A Hardware Testbed for Renewable-Aware Resource Management at the Edge

Bachelor's Thesis

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I hereby declare that the thesis submitted is my own, unaided work, completed without any unpermitted external help. Only the sources and resources listed were used. The independent and unaided completion of the thesis is affirmed by affidavit.

Berlin, June 7, 2022

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Zusammenfassung

Abstract

Contents

Chapter 1

Introduction

Edge computing is a promising, emerging paradigm in the area of distributed systems and while still primarily being a theoretical concept, the rise of new domains like Internet of Things (IoT) establishes numerous areas of application [1]. Because of the decentralized nature of edge computing, new devices at the edge of the network are essential for many of these approaches. In some cases though, edge devices do not have access to the electrical grid and require on-site energy generation. Some examples include portable weather stations, smart watering and metering in autonomous farming or numerous sensors in smart city designs. Large-scale data centers already profit from integration of on-site renewable energy generation and are able to achieve significant cost reductions while also reducing their greenhouse gas emissions [2]. In its current state however, renewable energy generation is rather volatile and unable to supply sufficient uninterrupted power on its own [3], resulting in a problem for edge devices without a connection to the electrical grid. If devices under these circumstances aim to operate self-sufficiently and maximize uptime, their resources need to be managed dynamically, relative to current on-site renewable energy production.

To allow for dynamic resource management, matching the system's energy consumption to the on-site production, numerous approaches for power management pose a viable option. Power management, in this case energy proportional computing, can generally be pursued on a hardware- and software-level [4]. On a hardware-level, dynamic voltage and frequency scaling (DVFS), the dynamic adjustment of both voltage and frequency to reduce dynamic power consumption, is vital for this intention as the CPU traditionally consumes the most power in a system.

Recent research in the area of energy-aware resource management in edge/fog computing utilizing DVFS for power management mainly relies on simulations to predict a real-world outcome [5, 6, 7]. Most simulators make the assumption, that computational load can be adjusted in a way that energy consumption perfectly matches the energy production [8, 9, 10, 11]. While the reasoning for using simulations as opposed to real hardware testbeds may be justified and opportune for most research projects, it remains unclear how close these assumptions are to reality and how this may change the accuracy of the predictions and consequently research outcomes.

1.1 Testbed Requirements

This bachelor's thesis proposes a hardware testbed for renewable-aware resource management in edge computing, capable of dynamically adjusting its computational load relative to the on-site renewable energy production. In order to examine the assumption of energy-aware simulators, that computational load is adjustable so that energy consumption is matched to production, this thesis proposes to compare simulations derived from real-world data to this physical hardware testbed. To provide the necessary data to compare the simulations to, a testbed with the following properties is required.

1. Renewable energy is produced and consumed respectively.
2. Excess energy produced, can be stored and retrieved if the production fails to provide sufficient power.
3. $$\frac{P_{\text{load}}}{P_{\text{idle}}} \geq 2.$$
   Adjusting the consumption to current production is more meaningful, in regard to energy savings, if the quotient between the power consumption under load and idle is as high as possible. In order to work properly with the data provided, the lower bound 2 was chosen.
4. The current energy production and resources' power draw can be measured in Volts and Amperes respectively. The amount of stored power can be measured.
5. Resources can be managed dynamically. This is necessary for adjusting the consumption depending on the current production of renewable energy.

1.2 Thesis Outline

This thesis is divided into 6 chapters.

Chapter 2 introduces the fundamental concepts discussed in subsequential chapters. First, edge and fog computing paradigms and their necessity for future information and communications technology (ICT) are presented. Second, the respective use cases of physical and simulation testbeds in edge and fog computing environments are outlined. Third, dynamic resource management, and specifically energy proportional computing for our use case, techniques are presented and DVFS, as the main technique for our physical testbed, along with its implementation in the Linux kernel, will be outlined.

Chapter 3 first reviews related research in the area of energy-aware resource management utilizing DVFS. The utilization of simulations in all presented papers leads to the described problem which is subsequently outlined. Then, these simulations are presented and aforementioned problem is demonstrated.

Chapter 4 presents the hardware testbed. First, all hardware components used and their conformity with the requirements listed in section 1.1 are presented. Second, the assembly of the individual components and their relations to each other are described. Third, the setup of the software, necessary to ensure functionality of the components, data transmission and operability, is presented. Fourth, the implementation of DVFS, customized for this testbed, is outlined.

Chapter 5 evaluates the testbed by assessing the accuracy of its capability to adjusting its computational load relative to the on-site energy generation. An error analysis is conducted and reviewed in regards to collected data by the testbed. The subsequent consequences for conducted research in the area of energy-aware resource management are discussed.

Chapter 6 concludes the thesis by summarizing the main points and contributions.

Chapter 2

Background

This chapter elaborates on relevant concepts revolving around energy-aware resource management in edge and fog computing. Section 2.1 introduces the motivation and explains the necessity for edge and fog computing paradigms. Section 2.2 focuses on the development process of edge and fog infrastructure and outlines the essential use of testbeds. Section 2.3 presents common techniques in dynamic resource management whilst focusing on energy proportional computing. Since the renewable energy source of the hardware testbed is not able to supply uninterrupted power, section 2.3.1 outlines specific techniques used in energy-aware resource management. Dynamic voltage and frequency scaling will be the primary technique used in the hardware testbed and is therefore elaborated on further in section 2.3.2.

2.1 Edge and Fog Computing Paradigms

In 2012 Xia et al. defines the Internet of Things as the networked interconnection of everyday objects, which are often equipped with ubiquitous intelligence [12]. Since then, IoT devices have spread to all aspects of our everyday lives. Cisco estimates that by 2023 there will be 14.7 billion machine-to-machine connections, more than a 140% increase to 2018 [13]. The rise of IoT results in a significant increase of devices connected to the internet and may, with its current rate of development, soon grow to a point, that our current network structure cannot manage. In specific, major challenges that are posed by traditional cloud-centric IoT architectures include the excess of bandwidth availability due to the increasingly large and high-frequent rate of data being produced by IoT devices, and high end-to-end latency along with unstable, intermittent network connectivity due to potentially large physical distance [14].

As an alternative to cloud-centric architectures, computing resources can be brought closer to end-devices. Using these resources, even partially, for data processing would reduce the amount of data sent to the cloud. With the physical proximity of provided services, latency for end-devices is highly lowered, cloud servers are relieved due to less network traffic and network throughput is consequently raised, favoring both end-devices and cloud servers. With these alternative paradigms, fog and edge computing are introduced.

The terms *fog* and *edge* computing are often used inconsistently throughout current literature. The research field is still rather young and allows for multiple interpretations. In the context of this thesis, the distinction from Iorga et al., from the National Institute of Standards and Technology, will be used. Iorga et al. define fog computing as a layered model for enabling ubiquitous access to a shared continuum of scalable computing resource, whereas edge computing describes the layer of end-devices that are used to do limited local computing or sensor metering [15]. A concurrent example for this interpretation of the terminology is presented by Atos' BullSequana edge computing servers, utilized for visual quality control in production lines. Possible defects are detected locally and may subsequently be transmitted to a nearby fog server for further processing [16, 17].

2.2 Testbeds in Edge and Fog Computing Environments

While some elaborate approaches are already in use, none of these are deployed on a large scale yet and are therefore, for the most part, unfit for research revolving around fog and edge computing. Deploying a large scale physical testbed for research or commercial purposes is not only very cost intensive, but also highly time consuming. Thus, simulating or emulating environments for fog and edge computing paradigms seems to be most opportune for development and research processes.

2.3 Dynamic Resource Management

2.3.1 Energy-Aware Resource Management

2.3.2 Dynamic Voltage and Frequency Scaling

Chapter 3

Related Work

3.1 Energy-Aware Resource Management with DVFS

3.2 Energy-Aware Simulators

Chapter 4

Testbed

This chapter presents the hardware testbed. The assembled setup system is capable of dynamically adjusting its computational load relative to the on-site energy production by photo-voltaic (PV) modules. Section 4.1 lists all main physical components and demonstrates the conformity with the requirements from section 1.1. Section 4.2 shows the assembly of all components and explains their interrelations. Subsequently section 4.3 shows the software setup, necessary to ensure functionality of the components, data transmission and operability. Section 4.4 presents the implementation of DVFS for this testbed.

4.1 Hardware Components

The testbed is mainly composed of the following hardware. As the compute node, the single-board computer *Raspberry Pi 3b+* serves as a viable choice due to its low energy consumption, cost effectiveness and a wide range of hardware applications.[1] Renewable energy is produced by 4 PV modules, each outputting 330 mA at 6 V. Excess energy produced by the PV modules is stored in a 3.7 V, 6600 mAh lithium-ion polymer (LiPo) battery as backup energy source in case of suboptimal solar conditions. Ultimately a component, connecting all components listed above, is needed to measure the energy production of the PV modules, the battery's state of charge and the energy consumption of the compute node. *SwitchDoc Labs* developed *SunControl*, an inexpensive solar power controller board, among multiple other things capable of these tasks [18] and is therefore ideal for this testbed.

In an idle state, with the HDMI driver and LEDs disabled to preserve energy, the node consumes about 400 mA (2 W). With the same configuration under load, the node consumes up to 980 mA (3.7 W), yielding a quotient between power consumption under load and idle of 2.45.

[1] `https://www.raspberrypi.com`

4.2 Hardware Assembly

4.3 Software Setup

As the testbed is self-sufficient, remote communication is most suitable for monitoring and operations. A Secure Shell (SSH) connection to the Raspberry Pi is easily configured alongside the installation process of Raspberry Pi OS Lite via their imager software.[2] To enable functionality of SunControl, installation of SwitchDoc's Python driver code libraries are necessary. The official code from 2017 was written in Python 2.7.[3] Since Python 2 is deprecated since 2020 and vital official libraries are no longer supported,[4] the codebase needed to be refactored and ported from Python 2.7 to 3.7.[5] To allow SunControl to communicate with the Raspberry Pi, Inter-Integrated Circuit (I^2C) support for the ARM core and Linux kernel need to be configured via `sudo raspi-config`. For this, the packages `python-smbus` and `i2c-tools` from the Debian 11 repositories need to be installed.[6]

4.4 Implementation of DVFS

[2] https://www.raspberrypi.com/software/

[3] https://github.com/switchdoclabs/SDL_Pi_SunControl

[4] https://www.python.org/doc/sunset-python-2/

[5] https://github.com/marvin-steinke/SDL_Pi_SunControl

[6] https://learn.adafruit.com/adafruits-raspberry-pi-lesson-4-gpio-setup/configuring-i2c

Chapter 5

Evaluation

Chapter 6

Conclusion

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