Decentralised IoT Architecture for Efficient Resources Utilisation

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Abstract: The exponentially growing number of devices connected to the Internet, the diversity of the Internet of Things (IoT), and the variety of IoT protocol stacks yield to concerns about IoT sustainability. A promising solution is in IoT integration platforms which can address challenges such as interoperability, scalability and adaptability surrounding IoT. Current implementations of IoT platforms are based on centralised architectures, yet a decentralised IoT architecture with logic moved to the (network) edge can offer several benefits to IoT platforms and devices. This paper identifies the feature set that a decentralised IoT platform should have. Based on the determined features, a general decentralised IoT architecture is proposed for efficient resource utilisation.

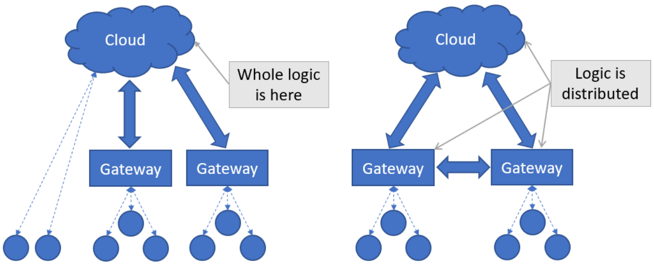
Keywords: Internet of Things, decentralised architecture, resource utilisation, efficiency, optimisation.

1. INTRODUCTION

Internet of Things (IoT) is a highly discussed paradigm aimed at connecting everyday devices to the Internet. It empowers the systems with the ability to sense and control the environment around us. However, as the number of IoT devices and the expectations towards the system increase, communication issues between IoT solutions will inevitably emerge. These subsequently lead to concerns about sustainability, in particular, issues related to interoperability, scalability, and adaptability. In addition, as IoT applications are often deployed in constrained environments using low-cost devices with limited computing and power resources, the execution of computationally intensive operations as well as the service life present further challenges.

A promising solution to improve IoT sustainability are IoT integration platforms. IoT platforms provide the foundation for connecting devices to the Internet, acquiring the generated data, and processing them in a meaningful way, i.e. they offer a standardised way to manage the connected devices.

The first wave of IoT platforms placed the control, operational and computational logic in a geographically centralised location, most commonly in the cloud (Fig. 1(a)). Amazon Web Services, Microsoft Azure, and IBM Bluemix are just a few examples of cloud platforms which found their place soon in production. However, although centralised architectures offer a simplified control and management, in practice, all the data must be forwarded to a central controller located in the cloud before any decision making can take place. Since several forwarding devices must be involved in the communication between the end devices and controller, centralised approaches often lead to unnecessary increase in the traffic utilisation and load of resources. A recent study on IoT network architectures performed by Verma et al. (2017) has shown that centralised solutions will face challenges in handling the increased number of IoT devices and the growing demands of users and services.



(a) Centralised architecture (b) Decentralised architecture

Fig. 1. Types of IoT architectures

Edge computing driven IoT platforms represent an alternative approach which moves part of the decision-making capabilities from the cloud to the network edge, e.g gateway, intermediate device, etc. (Fig. 1(b)). In contrast to centralised architectures, the advantage of distributing the logic between the devices throughout the entire network is the significant reduction of transferred data, which consequently leads to the decrease of communication delay and utilisation of resources including cloud services. IoT platforms based on the decentralised architecture also perform better in environments in which a high number of connected devices communicating over an unreliable and constrained network produce a large amount of data.

On the contrary, decentralised architectures bring a certain complexity into the management process. In consequence, they create a trade-off between the complexity of management and efficient utilisation of resources. However, as communication complexity challenges can be overcome with an appropriate architecture design, to address sustainability related challenges, we have decided to shift away from traditional approaches and propose a decentralised IoT architecture. This architecture is based on considerations, such as, the method for runtime monitoring including available resources and utilisation, operational requirements and costs, as well as, system adaptation to prolong the service life of battery-powered devices.

The contribution of this paper is threefold. First, we identify the optimal set of features required by a generalised form of decentralised IoT platforms. Second, we describe a novel approach for efficient resource utilisation. Third, we specify the structure of the overall architecture.

The rest of this paper is organised as follows. Section 2 describes the motivation and related work. Section 3 presents the optimal feature set for decentralised IoT platforms. Section 4 introduces a concept for achieving efficient utilisation of available resources, whereas a proposal of a decentralised IoT architecture is analysed in Section 5. Finally, Section 6 draws a conclusion and provides directions for future work.

2. MOTIVATION AND RELATED WORK

In a real-world environment, several factors influence IoT sustainability, including the heterogeneity and relocatability (e.g. static or mobile) of the devices, topology interconnecting the nodes, and condition of the environment. These factors are all present in the most common IoT application domains starting from smart manufacturing and retail (Lojka et al. (2015)), through smart buildings and living (Mekki et al. (2017)), smart agriculture (Paraforos et al. (2016)), up to smart city (Djahel et al. (2015)). An equally important factor is the type of energy source used to power the devices. Currently, either mains, batteries, renewable energy sources or the combination thereof are used. Among them, IoT devices are usually battery-powered (Somov and Giaffreda (2015)). Since resource utilisation, including power consumption, is a major concern in current solutions, it becomes essential to efficiently utilise the power sources in order to extend their lifespan. However, determining the optimal configuration is a challenge itself.

Network traffic characteristics as well as the environment can change rapidly over time depending on various factors such as reconfigurations, failures in the topology, the time of the day, whether is there an anomaly or only standard data transmissions are performed. Static or manual configuration becomes unfeasible due to the continuously changing conditions. A decentralised IoT platform with dynamic decision making and intelligent (re)configuration placed at the edge represent a paradigm which could be a step forward in utilising efficiently the available resources. However, although improvements can be hypothetically achieved, as the number of the variables that need to be considered rises, the complexity and computing demands of the entire system are increasing as well. As a result, this can similarly lead to efficiency drop in resource utilisation. Considering the above mentioned, our targeted research question can be formulated as follows:

What is the (1) optimal decentralised IoT architecture design suitable for (2) obtaining, selecting and using information to (3) achieve improvements in resource utilisation?

The architecture design of IoT platforms has been discussed by several works. Sarkar et al. (2014) proposed a scalable distributed architecture tackling characteristics like heterogeneity, scalability, interoperability, automation, zero-configuration and distributiveness. They introduced a three-layered architecture design aimed at supporting multi-application use cases with minimum management effort. This was achieved using distributed intelligence empowered devices which process the data and make decisions at the edge without the need for centralised logic in the cloud. However, as centralised computing can be beneficial in circumstances when, for example, further analysis or accounting is required, abandoning the cloud entirely should be avoided. In addition, the problem of energy efficiency was not addressed.

Datta et al. (2014) introduced an IoT architecture with a wireless gateway as the main intermediate device responsible for interactions between the sensors (actuators) and mobile clients. This gateway-centric approach consists of south and north interfaces that use generated metadata to expose the capability of the devices to mobile clients. A similar effort by Vallati et al. (2016) proposed a distributed architecture also utilising gateways. They claim that their platform implementation called BETaaS simplifies the deployment of horizontal solutions by exposing a unified service oriented interface to access things. Although these proposals discuss viable architecture design ideas including distributed logic, scalability, and interoperability, they fall short of addressing the challenges of resource utilisation.

Likewise, energy efficiency plays a vital role in the lifespan of IoT devices, and therefore should deserve more attention. Yet, there are only a few efforts targeted at energy efficiency. Rault et al. (2014) developed various mechanisms for improving resource efficiency, and Liu et al. (2014) focused on both ensuring Quality-of-Information (QoI) as well as energy efficiency in sensory environments. However, these consider only a small number of factors (characteristics) influencing the sustainability of IoT.

In contrast to the above-mentioned research, energy efficiency and resource utilisation are the key emphasis in this paper. In addition, we also reevaluate the expectations of decentralised IoT platforms and extend the optimal feature set with additional features such as multi-network approach and simplified device management (both central and individual).

3. OPTIMAL FEATURE SET FOR DECENTRALISED IOT PLATFORMS

Centralised architectures often perform inefficiently in present IoT environments. Efficient data processing, decision making and resource utilisation require new approaches such as a decentralised IoT platform. Obviously, to ensure its sustainability, an appropriate design is essential but itself a challenge, let alone an optimal design. As a step forward, we have identified the network traffic characteristics of the most common IoT services, categorized into eight application domains as per Mocnej et al. (2018). In particular, we examined *smart buildings and living, smart healthcare, smart environment, smart city, smart energy, smart transport and mobility, smart manufacturing and retail,* and *smart agriculture* from the perspectives of three user groups, *individuals, society,* and *industry.* One observation deduced from this study is a set of features that a decentralised IoT architecture of the future should meet. These features are as follow:

Feature 1. Multi-network approach – an IoT platform is destined to connect devices regardless of the underlying network technology in use. IoT is diverse and since different constraints may require different solutions, many network technologies exist designed specifically for different parts of the IoT. Ideally, an IoT platform should enable communication with all heterogeneous devices in a standardised way by hiding the underlying network technologies.

Feature 2. Scalable and interoperable implementation – the shift from application-specific to application-independent solutions is highly desired. As the conditions and expectations of IoT application domains may dynamically change over time, an adaptive IoT architecture should recognise and react to these changes in a timely manner. In conclusion, an IoT platform of the future needs to be scalable and non-invasive, and ready to integrate new applications in any circumstances.

Feature 3. Low power consumption – low power consumption and efficient utilisation of resources must be a priority to achieve the desired sustainability of the solution. An IoT platform should therefore support mechanisms such as event-driven M2M (Verma et al.) communication and other optimisation methods to achieve improvements in energy utilisation.

Feature 4. Intuitive data and device management – to keep pace with the rapid development and innovation, efficient device control and data collection should be present in IoT by design. A platform should support both individual and central management for accessibility, control and modifications. Furthermore, many routines should be automated to make the configuration process simpler and more intuitive.

Feature 5. Artificial Intelligence at the edge – Artificial Intelligence (AI) and Machine Learning (ML) are gaining on popularity year by year. Today, they are utilised in the vast majority of technologies and services. IoT is not an exception where AI is most commonly utilised in the cloud to provide a number of improvements. However, in the case of a decentralised architecture, part of the services should be moved from the cloud to the network edge including AI. The most suitable device for hosting AI is an unconstrained gateway which offers reasonable computing resources and sustained energy source. A decentralised IoT platform should be also designed to support context-awareness.

These five key features have been carefully incorporated into the architecture of our proposed decentralised solution.

4. A CONCEPT FOR ACHIEVING EFFICIENT RESOURCE UTILISATION

Our objective is to achieve improvements in the utilisation of available resources. Available resources denote connected devices providing sensing/actuating services to the IoT platform. How these resources are utilised depend on the applications implemented in the platform and their requirements (expectations). Since the requirements may change over time (which subsequently affects the resource utilisation), the individual changes have to be tracked and recorded over time. This requires:

(i) *Monitoring the platform in runtime* to obtain insight into the system and its processes;
(ii) *Ensuring the desired quality of the output* by taking the appropriate measures; an example output would be optimal subset of active resources for a particular scenario;
(iii) *Optimising the utilisation of available resources.*

In the following, these three research topics will be discussed in more details. In general, tasks (i)–(iii) represent our main research topics.

4.1 Monitoring IoT Platforms in Runtime

To monitor IoT platforms in runtime, a number of measures can be used:

- Quality of Device (QoD) – is responsible for expressing the quality of a particular device and can monitor various attributes, including, but not limited to, battery life, precision, and sending rate (Buchholz and Schiffers (2003)).
- Quality of Service (QoS) – uses attributes such as bandwidth, delay, jitter, and packet loss to monitor the performance characteristics of the network (Bhuyan et al. (2010)).
- Quality of Information (QoI) – characterises the fitness-for-use of data, and therefore is suitable for measuring the quality of the obtained data from a particular device but can also define the quality of the output by using attributes like accuracy, precision, and freshness (Bisdikian et al. (2013)).

Fig. 2 depicts an IoT integration scenario of these measures, i.e. QoD for end device monitoring, QoS for network performance monitoring, and QoI for transferred data quality monitoring is used. One advantage of these measures is that, although they are principally destined to describe a specific part of a system, when used together, they can also provide performance overview of the entire system.

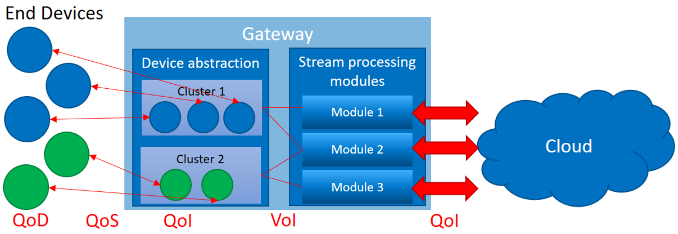


Fig. 2. Implementation of measures in an IoT integration scenario.

4.2 *Ensuring the Desired Output Quality*

The applications determining the requirements (expectations) for the resources are communicating through gateway(s) where each application has its own stream processing unit as per Fig. 2. In general, both the requirements and the capabilities of the resources can be expressed as functions with QoI attributes. To ensure the desired output quality the correlation between these functions have to be identified. To achieve this, we define a further measure:

- Value Of Information (VoI) – deals with an assessment of the information utility for a specific use case scenario using attributes such as relevance, integrity, timeliness, and understandability (Bisdikian et al. (2013)).

From a decentralised architecture perspective, we can utilise this measure to evaluate the significance of resources for an application. More specifically, by leveraging VoI a subset of optimal resources can be selected for every stream processing module. This provides an option to determine what constitutes to the desired output quality and under what conditions this quality can be achieved.

4.3 *Optimising the Utilisation of Available Resources*

Assuming Section 4.1 and Section 4.2 are achieved, the utilisation of available resources can be optimised. Since the majority of IoT devices is constrained (e.g. by their battery lives), it is preferred to utilise them efficiently. Keeping the transceiver powered on of a device is an energy expensive task, as shown by Harrison et al. (2016).

Therefore, one approach to extend the lifespan is to power off those battery-powered devices which generate duplicate data or whose absence is acceptable by any stream processing. In general, this represents an optimisation problem of finding a subset of active devices that would minimise the overall consumption of limited energy resources in the network while satisfying at the same time the requirement of minimal output quality. Another approach is to predict the sensed value of a device rather than powering it on to execute its task(s). This subsequently leads to the minimisation of communication between the devices and the gateways, extending the lifespan. Prediction could be realised as long as QoI of a device satisfies the minimum requirements, which could be specified by the stream processing modules and affected by the dynamics of the environment.

Consequently, our approach consists of duty-cycling and adaptive sampling for controlling the power plans and sending rates of devices to conserve their energy. We particularly highlight the significance of the following three power plan modes to achieve optimal energy efficiency: (1) OFF; (2) ON and sensing; and (3) ON and transmitting.

5. DECENTRALISED IOT ARCHITECTURE

Our decentralised IoT architecture is composed of three main functional blocks: *end device*, *gateway* and *cloud*. We provide a stack diagram for the end device and gateway blocks which outline the modules and their function.

5.1 *End Device*

The computing capabilities of end devices can be diverse. This fact was taken into consideration when the three-layered architecture depicted in Fig. 3 was proposed. The description of the individual layers is as follows:

- *Connectivity abstraction layer* – is responsible for connecting a device to a network. The layer includes a single module called Connectivity SDK that hides the underlying network technology and provides the standardised communication capabilities for the upper layers.
- *Device services layer* – defines services necessary for each device to efficiently utilise its resources. This layer contains four modules:
  - data filtering – is responsible for a very simple and lightweight selection of important data from all sensed values.
  - communication service – uses communication capabilities from Connectivity SDK and wraps them to the publicly accessible functions. It also provides a way to remotely control the services of devices.
  - power plan – manages how a device uses power to achieve Feature 3. By default, it supports at least three power plans - ON, ON with a transmitter turned off, and OFF.
  - Over-The-Air (OTA) – permits updates over the air to always keep a device's software up-to-date.
- *Custom application layer* – for a device serving a particular task. It can also enhance the supported functionalities if a device has enough computing resources. An application is installed on a device during its manufacturing process but can be later modified by the OTA module.

5.2 *Gateway*

Since a gateway usually has unconstrained power resources, it can be utilised to support computing-intensive tasks to minimise the load (e.g during decision making)

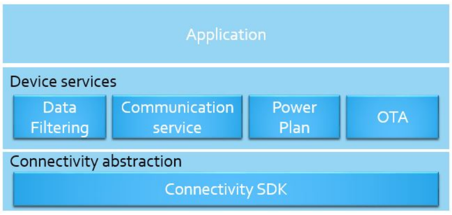


Fig. 3. End device architecture.

of other IoT devices. The architecture showed in Fig. 4 contains three main functionalities: connectivity, end device management, and data management. *Connectivity* is an essential functionality of the gateway provided by the lower layers of the architecture. To ensure the conformity of our solution with Feature 1, in the *connectivity abstraction layer* we implement public and well-known IoT specifications such as those defined by OCF[1] or OneM2M[2]. However, our approach is not limited to only these standards. Custom communication protocols can be implemented using a designated custom module. All connectivity abstraction modules are unified by the *network manager*, which is responsible for the interactions between the services residing at higher layers and connectivity functionalities at the lower layers.

End device and data management functionalities are provided by the *gateway services layer*. In general, this layer is responsible for providing Feature 5. When data from a network arrives at the inbound interface of a gateway, it is processed by the data services module. This module provides functionalities such as QoI measurement and prediction. The obtained data are subsequently transferred to the stream processing module which is the pipeline for various custom applications. Data selection by these applications from the pipeline is performed based on the significance level expressed by VoI. When the appropriate input is determined, applications continue in the execution of their tasks. Application outputs can be further processed in a number of ways. One option is to pass the data to the end devices or another gateway directly. Another option is to store the output in a temporary database and forward it later (if real-time forwarding in not necessary) to, for example, the cloud.

The interaction between the individual blocks and modules including the type of communication and measurement method is depicted in Fig. 5. An important component of loosely coupled systems is service orchestration. It provides an efficient way to define functionalities as small independent services which are added to a central list and linked together. This approach is more efficient than presenting all functionalities as one complex application since this way services can be dynamically modified over time, ensuring Feature 2. Service orchestration based on service-oriented architecture (SOA) is implemented in our solution at the *service orchestration layer*.

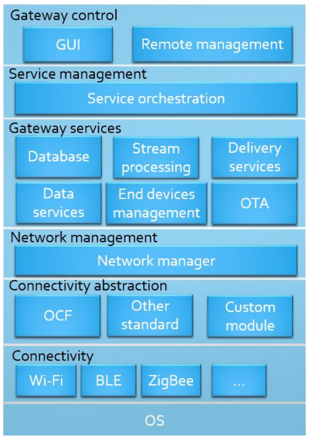


Fig. 4. Gateway architecture

Lastly, we offer the options for gateway communication: (1) via a user-friendly GUI and/or (2) remote connection using the exposed API. This way, both simple as well as advanced gateway control is achieved, ensuring the satisfaction of Feature 4.

5.3 The Cloud

Due to the number of services offered by providers, cloud solutions present an advantageous foundation for IoT solutions and cloud-based IoT solutions have already been proposed (Zhou et al. (2013); Hou et al. (2016)). From the perspective of our architecture, one important service we would like add is network management. The *network management service* module provides control of the entire network from a centralised place. It utilises the acquired metadata to generate the scheme of the network and subsequently provides the user with a way to execute configuration changes and updates without the need for connecting to every single gateway individually. Its main advantage is to deliver a solution using a system which can be configured once and then deployed everywhere. This intuitive data and device management at a centralised place satisfies Feature 4.

6. CONCLUSION

This paper addresses the problem of achieving sustainability in diverse IoT platforms. Although the current wave of IoT platforms is based on centralised architectures, we outlined the benefits of decentralised architectures, especially when deployed in a complex real world environment.

The main contribution of this paper is the concept of a decentralised IoT architecture. This architecture incorporates five key features a decentralised IoT platform of the future should meet. Based on these features we proposed a solution intended to optimise the resource utilisation of IoT components. Lastly, we also presented the functional blocks of our proposed approach along with some key modules and features.

Future work will be aimed at the optimisation process for improving resource utilisation. To achieved this, the individual research topics (see Section 4 have to be investigated in greater details as each of them reveals further open issues and presents new challenges. Future work will also be focused on the development of a prototype based on the proposed decentralised IoT platform that will be used for evaluating the methods and procedures proposed to address IoT challenges.

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[1] `https://openconnectivity.org`

[2] `http://www.onem2m.org`

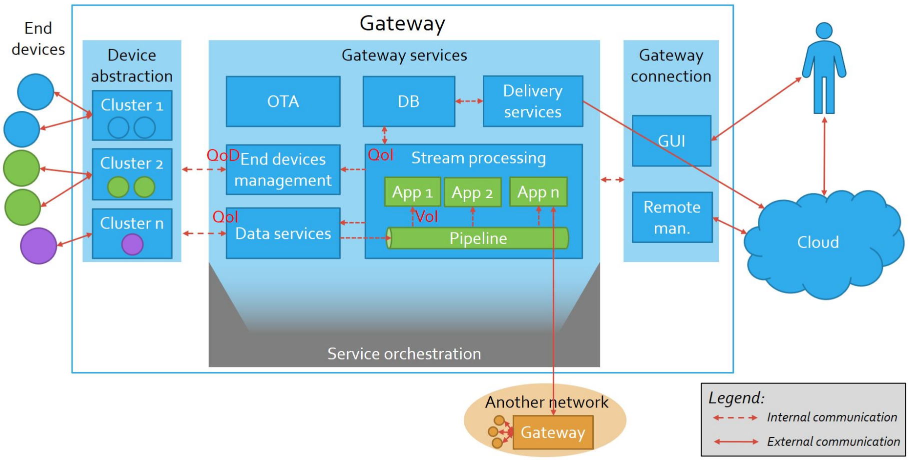

Fig. 5. Interactions between the functional blocks and modules.

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