The Internet-of-Things Open Source Ecosystem in 2021

Version 1.2

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The European IoT Hub

Growing a sustainable and comprehensive ecosystem for Next Generation Internet of Things

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ABBREVIATIONS

AI	Artificial Intelligence
AioT	Artificial Intelligence of Things
AMQP	Advanced Message Queuing Protocol
BSD	Berkley Software Distribution
CC	Creative Commons
CoAP	Constrained Application Protocol
DCS	Distributed Control System
DDS	Data Distribution Service
DGINT	European Commission Directorate General for Informatics
EC	European Commission
EU-IoT	European Union Internet of Things
ESF	Everywhere Software Framework
ETSI	European Telecommunications Standards Institute
FISSi	Future Internet Software and Services Initiative
FOTA	Firmware Over The Air
FPGA	Field-Programmable Gate Array
GPL	General Public License
H2020	Horizon 2020
HEU	Horizon Europe
HTTP	HyperText Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IA	Infrastructure Association
IIC	Industrial Internet Consortium
IICF	Industrial Internet Connectivity Framework
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol
IPv6	Internet Protocol version 6
IP	Intellectual Property
LGPL	Lesser General Public License
LSP	Large Scale Pilots
MQTT	Message Queuing Telemetry Transport
NGIoT	Next Generation Internet of Things
NFV	Network Functions Virtualisation
OPC-UA	OPC Unified Architecture
OpenMTC	Open Machine Type Communications
OS	Operating System
OSM	Open Source Mano
OSRF	Open Software Robotics Foundation
OSS	Open Source Software
PaaS	Platform as a Service
PLC	Programmable Logic Controller
R&D	Research and Development
ROS	Robot Operating System
SaaS	Software as a Service
SCADA	Supervisory Control and Data Acquisition
SDOs	Standards Development Organisations
SoC	System on a Chip
TSN	Tensor Stack Networks
WAN	Wide Area Network
WSN	Wireless Sensor Network

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1 INTRODUCTION

1.1 Scope and Purpose

For over a decade the Open Source Software (OSS) community has played a significant role in the development, deployment, and standardisation of the Internet of Things (IoT). This is evidenced by the increasing number of OSS projects that are developing essential components for the majority of IoT deployments worldwide, as well as by the number of innovative IoT projects that over the years have been developed and released as open source. Recently, the European Commission (EC) has released a policy brief on Open Source Software, which outlines and acknowledges the importance of OSS for ensuring more rapid innovation in several domains, including the IoT and Artificial Intelligence (AI).

This whitepaper aims at providing an overview of the IoT OSS projects landscape including:

- A presentation of IoT projects of prominent OSS ecosystems (e.g., Apache, Linux Foundation, Eclipse Foundation), including information on the role of European organisations and European OSS communities within these contexts.
- A review and analysis of more than 120 OSS projects covering different IoT themes, including OSS IoT hardware, IoT gateways, IoT device middleware, Edge Computing Middleware, IoT Cloud Platforms, and IoT development environments. The projects are analysed in terms of their different characteristics such as their OSS license, their community size, their acceptance by the OSS community, the language(s) they are written in, as well as the IoT standards that they support or promote.
- A presentation of recent open-source developments carried out in EU projects, including the projects of the H2020-ICT56-2020 call that are closely collaborating with the EU-IoT project.

Furthermore, the present whitepaper aims at introducing the EU-IoT IoT OSS projects catalogue, which is developed by the H2020 EU-IoT project and is already publicly accessible through the NGIoT website[1]. The catalogue aims at providing a searchable directory of IoT OSS projects. At the time of writing, it comprises a critical mass of over 100 projects, including most of the projects that are analysed in the scope of this whitepaper. The catalogue is extensible in terms of new projects, as EU-IoT enables the IoT and OSS communities to submit new OSS project entries. Overall, the EU-IoT Open Source project catalogue will facilitate the IoT community to access information about the rich set of available IoT projects through a single entry point. This will alleviate the fragmentation of information about OSS projects, which is currently faced by organizations that wish to use OSS components in their projects.

1.2 Policy Context

Open Source Software (OSS) is essentially free software, where the copyright holder provides a licence that enables users to run, study, and modify the software, but also to share the code with other parties. OSS provides several benefits to organizations that produce, adopt, and use it, including opportunities for effective collaboration with other organizations, as well as opportunities for greater agility and shorter innovation cycles.

The European Commission (EC) has recently communicated its open source strategy for the period 2020-2023 [EC-OSS20]. The strategy is motivated by the potential impact of OSS on the digital autonomy of Europe, including Europe's ability to control its processes and technologies in view of the rise of Cloud hyperscalers outside Europe. The Strategy outlines OSS as the leading

[1] https://www.ngiot.eu/archive-for-open-source-projects/

and more flexible model in several technological areas, including AI, IoT and blockchain. Furthermore, it foresees the establishment and operation of a Programme Office for OSS software, which will be under the responsibility of the European Commission Directorate General for Informatics (DGINT).

At a policy level, OSS is considered important for ensuring that Information and Communication Technology (ICT) infrastructures (e.g., cloud computing, IoT and AI) adhere to European principles such as data sovereignty, transparency, and compliance to European regulations including the General Data Protection Regulation (GDPR). For instance, OSS components are open to public scrutiny, which boosts the transparency of European software infrastructures. This is one of the reasons why key European projects like GAIA-X [Eggers20] and Data Spaces [Nagel21] opt to develop open and open source solutions.

Moreover, OSS plays a very important role in the development, deployment, and operation of IoT products and services. The vast majority of IoT system integrators and application developers use one or more open source components, as outlined in several surveys (e.g., [VisionMobile15], [Eclipse20]). According to [Eclipse20], 60% of IoT vendors and integrators consider IoT OSS in their plans. OSS components from the Eclipse Foundation, the Apache Software Foundation, and the Linux Foundation are among the most widely used according to the same survey. Likewise, [VisionMobile15] reported that 9 out of 10 IoT developers use some sort of OSS in their work.

IoT developers take advantage of different types of OSS components ranging from databases and open hardware to entire IoT cloud platforms offering Platform as a Service (PaaS) and Software as a Service (SaaS) functionalities. IoT OSS components are also particularly important for emerging IoT architectural paradigms at the edge of the network such as Artificial Intelligence of Things (AIoT). AIoT systems are comprised of many low level (i.e., system level) components such as wireless sensors, Systems on a Chip (SoC), actuators, network stacks, machine learning components (e.g., TinyML), Firmware Over The Air (FOTA) components, security algorithms, as well as components for reliability and energy efficiency. The development of such low-level components is challenging, which makes collaboration and reuse of prime importance. Open source adoption is therefore vital for the implementation of innovative AIoT systems and applications.

Europe's IoT Strategy as reflected in presentations of the European Commission's Unit E.4 for Internet of Things is focused on leading IoT's cloud/edge paradigm shift based on innovative developments in areas such as open distributed edge computing architectures, mesh computing topologies and swarm computing. In this context OSS is fully aligned to the EU's policy priorities.

1.3 IoT OSS Scope and Taxonomy

There are OSS projects covering several core aspects related to IoT systems development, i.e., from low-level hardware components to high-level cloud applications. Specifically, there are OSS IoT projects that implement one or more of the following:

- **Networking and IoT Protocols**, such as open source implementations of popular messaging protocols like the Advanced Message Queuing Protocol (AMQP), the Constrained Application Protocol (CoAP) and the Message Queuing Telemetry Transport (MQTT) protocol.
- **Operating Systems for IoT devices**, such as TinyOS, Contiki and Ubuntu Core.
- **IoT hardware boards,** like Arduino Ethernet Shield for Arduino Boards and BeagleBone for BeagleBoard devices.
- **IoT Search Engines**, such as Thingful.
- **IoT Middleware Platforms**, that enable end-to-end IoT application development.
- **IoT Workflow development platforms** like ThingsSpeak and Node-RED.

- **Visualization Platforms**, such as Freeboard.

IoT open source technologies can be also categorised based on IoT protocol stacks, including protocols stacks derived from the popular Open Systems Interconnection (OSI) stack such as the IoT connectivity stack of the Industrial Internet Connectivity Framework (IICF) [Joshi18], as well as IoT specific stacks [Soldatos20]. For instance, the following table presents a list of open source IoT projects that are categorized according to the IICF connectivity stack. However, there are OSS projects that cannot be matched to a single protocol stack. Therefore, a proper classification of IoT projects requires the combination of concepts from multiple taxonomies of IoT technologies and of IoT stacks.

IICF Stack Layer	Examples of OSS Projects
IoT Application	Node-RED, OpenIoT
Middleware Framework	Eclipse Milo (OPC-UA), Eclipse OM2M (oneM2M)
Transport	Eclipse Mosquitto (MQTT), Mainflux (HTTP, MQTT, CoAP)
Link/Physical	Eclipse Agail (ZigBee, LoRaWan, Zwave etc), OpenWSN (IEEE802.15.4e, IETF 6LoWPAN etc.)

Table 1: IoT OSS Projects Taxonomy according to the IoT connectivity stack of the Industrial Internet Connectivity Framework

The above-listed categories comprise components and projects that are exclusively used for developing IoT applications and services. Beyond these “pure IoT” projects, there is a very large set of open source projects in related areas like Big Data, Cloud Computing, and Machine Learning. For instance, Big Data middleware platforms like Apache Spark and Apache Kafka enable the development of IoT streaming and IoT analytics applications. [OpenLogic20] identifies the most popular open source infrastructures in areas like databases, analytics, and continuous developments. Most of these infrastructures are widely used by IoT developers as well.

The above-listed projects can be used as part of wider IoT systems that include non open source components as well. In several cases they are also used to build open source IoT applications. Considering these scenarios, developers must be provided with an easy way to locate the open source project that could serve their IoT development objectives. The present whitepaper introduces the EU-IoT catalogue that aims to help developers in this direction.

2 IOT ECOSYSTEM MAPPING

2.1 IoT OSS Ecosystem and Communities

The OSS ecosystem comprises several communities i.e., loosely organised groups of contributors that collaborate on one or more open source projects that are aimed at a common goal. In most cases open source communities are self-governed and self-organised. As part of their collaboration, open source communities improve the software over a common base, while sharing resources and improvements with other members of the community. There are numerous open source communities working on a variety of focus areas, including specific technologies (e.g., IoT, AI, BigData) or application areas (e.g., smart homes).

In this context, there are open source communities dedicated to IoT OSS. In most cases these communities operate and collaborate within wider open source communities. Specifically:

- The Eclipse IoT Community is the IoT open source community of the Eclipse Foundation. It includes over 45 projects covering different areas of IoT development.
- The Linux foundation hosts communities dedicated to IoT developments. Among the over 375 projects of the foundation, there are some popular state-of-the-art IoT projects such as the EdgeX Foundry, an IoT Plug n' Play platform for edge computing.
- The Apache Software foundation also includes various IoT projects within its portfolio of over 350 projects. Prominent examples are IoTDB and the Camel project that is used for IoT integration.
- The FIWARE foundation provides a rich set of open source components for building next generation internet applications, including components for IoT development such as the FIWARE Context Broker.
- Prominent open source companies like RedHat and Canonical have also developed vibrant open source communities around their IoT and cloud related open source projects and solutions (e.g., Ubuntu core).

These communities are joined by various contributors, including the private sector. For example, Bosch Software Innovations is one of the main contributors to the Eclipse IoT Working Group up to date, while being a user of open source components as part of the Bosch IoT Suite. As another example, Eurotech's main IoT product, the Everyware Software Framework (ESF) is based on Eclipse Kura project. The latter has contributed to Eclipse via Eurotech. Beyond Bosch and Eurotech, there are other companies all over the world that develop and release corporate scale OSS. For instance, the Dataart New York City based firm has developed and launched DeviceHive, a prominent open source cloud-based IoT development platform and M2M framework.

Several of the communities and projects listed above, have developed and demonstrated open source business models for future Internet applications, including IoT applications.

2.2 European Initiatives

European organisations have a very prominent position in the global IoT open source ecosystem. Specifically, the Eclipse IoT working group is largely influenced by European developers and their organisations. Furthermore, the FIWARE community supports a significant number of IoT developments and deployments, including many applications and use cases developed in the scope of European Research and Development (R&D) projects. For example, several IoT Large Scale Pilot (LSP) projects like H2020 IoF2020 make use of OSS projects.

The OW2 community is also a very prominent open source community in the European software ecosystem. It has a technology focus on infrastructure software and includes various projects that support the creation of the future Internet. For example, it includes projects on service-oriented

middleware, cloud services orchestration and other technologies that support the development and deployment of scalable IoT applications. Within OW2, there is the OW2 Future Internet Software and Services Initiative (FISSi), which focuses on scalable technologies for the future Internet. Although OW2 does not include many projects with an exclusive IoT focus, the FIiSSi initiative supports relevant developments in the cloud/edge technologies continuum.

There are also European Standards Development Organizations (SDOs) like the European Telecommunications Standards Institute (ETSI) that engage with IoT-related projects like the Open Source Mano (OSM). The OSM reflects the evolution of ETSI's Network Functions Virtualization (NFV) standardisation efforts. This is also a demonstration of how the open source community boosts the development and validation of open standards.

2.3 IoT OSS Links to SDOs and Standardisation Impact

In addition to boosting innovation and collaboration, the value of OSS developments is also reflected in standardisation efforts. Open source software communities aim at creating and sharing value, based on the development of novel software libraries. In complementarity, SDOs work in many cases on open standards towards enabling their members to create shared Intellectual Property (IP) in the form of open specifications. In most cases they also boost the compliance of their products and services to the produced specifications. The mandate of open source communities and open standards development organisations feature similarities and follow similar principles such as clarity, openness, and transparency. This is for example the case with their collaboration and documentation processes. Leveraging these commonalities, OSS communities support open standards development processes through prototyping standardisation ideas, providing reference implementation of standards, and boosting standards adoption. Furthermore, OSS communities promote technical innovations associated with the use of or extensions to existing standards. At the same time, SDOs use open source implementations to boost the engagement of relevant stakeholders including researchers, industrialists, and policy makers.

In this context, the IoT OSS community boosts open source standardisation processes. Moreover, the IoT OSS community has already implemented IoT standards. As a prominent example, a variety of OSS projects have focused on the implementation of different parts of the ETSI OneM2M standard. These projects range from general platforms like Eclipse OM2M that enables the implementation of horizontal OneM2M compliant M2M systems (i.e., servers, gateways, devices) and OpenMTC that provides an integration middleware based on the oneM2M standard, to projects focused on more specific aspects like oneM2MTester which is an OneM2M conformance testing tool.

2.4 Open Experimentation Platforms

Along with open source implementations of IoT standards there are also open experimentation platforms and testbeds. The latter enable the IoT community to experiment with innovative technologies and applications beyond specific standards. As a prominent example, the FIT-IoT project provides a scalable IoT testbed, which enables testing of networked IoT systems, notably systems that comprise small wireless sensor devices and heterogeneous communicating objects. The testbed is accessible through open APIs, while providing open software libraries that can be extended and customised to the needs of IoT experimenters. Moreover, the testbed provides access to various nodes, which boosts scalable experimentations with various IoT technologies and protocols (e.g., IPv6 and MQTT). As another example, EdgeNet is a scalable distributed edge cloud for Internet researchers, which provides resources at global scale. It is based on industry-standard cloud software, using Docker for containerisation and Kubernetes for deployment and node management.

3 IOT OPEN SOURCE PROJECTS ANALYSIS

3.1 Overview and Scope

To provide insights and information on the status of IoT OSS in 2021 EU-IoT collected and analysed more than 120 projects, including some of the most popular projects of the IoT community. Although not exhaustive, the list of analysed projects may be considered representative of the status of the global IoT ecosystem. This is due to the fact that the analysed projects include:

- **IoT projects from the most prominent IoT ecosystems worldwide**, including projects hosted by Apache, the Linux foundation, and the Eclipse Foundation.
- **IoT projects that are reported in on-line reviews, surveys, and tutorials**. Such surveys are published frequently and tend to include lists of popular and high-impact projects.
- **Projects that are directly related to IoT systems and technologies**. The assesment does not include projects that relate to supporting infrastructures (e.g., cloud computing infrastructures, DevOps infrastructures) that are widely used as part of IoT applications. Rather, the focus is on projects and libraries that are exclusively or primarily used for developing IoT modules and services.
- **Projects which address a broad range of IoT topics and technologies**. Efforts were made to include representative projects from every area of IoT systems development, including IoT devices and open source hardware, edge/cloud computing projects for IoT, IoT development environments, IoT analytics, as well as IoT data visualization projects.

The EU-IoT project offers access to these projects through an extensible on-line catalogue. This enables the IoT community to add more projects that will be considered in future releases of the EU-IoT whitepapers for the IoT OSS ecosystem.

3.2 Analysis Methodology and IoT projects Taxonomy

The methodology for analysing the various projects involved the collection and analysis of a set of characteristics for every project. These include:

- **Type**: The (general) type of the IoT project i.e., whether it concerns software, hardware, middleware.
- **IoT technology area**: This denotes a more detailed characterisation of the technology area of the project, such as whether it concerns IoT devices, edge/cloud computing, Big Data/IoT Analytics etc.
- **IoT standards**: This lists the standards that relate to the project, including standards supported by the project. In several cases, there are projects that provide reference implementations of standards.
- **Primary programming language**: This concerns the main programming language(s) of the project. The term ‘main’ is used for projects that comprise code in several languages. In these cases, the analysis has focused on the most dominant languages.
- **License**: This denotes the open source license of the project, which is an important piece of information for stakeholders wishing to adopt, use and integrate an OSS project within their developments.
- **Community information**: This includes a variety of attributes that indicate the popularity of the project in the OSS community, as well as the recency of the activity and engagement around the project. Specifically, wherever possible, the following information was collected:

- **Days Since Last Push**: This is the number of days since the last time there was a push of code in the project i.e., it indicates the most recent activities from OSS contributors on the project.
- Days Since Created: This is the number of days since the project was created. It is a measure on the "age" of the project.
- Github Stars: The number of stars that the project has on GitHub. It is an indicator of the popularity of the project.
- Number of Commits: Indicates the total number of commits of the project. It is a measure of the activity around the project.
- Number of Watchers: Provides the number of GitHub users that have selected to 'watch' the project and receive updates about its status. Any user can select to be a 'watcher' of a public repository and to receive notifications about events (e.g., commits, pull requests, issues). A watcher is usually interested in the activity of the project and potentially interested in contributing to it [Dabbish12]. As such watching is considered as a passive type of project membership [Sheoran14].
- Number of Forks: This is another indicator of the community activity around the project. A fork occurs when a completely independent line of development based on the source code basis of the project starts. This is usually done either by the community of the project or by a third-party, independent from the project's community.

To collect community information, a static React application was utilised to display statistics from GitHub repositories like Star History, Fork History and more[2]. The application produces graphical representations of the repositories' information (
Figure 1), yet it can be also used as a command line application to offer instant and faster extraction of statistics.

[2] vesoft-inc.github.io/github-statistics/

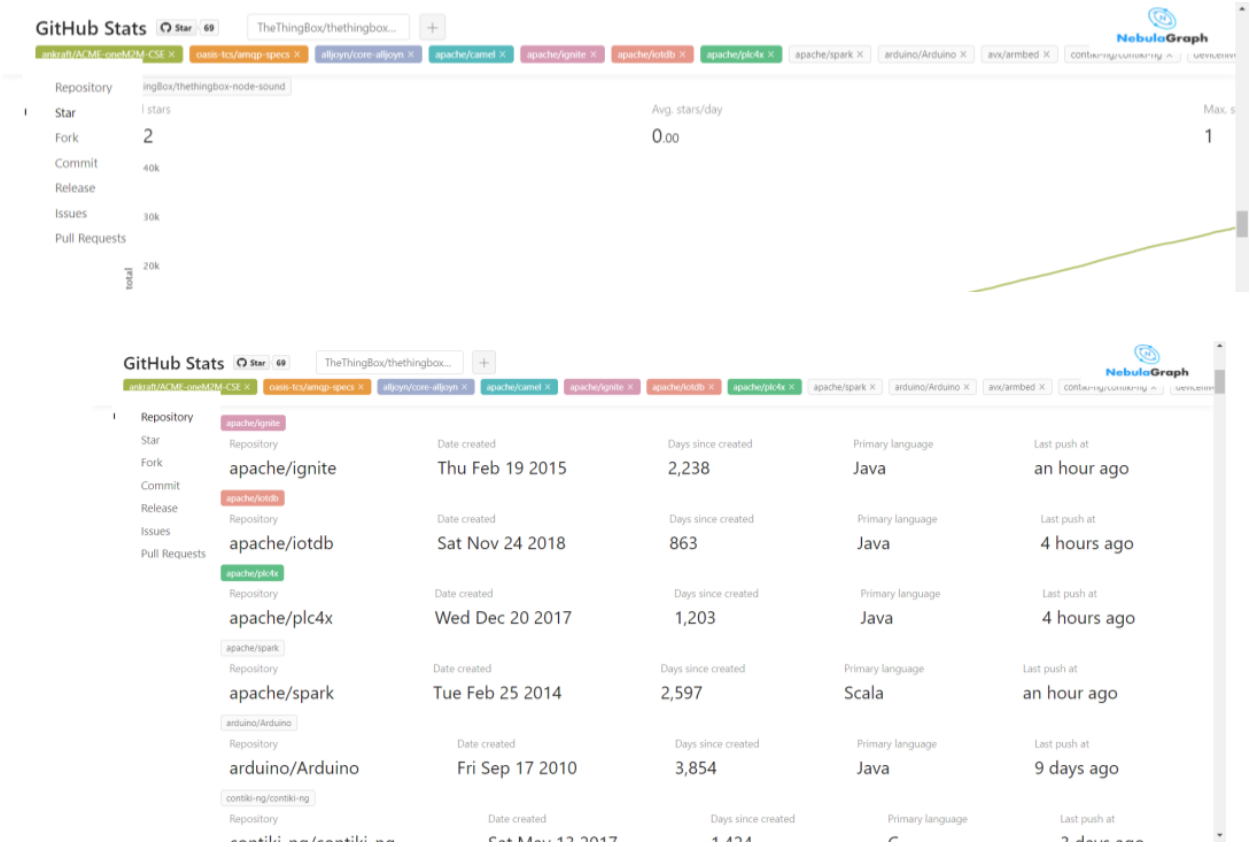

Figure 1: Snapshot of Graphs produced by the GitHub repositories analysis/statistics applications

Even though the analysis covered over 120 IoT projects, the above-listed information was not always available. For instance, there were some OSS projects that were not in GitHub and some others for which the community information was not available. Therefore, the total number of projects in the representations and charts presented below is typically below the total number of projects analysed.

3.3 Analysis by IoT Area

The analysed projects cover a variety of technology areas including edge computing, cloud computing, IoT device/hardware, embedded IoT, IoT connectivity, data/big data, industrial IoT areas and IoT security, as illustrated in Figure 2. In many cases IoT projects covered more than one of the above areas, in which case the primary focus of the project was recorded. For instance, many of the analysed projects included some IoT security aspects, yet not primarily focused on IoT security.

Most of the projects focus on the lower levels of the IoT stack (i.e., IoT devices, device connectivity, embedded IoT). This is reasonable and in-line with the traditional positioning of the IoT community towards the development of 'things'. Higher layers of the IoT Stack (e.g., Big Data analysis) are sometimes covered by non-IoT OSS projects (e.g., Apache Kafka). The latter are widely used in IoT deployments, yet they are not considered 'pure' IoT projects.

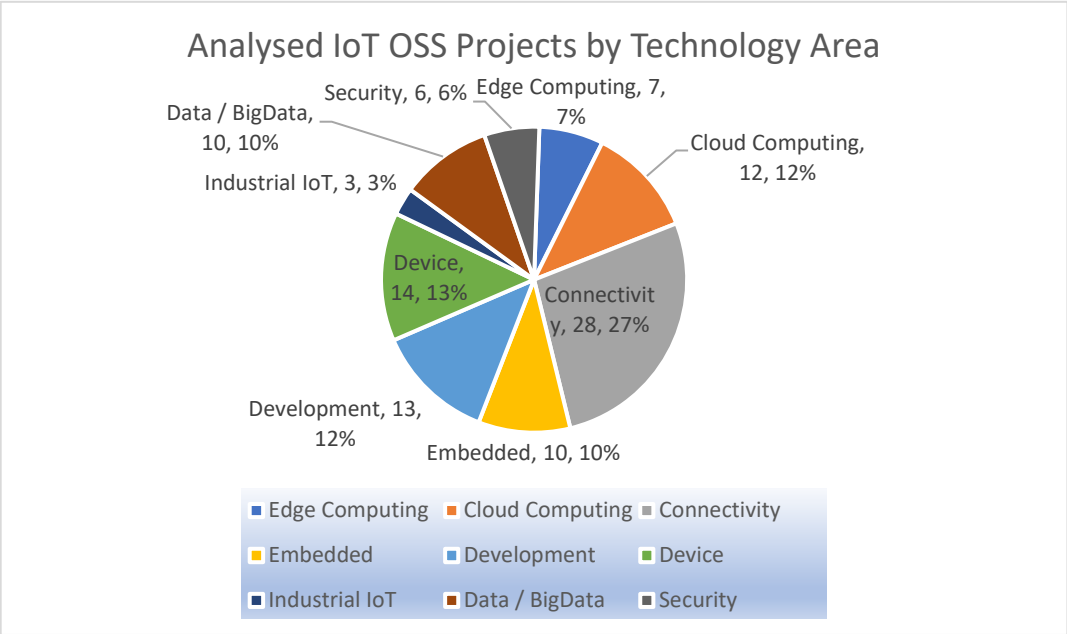

Figure 2: Analysed OSS projects by Technology Area

Nevertheless, there are also OSS projects operating in 'niche' IoT areas such as edge computing (e.g., Eclipse fog05, Eclipse iofog). These projects tend to be more recent than device-level projects.

3.4 Analysis by Language

Figure 3 provides an overview of the most popular programming languages of the analysed OSS projects i.e., Java, Python, JavaScript and C/C++. Several projects comprise code in more than two and in several cases in more than three languages, which is the reason why the count of the data in the chart exceeds the total number of analysed projects. There are also other languages used in some of the projects: Most notable mentions include Go, Perl, Rust, Objective C, SQL, and various more specialised package specific languages like HiveQL. Nevertheless, these languages are used in less than five projects each and therefore are not within the dominant languages that are listed in the chart.

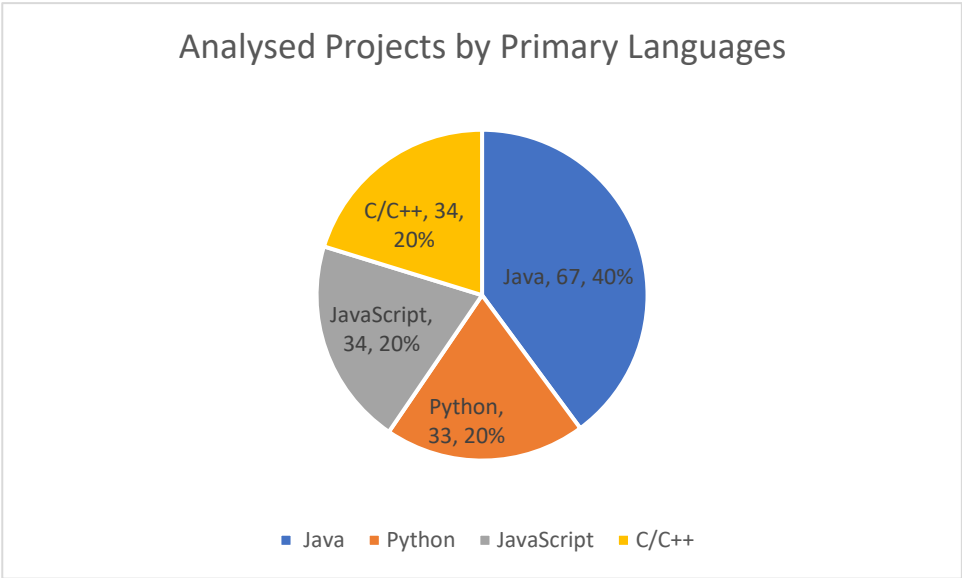

Figure 3: Most common primary language(s) in the analysed projects

Java is the dominant language in the entire groups of projects, such as the IoT projects of the Eclipse foundation. Moreover, pure Java projects (i.e., Java-only projects) are by far a majority. There are few projects that are pure C/C++ based (e.g., Zephyr and other Robotics projects) or Python (e.g., OpenMTC) based, while there are also a few projects with other primary languages (e.g., Eclipse Zenoh uses Rust). C/C++ remains the primary choice for projects with real-time requirements and constraints, such as projects of the OSRF (Open Software Robotics Foundation). There are also projects that aim at creating developer friendly languages such as Eclipse Mita, which provides a developer-friendly programming language for embedded systems.

3.5 Analysis by Standards Relevance

Figure 4 presents the main standards that are associated with the analysed projects. Most of the analysed projects are not directly linked to some IoT standard or protocol. However, the Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP) and oneM2M standards are integrated and used in several projects, as primary IoT connectivity protocols. In the case of oneM2M there are also projects that provide reference implementations of the standards (e.g., Eclipse OM2M) Other connectivity protocols like the Data Distribution Service (DDS) and message protocols like the AMQP (Advanced Message Queuing Protocol) are also found in a few projects.

Several projects focus on industrial standards, systems, protocols, and devices, including Programmable Logic Controllers (PLC), Distributed Control Systems (DCS), and Supervisory Control and Data Acquisition (SCADA) systems (e.g., Eclipse neoSCADA). In this context there are also various projects that implement or use the OPC-UA standard for industrial connectivity, as well as the IEC 61499 for distributed control.

IoT has been also used in conjunction with version 6 of Internet Protocol (IPv6), which is the reason why various projects provide support for IPv6 based IoT deployments. Some of these projects provide open source implementations of related standards like IETF 6LoWPLAN.

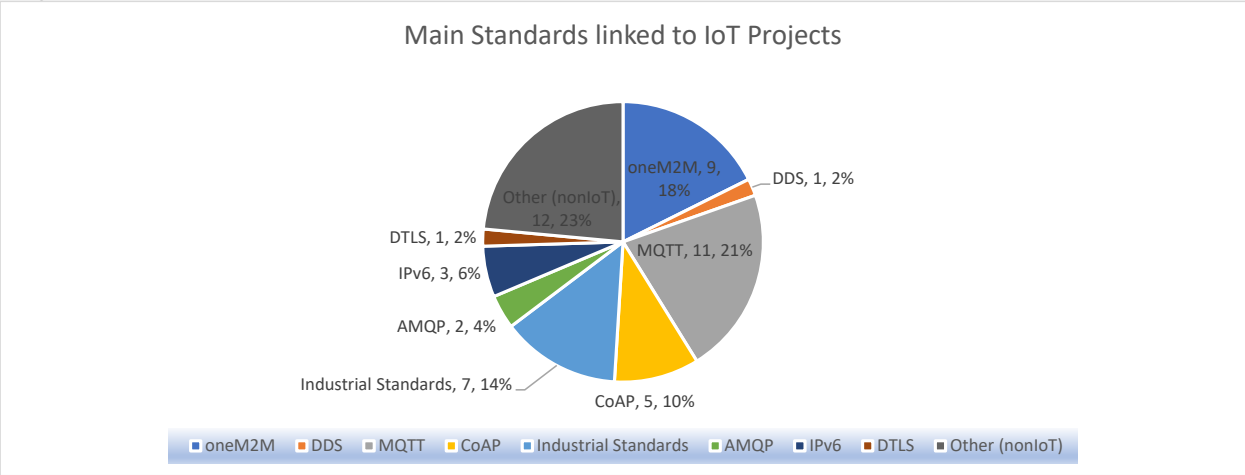

Figure 4: Standards Relevance for analysed projects

3.6 Analysis by Open Source License

Over 100 of the analysed projects were protected by a single license. As depicted in Figure 5, most the projects were associated with Apache and Eclipse licenses. This is to some extent expected given that the list of analysed projects included the IoT projects of the Apache and Eclipse open source ecosystems. Other licenses that were associated with a notable number of projects, include Berkeley Source Distribution (BSD) licenses, MIT licenses, as well as General

Public License (GPL), Creative Commons (CC) and the LGPL (Lesser General Public License). Different versions of the various licenses were used. Figure 5 consolidates the different versions according to the type of license.

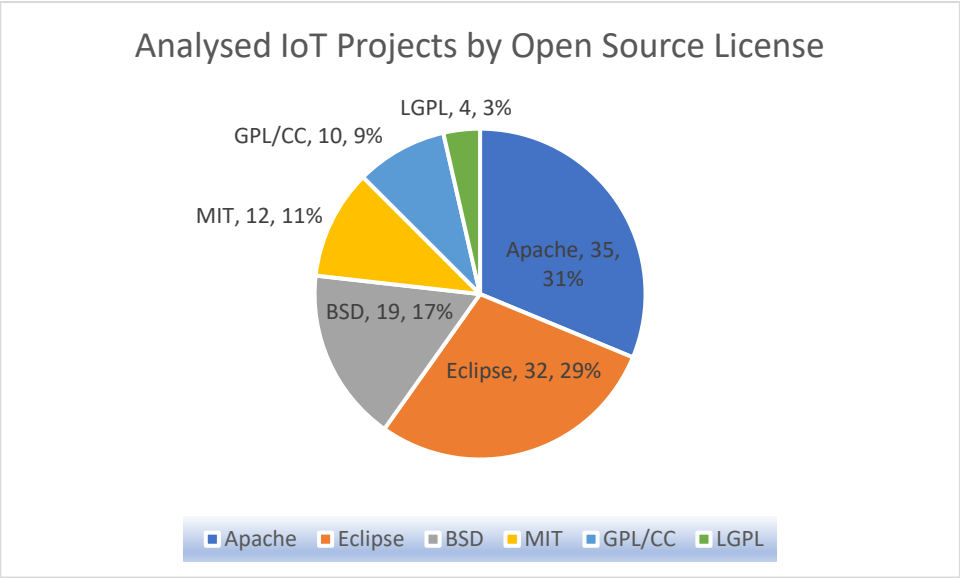

Figure 5: Open Source Licenses of Analysed Projects

Most of the above-listed licenses are business friendly (e.g., Apache, Eclipse, LGPL). Therefore, private enterprises are generally offered opportunities to use open source libraries in their projects.

3.7 Analysis by Community Size and Characteristics

The analysis of the community figures and statistics of the different projects revealed that the projects have varying popularity within the community. The following table provides the maximum, the minimum, the average value, and the standard deviation for the statistics analysed. Note that only 91 projects out of the 120 were analysed based on the GitHub statistical analysis tools. The rest had limitations that prevented this analysis.

Metrics/Statistics	MIN	MAX	AVERAGE	STDEV
Days Since Last Push	0	2913	263	595
Days Since Last Created	139	4370	1982	935
GitHub Stars	0	119760	3372	13671
Number of Commits	1	52401	6576	12106
Number of Watchers	1	3534	179	468
Number of Forks	0	23815	1137	3491

Table 2: Statistical Properties of different metrics for the analysed projects

The values in the table indicate that the list of projects is diverse in terms of popularity and community engagement. The list includes projects with very high popularity among the IoT community such as Arduino (over 11,700 stars), Node-Red (over 12,000 stars), and ThingsBoard (over 8,000 stars). On the other hand, there are projects with a few hundred stars, which reflects lower popularity and small community (e.g., OpenIoT with over 450 stars), recently created projects, or projects that are more specialised (e.g., Eclipse Paho with over 1,470 stars or Eclipse Ponte with over 350 stars) rather than general purpose with broader applicability. However, there are also projects with significantly lower popularity (i.e., tens of stars) and smaller communities. The board range of popularities is reflected in Figure 6, which presents that most (i.e., over 30%) projects are distributed in the range of 0-100 stars, while more than 40% are in the range of 100-2000 (i.e., having several hundreds of stars).

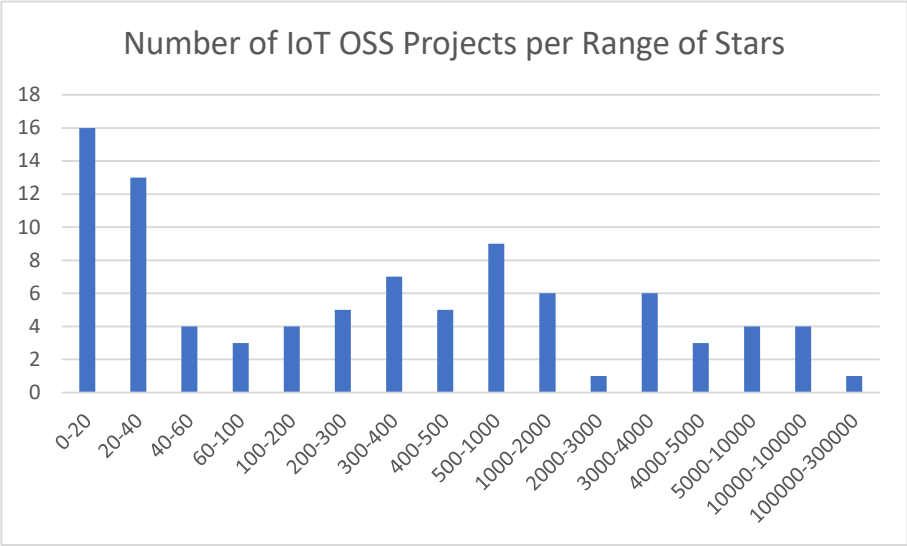

Figure 6: Histogram of IoT OSS projects according to their GitHub Stars

Popularity (e.g., Stars) and community statistics (e.g., number of commits, number of forks) are correlated. As expected, popular projects have larger and more committed communities. As a prominent example, Arduino (over 7,300 commits and over 6,850 forks) and Node-Red (over 6,250 commits and over 2,390 forks) are among the projects with the highest community engagement, despite lagging behind top outliers in the list such as the RIOT operating system with over 35,000 commits and the Apache Ignite project with over 27,000 commits. The diversity in the number of commits is presented in Figure 7.

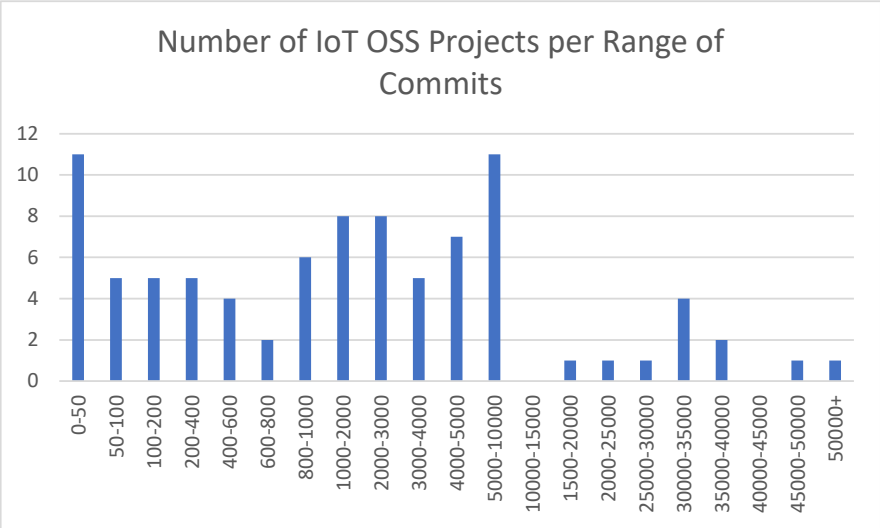

Figure 7: Histogram of IoT OSS projects according to their GitHub Commits

Figure 8 illustrates the correlation between the commits and forks of the various projects. This correction is moderate to strong (i.e., the correlation co-efficient for the two variables is over 0.5) as projects with significant numbers of commits are likely to attract potential third-party contributors or to be extended by members of their community in new directions.

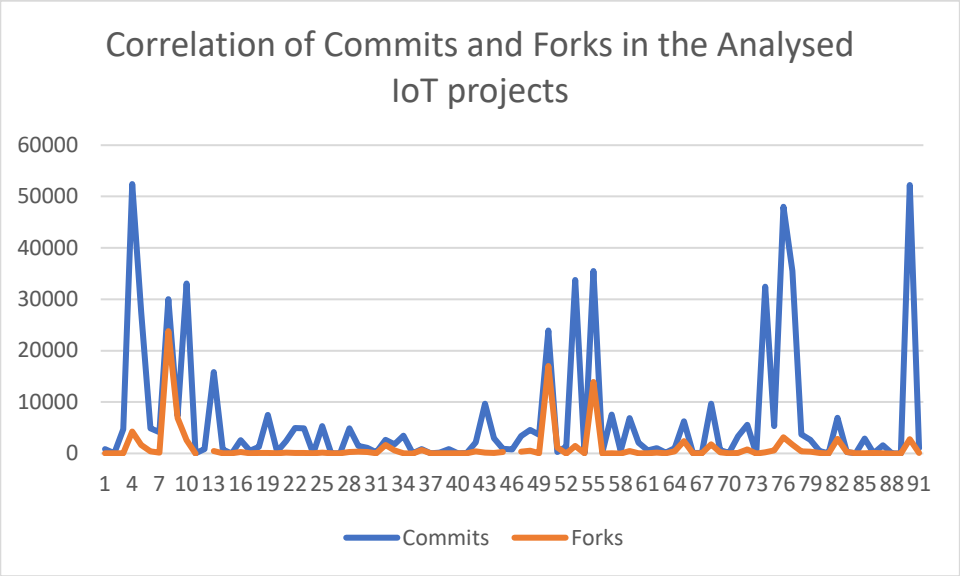

Figure 8: Correlation of the GitHub Commits and Forks for 91 of the analysed projects

4 IOT OSS AND H2020 PROJECTS IN 2021

4.1 Background

EU projects have a good track record of open source contributions. Many EU projects of the FP7 and H2020 frameworks have provided contributions to the analysed projects, for instance some associated with the Eclipse Foundation. Also, the FIWARE community was initiated within the EC Future Internet Private Public Partnership (FI-PPP) context. FIWARE provides several open source components that are widely used, including IoT components and platforms such as the FIWARE Context Broker that simplifies the development of IoT applications. Furthermore, various projects established their IoT OSS from scratch and created their own communities. Prominent examples include:

- The FP7 OpenIoT project, which established the OpenIoT open source IoT middleware platform. It was one of the analysed projects that has still an active community and frequent mentions.
- The FP7 WebInOS (Secure WebOS Application Environment) also established an open source project with an active community for several years.

EU-IoT collaborates closely with the most recent EC funded IoT projects, namely the Research and Innovation Actions (RIAs) that have been funded as part of the H2020-ICT-56-2020 'Next Generation Internet of Things' call. The following paragraphs provide initial information about these projects and their open source activities. The projects are in their early implementation stage. Therefore, their outcomes and contributions will be analysed in future EU-IoT publications.

4.2 H2020 ICT56 Projects

4.2.1 ASSIST-IoT (https://assist-iot.eu/)

Project Summary	The project designs, implements and validates an open, decentralised reference architecture, associated enablers, services and tools, to assist human-centric IoT applications in multiple verticals. ASSIST-IoT will deliver, in a realistic, measurable, and replicable way, a unified innovative multi-plane (semi-)autonomous edge-to-cloud-continuum architecture for the future IoT deployments. ASSIST-IoT proposes to be primarily based on OSS technologies, relying on the most recent trends on microservice, containerisation and orchestration, supplemented by cross-cutting digital enablers. The architecture supports continuous integration and long-term sustainability of domain-agnostic, interoperable, self-* capable, intelligent, distributed, scalable, secure, and trustworthy IoT ecosystems.
Planned OSS Developments	ASSIST-IoT is working with open source hardware (Linux-based) and software (containerisation, lightweight K8s), and aims to produce outcomes as open source by default. The proposed license to be used is a type of Open Source Software License, Apache 2.0, GNU GPL or others, that enables distributing of the results to the community. Some results will be patentable, yet it is expected that open source by design will be the strategy for most outputs.
Contact	Carlos Palau (cpalau@dcom.upv.es)

4.2.2 VEDLIOT (https://vedliot.eu/)

Project Summary	VEDLIoT builds a distributed Very Efficient Deep Learning IoT platform. Instead of traditional algorithms, artificial intelligence (AI) and deep learning (DL) are used to handle large complexity in IoT applications. Due to the distributed approach, VEDLIoT allows dividing the application into smaller and more efficient components and work together in large collaborative systems in the Internet of Things (IoT), enabling AI-based algorithms that are distributed over IoT devices from edge to cloud.
Planned OSS Developments	Most of the technology will be open source, although for some of the applications that the partners are working on in the automotive sector some of the technology is proprietary.
Contact	Jens Hagemeyer (jhagemey@cit-ec.uni-bielefeld.de)

4.2.3 IoT-NGIN (https://iot-ngin.eu/)

Project Summary	IoT-NGIN introduces novel research and innovation concepts, acting as the 'IoT Engine' which will fuel the Next Generation of IoT as a part of the European Next Generation Internet. IoT-NGIN uncovers a patterns-based meta-architecture that encompasses evolving, legacy, and future IoT architectures. The project also optimizes IoT/M2M and 5G/MCM communications, including using secure-by-design micro-services to extend the edge cloud paradigm. Moreover, it enables user and self-aware, autonomous IoT systems through privacy-preserving federated ML and ambient intelligence, with AR support for humans.
Planned OSS Developments	The project developments will be released as open source, almost entirely, the source code being available under the projects gitlab.com repository (https://gitlab.com/h2020-iot-ngin).
Contact	Ghasan BHATTI (ghasan.bhatti@capgemini.com) Artemis Voulkidis (voulkidis@synelixis.com)

4.2.4 INGENIOUS (https://ingenious-iot.eu/)

Project Summary	INGENIOUS designs and evaluates the Next-Generation IoT (NGIoT) solution, with emphasis on 5G and the development of Edge and Cloud computing extensions for IoT, as well as providing smart networking and data management solutions with Artificial Intelligence and Machine Learning (AI/ML). The project embraces the 5G Infrastructure Association (5G IA) and Alliance for Internet of Things Innovation (AIOTI) vision for empowering smart manufacturing and smart mobility verticals.
Planned OSS Developments	Part of the project's development deals with safe and secure communication between parts of the computer that separate process cores. This will comprise open source parts, to complement proprietary modules running on FPGAs (Field-Programmable Gate Arrays).
Contact	Gomez-Barquero David (dagobar@iteam.upv.es)

4.2.5 IntellIoT (https://intelliot.eu/)

Project Summary	IntellIoT focuses on the development of integrated, distributed, human-centered and trustworthy IoT frameworks applicable to agriculture, healthcare and manufacturing. Enabling technologies such as 5G, cybersecurity, distributed technology, Augmented Reality, and tactile internet. IntellIoT also champions end-user trust, adequate security and privacy by design.
Planned OSS Developments	IntellIoT's contributions to open-source projects will focus on its 5G platform which is based on the OpenAirInterface and Mosaic5G. OpenAirInterface and Mosaic5G are open-source solutions for 5G and are backed by large international communities of academic and industrial stakeholders. The results on advanced network management for the NGIoT solutions e.g., open-source extension of OAI/Mosaic5G will be made publicly accessible via GitLab. The project will contribute components of its hypermedia-based Multi-Agent System, which might be integrated with the IoT Standards resources of the open source community. This will include libraries and tooling for researchers and practitioners to design, deploy, and manage IoT/edge infrastructures. Additionally, the project will deliver open source AI algorithms focusing on the use cases that are investigated under the project.
Contact	Vivek Kulkarni (vivekkulkarni@siemens.com)

4.2.6 TERMINET (https://terminet-h2020.eu/)

Project Summary	The vision of TERMINET is to provide a flexible, open, and decentralised next generation IoT reference architecture based on cutting-edge technologies such as software-defined networking, multiple-access edge computing, and virtualisation for new real-time capable solutions. This goal will be achieved by enabling secure and privacy-preserving IoT services, user-aware solutions, semi-autonomous devices, and self-aware mechanisms, frameworks, and schemes, supported by distributed AI and new intelligent IoT devices within a virtualized edge-platform-cloud environment.
Planned OSS Developments	In TERMINET's integrated platform, open-source software tools will be utilised. However, either the hardware (i.e., smart glasses) or other tools required will be proprietary. The open calls of the project will look to on-board new, state-of-the-art open source tools and to integrate them in the project's developments.
Contact	Panagiotis Sarigiannidis (psarigiannidis@uowm.gr)

5 THE EU-IOT OPEN SOURCE CATALOGUE

5.1 Scope

At this point in time, the IoT community has access to a very rich set of open source projects and libraries. The latter provide significant innovation opportunities for IoT vendors and solution providers. Moreover, they facilitate IoT standardisation, including reference implementations. It is therefore vital for IoT solution integrators and other stakeholders to have easy access to the rich and rapidly evolving collection of IoT projects. In line with this, EU-IoT offers to the IoT community a searchable catalogue of IoT OSS projects and other resources, which is destined to ease efforts to locate open source assets for their projects and innovation endeavours. The aim of the searchable catalogue of IoT projects is manifold:

- To centralise access to IoT projects and to facilitate discovery of relevant resources.
- To propose a list of projects as an open data set that could be used by interested parties.
- To boost IoT OSS information curation by interested parties.

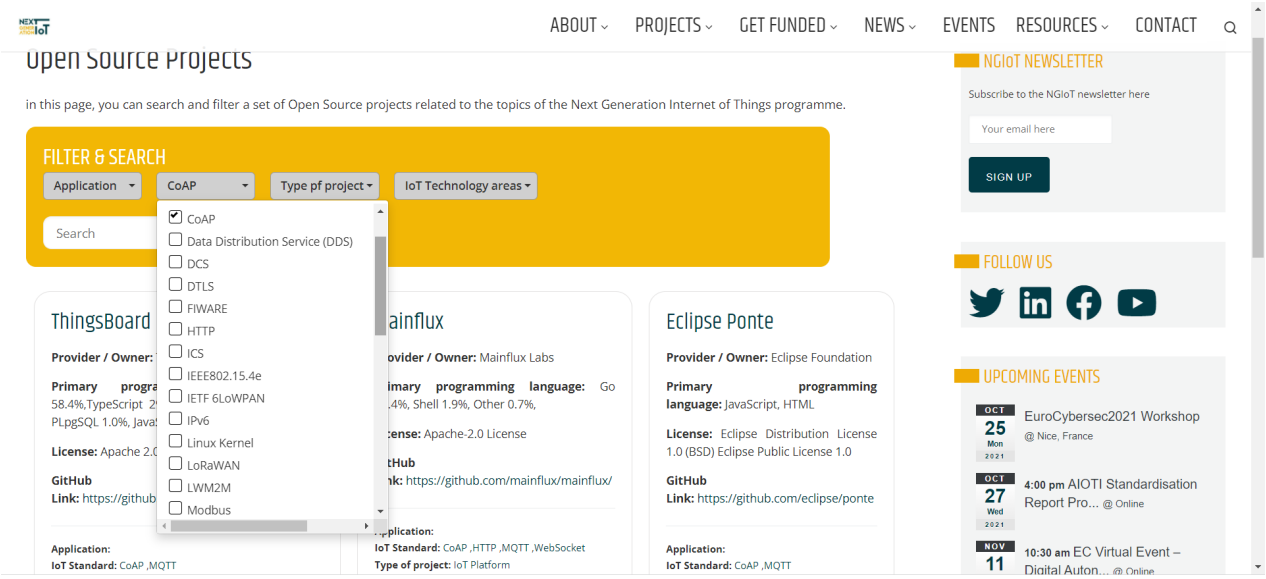

Figure 9: Screenshot of the EU-IoT Catalogue of IoT OSS projects

Figure 9 provides a screenshot of the catalogue. The catalogue is extensible to facilitate the inclusion of information about existing or new OSS projects and initiatives, beyond the initial list. Specifically, interested parties can submit an IoT OSS project entry, which will be accordingly reviewed and included in the catalogue by the EU-IoT consortium.

5.2 How to Engage

EU-IoT invites IoT stakeholders to engage with the OSS projects catalogue in different ways:

- Accessing and searching the catalogue as part of their IoT projects and initiatives.
- Contributing new projects and information, which will boost future efforts to provide a credible mapping of the European and global IoT ecosystem. This will also facilitate a more complete and detailed analysis of IoT projects as part of future EU-IoT whitepapers.
- Accessing other resources and content produced by the project such as whitepapers, training webinars, and other on-line resources.

IoT vendors, developers, integrators and projects are strongly encouraged to join the EU-IoT community and stay tuned for future whitepapers on IoT OSS topics.

REFERENCES

[Biasin20] Biasin, E and Kamenjašević, E. 2020. Open Source Hardware and Healthcare Collaborative Platforms: Common Legal Challenges. Journal of Open Hardware, 4(1): 7, pp. 1–8. DOI: https://doi.org/10.5334/joh.31

[Dabbish12] L. Dabbish, C. Stuart, J. Tsay, and J. Herbsleb. "Social Coding in GitHub: Transparency and Collaboration in an Open Software Repository," Proc. CSCW '12, ACM, pp. 1277-1286, 2012.

[EC-OSS20] COMMUNICATION TO THE COMMISSION, OPEN SOURCE SOFTWARE STRATEGY 2020 – 2023, Think Open, C(2020) 7149 final, Brussels, 21.10.2020

[Eclipse18] Eclipse Foundation, "IoT Developer Survey 2018 Results" April 2018, Copyright (c) 2018, Eclipse Foundation, Inc. | Made available under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

[Eclipse19] Eclipse Foundation, "IoT Developer Survey 2019 Results", April 2019, COPYRIGHT (C) 2019, ECLIPSE FOUNDATION, INC. | MADE AVAILABLE UNDER THE ECLIPSE PUBLIC LICENSE 2.0 (EPL-2.0)

[Eclipse20] Eclipse Foundation, "IoT Commercial Adoption Survey 2019 Results", March 2020, COPYRIGHT (C) 2020, ECLIPSE FOUNDATION, INC.

[ECOSS20] European Commission, OPEN SOURCE SOFTWARE STRATEGY 2020 – 2023, C(2020) 7149 final, Brussels, 21.10.2020

[Eggers20] Günter Eggers, Bernd Fondermann, Berthold Maier, Klaus Ottradovetz, Julius Pfrommer, Ronny Reinhardt, Hannes Rollin, Arne Schmieg, Sebastian Steinbuß, Philipp Trinius, Andreas Weiss, Christian Weiss, Sabine Wilfling, "GAIA-X Technical Architecture", Federal Ministry for Economic Affairs and Energy (BMWi), June 2020.

[Joshi18] Rajive Joshi, Stephen Mellor, Paul Didier, "The Industrial Internet of Things Volume G5: Connectivity Framework", V1.01, Ferbuary 2018, IIC:PUB:G5:V1.01:PB:20180228, available at: https://www.iiconsortium.org/IICF.htm

[Nagel21] Lars Nagel (ed), "Design Principles for Data Spaces", Position Paper, International Data Spaces Association, April 2021, available at: https://design-principles-for-data-spaces.org/

[OpenLogic20] OpenLogic,"2020 State of Open Source Report Market Trends, Analysis, & Looking Ahead", OpenLogic by Perforce © Perforce Software, Inc. All trademarks and registered, available at: www.openlogic.com

[Qutqut18] Qutqut, Mahmoud & Al-Sakran, Aya & Almasalha, Fadi & Hassanein, Hossam. (2018). Comprehensive Survey of the IoT Open Source OSs. IET Wireless Sensor Systems. 8. 10.1049/iet-wss.2018.5033.

[Sheoran14] Jyoti Sheoran, Kelly Blincoe, Eirini Kalliamvakou, Daniela Damian, and Jordan Ell. 2014. Understanding "watchers" on GitHub. In Proceedings of the 11th Working Conference on Mining Software Repositories (MSR 2014). Association for Computing Machinery, New York, NY, USA, 336–339. DOI:https://doi.org/10.1145/2597073.2597114

[Soldatos20] John Soldatos, "A 360-Degree View of IoT Technologies", Artech House, ISBN: 9781630817527, December 2020.

[VisionMobile15] The essential guide to Open Source in IoT | © VisionMobile |CC BY-SA 4.0 | White Paper

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