six use cases, flexible deployment options described in Section 3.1and user guide described in Section 3.3 was used by four use cases and current consumption measurement system described in Section 3.2 was used by two of them. The described use cases demonstrated and validated the proposed improvements in actual projects and tasks related to the research, development, testing, and evaluation of WSNs up to TRL7.

Use case	TRL	CMS	FD	SI	UM
Sensor network deployment replication	TRL4			✓	✓
Communication technology comparison (ongoing)	TRL4	✓	✓	✓	✓
Wireless Sensor Networks university course	TRL3			✓	✓
Mobility point	TRL7		✓		
Intelligent Transport System	TRL3			✓	
Rapid hardware development, prototyping, testing and evaluation	TRL7		✓	✓	✓
One step open digital building logbook (ongoing)	TRL7	✓	✓	✓	
	Total	**2**	**4**	**6**	**4**

Note: CMS (Current measurement system) , FD (Flexible deployment) , SI (Scriptable interface) , UM (User manual)

Table 4.1: Provided improvement usage between the use cases

5 CONCLUSIONS

To provide a clear view of the testbed facility usage and functionality as part of this thesis two systematic reviews were carried out. Sensor network deployment systematic review described in Section 1.1 provides an insight into tendencies and usage of sensor networks in research studies for a five-year period from 2013 to 2017 resulting in a knowledge base for the testbed facilities with regards to the possible users and their requirements. It is followed by a literature review about testbed facilities where it was identified that the widely used term testbed is too broad in the context of testbed-related literature and this thesis, therefore a term 'testbed facility' was introduced in Section 1.2 in accordance with **Thesis 2** stating that such term is necessary. With clear terminology regarding the testbed facilities, a systematic review of testbed facilities was carried out as described in Section 1.3 where a total of 32 testbed facilities were identified and codified for a ten-year period from 2011 to 2020 providing a landscape of the testbed facility field. The fact that from 359 identified articles only 32 testbed facilities were identified strongly supports the necessity for the introduced terminology. The combination of the results from both systematic reviews allowed to provide an insight into the supply and demand of the testbed facility domain resulting in 5 observations made in Section 1.4 which provided the justification for the **Thesis 1**, stating the necessary improvements for testbed facility to support WSN development up to TRL7, in the form of a relation between provided observations and Technology Readiness Levels revealing that for testbed facility to support WSN development and research up to TRL7 the following functionality is necessary: flexible deployment options, current consumption measurement system, scriptable interface, and user guide. A comparative Table 1.21 of the 32 identified testbed facilities revealed that none of them had the necessary functionality before the work described in this thesis.

In order to provide the testbed facility improvements they were developed in the EDI TestBed by [Ruskuls et al., 2015] described in Section 2. Research and development of the proposed improvements together with guidelines and requirements are described as follows: flexible deployment options described in Section 3.1, current consumption measurement system described in Section 3.2, scriptable interface described in Section 3.3 and user guide described in Section 3.3.

In order to evaluate the proposed testbed facility improvements in relation to **Thesis 1** seven use cases with different TRLs are described in Section 4, five of them are research related, one is related to education and another one is related to publicity. Two of the described use cases were a part of the European Union Horizon2020 programme and one was part of the European Union Horizon Europe programme. The usage of provided improvements is summarized in Table 4.1 demonstrating the applicability of the improved EDI TestBed to support WSN research and development up to TRL7 in accordance with **Thesis 1**.

The main conclusions of this thesis are as follows:

- Testbed facilities are capable of supporting the research and development of Wireless Sensor Networks up to TRL7 if the following functionality is provided: flexible deployment option, current measurement system, scriptable interface, and user manual.
- The terminology used in the testbed facility domain needs to be clarified, as in the existing literature there are no distinct divisions between testbed, testbed facility, and other testing facilities.
- Majority of testbed facilities are not easily reproducible significantly limiting the possibilities of creating new testbed facilities based on previous work and functionality exchange between existing testbed facilities.
- The biggest culprit of testbed facilities is the vast heterogeneity of available Wireless Sensor Networks hardware making it impossible to provide all of the embedded hardware the user might want or even a representative subset.
- Presently, the utilization of testbed facilities seems limited, the improvements such as those described in this thesis are helpful, but a larger involvement from the community is necessary to create an effective ecosystem of WSN testbed facilities which fosters growth and utilization.
- The utilization of low-performance embedded devices is high in the research community, so the testbed facilities should still prioritize deploying large numbers of such devices over high-performance devices.

5.1 Results

The main results and scientific contribution of this thesis are a comprehensive description of the testbed facility domain and a number of improvements in order to facilitate testbed facility usage for the research and development of Wireless Sensor Networks up to TRL7, including:

- Extensive review of actual sensor network deployments in research studies for 5 year period from 2013 to 2017 (Section 1.1);
- Recognition of the need and formulation of the term ”testbed facility” (Section 1.2);
- Comprehensive overview of current Wireless Sensor Networks and Internet of Things testbed facilities available for scientific and commercial use for a ten-year period from 2011 to 2020 (Section 1.3);
- Analysis of the supply and demand in testbed facility domain and formulation of necessary testbed facility improvements to facilitate the research and development of Wireless Sensor Networks up to TRL7 (Section 1.4);
- Approach for the introduction of flexible deployment options in testbed facilities (Section 3.1), which is patented in Latvia under Application number: P-17-69;
- Evaluation of requirements and approach for the introduction of a capable current measurement system in testbed facilities (Section 3.2);
- Approach for scriptable user interface in testbed facilities (Section 3.3).

The scientific importance of supporting research and development of Wireless Sensor Networks up to TRL7 is related to the outcomes of Horizon Europe Innovation Action projects, which are expected to be in the range of TRL 6 to 8. In order for a tool such as a testbed facility to be useful and successful for application in the research domain, being applicable to the requirements of the main research framework in Europe is a must. The scientific novelty lies in the identification of a common unifying goal to be used as the driving force behind the development of testbed facilities, as previous works on the subject of testbeds and testbed facilities do not identify such general goals but mostly focus on applicability on a single domain. The identified lack of terminology and proposition of new terminology for testbed facilities enables scientific research and development in the domain. The developed testbed facility improvement - flexible deployment option is the first of its kind as no other testbed facility provides a flexible deploy anywhere solution for Wireless Sensor Networks development and testing.

Even though the proposed testbed facility improvements at this point are implemented in the EDI TestBed, they can be applied to any testbed facility as the description is also provided for implementation together with requirements and practical guidelines.

The analysis of the testbed role in actual sensor network deployment systematic review underscores the potential for increased utilization of testbed facilities in sensor network deployments, particularly in contexts where industry relevance and complex interactions are key considerations. Testbed facilities can play a crucial role in validating and refining sensor networks, and their adaptation to evolving requirements and technologies is vital for ensuring their continued effectiveness.

The discussion about the results of the systematic literature review about the testbed facilities delves into the challenges of limited replicability and reusability of published testbed facilities, suggesting solutions such as open-sourcing, cost estimates, and encouraging replication. The importance of ground truth data, accurate sensor measurements, communication challenges, and the significance of diverse testing environments are brought forward. The need for a comprehensive ecosystem for testbed facilities is emphasized, encompassing hardware, software, and community support. A call is made for active engagement, collaboration, and integration of testbed facilities within centralized information hubs.

5.2 List of publications and other academic achievements

The results of this thesis have been included in 12 scientific publications, of which ten are indexed in the SCOPUS database, and two are under peer review and already published in the Open Research Europe publishing platform.

1. **Judvaitis, J.**, Salmins, A. and Nesenbergs, K., 2016, November. Network data traffic management inside a TestBed. In 2016 Advances in Wireless and Optical Communications (RTUWO) (pp. 152-155). IEEE, [Judvaitis et al., 2016], *indexed in SCOPUS*;

2. Lapsa, D., Balass, R., **Judvaitis, J.** and Nesenbergs, K., 2017, November. Measurement of current consumption in a wireless sensor network TestBed. In 2017 25th Telecommunication Forum (TELFOR) (pp. 1-4). IEEE, [Lapsa et al., 2017], *indexed in SCOPUS*;

3. Salmins, A., **Judvaitis, J.**, Balass, R. and Nesenbergs, K., 2017, November. Mobile wireless sensor network TestBed. In 2017 25th Telecommunication Forum (TELFOR) (pp. 1-4). IEEE, [Salmins et al., 2017], *indexed in SCOPUS*;

4. **Judvaitis, J.**, Nesenbergs, K., Balass, R. and Greitans, M., 2019. Challenges of DevOps ready IoT Testbed. In MDE4IoT/ModComp@ MoDELS (pp. 3-6), [Judvaitis et al., 2019], *indexed in SCOPUS*;

5. **Judvaitis, J.**, Mednis, A., Abolins, V., Skadins, A., Lapsa, D., Rava, R., Ivanovs, M. and Nesenbergs, K., 2020. Classification of Actual Sensor Network Deployments in Research Studies from 2013 to 2017. Data, 5(4), p.93, [Judvaitis et al., 2020], *indexed in SCOPUS*;

6. **Judvaitis, J.**, Balass, R. and Greitans, M., 2021. Mobile IoT-Edge-Cloud Continuum Based and DevOps Enabled Software Framework. Journal of Sensor and Actuator Networks, 10(4), p.62, [Judvaitis et al., 2021], *indexed in SCOPUS*;

7. Parrilla, F., Gómez, S.J., Greitans, M. and **Judvaitis, J.**, 2021, Intelligent Transport System: The Indra Use Case, in book Devops for Trustworthy Smart Iot Systems, pp 224-240, [Parrilla et al., 2021], *indexed in SCOPUS*;

8. Elkenawy, A. and **Judvaitis, J.**, 2022. Transmission power influence on wsn-based indoor localization efficiency. Sensors, 22(11), p.4154, [Elkenawy and Judvaitis, 2022], *indexed in SCOPUS*;

9. **Judvaitis, J.**, Abolins, V., Mednis, A., Balass, R. and Nesenbergs, K., 2022. The Definitive Guide to Actual Sensor Network Deployments in Research Studies from 2013–2017: A Systematic Review. Journal of Sensor and Actuator Networks, 11(4), p.68, [Judvaitis et al., 2022b], *indexed in SCOPUS*;

10. **Judvaitis, J.**, Abolins, V., Elkenawy, A. and Ozols, K., 2022. Available Wireless Sensor Network and Internet of Things testbed facilities: dataset. Open Research Europe, 2(127), p.127, [Judvaitis et al., 2022a], *under peer review*;

11. Balass, R., Medvedevs, V., Mackus, A.I., Ormanis, J., Ancans, A. and **Judvaitis, J.**, 2023. Precise realtime current consumption measurement in IoT TestBed. Open Research Europe, 3(27), p.27, [Balass et al., 2023], *under peer review*;

12. **Judvaitis, J.**, Abolins, V., Elkenawy, A., Balass, R., Selavo, L. and Ozols, K., 2023. Testbed Facilities for IoT and Wireless Sensor Networks: A Systematic Review. Journal of Sensor and Actuator Networks, 12(3), p.48, [Judvaitis et al., 2023], *indexed in SCOPUS*.

The results of this thesis have been presented and discussed at four international scientific conferences:

1. Advances in Wireless and Optical Communications (RTUWO 2016), Riga, Latvia;
2. 25th Telecommunication Forum (TELFOR 2017), Belgrade, Serbia;
3. 22nd International Conference on Model Driven Engineering Languages and Systems (MODELS), Workshop on Model-Driven Engineering for the Internet of Things (MDE4IoT 2019), Munich, Germany;
4. International Workshop on Embedded Digital Intelligence (IWoEDI 2023), Riga, Latvia.

The author has supervised five bachelor’s theses, of which four are related to the topic of this work.

BIBLIOGRAPHY

[AbdelHafeez and AbdelRaheem 2018] Mahmoud AbdelHafeez, and Mohamed AbdelRaheem. Assiut iot: A remotely accessible testbed for internet of things. In *2018 IEEE Global Conference on Internet of Things (GCIoT)*, IEEE, 2018, p. 1–6

[AbdelHafeez et al. 2020] Mahmoud AbdelHafeez, Ali H Ahmed, and Mohamed AbdelRaheem. Design and operation of a lightweight educational testbed for Internet-of-Things applications. In *IEEE Internet of Things Journal*, 2020, vol. 7, Nr. 12, p. 11446–11459

[Adjih et al. 2015] Cedric Adjih, Emmanuel Baccelli, Eric Fleury, Gaetan Harter, Nathalie Mitton, Thomas Noel, Roger Pissard-Gibollet, Frederic Saint-Marcel, Guillaume Schreiner, Julien Vandaele, and others. FIT IoT-LAB: A large scale open experimental IoT testbed. In *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, IEEE, 2015, p. 459–464

[Aksu et al. 2018] Hidayet Aksu, Leonardo Babun, Mauro Conti, Gabriele Tolomei, and A Selcuk Uluagac. Advertising in the IoT era: Vision and challenges. In *IEEE Communications Magazine*, 2018, vol. 56, Nr. 11, p. 138–144

[Albaladejo et al. 2010] Cristina Albaladejo, Pedro Sánchez, Andrés Iborra, Fulgencio Soto, Juan A López, and Roque Torres. Wireless sensor networks for oceanographic monitoring: A systematic review. In *Sensors*, 2010, vol. 10, Nr. 7, p. 6948–6968

[Alsukayti 2020] Ibrahim S Alsukayti. A multidimensional internet of things testbed system: Development and evaluation. In *Wireless Communications and Mobile Computing*, 2020, vol. 2020, p. 1–17

[Alvanou et al. 2020] Aikaterini Georgia Alvanou, Alexandros Zervopoulos, Asterios Papamichail, Konstantinos Bezas, Spiridon Vergis, Andreana Stylidou, Athanasios Tsipis, Vasileios Komianos, Georgios Tsoumanis, George Koufoudakis, and others. CaBIUs: description of the enhanced wireless campus testbed of the Ionian University. In *Electronics*, 2020, vol. 9, Nr. 3, p. 454

[Analog Devices 2022] Analog Devices. *Analog Devices LTC2500-32*. `https://www.analog.com/media/en/technical-documentation/data-sheets/250032fb.pdf`. 2022. – Accessed: 2022-27-07

[APRE 2023] CDT APRE. *Guiding notes to use the TRL self-assessmentto*. https://horizoneuropencpportal.eu/sites/default/files/2022-12/trl-assessment-tool-guide-final.pdf. 2023. – [Online; accessed June 1, 2023]

[Balass et al. 2023] Rihards Balass, Vladislavs Medvedevs, Andris Ivars Mackus, Juris Ormanis, Armands Ancans, and Janis Judvaitis. Precise realtime current consumption measurement in IoT TestBed. In *Open Research Europe*, 2023, vol. 3, Nr. 27, p. 27

[Bekan et al. 2015] Adnan Bekan, Mihael Mohorcic, Justin Cinkelj, and Carolina Fortuna. An architecture for fully reconfigurable plug-and-play wireless sensor network testbed. In *2015 IEEE Global Communications Conference (GLOBECOM)*, IEEE, 2015, p. 1–7

[u blox 2021] blox u. *SARA-N2 series*. https://www.u-blox.com/sites/default/files/SARA-N2_DataSheet_%28UBX-15025564%29.pdf. 2021. – [Online; accessed September 13, 2021]

[Brodard et al. 2016] Zacharie Brodard, Hao Jiang, Tengfei Chang, Thomas Watteyne, Xavier Vilajosana, Pascal Thubert, and Géraldine Texier. Rover: Poor (but Elegant) Man's Testbed. In *Proceedings of the 13th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks*, 2016, p. 61–65

[Brunisholz et al. 2016] Pierre Brunisholz, Etienne Dublé, Franck Rousseau, and Andrzej Duda. WalT: A reproducible testbed for reproducible network experiments. In *2016 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, IEEE, 2016, p. 146–151

[Croce et al. 2008] Silvio Croce, Francesco Marcelloni, and Massimo Vecchio. Reducing power consumption in wireless sensor networks using a novel approach to data aggregation. In *The Computer Journal*, 2008, vol. 51, Nr. 2, p. 227–239

[Dludla et al. 2013] Angeline G Dludla, Adnan M Abu-Mahfouz, Carel P Kruger, and John S Isaac. Wireless sensor networks testbed: ASNTbed. In *2013 IST-Africa Conference & Exhibition*, IEEE, 2013, p. 1–10

[Doddavenkatappa et al. 2012] Manjunath Doddavenkatappa, Mun Choon Chan, and Akkihebbal L Ananda. Indriya: A low-cost, 3D wireless sensor network testbed. In *Testbeds and Research Infrastructure. Development of Networks and Communities: 7th International*

ICST Conference, TridentCom 2011, Shanghai, China, April 17-19, 2011, Revised Selected Papers 7, Springer, 2012, p. 302–316

[Dorofeeva and Nyurenberger 2019] Anna A Dorofeeva, and Larisa B Nyurenberger. Trends in digitalization of education and training for industry 4.0 in the Russian Federation. In *IOP Conference Series: Materials Science and Engineering*, vol. 537, IOP Publishing, 2019, p. 042070

[DSLogic 2023] DSLogic. *DSLogic U3Pro16 logic analyser*. `https://www.mouser.com/datasheet/2/744/DSLogic_U3Pro16_Datasheet-1825057.pdf`. 2023. – Accessed: 2023-05-11

[Elkenawy and Judvaitis 2022] Amr Elkenawy, and Janis Judvaitis. Transmission power influence on wsn-based indoor localization efficiency. In *Sensors*, 2022, vol. 22, Nr. 11, p. 4154

[Environmental Expert 2021] Environmental Expert. *Advanticsys XM1000 sensor node*. `https://www.environmental-expert.com/products/advanticsys-model-as-xm1000-mote-module-262761`. 2021. – [Online; accessed July 21, 2021]

[Evdokimova et al. 2019] Yulia Evdokimova, Olga Shinkareva, and Anastasia Bondarenko. Digital banks: development trends. In *2nd International Scientific conference on New Industrialization: Global, national, regional dimension (SICNI 2018)*, Atlantis Press, 2019

[Falkenberg et al. 2017] Robert Falkenberg, Mojtaba Masoudinejad, Markus Buschhoff, Aswin Karthik Ramachandran Venkatapathy, Daniel Friesel, Michael Hompel ten, Olaf Spinczyk, and Christian Wietfeld. PhyNetLab: An IoT-based warehouse testbed. In *2017 Federated Conference on Computer Science and Information Systems (FedCSIS)*, IEEE, 2017, p. 1051–1055

[Farooq and Kunz 2014] Muhammad Omer Farooq, and Thomas Kunz. Wireless sensor networks testbeds and state-of-the-art multimedia sensor nodes. In *Applied Mathematics & Information Sciences*, 2014, vol. 8, Nr. 3, p. 935

[Ferry et al. 2018] Nicolas Ferry, Arnor Solberg, Hui Song, Stéphane Lavirotte, Jean-Yves Tigli, Thierry Winter, Victor Muntés-Mulero, Andreas Metzger, Erkuden Rios Velasco, and Amaia Castelruiz Aguirre. ENACT: Development, Operation, and Quality Assurance of

Trustworthy Smart IoT Systems. In *International Workshop on Software Engineering Aspects of Continuous Development and New Paradigms of Software Production and Deployment*, Springer, 2018, p. 112–127

[Ferry et al. 2021] Nicolas Ferry, Hui Song, Andreas Metzger, and Erkuden Rios. *DevOps for Trustworthy Smart IoT Systems*. Boston-Delft: now publishers, 2021

[Forecast 2019] Cisco VNI Forecast. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022 White Paper. In *Cisco Public Information*, 2019

[Forghani-Zadeh and Rincon-Mora 2002] Hassan Pooya Forghani-Zadeh, and Gabriel A Rincon-Mora. Current-sensing techniques for DC-DC converters. In *Circuits and Systems, 2002. MWSCAS-2002. The 2002 45th Midwest Symposium on*, vol. 2, IEEE, 2002, p. II–II

[Förster et al. 2015] Anna Förster, Alexander Förster, Kamini Garg, Silvia Giordano, and Luca Maria Gambardella. MOTEL: Mobility Enabled Wireless Sensor Network Testbed. In *Ad Hoc Sens. Wirel. Networks*, 2015, vol. 24, Nr. 3-4, p. 307–331

[Gao et al. 2020] Yi Gao, Jiadong Zhang, Gaoyang Guan, and Wei Dong. LinkLab: A scalable and heterogeneous testbed for remotely developing and experimenting IoT applications. In *2020 IEEE/ACM Fifth International Conference on Internet-of-Things Design and Implementation (IoTDI)*, IEEE, 2020, p. 176–188

[Grand View Research 2023] Grand View Research. *Consumer IoT Market Size & Trends Analysis Report, 2030*. `https://www.grandviewresearch.com/industry-analysis/consumer-iot-market-report`. 2023. – [Online; accessed June 1, 2023]

[Guo et al. 2012] Cheng Guo, R Venkatesha Prasad, Jiang Jie He, Martin Jacobsson, and Ignas GMM Niemegeers. Designing a flexible and low–cost testbed for Wireless Sensor Networks. In *International Journal of Ad Hoc and Ubiquitous Computing*, 2012, vol. 9, Nr. 2, p. 111–121

[Handbook 2004] Low Level Measurements Handbook. 6th. In *Chapter*, 2004, vol. 6, p. 54–57

[Handziski et al. 2006] Vlado Handziski, Andreas Köpke, Andreas Willig, and Adam Wolisz. Twist: a scalable and reconfigurable testbed for wireless indoor experiments with sensor networks. In *Proceedings of the 2nd international workshop on Multi-hop ad hoc networks: from theory to reality*, ACM, 2006, p. 63–70

[Harter et al. 2015] Gaetan Harter, Roger Pissard-Gibollet, Frederic Saint-Marcel, Guillaume Schreiner, and Julien Vandaele. FIT IoT-LABA: Large Scale Open Experimental IoT Testbed. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, 2015, p. 176–178

[Héder 2017] Mihály Héder. From NASA to EU: the evolution of the TRL scale in Public Sector Innovation. In *The Innovation Journal*, 2017, vol. 22, Nr. 2, p. 1–23

[Horneber and Hergenröder 2014] Jens Horneber, and Anton Hergenröder. A survey on testbeds and experimentation environments for wireless sensor networks. In *IEEE Communications Surveys & Tutorials*, 2014, vol. 16, Nr. 4, p. 1820–1838

[Imran et al. 2010] Muhammad Imran, Abas Md Said, and Halabi Hasbullah. A survey of simulators, emulators and testbeds for wireless sensor networks. In *2010 International Symposium on Information Technology*, vol. 2, IEEE, 2010, p. 897–902

[Jara et al. 2015] Antonio J Jara, Dominique Genoud, and Yann Bocchi. Big data for smart cities with KNIME a real experience in the SmartSantander testbed. In *Software: Practice and Experience*, 2015, vol. 45, Nr. 8, p. 1145–1160

[Jiménez-González et al. 2011] Adrián Jiménez-González, José Ramiro Dios Martínez-de, and Anibal Ollero. An integrated testbed for cooperative perception with heterogeneous mobile and static sensors. In *Sensors*, 2011, vol. 11, Nr. 12, p. 11516–11543

[Johansson 2013] Håkan Johansson. Sampling and quantization. In *Signal Processing Theory and Machine Learning*, 2013

[Ju et al. 2012] Xi Ju, Hongwei Zhang, and Divya Sakamuri. NetEye: a user-centered wireless sensor network testbed for high-fidelity, robust experimentation. In *International Journal of Communication Systems*, 2012, vol. 25, Nr. 9, p. 1213–1229

[Judvaitis et al. 2023] Janis Judvaitis, Valters Abolins, Amr Elkenawy, Rihards Balass, Leo Selavo, and Kaspars Ozols. Testbed Facilities for IoT and Wireless Sensor Networks: A Systematic Review. In *Journal of Sensor and Actuator Networks*, 2023, vol. 12, Nr. 3, p. 48

[Judvaitis et al. 2022a] Janis Judvaitis, Valters Abolins, Amr Elkenawy, and Kaspars Ozols. Available Wireless Sensor Network and Internet of Things testbed facilities: dataset. In *Open Research Europe*, 2022, vol. 2, Nr. 127, p. 127

[Judvaitis et al. 2022b] Janis Judvaitis, Valters Abolins, Artis Mednis, Rihards Balass, and Krisjanis Nesenbergs. The Definitive Guide to Actual Sensor Network Deployments in Research Studies from 2013–2017: A Systematic Review. In *Journal of Sensor and Actuator Networks*, 2022, vol. 11, Nr. 4, p. 68

[Judvaitis et al. 2021] Janis Judvaitis, Rihards Balass, and Modris Greitans. Mobile IoT-Edge-Cloud Continuum Based and DevOps Enabled Software Framework. In *Journal of Sensor and Actuator Networks*, 2021, vol. 10, Nr. 4, p. 62

[Judvaitis et al. 2020] Janis Judvaitis, Artis Mednis, Valters Abolins, Ansis Skadins, Didzis Lapsa, Raimonds Rava, Maksims Ivanovs, and Krisjanis Nesenbergs. Classification of Actual Sensor Network Deployments in Research Studies from 2013 to 2017. In *Data*, 2020, vol. 5, Nr. 4, p. 93

[Judvaitis et al. 2019] Janis Judvaitis, Krisjanis Nesenbergs, Rihards Balass, and Modris Greitans. Challenges of DevOps ready IoT Testbed. In *CEUR Workshop Proceedings: MDE4IoT/ModComp@ MoDELS*, vol. 2442, 2019, p. 3–6

[Judvaitis et al. 2016] Janis Judvaitis, Arnis Salmins, and Krisjanis Nesenbergs. Network data traffic management inside a TestBed. In *2016 Advances in Wireless and Optical Communications (RTUWO)*, IEEE, 2016, p. 152–155

[Kim et al. 2015] Hiecheol Kim, Won-Kee Hong, Joonhyuk Yoo, and Seong-eun Yoo. Experimental research testbeds for large-scale WSNs: A survey from the architectural perspective. In *International Journal of Distributed Sensor Networks*, 2015, vol. 11, Nr. 3, p. 630210

[Kosareva et al. 2019] Olga A Kosareva, Mikhail N Eliseev, Vyacheslav P Cheglov, Alla N Stolyarova, and Svetlana B Aleksina. Global trends of digitalization of agriculture as the basis of innovative development of the agro-industrial complex of Russia. In *Eurasian Journal of Biosciences*, 2019, vol. 13, Nr. 2, p. 1675–1681

[Lanza et al. 2015] Jorge Lanza, Luis Sánchez, Luis Muñoz, José Antonio Galache, Pablo Sotres, Juan R Santana, and Verónica Gutiérrez. Large-scale mobile sensing enabled internet-of-things testbed for smart city services. In *International Journal of Distributed Sensor Networks*, 2015, vol. 11, Nr. 8, p. 785061

[Lapsa et al. 2017] Didzis Lapsa, Rihards Balass, Janis Judvaitis, and Krisjanis Nesenbergs. Measurement of current consumption in a wireless sensor network TestBed. In *2017 25th Telecommunication Forum (TELFOR)*, IEEE, 2017, p. 1–4

[Latre et al. 2016] Steven Latre, Philip Leroux, Tanguy Coenen, Bart Braem, Pieter Ballon, and Piet Demeester. City of things: An integrated and multi-technology testbed for IoT smart city experiments. In *2016 IEEE international smart cities conference (ISC2)*, IEEE, 2016, p. 1–8

[Li et al. 2019] Fan Li, Jianxin Yang, Jianmei Wang, Shuangshou Li, and Li Zheng. Integration of digitization trends in learning factories. In *Procedia Manufacturing*, 2019, vol. 31, p. 343–348

[Lim et al. 2013] Roman Lim, Federico Ferrari, Marco Zimmerling, Christoph Walser, Philipp Sommer, and Jan Beutel. Flocklab: A testbed for distributed, synchronized tracing and profiling of wireless embedded systems. In *Proceedings of the 12th international conference on Information processing in sensor networks*, 2013, p. 153–166

[Lima et al. 2019] Luis Eduardo Lima, Bruno Yuji Lino Kimura, and Valério Rosset. Experimental environments for the internet of things: A review. In *IEEE Sensors Journal*, 2019, vol. 19, Nr. 9, p. 3203–3211

[Linden and Fenn 2003] Alexander Linden, and Jackie Fenn. Understanding Gartner's hype cycles. In *Strategic Analysis Report Nº R-20-1971. Gartner, Inc*, 2003, vol. 88, p. 1423

[Ma et al. 2017] Junyan Ma, Jin Wang, and Te Zhang. A survey of recent achievements for wireless sensor networks testbeds. In *2017 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC)*, IEEE, 2017, p. 378–381

[Manrique et al. 2016] Johana A Manrique, Johan S Rueda-Rueda, and Jesús MT Portocarrero. Contrasting internet of things and wireless sensor network from a conceptual overview. In *2016 IEEE international conference on Internet of Things (iThings) and IEEE* *green computing and communications (GreenCom) and IEEE cyber, physical and social computing (CPSCom) and IEEE smart data (SmartData)*, IEEE, 2016, p. 252–257

[Merriam-Webster.com Dictionary 2020] Merriam-Webster.com Dictionary. *s.v. "test bed,"*. `https://www.merriam-webster.com/dictionary/test%20bed`. 2020. – [Online; accessed July 22, 2020]

[Michelinakis et al. 2020] Foivos Michelinakis, Anas Saeed Al-Selwi, Martina Capuzzo, Andrea Zanella, Kashif Mahmood, and Ahmed Elmokashfi. Dissecting Energy Consumption of NB-IoT Devices Empirically. In *IEEE Internet of Things Journal*, 2020, vol. 8, Nr. 2, p. 1224–1242

[Mir et al. 2012] Zeeshan Hameed Mir, Hyeon Park, Young Bag Moon, Nae Soo Kim, and Cheol Sig Pyo. Design and deployment of testbed for experimental sensor network research. In *Network and Parallel Computing: 9th IFIP International Conference, NPC 2012, Gwangju, Korea, September 6-8, 2012. Proceedings 9*, Springer, 2012, p. 264–272

[Morf et al. 1979] M Morf, T Kailath, B Friedlander, J Newkirk, and DT Lee. *Investigation of new algorithms for locating and identifying spatially distributed sources and receivers*. 1979

[Moteiv Corporation 2006] Moteiv Corporation. *Tmote sky datasheet*. `https://insense.cs.st-andrews.ac.uk/files/2013/04/tmote-sky-datasheet.pdf`. 2006. – [Online; accessed September 9, 2021]

[Muduli et al. 2018] Lalatendu Muduli, Devi Prasad Mishra, and Prasanta K Jana. Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review. In *Journal of Network and Computer Applications*, 2018, vol. 106, p. 48–67

[Munoz et al. 2019] Jonathan Munoz, Fabian Rincon, Tengfei Chang, Xavier Vilajosana, Brecht Vermeulen, Thijs Walcarius, Wim Meerssche Van de, and Thomas Watteyne. OpenTestBed: poor man's IoT testbed. In *IEEE INFOCOM 2019-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, IEEE, 2019, p. 467–471

[Nati et al. 2013] Michele Nati, Alexander Gluhak, Hamidreza Abangar, and William Headley. Smartcampus: A user-centric testbed for internet of things experimentation. In *2013*

16th International symposium on wireless personal multimedia communications (WPMC), IEEE, 2013, p. 1–6

[Nati et al. 2017] Michele Nati, Alexander Gluhak, Jaroslaw Domaszewicz, Spyros Lalis, and Klaus Moessner. Lessons from smartcampus: External experimenting with user-centric internet-of-things testbed. In *Wireless Personal Communications*, 2017, vol. 93, p. 709–723

[Nordic Semiconductor 2021] Nordic Semiconductor. *nRF52 Product Specification*. `https://infocenter.nordicsemi.com/pdf/nRF52832_PS_v1.1.pdf`. 2021. – [Online; accessed September 13, 2021]

[Noussan et al. 2020] Michel Noussan, Manfred Hafner, and Simone Tagliapietra. Digitalization Trends. In *The Future of Transport Between Digitalization and Decarbonization*. Springer, 2020, p. 51–70

[Noussan and Tagliapietra 2020] Michel Noussan, and Simone Tagliapietra. The effect of digitalization in the energy consumption of passenger transport: An analysis of future scenarios for Europe. In *Journal of Cleaner Production*, 2020

[Olivares et al. 2013] Teresa Olivares, Fernando Royo, and Antonio M Ortiz. An experimental testbed for smart cities applications. In *Proceedings of the 11th ACM international symposium on Mobility management and wireless access*, 2013, p. 115–118

[Omiyi et al. 2008] Eitan Omiyi, Kaan Bür, and Yang Yang. A technical survey of wireless sensor network platforms, devices and testbeds. In *a report for the Airbus/ESPRC Active Aircraft Project EP/F004532/1: Efficient and Reliable Wireless Communication Algorithms for Active Flow Control and Skin Friction Drag Reduction*, 2008

[Ormanis and Elsts 2020] Juris Ormanis, and Atis Elsts. Towards body coupled communication for ehealth: Experimental study of human body frequency response. In *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*, IEEE, 2020, p. 1–7

[Ott 1988] Henry W Ott. *Noise reduction techniques in electronic systems*. , vol. 442. Wiley New York, 1988

[Paniagua and Delsing 2020] Cristina Paniagua, and Jerker Delsing. Industrial frameworks for internet of things: A survey. In *IEEE Systems Journal*, 2020, vol. 15, Nr. 1, p. 1149–1159

[Parrilla et al. 2021] F. Parrilla, S. J. Gómez, M. Greitans, and J. Judvaitis. Intelligent Transport System: The Indra Use Case. In *DevOps for Trustworthy Smart IoT Systems*. Now Publishers, 2021, p. 224–240

[Peng et al. 2014] Zheng Peng, Li Wei, Zigeng Wang, Lei Want, Michael Zuba, Jun-Hong Cui, Shengli Zhou, Zhijie Shi, and James O'Donnell. Ocean-TUNE UCONN testbed: A technology incubator for underwater communication and networking. In *2014 Underwater Communications and Networking (UComms)*, IEEE, 2014, p. 1–4

[Polastre et al. 2005] Joseph Polastre, Robert Szewczyk, and David Culler. Telos: Enabling ultra-low power wireless research. In *IPSN 2005. Fourth International Symposium on Information Processing in Sensor Networks, 2005.*, IEEE, 2005, p. 364–369

[Polese et al. 2015] Davide Polese, Luca Pazzini, A Minotti, Luca Maiolo, and A Pecora. Tunable Transmission Power to Improve 2D RSSI Based Localization Algorithm. In *SENSORNETS*, 2015, p. 151–156

[Portaluri et al. 2019] Giuseppe Portaluri, Mike Ojo, Stefano Giordano, Marialaura Tamburello, and Giuseppe Caruso. Open CLORO: an open testbed for cloud robotics. In *2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, IEEE, 2019, p. 1–5

[Potsch 2016] Albert Potsch. Ph. D. forum abstract: A scalable testbed infrastructure for embedded industrial wireless sensor and actuator networks. In *2016 15th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, IEEE, 2016, p. 1–2

[Pötsch et al. 2014] Albert Pötsch, Achim Berger, Georg Möstl, and Andreas Springer. TWECIS: A testbed for wireless energy constrained industrial sensor actuator networks. In *Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA)*, IEEE, 2014, p. 1–4

[Pradeep et al. 2015] Preeja Pradeep, P Divya, RD Arya Devi, P Rekha, K Sangeeth, and Maneesha Vinodini Ramesh. A remote triggered wireless sensor network testbed. In *2015 Wireless Telecommunications Symposium (WTS)*, IEEE, 2015, p. 1–7

[Quectel Wireless Solutions 2020] Quectel Wireless Solutions. *Quectel-BC95 specification*. `https://www.quectel.com/wp-content/uploads/pdfupload/Quectel_BC95-G_NB-IoT_Specification_V1.9.pdf`. 2020. – [Online; accessed September 13, 2021]

[Rodin et al. 2019] BK Rodin, RG Ganiev, and ST Orazov. «Fintech» in digitalization of banking services. In *International Scientific and Practical Conference on Digital Economy (ISCDE 2019)*, Atlantis Press, 2019

[Burin des Rosiers et al. 2012] Clément Rosiers Burin des, Guillaume Chelius, Eric Fleury, Antoine Fraboulet, Antoine Gallais, Nathalie Mitton, and Thomas Noël. SensLAB: Very Large Scale Open Wireless Sensor Network Testbed. In *Testbeds and Research Infrastructure. Development of Networks and Communities: 7th International ICST Conference, TridentCom 2011, Shanghai, China, April 17-19, 2011, Revised Selected Papers 7*, Springer, 2012, p. 239–254

[des Roziers et al. 2011] C Burin Roziers des, Guillaume Chelius, Tony Ducrocq, Eric Fleury, Antoine Fraboulet, Antoine Gallais, Nathalie Mitton, Thomas Noel, Erkan Valentin, and Julien Vandaële. Two demos using senslab: Very large scale open wsn testbed. In *2011 International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS)*, IEEE, 2011, p. 1–2

[Ruskuls et al. 2015] Rinalds Ruskuls, Didzis Lapsa, and Leo Selavo. EDI WSN TestBed: Multifunctional, 3D Wireless Sensor Network Testbed. In *Advances in Wireless and Optical Communications (RTUWO), 2015*, IEEE, 2015, p. 50–53

[Ruskuls and Selavo 2010] Rinalds Ruskuls, and Leo Selavo. EdiMote: a flexible sensor node prototyping and profiling tool. In *International Workshop on Real-world Wireless Sensor Networks*, Springer, 2010, p. 194–197

[Salmins et al. 2017] Arnis Salmins, Janis Judvaitis, Rihards Balass, and Krisjanis Nesenbergs. Mobile wireless sensor network TestBed. In *2017 25th Telecommunication Forum (TELFOR)*, IEEE, 2017

[Salmins et al. 2015] Arnis Salmins, Kaspars Ozols, and Rinalds Ruskuls. Data management in TestBed for large scale wireless sensor networks. In *2015 Advances in Wireless and Optical Communications (RTUWO)*, IEEE, 2015, p. 54–57

[Sanchez et al. 2014] Luis Sanchez, Luis Muñoz, Jose Antonio Galache, Pablo Sotres, Juan R Santana, Veronica Gutierrez, Rajiv Ramdhany, Alex Gluhak, Srdjan Krco, Evangelos Theodoridis, and others. SmartSantander: IoT experimentation over a smart city testbed. In *Computer Networks*, 2014, vol. 61, p. 217–238

[Schaerer et al. 2019] Jakob Schaerer, Zhongliang Zhao, Jose Carrera, Severin Zumbrunn, and Torsten Braun. Sdnwisebed: A software-defined wsn testbed. In *Ad-Hoc, Mobile, and Wireless Networks: 18th International Conference on Ad-Hoc Networks and Wireless, ADHOC-NOW 2019, Luxembourg, Luxembourg, October 1–3, 2019, Proceedings 18*, Springer, 2019, p. 317–329

[Sherry 2019] James Sherry. *NB-IoT Market Size Worth $6.02 Billion by 2025*. `https://www.bloomberg.com/press-releases/2019-07-23/nb-ioT-market-size-worth-6-02-billion-by-2025-cagr-34-9-grand-view-research-inc`. 2019. – [Online; accessed June 16, 2020]

[Singh et al. 2020] Dhawan Singh, Amanpreet Sandhu, Aditi Sharma T., and Nikhil Priyank. An Overview of IoT Hardware Development Platforms. In *International Journal on Emerging Technologies*, 2020

[Smite and Smits 2018] Rasa Smite, and Raitis Smits. *Swamp Radio*. `http://smitesmits.com/SwampRadio.html`. 2018. – [Online; accessed September 8, 2021]

[Steyn and Hancke 2011] Leon P Steyn, and Gerhard P Hancke. A survey of wireless sensor network testbeds. In *IEEE Africon'11*, IEEE, 2011, p. 1–6

[STMicroelectronics 2019] STMicroelectronics. *Datasheet - STM32L476xx*. `https://www.st.com/resource/en/datasheet/stm32l476je.pdf`. 2019. – [Online; accessed September 13, 2021]

[STMicroelectronics 2021] STMicroelectronics. *STM32WLEx Wireless MCUs with LoRa support*. `https://www.st.com/en/microcontrollers-microprocessors/stm32wlex.html?icmp=tt13669_gl_pron_jan2020&utm_source=everythingrf`. 2021. – [Online; accessed September 13, 2021]

[Strazdins et al. 2010] Girts Strazdins, Atis Elsts, and Leo Selavo. Mansos: easy to use, portable and resource efficient operating system for networked embedded devices. In

Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems, ACM, 2010, p. 427–428

[Taivalsaari and Mikkonen 2017] Antero Taivalsaari, and Tommi Mikkonen. A roadmap to the programmable world: software challenges in the IoT era. In *IEEE Software*, 2017, vol. 34, Nr. 1, p. 72–80

[Texas Instruments 2018] Texas Instruments. CC1352R SimpleLink™ High-Performance Multi-Band Wireless MCU. In *CC1352R2018 Data Sheet*, 2018

[Texas Intruments 2013] Texas Intruments. CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver Data Sheet (rev. SWRS041c) https://www.ti.com/lit/ds/symlink/cc2420.pdf. In *CC2420 Data Sheet*, 2013. – Accessed: 2023-06-06

[The Python Software Foundation 2020] The Python Software Foundation. *cmd — Support for line-oriented command interpreters*. `https://docs.python.org/3/library/cmd.html`. 2020. – [Online; accessed September 17, 2021]

[The TRINITY network 2023] The TRINITY network. *EDI WSN/IOT TestBed - trinity*. `https://trinityrobotics.eu/modules/edi-wsn-iot-testbed-2/`. 2023. – [Online; accessed November 4, 2023]

[Tonneau et al. 2014] Anne-Sophie Tonneau, Nathalie Mitton, and Julien Vandaele. A survey on (mobile) wireless sensor network experimentation testbeds. In *2014 IEEE International Conference on Distributed Computing in Sensor Systems*, IEEE, 2014, p. 263–268

[Tonneau et al. 2015] Anne-Sophie Tonneau, Nathalie Mitton, and Julien Vandaele. How to choose an experimentation platform for wireless sensor networks? A survey on static and mobile wireless sensor network experimentation facilities. In *Ad Hoc Networks*, 2015, vol. 30, p. 115–127

[Trüb et al. 2019] Roman Trüb, Reto Da F., Tonia Gsell, Jan Beutel, and Lothar Thiele. Demo abstract: A testbed for long-range lora communication. In *2019 18th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, IEEE, 2019, p. 342–343

[Venkatapathy et al. 2015] Aswin Karthik Ramachandran Venkatapathy, Moritz Roidl, Andreas Riesner, Jan Emmerich, and Michael Hompel ten. PhyNetLab: Architecture design of ultra-low power Wireless Sensor Network testbed. In *2015 IEEE 16th international Symposium on A world of wireless, mobile and multimedia networks (WoWMoM)*, IEEE, 2015, p. 1–6

[Wang et al. 2019] Zheng Wang, ZhenQiang Xu, BaiShun Dong, WeiMin Xu, and Jing Yang. Dandelion: An Online Testbed for LoRa Development. In *2019 15th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN)*, IEEE, 2019, p. 439–444

[Wen et al. 2017] Jianjun Wen, Zeeshan Ansar, and Waltenegus Dargie. Mobilab: A testbed for evaluating mobility management protocols in wsn. In *Testbeds and Research Infrastructures for the Development of Networks and Communities: 11th International Conference, TRIDENTCOM 2016, Hangzhou, China, June 14-15, 2016, Revised Selected Papers*, Springer, 2017, p. 49–58

[Winkler and Zinsmeister 2019] Hannes Winkler, and Lena Zinsmeister. Trends in digitalization of intralogistics and the critical success factors of its implementation. In *Brazilian Journal of Operations & Production Management*, 2019, vol. 16, Nr. 3, p. 537–549

[Zedalis 1978] Rex J Zedalis. Military Uses of Ocean Space and the Developing International Law of the Sea: An Analysis in the Context of Peactime ASW. In *San Diego L. Rev.*, 1978, vol. 16, p. 575

[Zhao et al. 2010] Ze Zhao, Guang-Hua Yang, Qiang Liu, Victor OK Li, and Li Cui. EasiTest: A multi-radio testbed for heterogeneous wireless sensor networks. In *IET International Conference on Wireless Sensor Network 2010 (IET-WSN 2010)*, IET, 2010, p. 104–108

[Zolertia 2010] Zolertia. *Z1 datasheet*. `http://wiki.zolertia.com/wiki/images/e/e8/Z1_RevC_Datasheet.pdf`. 2010. – [Online; accessed July 21, 2021]