Institute of Architecture of Application Systems

University of Stuttgart
Universitätsstraße 38
D–70569 Stuttgart

Masterarbeit

Scalable IoT Platforms

Stefan Hill

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Examiner: Prof. Dr. Marco Aiello

Supervisor: Dr. Dipl.-Inf. Ilche Georgievski

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Abstract

In today's world the internet is connecting not only people but things. The computing concept of the "Internet of Things (IoT)"describes the idea to connect everyday physical objects to the internet. IoT platforms provide the backbone for applications in areas like Smart Home, Connected Vehicles and Industrial IoT.

In this thesis, we explore the question of the best IoT platform with a focus on reliability, scalability and heterogeneity. To answer this question, we search the market for IoT platforms, prototypes and proposals, examine them based on our comparison model and rate the platforms in a five star system. The criteria for the parts of the comparison model include replication, availability, authentication and authorization, encryption, security incidents and audits, development and market longevity for reliability, hosting, Edge and Fog Computing, limits of the infrastructure and network and load balancing for scalability, device restrictions, messaging and device protocols, programming languages and flexibility for heterogeneity as well as usability, pricing models and unique selling points.

We discover that most criteria do not differ in the used technologies or algorithms, but if they is implemented or not. Despite there is a low level of standardization, most criteria is implemented in a similar way across the platforms. The overall best rated platform is Microsoft Azure IoT Hub with 4.25 out of 5.0 stars, followed by IBM Watson IoT (3.88 stars). The prototype platform OceanConnect by Huawei shows promising results as well (3.0 stars).

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List of Abbreviations

ACP Aeris Connectivity Platform. 44

AD Active Directory. 28

AEP Application Enablement Platform. 25

AES Advanced Encryption Standard. 28

AI Artificial Intelligence. 15

AMAP Agile Mobile Application Platform. 44

AMP Aeris Mobility Platform. 44

AMQP Advanced Messaging Queuing Protocol. 32

API Application Programming Interface. 20

AWS Amazon Web Services. 42

BI Business Intelligence. 35

BLE Bluetooth Low Energy. 32

CAN Controller Area Network. 78

CoAP Constrained Application Protocol. 74

CPAL Common Public Attribution License. 46

DECT ULE Digital Enhance Cordless Telecommunications Ultra Low Energy. 78

DES Data Encryption Standard. 28

DSA Distributed Services Architecture. 46

DTLS Datagram Transport Layer Security. 29

ECDH Elliptic Curve Diffie-Hellman. 28

EGD Ethernet Global Data Protocol. 78

EPL Eclipse Public License. 46

FAQ Frequently Asked Questions. 84

FOKUS Fraunhofer-Institut für Offene Kommunikationssysteme. 46

FTP File Transfer Protocol. 32

GE General Electric. 41

HPE Hewlett Packard Enterprise. 43

HR Human Resources. 87

HTTP Hypertext Transfer Protocol. 31

HTTPS Hypertext Transfer Protocol Secure. 32

HW Hardware. 36

IAAS Institute of Architecture of Application Systems. 25

IDE Integrated Development Environment. 44

IGS Industrial Gateway Server. 78

IIoT Industrial Internet of Things. 22

IoT Internet of Things. 3, 15, 16, 19

IoV Internet of Vehicles. 80

IP Internet Protocol. 64

IRC Internet Relay Chat. 86

JSON JavaScript Object Notation. 79

JWT JSON Web Token. 28

KVM Kernel-based Virtual Machine. 70

LAN Local Area Network. 77

LDAP Lightweight Directory Access Protocol. 28

LoRaWAN Long Range Wide Area Network. 78

LPWAN Low Power Wide Area Network. 78

LWM2M Lightweight M2M. 76

M2M manufacturer to manufacturer. 46

MIT Massachusetts Institute of Technology. 46

ML Machine Learning. 22

MQTT Message Queuing Telemetry Transport. 32

NASA National Aeronautics and Space Administration. 23

NFC Near Field Communication. 78

NoSQL Not only SQL. 51

ONVIF Open Network Video Interface Forum. 78

OPC UA Open Platform Communications Unified Architecture. 32

OS Operating System. 20

PKI Public Key Infrastructure. 55

PL Programming Language. 26, 31

PLC Programmable Logic Controller. 70

REST Representational State Transfer. 26, 71

RF Radio Frequency. 78

RFID Radio Frequency Identification. 78

RSA Rivest-Shamir-Adleman. 28

RTOS Real-Time Operating System. 70

RugDS distributed systems group at the Rijksuniversiteit Groningen. 39

SaaS Software as a Service. 64

SCP Secure Copy Protocol. 74

SDK Software Development Kit. 9, 31

SLA Service Level Agreement. 52

SMS Short Message Service. 54

SOAP Simple Object Access Protocol. 74

SoC System on a Chip. 16

SSL Secure Sockets Layer. 29

SW Software. 36

TCP Transmission Control Protocol. 32

TLS Transport Layer Security. 29

UDP User Datagram Protocol. 32

VM Virtual Machine. 70

VPN Virtual Private Network. 55

W3C World Wide Web Consortium. 20

XML Extensible Markup Language. 79

XMPP Extensible Messaging and Presence Protocol. 32

1 Introduction

Today we live in a world where everyone is connected. People can check the news, the weather, the latest result of the favourite sports team - no matter at what time and what place: The internet is everywhere and connects people - and things.

In 2011, the Internet of Things (IoT) appeared on the Gartner Hype Cycle for the first time [257]. In 2015, it reached the peak of inflated expectations [258]. In 2018, the IoT is no longer just one innovation but consists of multiple emerging technologies. In the Gartner Hype Cycle of 2018 (see Figure 1.1, [318]), the IoT is represented by multiple technologies. The IoT Platform, Digital Twin and Smart Workspace technologies are in the peak section. Edge Artificial Intelligence (AI) is still in the position of an innovation trigger, while Connected Home is already in the third stage "Through of Disillusionment". According to Gartner, all of these five emerging technologies are expected to reach the "Plateau of Productivity" in five to ten years.

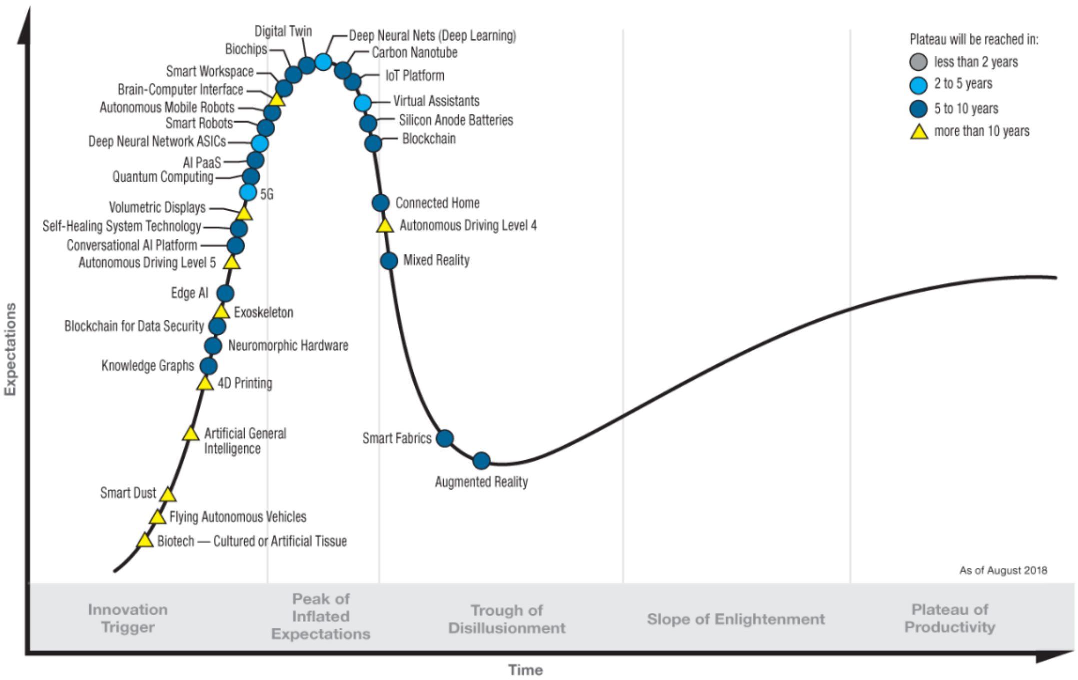

Figure 1.1: Hype Cycle for Emerging Technologies, 2018 (Gartner, [318])

1.1 Scalable IoT Platforms

The topic of IoT platforms is in the peak of the hype cycle and therefore many companies - especially of the IT sector - want to be part of this development. Most of the biggest IT companies, as well as companies of other sectors interested in this topic (for example telecommunications) have developed their own platforms for the IoT. Some startups were founded just to distribute the platform implementing their idea, other platforms were implemented in open source projects. Since there is no standard enforced, these platforms differ not only in their origin, but also in their design and aim.

This thesis focuses on “Scalable IoT Platforms” and to define the term “scalable IoT platform”, we have to define word by word. First, “Scalability is an attribute that describes the ability of a process, network, software or organization to grow and manage increased demand” [388]. A scalable product has to be able to handle a private projects for Smart Home with a small amount of devices and computing as well as enterprise level projects like managing a whole manufacturing process using much more computational power. Second, the Internet of Things (IoT) is “a computing concept that describes the idea of everyday physical objects being connected to the internet and being able to identify themselves to other devices” [389]. The key point of this concept is that any “thing” could be used as a device, if it is able to connect to the internet. This means an IoT product can not be restricted to high class multi-core systems, but also systems like microcontroller or System on a Chip (SoC). Third, a platform is defined as “group of technologies that are used as a base upon which other applications, processes or technologies are developed” [387]. This excludes products offering only one or more pre-built applications with no possibility for users to create their own applications.

Overall, a scalable IoT platform has to fulfill the following requirements:

- Independent of the size of the project
- Independent of the kind of devices used
- Enable the development of applications

1.2 Outline

The goal of this thesis is to find the “best” scalable IoT platforms considering the focus topics reliability, scalability and heterogeneity.

In Chapter 2, we explain the IoT, challenges, use cases and some concepts. In Chapter 3, we present related work and its importance for this thesis. The main part focuses on the procedure of finding (Chapter 5) and comparing IoT platforms (Chapter 6) as well as rating them in a five star system.

The first step of the procedure is to develop a comparison model. Focus of the comparison are reliability, scalability and heterogeneity. We split those topics into subtopics and develop criteria to compare platforms. The second part of the comparison model consists of a rating system. We develop an unweighted rating system for the topics of the comparison model.

The first step in creating the list of platforms is to search the market for available products. This list should include not only the best-known platforms, but also open source platforms as well as prototypes and proposals. Next, we have to verify that the found products actually are fitting into the definition of “scalable IoT platforms”. Platforms with similar attributes are grouped to be able to work out their differences more precisely.

The analysis starts with the examination of every platform regarding the criteria of the comparison model. We work out differences between platforms of a group for every criteria. Then, the platforms are rated for every topic.

The discussion starts with a summary of the analysis. The second part of the discussion is the aggregation of the ratings of the separate topics and working out differences and possible reasons. The discussion also names the best rated platforms and groups overall and per section.

2 Background

2.1 The Internet of Things

The Internet of Things (IoT) is a "computing concept that describes the idea of everyday physical objects being connected to the internet" [389]. The German Bundestag calls the IoT a "technical vision to integrate things of any kind to a universal, digital network" [203]. Corsaro, Angelo [120] states that the IoT is about "extracting value through the insights derived from the real-time and historical data produced by a cyber-physical system". In general, the IoT connects everyday things in a technical way that these things become devices and get the ability to communicate with each other over a common network like the internet with the goal to make use of the collected data.

Figure 2.1 shows a simplified system model of the IoT. Devices (called IoT nodes in the Figure 2.1) are connected to the internet through the router. Nodes can host sensors (as shown in the figure) which collect data and send it to the cloud and actuators that can be controlled over devices connected to the network [271].

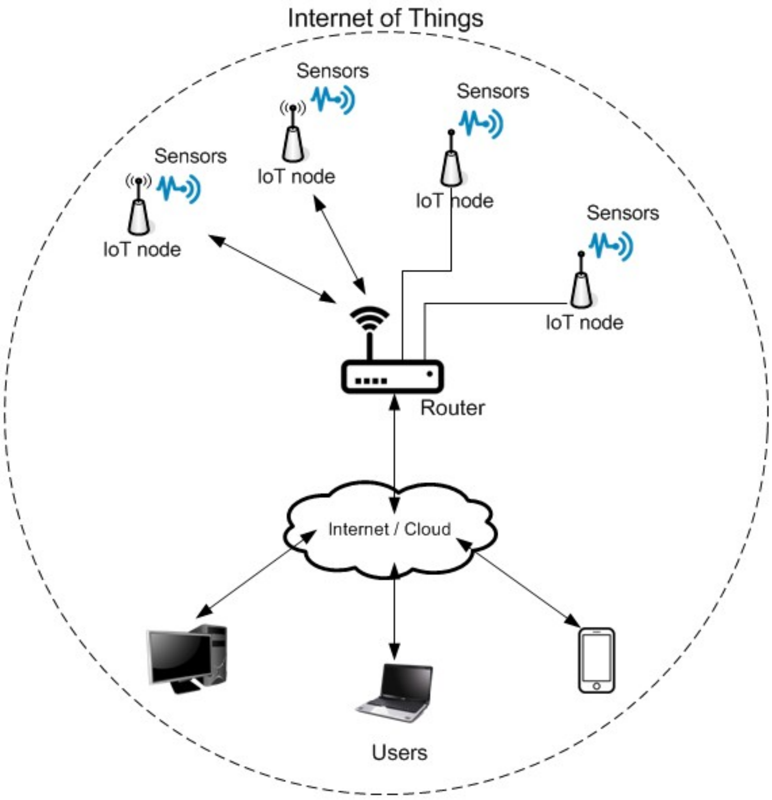

Figure 2.1: The idea behind the IoT [271])

2.1.1 Challenges

However IoT has some big forces bringing it forward, it still has challenges. What are those challenges and how can they be resolved?

In the “Top 10 Internet Of Things Technologies For 2017 & 2018”, Gartner lists the IoT Security as the first key takeaway stating that “many security problems are the result of poor design, implementation and lack of training” [117]. According to Prismtech, security on data level is needed to be able to deploy IoT systems securely [120]. Hwang, Yong Ho [212] states that the IoT will change our lifes and thus expose us to security threads not only on the virtual, but in the daily, non-virtual life. Issues like information leakage and loss of service will transform to threads directly influence the physical security [212]. The heterogeneity and complexity of the IoT make security “much more difficult to deal with” [468]. The main challenges of IoT security include identification of objects and authentication of users, data integrity, encryption, lightweight cryptosystems and security protocols [1, 468].

Low-Power Networks - no matter if short-range or wide-area networks - as well as minimal IoT Operating Systems (OSs) with small footprints are also key technologies for the IoT, since IoT devices usually do not have the amount of computing power like a desktop computer and often run on battery with limited amount of power. OSs like Windows and iOS are “too complex and resource-intensive for the majority of IoT applications” [117]. “Ultra low power circuits” which are able to “tolerate harsh environments” are important technologies for the IoT [1].

But even in resource-friendly networks, there is no guarantee that devices can be connected all the time as “Device-2-Cloud connectivity is not always possible due to connectivity challenges, response time or data volumes” [120]. Especially in industrial or emergency use cases, “temporary outages cannot be accepted” [1]. Hence, availability, robustness and flexibility are key attributes to achieve resilience and reliability [1]. Two concepts have been introduced to the IoT sector to address this challenge: Digital Twins (see section 2.3.1) and Edge and Fog Computing (see section 2.3.2).

Developing standards, especially for Application Programming Interfaces (APIs), will be essential for communication and interoperability in the IoT [117]. i-SCOOP [213] also criticizes the “lack of standards and interoperability” in the IoT sector. Prismtech calls data sharing “a preprerequisite for IoT”. The article also states that there is a need for standards to achieve interoperability and that there is no IoT without interoperability [120]. Examples for standards already existing but not widely implemented are the World Wide Web Consortium (W3C) Web of Things [452] and oneM2M [297]. Interoperability both technically and semantically is essential for seamless interaction of devices and correct intepretation of data [1].

2.1.2 IoT Platforms

Another key technology for the IoT according to Gartner are IoT platforms bundling “infrastructure components of an IoT system into a single product” [117]. McKinsey sees the IoT platform space as “important, but crowded and confusing” [254].

The importance of IoT platforms is undoubted as they “abstract a lot of common functions away from the specific application logic” and work “like an operating system for a laptop” since they do “a lot of things in the background that makes life easier and less expensive for developers, managers, and users” [254]. The key benefit of platforms is the reusability for multiple or optimally any use case, as the “underlying technology needs are essentially the same” which is why “a good platform dramatically reduces the cost of developing and maintaining applications” [254]. IoT platforms have to be scalable, flexible and secure to satisfy customer needs [213].

As IoT platforms are supposed to be a big (underlying) part of the IoT and can be used for multiple use cases, “people and companies don’t switch platforms very often” [254]. Switching platforms is a costly operation and because of this, platforms choices are meant to persist for many years. This opportunity leads to many start-ups pushing into the IoT platform market aspiring to become a successful platform because “the winners create enormous shareholder value” and “winning platform companies can create 100-fold returns” [254].

The previously mentioned lack of standards lead to a big offering of IoT platforms which is over 450 platforms in 2017 and possibly as much as 1000 platforms at the end of 2018 [272]. McKinsey states that - despite the big offering - there is no “one-size-fits-all best platform for every application” and it could take years for the market to find “the winners in the IoT platform derby” [254].

2.2 What is the IoT used for?

“A pure-play platform alone won’t solve a business problem; an application is still needed” [254]. Platform providers are not targeting private customer, but other companies creating value of the platform by developing applications to be deployed on top of the platform. The following sections show some of the possible use cases of the IoT.

2.2.1 Smart Home and Smart Buildings

An obvious use case for connecting everyday things is the place to be every day: home. Examples of things being used for IoT applications are shown in Figure 2.2.

As a home automation system, the IoT can “automate the bulk of electronic, electrical and technology-based tasks within a home”, creating the so-called “Smart Home” [386]. A Smart Home is “a home that provides intelligent living environment for daily convenient life” [348] and therefore is not smart because it was built well or environmentally friendly but because of interactive technology [199]. These technologies may include lighting, heating or security and can be controlled by devices connected to the network [199]. However the Smart Home was already a thing over 15 years ago, the level of standardization is still low [199, 348].

The next level is to extend the “smartness” of the home to the whole building or even a whole city. In general, Smart Homes, Smart Buildings and Smart Cities have the goal to “increase the life quality of the residents” [83]. A big topic is sustainability and energy efficiency, as cities “cause 75% of the climate-damaging emissions and 80% of the global energy consumption” [83]. “Smart Buildings” are for example in use in office buildings to save energy while still preserving user comfort [300]. Smart Cities may include technologies like “Smart Parking” where sensors tell cars the location of free parking spots and “Autonomous Driving” (also called “Autonomous Vehicles”) [83].

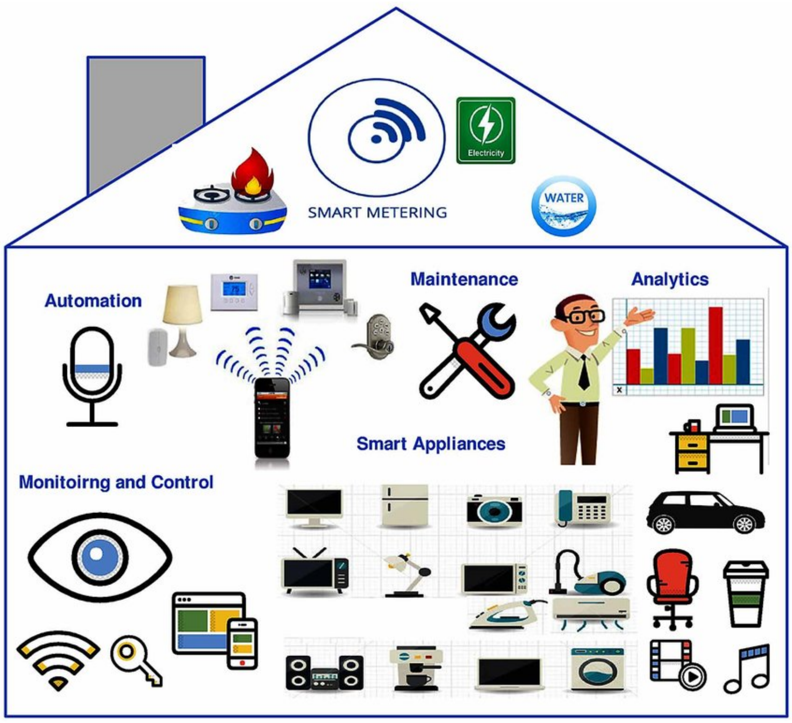

Figure 2.2: An IoT smart home example [157])

2.2.2 Connected Vehicles

For both Smart Parking and Autonomous Driving cars need to communicate and therefore be connected. The first step to this is called "Connected Cars" or "Connected Vehicles". This concept is about "supplying useful information to a driver or a vehicle to help the driver make safer or more informed decisions" [298]. The concept of Connected Vehicles does not yet include cars to drive autonomously but to assist the driver with additional information. Many vehicles already have the ability to avoid collisions or park on its own, but most still require a human driver. However, true autonomous vehicles do not require a human to be able to do anything [298]. New technologies lead to new legal issues and laws. For example autonomous vehicles legally require a human driver in Germany [140], but in several states of the US there are already bills which legalize autonomous driving [355].

2.2.3 Industrial Internet of Things

Another use case of great importance yet not as much attention as applications concerning consumers like Smart Home and Connected Vehicles is the Industrial Internet of Things (IIoT). However, the IIoT "can create significant value" and is expected to "generate nearly 70 percent of potential value enabled by IoT" [120]. The IIoT aims to improve efficiency and reduce costs in the production [263] as well as improving reliability [426]. Using big data and Machine Learning (ML), the IIoT further automates processes in production [263, 426].

Although Smart Home, Connected Vehicles and the IIoT can boost life quality and productivity, they still have weaknesses and challenges. As previoulsy mentioned, the standardization level is still very low and many "things" only have low resources of computing power and energy. As for all devices connected to the internet, security is a big concern as well as attacks and intrusions on the operational stability of production processes or the computing in vehicles could have a monumental impact on the business or even human lifes.

2.3 Concepts used in the IoT

In this section, we introduce some concepts used in the IoT. These concepts may be used by some IoT platforms and will be taken up again in the analysis.

2.3.1 Digital Twins

"Digital Twins" is a paradigm developed at the National Aeronautics and Space Administration (NASA) in 2012 [184] with the goal of moving computing operations from rockets and space shuttles to a data center to make the transport lighter and less expensive. The idea behind is to create a digital copy of a vehicle including health metrics, maintenance history and all historic data available. This digital twin can be used for simulations without having to provide the computing resources in the vehicle itself. By having the same data available as on-board, the twin simulation is ultra-realistic and can help forecasting "the health of the vehicle or system, the remaining useful life and the probability of mission success" [184].

Transfered to the IoT, this paradigm can be used to move computing operations from the devices at the edge of the network to the cloud. Similar to the space shuttle, IoT edge device then do not have to provide as much computing power and energy resources. The digital twin of an IoT device then can be used to predict health or sensor data.

2.3.2 Edge and Fog Computing

Contrary, moving some computational operations to the edge of the system can also increase the performance (especially lower the latency) and therefore boost scalability. The devices at the edge usually have very limited computing power and disk storage, thus limiting the capacity at the edge. Additional nodes or resources at the edge increase the computing power at the edge. This technique is called Edge (for devices) or Fog (for devices, gateways or additional nodes at the edge) Computing [247].

Benefits of Edge Computing are saving of time and resources and - because of not exposing data by transfering it over the internet - also improved security. The challenge is to find the perfect balance of what should be handled in the cloud and what is best kept at the edge. Fog Computing combines the benefit of Edge Computing (faster, less traffic) with the benefits of the cloud (more resources and more data) at the cost of more infrastructure [247].

3 Related Work

In this chapter, we discuss results, strengths and weaknesses of related works.

The biggest project in this topic is the website IoT ONE [244] which is - according to its own statement - “mapping the Global Ecosystem of the Industrial Internet of Things”. Case studies, use cases, suppliers, software and hardware are listed on its website amongst a lot of other sections. IoT platforms as discussed in this thesis are part of the software section. The website counts 158 IoT applications, 76 middleware softwares and 54 Application Enablement Platforms (AEPs). The benefit of this work is of course the huge source of platforms to be selected for the analysis in this thesis. One drawback of IoT ONE is that the available data is superficial. A software category, deployment type, first launch, current version and a short description are available for most platforms, for some there is an overview of support offering or pricing methods. For a few platforms, there are also case studies linked. However, a lot of the given information on IoT software is not up to date. For example, Google Cloud IoT Core is still listed as private beta despite of the official launch for general availability in February 2018 [191] and Macchina.io has not listed any other version since its first release in January 2014 which is not even listed on Macchina’s own release notes and despite having had nine releases since then [43]. Other platforms are listed as AEP despite being just a full-built application with no possibility to create an application on top and vice-versa. The best thing that could have been used from IoT ONE would be its pricing rating which rated software in four steps: “price leader”, ”below market average”, “market average” and “above market average”. However, this rating was deactivated in April 2019. Overall, IoT ONE gives an overview of IoT software without technical details. In comparison, the goal of this thesis is to offer a comparison on a more in-depth and more technical level.

Postscapes also lists a lot of software used for the IoT [331]. However, not all of these are actually IoT platforms (see definition in chapter 1.1) as some of them are full-built applications like monitoring tools. Others have been discontinued like Xively. This work mostly collects information and lists some highlights and links for every software included without any analysis or comparison, thus the given information is short and superficial.

Tredwell, James [425], Sam Solutions [338] and Carey, Scott et al. [110] provide more lists of “the best platforms”. Their analysis is also superficial, but slightly more extensive. However, they mostly name the same big, established companies like Amazon and Google, but no smaller company or open source projects as Postscapes. Singh, Santosh [362] lists more smaller companies and their platforms, but does still not provide more technical detail.

Guth, Jasmin et al. [196] provide a (more) detailed analysis of IoT platforms and especially their architectures. This work shortly describes the functioning of every platform and gives a deeper view on the underlying architectures. The analysis of the Institute of Architecture of Application Systems (IAAS) also includes just eight - each four open source and proprietary - platforms, whereas this thesis aims to be as inclusive as possible. However, except the architecture there is not much of a qualitative comparison as well. Guth, Jasmin et al. [196] compare the architecture by picturing the modules in every component of their reference architecture. In this thesis, we focus not so much on the architecture differences in the modules and components, but what different components are actually present and which are not.

Julien Mineraud et al. [249] reviewed 39 platforms for seven criteria. The criteria used were support of heterogeneous devices, type and architecture of the platform, open source, Representational State Transfer (REST), data access control and service discovery. The support of heterogeneous devices is a topic in this thesis as well. However, Julien Mineraud et al. [249] only analyzed, if heterogeneous devices are supported directly or via gateway and if the device type is restricted, whereas this thesis will go deeper into technical details and analyze, what the restrictions for devices are considering hardware, operating systems and software. Licenses of the open source platforms are named but not compared to each other which will be done similarly in this thesis, as the differences in the license do not influence the focus attributes reliability, scalability and heterogeneity. For the analysis of the REST APIs, Julien Mineraud et al. [249] provides only information if such an interface is present or not, whereas this thesis will also analyze the messaging protocols used in platform interfaces like REST APIs. While the analysis of the platform security is limited to the protection of data storage and access in the work of Julien Mineraud et al. [249], this thesis will go deeper and analyze the data encryption both at rest and in motion as well as used technologies for authentication and authorization. Julien Mineraud et al. [249] differentiate the architecture as either “cloud-based”, “centralized” or “decentralized”, whereas we will compare the design on a component-based level.

Ganguly, Pankaj [170] compares platforms on a more technical level, as this work also considers messaging protocols and SDKs for both things and applications as well as data encryption and access, support and community forums. However, this work only lists ten platforms and only considers some specific topics. Data encryption and access are the only topics for reliability, protocol and Programming Language (PL) variety the only topics of heterogeneity, while scalability is not considered at all. Compared to Ganguly, Pankaj [170], we want to achieve a broader analysis in both the amount of platforms and the criteria to be analyzed.

Overall, the related work either provides a bigger list of platforms or a deeper analysis of some subtopics. None of the mentioned works put a focus on reliability, scalability or heterogeneity. We aim to provide a comparison considering these focus attributes with multiple criteria each, as well as a list of platforms extracted in a systematic way.

4 Quality Attributes

In this chapter we explain which topics and criteria are important for scalable IoT platforms. The focus is on the three main topics reliability, scalability and heterogeneity.

4.1 Reliability

"In theory, a reliable product is totally free of technical errors" [337]. Such technical errors can occur in different parts of a system and due to different reasons. Hardware failures are prevented by techniques like replication and clustering. Failures due to attackers are avoided by increasing the system's and software's security. Software failures are reduced by continuous improvement and development of the software. The impact of any failure can be minimized by monitoring and technical support for customers. Figure 4.1 displays all of the chosen topics related to reliability. Subtopics are displayed as smaller nodes in the same color.

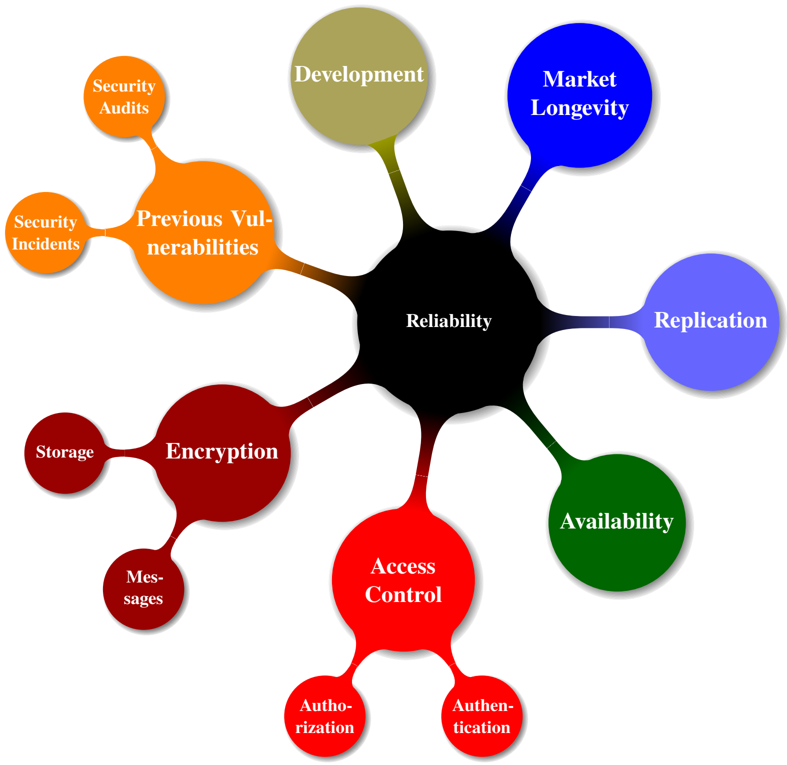

Figure 4.1: Topics to be analyzed in the reliability section

4.1.1 Replication

One very important goal for any application dealing with real-time data is to ensure the data is never lost. This includes several aspects, in general data in motion and at rest.

First, the collected data has to be stored somewhere safe. In case of a power outage, disk failure or even theft of the hardware, there should be some kind of backup where users can restore the lost data from. Second, if the application server or database is not reachable, the collected data cannot be just dropped and forgotten. Replicating servers and databases can help to prevent this kind of data loss by multiplying access points, so in case one server cannot be reached, another one steps in its place.

By distributing servers across the globe, users can implement replication and data safety while also achieving a shorter thus better access time for users all over the world.

4.1.2 Availability

Sometimes, servers have to be shut down or restarted, for example during the installation of updates. However, the downtime should be as short as possible. So the next point to be analysed is availability of the infrastructure and the software. A metric for this criterion could be an uptime guarantee by the provider.

In some cases, software can be hosted on the infrastructure of a user instead of using the provider's managed hosting solution. In this case, users are responsible for availability and backups on their own. Some of the providers might offer clustering or replication functionalities, otherwise users have to think of a way to backup data on their own.

4.1.3 Authentication and Authorization

Security is a big concern in distributed systems, especially on public networks like the internet where anyone could intercept traffic. Authentication and authorization are aspects to be looked at here. Authentication (who is accessing?) and authorization (is this user allowed to access?) methods [100] increase the security of a system as well. JSON Web Tokens (JWTs) are a common method for stateless authentication also including authorization information [66]. Other methods for authorization are OAuth2 [319], Active Directory (AD) and Lightweight Directory Access Protocol (LDAP) [369].

4.1.4 Encryption

Encryption of data in motion (messages) and at rest (storage) are important aspects of IT security as well. "Message encryption shields messages and attachments from being read or opened by anyone except the intended recipients", and although there are still vulnerabilities encryption is a common method when sharing confidential data [303]. Additionally to data in motion, data at rest should also be encrypted to stop attackers from reading and/or changing data at devices, servers and databases. Common encryption methods include Rivest-Shamir-Adleman (RSA), Advanced Encryption Standard (AES), Data Encryption Standard (DES) and 3DES [443] as well as Elliptic

Curve Diffie-Hellman (ECDH) [119]. Secure Sockets Layer (SSL), Transport Layer Security (TLS) and Datagram Transport Layer Security (DTLS) are protocols implementing encryption for applications sending data over the internet [228].

4.1.5 Security Incidents and Audits

If there have been bugs, leaks or security incidents in the past, it is interesting for users how the provider handled such problems in the past. How much time took it to find and to fix theses vulnerabilites? Is there a program to find more vulnerabilities in the software? Security audits by third-party providers improve the confidence in the product's security as well.

4.1.6 Development

Another very important aspect is the on-going development. This includes overall code development as well as fixing bugs and vulnerabilities. How often are new updates released? Do these updates include new functionality or just fixes?

4.1.7 Market Longevity

A product that has been on the market for a long time is also more likely to be continued for a longer time than one that has just been there for a few months. The same logic applies for the platform provider: a provider that has been in the business for many years can endure a short-term loss better than a company that was just founded to distribute its platform. How likely are the platforms and their providers to endure?

4.2 Scalability

Scalability describes the ability of a software - in this case a platform and its infrastructure - to "grow and manage increased demand". It often means to be "more adaptable to the changing needs" and is seen as a "sign of stability" [388]. For companies distributing IoT applications, scalability is important to be able to manage the enormous amount of data collected by a huge number of devices. Important aspects are the hosting possibilities, computing power and storage, for example in databases. Figure 4.2 displays all of the chosen topics related to scalability. Subtopics are displayed as smaller nodes in the same color.

4.2.1 Hosting

The first interesting aspect to analyze the scalability of a platform is where it is actually deployed to. A public cloud usually has more resources compared to an on premise solution, whereas a local hosting or dedicated cloud has improved security and privacy due to physical or logical separation. A platform that is hosted locally in the same physical space as the devices reduces latency between the physical units. A hybrid solution combines benefits of multiple of these approaches.

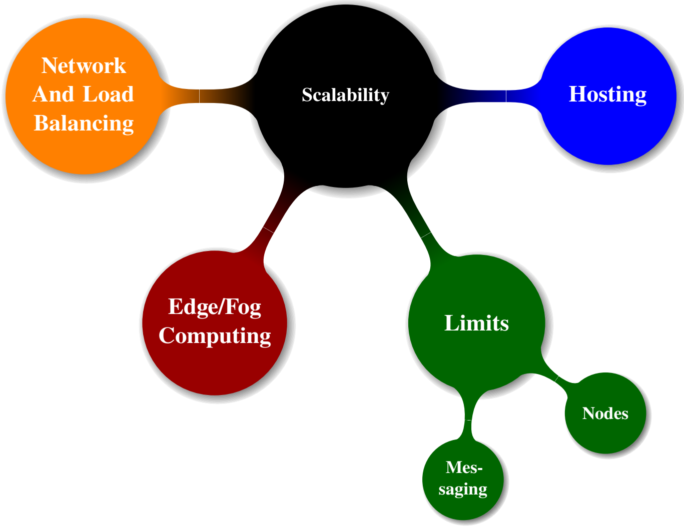

Figure 4.2: Topics to be analyzed in the scalability section

4.2.2 Limits of the Infrastructure and Software

The big question in scalability is the hardware capacity and how many devices, applications and their data flow a software and infrastructure are able to handle. An interesting metric in this field is the amount of nodes that the software is able to handle. Another important metric is the possible message throughput.

4.2.3 Edge and Fog Computing

We introduced the concepts of Edge and Fog Computing in Section 2.3.2. Which platforms are moving computational operation to the edge? What can be done there? Are there any unique features in the Edge and Fog Computing Solutions?

4.2.4 Network and Load Balancing

The network between devices and servers of a platform has to be able to manage the traffic created by the IoT as well as the servers. On the other side, accessing applications create even more traffic. Since all the devices and applications connect to one respective access point of the system, these two points tend to be bottlenecks, if the network cannot handle the amount of incoming requests. The enormous amount of incoming data usually also requires a load balancing mechanism at the servers to assign computing units to handle each request.

4.3 Heterogeneity

Thanks to a lot of standards for hardware and software interfaces, networks like the internet are heterogeneous [336]. To make IoT platforms and their networks heterogeneous, providers have to implement common standards as well. This means to not restrict the platform usage to certain devices, operating systems or programming languages. A platform might be designed for a specific use case or device type, but it also can be usable for other use cases or devices, if standardized interfaces are used. Figure 4.3 displays all of the chosen topics related to heterogeneity. Subtopics are displayed as smaller nodes in the same color.

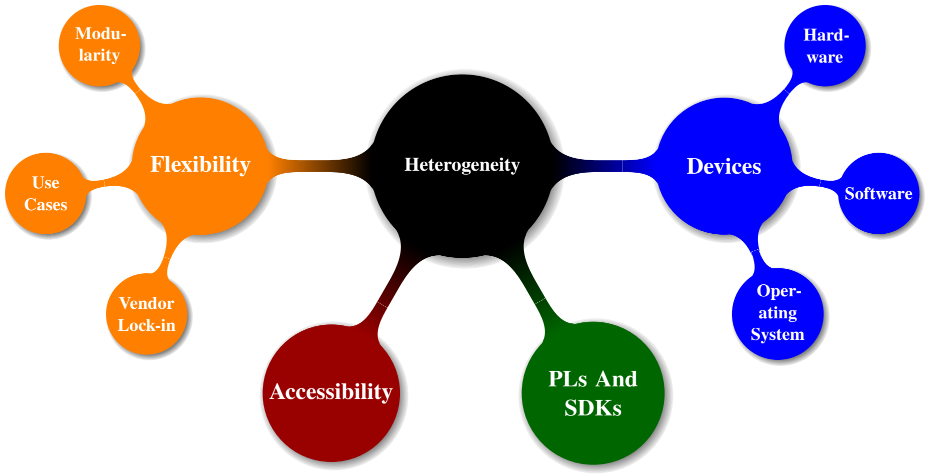

Figure 4.3: Topics to be analyzed in the heterogeneity section

4.3.1 Device Restrictions

A heterogeneous platform should not restrict devices to a specific piece of hardware or operating system. To achieve a high heterogeneity and abstraction, platforms should work with multiple OSs like Windows, macOS and different distributions of Linux. Heterogeneity is also limited if a platform depends on software that is running on only specific hardware and OSs.

4.3.2 Programming Languages

In the best case, providers also publish libraries or Software Development Kits (SDKs) to use their platform interfaces for common Programming Languages (PLs). The most used PLs today are JavaScript/TypeScript, Java, Python, php, Ruby, C++, C#, C [111, 146]. Pre-built SDKs simplify the work of every developer who are programming applications for a platform.

4.3.3 Accessibility

The more interfaces for devices and applications (also called APIs) a system offers, the higher is its heterogeneity. A desirable scenario could be a platform providing multiple interfaces with already included security. Common and possible interface protocols are Hypertext Transfer Protocol

(HTTP)/Hypertext Transfer Protocol Secure (HTTPS) [354], (secure) Message Queuing Telemetry Transport (MQTT), Advanced Messaging Queuing Protocol (AMQP), Extensible Messaging and Presence Protocol (XMPP) [349], Transmission Control Protocol (TCP), User Datagram Protocol (UDP) and File Transfer Protocol (FTP) [435].

Many platforms allow gateways which also support other protocols for connecting local devices. Common and possible interface protocols are WiFi, Bluetooth and Bluetooth Low Energy (BLE), ZigBee, Z-Wave or industrial protocols like Open Platform Communications Unified Architecture (OPC UA) and Siemens S7.

4.3.4 Flexibility

Some platforms might be designed for a special application, others are designed as abstract as possible to fit for every use case. If a user chooses a platform as an IoT solution, how easy is it to transfer more applications to this platform or an application from this platform to the newly chosen one? Sometimes configuration can not be exported or the application development is done inside a platform so it takes more effort to deploy it somewhere else. In other cases, users do not like just a part or a module of a platform. How easy would it be to exchange this part for another solution?

4.4 Usability and Pricing

A platform that is perfect in terms of reliability, scalability and heterogeneity still needs to offer a good usability. According to the ISO 9241-11:2018 standard usability is the “extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use” [227]. This means that for a good usability platform providers have to give developers the tools to achieve their specified goal effectively, efficiently and in a satisfying way. The second part of this section is a comparison of pricing models for the platforms, followed by unique attributes or functionality of the platforms. Figure 4.4 displays all of the remaining topics not related to one of the previous topics. Subtopics are displayed as smaller nodes in the same color.

4.4.1 Usability

Tools to achieve specific goals according to the ISO 9241-11:2018 can be knowledge on the system (complete and sound documentations) for effectiveness, tutorials and examples for efficiency and an intuitive user interface and easy accessibility for satisfaction with the platform. We limit this thesis to analyzing written information, thus excluding actual user experience like the analysis of the user interface. Documentations, tutorials and examples are equally important because the best platform will not be used, if there is no explanation on its way of working and how to use it. Documentations and tutorials on how to use the product may also simplify the deployment and development.

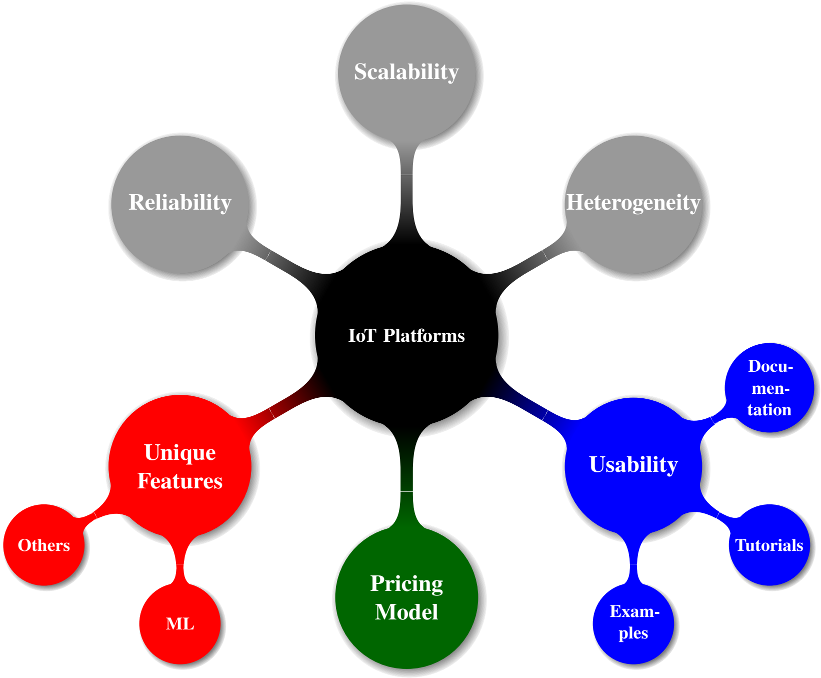

Figure 4.4: Topics to be analyzed in the usability and pricing section

4.4.2 Support

Especially for enterprise customers, the support offering for a platform is important. An active community users may ask for help or best practices are benefits as well. For popular products, stackoverflow.com is a great choice to ask for help, but for less popular products or simply less known providers, an own community platform could make sense.

4.4.3 Pricing

What is the price for the platform usage and what pricing models are available? Is there a free trial version or the possibility of free usage as a student? Is there a data plan or additional services like Machine Learning offered? And if users need training to be able to use, deploy or develop applications for a platform, is this training available online and do users have to pay for it separately?

4.4.4 Unique Selling Points

Some platforms offer unique features or implemented unique concepts, for example ML. This may be in the design, in the infrastructure or just a functionality others do not provide. How useful are these uniquenesses and how can they be used? Do they just affect some tiny edge cases?

4.5 Platform Design

The final step in the analysis is the comparison of the design of the platforms. We extended the reference architecture of Guth, Jasmin et al. [196] to the levels of Cisco [115] by splitting the part of the "IoT Integration Middleware (IoTIM)" and added the platform components for every level. By starting with the architecture of Guth, Jasmin et al. [196], we have a simple yet accurate model. With integrating the architecture of Cisco [115], we get a more precise representation of the middleware without creating a too complex model. With our reference architecture, we are able to differentiate components more precisely in the integration middleware and categorize them according to their purpose.

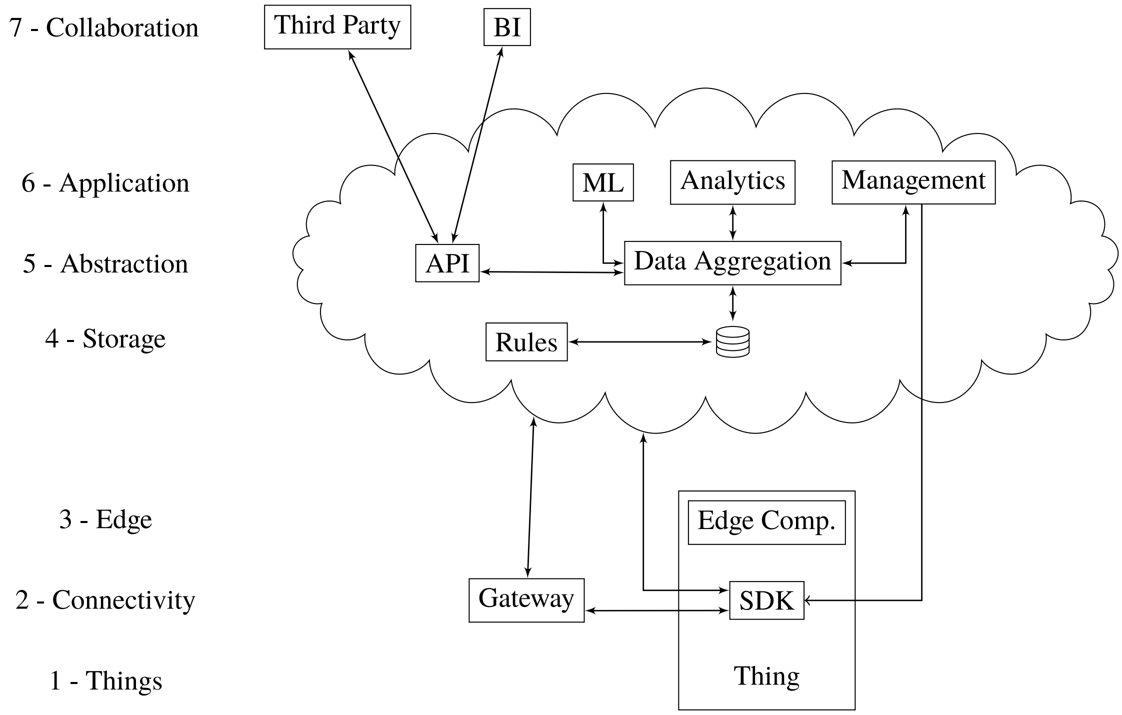

Figure 4.5: Reference architecture of IoT platforms

The bottom level is called "Physical Devices & Controllers" (simplified "Things"). These devices are generating data and are queried and controlled over the network. The next level is handling the "Connectivity". Basically, this level connects devices in the first level to the platform in the levels above. The connection may be directly to the platform or with the use of a gateway. This level may or may not include a protocol translation for various protocols used by the devices. The third level "Edge Computing" is implemented on devices and/or gateways and represents the outsourcing of computational operations to the edge of the network. These operations may include the actual assessment of data or simply filtering, cleansing and aggregation of the collected data. These three bottom levels represent the edge of the network and are implemented on devices and/or gateways.

"Data Accumulation" (simplified "Storage") is the first level included in the cloud part of the architecture. Here, the data is converted from in-motion to at-rest and may be stored in a database. Event based rule activation (also called "Rules Engine") is performed at this level as well. The next level, "Data Abstraction", is used for normalization, aggregation and preparing data - also from different sources - for the application level to access. Usually, this level includes an API for external applications to access data. The “Application” level in general provides the collected and aggregated data in a clear way for the users. An example for an application could be a reporting or analyzing tool. Modules for controlling the devices are also positioned in the application level. These three levels form the actual platform server the devices are connected to and together with the “Edge Computing” level are represented in [196] as “IoTIM”.

The final level is not actually implemented in the IoT platform itself. “Collaboration” and processes represented in this level might have existed before the usage of an IoT platform and are now supplied with the data collected by the IoT platform. Applications in this level include Business Intelligence (BI) or business processes. This level is not included in [196].

Security is also an important part of the architecture. However, security is not just a component or level of a platform but must be present at any level. In general, Cisco [115] says that security measures must “secure each device or system”, “provide security for all processes at each level” and “secure movement and communicatation between every level”.

The created architecture will be used to compare platforms and groups and is shown in Figure 4.5. There will be one general diagram created per group displaying the levels and components implemented by most or all of the group’s platforms. The differences between the groups’ diagrams will be analyzed afterwards.

4.6 Rating System

The platforms will get rated in an unweighted system. Every platform can receive up to five stars for each of the attributes reliability, scalability, heterogeneity as well as usability and pricing. The overall rating is calculated as the average score of all four sections. An overview of the rating system is shown in Table 4.1.

The reliability section starts with “Replication and Availability”, “Authentication and Authorization” and “Encryption” that each will be rated based on the completeness of the implementation (not, partially or completely implemented). The “Security History” will be rated on the existence of past security incidents (0.5 stars for no incident) and third party security testing like audits (0.5 stars for having one or multiple audits). The maintenance is rated by a combination of the publisher and the development status as well as age and current developments of the platform. If the provider is a bigger, established IT company, the platform has been released at least two years ago and is getting new feature updates at least twice a year, it receives 1.0 stars. If none of these requirements is satisfied, the rating will be 0.0, if at least one requirement is satisfied the rating will be 0.5 stars.

The scalability section starts with “Hosting” which will be rated on the available possibilities (one option, cloud or on-premise and hybrid). 1.0 star is given, if the provider’s cloud is hosted on its own infrastructure instead of a third party solution. “Edge/Fog Computing” will be rated 1.0 star if either is available. “Limitations on apps and devices” is worth 1.0 star when at least one million nodes are possible being handled by the platform. Platforms able to handle one thousand possible nodes receive 0.5 stars. A maximum “Message throughput” of one per second or 100 per second receive 0.5 stars or 1.0 star respectively. Platforms not offering information on limits below the treshold will be given 0.0 stars.

The heterogeneity section starts with “Device Restictions” which are rated based on how many of the criteria Hardware (HW), Software (SW) and OS are restricted. A platform supporting three or more messaging protocols will receive 0.5 stars, plus another 0.5 stars if the most supported protocols (HTTPS and MQTT) are supported. The “Device Protocols” and “SDK” support will be rated with 0.0, 0.5 or 1.0 stars for zero, at least one or at least three supported protocols or programming languages respectively. The flexibility is rated whether a platform is abstract to fit any use case and has a modular architecture. The possible rating 0.0, 0.5 and 1.0 are given for not, partially or completely applicable respectively.

The final section “usability and pricing” starts with 1.0 star given for the availability of each documentation, tutorials and examples. A possible support offering by the provider is rated with 0.5 (general support) or 1.0 stars (support dedicated for this product). “Unique Features” and ML are each given 0.5 stars if available.

Table 4.1: Overview of the rating system for all topics

Topic	☆	⯪	★
		Reliability	
Replication and Availability	n/a	partially	completely
Authentication and Authorization[1]	n/a	partially	completely
Encryption[2]	n/a	partially	completely
Security History[3]	Incidents, no audits	No incidents or audits	No incidents, an audit
Market Longevity	small/new company prototype status slow development	anything in between	established company 2+ year old platform continuous development
		Scalability	
Hosting	one option	cloud and on-premise	hybrid
Third party cloud infrastructure	yes	-	no
Edge and/or Fog Computing	n/a	-	available
Limitations on apps and devices	$\leq$1K	>1K	>1M
Message throughput	$\leq$1/second	>1/second	>100/second
		Heterogeneity	
Device Restrictions (HW, SW, OS)	all 3 topics	1-2 topics	0 topics

Continued on next page

[1]Including roles and/or permissions
[2]Message and Storage
[3]Security incidents and third party security audits

Table 4.1 – continued from previous page

Topic	☆	⯪	★
Messaging Protocols	<3 and no HTTPS/MQTT	3+ or HTTPS/MQTT	3+ and HTTPS/MQTT
Device Protocols	0	1+	3+
SDKs	0	1+	3+
Flexibility (abstract and modular)	not applicable	partially applicable	completely applicable
Usability And Pricing			
Documentation	n/a	-	available
Tutorials	n/a	-	available
Examples	n/a	-	available
Support	n/a	general	dedicated
Unique Features	n/a	ML or others	ML and others

5 Methodology and Overview of IoT platforms

In this chapter, we explain the process of finding and grouping platforms. Then, the groups and platforms are presented shortly.

5.1 Methodology

To be able to compare platforms, there has to be a list of candidates at first. In the proposal for this thesis, several platforms providers have been mentioned: Google, Amazon, Microsoft and IBM, as well as the platform of the distributed systems group at the Rijksuniversiteit Groningen (RugDS). The lists found in Chapter 3 ([110, 196, 331, 338, 362, 425]) offer candidates as well. The process of creating a list of IoT platforms is presented in Figure 5.1.

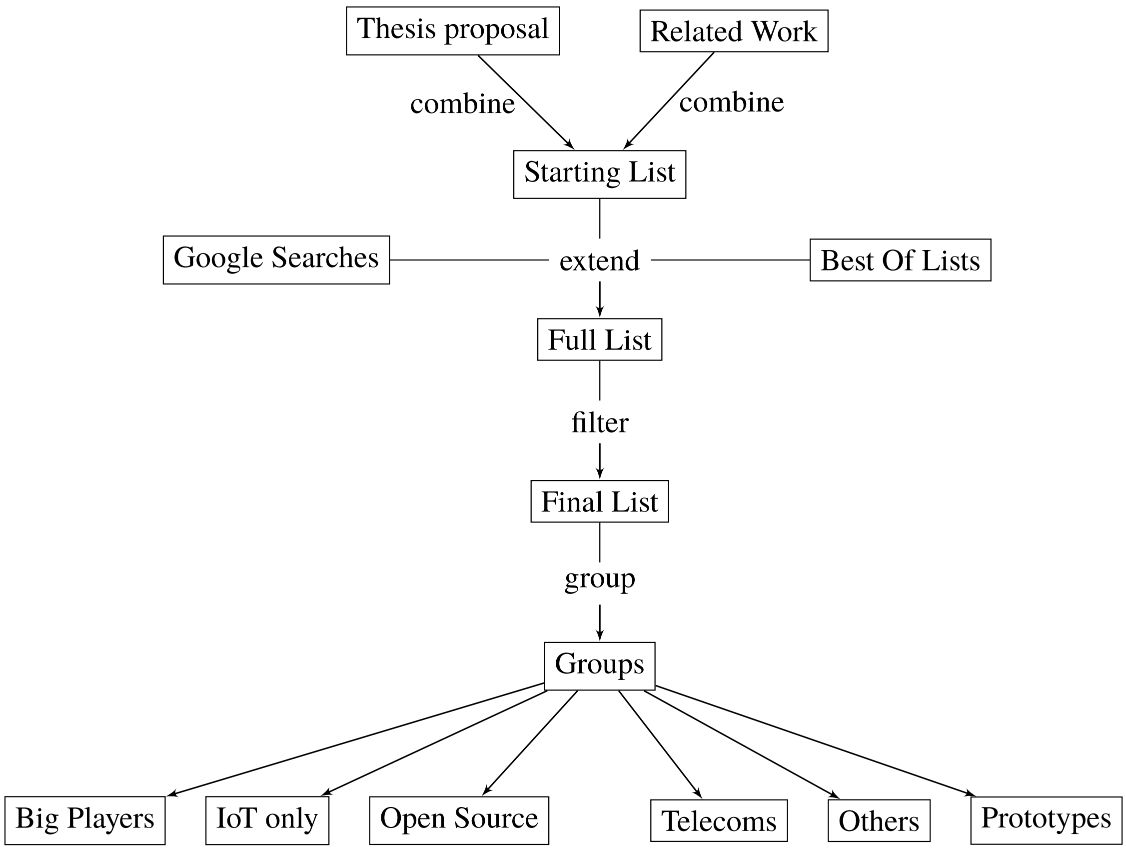

Figure 5.1: Process of finding, selecting and grouping IoT platforms

We adopted the first three steps of the systematic method created by Huang, Ying et al. [205] to gather more IoT platforms. In the first step, we combined the platforms already given in the proposal and the related work. To further extend this starting list of platforms, we conducted a first Google search in the next step using the term “IoT Platforms” which represents the “Core Lexical Query”. The terms “IoT Platforms open source” and “IoT Platforms prototype” were used for the step called “Expanded Lexical Query” to especially increase the amount of open source and prototype solutions. For each search, we examined the first five pages of results which led to platforms and some “Best Of” lists which we interpret as “specialized journal search”, the third step of the systematic method. The platforms in these “Best Of” lists were also included in the resulting overall list of platforms. The full list covers a number of 85 products. However, entries not fitting the definition of scalable IoT platform (see Section 1.1) have been sorted out as well as platforms not having a release published for at least twelve months (since June 2018), leaving 54 IoT platforms. This list offers platforms of big and small companies as well as some open source platforms and prototypes.

As there are several similiarities in many platforms, those platforms are grouped in the next step. This way, the bigger differences are analyzed between groups and the more detailed variations between the platforms of the same group. During the search for platforms, it became clear that there are some obvious differences in the platforms themselves or the companies developing them. The platforms have been grouped into the six groups shown in Table 5.1.

Table 5.1: Overview of the grouping system

Group	Description	Size
Big Players	Platforms whose providers are in the Global Fortune 500 list of 2018	13
IoT Only	Platforms whose provider companies are only active in the IoT field	11
Open Source	Platforms whose source code is open	9
Telecom	Platforms provided by telecommunications companies	5
Others	Platforms not fitting any other group	9
Prototypes	Platforms in a developmental state	7
Total		54

The Big Players group includes all platforms provided by companies of the Fortune 500 list of 2018 [166], the IoT Only group includes mostly smaller companies focusing only on the IoT sector. All platforms whose source code is open for everyone form the next group, platforms provided by telecommunication companies are included in another group. Finally, there is one group for all platforms not yet released[1] and another group for all remaining platforms not yet put into groups.

Some open source platforms might fit into other groups, but all of those who have their platform’s source code publicly available were put into this group. Most of the open source platform providers are doing only IoT, thus are fitting into the “IoT only” group as well, except Zetta which is a fund focused on intelligent software [129]. Prototype and proposal platforms were put into the prototype group, but some also will fit into other groups now or on release. For example, the prototype platform Mainflux is open source [267]. The RugDS platform will be open sourced once ready to be

[1]No official launch or a current version below 1.0

published [353], and those platforms would move into the open source group on release. Huawei's platform OceanConnect will move into the "Big players" group on release as Huawei is ranked on #72 of the Fortune 500 list [166]. All the other platforms fit perfectly into just one of the groups.

For the analysis, we examined the websites and documentations of the platforms where available. For some platforms, there are product briefs, presentations, whitepapers or GitHub repositories with additional information available which were used as well. For information on the company behind the platform, we used Crunchbase [123] to get information on the sectors the company is active in as well as founding date and number of employees. The launch dates were found by conducting Google searches with the platform name combined with the key words "launch" and "release". If any information was not included in the already mentioned sources, especially for "security incident" or "security audit", we conducted Google searches with the platform name combined with the criteria. If the first three pages would not give an answer, we marked the information as not available.

5.2 Overview of IoT Platforms

In this section, we shortly present all the selected IoT platforms.

5.2.1 Honorable Mentions

Some companies may have their own IoT solution which is not an actual platform or not distributed as such, some are not developed or distributed any more. This could be a product specifically designed and implemented for only one single use case or an application for another, maybe bigger platform.

Intel and Dell developed concepts with the aim of creating a more secure platform or smarter edge devices respectively [226, 385]. Both visions might be implemented as platforms in the future. SAP Leonardo actually is an IoT platform, but it is not distributed as platform. This means, SAP is reusing the platform to sell complete solutions based on Leonardo to customers, but the company is not offering the platform on its own for customers to create their own applications [109]. Platforms like Samsara and Webinos were already developed in the past, but have not been pushing new releases for at least a year and have therefore been cut out of this thesis. Other platforms like Hitachi Lumada are not meant to be a platform to build applications on, but they serve one single use case - in this case maintenance. Lumada was designed for intelligent maintenance and optimization of asset performance [436]. This may fit the goal to utilize collected data to improve a process and even predict the behaviour, but overall this pictures just a monitoring tool with no option to utilize collected data in any other way, thus representing a simple software instead of an actual platform to enable other applications.

5.2.2 Big Players

This group includes 13 platforms. The launch dates of these platforms are shown in Figure 5.2. Most of their respective providers are listed in the technology sector of the 2018 Fortune Global 500 list [166]. Additionally, the list includes Predix and its provider General Electric (GE) (industrials sector, #41) as well as Bosch with its IoT Suite (motor vehicles and parts sector, #75).

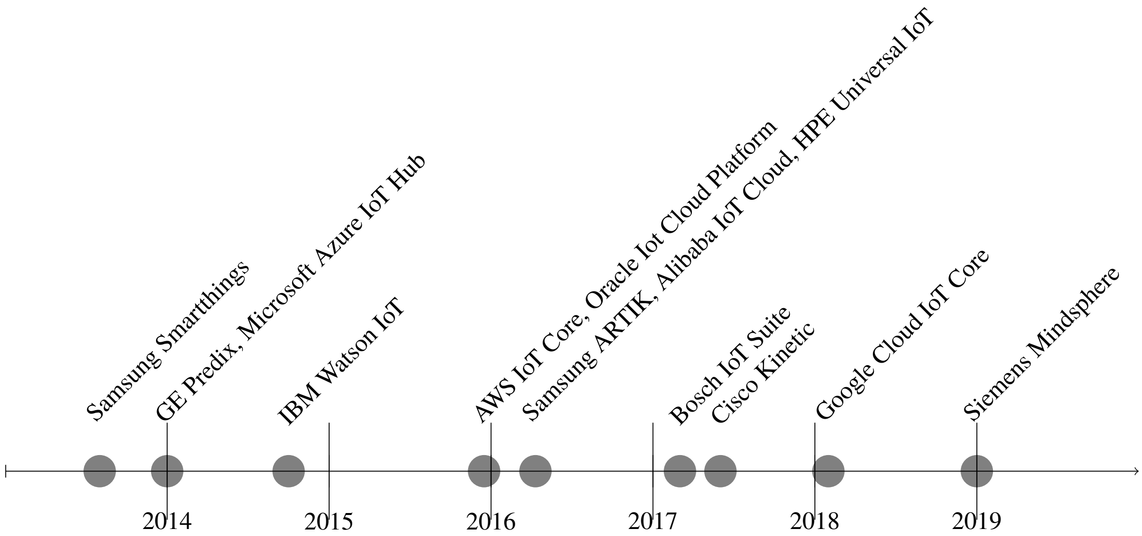

Figure 5.2: Timeline of the launch of the “Big Player” platforms

Samsung is the highest listed company offering an IoT platform at #12, in fact Samsung even owns two platforms. The first one, ARTIK cloud, was launched in April 2016. The characteristic feature of ARTIK is its interoperability and the fact that devices are not running isolated. It is described as open platform for data exchange [194]. Since February 2019, the ARTIK website does not provide log-on required services any more. After November 30 2019 ARTIK will be completely shut down and all data will be destroyed safely, according to a notification on the ARTIK website [342].

The second platform called SmartThings was initially a campaign on Kickstarter in 2012 which was so popular that it got funded with $1.2 million of its initial target of $250,000 by almost 5,700 backers. The idea of SmartThings was created when a bursting pipe caused a flooding in the basement of one of the founders. SmartThings was meant to be the solution to this by being able to monitor and prevent such things in the future [368]. In 2014, Samsung acquired the SmartThings company and its platform for $200 million [20].

Amazon (ranked #18 on the Global Fortune 500 list) launched its product Amazon Web Services (AWS) IoT Core in December 2015 [34]. Data and applications on this platform can also be forwarded or used in other AWS products like the database products S3 and DynamoDB or for Machine Learning with SageMaker. AWS IoT Core utilizes the Digital Twin concept (see Section 2.3.1) to that degree that users can always see and change their devices and their latest known information, even if the device is not connected. Amazon calls this feature “Device Shadows” [37].

The one entry in this class not belonging to the technology but the industrials sector is GE. Its platform Predix was launched in January 2014 [237]. GE describes the platform as the “result of GE’s billion+ dollar investment in its own digital transformation” [176].

Next on the list is Google parent Alphabet (#52) with the Google Cloud IoT Core platform. After a five month public beta in 2017, Google officially launched its platform in February 2018 [273]. The characteristic of this platform is the Machine Learning component on the edge called TensorFlow Lite. Google also enables the integration into its other services like Bigtable or Datalab [186].

Just like Samsung, Google also acquired another platform called Xively (originally Pachube) in 2018. However, Google integrated the product in its own cloud solution to complete its existing portfolio and Xively was not continued as a separate product [351].

Ranked 66 Siemens published its Mindsphere platform in January 2019 [183], after running a beta phase since March 2016 [358]. The platform can be used on its own and is also the basis for other Siemens products, the so called Mind Apps [358].

Microsoft is ranked just a few places lower at 71 and officially launched its platform in February 2016 after a four month public preview. The Azure IoT Hub is one product in the bundle put together as Azure IoT Suite [301]. One aspect worth noting at Azure IoT Hub is the big security program Microsoft set up for its IoT portfolio. This includes giving customers a better understanding of and confidence in the security of their assets as well as working with third-party auditors evaluating the security of the IoT solution [282].

Bosch is the second provider listed in the Fortune 500 list not belonging to the technology sector. The motor vehicles and parts company launched its platform in January 2014 [234]. The Bosch IoT Cloud was released in March 2016 and went public in 2017 [334]. Other modules like Analytics, Insights, Hub and the Gateway were launched since then to complete the current Bosch IoT Suite.

IBM is listed as #92 in the Global Fortune 500 list and also got its own platform in Watson IoT, launched in July 2017 [218] and formerly known as IBM IoT Connection [221]. IBM Watson IoT is subject to regular security checks of third-party auditioners Bureau Veritas since November 2015 [104]. Another partnership was announced in August 2016 when IBM and Whirlpool Corporation started building Smart Kitchen and Smart Washer and Dryer together [116].

Cisco (#212) launched its self-made platform Kinetic in 2017 to supersede the previously acquired Jasper platform which is not kept up to date any more. Kinetic was meant to leverage on Jasper and eventually outgrow its. Unlike Jasper, Kinetic is not limited to cellular networks and also enables Edge Computing [274].

Alibaba initially launched its IoT Cloud in April 2016 [118] and announced to build the “world’s first ubiquitous cloud” [299] in 2018. Over the next five years, Alibaba’s aim is to connect ten billion devices using this platform. The platform heavily focuses on AI capabilities [299].

The final two spots belong to Oracle (#302) and Hewlett Packard Enterprise (HPE) (#409). Oracle IoT platform was launched in August 2016 [197] whereas HPE Universal IoT is on the market since May 2016 [332]. Both companies are targeting larger enterprises as customers and have not published much information but aim to distribute their platforms over their consultants. Despite the limited access on information about its platform, HPE was named a “sleeping giant” [286] and a “major player” [434] in the IoT platform sector.

ARTIK, SmartThings, AWS IoT Core, GE Predix[2], Azure IoT Hub, Watson IoT and Oracle’s IoT Platform also offer coding examples or public apps, libraries or (Edge) SDKs on their GitHub pages[3] [40, 68, 179, 220, 277, 314, 339, 347].

[2] only with Predix account

[3] Except Artik, GE and Oracle who hosts their libraries on their websites

Unfortunately, Oracle and escpecially HPE target larger enterprises with their platforms and have therefore given only very little information public which is mostly an overview of their platforms. Because of this, the following analysis focuses more on the other platforms in their group.

5.2.3 IoT Only

In this group, there are eleven platforms. The launch dates of these platforms are shown in Figure 5.3. All of these platforms are developed and distributed by companies whose focus is solely on the IoT. Some even were just founded to distribute their platform.

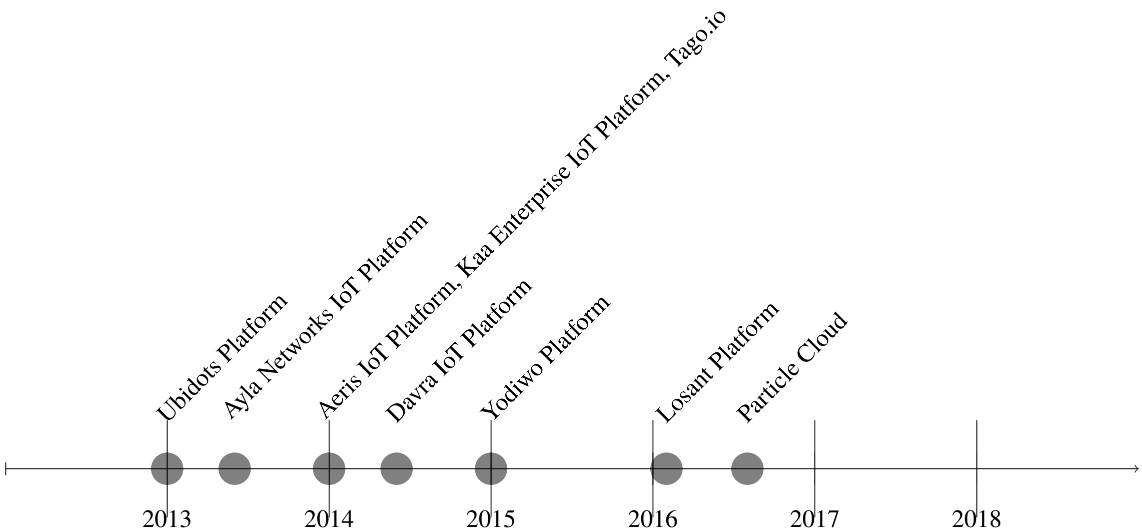

Figure 5.3: Timeline of the launch of the “IoT Only” platforms

The Aeris IoT Platform by Aeris Communications was launched in January 2014 [233]. This provider was founded in 1992 and offers the platform as two key parts: Aeris Connectivity Platform (ACP) and Aeris Mobility Platform (AMP). ACP focuses on the application part, whereas AMP provides functionality for moving things [11]. 2010 founded Ayla Networks launched its IoT Platform in June 2013 and extended the product by its Agile Mobile Application Platform (AMAP) to simplify the mobile control of IoT devices. Both providers offer business intelligence integration in their products [11, 74, 75, 202, 394, 444].

Davra Networks introduced its RuBAN platform in June 2014. Since then it has been also called Davra IoT Platform. In the current documentation only the API is still called RuBAN. In March 2016 the platform was added to longtime partner Cisco’s Global Price list [142, 145, 335].

IoT Factory was founded in 2013 and since then has published its IoT Software Platform, targeting especially startups by offering 50.000 € fundings for every startup using its IoT Software platform [232, 238]. Unfortunately, the company does not offer much technical information.

Founded in 2012 and having a successful campaign on Kickstarter in 2013, Particle published its Particle Cloud in August 2016, just six months after the release of the Losant Platform, created by Losant which was founded just under a year earlier in October 2015. Both companies focus on making it easier for developers with Particle offering an Integrated Development Environment

(IDE) and Losant providing an workflow editor to create applications without writing any code [124, 260, 324, 326]. Tago which was also founded in 2012 launched another platform. The changelog of its API starts with version 3.0.0 in March 2017 [378], but the SDK was first released in October 2014 [379], so the platform probably was launched before that. The origin of the next company and the date to launch its platform is also not quite clear. Depending on the source, the Spanish company Thinger.io was either founded in 2016 [241] or 2018 [125], while the launch date of its platform is unknown. The Ubidots Platform (also called Ubidots IoT Application Development Platform in IoT ONE) was launched in January 2013, the year after its provider company Ubidots was originally founded [243, 427]. These five platform providers (Losant, Particle, Tago.io, Thinger.io and Ubidots) all open-sourced their client libraries by publishing them on their respective GitHub accounts [262, 325, 419, 433]. Despite calling its platform "open source" on its website [420], the Thinger.io Platform's server source code is not open source and neither will be in the near future [417].

Yodiwo was founded in 2015 to release its Yodiwo Platform in the same year. The company is still small today with eleven to 50 employees. After announcing a partnership with the Indian network provider SenRa in August 2017, there were no news about Yodiwo and the platform until another partnership announcement with another network provider, South African Vox Telecom in March 2019 [128, 269, 304, 352].

5.2.4 Open Source

All nine platforms in this group are open sourced. The launch dates of these platforms are shown in Figure 5.4. Whereas platform providers of other groups may only have published the source code for libraries or SDKs for their platforms, the source code of the platforms in this group is completely open. This means anyone can get the source code for any part of the platform, run a functioning version and - depending on the license - also edit or exchange parts of it.

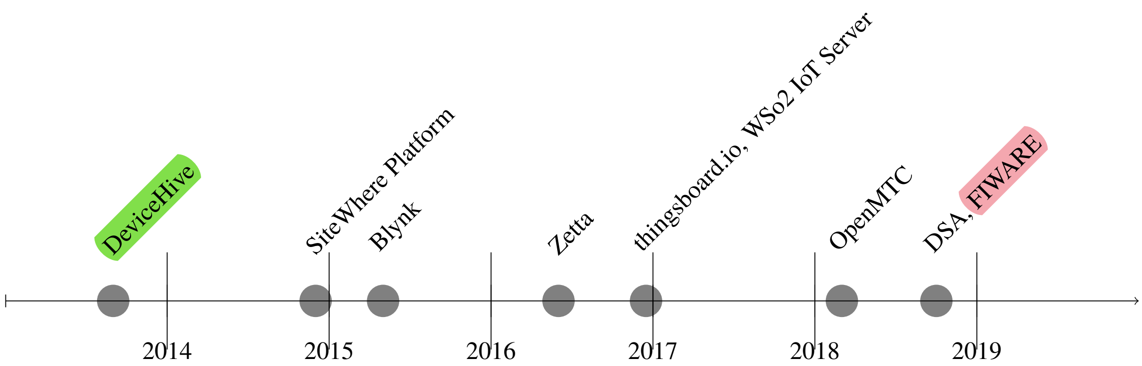

Figure 5.4: Timeline of the launch of the "Open Source" platforms

Another successful kickstarter campaign led to the launch of Blynk's platform in May 2015 [90]. Zetta Venture Partners (founded in 2013 [246] or 2014 [129]) launched the Zetta platform in June 2016 [466]. The latest version was released in November 2017 with Zetta only creating three more commits since then [466] and its Twitter account [465] going silent in 2016. However, Zetta states that a new release is coming “soon” in an issue on GitHub in December 2018 asking if Zetta is still alive [467]. Both the Blynk and Zetta platforms are available under Massachusetts Institute of Technology (MIT) license [89, 466].

DeviceHive was founded in 2012 [236] and launched its platform on GitHub in September 2013[4] [149]. It is not clear when Distributed Services Architecture (DSA) Initiative launched its DSA platform, however, the last of the three main components was first released in October 2018[5] [151]. Thingsboard Inc. was founded in 2016 and released its platform thingsboard.io in December the same year [126, 423]. 2005 founded WSo2 launched its platform as version 3.0.0[6] in January 2017 [127, 460]. DeviceHive, DSA, ThingsBoard and WSo2 are available under the Apache 2.0 license [147, 155, 423, 460].

The next open sourced platform is FIWARE which is funded by private investor companies via the FIWARE Foundation e.V. as well as the European Commission. The FIWARE Foundation consists of telecommunication companies (like Orange and Telefónica), IT companies (like IBM) and universities amongst many others. The FIWARE project was launched in 2014 with a budget of $100 million which turned out to be “a waste of public money and entrepreneur’s time” as the project is seen as a way of promotion of the companies and justification of a budget and to use the resulting platform is “much of a pain” [164, 165, 302].

The OpenMTC platform was initiated by Fraunhofer-Institut für Offene Kommunikationssysteme (FOKUS) and the Chair “Next Generation Network”[7] of the Technische Universität Berlin [198, 305]. Version 1.0.0 was released in March 2018 under the Eclipse Public License (EPL) version 1.0 [308].

SiteWhere originally launched its platform in October 2014, but redesigned the architecture to now using microservices and relaunched version 2.0 in December 2018. The platform is available under the Common Public Attribution License (CPAL) 1.0 license [363, 365].

5.2.5 Telecoms

Telecommunication companies have been already running an important part for the IoT landscape for years - the network. It is just a logical conclusion to use this available infrastructure to create their own platforms for the IoT. This group includes five companies of the telecommunication sector. The launch dates of their platforms are shown in Figure 5.5.

Actility’s ThingPark was first mentioned as a manufacturer to manufacturer (M2M) solution in March 2014 [158] and is now running as an “IoT connectivity platform dedicated to enterprise applications” since February 2018 [77]. Partnerships with companies active in the IoT and telecommunication businesses allowed Actility to make its product more secure and international [78, 79].

AT&T started exploring the IoT already in November 2008 and has had nearly 22 million devices connected to its M2X platform in June 2015 [57].

[4] The first version on GitHub is 1.2.0.0, so it is possible that there was already another release before this version

[5] DSA states on its website that the DS Broker is written in Dart, however there are some prototype brokers in other languages with earlier pre-releases

[6] Version 1.0.0 was apparently scrapped after the fifth alpha version

[7] Also called “Architekturen der Vermittlungsknoten (AV)” in German

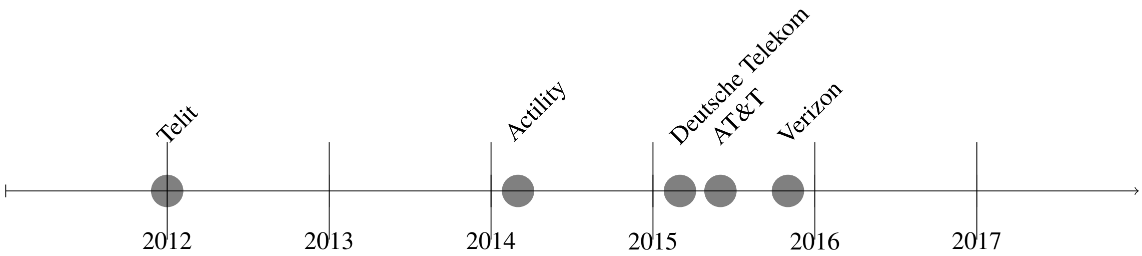

Figure 5.5: Timeline of the launch of the 'Telecoms" platforms

Deutsche Telekom launched its so called "Cloud der Dinge" (german for Cloud of Things) in March 2015 as its IoT platform solution [192]. In June 2016, the company also announced a starter kit including a device able to collect data about position, movement and temperature [253].

Telit's deviceWISE and IoT Portal form another platform. The first document for the platform dates back to June 2016 [402] and the platform currently connects over 100 million devices [395].

Verizon built its ThingSpace platform integrating the dweet.io platform and the freeboard visualization tool both created by BugLabs [101]. Both dweet.io and freeboard were launched in 2014 [252]. Verizon's ThingSpace was launched in November 2015 [169]. As dweet.io is integrated in ThingSpace, we assume that all the information on dweet.io also applies to ThingSpace. Because of this in the following analysis all three products are seen together as the ThingSpace platform. Dweet.io might be still continued as a separate platform as well.

5.2.6 Others

All remaining platforms that are already on the market are included in this group. The platforms are mostly made by smaller companies, but the IoT is not their only field of business. This group contains nine IoT platforms. The launch dates of these platforms are shown in Figure 5.6.

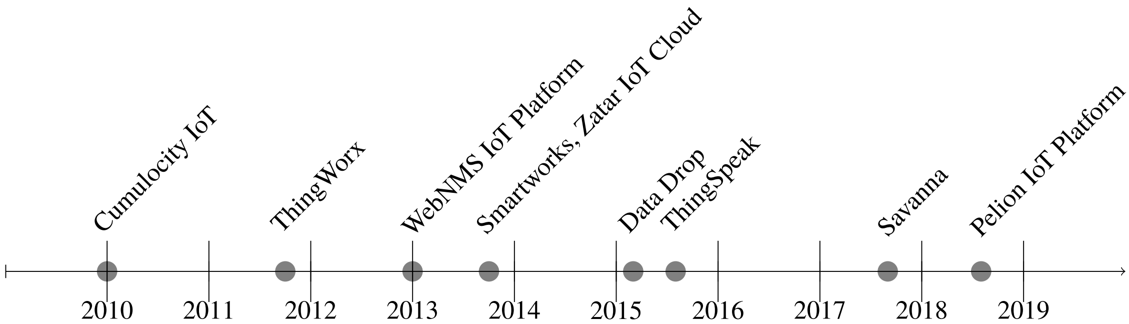

Figure 5.6: Timeline of the launch of the "Other" platforms

Carriots was another IoT platform launched around 2013 [159]. It was later acquired by another company, in this case Altair Engineering Inc. in 2017 and is now called Smartworks [29].

ARM Limited acquired the two companies Stream Technologies and Treasure Data. Together with its device operating system Mbed OS the products of those two companies were used to launch its IoT platform Pelion in August 2018 [350, 445].

Software AG's subgroup Cumulocity is running a platform with the same name since 2010. It has been called "the leading independent Device and Application Management Internet of Things (IoT) Platform" since its launch [235].

WebNMS is the IoT division of Zoho Corporation providing a multi award winning platform with the WebNMS IoT Platform. This platform won the Aegis Graham Bell Awards for "Innovation in M2M" and "Network Management Solutions (NMS)" in 2013 [317], was named the "Best Application of Wireless Sensor Networks/Internet of Things" in 2014 [476], and also won the "Best IoT Platform" award at the IoT Evolution Expo 2016 [361].

Finally, this group covers five more platforms which offer very limited information, especially on technical details. These platforms are Mosaic Things by Larsen & Toubro Infotech Limited, ThingSpeak by Mathworks (launched in August 2015), Data Drop by Wolfram (launched in March 2015), Zatar IoT Cloud by Zebra Technologies which was launched in October 2013 and later renamed and/or relaunched as Savanna[8] in September 2017, and most notably ThingWorx (launched in 2011 and acquired by PTC Inc. in 2013) which was - according to IoT Analytics [229] - the "clear market leader" of any IoT platform in the fourth quarter of 2015 with 18% of the market share and the first competitor following with just 4%. Though the insight on these platforms is limited, the available information will be used where possible.

5.2.7 Prototypes

The final group includes all the platforms not yet released with a version 1.0 or later. This includes proposals, prototypes and platforms in experimental, beta or early access phases. There are seven platforms in this group.

Bacsoft published a whitepaper on an IoT platform in 2015. The company also offers Smart Communications Controller that can be used as gateways for the platform. There has not been an official announcement or launch yet, however the platform seems to be already in use for some customers and interested users can request a demo on the website [80, 82].

Huawei published a short introduction on its OceanConnect IoT Platform in 2017 [211]. The platform is based on the oneM2M standard [12] and as a beta version was released in August 2017 [56].

Macchina.io is distributed by Applied Informatics Software Engineering GmbH. In fall 2015, it was among selected projects to receive funding by Internet Foundation Austria's netidee program [45]. The latest version 0.10.0 of its Edge Computing solution was released in 2018 as well as the company's whitepaper [48].

Mainflux is another platform still in a developmental phase. The latest version 0.7.0 was released in December 2018 under the Apache 2.0 license on GitHub. The Mainflux company is a "member of the Linux Foundation and an active contributor to the EdgeX Foundry project" [267].

[8] Zebra Zatar and Savanna will be simplified to Zebra Zatar in this thesis

Mozilla's WebThings platform "is graduating from its early experimental phase" to a "new phase of development" and was undergoing a name change from Project Things in April 2019. The newly released version is 0.8 [167]. The WebThings platform implements the "Web of Things" W3C standard (for more information see [452]) [292].

The RugDS is developing yet another IoT platform. The platform is already being used in multiple projects, but has not yet been officially published. It is set to go open source in the future [353].

Temboo's Kosmos platform is the final entry in this list. In October 2018, Temboo released an early access version of its platform [122].

6 Analysis of Platforms

In this chapter, the selected platforms are analyzed according to the criteria explained in Chapter 4. Each of the four section will be rated for every platform with the star rating system explained in Section 4.6. In the end, the results and overall ratings are aggregated and discussed.

6.1 Reliability

In the following section all the platforms are analyzed in terms of reliability. The topics to be reviewed are explained in Section 4.1.

6.1.1 Replication

Most big IT companies have multiple data centers across the globe. Despite not having information on backup and clustering methods, users would expect a cloud or database provider to backup their data as a customer. Microsoft offers disaster recovery [279], IBM backups customer data at rest [223]. AWS IoT Core is running on different continents, but not in every server region [42]. Cisco runs a backup strategy offering recovery points losing at most four hours of data [113]. Alibaba does not mention replication or clustering for its IoT platform, but offers such services for its cloud, so it is probably possible to use for the IoT product as well [15]. As all of these big players have similar conditions and environments, we assume backups and clustering over the globe are done by at least most if not all of these companies. As a company not originally known as IT company, Bosch offers its IoT modules hosted on the AWS platform or on the Bosch IoT Cloud for some modules, the Remote Manager can even be hosted on premise [97]. For the Bosch Cloud, there is no information on replication and clustering, except that it is hosted in Germany only [334].

As the IoT companies are mostly using third party infrastructure, they do not need to have their own clustering or backup strategy and most of them do not mention these topics at all. Only Kaa Technologies promises a “high availability deployment with no SPOF” (single point of failure) [250] and Ubidots offers “automated failover and replication” across its partner’s (IBM) infrastructure [429].

Out of the open source providers offering a managed hosting solution, Blynk does not provide any information on backup or clustering. FIWARE suggests a deployment including multiple computing nodes thus there has to be some kind of clustering functionality included in the platform. It also includes multiple storage nodes, however these provide different types of storage [163]. These storage nodes probably do not enable replication unless users multiplicate them individually. ThingsBoard provides fault-tolerance, allows clustering as well as Not only SQL (NoSQL) database replication and promises that users “will never lose [their] data” [421]. WSo2 offers backup and disaster recovery for paying users, however clustering is not mentioned [457]. The other platforms have to be hosted by users on their own infrastructure, therefore responsibility for backups and replication lies with the users.

In the telecommunications group only Telit's "multi-geography global IoT Platform deployment" [397] indicates some kind of replication. The fact that the infrastructure of Deutsche Telekom is located in Germany only [373] even indicates the other way which means there is no kind of at least geographic replication.

The edge solution of WebNMS enables devices to store data when the connection is lost and later resend it on reconnection [470]. Cumulocity offers retention rules [138]. The other platforms do not provide information on replication or backups.

Prototype platform Bacsoft "features server redundancy and automatic field unit roaming between servers" and also supports database replication [81]. Huawei is running servers in multiple regions with a load balancer [12, 209] and Macchina.io can be run in a load-balancing setup as well [45, 48], both indicating clustering and replication. Temboo states that events like sudden spikes in execution or a fire in a data center lead to the launch of more nodes or replacing nodes in other physical locations. In a catastrophic loss of multiple data centers or providers, Temboo is able to "rapidly relaunch and restore [their] customers' data" thanks to "redundant secure backups at multiple layers" [408].

6.1.2 Availability

Most of the platforms in the class "Big Players" have guaranteed uptimes of 99.5% per a Service Level Agreement (SLA) on their website [38, 96, 113, 187, 200, 217, 284], Oracle offers 99% uptime per month for its cloud services and resources, but it is not clear whether the IoT platform is included or not [316]. Siemens guarantees 99% uptime as well [357]. Alibaba even promises 99.9% availability of its platform [19]. The other platforms offer no information on availability, but the providers might negotiate SLAs with enterprise customers. GE offers "mission-critical availability" [176] whereas a reply to a post in its forum indicates an SLA guaranteeing 99.9% availability [171].

Unlike these allrounders, companies only offering IoT services do not always have their own infrastructure (or at least not as big) and have to host their platform on third party infrastructure like AWS or Google's Cloud. Ayla Networks [74] and Davra [142] for example have partnerships with AWS, Google, IBM or Cisco respectively. Most of the other companies in the "IoT only" class offer individual SLAs for corporate customers [7, 260, 323] except Ubidots which guarantees 99.9% uptime by default but also offers additional SLAs for custom prices [428]. Tago states that it "runs on cloud so that customers can get the best of redundancy [and] uptime", but does not mention a exact percentage or information on an SLA [382]. IoT Factory, Thinger.io and Yodiwo do not mention any metrics or SLAs for availability, Kaa Technologies promises "elastic, zero-downtime scalability" [250].

All of the open source platforms can be hosted on any infrastructure, so it is the user's responsibility to minimize the downtime and have a strategy to avoid data loss. Blynk and WSo2 however also offer public instances of their platforms. WSo2 is promising a 99.9% uptime per SLA for its paying customers [457], Blynk states that its cloud servers have had a 99.99% uptime since its release in May 2015 [87]. FIWARE's previously mentioned suggested deployment architecture includes three controllers and high availability [163], SiteWhere's new microservices structure enables high availability by simply using multiple instances of a microservice and managing these services and their configuration with Apache Kafka, Apache ZooKeeper and Hashicorp Consul [366], and ThingsBoard states that all servers are identical, the failure of any node will be automatically detected and the node will be replaced without downtime [421].

In terms of availability the telecommunications companies are prepared as well. AT&T states to have had about one hour outage in the last twelve months, Actility promises "high availability" by individual SLAs [3, 61, 78]. Deutsche Telekom (up to 99%) and Telit (99.9% by SLAs) offer high availability for all customers [390, 401]. ThingSpace offers custom SLAs for enterprise customers which might include an uptime promise [102].

The Smartworks platform has been "designed for high availability" and has different SLAs available depending on the payment tier [193], Pelion promises "better availability, with access data collected from devices even if they are temporarily disconnected" with an SLA guaranteeing 99% uptime [51, 121]. Cumulocity ensures availability with its Kubernetes setup although this is not exposed to developers or users [137]. WebNMS Edge restarts devices automatically after a failure but does not offer an SLA [470].

Out of the prototypes, Macchina.io, Mozilla WebThings and RugDS are not hosted on the provider's infrastructure, thus none of these is offering an SLA for the uptime of the platform. Temboo does not provide a promise as well, but states that the automated and modularized architecture of Kosmos also works as downtime protection [408]. Only Huawei names a percentage for the guaranteed uptime which is according to different sources either 99.9% [209] or 99.999% [248].

The availability promises of all platforms where available are shown in Figure 6.1. The abbreviations in brackets represent their group.

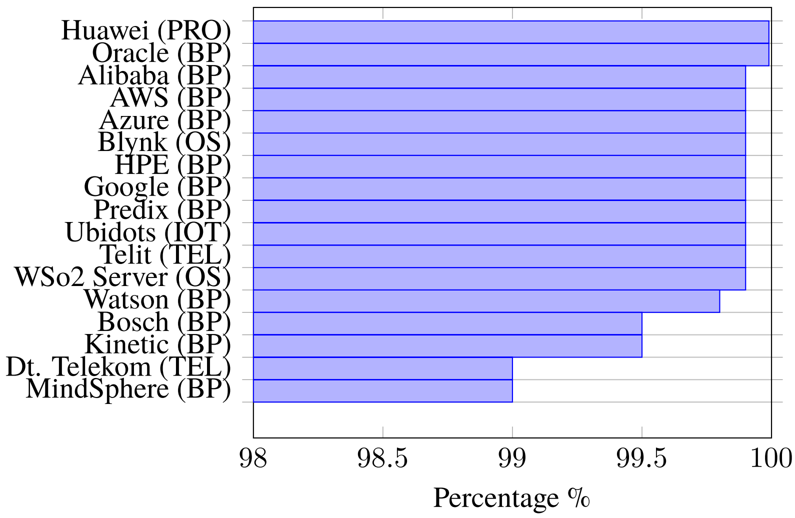

Figure 6.1: Overview of the availability promises of the platforms where available

6.1.3 Authentication and Authorization

Authentication is done via LDAP (Microsoft) and token methods like JWT or signatures complying with the X.509 standard. Authorization often is role-based, sometimes with pre-defined roles (Oracle), custom roles and/or policies. Samsung offers no differences in authorization for the ARTIK cloud platform. The permission models of Alibaba and Samsung SmartThings are device-based, SmartThings also offers OAuth integration [16, 17, 19, 35, 84, 98, 177, 189, 219, 278, 339, 356, 367].

The authentication for the "IoT Only" platforms works via key pairs (Ayla Networks), tokens (Davra, Losant, Particle, Tago.io, Thinger.io, Ubidots and Yodiwo) or even two factor authentification based on the RFC 6238 standard (Losant), all with role-based authorization [1] except Yodiwo which has its own pairing and sharing mechanism. Some platforms even allow third party libraries for authentication like OAuth (Davra, Particle), LDAP, AD (Davra) [10, 73, 144, 259, 324, 374, 375, 384, 418, 420, 430, 462]. IoT Factory indicates a "fine management of access rights" [230], Aeris Communications mentions the existance of access security and data privacy without providing technical details [7], and Kaa Technologies have no public information about security at all.

Blynk and Zetta offer no information on their user management and authentication/authorization methods. DeviceHive and SiteWhere use JWT as authentication method [148]. SiteWhere additionally requests a second token to verify access to tenant information [363]. DSA implemented a handshake mechanism based on ECDH with curve and authentication via credentials, LDAP or OpenID [154]. FIWARE supports OAuth2 and the Keyrock identity manager and a single sign-on mechanism to share login information with any app using the FIWARE platform [163]. ThingsBoard allows device and user authentication via tokens or certificates [421, 422]. OpenMTC and WSo2 use certificates for authentication, however users have to enable certificates manually [307, 459]. Apache DS is integrated for development but not recommended for production stage, WSo2 suggets using LDAP services like OpenLDAP [460]. DeviceHive, DSA[2], FIWARE and WSo2 implemented role-based authorization [148, 154, 163, 459]. SiteWhere implemented its own authorization method using customer types with inheritance [363]. OpenMTC does not offer any kind of a permissions model.

AT&T authenticates users, devices and more via API keys, Deutsche Telekom uses certificates and Telit implemented authentication via credentials and JWTs. AT&T's authorization is done on a granular level, the other platforms use role-based authorization methods [3, 63, 390, 400]. ThingSpace implemented authentication by credentials or tokens and authorization by policies to be able to share access for individuals or groups with a fine-grained permission model and a flexible user hierarchy [103, 438].

For authentication the "Other" platforms use API keys (Smartworks, ThingSpeak), credentials (Pelion, WebNMS) or tokens (WebNMS at gateway commands) [51, 193, 415, 470]. Cumulocity states to have "a standard authentication and authorization process" and also enables OAuth2 and two factor authentication via Short Message Service (SMS) [131, 136, 138]. Gravelle, Robert [193] mentions a "seven level hierarchy" for Smartworks authorization, Cumulocity and WebNMS use policies and roles for authorization [131, 472].

[1] Particle only in private beta
[2] Only pre-defined roles

Huawei authenticates devices via certificates, Mainflux uses API keys and scoped JWTs. Temboo creates application keys for client code and RugDS just stores credentials in a file. Mozilla supports TLS certificates, Public Key Infrastructure (PKI) and Certificate Authorities for authentication. WebThings and RugDS did not implement roles or a permission model yet, but it is planned for at least Mozilla's platform. Bacsoft enforces user access control with multiple levels of authorization, Huawei implemented an authorization method for applications. Mainflux enforces a "fine-grained access control" and even offers an advanced, database-based authentication and authorization or an optional LDAP for commercial users. Mainflux and Mozilla also support OAuth [47, 81, 150, 209, 264, 266, 267, 291, 292, 408].

6.1.4 Encryption

All of the Big Players' platforms encrypt data both in motion and at rest.[3] Messages and keys are encrypted via TLS and AES. Alibaba additionally support DTLS and custom encryption for protocols based on TCP or UDP and Cisco is additionaly using an IPSEC tunnel with Virtual Private Network (VPN) support between gateways and the cloud. AES is also used for some of the respective database systems, other providers just state that the data is encrypted but not how.[4] Key exchanges are encrypted using RSA or ECDH [16, 17, 19, 35, 84, 98, 177, 189, 219, 278, 339, 356, 367].

The IoT companies do not handle storage encryption on their own as they are using third party databases, only Losant notes that its data in transit and at rest is encrypted using the engine and persistent disk functionality of the provider of its underlying infrastructure (Google Compute). However, messages in the IoT only platforms are encrypted with TLS (Ayla Networks, Davra, Losant, Tago.io, Thinger.io, Ubidots and Yodiwo) or hardware keys (Losant, Particle) [73, 144, 259, 324, 374, 375, 384, 418, 420, 430, 462].

Blynk, DeviceHive, ThingsBoard and WSo2 offer SSL/TLS encryption for their commmunication [89, 148, 421, 422, 459], SiteWhere indicates that some kind of encryption already existed in the outdated architecture [364] and Zetta ensures data security via a tunneled link [466]. OpenMTC offers SSL/TLS encryption as well, but it seems to be disabled by default [307]. FIWARE does not provide any information on encryption. All platforms use third party or self-hosted database where users have to ensure encryption as a host. There is no information, if database encryption is enabled or not for the managed hosting solutions.

Actility does not provide information on encryption, whereas the other telecommunication platforms use TLS to encrypt messages [63, 397]. Deutsche Telekom even lists the additionally used encryption methods AES, 3DES and Camellia which are probably used for storage encryption [390]. The possibility to access ThingSpace via HTTPS indicates the usage of TLS in this platform as well [438].

[3] Not applying for Samsung ARTIK cloud and Samsung SmartThings as they only move data without storing it by default, and Cisco Kinetic and GE Predix which have no built-in data storage either

[4] No information about database encryption at HPE

Smartworks ("data-in-flight is SSL encrypted" [26]), Pelion (SSL/TLS and DTLS [51, 53]) and WebNMS (SSL [470]) offer message encryption, whereas Cumulocity, ThingSpeak and Data Drop only indicate encryption by stating the use of HTTPS[5] [131, 415, 449]. Smartworks ("data at rest is secured by multiple layers of industry accepted protocols" [26]) and Pelion ("protected storage", "secure storage" [51]) indicate storage encryption as well. WebNMS uses third party databases (PostgreSQL, MySQL and MS SQL are named in [472]) which might offer their own storage encryption methods.

The prototype platforms mostly support SSL/TLS (Bacsoft, Macchina, Mainflux, Mozilla, Temboo), Mainflux additionally supports DTLS as well as Huawei. Bacsoft also allows to use self-signed certificates instead [45, 81, 209, 264, 292, 409].

The following table (Table 6.1) shows an overview of which platform used which encryption for messaging and storage. A ‘‘-" symbolizes that there was no information that an encryption is used for this platform. Other providers state to have "multiple layers" or "protected storage", but it is not clear what method is used. These cases are marked as "unclear". If there is storage system like a database used to store data at rest which could be encrypted, the cell is marked with "n/a".

Table 6.1: Overview of the used encryption algorithms for messages and storage

Platform Provider	**Message Encryption**	**Storage Encryption**
Big players		
Samsung (ARTIK)	AES/RSA	n/a
Samsung (SmartThings)	AES/RSA	n/a
AWS	TLS	AES
GE	TLS	n/a
Google	TLS	AES
Siemens	TLS	n/a
Azure	TLS	AES/3DES
Bosch	TLS	n/a
IBM	TLS	RC4/AES
Cisco	TLS	n/a
Alibaba	TLS	RSA/AES
Oracle	TLS	AES/3DES
HPE	unclear	-
IoT Only		
Aeris Comm.	unclear	unclear
Ayla Networks	TLS/AES	n/a
Davra	TLS	n/a
IoT Factory	-	-
Kaa Techn.	-	-
Losant	TLS	n/a
Particle	HW keys	n/a
Continued on next page		

[5]ThingSpeak then probably supports TLS for MQTT as well

Table 6.1 – continued from previous page

Platform Provider	**Message Encryption**	**Storage Encryption**
Tago.io	TLS	-
thinger.io	TLS	n/a
Ubidots	TLS	-
Yodiwo	TLS	-
	Open Source	
Blynk	TLS	n/a
DeviceHive	TLS	n/a
DSA	SSL	n/a
FIWARE	-	n/a
OpenMTC	TLS	-
SiteWhere	unclear	-
thingsboard.io	TLS	n/a
WSo2	TLS	n/a
Zetta	unclear	-
	Telecoms	
Actility	-	-
AT&T	TLS	-
Dt. Telekom	TLS/AES/3DES	unclear
Telit	TLS and more[6]	n/a
Verizon	-	-
	Others	
Altair	TLS	unclear
ARM	TLS/DTLS	unclear
Cumulocity	TLS	-
WebNMS	TLS	n/a
LTI Mosaic	-	-
Mathworks	TLS	-
PTC	-	-
Wolfram	TLS	-
Zebra	-	-
	Prototypes	
Bacsoft	SSL	-
Huawei	DTLS	-
Macchina.io	TLS	-[7]
Mainflux	TLS/DTLS	unclear
Mozilla	TLS	n/a
RugDS	-	n/a

Continued on next page

[6] RSA/RC4/3DES/AES/ECDHE
[7] SQLite not encrypted by default, but extensions available

Table 6.1 – continued from previous page

Platform Provider	Message Encryption	Storage Encryption
Temboo	TLS	AES

6.1.5 Security Incidents and Audits

There were no serious incidents documented for any platform. The only thing to find are history of issues on status pages for SmartThings [345] and Particle Cloud [328] which are only smaller bugs or downtimes. WSo2 runs a reporting program for security vulnerabilities [461] and lists all fixed issues in its security patch releases [456]. However, there is no indication that any of these vulnerabilities led to an actual exploit to lose data or control at any time. Actility provides a similar reward program for bugs and leaks for its ThingPark platform [2]. Tembbo states to actively monitor the whole system and promises reponses to incidents within minutes [408].

Veracode has done a security study in 2005 [437] which included Samsung SmartThings Hub and succeeded in all tests. Some other providers work together with third-party auditors. Google has its platform (and other products) checked quarterly [190], Azure has its own security program including audits [282], IBM is certified by Bureau Veritas since 2015 [104], and Oracle also has audits done as part of its security strategy [311]. GE runs its own penetration tests for the platform as well as periodic security reviews before publishing custom applications to its market place [175]. Ayla Networks is penetration tested by a third party vendor not named [73]. DeviceHive listed a planned security audit in its roadmap for the first quarter of 2018, but there is no information if it actually happened [148]. AT&T has annual security audits for its network [65]. The M2X platform is not specifically mentioned, but may be included in this security policy. Deutsche Telekom runs penetration and other security tests on its own, third party tests are not included [390]. Telit is doing "Comprehensive auditing, monitoring and reporting", but it is not clear if this affects the platform or just applications published by users [397]. Cumulocity states that its encryption technology has been rated as "A" and "up-to-date" by SSLLabs [131]. The other platforms do not have third party security tests or audits.

6.1.6 Development

Most of the "Big Players" platforms have irregular software updates (one week to six months span)[8], except Bosch that is releasing updates twice a month[9] [99], IBM that offers beta features regularly before officially distributing them as updates and Oracle that releases an update every month. Release notes and dates of the updates are listed in the documentations [189, 219, 278, 313, 339, 367]. GE's Predix platform offers open source libraries and samples for devices on GitHub [181] with new commits every few days.

[8]No information on AWS, Siemens, Cisco, Alibaba and HPE
[9]at least for some modules

In the “IoT only” class, no one offers any insight on a development or releasing schedule. Only Tago.io’s changelog indicates regular updates every two weeks [378]. However, Particle Cloud’s incident history indicates that issues are fixed in just a few hours [328]. On the opposing side, Yodiwo’s platform documentation has not been updated since February 2018 [462] indicating there has not been a new development or update since then.

The only open source platform with a roadmap is DeviceHive [148]. However, after frequent updates every few weeks to at most half a year, DeviceHive did not release an update since May 2018 [149], WSo2 has had its last release in October 2018 [460]. OpenMTC had just five releases over all in the 14 months of existence [308]. ThingsBoard still provides new versions every few weeks to months [423]. SiteWhere promises a “steady stream of new features” [366]. Zetta also did not release a new version for over a year, but indicated a new release coming soon in the previously mentioned issue on GitHub [466]. The DSA and FIWARE platforms are split into several repositories, some of them are worked on almost daily, others did not have a commit for a long time. The broker repository for DSA has had only one release so far, while its links repository already has 684 releases [151]. Some of the FIWARE components were changed lately, others have not been touched for years [165].

Actility released its last two big versions of ThingPark in October 2016 (version 4) [105] and February 2018 (version 5) [79]. AT&T provided updates every few months on average until August 2018 [58], Telit even released a new update every month until the end of 2018 [400]. Both platforms have not been updated since then. Deutsche Telekom does not provide information on new developments, however, its open source SDKs have been on version 1 since October 2017 [392] indicating there has not been a big update since then. Some of AT&T’s SDKs have not been updated for at least eleven months, other have been unchanged for years [60]. For ThingSpace there is no information on releases or updates.

Pelion (every month [54]), WebNMS (six releases in twelve months [474]) and ThingSpeak (at least one release per month [415] have been receiving updates including features and/or fixes irregularly. Cumulocity has a planned schedule of one (feature) release per quarter since the beginning of 2019, up until 2018 those updates were irregular as well [139].

Some prototype platform providers offer information on planned updates which will be approximately quarterly for WebThings, every one to three months for Mainflux, and monthly to bi-monthly for RugDS. Macchina’s releases are irreguarly in steps of one to eleven months [43, 267, 292, 353].

6.1.7 Market Longevity

Platforms provided by Fortune 500 companies do not have a big risk of being shutdown or acquired by another company, no matter if they have been on the market for one (Google), or five years (Bosch, IBM, SmartThings). Unlike these big players, smaller companies or companies only founded to distribute their IoT platform have a much bigger financial and even existential risk, if their platform is not as successful as they expected it to be. A possible shutdown or acquisition of a platform is something that can make users reevaluate their platform decision and maybe even force them to move to another solution, so the certainty to be able to use the platform for years to come simplifies planning for the user’s or company’s IoT future.

All of the IoT companies' platforms [10] have been on the market since 2016 [239, 270] or earlier [243, 251, 269, 453] except Aeris Communications (2018) [444]. The beginning of Thinger.io is not clear, but there have been commits on the GitHub repository in the beginning of 2015 already [419]. Ayla Networks even calls its platform the "industry's first Agile IoT platform" [71] and Davra lists a quote by 451 Research on its website calling Davra "the hottest industrial IoT software vendor you've never heard of" [143]. Even though these companies have different backgrounds (Particle successfully crowdfunded themselves on Kickstarter [326] and IoT Factory funds startups using its platform [232]) and different company sizes and ages, all of them heavily focus on their IoT product, so there is no doubt that the focus of the company will be on the platform in the future as well. Only Yodiwo has not released anything for the actual platform[11] since February 2018 [462].

The big benefit of open source is that anyone can see and edit the source code of a project. For open source platform this means that any developer using the platform is able to change some lines of code, a part of or even a whole component to what he thinks works better. So even if the actual producers of the platform do not develop new features or fix vulnerabilities, the platform development still continues. For the future this means that if there is a certain amount of people using this platform, it will always be adjusted to new conditions or technologies by its user base, even if the original producer discontinues the project. On the downside, those user developments might not be as well-planned, documented or secure as previous updates made by the provider's developers themselves. Additionally, FIWARE has got great fundings by companies as well as the European Commission [302] which makes it unlikey to have an abrupt ending.

The platforms of the telecommunication companies have all been on the market for multiple years already. With new developments and upgrades to be expected in this sector like 5G [204], the providers probably will not shutdown their IoT platforms in the near future but even extend and upgrade them as well.

In the "Others" group the market longevity and life expectance is very differing. On the one side, there is ARM's Pelion platform with the age of just one year, and on the other side, there are the eight year old Cumulocity and PTC's ThingWorx which (in 2015) had the highest market share by far. Smartworks, WebNMS, ThingSpeak, and Data Drop are in the middle with four to six years on the market, however ThingSpeak and Data Drop have a higher life expectance based on other products of their providers (Mathworks and Wolfram respectively) that can be integrated and leveraged with the platforms.

Due to their status as proposal or prototype, platforms of this class are not yet published on the market. Some of them might never release a version 1.0. However, for the platforms to be released in the future, potential users can expect at least some if not all vulnerabilities and bugs fixed until then. Some new or creative ideas and approaches might be integrated into other platforms as well.

[10] No information on the beginning of the IoT Factory platform

[11] Not including libraries for devices

6.1.8 Rating

The reliability rating of all platforms is shown in Table 6.2. “R+A” represents replication and availability, “A+A” is for authentication and authorization, “ENC” stands for encryption (both message and storage), “SEC” shows the security history and market longevity is rated in the “LON” column.

There are two platforms with full 5.0 stars (Google IoT Cloud and IBM Watson IoT), while the lowest achieved rating is 1.0 star (“IoT Only” IoT Factory Software Platform, and “Others” Mosaic Things, PTC ThingWorx and Zebra Zatar). However, this low rating is mostly due to incomplete information on most topics for these four platforms. “Big Player” platforms received the highest average with 3.54 stars, while the “Others” platforms are the lowest rated group with 2.17 stars on average which is also due to the little information available for some platforms in this group. Smartworks, Pelion, WebNMS (3.0 stars) and especially Cumulocity (3.5 stars) still received above average (2.7 stars) ratings despite being in the lowest rated group. The overall average for reliability is at 2.69 stars.

Table 6.2: The reliability rating of all platforms for the criteria: replication and availability (R+A), authentication and authorization (A+A), encryption (ENC), security incidents and audits (SEC) and market longevity (LON)

Platform	**R+A**	**A+A**	**ENC**	**SEC**	**LON**	**Total**
Samsung ARTIK	⯪	⯪	⯪	⯪	⯪	2.5
Samsung SmartThings	☆	⯪	⯪	★	★	3.0
AWS IoT Core	⯪	★	★	⯪	⯪	3.0
GE Predix	⯪	★	⯪	⯪	⯪	3.0
Google IoT Cloud	★	★	★	★	★	5.0
Siemens MindSphere	⯪	★	⯪	⯪	★	3.5
Azure IoT Hub	★	⯪	★	⯪	★	4.0
Bosch IoT Suite	⯪	★	⯪	⯪	★	3.5
IBM Watson IoT	★	★	★	★	★	5.0
Cisco Kinetic	⯪	★	⯪	⯪	⯪	3.0
Alibaba IoT Cloud	⯪	★	★	⯪	⯪	3.5
Oracle IoT Platform	⯪	⯪	★	⯪	★	3.5
HPE IoT	⯪	★	⯪	⯪	⯪	3.0
Big Players Overall	0.58	0.85	0.73	0.62	0.77	**3.5**
Aeris IoT Platform	⯪	⯪	⯪	⯪	⯪	2.5
Ayla Networks IoT Platform	☆	★	⯪	★	⯪	3.0
Davra IoT Platform	☆	★	⯪	⯪	⯪	2.5
IoT Software Platform	☆	⯪	☆	⯪	☆	1.0
Kaa Enterpise IoT	★	☆	☆	⯪	⯪	2.0
Losant Platform	⯪	★	★	⯪	⯪	3.5
Particle Cloud	⯪	⯪	⯪	⯪	⯪	2.5
Tago.io	★	★	⯪	⯪	⯪	3.5
thinger.io	☆	⯪	⯪	⯪	⯪	2.0

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Table 6.2 – continued from previous page

Platform	R+A	A+A	ENC	SEC	LON	Total
Ubidots Platform	★	★	⯪	⯪	⯪	3.5
Yodiwo Platform	☆	⯪	⯪	⯪	⯪	2.0
IoT Only Overall	0.41	0.68	0.45	0.55	0.45	**2.55**
Blynk	⯪	⯪	⯪	⯪	⯪	2.0
DeviceHive	☆	★	⯪	⯪	⯪	2.0
DSA	☆	★	⯪	⯪	⯪	2.0
FIWARE	☆	★	☆	⯪	⯪	1.5
OpenMTC	☆	⯪	⯪	⯪	⯪	1.5
SiteWhere Platform	⯪	★	⯪	⯪	⯪	2.5
thingsboard.io	⯪	⯪	⯪	⯪	⯪	2.0
WSo2 Server	⯪	★	⯪	⯪	⯪	2.5
Zetta	☆	☆	⯪	⯪	⯪	1.0
Open Source Overall	0.22	0.72	0.44	0.50	0.50	**1.89**
Actility ThingPark	⯪	⯪	☆	⯪	⯪	2.0
AT&T M2X	☆	★	⯪	⯪	★	3.0
Deutsche Telekom Cloud der Dinge	⯪	★	★	⯪	⯪	3.5
Telit IoT Portal	★	★	⯪	⯪	★	4.0
Verizon ThingSpace	☆	★	☆	⯪	⯪	2.0
Telecoms Overall	0.40	0.90	0.40	0.50	0.70	**2.90**
Altair Smartworks	⯪	⯪	★	⯪	⯪	3.0
ARM Pelion IoT Platfom	⯪	⯪	★	⯪	⯪	3.0
Cumulocity IoT	⯪	★	⯪	★	⯪	3.5
WebNMS IoT Platform	⯪	★	⯪	⯪	⯪	3.0
LTI Mosaic Things	☆	☆	☆	⯪	⯪	1.0
Mathworks ThingSpeak	☆	⯪	⯪	⯪	⯪	2.0
PTC ThingWorx	☆	☆	☆	⯪	⯪	1.0
Wolfram Data Drop	☆	⯪	⯪	⯪	⯪	2.0
Zebra Zatar	☆	☆	☆	⯪	⯪	1.0
Others Overall	0.22	0.44	0.44	0.56	0.50	**2.17**
Bacsoft IoT Platform	⯪	⯪	⯪	⯪	☆	2.0
Huawei OceanConnect IoT Platform	★	⯪	⯪	⯪	☆	2.5
Macchina.io	⯪	⯪	⯪	⯪	☆	2.0
Mainflux	☆	★	★	⯪	☆	2.5
Mozilla WebThings	☆	⯪	⯪	⯪	⯪	2.0
RugDS	☆	⯪	⯪	⯪	☆	1.5
Temboo Kosmos	★	⯪	★	⯪	☆	3.0
Prototypes Overall	0.43	0.57	0.64	0.50	0.07	**2.21**
Platforms Overall	0.39	0.69	0.54	0.55	0.52	**2.69**

6.2 Scalability

In the following section all the platforms are analyzed in terms of scalability. The topics to be reviewed are explained in Section 4.2.

6.2.1 Hosting

Samsung, AWS, Google, Azure, IBM, Bosch and Alibaba are running their platforms in their respective own cloud hosting solutions with no indication to using a private cloud. GE, Cisco and Oracle explicitly state to have their platforms run on a public cloud environment [84, 176, 313], but GE also offers the possibility of an on premise deployment [172]. HPE's platform can be deployed on-premise or in any cloud environment [201]. Siemens is running the MindSphere on an AWS, Azure or Alibaba hosted cloud [67, 359].

Ayla Networks and Davra are running their platforms on cloud solutions hosted by companies like AWS or Google, Davra additionally supports an on premise deployment [74, 143]. IoT Factory, Losant and Yodiwo offer hosting in their cloud or an on premise deployment [231, 260, 463]. The platform of Kaa Technologies is running in either a private, public or even hybrid cloud environment [250]. Particle, Tago, Thinger and Ubidots all use a cloud environment with no indication that a private cloud hosting could be possible as well [321, 382, 420, 429].

The Blynk cloud can be hosted anywhere users want to deploy it. This can be locally or on premise, in a private or public cloud [88]. DeviceHive, FIWARE, OpenMTC and Zetta have to be hosted by users themselves as well. SiteWhere's platform is deployed with Kubernetes which can be run on premise or at "almost any cloud provider" [366]. ThingsBoard and WSo2 can be deployed on premise or in any cloud as well [422, 458], WSo2 additionally supports a hybrid setup [455].

AT&T is running the M2X platform in the Azure cloud environment since August 2018 [62]. Deutsche Telekom is using their own infrastructure to host its platform with no indication whether it is a private or public cloud setup [373]. Telit offers private cloud, public cloud and on premise hosting for its platform [397]. Actility and Verizon do not offer information on their hosting solutions.

Altair Smartworks, Cumulocity and Wolfram Data Drop are offered as public and private cloud hosting solutions [193, 371, 446]. Mosaic, Pelion and ThingWorx are running on premise, in private or public clouds [255]. Pelion and ThingWorx additionally support hybrid cloud environments [51, 333, 350]. WebNMS is hosted on Azure or AWS, but can be self-hosted as well [475].

The Bacsoft platform is running in a private or public cloud environment [81], Huawei uses a hybrid cloud setup [248]. Mainflux can be deployed on premise, in a hybrid or public cloud [264]. Macchina, Mozilla and RugDS offer no hosted solution and have to be hosted by the users in the environment of their choice.

6.2.2 Limits of the Infrastructure and Software

Unfortunately, most platform providers do not mention limits of their software. However, many providers include programmed limits in their platform to avoid spamming. Often this limit is set higher or even removed for upper payment tiers.

Many big and global companies usually have their own, big data centers which they use for all of their services like the IoT platforms. For these providers, computing power, memory and disk storage is nearly unlimited and they usually have data centers all over the globe to ensure rapid communication and low latency. Most providers have offers that users only pay for the power and traffic they actually use (pay-as-you-go), sometimes there are all-inclusive offers for larger companies. Some providers additionally put software limits (for example for the message throughput) in their platform, presumably to avoid spam attacks, however users often can request higher limits. AWS is able to handle “billions of devices” and Google’s default limit allows 100,000 devices per project and region. Millions of simultaneously connected devices and millions of events are possible per second on Azure’s platform. Watson does not limit the amount of devices, but the allowed device connections per second are limited to ten. Alibaba is able to handle connections for hundreds of millions of devices overall and millions of devices at the same time [19, 35, 189, 219, 278, 313, 339, 367]. The Siemens Mindsphere platform is running on an AWS, Azure or Alibaba Cloud infrastructure [356]. As previously mentioned, Bosch offers hosting on AWS infrastructure, in the Bosch IoT Cloud or on-premise. For its own cloud, there is no technical information on scalability available.

In the “IoT only” class, most companies use third party infrastructure to provide scalability. Therefore, little to no technical information is available. Aeris Communications promises “a highly scalable and secure environment” [9], whereas the Kaa Enterprise IoT Platform “provides elastic scalability and mission-critical resilience for your IoT device ecosystems” [250]. Particle Cloud is able to “scale infinitely”, but limits API calls to ten per second per public Internet Protocol (IP) address [324]. Tago states that its databases are in the United States, and other continents are only possible upon request. These database are called buckets in [377] and [375] which indicates the use of a Key Value Store NoSQL database. The API changelog however only mentions MongoDB and AWS Aurora [378]. The Tago.io platform runs in its cloud[12], but an on-premise installation is not yet possible [382]. Thinger.io hosts a “ready to use scalable cloud infrastructure” [420] for its platform, unless users want to deploy the server application on their own via its provided Docker container. The platforms of Davra and Kaa Technologies run in a public, private or hybrid cloud, the solutions of IoT Factory, The Losant platform and Particle Cloud are deployed on-premise or as Software as a Service (SaaS) solution. Public cloud usually refers to the infrastructure of another provider, most likely provided by one of the “Big Players” companies, although this is not mentioned by most platform providers [143, 250, 260, 324].

However none of these providers mentioned a message throughput or node limit, Aeris Communications states that its platform is “managing a total of more than one billion IoT events per day” [9], Thinger.io’s infrastructure can scale up to connecting millions of devices [420] and Ubidots notes that it “optimized [the platform] to receive, compute, and return millions of data points each second across the globe” [429]. Ubidots Platform is also promised to “scale from one device to

[12]There is no information, if Tago hosts own data centers or uses third party infrastructure

1,000s with confidence" [429], Particle Cloud "to millionth shipped unit" [323], Aeris IoT Platform will "seamlessly scale up to millions of devices" [9], Losant Platform's scalability "has been proven with tens of millions of devices and thousands of payloads per second" [260].

Unless users are using Blynk or WSo2, they have to host the open source platforms on their own cloud and therefore have to provide a scaling infrastructure. Blynk limits requests to its API to 100 per minute per device to avoid flooding [86] and allows up to 15,000 devices in its top tier pricing model. The database storage is also limited depending on the pricing tier up to one terabyte [88]. WSo2 does not mention any limit of its platform.

None of the telecom companies provides any information on computing hardware. Also, all of them use some kind of database, Deutsche Telekom even mentions its "Data Lake" [372] but without giving any technical details.

However, they provide some information on the message throughput. AT&T allows 50 requests per second per API key and ten request per second per device altering any resources [63]. Telit state a limit of 100 API calls per second by default [400]. Actility promises "sub-second response time" while not mentioning any limitations and being able to scale up to "millions of endpoints" [3], Telit is able to "scale to any size system" [396].

Altair, ARM, Cumulocity and WebNMS use external infrastructure like AWS to host their platforms and therefore do not provide information on the limits of their infrastructure. Altair's Smartworks platform "scale[s] up to millions of devices" [27, 193], the Pelion platform is even "capable of managing any number or type of devices" [350]. Smartworks limits requests to 1,000 per day unless the platform is hosted on-premise [193], Pelion "processes over 30 trillion records per day" [51]. ThingSpeak and Data Drop limit the available computing power (no numbers) and message throughput (one update every 15 or one second for ThingSpeak, 60 or 3,600 messages per hour for Data Drop) depending on the usage of the free or paid model [411, 446].

Out of the prototype platforms, Bacsoft and Huawei have their own infrastructure [81, 248]. Bacsoft's gateway device "B-Connect is [...] highly scalable for up to thousands of devices" and the providers promises that "each deployment scales to support thousands of connected remote devices and users" [81]. Huawei promises that the gateway modules of its platform can manage "up to a million devices in the cloud" [12] "mass connections for up to 100 million devices based on flexible capacity expansion, distributed design, and microservices" [209, 248]. Macchina's server instances can "easily handle many thousands of devices" [48]. Mainflux is "deployable from multi-datacenter scale to RPi class devices" [264]. Temboo states that "every component [is] designed not only to scale with demand but to do so independently from other components" but does not offer information on the underlying infrastructure or its limits [408].

6.2.3 Edge and Fog Computing

AWS offers Edge Computing via AWS IoT Greengrass and AWS Lambda@Edge [39] and GE provides Predix Edge which can even do machine learning operations on the edge [175]. Google[13], Microsoft, Oracle and HPE also have their edge solutions [188, 278, 312, 330], whereas Cisco additionally enables Fog Computing [114]. Siemens provides MindConnect Edge Services which

[13] Also able to do machine learning at the edge

can be run on devices as well as gateways thus enabling both Edge and Fog Computing [359, 360]. Bosch only offers computing on the gateways with the IoT Gateway Software [91]. IBM's Watson only offers a limited preview of its edge component [224]. Samsung and Alibaba do not offer Edge Computing solutions for their platforms.

Aeris Communications, Ayla Networks, Davra, Kaa Technologies and Yodiwo offer Edge Computing solutions, Losant additionally offers Fog Computing on its gateways. Particle pursued a Raspberry Pi Edge Computing project which was later discontinued, Thinger.io and Ubidots do not support Edge Computing at all [11, 72, 143, 250, 259, 324].

Out of the open source platforms, only FIWARE (FogFlow [162]) and WSo2 ("powered by the WSo2 Complex Event Processor (CEP) streaming engine" [460]) offer a solution for Edge Computing.

None of the telecommunication companies provide a solution for Edge Computing for their platforms.

Smartworks can outsource operations to the edge using Altair SmartEdge [25], ARM offers Device Management Edge [51]. Cumulocity IoT Edge and WebNMS EdgeX probably can be used for Fog Computing as well [133, 470].

Huawei already released an Edge Computing solution called EC-IoT ahead of the OceanConnect platform in 2015 [12], Macchina.io offers an SDK for Edge Computing [43, 45]. Being contributing member of the EdgeX Foundry project [267], Mainflux is assumed to be compatible with this Edge Computing solution. Temboo implemented edge intelligence and an offline storage functionality for devices who lost connection to the cloud [409].

6.2.4 Network and Load Balancing

Except for Google that has its own high speed network, the bottleneck in performance usually is the network at the user's side. Some platform providers offer a solution for load balancing, but it is usually not enabled by default. Enabling or integration a load balancer might cause additional costs [35, 189, 219, 278, 313, 339, 367]. Azure IoT Hub offers a load balancing solution and a tutorial on how to enable and use it [285]. Alibaba offers a load balancer service for its cloud [15], but not explicitly for the IoT product. Siemens and Bosch might offer load balancing via their hosting provider[14], but no own solution.

Out of the "IoT only" companies, "with more than 480 partners across 190 countries, Aeris Communications provides unmatched global coverage" and "the Aeris solution has a scalable and flexible global architecture providing regional autonomy (think regional rules, currency, compliance)" [8]. Load balancing is mentioned by none of the providers.

The only "Open Source" platform indicating to use load balancing on its own is SiteWhere. This platform uses Kubernetes to manage all running microservices [363]. ThingsBoard recommends using HAProxy for load balancing, but does not restrict users to this single option [422].

[14] AWS for both, Azure and Alibaba Cloud for Siemens

For the telecommunication companies and their platforms, the network is obviously the key part of the product. Actility scores with its global network alliance [78], AT&T's M2X is backed by its established network infrastructure [62] and Deutsche Telekom advertised its network as "the best network" in Germany for years [391]. Verizon states to connect 170 countries with its network [440]. A load balancing solution is mentioned by none of them.

As Cumulocity is using Kubernetes for its deployment, they might use it for load balancing as well [137].

Huawei implemented load balancing on both device-side and application-side of its cloud [209]. Macchina can be setup with a load balancer to "reliably handle a very large number of simultaneously connected devices and user sessions" [45], Mainflux includes such a solution as well [266]. Temboo indicates the usage of a load balancing module with its autoscaling architecture [408].

6.2.5 Rating

The scalability rating of all platforms is shown in Table 6.3. "HOST" and "OWN" represent the hosting possibility and whether the used infrastructure is owned by the respective platform provider. "EDGE" symbolizes the availability of an Edge and/or Fog Computing solution. "NOD" and "MSG" represent limits for the maximum amount of nodes and the highest possible messaging throughput respectively. There are a lot of 0.0 star ratings, notably in the "IoT Only", "Open Source", "Others" and "Prototype" groups. Especially the "OWN" column shows a big difference between groups: only "Big Players", "Telecoms" platforms and most notably Huawei ("Prototype" group, but also a Fortune 500 company) own the infrastructure they host their platforms on. The other platforms - if a cloud deployment is possible - use a third party cloud solution. The high amount of 0.0 star ratings in the node and messaging limit columns are justified by the low amount of information on limits given by the platform providers.

AWS, Azure and Huawei received the highest rating with 4.0 stars, only scoring no star in the hosting (AWS and Azure) and message throughput (Huawei, no information available) respectively. Six platforms (Ayla Networks IoT Platform and Yodiwo Platform of "IoT Only", OpenMTC and Zetta of "Open Source", Zebra Zatar of "Others" and RugDS of "Prototypes") were given the lowest rating of 0.0 stars. This is once more justified by no available information on both limit criteria as well as only one hosting option and no Edge or Fog Computing solution. The highest rated group are the "Big Players" with 2.35 stars on average and each platform scoring with either own infrastructure, an Edge/Fog Computing solutions or both. The lowest rated group is the "Open Source" group (0.89) where most provider have users host the platform on the user's infrastructure and therefore not giving a limit for either nodes or messaging. The overall average is 1.48 stars.

Table 6.3: The scalability rating of all platforms for the criteria: hosting options (HOST), provider-owned infrastructure (OWN), Edge/Fog Computing (EDGE), limits for nodes (NOD) and message throughput (MSG)

Platform	HOST	OWN	EDGE	NOD	MSG	Total
Samsung ARTIK	☆	★	☆	☆	⯪	1.5
Samsung SmartThings	☆	★	☆	☆	⯪	1.5

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Table 6.3 – continued from previous page

Platform	HOST	OWN	EDGE	NOD	MSG	Total
AWS IoT Core	☆	★	★	★	★	4.0
GE Predix	⯪	★	★	☆	☆	2.5
Google IoT Cloud	☆	★	★	☆	☆	2.0
Siemens MindSphere	☆	☆	★	☆	☆	1.0
Azure IoT Hub	☆	★	★	★	★	4.0
Bosch IoT Suite	⯪	☆	★	☆	☆	1.5
IBM Watson IoT	⯪	★	★	☆	★	3.5
Cisco Kinetic	☆	★	★	☆	☆	2.0
Alibaba IoT Cloud	☆	★	☆	★	★	3.0
Oracle IoT Platform	☆	★	★	☆	☆	2.0
HPE IoT	☆	★	★	☆	☆	2.0
Big Players Overall	0.12	0.85	0.77	0.23	0.38	**2.35**
Aeris IoT Platform	☆	☆	★	★	★	3.0
Ayla Networks IoT Platform	☆	☆	☆	☆	☆	0.0
Davra IoT Platform	⯪	☆	★	☆	☆	1.5
IoT Software Platform	⯪	☆	☆	☆	☆	0.5
Kaa Enterprise IoT	★	☆	★	☆	☆	2.0
Losant Platform	⯪	☆	☆	★	★	2.5
Particle Cloud	⯪	☆	☆	★	⯪	2.0
Tago.io	☆	☆	☆	☆	★	1.0
thinger.io	☆	☆	☆	★	☆	1.0
Ubidots Platform	☆	☆	☆	⯪	⯪	1.0
Yodiwo Platform	☆	☆	☆	☆	☆	0.0
IoT Only Overall	0.27	0.00	0.27	0.41	0.36	**1.32**
Blynk	⯪	☆	☆	⯪	⯪	1.5
DeviceHive	⯪	☆	☆	☆	☆	0.5
DSA	⯪	☆	☆	☆	☆	0.5
FIWARE	☆	☆	★	☆	★	2.0
OpenMTC	☆	☆	☆	☆	☆	0.0
SiteWhere Platform	⯪	☆	☆	☆	☆	0.5
thingsboard.io	⯪	☆	☆	★	☆	1.5
WSo2 Server	⯪	☆	★	☆	☆	1.5
Zetta	☆	☆	☆	☆	☆	0.0
Open Source Overall	0.33	0.00	0.22	0.17	0.17	**0.89**
Actility ThingPark	☆	★	☆	★	☆	2.0
AT&T M2X	☆	★	☆	★	⯪	2.5
Deutsche Telekom Cloud der Dinge	☆	★	☆	☆	☆	1.0
Telit IoT Portal	⯪	★	☆	☆	☆	1.5
Verizon ThingSpace	☆	★	☆	☆	☆	1.0
Telecoms Overall	0.10	1.00	0.00	0.40	0.10	**1.60**

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Table 6.3 – continued from previous page

Platform	HOST	OWN	EDGE	NOD	MSG	Total
Altair Smartworks	⯪	☆	★	★	☆	2.5
ARM Pelion IoT Platfom	★	☆	☆	☆	☆	1.0
Cumulocity IoT	⯪	☆	★	☆	☆	1.5
WebNMS IoT Platform	⯪	☆	★	☆	☆	1.5
LTI Mosaic Things	⯪	☆	☆	☆	☆	0.5
Mathworks ThingSpeak	⯪	☆	☆	☆	⯪	1.0
PTC ThingWorx	★	☆	☆	☆	☆	1.0
Wolfram Data Drop	⯪	☆	☆	☆	☆	0.5
Zebra Zatar	☆	☆	☆	☆	☆	0.0
Others Overall	0.56	0.00	0.33	0.11	0.06	**1.06**
Bacsoft IoT Platform	⯪	☆	☆	⯪	☆	1.0
Huawei OceanConnect IoT Platform	★	★	★	★	☆	4.0
Macchina.io	☆	☆	★	☆	☆	1.0
Mainflux	★	☆	★	☆	☆	2.0
Mozilla WebThings	⯪	☆	☆	☆	☆	0.5
RugDS	☆	☆	☆	☆	☆	0.0
Temboo Kosmos	☆	☆	★	☆	☆	1.0
Prototypes Overall	0.43	0.14	0.57	0.21	0.00	**1.36**
Platforms Overall	0.30	0.34	0.42	0.25	0.21	**1.48**

6.3 Heterogeneity

In the following section all the platforms are analyzed in terms of heterogeneity. The topics to be reviewed are explained in Section 4.3.

6.3.1 Device Restrictions

Some "Big Players" companies have partnerships with hardware producers and recommend their products [33, 283, 341], others offer a certification program for either devices suited for edge computing [281] or a certification of applications [344]. Siemens and Bosch even list some of their own devices to be used with their platform [95, 360]. None of the providers names hardware or software that will not work, they only state operating systems and programming languages they tested, some even encourage users to program their own software to connect devices to their platform. Tested operating systems included versions of Windows and Windows Server, Linux distributions like Red Hat Enterprise Linux, CentOS, Debian and Ubuntu as well as MacOS [35, 91, 189, 219, 278, 313, 339, 367].

In the "IoT only" class there are also no named exceptions of hardware which are not supported. Losant, Particle and Ubidots have a list of supported devices on their websites [259, 324, 432], Thinger.io additionally runs a shop selling its own hardware [420]. Kaa Technologies offers an "Integration Package" which includes the verification if the hardware is supported or not [250].

Ayla Networks only offers an SDK in the form of a white-labeled application for Android and iOS [74] and Particle provides its own device firmware “Device OS” for things [320], whereas the other platforms do not exclude any operating system on both sides.

The open source platforms do not restrict devices or applications to any specific hardware or programming languages. Blynk offers a list of over 400 devices that are supported, but it is possible to “add your own connection types easily” [89]. DeviceHive and SiteWhere need container support to be deployed [149, 365], OpenMTC recommends Docker for the deployment of the gateway [305]. The only other restriction for the open source platforms is that users need a server running Java to be able to host WSo2’s platform [459]. Apart from this any combination of hardware and operating system can be used as a device for or to host one of the open source platforms.

“Telecom” platform ThingPark is “totally agnostic from device” [77]. AT&T (Android, Arduino, Beagle Bone, iOS and more [63]) and Telit (Siemens, Mitsubishi and more Programmable Logic Controllers (PLCs) [397]) list some supported devices, Deutsche Telekom certifies devices [373]. Telit states to have the “broadest library of pre-built device drivers” [397]. “Anything that can establish a TCP/IP connection on the Internet” can connect to ThingSpace [103].

The last platforms group also does not restrict, but recommend tested devices. Smartworks is tested on devices like Arduino, Raspberry Pi and Beagle Bone [193], Thingspeak recommend Arduino, Particle or Raspberry Pi [413]. Pelion does not mention any restriction or requirement, WebNMS requires 50 MB memory and up to 50 MB disk space [470]. Cumulocity states to have “150+ pre-integrated devices” [132], Data Drop’s lists 4,359 compatible devices in its connected devices project [448]. Pelion has its own operating systems for devices in Mbed Linux OS and Mbed OS, but Arduino or any other Real-Time Operating System (RTOS) or Linux distribution can be used as well [53] and WebNMS can run both devices and the server on Linux or Windows or other operating systems when using its C or Python SDK for a basic integration [469, 470]. The other platforms do not restrict or recommend any operating system.

Huawei developed its own IoT chipset called Boudica which is integrated in the Huawei LiteOS running on devices connecting to the platform [12]. Macchina’s server is running on Linux and macOS and it is based on the POCO C++ libraries and the JavaScript V8 Engine. The Edge SDK is running on Linux-based devices and is hardware independent [43, 45]. Mainflux is device agnostic as well since the server is deployed as Docker container and orchestrated with Kubernetes [264]. Mozilla lists lots of compatible hardware for devices and gateways as well as protocols available as adapters on its GitHub wiki, and is adding support for new adapters “all the time” [294]. The proposal states Mozilla’s platform to be hardware and transport agnostic [291]. The RugDS platform is deployed on a Kernel-based Virtual Machine (KVM)-based hypervisor running Virtual Machines (VMs) which run Docker containers [353], for devices there is no restriction mentioned. Temboo published “hardware independent software libraries designed to work on any embedded chipsets” [410] and maintains partnerships with hardware producers Texas Instruments, Samsung and Arduino to further extend the list of compatible hardware [404, 407].

6.3.2 Programming Languages

Many platform providers offer pre-built libraries also called SDKs for different programming languages. Representational State Transfer (REST) APIs can be consumed by many programming languages, however there is not an SDK provided for every of these languages for every platform. If a language is not provided, developers can usually write their own library assuming the chosen language is able to consume one of the available APIs.

Common modern programming languages like C, C++, Embedded C, Java, JavaScript, node.js and Python are supported by most of the providers, some include C# and .NET (Google, Microsoft, IBM), Swift and/or Objective-C (Samsung ARTIK, Alibaba), Android (Samsung ARTIK, Alibaba and Oracle), PHP and Ruby (Microsoft). Samsung SmartThings currently only supports Groovy, but might offer more languages in the future. Siemens and Bosch only provide Java SDKs [17, 19, 35, 91, 189, 219, 278, 313, 339, 356, 367].

Ayla Networks only provides SDKs for mobile (native for Android and iOS) and web applications, Davra's platform offers customizable connectors but no SDK and Particle Cloud only supports JavaScript. Tago provides a node.js SDK, allows node.js, Python and Java script executing on its servers and states that code scripts in any language are possible running on any computer [377, 380, 384]. Yodiwo is the only platform to explicitly offer a SDK for an embedded environment (in C). Ubidots offers multiple SDKs on its own, while there also exist over 200 user-proven libraries to use [76, 144, 145, 262, 324, 419, 429, 433, 462]. Aeris Communications, IoT Factory and Kaa Technologies either do not provide information about SDKs or offer no SDKs at all.

While OpenMTC (Python [307, 308]), ThingsBoard (Arduino [423]), WSo2 (none) and Zetta (JavaScript [466]) have published only one or even no offical SDK, Blynk, DeviceHive and DSA offer SDKs for multiple languages [89, 149, 151]. SiteWhere supports mobile applications [365]. For FIWARE, there is no information public on any SDK.

Actility (none), Deutsche Telekom (Java [392]) and Telit (Java and C [400]) do not provide many SDKs. AT&T on the other hand published SDKs for a lot of different programming languages [63]. Verizon offers an open source SDK in C on GitHub and SDKs for Android, iOS, Java, JavaScript, node.js, PHP, Python and Ruby in its documentation. The description on GitHub indicates that the C module is used to integrate devices whereas the other libraries are used to develop applications [438, 441].

There are very few official SDKs for the "Other" platforms available. Java, C, C++, C# and Python are the most supported languages with just two platforms each [51, 54, 131, 135, 414, 470]. Smartworks supports just Groovy [27, 193], Data Drop has not even published a single official SDK, the only available one for Squirrel is made by Electric Imp [156]. Mosaic Things states to have "various SDKs" [255] which might just not be public, ThingWorx and Zatar do not provide any information on SDKs.

The most supported languages are C++ and Python, but there might be more SDKs developed until the first release of the respective platforms. Mozilla also mentions community-made libraries without naming the programming languages they are developed for. Overall, most of the supported languages are just offered for one or two platforms [43, 150, 210, 266, 267, 290, 296, 406].

Table 6.4 shows an overview of all supported SDKs for each platform. The column of C also includes Embedded C and C POSIX and C++ included mBed C++. The Android and iOS columns represent the native languages Java and Objective-C/Swift respectively. A ✓ shows that an official SDK is available for the respective programming language, an "r" means the SDK is planned or in the roadmap. A "p" means the implementation is already in progress and SDKs in programming languages marked with "c" are community-made. Question marks indicate that there is no information on SDKs or supported languages at all for this platform. If a language is not available as SDK for a platform at all, the cell is marked with a ''-".

Table 6.4: Overview of provided SDKs for all platforms

Platform	**Java**	**Javacript**	**node.js**	**C**	**C++**	**C#**	**Go**	**PHP**	**Ruby**	**Python**	**Android**	**iOS**	**Other**
Big players													
Samsung ARTIK	✓	✓	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓[15]
Samsung SmartThings	-	r	-	-	-	-	-	-	r	r	-	-	✓[16]
AWS IoT Core	✓	✓	-	✓	✓	✓	-	-	-	✓	-	-	✓[17]
GE Predix	-	-	-	-	-	-	-	-	-	-	-	✓	-
Google IoT Cloud	✓	-	✓	-	-	✓	✓	-	✓	✓	-	-	-
Siemens MindSphere	✓	-	-	-	-	-	-	-	-	-	-	-	-
Azure IoT Hub	✓	-	✓	✓	-	✓	-	-	-	✓	-	-	✓[18]
Bosch IoT Suite	✓	-	-	-	-	-	-	-	-	-	-	-	-
IBM Watson IoT	✓	✓	✓	✓	✓	✓	-	-	-	✓	-	-	-
Cisco Kinetic	✓	-	-	✓	✓	✓	-	-	✓	✓	-	-	✓[19]
Alibaba IoT Cloud	✓	-	✓	✓	-	-	-	-	-	✓	✓	✓	-
Oracle IoT Platform	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-
HPE IoT	?	?	?	?	?	?	?	?	?	?	?	?	?
IoT Only													
Aeris IoT Platform	?	?	?	?	?	?	?	?	?	?	?	?	?
Ayla Networks IoT Platform	-	✓	-	-	-	-	-	-	-	-	✓	✓	-
Davra IoT Platform	-	-	-	-	-	-	-	-	-	-	-	-	-
IoT Software Platform	?	?	?	?	?	?	?	?	?	?	?	?	?
Kaa Enterprise IoT	?	?	?	?	?	?	?	?	?	?	?	?	?
Losant Platform	-	✓	-	-	-	-	-	-	✓	✓	-	-	✓[20]
Particle Cloud	-	✓	-	-	-	-	-	-	-	-	✓	✓	[21]

Continued on next page

[15] ARTIK supports Tizen
[16] SmartThings supports Groovy and has planned to release a Clojure SDK
[17] AWS supports Arduino
[18] Azure supports .NET and more
[19] Cisco supports Dart and Scala
[20] Losant provides an SDK for Arduino
[21] Particle once had SDKs for Raspberry Pi and Windows, but the projects were discontinued

Table 6.4 – continued from previous page

Platform	**Java**	**Javacript**	**node.js**	**C**	**C++**	**C#**	**Go**	**PHP**	**Ruby**	**Python**	**Android**	**iOS**	**Other**
Tago.io	✓	-	✓	-	-	-	-	-	-	✓	-	-	-
thinger.io	-	✓	-	-	✓	-	-	-	-	-	✓	-	✓[22]
Ubidots Platform	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	-	-	✓[23]
Yodiwo Platform	-	✓	-	✓	-	-	-	-	-	-	✓	✓	-
Open Source													
Blynk	-	-	✓	-	✓	✓	-	-	-	✓	-	-	✓[24]
DeviceHive	✓	✓	-	-	✓	✓	✓	-	-	✓	✓	✓	-
DSA	✓	✓	-	-	-	-	✓	-	✓	-	-	✓	✓[25]
FIWARE	?	?	?	?	?	?	?	?	?	?	?	?	?
OpenMTC	-	-	-	-	-	-	-	-	-	✓	-	-	-
SiteWhere Platform	-	-	-	-	-	-	-	-	-	-	✓	✓	-
thingsboard.io	-	-	-	-	-	-	-	-	-	-	-	-	✓[26]
WSo2 Server	-	-	-	-	-	-	-	-	-	-	-	-	-
Zetta	-	✓	-	-	-	-	-	-	-	-	-	-	-
Telecoms													
Actility ThingPark	-	-	-	-	-	-	-	-	-	-	-	-	-
AT&T M2X	✓	✓	✓	✓	✓	✓	c	-	✓	✓	✓	✓	✓[27]
Dt. Tel. Cloud der Dinge	✓	-	-	-	-	-	-	-	-	-	-	-	-
Telit IoT Portal	✓	-	-	✓	-	-	-	-	-	-	-	-	-
Verizon ThingSpace	✓	✓	✓	✓	-	-	-	✓	✓	✓	✓	✓	-
Others													
Altair Smartworks	-	-	-	-	-	-	-	-	-	-	-	-	✓[28]
ARM Pelion IoT Platfom	✓	✓	-	-	-	✓	-	-	-	✓	-	-	-
Cumulocity IoT	✓	-	-	✓	✓	✓	-	-	-	-	-	-	✓[29]
WebNMS IoT Platform	-	-	-	✓	-	-	-	-	-	✓	-	-	-
LTI Mosaic Things	?	?	?	?	?	?	?	?	?	?	?	?	?
Mathworks ThingSpeak	-	-	-	-	✓	-	-	-	-	-	-	-	✓[30]
PTC ThingWorx	?	?	?	?	?	?	?	?	?	?	?	?	?

Continued on next page

[22] Thinger.io offers libraries for Arduino and node-RED

[23] Ubidots provides libraries for Arduino, Lua, node-RED, some specific devices or device types, and over 200 user-proven libraries

[24] Blynk offers support for Browsers, Espruino, LabVIEW, Lua, MicroPython, MBED, NodeMCU, Node-RED, OpenWRT and Particle

[25] DSA supports Dart, .NET, Scala, TypeScript, Apache Spark and HoloLens

[26] ThingsBoard supports Arduino

[27] AT&T supports Elixir, Erlang, Groovy, mruby, node-RED, Squirrel and has a community glssdk for Cylon

[28] Smartworks supports Groovy

[29] Cumulocity supports Lua

[30] ThingSpeak supports Arduino

Table 6.4 – continued from previous page

Platform	**Java**	**Javacript**	**node.js**	**C**	**C++**	**C#**	**Go**	**PHP**	**Ruby**	**Python**	**Android**	**iOS**	**Other**
Wolfram Data Drop	-	-	-	-	-	-	-	-	-	-	-	-	c[31]
Zebra Zatar	?	?	?	?	?	?	?	?	?	?	?	?	?
Prototypes													
Bacsoft IoT Platform	-	-	-	-	-	-	-	-	-	-	-	-	-
Huawei OceanConnect	-	-	-	-	-	-	-	-	-	-	✓	✓	-
Macchina.io	-	✓	-	-	✓	-	-	-	-	-	-	-	-
Mainflux	-	✓	-	✓	✓	-	✓	-	-	✓	-	-	-
Mozilla WebThings	✓	-	✓	-	✓	-	-	-	-	✓	-	-	✓[32]
RugDS	-	-	-	-	-	-	-	-	-	-	-	-	✓[33]
Temboo Kosmos	✓	-	✓	-	-	✓	-	✓	✓	✓	✓	✓	✓[34]

6.3.3 Accessibility

MQTT is supported by most of the “Big Player” platforms, Google and Microsoft specifically mention version 3.1.1. AMQP (Siemens, Azure, Bosch and Cisco), WebSockets (ARTIK, AWS, Siemens, Cisco) and Constrained Application Protocol (CoAP) (ARTIK, Siemens, Bosch, HPE) are only implemented for some platforms [16, 17, 19, 35, 84, 92, 176, 189, 200, 216, 278, 339, 356, 360]. Alibaba claims that the “Alibaba IoT platform can support over 95% of communication protocols” [14]. SmartThings and Oracle do not provide public information on the protocols used for their APIs.

HTTP(S) and (secure) MQTT are also the most supported protocol of the “IoT only” platforms. Some platforms additionally support TCP, UDP and/or Simple Object Access Protocol (SOAP), and Davra even offers the possibility to use AMQP, CoAP and Secure Copy Protocol (SCP) [9, 145, 231, 324, 374, 418, 429, 462].

DeviceHive, OpenMTC, ThingsBoard and WSo2 support HTTP and MQTT and also mention SSL/TLS support, so we assume they support the secured versions of these protocols as well. Overall, HTTP/HTTPS and (secure) MQTT are the most supported protocols in this group as well. WebSockets, TCP, CoAP and XMPP are supported by or are even just in development for only few platforms [86, 148, 155, 162, 363, 422, 459, 466].

The telecommunication providers also prefer HTTP(s) and (secure) MQTT as messaging protocols [4, 400, 438, 442]. AT&T additionally supports AMQP for applications and other services [63].

31 There is a community-made SDK for Squirrel
32 Mozilla supports Arduino, MicroPython and Rust
33 RugDS offers a Scala template
34 Temboo supports Processing

HTTP(S) and (secure) MQTT are the most supported messaging protocols int the “Others” group as well. TCP, UDP and AMQP are supported by just one (WebNMS), CoAP by three platforms (ARM Pelion, WebNMS and Zebra Zatar) [51, 245, 469]. Cumulocity Agents can be developed to translate or mediate any protocol [131]. ThingWorx states to have libraries with adapters for over 150 protocols [107], Mosaic Things mentions a “pre-built library of connectors” [255].

The most supported protocols for “Prototypes” are once again HTTPS and (secure) MQTT. AMQP (Mozilla WebThings and RugDS) and CoAP (Huawei and Mainflux) are supported by two platforms [46, 81, 150, 209, 266, 267, 290, 404, 409].

All of the platforms offer some kind of REST API. The following table (Table 6.5) shows an overview of supported messaging protocols for all platforms. The protocols included in the table are HTTP, HTTPS, TCP, UDP, FTP, MQTT, secure MQTT, AMQP, WebSockets, CoAP, SOAP and SCP. The last two columns display if additional protocols are supported and if users can use custom protocols with some kind of interface or mediation. Analogous to the SDK table, a ✓ shows that a protocol is supported by a platform, an “r” means the SDK is planned or in the roadmap and a “p” means the implementation is already in progress. Question marks indicate that there is no information on supported messaging protocols at all for this platform. If a protocol is not supported for a platform at all, the cell is marked with ‘‘-”. HTTPS and secure MQTT is not explicitly mentioned for all platforms, but we assumed these protocols to be supported, if a platform supports the unsecured protocol (HTTP or MQTT) as well as TLS encryption. This is marked in the table as “(✓)”.

Table 6.5: Overview of supported messaging protocols for all platforms

Platform	**HTTP**	**HTTPS**	**MQTT**	**Secure MQTT**	**AMQP**	**WebSockets**	**CoAP**	**Other**	**custom**
Big Players									
Samsung ARTIK	-	-	✓	(✓)	-	-	✓	-	-
Samsung SmartThings	?	?	?	?	?	?	?	?	?
AWS IoT Core	✓	(✓)	✓	✓	-	✓	-	✓[35]	✓
GE Predix	-	-	✓	(✓)	-	-	-	✓[36]	✓
Google IoT Cloud	✓	(✓)	✓	(✓)	-	-	-	-	-
Siemens MindSphere	-	✓	✓	(✓)	✓	✓	✓	✓[37]	-
Azure IoT Hub	-	✓	✓	✓	✓	-	-	-	-
Bosch IoT Suite	-	✓	✓	(✓)	✓	-	✓	✓[38]	✓
IBM Watson IoT	✓	(✓)	✓	(✓)	-	-	-	-	-
Cisco Kinetic	-	-	✓	✓	✓	✓	-	✓[39]	✓

Continued on next page

[35]AWS supports (unnamed) “other industry-standard and custom protocols” [37]
[36]Predix supports OPC UA and Modbus TCP
[37]Siemens supports LWM2M, LoRaWAN, 6LowPan and others
[38]Bosch supports its own Bosch IoT Messaging Protocols
[39]Cisco supports Unix Domain Sockets

Table 6.5 – continued from previous page

Platform	**HTTP**	**HTTPS**	**MQTT**	**Secure MQTT**	**AMQP**	**WebSockets**	**CoAP**	**Other**	**custom**
Alibaba IoT Cloud	✓	✓	✓	(✓)	-	-	✓	✓	-
Oracle IoT Platform	?	?	?	?	?	?	?	?	?
HPE IoT	-	-	✓	?	-	-	✓	✓[40]	-
IoT Only									
Aeris IoT Platform	-	-	✓	?	-	-	✓	-	✓
Ayla Networks IoT Platform	?	?	?	?	?	?	?	?	?
Davra IoT Platform	✓	✓	✓	(✓)	✓	✓	✓	✓[41]	-
IoT Software Platform	-	✓	✓	?	-	-	-	✓[42]	-
Kaa Enterprise IoT	?	?	?	?	?	?	?	?	?
Losant Platform	-	-	✓	(✓)	-	-	-	✓[43]	-
Particle Cloud	-	✓	-	-	-	-	-	-	-
Tago.io	✓	✓	✓	(✓)	-	-	-	-	-
thinger.io	-	✓	-	-	-	-	-	-	-
Ubidots Platform	✓	✓	✓	(✓)	-	-	-	✓[44]	-
Yodiwo Platform	-	✓	✓	(✓)	✓	-	-	-	-
Open Source									
Blynk	-	✓	-	-	-	-	-	-	-
DeviceHive	✓	(✓)	✓	(✓)	-	✓	p	-	-
DSA	✓	?	-	-	-	✓	-	-	-
FIWARE	✓	?	✓	?	-	-	-	✓[45]	✓[46]
OpenMTC	✓	✓	✓	(✓)	-	-	-	-	-
SiteWhere Platform	✓	?	✓	(✓)	-	-	-	-	-
thingsboard.io	✓	(✓)	✓	(✓)	-	-	✓	-	✓
WSo2 Server	✓	(✓)	✓	?	-	✓	-	✓[47]	-
Zetta	✓	?	-	-	-	-	-	-	✓[48]
Telecoms									
Actility ThingPark	✓	✓	-	-	-	-	-	-	-
AT&T M2X	✓	✓	✓	(✓)	✓	-	-	-	-

Continued on next page

[40]HPE supports Lightweight M2M (LWM2M)
[41]Davra supports UDP, SOAP and SCP
[42]IoT Factory supports TCP, FTP and SOAP
[43]Losant supports third party integrations
[44]Ubidots supports TCP and UDP
[45]FIWARE supports LWM2M/NGSI, OPC UA and Sigfox
[46]FIWARE supports the usage of own protocol libs
[47]WSo2 supports XMPP
[48]Zetta allows almost any other protocol and mediates it to HTTP

Table 6.5 – continued from previous page

Platform	**HTTP**	**HTTPS**	**MQTT**	**Secure MQTT**	**AMQP**	**WebSockets**	**CoAP**	**Other**	**custom**
Deutsche Telekom Cloud der Dinge	-	-	✓	(✓)	-	-	-	-	-
Telit IoT Portal	✓	✓	✓	(✓)	-	-	-	-	-
Verizon ThingSpace	-	✓	-	-	-	-	-	-	-
Others									
Altair Smartworks	✓	✓	✓	(✓)	-	-	-	-	-
ARM Pelion IoT Platfom	-	✓	-	-	-	-	✓	✓[49]	-
Cumulocity IoT	✓	✓	✓	(✓)	-	-	-	-	✓
WebNMS IoT Platform	-	✓	✓	(✓)	✓	-	✓	✓[50]	-
LTI Mosaic Things	?	?	?	?	?	?	?	?	?
Mathworks ThingSpeak	-	✓	✓	(✓)	-	-	-	-	-
PTC ThingWorx	?	?	?	?	?	?	?	✓[51]	-
Wolfram Data Drop	-	✓	-	-	-	-	-	-	-
Zebra Zatar	-	-	-	-	-	-	✓	✓[52]	-
Prototypes									
Bacsoft IoT Platform	-	-	-	-	-	-	-	✓[53]	-
Huawei OceanConnect IoT Platform	-	✓	-	✓	-	-	✓	✓[54]	-
Macchina.io	✓	✓	✓	✓	-	✓	-	✓[55]	-
Mainflux	✓	(✓)	✓	(✓)	-	-	✓	-	-
Mozilla WebThings	-	-	✓	(✓)	✓	-	-	-	-
RugDS	✓	-	-	-	✓	-	-	-	-
Temboo Kosmos	✓	(✓)	✓	(✓)	-	-	-	-	-

Many platforms additionally support device-specific protocols. These protocols can be used for connections to local gateways or hubs.

The Samsung ARTIK 5, 7, and 10 series modules support Wi-Fi, Bluetooth, BLE, ZigBee and Thread to connect local devices [339], SmartThings allows device connection to Smart Hubs via ZigBee, Z-Wave and Local Area Network (LAN) [344, 367]. AWS supports ZigBee and BLE using a physical hub as well [36], devices using protocols “such as a ZigBee or Bluetooth device” can connect via gateway to the platforms of Google, Azure and Oracle [189, 276, 313]. IBM allows connections via “cellular, wifi, and Ethernet, as well as more specialized solutions such as

[49] Pelion supports OMA LWM2M
[50] WebNMS supports TCP and UDP
[51] ThingWorx offers libraries with over 150 protocol adapters
[52] Zatar supports LWM2M
[53] Bacsoft supports SOAP
[54] Huawei supports TCP and UDP
[55] Macchina supports UDP and SOAP

LPWAN, Bluetooth Low Energy (BLE), ZigBee, NFC, and RFID" [182]. Predix supports OPC UA, Modbus, Ethernet Global Data Protocol (EGD) and Industrial Gateway Server (IGS) [175, 176], Siemens provides connectivity via its own S7 protocol, OPC UA, Modbus and others [360]. Bosch provides "out-of-the-box support for predominant IoT protocols" like BLE, Digital Enhance Cordless Telecommunications Ultra Low Energy (DECT ULE), EEBus, Modbus, Open Network Video Interface Forum (ONVIF), ZigBee and Z-Wave [99].

Ayla Networks implemented a "phone-as-a-gateway capability" to allow the connection of local Bluetooth devices [70], IoT Factory allows the connection of its own Long Range Wide Area Network (LoRaWAN) sensors and is testing other sensors using protocols like Bluetooth, LoRaWAN and Sigfox [231]. Losant, Particle and Yodiwo implemented at least Bluetooth connections via gateway [259, 323, 462]. Tago allows devices to connect via Bluetooth, LoRaWAN, Sigfox, ZigBee and Z-Wave [381]. Davra offers support for Canbus, J1939, Modbus and profinet [144].

Bluetooth connections are supported by Blynk (beta, [88], DeviceHive ([148]) and FIWARE, FIWARE additionally supports ZigBee [163]. OpenMTC offers adapters for "Cul868(FS20) for Smart Building" and NGSI-9/NGSI-10 (FIWARE)" [305], ThingsBoard allows connections via Modbus, OPC UA and Sigfox [422].

Actility supports device connections via LoRaWAN, AT&T and Deutsche Telekom support Bluetooth [59, 253]. The other "Telecoms" platforms do not provide information on supported device protocols.

Altair SmartEdge promises to "automatically connects with devices from a wide variety of protocols" [28], including Sigfox [21], Radio Frequency (RF) and ZigBee [159]. Pelion supports Bluetooth and BLE, LoRaWAN, Low Power Wide Area Network (LPWAN), Near Field Communication (NFC), Radio Frequency Identification (RFID), Thread and ZigBee [51, 53]. Cumulocity implemented support for Modbus, Controller Area Network (CAN) bus and OPC UA, but basically any protocol can be used, if an Agent is developed for it [131]. WebNMS can be accessed via Modbus, RF and ZigBee [470]. Mosaic Things provides a "pre-built library of connectors" [469] and ThingWorx offers a library with "over 150 protocol adapters" [107], both not mentioning specific protocols.

Bacsoft supports Modbus and Melsec and "can be easily adapted to work with any proprietary protocol, binary or ASCII" [81]. Huawei states to be able to connect devices via "more than 17 types of IoT interfaces and protocols including industrial protocols" [12], for example Modbus and OPC UA [211]. Huawei is also offering "pre-integrated IoT chips and modules for device access using 20+ standard IoT protocols" including Z-Wave and ZigBee [209]. Macchina allows connections via BLE and ZigBee [47], Mainflux simply states to have "multi-protocol support" [264]. Mozilla supports BLE, Thread, ZigBee and Z-Wave [290, 293], Temboo's platform allows device connections via Bluetooth 5, Modbus and ZigBee [409].

6.3.4 Flexibility

The "Big Player" platforms are not restricted to a single use case. All of the platforms are built modular, so that optional modules can be added or removed without having to redeploy the whole platform. The basic functionality works all the same, so there is no vendor lock-in, only SmartThings might be difficult to transfer as they only support applications written as Groovy scripts which is not supported by many other platforms. Alibaba even mentions that providing "an open and convenient

IoT platform" is an important goal for them [118]. What might lock users in nevertheless are the additional modules, like machine learning or other optional vendor-specific applications, as they might not be able to be exported or transfered to other platforms. Configurations which are not stored in files (Extensible Markup Language (XML), JavaScript Object Notation (JSON), etc.) might be hard to transfer as well [17, 35, 99, 112, 175, 189, 219, 278, 313, 339, 359, 367].

None of the "IoT only" companies' platforms are limited in their use cases. In fact, Aeris Communications, IoT Factory and Tago offer some off-the-shelf applications as well [8, 231, 377]. The platform by Ayla Networks was meant to be a Smart Home platform [74], but as long as the needed devices can be connected, users are free to do what they want to.

Except Ayla Networks which has its white-labeled mobile application [74], Losant which does not really need code but only point and click configuration [259], and the Particle Cloud which uses its own operating system for devices [320], all of the platforms do not have any vendor lock-in as they have open architectures, APIs and in case of Aeris Communications, Davra and Ubidots also offer the possibility to create custom connectors and APIs [9, 144, 429]. Tago.io generates code of scripts which can then run on its server, but since developers have to write the node.js code anyway, this is not a lock-in [384].

Kaa Technologies is designed for modularity as any module of the Kaa Enterprise IoT Platform is a portable microservice and can be customized or even exchanged [250]. Davra is also made of microservices modules, but not everything is exchangeable [145] and Yodiwo is also built of modules which are not all mandatory [463]. The platforms of Ayla Networks, Particle, Tago.io, and Ubidots are monolithic software, but users can add third party modules to them [74, 321, 374, 384, 429].

So most of the "IoT only" companies provide a platform with great flexibility. Only Losant hinders code transfer to other vendors and Particle Cloud locks the devices into its own operating system. Devices produced and sold by Thinger.io are possibly also not supported by other platforms. But other than that these platforms can be used for any use case and also add third party sources and applications to most of them.

The open source platforms can be chosen for any use case as none of the providers limits the possibilities. In fact, DSA even offers templates called links for several integrations like databases, third party processing, protocols and users can implement other links to integrate any service they need [155]. None of the platforms or used devices is limited to specific hardware and applications are connected via standard APIs thus eliminating the threat of a possible vendor lock-in. Except Blynk, OpenMTC, WSo2 and SiteWhere before version 2.0, all of the platforms are designed as modular. For all of them, there is a mandatory core of the platform and some offer optional components (plugins in DeviceHive, generic enablers in FIWARE, some microservices in SiteWhere). The limited amount of SDKs and supported protocols can be an issue for edge cases, but all platforms support HTTP and/or HTTPS and most also support (secure) MQTT APIs which can be consumed with any modern programming language even without pre-built SDKs. On the device side, OpenMTC even offers protocol adapters which extend the flexibility even more [86, 148, 152, 162, 305, 363, 421, 459, 464].

The platforms of the telecommunication companies are not restricted to specific use cases either. There is also no risk of a vendor lock-in when using one of these platforms as all of them use standard programming languages, protocols and APIs. Telit advertises its platform as "future-proof" and promises to eliminate conversion risks and to never have to “worry about being “locked into” one vendor now or in the future” [396]. ThingSpace supports exporting to popular reporting tools [103].

The “Other” platform class does not restrict the usage of their platforms to specific use cases. Mathworks ThingSpeak was meant to be for analytics and predictions with MATLAB and WebNMS offers complete solutions for use cases like energy management or fleet management [469], but in reality they can be used for any IoT scenario. The only possible lock-in for this group is the language restriction in Smartworks to Groovy. Cumulocity enables customers to use any device, any protocol and any programming language by its Agent design with minimal effort, WebNMS promises “vendor neutrality” and “limitless compatibility” [470]. Pelion pursues a “modular approach” [51], Cumulocity implemented a microservices architecture and Smartworks seems to be modular as well. It is possible for the ThingSpeak and Data Drop platforms as well to add other Mathworks or Wolfram products respectively.

Bacsoft states to have a highly customizable, “market and vendor neutral”, “unified cloud platform” that can handle “all standard and proprietary data and protocols” and is designed to be the platform integrating everything [81]. Bacsoft’s platform is not restricted to a specific use case but even offers some pre-built applications [82]. Huawei’s OceanConnect offers functionality for some specific use cases (Smart Home, Internet of Vehicles (IoV), oil/gas and Utility) [206], but it seems to be open for any use case and the development of own application as well [210]. Macchina.io is highly customizable in design, modular in the architecture and extensible via plug-ins and APIs [45]. The “open, modularized and flexible architecture” of Mainflux and the design goal extensibility combined with the possibility of “seamless 3rd-party integration” proves its flexibility [264]. Mozilla WebThings is made of two completely separated modules implementing the standard of the W3C which can be extended by using add-ons. RugDS is used in multiple different (mostly university) projects and its ultimate purpose is to save time by being a reusable framework and not having to “reinvent the wheel” for every project [353]. Temboo Kosmos offers a “fine-grained modular architecture” with some pre-built applications and cloud services to integrate applications with other cloud services [408, 410].

6.3.5 Rating

The heterogeneity rating of all platforms is shown in Table 6.6. “DEV” represents the restrictions for devices and “MSG” and “DEV” symbolize the rating for messaging and device protocols respectively. “SDK” shows the rating for SDKs and the rating for flexibility is shown in the “FLEX” column.

The ARM Pelion IoT Platform is the only platform to score the full 5.0 stars in this section, but it is followed by five more platforms with 4.5 and 15 platforms scoring 4.0 stars. Nine of the followers belong to the “Big Players” group which has the highest group average at 3.77 as well. The lowest rated platform is Zebra Zatar scoring 1.5 stars due to no information on support of messaging and device protocols as well as no official SDK. The lowest rated group is the “Others” group (2.89) with Zebra Zatar and three more platforms with a 2.0 star rating despite also having the heterogeneity leader ARM Pelion and two more 4.0 rated platforms with Cumulocity and WebNMS. The overall average is at 3.32 stars.

Table 6.6: The heterogeneity rating of all platforms for the criteria: device restrictions (RES), messaging protocols (MSG), device protocols (DEV), SDKs (SDK) and flexibility (FLEX)

Platform	RES	MSG	DEV	SDK	FLEX	Total
Samsung ARTIK	★	⯪	★	★	⯪	4.0
Samsung SmartThings	★	☆	★	⯪	⯪	3.0
AWS IoT Core	★	★	⯪	★	⯪	4.0
GE Predix	★	★	★	⯪	★	4.5
Google IoT Cloud	★	⯪	⯪	★	⯪	3.5
Siemens MindSphere	⯪	★	★	⯪	★	4.0
Azure IoT Hub	★	★	⯪	★	⯪	4.0
Bosch IoT Suite	⯪	★	★	⯪	★	4.0
IBM Watson IoT	★	⯪	★	★	⯪	4.0
Cisco Kinetic	★	★	☆	★	★	4.0
Alibaba IoT Cloud	★	★	☆	★	★	4.0
Oracle IoT Platform	★	☆	★	★	⯪	3.5
HPE IoT	★	★	☆	☆	⯪	2.5
Big Players Overall	0.92	0.73	0.65	0.77	0.69	**3.77**
Aeris IoT Platform	★	★	☆	☆	★	3.0
Ayla Networks IoT Platform	⯪	☆	⯪	★	⯪	2.5
Davra IoT Platform	★	★	☆	☆	★	3.0
IoT Software Platform	★	★	★	☆	⯪	3.5
Kaa Enterprise IoT	★	☆	☆	☆	★	2.0
Losant Platform	★	⯪	⯪	★	⯪	3.5
Particle Cloud	⯪	⯪	★	★	⯪	3.5
Tago.io	★	⯪	★	★	⯪	4.0
thinger.io	★	⯪	☆	★	⯪	3.0
Ubidots Platform	★	★	☆	★	⯪	3.5
Yodiwo Platform	★	★	⯪	★	⯪	4.0
IoT Only Overall	0.91	0.64	0.41	0.64	0.64	**3.23**
Blynk	⯪	⯪	★	★	⯪	3.5
DeviceHive	★	★	⯪	★	⯪	4.0
DSA	★	⯪	☆	★	⯪	3.0
FIWARE	★	★	★	☆	⯪	3.5
OpenMTC	★	⯪	⯪	⯪	⯪	3.0
SiteWhere Platform	⯪	⯪	☆	⯪	★	2.5
thingsboard.io	★	★	★	⯪	★	4.5
WSo2 Server	⯪	★	☆	☆	⯪	2.0
Zetta	⯪	⯪	☆	⯪	⯪	2.0
Open Source Overall	0.78	0.72	0.44	0.56	0.61	**3.11**
Actility ThingPark	★	⯪	⯪	☆	⯪	2.5

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Table 6.6 – continued from previous page

Platform	RES	MSG	DEV	SDK	FLEX	Total
AT&T M2X	★	★	★	★	⯨	4.5
Deutsche Telekom Cloud der Dinge	★	⯨	⯨	⯨	⯨	3.0
Telit IoT Portal	★	⯨	☆	⯨	⯨	2.5
Verizon ThingSpace	★	⯨	☆	★	⯨	3.0
Telecoms Overall	1.00	0.60	0.40	0.60	0.50	**3.10**
Altair Smartworks	⯨	⯨	★	⯨	⯨	3.0
ARM Pelion IoT Platfom	★	★	★	★	★	5.0
Cumulocity IoT	★	⯨	★	★	⯨	4.0
WebNMS IoT Platform	★	★	★	⯨	⯨	4.0
LTI Mosaic Things	★	☆	⯨	☆	⯨	2.0
Mathworks ThingSpeak	★	⯨	☆	⯨	⯨	2.5
PTC ThingWorx	★	☆	⯨	☆	⯨	2.0
Wolfram Data Drop	★	⯨	☆	☆	⯨	2.0
Zebra Zatar	★	☆	☆	☆	⯨	1.5
Others Overall	0.94	0.44	0.56	0.39	0.56	**2.89**
Bacsoft IoT Platform	★	☆	⯨	☆	⯨	2.0
Huawei OceanConnect IoT Platform	★	★	★	⯨	☆	3.5
Macchina.io	⯨	★	★	⯨	★	4.0
Mainflux	★	★	⯨	★	★	4.5
Mozilla WebThings	★	⯨	★	★	★	4.5
RugDS	★	⯨	☆	⯨	★	3.0
Temboo Kosmos	★	⯨	⯨	★	★	4.0
Prototypes Overall	0.93	0.64	0.64	0.64	0.79	**3.64**
Platforms Overall	0.91	0.64	0.53	0.61	0.64	**3.32**

6.4 Usability and Pricing

In the following section all the platforms are analyzed in terms of usability and support, pricing and unique selling points. The topics to be reviewed are explained in Section 4.4.

6.4.1 Usability

Most providers of the “Big Players” group offer documentations and/or coding examples for their platforms which make it easier to both use the platform and develop applications. Only Oracle and HPE do not have public documentations and code, probably since they prefer to create applications for their customers as a service [30, 35, 41, 93, 94, 112, 174, 175, 189, 219, 278, 339, 344, 347, 356]. Alibaba does not provide example applications but a collection of best practices in its documentation [17].

Azure, Google, Siemens, Bosch, IBM, Alibaba and Oracle offer quickstarts and tutorials on how to connect devices and services to their platforms [17, 94, 189, 214, 278, 313, 356]. To connect with Google's platform, users need to do a bit more manual work than just clicking through a setup tool. AWS and GE offer easy connectivity with their SDKs [35, 176]. Samsung simplified the connection process by making it easy by design for ARTIK [339] and by type and handler certifications for devices and applications respectively for SmartThings [367].

The "IoT only" companies provide good documentations for their products as well. Ayla Networks mentions a "highly concise HTML-based API documentation" on its website [74], but the actual documentation website [69] looks more like an incomplete draft and some tutorials. However, it is possible that the actual documentation is only available for customers signed up for the developer portal. This also applies to IoT Factory which states "APIs are documented" [231] as well as Aeris Communications, Davra and Kaa Technologies that neither have public documentation available. Particle, Tago.io, Thinger.io, Ubidots and Yodiwo all offer complete documentations. Unfortunately, only Tago.io provides any technical details or metrics to analyse weaknesses or limits of the product and Losant's documentation is complete and provides technical details on the implementation [259, 324, 374, 384, 418, 432, 462]. Aeris Communications lists a case study on its website [11], while only Losant, Particle, Thinger.io and Yodiwo included walk-through tutorials and quickstarts in their documentations to easily set up and use their products.

Aeris Communications was "designed to enable the rapid deployment, modification, or removal of applications while maintaining security and overall functionality" [8], Ayla Networks and Losant offer point and click setup of devices [74] and Kaa Technologies offers device integration in a package for purchase [250]. Davra promises a "Zero Touch Deployment" [143]. Tago.io provides a Web interface where users can configure and setup the platform with point and click, scripts are optional [375, 377]. Tago also provides a video to show how to develop a script for the platform [384], but does not offer much information about how to connect devices. Thinger.io states that the setup is done "within minutes" [420]. Losant, Particle, Thinger.io, Ubidots and Yodiwo explain the setup in their documentations [259, 324, 418, 432, 462].

For developing applications, Ayla Networks provides a browser tool for API testing, Davra and Particle offer some kind of developer suite or IDE, and Losant does not need any self-written code at all [74, 259, 324, 418, 462]. Thinger.io wants to provide an "awesome developer experience" by clean design and avoiding complex coding for simple things [420].

All of the open source platforms are documented and offer some kind of tutorials for an easy deployment and usage. The documentations of Blynk and DeviceHive are good to understand their functionalities, but do not offer much technical depth [86, 148]. WSo2 also just explains concepts and how to use its platform in its documentation without much technical details [459]. Zetta has an even thinner documentation which basically consists of some marketing and a few tutorials on its website [464], and the DSA documentation is too distributed to easily find information fast [152, 154, 155]. FIWARE's quality assurance states that its documentation provides completeness and soundness over 90% for all but one component. However, some anonymous developers "who have participated in various FIWARE-related projects" state that the documentation is far from complete [302]. OpenMTC's documentation covers the basic functionality, tutorials and additional samples as well as a webinar, training courses and a guide for the Docker setup to simplify the usage [305, 307, 309]. SiteWhere provides a well structured documentation and very low-level tutorials so that even non-IT people would be able to use its platform. The tutorials are currently only for version 1.0, but SiteWhere states to be “built with a framework approach using clearly defined API so that new technologies may easily be integrated as the IoT ecosystem evolves” [363].

Blynk states that it takes five minutes at most to connect a device and proofs this statement in a video [90]. Blynk also offers a drag and drop creation of mobile applications [90], ThingsBoard offers one SDK for MQTT with Arduino and some samples [423], whereas DeviceHive and DSA offer templates for several programming languages [149, 151]. Zetta put a focus on “Code with Joy” and provides helpful abstractions and direct access to underlying protocols to allow developers “to focus on the big picture without losing track of the details” [464].

The documentations for the “Telecom” platforms are not as good and comprehensive as for the other platform groups. The documents for ThingPark are distributed [4, 5, 6] and there are no tutorials, only success stories. However, Actility states it would be “straight forward” [3] to use the platform. AT&T offers a documentation for the API and SDKs, Frequently Asked Questions (FAQ) and tutorials, but not much technical information on its M2X platform [59, 63]. Information on ThingSpace and its technical implementation is distributed on sources of both Verizon and Bug Labs, for example [438] and [103], however the Verizon documentation offers guides and references for the application SDKs.

Actility calls the integration of devices and sensors into its ThingPark platform “straight forward”, as well as routing data to app services [3]. Deutsche Telekom’s certification for devices indicates an easier or supported integration of those devices.

AT&T also offers a help forum where the latest (serious) contribution dates back to 2018 [64]. Deutsche Telekom does not offer any documentation, but states the platform can be used with any programming with just internet access [393]. Telit has a big, yet distributed documentation and some courses and tutorials available [399, 400, 403]. Telit states that new users do not need custom code to integrate their existing applications into its platform [396].

The amount of information on the “Others” platforms is varying. For Mosaic Things, ThingWorx and Zatar, there is almost no information available, especially on technical details. For the other six platforms, there are big documentations available with almost every topic covered [21, 54, 130, 415, 449, 472]. Only ThingSpeak’s documentation is too little technical for users to really be able to understand how the platform works. The providers also offer tutorials for these platforms. There are a lot of samples and tutorials [50, 134], especially for Smartworks [21, 22]. Data Drop provides tutorials, crash courses, books, virtual courses and events [451]. ThingSpeak offers tutorials for its community [416]. The tutorial for WebNMS is outdated (2013) [471]. Smartworks (as Carriots in that year) has had a challenge in 2013 for users to submit their projects done with Carriots [160] which brought up some community made projects.

Altair states that “SmartEdge automatically connects with devices from a wide variety of protocols” [28] and offers fast and simplified integration for web applications as well as third party products [26] via push and pull functionality possible for every available HTTP API [159]. Cumulocity implemented a “plug and play” approach [235] and provides integration for apps like SAP and Salesforce [131]. WebNMS “integrates seamlessly with 3rd party enterprise applications” [469].

For most of the prototype platforms, documentation, samples and tutorials are not as comprehensive as for already released platforms. Huawei’s documentation page is already publicly available [208] and the Development Center is advertising tutorials as “coming soon” [210]. Macchina.io [46] and

Mainflux [265] provide an overview to understand the functionality which are not as good in-depth or for technical details. Macchina.io offers guides and how-to tutorials on its GitHub page [43] as well as a workshop teaching the fundamental steps [44]. RugDS offers technical detail and a list of used technologies, but not so much information on how to use the platform [353]. Mozilla provides API specifications [168] and a user guide [295] which give information on the functionality as well as how to use it. Mozilla provides an example repository [293], RugDS has a template on GitHub as well [150]. Temboo offers a well-structured documentation on the features of and how to use the platform as well as a list of supported sensors and actuators [405]. The Temboo pre-built applications might be open source, but Temboo does not offer other examples. Mainflux does not have any tutorials, Bacsoft offers neither a documentation nor tutorials. Since all of these platforms are still in developmental states, documentation and tutorials might be published or created for a first release in the future.

Huawei states that its cloud services “help enterprise customers easily integrate devices” and offers a graphical tool to achieve this integration without having to write code [248] thus providing an easy way to use the platform. Temboo also offers a code-generating functionality to create applications [409]. Mainflux offers getting started guides and a tutorial for an easy start with Docker [265, 267]. Mozilla provides setup guides for gateways and devices [288, 295] and simplifies programming by implementing standards and offering adapter add-ons to easily connect devices [293]. For RugDS, there is a guide on how to setup the IDE and a template to simplify developing features and applications [150].

6.4.2 Support

The big companies mostly operate one general support point for all of their products linked on their websites with many offering different tiers depending on the chosen pricing model. Some offer Slack or Twitter support channels or FAQs. Additionally for SmartThings, there still exists an active community which started in its kickstarter days, and also most of the other providers offer forums for their communities [13, 32, 112, 173, 215, 275, 343]. If users still need to ask other people for help, forums like stackoverflow.com can also be used, especially for products that are very common like exactly these “Big Players” services.

Aeris Communications offers a local language support which is “fast, efficient, and geared for a focused response” [8]. IoT Factory assists its users with “help with proof of concept” [231], but there is no information on technical support. Kaa Technologies offer two tiers of support plans differing in reponse time (two hours or one business day) and availability (24 hours for seven days or twelve hours for five days a week) [250], Losant offers support SLAs for enterprises as well [260]. Particle’s support is limited to the system status [327], FAQs and the possibility to contact the sales department [323]. Thinger.io offers support per mail and Skype depending on the pricing model [420]. Ubidots offers support SLAs as an add-on for paying users [428]. Tago provides a Slack instance for its community [376], Losant and Particle offer an active user community forum, whereas the community of Ubidots is not as active. The forum of Ubidots additionally provides a space for community projects [261, 322, 431].

Most open source platforms do not have a dedicated support, but only a user community with some kind of forum or help center. Blynk offers an SLA for support for its top pricing tier and email support or its help center for other tiers. DeviceHive only provides some questions and discussions on its website [147], FIWARE and ThingsBoard offer Q&A Forums [161, 423] and SiteWhere offers a "free basic support" [366]. WSo2 offers a "contact us" functionality [458], FAQs [459] and a "24x7 expert incident-level WSo2 Support with aggressive response and resolution times" for subscribed customers [457]. Zetta used to run a Twitter account which has been silent since 2016 [465] and it is not clear if there is another support service to replace it. Blynk has an active community [85], DSA provides a Slack instance and a Google+ community [155], and SiteWhere offers a Discord server for its community [366]. ThingsBoard hosts a Gitter community and a Q&A forum [423] and WSo2 operates a forum and a mailing list [454]. OpenMTC's community section on its website only lists projects and success stories, but no possibility to get help with the product [306].

The telecommunication companies also offer support solutions. Telit states its "team of experts is just a phone call away" [397] and additionally runs online help pages and support [402]. AT&T's website lists a support section, but the scope or if M2X is even included is unclear. The support of Deutsche Telekom is limited to consulting and integration of devices [373]. Verizon offers email support and custom support plans for enterprises [102, 438].

Altair offers phone and mail support for Smartworks [193], as well as Cumulocity for their platform [235]. The support for WebNMS is only online and for paying users [108]. ThingSpeak is covered by "Standard MathWorks support" [411], Wolfram offers FAQs and a community as well as phone, mail and live chat support with higher priority for paying users [447]. Smartworks, Pelion, Cumulocity, WebNMS and ThingSpeak also offer communities with forums, blogs, FAQs which are actively used today, only the WebNMS forum has not have a sign of life for almost a year [23, 24, 49, 370, 416, 473].

Huawei does not offer a support dedicated to the OceanConnect platform, as well as Bacsoft and RugDS. Macchina's support has a time limit based on the subscription plan and offers a direct contact for professional support [47]. Mainflux offers an amount of dedicated support hours varying depending on the payment tier (two hours, four hours or 24x7) per SLA [268]. Mozilla's support is available per Mail, Internet Relay Chat (IRC) and Twitter [289]. Temboo promises "in-depth answers and advice" by its engineers [410], support per email [407] and prides themselves on "both rapid response times and in-depth answers" [408]. Huawei has a community forum [207], Mainflux offers a Google group, a Gitter instance and a Twitter support for its community [267] and Mozilla provides a Discourse forum for its users [287].

6.4.3 Pricing

Many providers of the "Big Players" group offer different business models and limited usage which is mostly interesting for small home projects, most also offer a limited free trial. Pricing models often depend on the usage (traffic and/or computational unit and/or the amount of devices) except Oracle and HPE who also offer an all-inclusive payment model for enterprises [18, 37, 97, 173, 178, 186, 200, 222, 240, 280, 315, 340]. AWS sells some additional commercial tutorials [30], Siemens provides trainings [359], and Oracle offers training and exams for certifications [310]. Additional services like Machine Learning and modules for the platforms might cause additional costs, too.

The pricing for the platforms of Davra (via Cisco Global Price list [141], Aeris Communications, Particle and Ubidots are depending on the usage (devices and traffic) [9, 323, 428], Ayla Networks demands fees for licensing and maintenance, while Kaa Technologies and Losant provide their pricing only on request [250, 260]. Kaa Technologies offers developer training in its "Implementation Accelerator Package" and platform training in its "Architecture Accelerator" package [250], IoT Factory offers business coaching on finance, Human Resources (HR) and legal as part of its Startup Studio program [232], only Particle offers a data plan (via local carriers) as part of its subscription model [323]. Ayla Networks, Davra and Losant offer third party integrations for additional services which users have to subscribe to and pay for separately. Davra (also at the edge), IoT Factory and Kaa Technologies offer machine learning capabilities for predictive analysis [144, 230, 250]. Tago offers free usage for developers and students as well as the paid models "starter" and "scale" [383]. Thinger.io offers free usage for up to four devices which is "widely used by students worldwide", a cheaper model for "makers", a model for business and custom pricing on demand for bigger companies [420].

DeviceHive, DSA, OpenMTC and Zetta are completely free to use, SiteWhere even states that "SiteWhere CE will always be open source and free for private as well as commercial use" [366]. FIWARE states that all "specifications are public and royalty-free" [163]. OpenMTC offers training courses on different aspects of the IoT like basics, security or M2M standards, which probably are not for free [309]. The other platforms additionally offer paid subscriptions with extra services like more devices and components (Blynk [88]), unlimited usage (ThingsBoard Professional Edition [424]) or managed hosting and support (WSo2 [457]).

Actility and AT&T offer limited free usage of their platforms. AT&T also offers jumpstart programs for startup companies [62]. The "Cloud der Dinge" can be used for a one time payment or with a pay per use model using the starter kit [373, 393]. Telit also charges per usage [398]. Verizon's pricing model is also pay-as-you-go, charging users for traffic and per devices [439]. Verizon offers a Cloud Connectors development kit to work with AWS which might cause additional costs at Amazon [440]. All telecommunication providers obviously offer data plans for the internet connection as part of their traditional telecommunications business portfolio.

Smartworks [193][56], Cumulocity, ThingSpeak and Data Drop offer limited versions for free [371, 411, 446]. Those four platforms have payment models based on usage, as well as ThingWorx [242]. WebNMS offers its platform usage for a one-time payment as well as training for the documentation and in person [108]. For Pelion, there is training provided by ARM itself or partners. The training can be face to face, live virtual or online, cost will be available on request [55]. Mosaic offers Machine Learning as a Service, for example via solutions of Azure, AWS, Google or IBM [256]. Smartwork has its smartsight module for Machine Leanrning [26], ThingWorx uses artifical intelligence and machine learning to manage challenges specific for IoT [106]. Wolfram's Data Drop uses a highly automated machine learning system [450], ThingSpeak enables machine and deep learning by using MATLAB and Simulink [412].

Huawei offers its platform as an open beta version with a free trial option [209]. Cloud services are available but might be charged additionally. Macchina.io can be used for free, a paid version offers more functionality and support [47]. Mainflux is free to use, but hosting on the providers infrastructure will create costs as well as a support plan [268]. Mozilla WebThings is free to use, including add-ons [293]. Temboo offers a free trial as well as business, industrial and enterprise models charging users per asset per month. Educational and non-profit organisations can apply for a free license [407]. Pricing models might change once released.

[56] Source is for Carriots, but this might be similar with the new owning company as well

Table 6.7 shows an overview of the offered pricing models for every platform. A "✓" represents that a respective model is available, a '‘-" symbolizes that it is not. A "?" indicates there is not pricing information for a platform at all, or not enough information to assume whether a pricing model could be available or not.

Table 6.7: Overview of the available pricing models of all platforms

Platform	Free	Starter	Standard	Enterprise	Educational
Samsung ARTIK	✓	-	✓	✓	-
Samsung SmartThings	✓	-	-	-	-
AWS IoT Core	-	-	✓	-	-
GE Predix	✓	-	-	-	-
Google IoT Cloud	✓	-	✓	-	-
Siemens MindSphere	?	?	?	✓	?
Azure IoT Hub	-	✓	✓	✓	-
Bosch IoT Suite	✓	✓	✓	✓	-
IBM Watson IoT	-	-	✓	-	-
Cisco Kinetic	?	?	?	?	?
Alibaba IoT Cloud	✓	✓	✓	-	-
Oracle IoT Platform	-	-	✓	✓	-
HPE IoT	-	-	-	✓	-
Aeris IoT Platform	?	?	?	?	-
Ayla Networks IoT Platform	-	✓	-	✓	-
Davra IoT Platform	-	-	-	✓	-
IoT Software Platform	-	-	-	✓	-
Kaa Enterprise IoT	-	-	-	✓	-
Losant Platform	✓	-	-	✓	-
Particle Cloud	✓	-	✓[57]	-	-
Tago.io	✓	✓	-	✓	✓
thinger.io	✓	-	✓	✓	-
Ubidots Platform	✓	✓	✓	✓	-
Yodiwo Platform	✓	?	?	?	?
Blynk	✓	?	?	?	-
DeviceHive	✓	-	-	-	-
DSA	✓	-	-	-	-
FIWARE	✓	-	-	-	-
OpenMTC	✓	-	-	-	-
SiteWhere Platform	✓	-	-	-	-
thingsboard.io	✓	-	-	-	-
WSo2 Server	✓	?	?	?	?
Zetta	✓	-	-	-	-

Continued on next page

[57]Particle's standard model is made for scaling, reducing the price per device with increasing amount of devices

Table 6.7 – continued from previous page

Platform	Free	Starter	Standard	Enterprise	Educational
Actility ThingPark	✓	?	?	?	?
AT&T M2X	✓	?	?	?	?
Dt. T. Cloud der Dinge	-	-	-	✓	-
Telit IoT Portal	✓	?	?	?	?
Verizon ThingSpace	✓	-	✓	-	-
Altair Smartworks	✓	?	?	?	?
ARM Pelion IoT Platfom	?	?	?	?	?
Cumulocity IoT	✓	?	?	?	?
WebNMS IoT Platform	?	?	?	✓	?
LTI Mosaic Things	?	?	?	?	?
Mathworks ThingSpeak	✓	✓	✓	-	✓
PTC ThingWorx	?	?	?	?	?
Wolfram Data Drop	✓	✓	✓	-	-
Zebra Zatar	?	?	?	?	?
Bacsoft IoT Platform	-	-	-	-	-
Huawei OceanConnect	✓[58]	-	-	-	-
Macchina.io	✓	?	?	?	?
Mainflux	✓	-	-[59]	-	-
Mozilla WebThings	✓	-	-	-	-
RugDS	-	-	-	-	-
Temboo Kosmos	✓	-	✓	✓	✓

6.4.4 Unique Selling Points

Even if the "Big Player" platforms are similar, some of them have unique selling points. SmartThings for example is free and pre-installed on Samsung mobile devices, however it offers limited programmable functionalities as of now [344]. AWS, Bosch and Alibaba use the digital twin concept to provide so-called "device shadows" which enable always available access on the latest state and values, even if the device has since disconnected, and users can also set a new value for offline devices which will sync after they reconnect to the platform [16, 35]. GE's big point is its alliance with many other companies [180], Bosch scores with its cloud located in Germany [334] ensuring European privacy laws, and Microsoft offers a convincing security program [282], while Oracle and HPE are especially interesting for bigger companies.

The things that distinguish the platforms of the "IoT only" companies are diverse. Aeris Communications operates an unmatched global coverage with over 480 partners in 190 countries [8], Ayla Networks provides a white-labeled mobile app for both Android and iOS [74]. Davra offers not only a (text-based) REST API, but also interfaces for voice and video input [144], whereas in the

[58] Huawei is currently only offering a free beta version

[59] Mainflux is not offering a Standard model, but a managed hosting solution for their free platform

platform of Kaa Technologies any module is exchangeable [250]. IoT Factory offers a program to fund startups for using its product [232], Ubidots launched its Education program in 2018 to give easy access to the IoT world for enthusiasts and students [427]. And for users with no programming background, Losant provides a drag and drop workflow editor to avoid coding [259].

The big benefit of all open source platforms is obviously the open source code and the ability to edit parts or whole components. Some of these platforms offer additional unique features. Blynk provides the ability to connect a device or application in under five minutes [90] and DSA enables nesting in its network [153]. FIWARE scores with the big funding provided by the European commission and several private companies [302] and OpenMTC implements the oneM2M standard [305]. ThingsBoard states to have the “most comprehensive dashboard editor on the market” in a video on its website [421] and Zetta promises to be able to “[turn] any device into an API” [464, 466].

The “Telecom” platform of Telit scores with the support of offline storage on edge devices. The devices keep operating and synchronize the data on reconnection via the store-and-forward feature. These edge devices are also able to “act and make decisions locally on the data they generate without the need to rely on a central server or cloud to send directions or logic back and forth” [397].

Pelion and Cumulocity are unique in their flexibility. ARM implemented its platform with no restrictions in device hardware, operating system or programming language, Cumulocity enables the same flexibility with its architecture where Agents can be used on any point in the system to translate protocols or languages. Mathworks ThingSpeak and Wolfram Data Drop score with the possibility to integrate other products of their respective providers. ThingWorx offers Augmented Reality for its IoT applications.

Huawei and Mozilla stand out from the other platforms by implementing the oneM2M or W3C IoT standards respectively. All of the other platforms are divergent and do not implement any kind of standard.

6.4.5 Rating

The usability and uniqueness rating of all platforms is shown in Table 6.8. “DOC” represents having a public documentation, “TUT” is for tutorials on the platform and “SAM” stands for for the availability of example applications. “SUP” shows, if no, a general or a support point dedicated for this product is available for users and/or developers. “UNI” represents the implementation of unique features and/or ML in the platform.

There are three platforms with full 5.0 stars (“Big Players” GE Predix and Microsoft Azure as well as “Other” Mathworks ThingSpeak), while the lowest achieved rating is 0.0 star for “Others” platform Zebra Zatar and “Prototype” Bacsoft, mostly due to missing information on most topics for these two platforms. “Big Players” platforms received the highest average with 3.46 stars, however HPE’s platform received a low rating of just 1.5 stars because of the little public information available. The “Prototype” platforms are the lowest rated group with 1.93 stars on average. This is also due to the little information available for some platforms in this group. We expect the rating for documentation, tutorials and examples to increase once a prototype platform is released. Mozilla’s prototype for WebThings achieved a 3.5 star rating despite being in the lowest rated group, beating the overall average of 2.78 stars.

Table 6.8: The usability and uniqueness rating of all platforms for the criteria: documentation (DOC), tutorials (TUT), examples (SAM), support offering (SUP) and unique features (UNI)

Platform	**DOC**	**TUT**	**SAM**	**SUP**	**UNI**	**Total**
Samsung ARTIK	★	☆	★	★	☆	3.0
Samsung SmartThings	★	☆	★	★	⯪	3.5
AWS IoT Core	★	☆	★	⯪	★	3.5
GE Predix	★	★	★	★	★	5.0
Google IoT Cloud	★	☆	★	★	⯪	3.5
Siemens MindSphere	★	★	★	★	⯪	4.5
Azure IoT Hub	★	★	★	★	★	5.0
Bosch IoT Suite	★	★	★	★	⯪	4.5
IBM Watson IoT	★	☆	★	★	☆	3.0
Cisco Kinetic	☆	★	☆	★	☆	2.0
Alibaba IoT Cloud	★	☆	☆	★	★	3.0
Oracle IoT Platform	★	★	☆	⯪	⯪	3.0
HPE IoT	☆	☆	☆	★	⯪	1.5
Big Players Overall	0.85	0.46	0.69	0.92	0.54	**3.46**
Aeris IoT Platform	☆	☆	☆	★	⯪	1.5
Ayla Networks IoT Platform	★	☆	★	☆	⯪	2.5
Davra IoT Platform	☆	☆	☆	☆	★	1.0
IoT Software Platform	★	☆	☆	★	★	3.0
Kaa Enterprise IoT	☆	☆	☆	★	★	2.0
Losant Platform	★	★	☆	★	⯪	3.5
Particle Cloud	★	★	☆	★	☆	3.0
Tago.io	★	☆	★	☆	☆	2.0
thinger.io	★	☆	★	★	☆	3.0
Ubidots Platform	★	☆	☆	★	⯪	2.5
Yodiwo Platform	★	☆	★	☆	☆	2.0
IoT Only Overall	0.73	0.18	0.36	0.64	0.45	**2.36**
Blynk	★	☆	★	★	⯪	3.5
DeviceHive	★	★	☆	☆	☆	2.0
DSA	★	★	★	☆	⯪	3.5
FIWARE	★	★	★	☆	⯪	3.5
OpenMTC	★	★	★	☆	⯪	3.5
SiteWhere Platform	★	★	☆	★	☆	3.0
thingsboard.io	★	★	☆	★	⯪	3.5
WSo2 Server	★	★	☆	★	⯪	3.5
Zetta	★	★	☆	★	⯪	3.5
Open Source Overall	1.00	0.89	0.44	0.56	0.39	**3.28**
Actility ThingPark	☆	☆	☆	☆	⯪	0.5

Continued on next page

Table 6.8 – continued from previous page

Platform	DOC	TUT	SAM	SUP	UNI	Total
AT&T M2X	★	★	★	★	☆	4.0
Deutsche Telekom Cloud der Dinge	☆	☆	☆	⯪	⯪	1.0
Telit IoT Portal	★	★	☆	★	⯪	3.5
Verizon ThingSpace	★	☆	★	★	☆	3.0
Telecoms Overall	0.60	0.40	0.40	0.70	0.30	**1.80**
Altair Smartworks	★	★	☆	★	⯪	3.5
ARM Pelion IoT Platfom	★	☆	★	★	⯪	3.5
Cumulocity IoT	★	★	☆	★	⯪	3.5
WebNMS IoT Platform	★	☆	★	★	☆	3.0
LTI Mosaic Things	☆	☆	☆	☆	⯪	0.5
Mathworks ThingSpeak	★	★	★	★	★	5.0
PTC ThingWorx	☆	☆	☆	☆	★	1.0
Wolfram Data Drop	★	★	☆	★	★	4.0
Zebra Zatar	☆	☆	☆	☆	☆	0.0
Others Overall	0.67	0.44	0.33	0.67	0.56	**2.00**
Bacsoft IoT Platform	☆	☆	☆	☆	☆	0.0
Huawei OceanConnect IoT Platform	☆	☆	☆	⯪	★	1.5
Macchina.io	★	★	☆	★	☆	3.0
Mainflux	★	☆	☆	★	☆	2.0
Mozilla WebThings	★	☆	★	★	⯪	3.5
RugDS	☆	☆	★	☆	☆	1.0
Temboo Kosmos	☆	★	☆	★	⯪	2.5
Prototypes Overall	0.43	0.29	0.29	0.64	0.29	**1.50**
Platforms Overall	0.74	0.44	0.44	0.70	0.44	**2.56**

6.5 Platform Design

The “Big Players” group includes 13 platforms of which seven have their own collaboration tools like AWS QuickSight (see [31]) or Google Cloud Data Lab (see [185]). Alibaba, Bosch and IBM do not offer any collaboration tools to their customers, ARTIK, Cisco and HPE refer to external end points. Except both Samsung platforms, Bosch aand Cisco, all providers offer their own ML service to be integrated. IBM offers Watson Machine Learning [225], but does not specifically state that it works together with Watson IoT. ARTIK and SmartThings do not offer Edge Computing Solutions as well as Alibaba. The only providers to sell their own IoT devices are Samsung (for both platforms, smartphone, TVs, etc. [346]), HPE (Edgeline products [330]), Bosch and Siemens (MindConnect Nano devices [360]), whereas AWS, Google and Azure list partner devices in catalogues on their respective websites. Rules Engines, Analytics solutions and SDKs are offered by all “Big Players” platforms. The platforms ARTIK, SmartThings and Cisco do not include a database, the usage in IBM’s Watson IoT platform is optional. Overall, all of the design components suggested in Section 4.5 in level two to six were implemented by all or at least nine of the 13 platforms (see Figure 6.2).

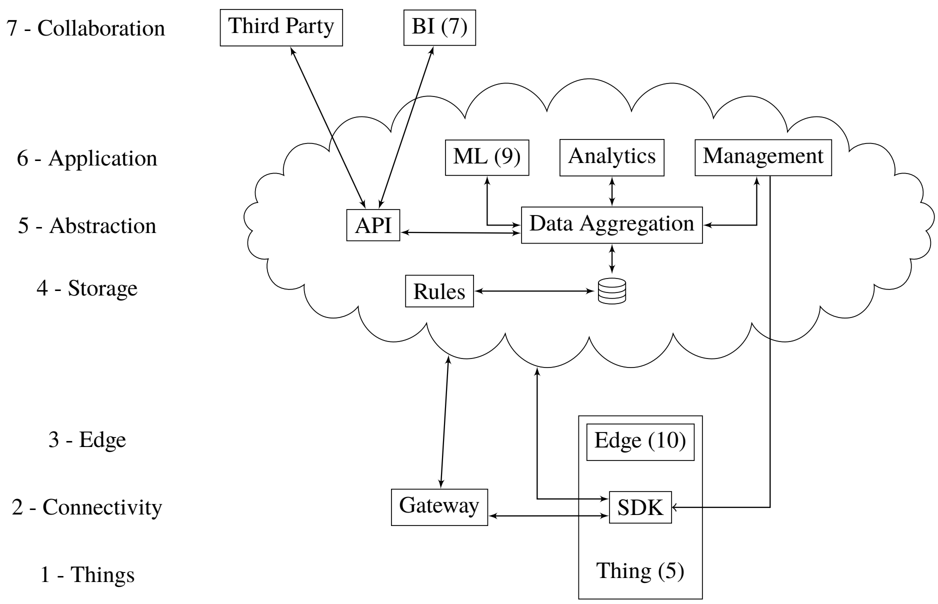

Figure 6.2: "Big Players" architecture (13 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

The "IoT Only" group includes eleven platforms. Aeris Communications is the only provider to offer collaboration in form of business rules. Ayla Networks and IoT Factory offer pre-built or white-label mobile applications which are not included by any other group. Analytic tools are provided by nine providers (all except Particle and Thinger.io), whereas ML is provided for just the platform of IoT Factory. Davra does not offer an SDK for any programming language, Aeris Communications, IoT Factory and Kaa Technologies do not provide information on this topic. All of the other platforms offer at least three SDKs for devices to connect. Aeris Communications,

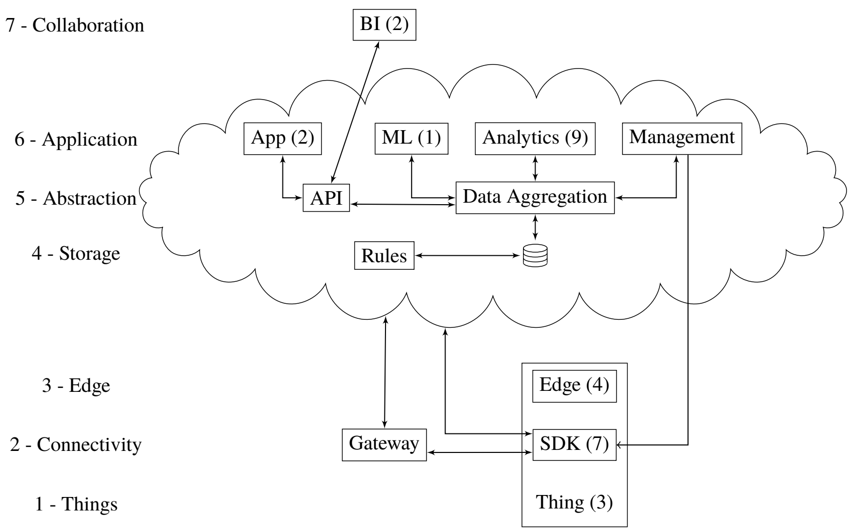

Figure 6.3: "IoT Only" architecture (11 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

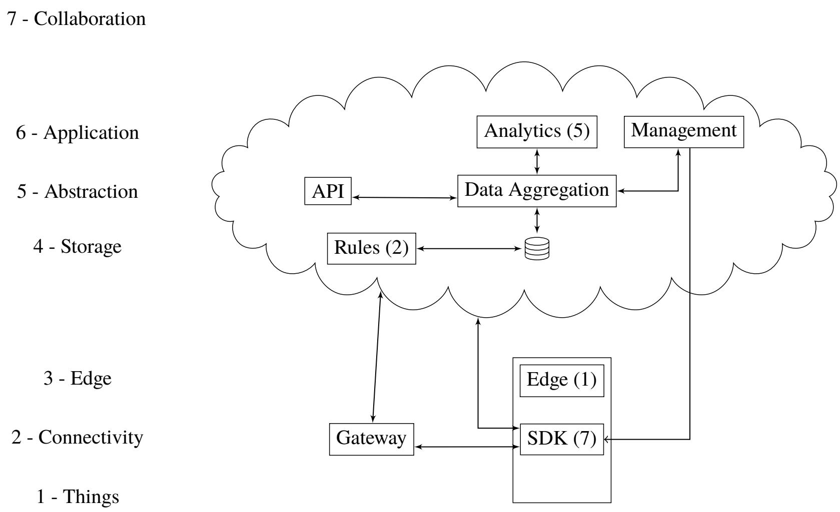

Figure 6.4: "Open Source" architecture (9 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

Davra Networks, Kaa Technologies and Losant offer Edge Computing solutions. Fog Computing is provided for the platform of Losant as well. Device HW is provided by IoT Factory [231], Particle [329] and Thinger.io [418]. As shown in Figure 6.3, the core components in the fourth and fifth level are provided by all platforms, however the infrastructure and database systems are not owned by the platform providers.

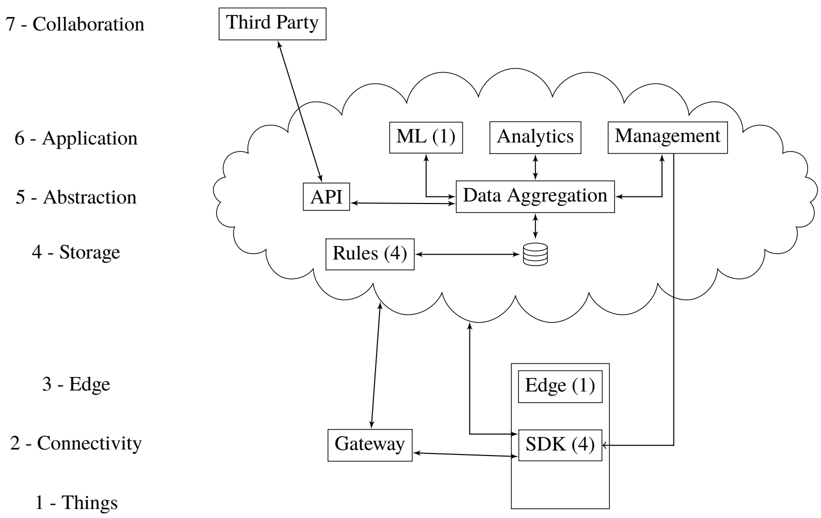

Figure 6.5: "Telecoms" architecture (5 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

The "Open Source" group includes nine platforms. Neither of them offers BI applications or its own HW. DeviceHive, FIWARE, OpenMTC, Thingsboard and WSo2 offer some kind of tool for analytics or visualization. A rules engine is only provided by Blynk and Thingsboard. DSA and

Zetta neither integrated a database. Edge Computing is supported by WSo2, whereas SDKs are offered for all platforms but WSo2 - FIWARE does not provide information on SDKs. The overall architecture of the “Open Source” platforms is shown in Figure 6.4.

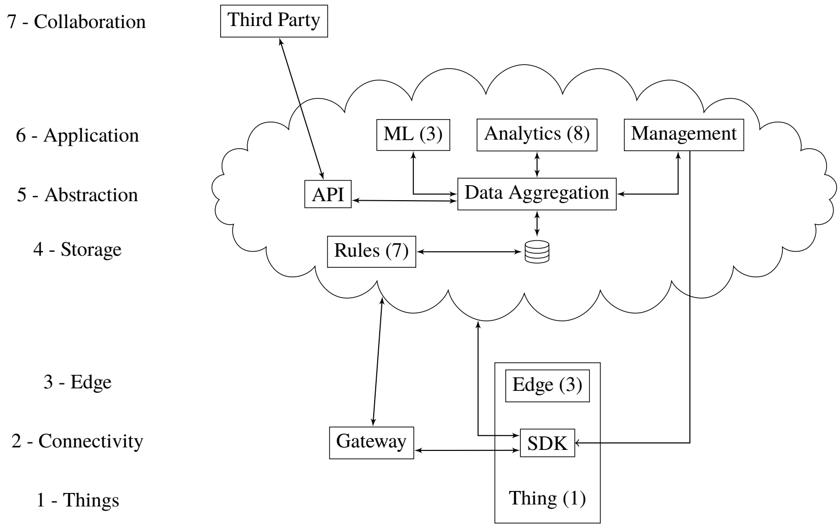

Figure 6.6: “Others” architecture (9 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

None of the five “Telecoms” platforms offers its own collaboration tools. All of the platforms integrated a database and an analytics tool. Unlike the other platforms, AT&T’s M2X includes ML but no rules engine. Telit provides an Edge Computing solution with offline on-device storage. All platforms but ThingPark offer at least one SDK. Deutsche Telekom is the only company to provide its own HW [253]. The overall architecture of the “Telecoms” platforms is shown in Figure 6.5.

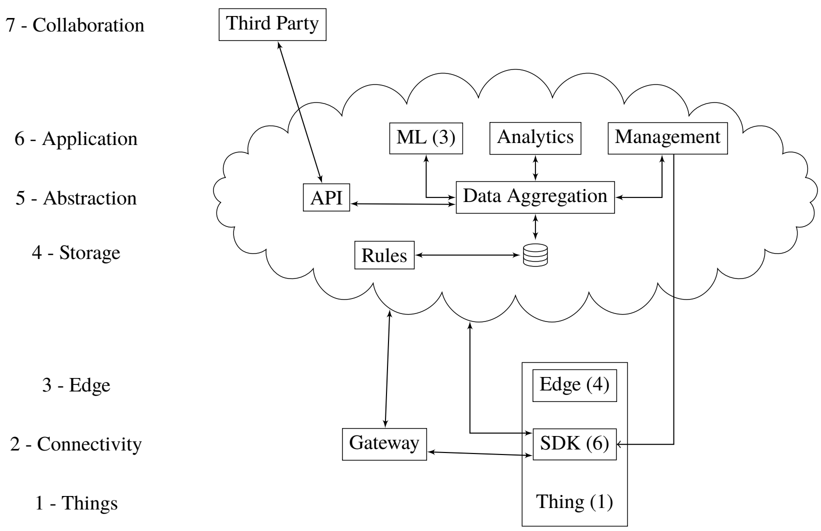

Figure 6.7: “Prototypes” architecture (7 platforms) and the components shared by some (number in brackets) or all (no number) of the platforms

Out of the nine “Others” platforms, the only offered BI application is SmartSight for Smartworks [26]. Except PTC Thingworx and Zebra Zatar where the information is missing, all of the platforms use some kind of database (except Mosaic Things) and rules engine. Mosaic, PTC and Zebra Technologies also do not offer an SDK for their platforms, while there is a community-made one for Wolfram and provider-made SDKs for the other five platforms. Eight platforms (except Zebra Zatar) offer an analytics tool as well. Edge Computing is possible for Smartworks, Cumulocity and WebNMS. Only ARM offers its own HW [52], whereas WebNMS refers to partner producers. The overall architecture of the “Others” platforms is shown in Figure 6.6.

The “Prototype” group includes seven platforms. None of these platforms offers any kind of collaboration application. ML and rules engines are only integrated in the platforms of Huawei, Mozilla and Temboo, whereas analytic tools are available for Huawei, Macchina and Mozilla. Databases are provided for Macchina, Mainflux and RugDS. SDKs are offered for all platforms but Bacsoft that does not provide information on this topic. Edge Computing solutions are integrated in Huawei’s OceanConnect, Macchina.io, Mainflux and Temboo’s Kosmos. Bacsoft [81] also distributes its own IoT devices. The core components in the fourth and fifth level are provided by all platforms (see Figure 6.7).

6.6 Results

In this section we aggregate the differences and ratings for a result of what the best-rated platforms and groups are.

6.6.1 Analysis

In terms of reliability, most platforms have space for improvement. Except the “Big Players”, most platforms do not have an availability promise or replication of nodes and/or storage. The authentication and authorization methods meet standards for most platforms, only the “Others” and “Prototypes” need to improve here. Messaging encryption is done by most platforms by using TLS, whereas storage encryption is only done by very few providers. For none of the platforms, there was a leak of data or control in the past, and some providers even have third party companies testing their product. Most platforms were published in 2013 or after, with only three exceptions: Telit (2012 or earlier), PTC ThingWorx (late 2011) and Cumulocity (2010). All selected platforms are still further developed in 2019, with the exception of ARTIK (shut down for the general public as of May 15 2019) and Zetta (stated to have a new release “soon” as of December 2018).

In the scalability section, there was unfortunately not much information available. Limits of scalability were often formulated vaguely and there is no benchmark system yet to rate platforms accurately in both amount of node and message throughput. Most providers offer only a cloud or on-premise hosting solution, five platforms can be hosted in a hybrid setup. Except most of the “Big Player” and all “Telecom” platforms, the platforms are hosted on a third party cloud solution. 41% of the platform offer an Edge and/or Fog computing solution.

All platforms aim for heterogeneity. The only restrictions for servers and devices are compatibility with container technologies and/or Java. About 75% of the providers offer SDKs to connect devices with a platform, often for multiple common PLs. The most supported programming languages are JavaScript (19%), Python (18%) and Java (17%). Supported messaging and device protocol are also diverse. The most supported messaging protocols are HTTPS (61%) and secure MQTT (65%) - all but two platforms support at least one of these protocols. Supported device protocols are Bluetooth/BLE, ZigBee and Sigfox amongst others. Most platforms are kept flexible to fit different use cases as well. About a quarter of the platforms is build modular and some can even exchange components freely.

The usability for developers can be improved for most platforms by providing (more) tutorials and examples. Around 75% of the providers offer a documentation and each 44% provide tutorials and example application as tools for developers to achieve their goals - but only 17% provide all three. For many platforms, there is also a dedicated support available. Half of the platforms have an ML solution available or integrated by their providers.

In general, platforms mostly differ in if a certain criterion was implemented or not. The way of implementation - for example encryption algorithms, PLs for SDKs or supported protocols - is mostly the same.

6.6.2 Rating

The best rated platform overall is Microsoft Azure IoT Hub with 4.5 stars. Azure scores the highest rating in scalability and usability, while only being beaten by two and six platforms in reliability and heterogeneity respectively. Rated just half a star lower, AWS, Predix and IBM follow Azure with 4.0 stars on average, Google, Siemens, Alibaba as well as AT&T and Losant - the first two platforms not belonging to the “Big Players” group - score good ratings at 3.5 as well. Unsurprisingly, the “Big Players” also score the highest group average with 3.5 stars - an average not a single other platform could beat.

The lowest scoring platform is once more Zebra Zatar with just 0.5 stars on average. The next two platforms following also belong to the “Others” group: LTI Mosaic Things scored 1.0 star, PTC ThingWorx scores 1.5 stars, joined by the “Prototype” platforms of Bacsoft and RugDS (1.5 stars as well). The “Others” group is the lowest scoring group just below the “Prototypes”, both scoring 2.0 stars on average.

The other groups (“Iot Only”, “Open Source” and “Telecoms”) all average at an overall rating of 2.5 stars. Most notably in these group are the already mentioned AT&T (“Telecoms”) and Losant (“IoT Only”) scoring 3.5 stars.

The “Big Players” group is overall better rated in the reliability section (also see Table 6.2 in Section 6.1.8) than all other groups which is because of the higher ratings in every single subtopic. This group scores 0.58 stars in replication and availability compared to 0.22 to 0.43 on average per group. In the authentication and authorization part, only the “Others” group is rated below 0.5 stars on average, while the other groups score up to 0.85 (“Big Players”) and 0.90 stars (“Telecoms”). Encryption is rated over 0.5 stars for only two groups: “Big Players” and “Prototypes”. In the security history section, only five platforms (three of these are in the “Big Players” group) score 1.0 star, while all the other platforms score 0.5 stars. In market longevity, only “Telecoms” (0.70) almost reach the level of the “Big Players” (0.77), whereas the remaining groups score only 0.07 to

0.50 stars on average. Overall, the “Big Player” group is clearly rated the best group (3.54 stars overall in reliability) for reliabity with winning four and being second best just behind “Telecoms” (second overall in reliability with 2.90 stars) in the fifth subtopic.

Scalability offers a similar difference between the groups (also see Table 6.3 in Section 6.2.5). Hosting options are the only subtopic where the “Big Players” (0.12) and “Telecoms” (0.10) score worse than the other groups (up to 0.56 for “Others”). On contrary, the “Big Players” (0.85) and “Telecoms” (1.00) platforms dominate the subtopic of self-owned infrastructure, whereas “IoT Only”, “Open Source” and “Others” score 0.00 stars for all of their platforms in this category and only the prototype platform of Huawei receives 1.0 stars. Edge Computing is also most supported in the “Big Players” platform (0.77 stars). The “Prototypes” score 0.57 stars on average, while the remaining groups score between 0.00 and 0.33 stars. For both the limits of the amount of nodes and the message throughput, no group scores over 0.5 stars on average with “Big Players” being the best rated group for the message throughput (0.38 stars) and “IoT Only” being the best rated group for the amount of nodes (0.41 stars). Overall, the “Big Players” do not dominate in every subtopic but in the overall average with a score of 2.35 stars, while the next group - the “Telecoms” - scores only 1.60 stars on average.

In the heterogeneity rating (also see Table 6.6 in Section 6.3.5) the overall average is much higher (3.32 stars) compared to reliability (2.69) and scalability (1.48). Especially the restrictions subtopic is rated high for most platforms. The lowest scoring group is “Open Source” with 0.78 stars, while all other groups score at least 0.91 stars on average. The supported messaging protocols subtopic is also evenly rated with all group except the “Others” (0.44 stars) scoring between 0.60 and 0.73 stars. In the device protocol rating, the “Big Players” score the best rating with 0.65 stars just before the “Prototype” group with 0.64 stars and 0.56 stars for the “Others”. The remaining groups all score between 0.40 and 0.44 stars. The SDK support rating is more split up: “Big Players” (0.77 stars) on the one side and “Others” (0.39) on the other side. “IoT Only”, “Open Source”, “Telecoms” and “Prototypes” score between 0.56 and 0.64 stars. In the flexibility rating, the “Prototypes” score the best average with 0.79 stars compared to the other groups between 0.50 and 0.69 stars. Overall, the “Big Players” receive the best average rating for heterogeneity with 3.77 stars with the “Prototype” group closely following at 3.64 stars.

The rating of the remaining topics usability, support and unique features (also see Table 6.8 in Section 6.4.5) is once more dominated by the “Big Players” group. Documentation is rated at least 0.60 stars for all groups but the “Prototypes” (0.43). The “Open Source” group is clearly rated best in the subtopic tutorials (0.89 stars), while the other groups score between 0.18 and 0.46 stars. Examples are best rated for the “Big Players” (0.69 stars), whereas the other groups are rated between 0.29 and 0.44 stars for this subtopic. The “Big Players” group is also best rated in the support subtopic by scoring 0.92 stars on average, but all the other groups score over 0.5 stars on average as well. For unique features, all groups are rated similarly between 0.29 and 0.54 with no clear best or worst group. Overall, this topic is also dominated by the “Big Players” group with 3.46 stars with the other groups following between 2.03 and 2.42 stars on average.

The overall ratings of all platforms are displayed in Table 6.9. The “REL”, “SCA” and “HET” columns represents the overall ratings given for the focus topics reliability (see Section 6.1.8), scalability (see Section 6.2.5) and heterogeneity (see Section 6.3.5). The “USA” column contains the overall rating for the remaining topics (mostly usability, plus support and uniquene features, see Section 6.4.5). The “Total” column shows the combined rating and the final star rating rounded to 0.5 star steps is shown in the last column “Stars”.

Table 6.9: Overview of the final star rating for all platforms for reliability (REL), scalability (SCA), heterogeneity (HET) and usability, support and unique features (USA)

Platform	REL	SCA	HET	USA	Total	Stars
Samsung ARTIK	2.5	1.5	4.0	3.0	2.75	★★★☆☆
Samsung SmartThings	3.0	1.5	3.0	3.5	2.75	★★★☆☆
AWS IoT Core	3.5	4.0	4.0	3.5	3.75	★★★★☆
GE Predix	3.0	2.5	4.5	5.0	3.75	★★★★☆
Google IoT Cloud	5.0	2.0	3.5	3.5	3.50	★★★⯪☆
Siemens MindSphere	3.5	1.0	4.0	4.5	3.25	★★★⯪☆
Azure IoT Hub	4.0	4.0	4.0	5.0	4.25	★★★★⯪
Bosch IoT Suite	3.5	1.5	4.0	4.5	3.38	★★★⯪☆
IBM Watson IoT	5.0	3.5	4.0	3.0	3.88	★★★★☆
Cisco Kinetic	3.0	2.0	4.0	2.0	2.75	★★★☆☆
Alibaba IoT Cloud	3.5	3.0	4.0	3.0	3.38	★★★⯪☆
Oracle IoT Platform	3.5	2.0	3.5	3.0	3.00	★★★☆☆
HPE IoT	3.0	2.0	2.5	1.5	2.25	★★⯪☆☆
Big Players Overall	**3.54**	**2.35**	**3.77**	**3.46**	**3.28**	★★★⯪☆
Aeris IoT Platform	2.5	3.0	3.0	1.5	2.50	★★⯪☆☆
Ayla Networks IoT Platform	3.0	0.0	2.5	2.5	2.00	★★☆☆☆
Davra IoT Platform	2.5	1.5	3.0	1.0	2.00	★★☆☆☆
IoT Software Platform	1.0	0.5	3.5	3.0	2.00	★★☆☆☆
Kaa Enterprise IoT	2.0	2.0	2.0	2.0	2.00	★★☆☆☆
Losant Platform	3.5	2.5	3.5	3.5	3.25	★★★⯪☆
Particle Cloud	2.5	2.0	3.5	3.0	2.75	★★★☆☆
Tago.io	3.5	1.0	4.0	2.0	2.63	★★⯪☆☆
thinger.io	2.0	1.0	3.0	3.0	2.25	★★⯪☆☆
Ubidots Platform	3.5	1.0	3.5	2.5	2.63	★★⯪☆☆
Yodiwo Platform	2.0	0.0	4.0	2.0	2.00	★★☆☆☆
IoT Only Overall	**2.55**	**1.32**	**3.23**	**2.36**	**2.36**	★★⯪☆☆
Blynk	2.5	1.5	3.5	3.5	2.75	★★★☆☆
DeviceHive	2.5	0.5	4.0	2.0	2.25	★★⯪☆☆
DSA	2.5	0.5	3.0	3.5	2.38	★★⯪☆☆
FIWARE	2.0	2.0	3.5	3.5	2.75	★★★☆☆
OpenMTC	2.0	0.0	3.0	3.5	2.13	★★☆☆☆
SiteWhere Platform	3.0	0.5	2.5	3.0	2.25	★★⯪☆☆
thingsboard.io	2.5	1.5	4.5	3.5	3.00	★★★☆☆
WSo2 Server	3.0	1.5	2.0	3.5	2.50	★★⯪☆☆
Zetta	1.5	0.0	2.0	3.5	1.75	★★☆☆☆
Open Source Overall	**2.39**	**0.89**	**3.11**	**3.28**	**2.42**	★★⯪☆☆
Actility ThingPark	2.0	2.0	2.5	0.5	1.75	★★☆☆☆
AT&T M2X	3.0	2.5	4.5	3.0	3.25	★★★⯪☆

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Table 6.9 – continued from previous page

Platform	**REL**	**SCA**	**HET**	**USA**	**Total**	**Stars**
Dt. Tel. Cloud der Dinge	3.5	1.0	3.0	1.0	2.13	★★☆☆☆
Telit IoT Portal	4.0	1.5	2.5	2.5	2.63	★★⯪☆☆
Verizon ThingSpace	2.0	1.0	3.0	2.0	2.00	★★☆☆☆
Telecoms Overall	**2.90**	**1.60**	**3.10**	**1.80**	**2.35**	★★⯪☆☆
Altair Smartworks	3.0	2.5	3.0	2.5	2.75	★★★☆☆
ARM Pelion IoT Platfom	3.0	1.0	5.0	2.5	2.88	★★★☆☆
Cumulocity IoT	3.5	1.5	4.0	2.5	2.88	★★★☆☆
WebNMS IoT Platform	3.0	1.5	4.0	2.0	2.63	★★⯪☆☆
LTI Mosaic Things	1.0	0.5	2.0	0.5	1.00	★☆☆☆☆
Mathworks ThingSpeak	2.0	1.0	2.5	4.0	2.38	★★⯪☆☆
PTC ThingWorx	1.0	1.0	2.0	1.0	1.25	★⯪☆☆☆
Wolfram Data Drop	2.0	0.5	2.0	3.0	1.88	★★☆☆☆
Zebra Zatar	1.0	0.0	1.5	0.0	0.63	⯪☆☆☆☆
Others Overall	**2.17**	**1.06**	**2.89**	**2.00**	**2.03**	★★☆☆☆
Bacsoft IoT Platform	2.0	1.0	2.0	0.0	1.25	★⯪☆☆☆
Huawei OceanConnect	2.5	4.0	3.5	1.5	2.88	★★★☆☆
Macchina.io	2.0	1.0	4.0	2.0	2.25	★★⯪☆☆
Mainflux	2.5	2.0	4.5	1.0	2.50	★★⯪☆☆
Mozilla WebThings	2.0	0.5	4.5	2.5	2.38	★★⯪☆☆
RugDS	1.5	0.0	3.0	1.0	1.38	★⯪☆☆☆
Temboo Kosmos	3.0	1.0	4.0	2.5	2.63	★★⯪☆☆
Prototypes Overall	**2.21**	**1.36**	**3.64**	**1.50**	**2.18**	★★☆☆☆
Platforms Overall	**2.69**	**1.48**	**3.32**	**2.56**	**2.51**	★★⯪☆☆

6.6.3 Remarks

The overall dominance of the "Big Players" group can be traced back to their status as established, top (Fortune 500) companies of the technology sector. Many of the used resources (cloud, partnerships, expertise) were already available for these providers before developing an IoT platform as well. Other platform providers, especially "IoT Only" companies and "Open Source" projects had to get the market to be aware of their products first. Because of this, the fact that eight of the top ten best scoring platforms belong to the "Big Players" group is not surprising (see Table 6.10).

Out of the overall Top Ten platforms eight belong to the Top Ten reliability platforms, seven to the Top Ten of scalability and six are in the ten best rated heterogeneity platforms. Usability, support and unique features are rated best for seven of the overall Top Ten list. Only Azure (rank 3, 1, 7, 1) and AWS (rank 5, 1, 7, 6) belong to the Top Ten for the topics reliability, scalability, heterogeneity as well as usability, support and unique features. Google and IBM, the #1 platforms for reliability lack scalability and heterogeneity (Google) or usability and unique features (IBM). Huawei (overall #13) ranked #1 in scalability together with Azure and AWS, but is not even positioned in the upper half for every other topic. The number one heterogeneity platform ARM Pelion scores an overall

13th place as well, but does not reach the Top Ten in any other topic. Together with Azure, GE predix is positioned at rank 1 for usability, support and unique features, but only ranked 15th in reliability.

Table 6.10: Top Ten IoT platforms

#	Platform	REL	SCA	HET	USA	Total	Stars
1	Azure IoT Hub	4.0	4.0	4.0	5.0	4.25	★★★★⯪
2	IBM Watson IoT	5.0	3.5	4.0	3.0	3.88	★★★★☆
3	AWS IoT Core	3.5	4.0	4.0	3.5	3.75	★★★★☆
-	GE Predix	3.0	2.5	4.5	5.0	3.75	★★★★☆
5	Google IoT Cloud	5.0	2.0	3.5	3.5	3.50	★★★⯪☆
6	Bosch IoT Suite	3.5	1.5	4.0	4.5	3.38	★★★⯪☆
-	Alibaba IoT Cloud	3.5	3.0	4.0	3.0	3.38	★★★⯪☆
8	Losant Platform (IOT)	3.5	2.5	3.5	3.5	3.25	★★★⯪☆
-	AT&T M2X (TEL)	3.0	2.5	4.5	3.0	3.25	★★★⯪☆
-	Siemens MindSphere	3.5	1.0	4.0	4.5	3.25	★★★⯪☆

Despite being in the lowest rated group, the ‘Prototype” platforms of Huawei (3.0), Macchina, Mainflux, Mozilla and Temboo (all 2.5) score promising ratings. We assume these ratings to get even higher once these prototypes are further developed and eventually released to the open market.

Some of the platform providers do not offer very much information on their platforms. Most notably are the platforms of HPE, IoT Factory, Kaa Technologies as well as Verizon ThingSpace and PTC ThingWorx. For these products, there is mostly marketing information without technical depth available. Especially ThingWorx should score a higher rating with more information provided, considering it is or at least was the market leading IoT platform by far at one point (18% with the first following competitor with 4% as of the fourth quarter of 2015 [229]).

7 Conclusion

In this chapter, we provide a summary of the goal, methods and results of this thesis. After that, we will give an outlook on the future of the IoT in general and IoT platforms.

7.1 Summary

The goal of this thesis was to find the “best” scalable IoT platforms by developing our own comparison model and rating system. The focus attributes were reliability, scalability and heterogeneity.

The selection of platforms started with multiple lists found in related work. This starting list was further extended by conducting Google searches which resulted in more platforms and “best of” lists. The full list of platforms was then filtered, thus sorting out products not fitting the definition of scalable IoT platforms (see Section 1.1) or not being updated for twelve months or longer. The platforms of the final list were then grouped by similarilities of their attributes.

The comparison model was split into four topics: reliability, scalability, heterogeneity and the combination of usability, support and unique selling points. The reliability criteria included replication, availability, data encryption in motion and at rest, authentication and authorization, security incidents and audits, development and market longevity. For scalability, we examined hosting options, limits of the infrastructure and software, Edge and Fog Computing and the network and load balancing. Restrictions for devices, programming languages, accessibility via messaging and device protocol as well as flexibility were identified as subtopics of heterogeneity. Usability (including documentation, tutorials and examples), support offering, pricing models and unique selling points were analyzed as additional criteria. The rating system was built on the comparison model.

According to our analysis, the platforms mostly differ in the presence of modules and features, but not the choice of technologies and algorithms. Most criteria are implemented similarly by most platforms. The rating is dominated by the “Big Players” group with an average that no single other platform could pass. The same group also scored the best average rating for every topic and is represented by eight platforms in the overall Top Ten list with the first non-“Big player” platform listed on #8. The best rated platform is Azure IoT Hub with 4.25 out of 5 stars, followed by IBM Watson IoT (3.88 stars) and AWS IoT Core and GE Predix (both 3.75 stars). Huawei’s prototype platform OceanConnect shows a promising result of 3.0 stars.

Overall, many platforms offer great value in our focus topics reliability, scalability and heterogeneity. While the analyzed platforms still can be improved in many subtopics, the top four to ten platforms are already in a promising state of development and especially the platforms of the “Prototype” group can be expected to improve a lot over the next years. In the Gartner Hype Cycle of 2018 IoT platforms were almost over the peak of inflated expectations with an expected duration of five to ten years to reach the plateau of productivity. The IoT in general is expected to reach the plateau of productivity over the next five years [257, 258] and multiple subtopics (Digital Twin, Smart Workspace and IoT Platforms) are on the way to productivity as well [318].

7.2 Limitations

In the selection of platforms in Section 5, we adopted three steps of the systematic method of [205], but not the fourth and final step. Including this step called “cited reference analysis” might isolate the more relevant platforms before the filtering step and/or extend the list of platforms even more.

In our rating system platforms that are not having much information public could actually have a better score than given in this thesis, as such platforms received zero stars when there was no information on a certain topic. These negative cases may be a threat to the validity of our results. More information on the affected topics may improve their ratings.

Another threat of validity is the fact that we mostly used the websites and documentations made by platform providers themselves as our sources for information on the platforms. Triangulation of multiple views can get a more accurate picture of the reality. In this case insights of customers and users could change the result given in information provided by the producer - especially the ratings of the platforms. Actually using these platforms for and comparing them in consideration of one or multiple specified IoT use cases instead of just analyzing written information on them may give other views for triangulation to get a more accurate result.

We also did not weigh any criteria over others. For users or developers different criteria might be more important than others. These differences in priority are not represented in this thesis.

7.3 Outlook

With a big amount of platforms on the market already, the IoT is connecting more things everyday, thus influencing our daily life more and more. Started with the domain of home and personal use and continuing with enterprise applications, the IoT is already taking influence in many environments [195]. The development of global addressing schemes such as IPv6, devices with low power and thin batteries as well as security in RFID and cloud environments paved the way for IoT applications in the home and personal domain. Networked sensors (things in the IoT), cloud computation as a service and intelligent analytics made the move to enterprise IoT possible. The next step is to use the IoT to enable the utility domain by creating self adaptive systems and further enhancing security for the IoT and the transportation domain by realizing connected vehicles and automated driving. Gubbi, Jayavardhana et al. [195] describe the “end goal” as having “Plug n’ Play smart objects which can be deployed in any environment with an interoperable backbone allowing them to blend with other smart objects around them”. This could mean that the IoT will be omnipresent and an integral part of our every day life in 2025 and beyond.

However, there are challenges that still have to be solved. Energy efficiency is important as things do not often have a lot of space for batteries and computing units needed to connect them to the network. Security is always a concern in network technologies and distributed systems as well. And - as shown by the analysis in this thesis - the level of standardization is still very low which needs to be improved for better communication and interoperability.

7.4 Future Directions

To get more accurate ratings on the selected IoT platforms, testing the platforms on a practical level could be a next step. Using a platform and developing applications for one or multiple specific scenarios can give a lot more insight and an even better basis for a comparison and rating. Possible scenarios could include Smart Home applications. Security testing and benchmarks may provide a basis for a more in-depth comparison as well.

In terms of quantitative analysis, more information may be accessible by interviewing the developers or distributors of a platform. Inspecting the code of open source platforms may give a deeper insight on some of the criteria as well.

For improving the qualitative analysis, specific use cases or scenarios could give a more accurate subjective rating as well. Analysing the platforms with regard to multiple different scenarios may reveal more specific strengths and weaknesses of a platform.

Priorities in criteria can be researched and integrated in the rating system as well. Surveys or reviews may show what attributes are more important in an IoT platform for users and developers.

To summarize, there are multiple IoT platforms on the market that objectively already offer great value in reliability, scalability and heterogeneity. The best rated platforms are provided by big IT companies listed in the Fortune 500 list, the best rated platform overall is Microsoft Azure IoT Hub. Challenges that are still to solve in the platform market include energy efficiency, security and standardization. If the platform providers surmount these challenges over the next years, we may be living in a world where not only every person is connected, but also every thing.

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A Zusammenfassung

In der heutigen Welt verbindet das Internet nicht nur Menschen, sondern auch Dinge. Das Konzept „Internet der Dinge (engl. Internet of Things, IoT)“ beschreibt die Idee, materielle Gegenstände mit dem Internet zu verbinden. IoT Plattformen bieten einen Rahmen für Anwendungen in Bereichen wie Smart Home, Connected Vehicles und industriellem IoT.

In dieser Arbeit untersuchen wir die Frage nach der besten IoT-Plattform mit dem Fokus auf Zuverlässigkeit, Skalierbarkeit und Heterogenität. Um diese Frage zu beantworten, durchsuchen wir den Markt nach IoT Plattformen und Prototypen, vergleichen diese mit einem Fokus auf Zuverlässigkeit, Skalierbarkeit und Heterogenität basierend auf unserem Vergleichsmodell und bewerten die Plattformen in einem Fünf-Sterne-System. Die Kriterien für die Teile des Vergleichsmodells umfassen Replikation, Verfügbarkeit, Authentifizierung und Autorisierung, Verschlüsslung, Sicherheitsvorfälle und –prüfungen, Entwicklung und Marktlebensdauer für Zuverlässigkeit, Hosting, Edge- und Fog-Computing, Grenzen der Infrastruktur, Netzwerk und Lastenausgleich für Skalierbarkeit, Geräteeinschränkungen, Nachrichten- und Geräteprotokolle, Programmiersprachen und Flexibilität für Heterogenität sowie Benutzerfreundlichkeit, Preismodelle und Alleinstellungsmerkmale.

Wir stellen fest, dass sich die meisten Kriterien nicht in den verwendeten Technologien oder Algorithmen unterscheiden, sondern ob sie implementiert sind oder nicht. Trotz des geringen Standardisierungsgrades werden die meisten Kriterien plattformübergreifend auf ähnliche Weise umgesetzt. Die insgesamt am besten bewertete Plattform ist Microsoft Azure IoT Hub mit 4,25 von 5,0 Sternen, gefolgt von IBM Watson IoT (3,88 Sterne). Auch der Plattform-Prototyp OceanConnect von Huawei zeigt vielversprechende Ergebnisse (3,0 Sterne).

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

Stuttgart, 28.5.2019 Stefan Hill

place, date, signature