TU WIEN Informatics

Wärmenetz 4.0

IoT Lösungen für intelligente Wärmeversorgungsnetze

BACHELORARBEIT

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TU WIEN Informatics

4th Generation District Heating

IoT Solutions for Smart Heat Networks

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Wien, 9. September 2021

Péter Szentkuti

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Kurzfassung

Die Vernetzung physischer und virtueller Geräte hat in allen Technologiebereichen zur Entstehung von neuen Geschäftsmodellen geführt. Dieser Vorgang ist für die Industrie von besonderer Bedeutung und ermöglicht die verbesserte Überwachung und Steuerung von Anlagen. Die mit dem Begriff Industrie 4.0 einhergehenden Spezifikationen und Technologien ermöglichen eine umfassende Digitalisierung der industriellen Produktion. Ein Anwendungsbeispiel dafür in der Großindustrie sind Fernwärmesysteme, die ebenfalls von technologischem Fortschritt und Wandel betroffen sind. Dieser Prozess wird zusätzlich verstärkt durch die Forderung nach besserer Nutzung der vorhandenen Ressourcen unter besonderer Berücksichtigung der Nachhaltigkeit.

Diese Arbeit konzentriert sich auf die Anwendung von Internet of Things (IoT) basierten Ansätzen in der Fernwärmeindustrie. Diskussionsgrundlage ist das von der Wien Energie GmbH betriebene Fernwärmesystem von Wien. Das Problemszenario wird sowohl im Austausch mit Stakeholdern als auch durch eine eigenständige Analyse der vorhandenen Systeme untersucht. Der vorgestellte Ansatz basiert auf Standardmethoden und Vorgehensweisen aus den Bereichen der System- und Anforderungsanalyse. Nach der Problemanalyse werden 4 Hauptziele identifiziert. Das Ergebnis der Anforderungsanalyse und die daraus abgeleiteten Ziele dienen dabei als Grundlage für den Entwurfsprozess. Darauf aufbauend wird ein Konzeptentwurf für folgende Bereiche vorgestellt: die Definition einer Middleware-Schicht, die Einführung von Edge/Fog-Praktiken und der Einsatz einer Kommunikationstechnologie zur Unterstützung dieser Bereiche. Die vorgestellten Konzepte zeigen das Potenzial von IoT-Ansätzen zur Verbesserung der Effizienz, Zuverlässigkeit und Flexibilität von Fernwärmesystemen.

Abstract

The interconnectivity of all physical and virtual devices has led to new approaches emerging in all areas of technology. This process is of particular importance for industrial practices, enabling their improved oversight and control. Its specifications and goals, laid down in the Industry 4.0 initiative, have grown well beyond a mere change in perspective, entailing a complete restructuring of the industry. As a large-scale industrial application, district heating systems are also facing a need for technological development and transition. This is complemented by a demand for better utilisation of existing resources, while paying special attention to sustainability.

This work focuses on the enablement of Internet of Things (IoT) based approaches in the district heating industry. The especially promising change of perspective brought on by the combination of Industry 4.0 methods and the IoT paradigm is a central theme throughout this thesis. The district heating system of Vienna operated by the Wien Energie GmbH serves as a use case. The problem scenario is explored through interaction with stakeholders and an analysis of systems in place. The presented approach is founded on standard methods and tools from the areas of requirements engineering and systems analysis. Having gained an understanding of the problem, 4 main objectives are identified. The output of the requirements engineering phase and the derived objectives serve as guidelines for the design process. Based on these, a concept design concerning the following areas is presented: definition of a middleware layer, introduction of edge/fog practices and a new communication technology to support them. Though limited in scope, these proposals reveal the potential of IoT approaches in improving the efficiency, reliability and flexibility of district heating systems.

Contents

CHAPTER 1

Introduction

1.1 Motivation

The global network of connected people, organizations and computer systems is growing at a rapid pace, fundamentally changing our environment and interactions. This extensive system, commonly referred to as the Internet of Everything (IoE) [MAEP15], is a main driver in transforming all human-made systems. At the forefront of said process is the Internet of Things (IoT), the incorporation of physical and virtual devices into a network; enabling their utilisation, management and supervision as a cohesive unit. These capabilities are today viewed as essential in any modern industrial setting, however they are the result of a long technological and social evolution, encompassing multiple subsequent phases of development, known today as the industrial revolutions. At the confluence of IoT and industrial advancement is Industry 4.0, the fourth industrial revolution, which aims to increase productivity by automating traditional manufacturing and production practices using smart technology.

As a large-scale industrial application, district heating systems are also facing a need for technological development and transition. The level of distribution and magnitude of interacting elements that is present in such a setting means an especially high potential for improvement in efficiency, reliability and flexibility through the adoption of Industry 4.0 practices [Lyo19]. At the same time, the complexity of the scenario translates to an increased need for foresight and planning when considering possible approaches. While various industry standards and efforts assist decision makers and engineers, there is a high demand for application specific tailored solutions.

The realisation of the Industry 4.0 vision means more efficient operation and better supervision of system resources in the case of district heating systems. This translates not only to savings in costs for both provider and consumer but also to more reliable operation through continuous optimisation and early detection of malfunctions.

1.2 Problem statement

Wien Energie GmbH (Vienna Energy Company) is the largest regional energy provider in Austria and a subsidiary of the municipal utility company Wiener Stadtwerke. Supplying 380.000 households and 6.800 business clients with district heating, Wien Energie is operating an extensive network of stations and heating plants all over Vienna. Apart from district heating, the organisation is also providing access to electricity, natural gas and infrastructural solutions. Figure 1.1 shows a simplified view of the district heating system of Vienna.

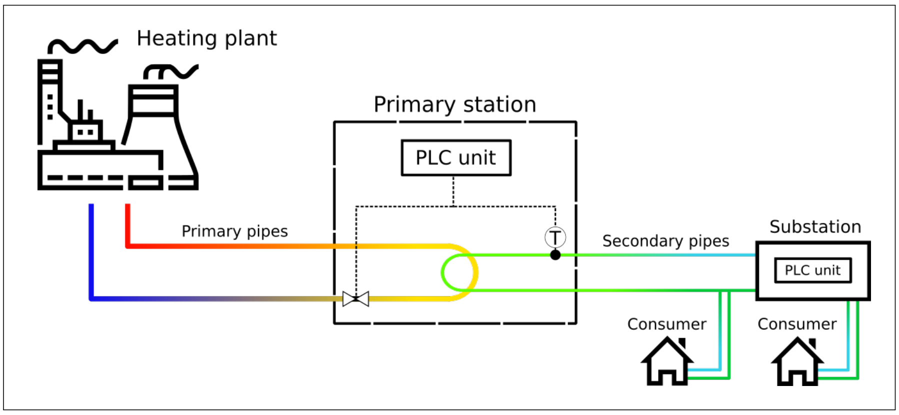


Figure 1.1: An abstract view of the district heating system of Vienna

Several heating plants around the city are producing hot water ranging in temperatures between 80 °C and 180 °C directed into a primary network of pipes. Areal heat exchange stations transfer heat between the primary and secondary networks. The temperature of the secondary district heating networks varies according to the ambient temperature between 63 °C and 90 °C. Return temperatures are usually lower; around 60 °C for the primary and 40 °C for the secondary pipes. Consumers are either connected through one of the 2000 substations or by tapping directly into the secondary network. The vast majority of stations are regulated by a Programmable Logic Controller (PLC) unit, controlling valves and reading technical parameters, such as water pressure and various temperature values. Thus, their connectivity is crucial for monitoring and overseeing operation. Currently, however, only 60% of areal stations and only 20% of substations are connected. These figures are even worse for remote control capability and real time data access; 25% and 2% respectively in the case of areal stations, while the integration of substations is still in an experimental phase. These low numbers can be attributed to an array of factors: technological heterogeneity and its resulting technical debt [RSZ19], the high level of geographical distribution and the lack of standardised interfaces between levels of system hierarchy. Addressing these challenges, the main focus of this thesis is to explore and discuss different IoT approaches which could enable and enhance the integration of heating stations into the IT infrastructure of Wien Energie.

1.3 Methodology

The presented approach is based on the comprehensive understanding of the problem at hand through the analysis of requirements and systems in place. Stakeholder interviews and walkthroughs are conducted with involved members of staff at Wien Energie. Documentation of this phase is supported by industry standard methods and tools, such as use case diagrams, their accompanying scenarios and a requirements specification. Having gained an overview of the problem setting, the next step is to study existing literature regarding relevant research and available experience from the field. The resulting findings are then used to discuss and compare possible solutions, focusing on 3 key areas: definition of a middleware layer, introduction of edge/fog practices and a new communication technology satisfying the changed requirements. To enable the integration of these paradigms into the infrastructure of Wien Energie, a concept design is proposed and evaluated through the definition and subsequent inspection of 4 design goals.

CHAPTER 2

Related Work

This chapter surveys research done in the IoT area, focusing on the Industrial Internet of Things (IIoT) and other related concepts relevant to the main theme of this thesis. These include applications in the energy sector, system architectures and connection technologies. Special attention is put on literature discussing smart solutions aimed at district heating systems. The goal of this chapter is to explore paradigms and approaches which can serve as foundation for the applied part of this work.

2.1 Industrial IoT

The emergence of the IoT paradigm has brought about rapid changes within the development, design, and integration of technology. Promising ubiquitous connection to the Internet, IoT paves the way for creating pervasively connected infrastructures to support innovative services and promises better flexibility and efficiency [SSH$^+$18]. These advantages make IoT attractive not only for consumer applications, but also for the industrial domain. The subcategory of IoT, covering the industrial scale use of automated, interrelated sensors, devices, and machinery is referred to as the IIoT. [BHCW18] defines IIoT it as follows:

> A system comprising networked smart objects, cyber-physical assets, associated generic information technologies and optional Cloud or Edge Computing platforms, which enable real-time, intelligent, and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment, so as to optimise overall production value. This value may include; improving product or service delivery, boosting productivity, reducing labour costs, reducing energy consumption, and reducing the build-to-order cycle.

This definition can be further extended to not only include machines and their connections, but also their human interfacing units [Gon09]. [KDB+19] analyzes the IoT concept and positions it in relation to Cyber-Physical System (CPS): ordinary objects embedded with smart components form constituents of CPS. This enables the further discussion of the concept, approached from a purely industrial standpoint presented in the next section.

2.1.1 Industry 4.0 and the Energy Sector

Originally defined in Germany, the Industry 4.0 concept has gained a global recognition and it is nowadays universally adopted for addressing the use of Internet technologies to improve production efficiency by means of smart services in smart factories. While IIoT and Industry 4.0 are similar terms, they cannot be used interchangeably [SSH+18]. The concept of Industry 4.0 arises when the IoT paradigm is merged with the CPS idea [WSJ17]. CPSs extend real-world, physical objects and provide digital representations for them. As a consequent benefit, such information stored in models and data objects can be updated in real time [SSH+18]. This enables the monitoring and control of equipment and processes, lowering the risk of loss of production or a complete interruption of service.

The main issues faced by operators of legacy systems within the energy sector are a reduction in reliability and efficiency. The age of equipment and its increased need for maintenance leads to financial losses and an increased environmental impact, elevating the problem to a global level. Assets are sometimes more than 40 years old, expensive, and difficult to replace. In these cases, IoT solutions can effectively address challenges in the management of power systems. By monitoring sensor values, connected devices are able to detect any malfunction or decrease in efficiency, signalling the need for maintenance. Consequently, the reliability and efficiency of the system is increased, at the same time, reducing maintenance costs. [HMMHZ20]

2.1.2 District heating

The efficacy of district heating systems is often underwhelming due to a lack of insight over ever-changing operational conditions and inefficient management of heating networks [LZL21]. To address these shortcomings, IIoT and Industry 4.0 provide viable approaches. [HMMHZ20] specifies two key areas where district heating solutions can benefit from IoT approaches. Firstly, automatic fault detection enables faster fixing of leakages and means reduced maintenance time. Secondly, improving efficiency by reducing the temperature of the hot water supply and identifying grid points with the need for reinforcement.

[GCN+17] proposes the concept of a smart heating system. It applies the IIoT and Industry 4.0 paradigms to district heating systems. This is done by connecting the various elements of the system (thermal source, network of pipes, substation, consumer) to a network integrated Intelligent Control System (ICS). The ICS is responsible for the the regulation, optimisation and forecasting of operational loads. Continuous collection of operational parameters from on-site sensors serves as the foundation of the ICS approach.

Based on gathered data, predictions are made and instructions are sent back accordingly. This feedback loop enables quick reaction times and adaptive operation. Collected data is compared against a historical database, the operation of heating stations is evaluated both independently and on an areal level. Compared to traditional heating systems, smart district heating systems offer increased efficiency, energy-savings and reliability. Moreover, smart heating systems facilitate the use of transparent heating modes [LZL21]. By making key characteristic parameters such as pipe pressure, heat transfer indicators and equipment efficiency in thermal substations completely transparent to the operator, two advanced management strategies are enabled: load self-prediction - prediction of heating loads based on big data technology and fault self-diagnosis - automated identification and response in case of failures. These solutions combined with the advancements in communication technology facilitate the design and development of modern IoT-enabled heating systems. Furthermore, their use results in reduced energy consumption, lowered carbon emissions and increased management efficiency.

2.2 System Architecture

To enable smart solutions and their integration, a variety of models and concepts have been proposed. These approaches serve to help design and development processes, at the same time providing an abstract view of the structures in question. A selection of them are presented here.

2.2.1 Reference Architectures

A comprehensive reference architecture for IIoT applications is laid down in [LMD+17]. The architecture proposed in [GBF+16] presents a simplified conceptual view of this design, enabling a pragmatic discussion of the main system components (Figure 2.1). The device component represents the hardware linking sensors and actuators, it is the entry point of the physical environment to the digital world. A device can communicate directly with the IoT integration middleware if it supports an appropriate communication technology, such as a Low-Power Wide-Area Network (LPWAN), a corresponding transport protocol; Hypertext Transfer Protocol (HTTP) or Message Queuing Telemetry Transport (MQTT), and a compatible payload format; such as JavaScript Object Notation (JSON) or Extensible Markup Language (XML). Otherwise the device needs to communicate over a gateway. An IoT gateway can translate between different protocols and communication technologies. The IoT integration middleware is in charge of receiving and pre-processing data from connected devices in order to enable its further use. The application component represents all software that uses the IoT integration middleware to gain insight into and control the physical environment by requesting sensor data and sending instructions.

The reference architecture (Figure 2.1) is easily translated to the 3-layered model presented in [SS17]. The 3-Layer architecture is depicted in Figure 2.2a. One important limitation of the 3-Layer architecture is the fact that there is no dedicated layer for managing the whole IoT system. To address this, the model is complemented with the Business and

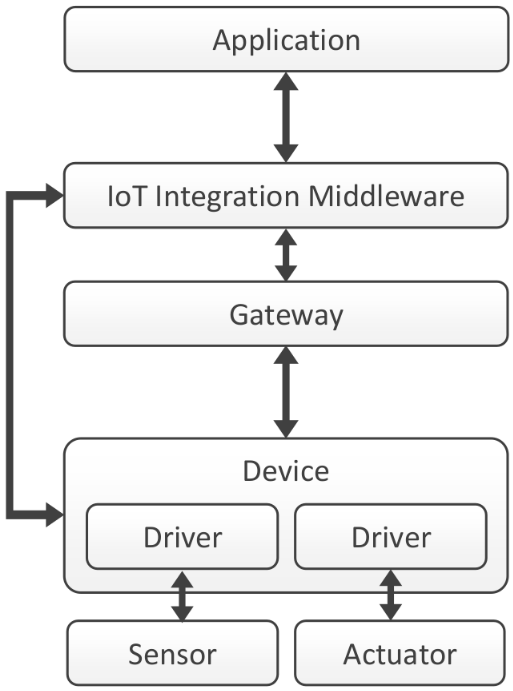
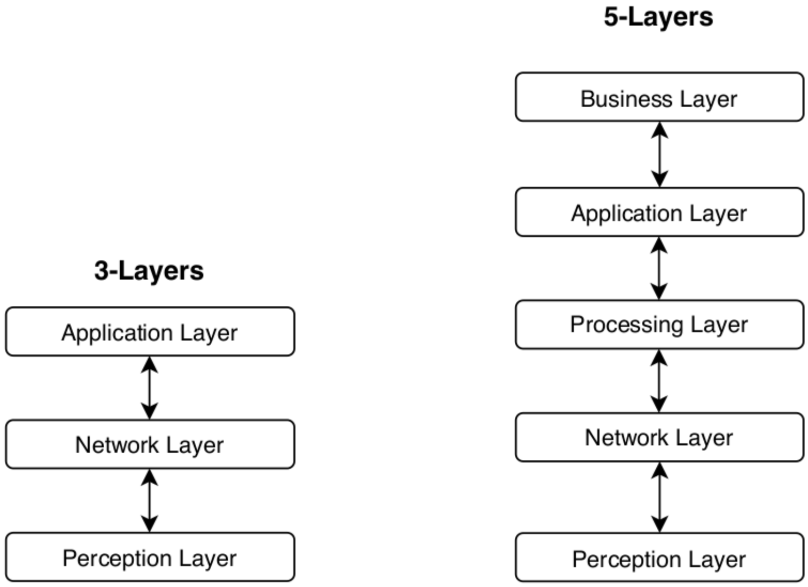


Figure 2.1: IoT Reference Architecture presented in [GBF+16]

Processing layers in the 5-Layer architecture (Figure 2.2b). This representation enables a more precise discussion of the components of an IoT system. Providing an abstract overview and management of the whole system, the business layer includes applications, business and profit models. Central to the theme of this thesis is the processing layer, also known as the middleware layer. It provide a diverse set of services and enables management of the lower layers. It can include many technologies such as databases, Cloud Computing, and big data processing modules. The Middleware concept is further elaborated in the next section.

2.2.2 Middleware

The IoT integration middleware element aims to provide a simple and flexible interface to interact with different devices. Located between the hardware layer and the application layer, the role of a middleware is to present standardised communications to interact with devices. In order to do so, it enables the use of standardised communications across physical devices by masking their heterogeneity [CM12]. It can include messaging queues (MQTT, AMQP), back-end servers, database repositories (SQL/NoSQL) and connectors among these components.



(a) 3-Layer Model (b) 5-Layer Model

Figure 2.2: Layered IoT Architecture Models [dSAP+20]

[NGM+16] divides middleware in three categories: service-based, cloud-based and actor-based. Cloud- and actor-based middleware rely on cloud services to fulfil their roles. This makes their deployment faster and less cost intensive, but limits their use, as they can only be accessed or controlled via either their vendor's provided application or cloud supported RESTful APIs. The service-based middleware orients itself closely to the 3 and 5-layered architectures presented in [dSAP+20]. Defining a Virtualized Plane between devices and applications, which includes main computational units and implements various services, such as access control, storage management and an event processing engine. The service-based architecture is suitable for applications, where multiple high-performing nodes are running in the cloud or on powerful gateways between IoT devices and their backend infrastructures. It is worth noting, that this solution is not designed to be deployed in resource constrained scenarios and does not support direct communication between edge devices.

2.3 Network Technologies

At its core, the IoT concept is based on the idea of ubiquitous connection between distributed devices. IoT applications have specific requirements such as long communication range, very low energy consumption, and cost effectiveness [MBCM18]. To fulfill these requirements appropriate network technologies are needed. Furthermore, the discussed problem domain presents unique challenges: a modern energy system requests a robust communication infrastructure that can accept greater variation in order to increase efficiency. This paves the way for increased system observability, which also means enhanced system controllability from the perspective of control theory [SLTD17].

All IoT approaches rely on the paradigm of Machine-to-Machine (M2M) communications to integrate a plethora of various sensors and actuators [AGP+15]. A significant proportion of heating stations are already connected through a physical medium, such as fibre or twisted cable, enabling their access through a Multiprotocol Label Switching (MPLS) network. However, the integration of the vast majority remains a challenge to be overcome. Establishing a physical connection is not possible in every case, due to geographical and legal limitations. To this end, only wireless M2M approaches are discussed. A comparison of them based on [BPB+18] is presented on Table 2.1 at the end of this chapter. A selection of possible solutions fitting the application scenario are introduced below. It is firmly emphasised to the reader, that these values are concerning optimal conditions, their real-world utilisation may show deviation. This is also kept in mind in subsequent parts of this work discussing the viability of these technologies.

2.3.1 LPWAN technology

A multitude of communication technologies aimed at IoT applications have appeared in the last decade, offering a broad spectrum of connectivity solutions. Short range M2M communication technologies (e.g. WiFi, BLE and ZigBee) are not adapted for distances exceeding a few hundred meters. Mesh topologies have been widely employed for expanding the coverage of these short range networks, however, they result in significantly elevated deployment costs. Cellular communication technologies (e.g. 3G, 4G and 5G) could ensure longer transmission ranges, however, they are more cost intensive and have excessive energy needs [MBCM18]. To address these shortcomings, LPWAN technologies have been developed. These solutions enable wireless connections covering long distances with minimum power consumption and maintenance. The key performance metrics defined for LPWAN are energy efficiency, scalability, and coverage [SLTD17]. Representative technologies of LPWAN are the Narrowband IoT (NB-IoT), Sigfox and Long Range (LoRaWAN) technology. The network architecture outlined by the LPWAN paradigm is presented in Figure 2.3.

2.3.2 NB-IoT

NB-IoT is a narrow-band LPWAN technology built on existing LTE functionality, reusing various principles and building blocks of LTE physical and higher protocol layers. NB-IoT reduces LTE protocol functionalities to the minimum and enhances them as needed for IoT applications. Optimized for small and infrequent exchanges of data and stationary deployments, it abstains from the features not required for IoT purpose (e.g. radio quality measurements, aggregation). In contrast to the other two presented LPWAN technologies, NB-IoT uses a licensed spectrum and has a significantly higher end-device cost compared to the other two solutions (€20 vs. €2-5). Additionally, NB-IoT has the shortest range, only reaching up to 1 km in urban areas [MBCM18].

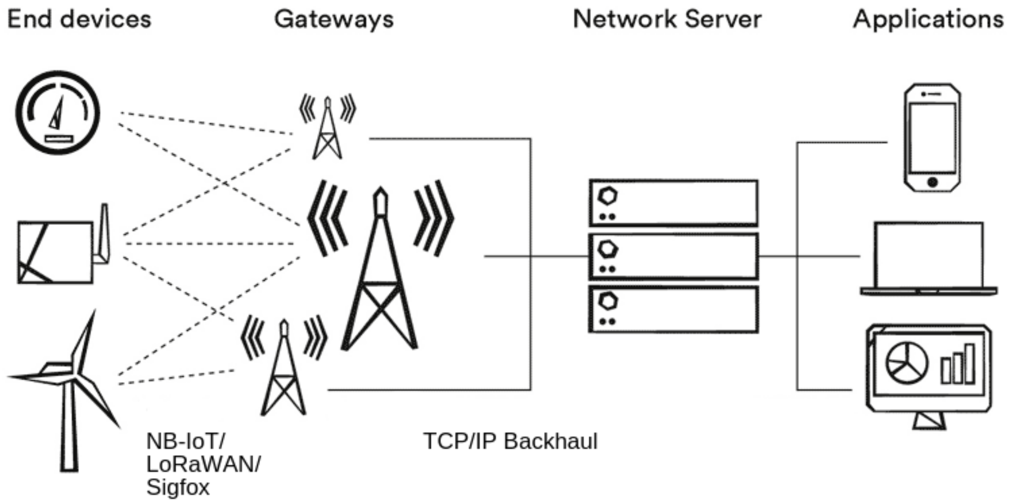


Figure 2.3: LPWAN-based Network Architecture [CZB20]

2.3.3 LoRaWAN

The LoRa based communication protocol called LoRaWAN was standardized in 2015 and quickly became the most widely used LPWAN technology. Its foundation, LoRa, is an unlicensed sub-GHZ band solution derived from the chirp spread spectrum. Not requiring authorization from radio frequency regulators and easily deployed over a range of more than several kilometers, LoRaWAN provides a cost effective solution in plenty of application scenarios. It enables full bidirectional communication, and the generated signal has low noise levels and enables high interference resilience. Deployed in 56 countries, its most common applications are: smart meters, traffic tracking, smart appliances, and smart healthcare [SLTD17].

2.3.4 SigFox

Sigfox uses a wide-reaching signal that passes freely through solid objects called "Ultra Narrowband" and deploys proprietary base stations. End-devices connect to these base stations at a maximum data rate of 0.1 kb/s. Initially only capable of uplink transmission, later it was revised to support bidirectional communication. However downlink transmission can only occur following an uplink transmission. This is further limited by the fact, that only 140 uplink messages are permitted in a day. Deliberately conserving resources where possible, Sigfox efficiently uses the frequency band, leading to very low power consumption, high receiver sensitivity and low cost antenna design.

		Technology	Max. Range	Max. Throughput	Min. Latency	Topology	Power Consumption
Short Range		Zigbee	100 m	250 kb/s	10 ms	Mesh	Low
		BLE	100 m	2 Mb/s	6 ms	Point-to-point	Low
		Wi-Fi HaLow	1 km	40 Mb/s	100 ms	Mesh	Low
Cellular		GSM/GPRS/EDGE	100 km	384 kb/s	150 ms	Star	High
		UMTS/HSPA		10 Mb/s	200 ms		High
		LTE Cat 1		10 Mb/s	50 ms		Medium
	LPWAN	LTE Cat-M1	10km[DBP16]	1 Mb/s	10 ms		Medium
		NB-IoT	10km[MBCM18]	250 kb/s	1.6 s		Medium
		LoRaWAN	20km[MBCM18]	50 kb/s	400 ms[PH19]	Star-on-star	Low
		SigFox	40 km[MBCM18]	0.1 kb/s[MBCM18]	3 s[Sig]	Star	Low

Table 2.1: Comparison of the most common wireless M2M technologies

CHAPTER 3

Requirements Engineering

3.1 Approach

The goal of this section is to explore the problem scenario, by identifying and documenting how different stakeholders interact with the system. The presented process is based on [Sch10]. Four key activities serve as the foundation of the approach. The discovery of user requirements is achieved through interaction with the different stakeholders (elicitation and analysis); converting these requirements into a standard form (specification); and checking that the requirements actually define the system that the customer wants (validation). The outcome of the process is a structured documentation of user needs, the so-called System Requirements Specification (SRS). Figure 3.1 shows the main objectives and order of the different steps.

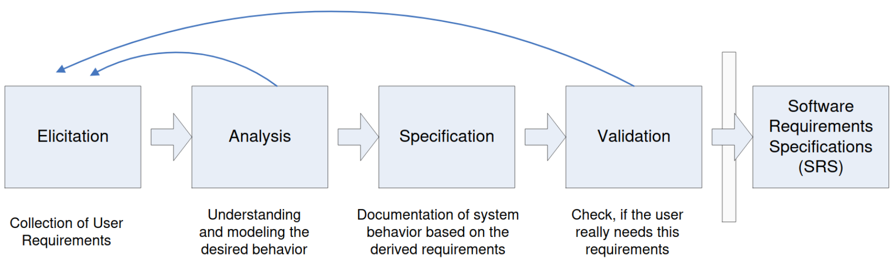


Figure 3.1: A visual representation of the presented process [Sch10]

Being an iterative approach, the steps can be revisited in an interleaving and repeating order according to the demands of the project. Various techniques and tools help the documentation and organisation of the gathered information. A selection of them is presented below.

3.2 Requirements Elicitation

This activity aims to understand the work that stakeholders do and how they use the system to help that work. To this end, interviews and an analysis of the company ethnography is carried out to provide data which can be further examined.

3.2.1 Interviewing

Interviews are conducted in a semi-structured manner to gain understanding of the domain-specific needs of the Wien Energie. A predefined set of questions serves as a basis for the talks:

- How do you define your role at the company?
- What do you want to accomplish with the project?
- What is the purpose of the system from your point of view?
- What are your expectations towards the system?
- Which parts of the system do you work on/with?
- What systems/persons does your work depend on?
- What makes your work harder than it needs to be?
- Is there anything that could work better?
- What is most important for the success of the project?

Interviews were conducted with the following stakeholders at the Wien Energie:
project owner, technical architect, data engineer and data scientist.

3.2.2 Ethnography

Software systems do not exist in isolation. They are used in a social and organizational environment, software requirements are often constrained by the given setting. This is not otherwise in the case of the Wien Energie, various internal departments and external partners are involved in operating, maintaining and developing the district heating system of Vienna. Relevant for our discussion are two of them: The Wiener Netze GmbH operates most of the communication lines used by the district heating system of Vienna, while the Wien IT GmbH provides various software and computing resources.

3.3 Analysis & Modeling

The information gained during the previous step is summarized and processed in a structured manner to further enhance its utility and to aid in the verification of the requirements. The two main pillars of this activity are use cases, providing a visual representation of system interactions and user stories describing them from the perspective of the respective human actors. These two elements come together in the form of scenarios and the formal specification of functional requirements, giving a structured form to the results of this phase.

3.3.1 Use cases

Visual representation of the interactions with their respective actors involved. In this thesis, the UML notation is used to model system behavior and assist in capturing requirements. Involved actors may be human or other systems. Each use case is additionally documented with a textual description in the form of scenarios. An outline of the discussed systems is presented in Figure 3.2 in the form of scenarios.

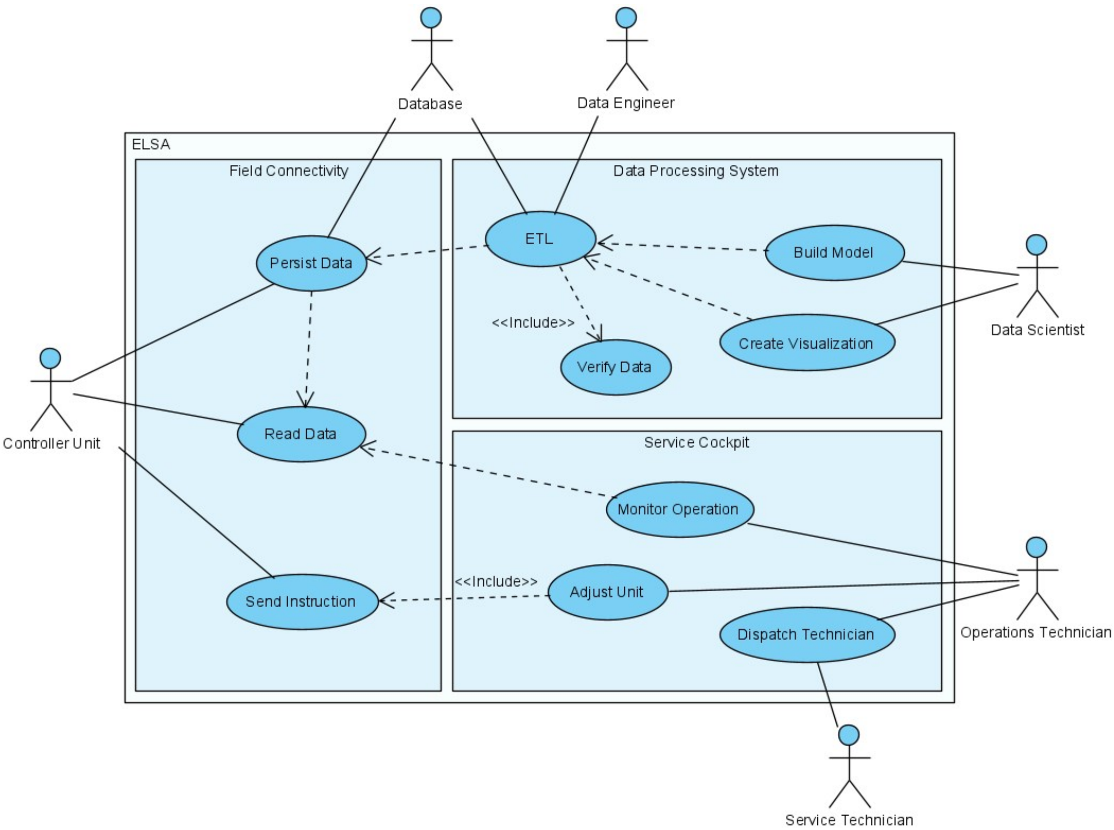


Figure 3.2: Use Case Diagram of the ELSA Project

Scenarios

Scenarios represent the descriptions of the previously defined use cases. Elaborating visual renditions, their main goal is to specify the possible flow of events in the system, and alternative paths depending on interactions between actors and the system.

Field Connectivity

Name	Read Data
Actors	Controller Unit
Scope	Field Connectivity System
Description	Read raw data from a network connected controller
Pre-Condition	• Device is functional and connected to network • Device is providing data to be read
Actions	1. Optional: Query field device 2. Read provided data into system memory
Post-Condition	Read data is in system memory

Name	Persist Data
Actors	Controller Unit
Scope	Field Connectivity System
Description	Save collected data into a centrally accessible database
Pre-Condition	• Data is successfully read from the Controller Unit • Database is available
Actions	1. Save data into database
Post-Condition	Data is persisted in central database

Name	Send Instruction
Actors	Controller Unit
Scope	Field Connectivity System
Description	Transmit an instruction to a controller unit in the field
Pre-Condition	• The instruction is transmitted from the Service Cockpit • Controller unit is reachable via network
Actions	1. Read instruction from service cockpit 2. Send instruction to specific controller unit
Post-Condition	Instruction is sent to the respective controller unit

Data Processing System

Name	Extract, Transform and Load Data
Actors	Database, Data Engineer
Scope	Data Processing System
Description	Extract data from the database, validate it and make it available for further processing in a usable format
Pre-Condition	• Database is connected • Data is available to be read from the database
Actions	1. Read data from the database 2. Validate data 3. Transform it into a format which enables further processing 4. Load it into the memory of the data processing system
Post-Condition	Transformed data from field devices is loaded into the memory of the Data Processing System

Name	Verify Data
Actors	Data Engineer
Scope	Data Processing System
Description	Compare available data with a set of rules to find out if it is reasonable
Actions	1. Compare data against pre-defined rules 2. Categorise data as valid or invalid
Post-Condition	Data is categorised as either valid or invalid

Name	Build Model
Actors	Data Scientist
Scope	Data Processing System
Description	Use statistical models to acquire meaningful information from the recorded data
Actions	1. Load data from system repository 2. Analyse data 3. Train model 4. Test model
Post-Condition	Data is described by a statistical model

Name	Create Visualisation
Actors	Data Scientist
Scope	Data Processing System
Description	Present the gathered data and its underlying relationships in a visual format
Actions	1. Load data from system repository 2. Create visualisation
Post-Condition	Data is presented in a visual format

Service Cockpit

Name	Monitor Operation
Actors	Operations Technician
Scope	Service Cockpit, Field Connectivity System
Description	Continuously monitor the operation and state of field devices and heat exchange stations
Pre-Condition	• Data is successfully read from the Controller Unit • The gathered data is transmitted to the Service Cockpit
Actions	1. Read data from Field Connectivity System 2. Display the received data 3. Refresh the data
Post-Condition	The state of the controller units and field devices is displayed and continuosly refreshed

Name	Adjust Unit
Actors	Operations Technician
Scope	Service Cockpit
Description	Send a specific command or adjust the parameters of a field device
Actions	1. Select station and operation/adjustment 2. Send command
Post-Condition	Data is sent to Field Connectivity System to be forwarded to a field device

Name	Dispatch Technician
Actors	Operations Technician, Service Technician
Scope	Service Cokcpit
Description	Assign a service technician to inspect, repair or maintain a field element on-site
Actions	1. Provide task description and select station. 2. Assign a service technician to the task. 3. Task appears and becomes available for service technician.
Post-Condition	Task is present in service technician's view.

3.3.2 User Stories

User stories are concise descriptions of a feature from the viewpoint of a stakeholder. Their main goal is to describe how a piece of work can be of value to the customer. Regardless of the order of their implementation, each user story should contribute to the overall value of the system.

Data Engineer

As a data engineer, I want to provide access to data gathered from field devices by automating the data flow. I need to transform and validate the collected data before its further processing can take place. The main challenges of my job include having to unify access over a plethora of different technologies/appliances and monitoring the accessibility of data. My work depends on being able to access data received from field devices.

Data Scientist

As a data scientist, I want to be able to analyse and visualise data, so that it can be used for reporting, optimisation and detection/prevention of potential issues. I need continuous access to historical and current system data to train my models and provide reports. My work depends on being able to centrally access verified and reliable sources of data.

Operations Technician

As an operations technician, I want to be able to monitor the stations belonging to my zone and take the necessary measures to keep them functioning. If action needs to be taken, two main assets are standing at my disposal: remotely adjusting the field device or dispatching a service technician to intervene on-site. In both cases, I want to be able to quickly detect and react to disruptions. I need to ensure, that the system is always operating efficiently and quickly reacting to changes of state. My work depends on having an overview of my zone and being able to quickly take action.

Service Technician

As a service technician, I want to have an overview of the tasks assigned to me. I need to know which heating station I am deployed to and I want to know what does my task entail. Additionally, I want to follow, which operations technician did assign a particular task to me and when.

3.4 Validation

This activity ensures that the gathered requirements provide a good coverage of actual user needs. Continuous reviewing and adjustment offer the necessary points of orientation. To this end, multiple requirements reviews are conducted with Wien Energie at different stages of development. Several system walkthroughs focusing on different domains facilitate the understanding of the current infrastructure and systems in place, ensuring that all relevant areas of interest are covered. Stakeholders are not only involved in validity and completeness checks, but are also providing their domain knowledge and perspective on the project in the form of realism checks. Additionally, workshops and interviews are conducted with multiple representatives (engineers and a project manager) of Wien Energie present, where the main challenges and requirements are laid down. A key purpose of these occasions is to gain an overview of the environment where the proposed system has to be implemented, from the perspective of all involved stakeholders, This ensures the consistency and validity of the gathered demands. Combined, these activities facilitate an extensive coverage of the underlying requirements.

The validation of requirements is not limited to the steps presented in this chapter, but accompanies the whole exploratory and design process. Of special importance for this work is the demonstration of possible approaches in the form of concept designs. These are presented for the purposes of analysis, experimentation and further assessment. Consequently, their evaluation provided as a part of this thesis also forms an integral element of the extended validation process.

3.5 Requirements Specification

The purpose of this activity is to give a detailed description and technical specification of the requirements for an IoT interface between the distributed control devices and central IT infrastructure of the Wien Energie. It also describes constraints and interactions with other external systems and applications. These specifications serve as a basis for the concept designs presented as a part of this work.

The first section gives a description of the scope and purpose of the software system proposed in this SRS. The second part introduces the interfaces between the system under development covered by the SRS and the larger system in which the product is embedded. Moreover, the main functionalities are described and dependencies are provided. The last two sections introduce external interface and non-functional requirements, respectively.

This chapter reports requirements based on the official meetings with staff members of Wien Energie.

3.5.1 Purpose

Wien Energie operates a large number of heating stations all around Vienna. However, they have been managed and monitored only on an as-needed basis for the most part, greatly reducing the accessibility and utility of their produced data for operation-relevant, multi-site analyses. To enable their continuous observation and supervision, a unified software interface is developed, enabling the use of IoT solutions and modern low-power wide-area network technologies.

3.5.2 External interfaces

This section identifies the hardware, software and communication interfaces the system will interact with.

Software interfaces

The system will use software resources provided by Wien Energie. This means that all software has to support Microsoft Windows, nevertheless the implementation has to be operating system independent. To achieve this, components are containerized and running on top of the Docker platform [Doc].

Hardware interfaces

The necessary hardware interfaces (gateways) to establish a data link through a low-power wide-area network solution has to be provided by Wien Energie. In case of stations that are already connected by means of a physical connection, the existing MPLS network will be used. All data with the central infrastructure of the Wien Energie will be exchanged over the private company network.

Communications interfaces

The system will use communication resources agreed upon with Wien Energie. This includes, but is not limited to the use of a publish-subscribe-based messaging protocol for communication with the heating stations and the field connectivity system of the central IT infrastructure. Further information about the number and state of connected stations will be made available through HTTP requests for the central infrastructure.

3.5.3 Assumptions and dependencies

The availability of the human and technical resources to establish a data link with the proposed interface is expected at each heating station. This should be achieved by means of a physical medium (twisted pair, fiber, coaxial) or through the use of a low-power wide-area network technology (SigFox, LoRaWAN, NB-IoT).

3.5.4 Functions

This part provides a summary of the major functions that the software will perform. These are grouped into five categories: data access, data transfer, station management, data modeling and database related functions.

FR-1: DATA ACCESS

[**FR-1.1**]: View entire universe of heating stations
List all connected heating stations with their class, locality and means of connection.

[**FR-1.2**]: View heating station descriptive data
View the connectivity entries and traffic statistics of a given station.

[**FR-1.3**]: Subscribe to the message stream of a heating station
Receive all data produced by a heating station.

FR-2: DATA TRANSFER

[**FR-2.1**]: Send data to a station
Forward received data to a given station.

FR-3: STATION MANAGEMENT

[**FR-3.1**]: Station registration
Register a station in the system with additional metadata. The system attempts to establish connection with the station and forward its collected data.

[**FR-3.2**]: Station removal
Close connection to a station and remove it from the database.

FR-4: DATA MODELING

[**FR-4.1**]: RULE-BASED DATA ASSOCIATION

Models will require specific input data and will generate output data based on rules supplied to the Message Broker component. The current scope of the system is to provide direct associations based on key-value pairs.

FR-5: DATABASE

[**FR-5.1**]: MAINTAIN STATION METADATA

Maintain a database of the registered stations and their metadata, such as class, locality and means of connection.

[**FR-5.2**]: MAINTAIN STATION CONNECTIVITY

Changes in state e.g. connection establishment and loss of connection will be persisted.

[**FR-5.3**]: MAINTAIN STATION TRAFFIC STATISTICS

The number of messages to and from stations over predefined time intervals are kept track of.

3.5.5 External Interface Requirements

This section provides a detailed description of all inputs into and outputs from the software.

Hardware requirements

HR-1: Data Storage

The system needs to be able to store tens of gigabytes of data on demand. As the number of connected heating stations increases, so does the amount of stored data. Further requirements gathering is needed to get real-world estimates of data storage needs.

HR-2: Networking

The system requires connectivity to the private network environment of Wien Energie. This entails the MPLS network and gateways to connect to the heating stations and the company network.

Software requirements

SR-1: Container Platform

The system will use the Docker container platform to instantiate its components.

SR-2: Backup Software

Data backups will be managed through fully supported backup software solutions.

3.5.6 Other Non-functional Requirements

This section describes additional important characteristics of the system and specifies global constraints.

Performance requirements

PR-1: Processing delay
The system shall show no significant deterioration in processing time as the number of heating stations increases. Response times for transmitting messages should be on the order of a few tenths of a second or less.

PR-2: Response time
The system shall show no visible significant in response time as the number of heating stations increases. Response times for querying metadata should be on the order of a few seconds or less.

Software System Attributes

SA-1: Reliability

[**SA-1.1**]: The reliability that the system gives the right result on a search request should be at least 99%.

[**SA-1.2**]: The reliability that the system correctly brokers communication in either direction should be at least 99%.

SA-2: Availability

[**SA-2.1**]: The system must be available 99% of the time. Availability will be concerned with the reliability of software components. Network and hardware failures are not considered.

SA-3: Security

[**SA-3.1**]: Encryption
Every exchange of information between the system and stations or company infrastructure should be encrypted.

[**SA-3.2**]: Access control
All access will be validated with a unique identifier used to authenticate the user or calling program.

SA-4: Maintainability

[**SA-4.1**]: Extensibility
The application should be easy to extend. Application software/code and design of database structure should be flexible enough for necessary changes or implementation of new functions and components in a later phase.

SA-5: Portability

[**SA-5.1**]: Platform independence
The application should be compatible with any system running the Docker Engine.

CHAPTER 4

Systems Analysis and Design

4.1 Systems Analysis

Wien Energie operates a large enterprise IT infrastructure supporting an array of various business needs. A subset of these systems is involved in the collection of heating data and the control of the district heating system. The aim of this unit is to explore and document the essential components in order to support subsequent design processes.

4.1.1 Data Accumulation Pipeline

The operation of the district heating system results in a large amount of data being constantly produced. For the management and processing of this continuous dataflow a layered pipeline is responsible at Wien Energie. (Figure 4.1)

The Data Accumulation Pipeline (DAP) can be divided into 3 layers. The bottom layer represents data producers, they are providing data relevant to the operation of the district heating system. Three different types of data producers are differentiated: control devices at heating stations transmitting sensor values, archives storing historical data and Enterprise Resource Planning (ERP) systems handling enterprise data. The data originating from this layer is directed at a datalake, serving as a repository storing a large amount of structured and unstructured data. This repository is complemented by databases storing data that has been pre-processed. Data analysis applications make use of this layer to gain useful information, draw conclusions, and supporting decision-making. The generated visualisations and business intelligence is made available for end-users through the service cockpit.

4.1.2 Connectivity

To collect data and establish a connection to a limited subset of heating stations a multi-layered network architecture is currently in place as shown in Figure 4.2. PLC

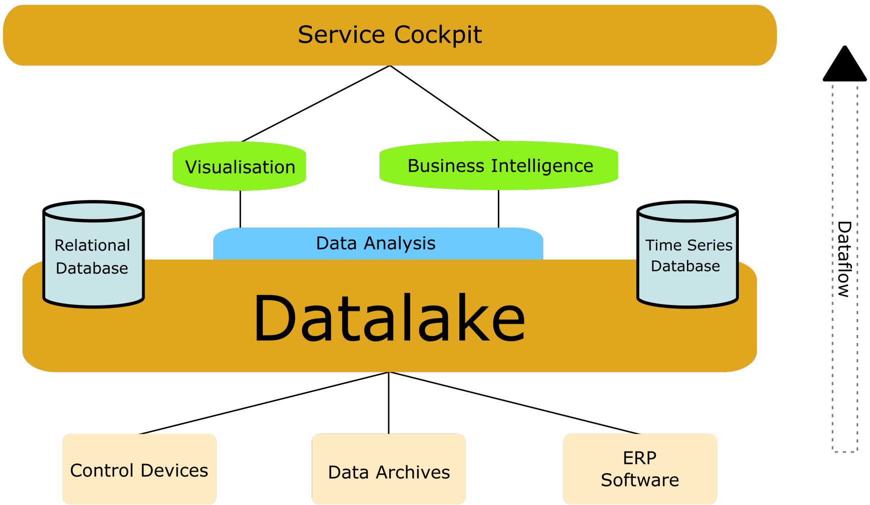


Figure 4.1: The Data Accumulation Pipeline of Wien Energie

units placed at heating stations are either directly connected or through the use of a Multifunction Device (MFD). The collection of meter readings and sensor data takes place on this network by an automated process. This process is also responsible for enabling data exchange with heating stations. A firewall forms a barrier to the private network infrastructure of the Wien Energie. The final processing of all data streamed originating from the heating stations takes place here through an Apache Kafka cluster. Other processes can subscribe to the continuous flow of data outputted by Apache Kafka.

4.1.3 Limitations

A cardinal objective of the system to be developed is to address the limitations posed by the designs currently in place. Three main issues are considered: deployment of new stations, accessibility of communication, and the availability and usability of gathered data.

The rapid and efficient deployment of new stations is substantially hindered by technological heterogeneity and a lack of standardised solutions. A diverse range of controller devices are employed at the heating stations from various manufacturers. Even in the case of a single vendor, multiple product generations and models are used. This results not only in an increased workload for technicians installing and connecting new devices, but also introduces an enormous technical debt to the central IT infrastructure [RSZ19]. These factors are especially crucial in the case of a service-oriented architecture, such as the one operated by the Wien Energie.

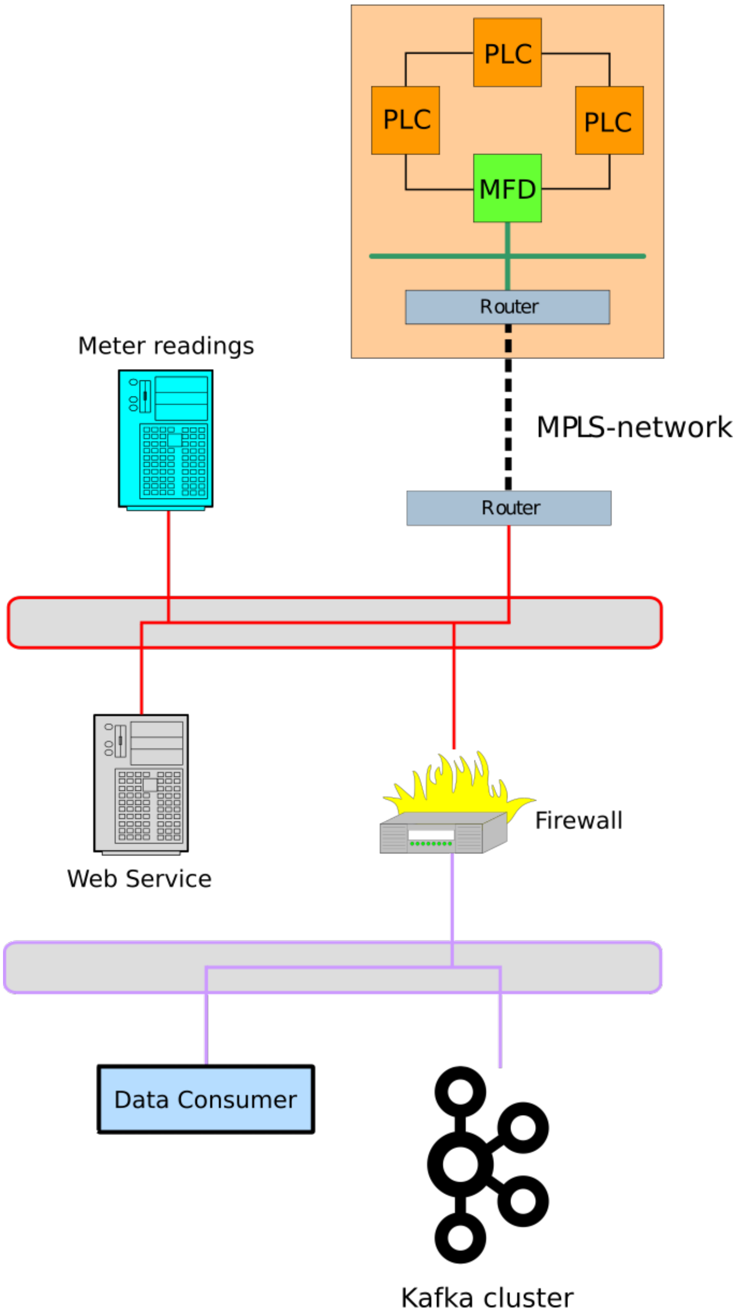


Figure 4.2: The network infrastructure connecting heating stations

The availability of communication with the stations poses an additional problem. A data link can only be established to a minority of the stations. Even if a data link is present, full duplex channels are only available in a limited number of cases. Furthermore, the use of different connection methods and mediums does not always guarantee continuous access.

Availability and usability of the gathered data represent a crucial aspect for the operation of the system. However, the lack of standardised data protocols, structures and formats limit the usability of the data. In most cases, collected data has to be manually cleaned and transformed before it is processed. Data loss poses a further issue. Malfunctions in data collection often go undetected, resulting in a partial or complete interruption of system observability.

4.2 Concept Design

To enable the integration of the IoT paradigm into the infrastructure of the Wien Energie a concept design is proposed focusing on three key areas: definition of a middleware layer, introduction of edge/fog practices and a new communication technology satisfying the changed requirements. As a basis for the design, four objectives are identified based on the requirements documented in Chapter 4 and the above mentioned limitations. These objectives then serve as guidelines for the proposed concept design.

Through the exploration of requirements and existing systems a well-defined outline of the system to be developed has been drawn. To enhance the design process and serve as points of orientation, four main design goals are laid down. These technical objectives are meant as guidelines, that should be taken into account through the whole planning process. Their accomplishment ensures that the system in question fulfils the widest range of application specific needs and addresses the limitations posed by currently used solutions. The attainment of the goals defined here is discussed in the following chapter.

<u>1) Bidirectional transmission</u>

The design should enable communication in both directions between heating stations and central infrastructure. This means being able to handle multiple messages to and from dispersed nodes every minute with high reliability.

<u>2) Compatibility with the existing infrastructure</u>

The developed system has to be able to work along the existing infrastructure.

<u>3) Scalability</u>

The design should enable the deployment of new stations with no limit on the maximal number of system nodes.

4) Real-time data availability
All system nodes should be continuously accessible (transmission and receiving of data should be possible at least once every 30 seconds) to ensure efficient surveillance of operation and early detection of malfunctions.

4.2.1 Architecture

The reference architecture proposed in [GBF+16] serves as a good starting point for the planning process, as it provides a good abstraction of the main system components present in the discussed scenario (Figure 2.1). The arrangement of this architecture is easily equated to the previously introduced systems and enables the establishment of clearly defined system boundaries. The *Device* component represents the hardware placed at the heating stations, while the *Application* component can be equated to the central infrastructure of Wien Energie. To enable the realisation of the IoT Middleware concept between these two layers, while keeping design objectives in mind, an IoT integration middleware (Section 2.2.2) implementation is proposed.

The design aims to enable duplex communication between edge devices at heating stations and the central IT infrastructure of Wien Energie. It provides a standardised means for connection establishment, data collection and remote supervision of distributed control devices of the district heating system. Acting as the processing layer between heating stations and central facilities, it keeps track of connectivity and delivers messages between the field connectivity system of the central infrastructure and distributed heating stations.

The proposed system consists of four main components - IoT Agent, Message Broker, Web Server and Database. An overview of these components is presented in Figure 4.3.

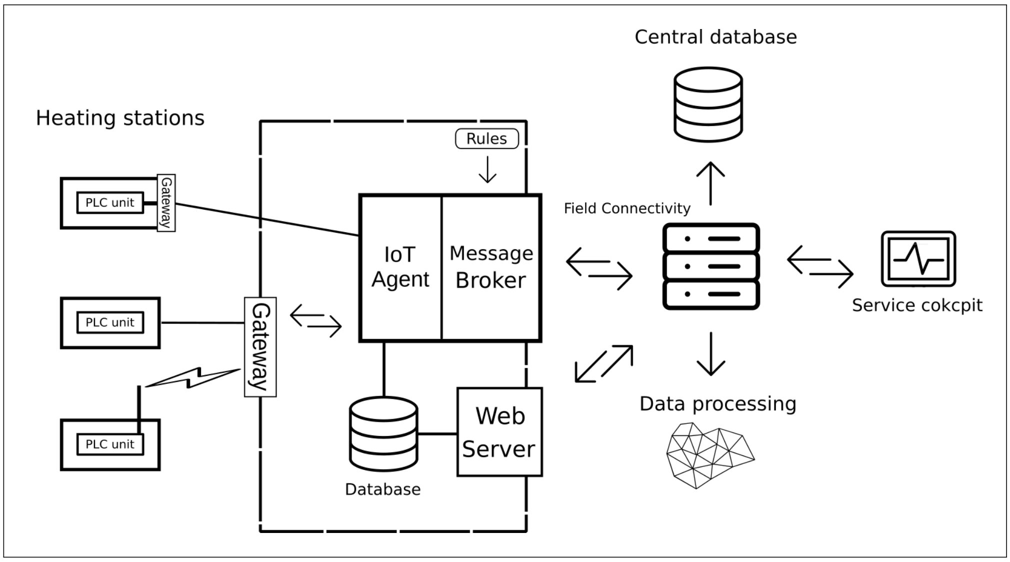


Figure 4.3: Proposed IoT Integration Middleware implementation

IoT Agent

The IoT Agent component enables devices to send and receive data from the Message Broker using their own native protocols. Heating stations can either directly receive data from the IoT agent or through a gateway, if they are connecting through a low-power wide-area network. The use of this component enables message exchange with constrained devices and communication mediums where bandwidth and device memory are limited resources. If a heating station has its own gateway and IoT agent, messages simply bypass this component.

Message Broker

The Message Broker component is responsible for the validation, transformation and routing of messages between the field connectivity system of Wien Energie and the heating stations. Message exchange happens using a Message Orientated Middleware implementation such as MQTT or AMQP. The transformation and formatting of northbound data is done by direct associations based on key-value pairs.

Web Server

A web server is used to manage stations and query the operational database. Data exchange with the central infrastructure takes place using HTTP requests.

Database

A database is used to keep track of connected stations and their metadata. Changes of state, such as connection establishment and loss of connection are also persisted here. This component is also responsible for keeping track of traffic counters.

Together, these components ensure a simplified flow of all station relevant data to and from the central company infrastructure. Enabling its use for specialised applications, such as further data processing, system supervision and central persistence.

To enable the incorporation of the presented middleware implementation into the existing infrastructure, the above presented systems analysis provides an overview of available interfaces. Heating stations are producing data that is sent back to the central servers for storage and further processing, thus the middleware (relaying all edge device data) acts as a data producer. The Kafka cluster serves as a good-entry point, because producer side APIs provide a standardised interface to put messages into Kafka. For southbound communication the currently used web service can be used as a relay, eliminating the need for additional connectors. This way, the use of standardised protocols can prevent the accumulation of further technical debt.

4.2.2 Edge and Fog Computing

Cloud Computing does not offer the best results in every scenario. One of the main issues is the centralization of data storage and computing resources. This demands a stable network connection and massive amounts of data localized at data centers, pushing network bandwidth requirements and energy consumption to the limit [APZ18]. Edge Computing is a distributed computing paradigm that addresses some of the above issues by moving computing and storage away from centralized points. This is done by placing applications, data, and services geographically closer to where such services are requested. Taking it one step further, Fog Computing uses edge devices to carry out most computation and data storage locally [CDPLR19]. Figure 4.4 visualises the hierarchical relation of the three paradigms in the form of layers. These features make Edge and Fog Computing more suitable to be integrated with IoT solutions, providing efficient and secure services for a large number of edge devices [APZ18]. Moreover, placing data analysis close to the device minimises latency, which translates to the system reacting faster to interruptions and failures [Cis15]. To sum it up, the use of edge and fog approaches delivers more efficient and cost effective IoT services [WA18].

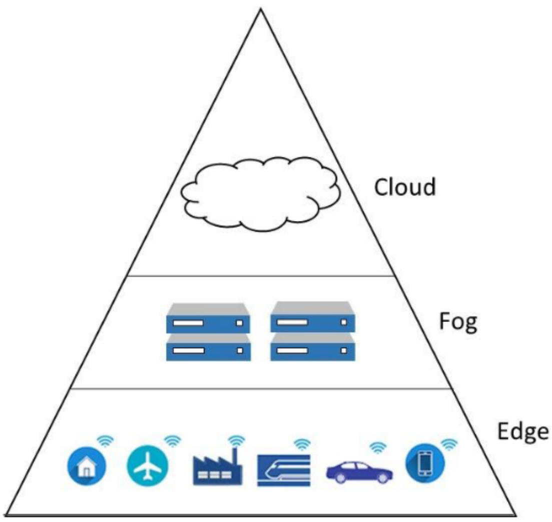


Figure 4.4: Edge-Fog-Cloud Architecture as presented in [GBdlO20]

The 3-layer model discussed above is also suitable to be used as a performance model for edge and fog approaches. A certain class of sensor values is filtered out and processed by the edge devices. This is especially useful in the case of failure mitigation and detection of local anomalies. The rest of the values requiring more processing are forwarded to the fog layer. The fog layer operates in the same mode as the edge layer: A percentage of requests obtain their final processing, and the rest is forwarded to the cloud layer. Additionally, this layer has an overview over a set of associated devices belonging to a given area/zone. This split can also be used to model the aggregation of sensor values such that only the aggregate value is forwarded to the cloud layer for further data analytics and long-term storage. The use of a layered architecture translates to significant improvements in response time, traffic volume and computational resources [GBdlO20]. To apply this concept to the presented problem setting an area-based division is proposed, shown in Figure 4.5. Primary stations with stable network connectivity are assigned to the edge layer. More powerful hardware is placed at these locations to enable the supervision of an area. Each substation is assigned to an area, sending its data to its respective edge node. Only the most important parameters are evaluated at the fog layer, to be able to react to malfunctions as quickly as possible. This keeps computational requirements, and therefore deployment costs low. Data is aggregated and further evaluated at edge nodes. Area level management and optimisation takes place at these nodes. All aggregated data and area level operational parameters are transmitted to the cloud layer.

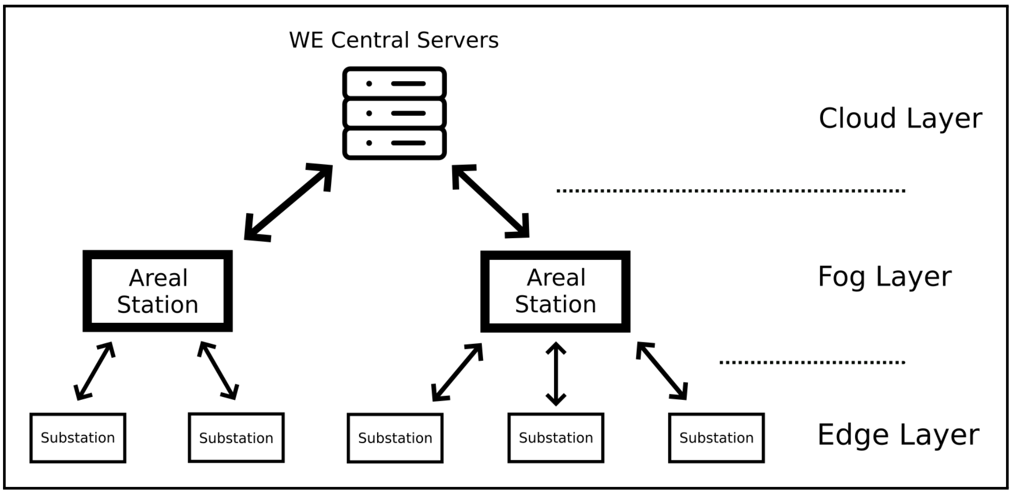


Figure 4.5: Proposed Edge-Fog-Cloud Architecture

4.2.3 Connectivity

Connectivity plays a central role in the integration of heating stations. Under optimal circumstances, every heating station could be connected by a physical link. However, due to legal, physical and financial limitations this is not always possible. To enable communication in such scenarios wireless technologies are considered. The solution has to support bidirectional communication and be able to cover longer distances (1-3 km) in an urban setting. Latency does not play a critical role, but to enable real time supervision, data has to be refreshed at least once every 30 seconds. A comparison of wireless communication technologies is presented in Figure 4.6. The range requirement narrows down the range of possible solutions: Bluetooth Low Energy, Zigbee and WiFi technologies only cover distances shorter than 1 km (cf. Table 2.1). With the use of a mesh topology can increase the range of these solutions, but this results in congestion and increased deployment costs [MBCM18]. This leaves cellular and LPWAN solutions, the former providing much higher bandwidths at the expense of cost and energy consumption. (Very Small Aperture Terminal (VSAT) is not considered because of its exceptionally high cost, infrastructural requirements and low market penetration.) Stations only need to transmit 3-5 kb of data at one time, keeping the bandwidth demand low. With the use of Fog Computing approaches, the bandwidth can be kept at a minimum. These factors, paired with the long transmission range and low cost of deployment [MBCM18] make LPWAN technologies the optimal choice in this setting.

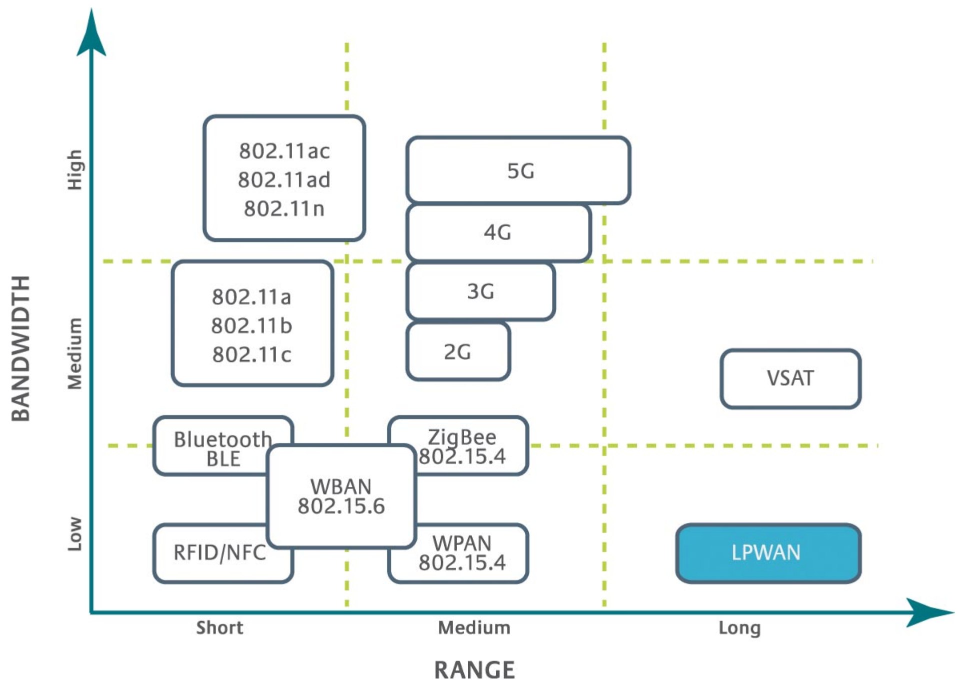


Figure 4.6: Comparison matrix of Wireless M2M Technologies [AGP+15]

Three LPWAN implementations are considered: NB-IoT, LoRaWAN and Sigfox. All 3 technologies provide high scalability, supporting more than 50K devices per base station, greatly exceeding the number of heating stations around Vienna. Sigfox and LoRaWAN keep power requirements at a minimum, but NB-IoT has the advantage of being able to operate over existing GSM and LTE networks. Sigfox provides the least cost intensive solution with an advertised reach of 10 km-s in urban areas, but uses a proprietary network and has strict limits on the amount of messages that can be transmitted in a day from a device. The lack of encryption presents security threats in the case of enterprise and client data [MBCM18]. These characteristics make Sigfox unsuitable for this application scenario. NB-IoT and LoRaWAN have seemingly similar properties, nonetheless, in a real world setting, there are key differences between the two approaches. NB-IoT offers better Quality of Service (QoS) due to faster response times and much higher data rates. [VTP17] has found, that LoRaWAN greatly underperforms its specifications, covering distances only up to 2 km in outdoor rural areas and 55-100 m in an indoor urban environment. This is supported by [SLTD17], recommending the use of LoRa only in outlying districts without cellular coverage and the use of NB-IoT in urban settings. These factors justify the increased costs of NB-IoT: requiring the use of licensed frequency bands and additional fees from cellular providers to use their GSM networks or the excessive initial investment to operate a standalone carrier. [LCC+18] introduces NB-IoT as a potential solution within the energy sector for smart grid communications, and recommends it for latency insensitive applications, as NB-IoT can only guarantee latencies no lower than 10 seconds. NB-IoT networks support multiple deployment operation modes to provide flexibility based on existing cellular infrastructure. Depending on the mode of deployment, additional security measures may be required: the establishment of a virtual private network with secured channels is a feasible solution [SLTD17]. The flexibility and QoS offered by NB-IoT makes it a good fit for the application scenario of Wien Energie. In a case study conducted by [LZL21] NB-IoT was successfully implemented in a district heating setting, enabling the local heating provider to take full advantage of IoT enablement. Furthermore, NB-IoT was found to perform exceptionally well in an urban setting, even in semi-submerged underground enclosures. A proposed network architecture complementing the fog-edge-cloud design is presented in Figure 4.7. Stations where a physical link cannot be established are connected over NB-IoT and are assigned the role of a fog node. They are connected to the central infrastructure through LTE base stations operated by cellular providers. Each station produces 3-5 kB of data to describe its current state, this is well below the technical specifications of NB-IoT. Under optimal circumstances, the amount of this data can be reduced with the use of Fog Computing approaches. The maximal 10 second latency offered by NB-IoT is also sufficient to enable real time supervision of stations. To facilitate the assignment of additional stations to the edge layer, a 4G/5G link can be established to enable greater bandwidths and lower latency where a physical connection is not possible. This allows for more flexibility in the designation of stations forming the computational backbone of the edge layer, while keeping deployment costs low. These stations use a physical or 4G/5G link to backhaul data to the central infrastructure.

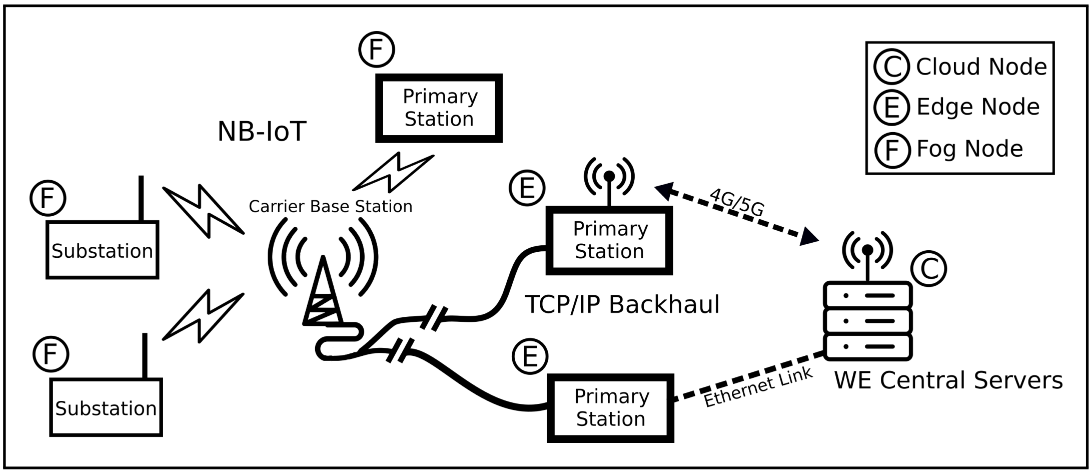


Figure 4.7: Proposed Network Architecture

CHAPTER 5

Discussion and Future Work

This work explored approaches which can enable the integration of IoT solutions into heat networks. The infrastructure of Wien Energie was examined as a representative setting. As a basis, understanding of the problem scenario was gained through a requirements engineering process mapping out stakeholder needs and a subsequent analysis of current systems in place. Information was gathered during a three month period in which the problem setting was explored, mainly through interviews and walkthroughs with members of staff at Wien Energie. A formal definition of these requirements was compiled together in the form of a System Requirements Specification. To complement the output of the exploratory phase, a set of objectives were defined to serve as guidelines for the design process. Three key areas were designated for the practical part: definition of a middleware layer, introduction of edge/fog practices and a new communication technology satisfying the changed requirements. A concept design was presented and discussed for each of these areas focusing on the fulfilment of the goals set. The main contribution of this work lies in the surveying of potential improvement for the whole system with IoT approaches. To provide a cumulative evaluation of the designs presented as the main contribution of this work, the attainment of the 4 objectives defined in Section 4.2 are discussed here. (It is assumed that all heating stations are within the reach of a carrier base station.)

1) Bidirectional transmission

The presented IoT integration middleware implementation and the NB-IoT technology both support bidirectional communication, thus enabling data transmission both ways.

2) Compatibility with the existing infrastructure

Taking the existing infrastructure and its interfaces into account, the proposed designs enable seamless integration. By providing an abstract overview of edge devices and their supporting assets (communications, edge/fog hierarchy), the middleware implementation simplifies development, and as a result, only a single new interface has to be established.

3) Scalability

With the use of edge and fog approaches an unlimited number of stations can be integrated. This requires that computational and communications resources are kept at an optimal level with the matching division of edge and fog nodes.

4) Real-time data availability

The maximal 10 second latency offered by NB-IoT is sufficient to enable real time supervision of stations. An adequate number of middleware instances prevents system delay from becoming noticeable.

Many different approaches and technologies have been left for the future due to the limits on the scope and magnitude of this work. This section present different potential lines of research arising from the examined problem scenario. These concern the deeper analysis of particular technologies/concepts, new proposals and their possible realisation. They can be divided into two areas, one of them being the application of paradigms from related fields. To be able to meet heating demands more efficiently and economically, the demand response approach from electric power sector offers considerable potential [KKK+17]. Also originating within the electric power industry, the idea of smart grids addresses these needs by providing a state-of-the-art viewpoint and approach on all levels of the pipeline from production to consumer. Moreover, the increased level of system observability achieved through the presented approaches gives way to the application of traffic optimization and active traffic management methods. Originating from the realm of intelligent transportation systems, these technologies aim to enable safer and more coordinated use of transport networks. Their added benefits can be translated exceptionally well to heat networks due to their similar architecture. The other area concerns itself with the integration of IoT-based solutions, focusing on the possible realisation of the concepts presented in this work and the discussion of their further elaboration. Especially relevant are the areas of IoT frameworks and big data methods, as they provide a level of abstraction and proven solutions that can be selectively picked out according to the specific needs of the application scenario. Their use can reduce development time, costs and offer further functionality e.g., model-based outlier detection at the fog level. Privacy and security also represent key issues for the success of the system, thus their consideration should also be kept in mind during further elaboration of possible solutions.

List of Figures

Acronyms

AMQP Advanced Message Queuing Protocol. 8, 34

API Application Programming Interface. 9, 34

BLE Bluetooth Low Energy. 10, 12

CPS Cyber-Physical System. 6

DAP Data Accumulation Pipeline. 29

EDGE Enhanced Data Rates for GSM Evolution. 12

ERP Enterprise Resource Planning. 29

GPRS General Packet Radio Service. 12

GSM Global System for Mobile Communications. 12, 37, 38

HSPA High Speed Packet Access. 12

HTTP Hypertext Transfer Protocol. 7, 24, 34

ICS Intelligent Control System. 6

IIoT Industrial Internet of Things. 5–7

IoE Internet of Everything. 1

IoT Internet of Things. xi, xiii, 1, 2, 5–10, 23, 35, 38, 41, 42

JSON JavaScript Object Notation. 7

LPWAN Low-Power Wide-Area Network. 7, 10, 11, 36, 37

LTE Long-Term Evolution. 10, 12, 37, 38

M2M Machine-to-Machine. 10, 12, 37, 43

MFD Multifunction Device. 30

MPLS Multiprotocol Label Switching. 10, 23, 25

MQTT Message Queuing Telemetry Transport. 7, 8, 34

NB-IoT Narrowband IoT. 10, 12, 24, 37, 38, 41, 42

PLC Programmable Logic Controller. 2, 29

QoS Quality of Service. 37, 38

SQL Structured Query Language. 8

SRS System Requirements Specification. 13, 23

UMTS Universal Mobile Telecommunications System. 12

VSAT Very Small Aperture Terminal. 37

XML Extensible Markup Language. 7

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