ITMO University
Department of Information Technologies
PERCCOM Master Program

Master's Thesis in
Pervasive Computing & COMmunications
for sustainable development

Manish Lamichhane

A SMART WASTE MANAGEMENT SYSTEM USING IOT AND BLOCKCHAIN TECHNOLOGY

2017

Supervisors: *Oleg Sadov* (ITMO University)
Arkady Zaslavsky (CSIRO)
Andrei Rybin (ITMO University)

Examiners: *Professor Eric Rondeau* (University of Lorraine)
Professor Jari Porras (Lappeenranta University of Technology)
Associate Professor Karl Andersson (Luleå University of Technology)

This thesis is prepared as part of an European Erasmus Mundus programme PERCCOM - Pervasive Computing & COMmunications for sustainable development.

This thesis has been accepted by partner institutions of the consortium (cf. UDL-DAJ, n°1524, 2012 PERCCOM agreement).

Successful defense of this thesis is obligatory for graduation with the following national diplomas:

- Master in Complex Systems Engineering (University of Lorraine)
- Master of Science in Technology (Lappeenranta University of Technology)
- Degree of Master of Science (120 credits) –Major: Computer Science and Engineering, Specialisation: Pervasive Computing and Communications for Sustainable Development (Luleå University of Technology)

ABSTRACT

ITMO University
Department of Information Technologies
PERCCOM Master Program

Manish Lamichhane

A Smart Waste Management System using IoT and Blockchain Technology

Master's Thesis

2017

60 pages, 22 figures.

Examiners: *Professor Eric Rondeau* (University of Lorraine)
Professor Jari Porras (Lappeenranta University of Technology)
Associate Professor Karl Andersson (Luleå University of Technology)

Keywords: Waste Management; IoT; Ethereum; blockchain; Decentralized Autonomous Organization, Smart Contracts, Cryptocurrency

Blockchain technology and Internet of Things are two of the most popular technologies today. IoT is an interconnection of devices that has the capability to sense, measure, process the state of environmental indicators as well as themselves and actuate based on the input provided. It can help create smart solutions that can enhance the quality of life of people. Likewise, blockchain is distributed database systems that promise high level of security and availability of data with least transaction overhead. In this thesis, we attempt to bring together these two technologies to develop a Smart Waste Management System (SWMS). The SWMS is weight-based i.e. users have to pay for use of services as per the amount of waste they produce. Payments are made using a custom cryptocurrency regulated by *Smart Contracts* and the entire SWMS can be funded by a *DAO* through a totally automate, highly secure process. Blockchain can help lower the penetration and service cost which can be specially beneficial to developing countries where governments are not very resourceful. This thesis attempts to establish a *proof of concept* through measurement of performance and assessment of applicability of such a system.

ACKNOWLEDGEMENT

May 24, 2017

The research reported here was supported and funded by the PERCCOM Erasmus Mundus Program of the European Union [Klimova et al. 2016] [1]. Part of this work has been carried out in the scope of the project bIoTope [2] which is co-funded by the European Commission under Horizon-2020 program, contract number H2020-ICT-2015/ 688203 – bIoTope. The research has been carried out with the financial support of the Ministry of Education and Science of the Russian Federation under grant agreement RFMEFI58716X0031.

I would like to express my sincere gratitude towards European Commission and all the people involved in making PERCCOM program what it is today.

This thesis would not have been possible without the expert advice and encouragement of my supervisor, Oleg Sadov. Thank you for always being there and always pushing my imagination. Thank you Prof. Arkady Zaslavsky for your valuable guidance to structure and organize this thesis.

Also, thanks to Andrei Rybin and Margarita Yashina for the support they have provided through out my thesis period. I would like to specially mention Prof. Eric Rondeau, Prof. Jari Porras and Prof. Karl Andersson for facilitating our semester in France, Finland and Sweden respectively.

Lastly, to my "PERCCOMIES", thank you for the beautiful memories you all gave me in the past two years. You all will be in my heart and mind, always.

Manish Lamichhane

CONTENTS

List of Figures

ABBREVIATIONS AND SYMBOLS

AFR	Africa Region
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface CPU Central Processing Unit
CoAP	Constrained Application Protocol
DAO	Decentralized Autonomous Organization
DB	Database
DSS	Decision Support System
DTSL	Datagram Transport Layer Security
EAP	East Asia and Pacific
ECA	Eastern and Central Asia
ETH	ETHER
EU	European Union
GB	Giga Bytes
GHG	Green House Gases
GSM	Global System for Mobile communication
HSGB	Head Smart Garbage Bin
ICT	Information and Communication Technology
IP	Internet Protocol
IoT	Internet of Things
JSON	Javascript Standard Object Notation
LAC	Latin America and the Caribbean
LLL	Lisp Like Language
MB	Mega Bytes
MENA	Middle East and North Africa region
MQTT	Message Queue Telemetry Transport
OECD	Organisation for Economic Co-operation and Development
PoS	Proof of Stake PoW Proof of Work
QoS	Quality of Service
RAM	Random Access Memory
REST	Representational State Transfer
RFID	Radio Frequency Identification

RPC	Remote Procedure Call
SAR	South Asia Region
SGB	Smart Garbage Bin
SSL	Secure Socket Layer
SWMS	Smart Waste Management System
TCP	Transfer Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
URL	Uniform Resource Locator
WSN	Wireless Sensor Networks

1 Introduction

The Introduction section describes the motivation behind the thesis, the aim of the thesis, the scope of impact and implementation, and an outline of the following sections with short description of each of them.

1.1 Motivation

World *Bank's* data from 2012 suggests that by 2025 there are going to be 4.3 billion urban residents generating about 1.42 kg/capital/day of municipal solid waste. The waste management costs is projected to increase to about $375.5 billion in 2025 from an annual of about $205.4 billion in 2012 [3]. *Figure* 2 shows the generation of waste per capita by region, according to World Bank's report of 2012. It indicates that waste generation is directly proportional to economic prosperity, development and industrialization. Similarly, a strong correlation is established between the income levels, quality of life and waste generation as higher the income of people, more is their consumption of goods and services. At present, approximately 50% of total population of world are residing in cities. These data show that the waste management is and is going to be a very expensive aspect of governance.

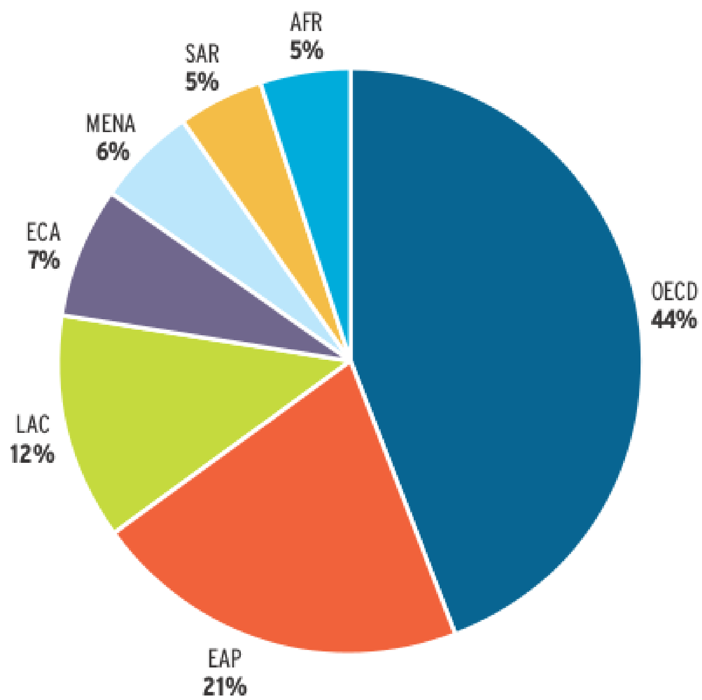


Figure 1. Waste Generation by Region (What A Waste: World Bank 2012)

European Commission describes IoT as,"Internet of Things (IoT) represents the next step towards the digitisation of our society and economy, where objects and people are interconnected through communication networks and report about their status and/or the surrounding environment". With the rise of IoT, Pervasive computing has a greater reach into many aspects of society. Communication between the devices are meaningful to common users in a sense that it helps them simplify different day-to-day tasks. Common examples could be automatic doors, fire alarms etc. However, these are simple examples of application of IoT devices. They can have much deeper impact when used together with other technologies. Today, IoT has the capability to sense, actuate, collect, process and store data. Smart Cities will therefore have even wider implementation of these devices.To name a few, from citizen observatory, traffic management, energy management and use of smart grids to flood detection and prediction systems.
Centralized financial systems are trust based. Users have to trust them with their wealth and the security associated. Their massive overhead costs makes micropayments extremely difficult [4] [5]. With the introduction of Bitcoin in 2009 [6], blockchain technology was introduced to the world. It enables financial transactions beyond borders and completely displacing intermediaries in terms of security and transaction overhead cost. Though bitcoin is successful and equally controversial, blockchain technologies have proved their worth in both financial and non-financial systems .The implementation of smart contracts [7] on top of blockchain largely widened the scope of the impact of blockchain. *DAO* or *Decentralized Autonomous Organization* [8] is a concept of a democratic organization that can exist on Ethereum blockchain whose objective and manifesto can be defined as a collection of smart contracts. It then runs on its own without human intervention. Any changes made to the organization has to be passed through voting of its members or else it wont take place. A DAO can execute other smart contracts and also interact with other DAOs. This could give rise to totally new business models and can have a very wide implementation scope. One can even imagine government bodies and different companies running on top of blockchain using the concept of DAO.
Developed countries have some sort of waste management system already in place. Many developing countries, however, are struggling with serious problems problems related to Waste Management [9].
Various IoT based waste management approaches have been proposed to establish a proper waste management system. However, they all rely on third party services for the payment of service. Majority of the population in many developing world countries don't own a bank account, let alone online banking services [10]. This thesis is a proof of concept of a system that brings together two powerful technologies: IoT and blockchain technology, to address real world problems in (but not limited to) developing countries. The focus of this thesis will be on the implementation of DAO, which will be dealt in detail in coming sections. The proposed solution is named as "*Thrift and Green*" and will be called *TAG*, for convenience, hereafter. TAG is a proof of concept of a system that brings together two cutting edge technologies: IoT and

Region	Waste Generation Per Capita (kg/capita/day)		
	Lower Boundary	Upper Boundary	Average
AFR	0.09	3.0	0.65
EAP	0.44	4.3	0.95
ECA	0.29	2.1	1.1
LAC	0.11	5.5	1.1
MENA	0.16	5.7	1.1
OECD	1.10	3.7	2.2
SAR	0.12	5.1	0.45

Figure 2. Current Waste Generation Per Capita by Region (What A Waste: World Bank 2012)

blockchain to solve real world problems. Waste Management is used as a use case of this idea. This thesis is motivated by the idea of solving real world problems by the use of Internet of Things and Decentralized Autonomous Organization concept of blockchain technology.

1.2 Aim

This section outlines the impact area of this thesis. The emphasis of this thesis, as being part of PERCCOM program, is to focus on addressing sustainability issues of society. Generation of waste and its management can directly impact sustainability. Sustainability in itself has multiple dimensions which can be unique to a time and situation. Mismanaged waste can be responsible for emission of *Green House Gases* or *GHG*. There can be direct and indirect impact in the health of people in proximity to the improperly disposed waste. A proper waste disposal and management can pave path for recycle and reuse of materials. Not only recycle and reuse, the generated waste can also be converted into energy that in turn can be used to enrich the quality of life of people. Sweden has made a remarkable progress in terms of recycling of waste. The Independent writes ,"Sweden's recycling is so revolutionary, the country has to import rubbish from other countries to keep its recycling plants going". [11]. Furthermore, if the waste management system is properly backed by technology, factual data regarding the waste and consumption behaviour can be obtained that can be used in planning investments and allocating resources for improvement of existing problems.

Most of the waste management systems in practise use flat-rate based pricing system to compensate for the waste management services. There is no motivating factor that makes people produce less waste. A weight-rate based system on the other hand charges user certain percent of money as per the amount of waste they produce. The lower they produce, the lower they pay and vice-versa. Deployment of this kind of system in South Korea [12] resulted in 33% decrease in the amount of waste produced in the deployed region.

DAO enables formation of different kinds of organization on top of blockchain. The core idea of this thesis is to form a DAO for waste management system that is supported by some other

Smart Contracts to function well. This kind of system can lower the economic barrier, security and transparency issue for investments, thus promoting new kind of business models. In this particular scenario, it can be people coming together and creating waste management DAOs for their local community or region. As mentioned above, a weight-rate based system charges user certain sum as per the weight of waste generated. What blockchain technology does best is it reduces the overhead of financial transactions which is crucial in this kind system where payments can be minimal. This can specially be effective in both developing countries with lack of proper payment infrastructures and in developed countires where micropayment still is an issue. *Figure* 3 shows an example of an ecosystem of DAOs and Smart Contracts that can represent real world organizations on top of blockchain and how they can interact with each other to serve their purpose.

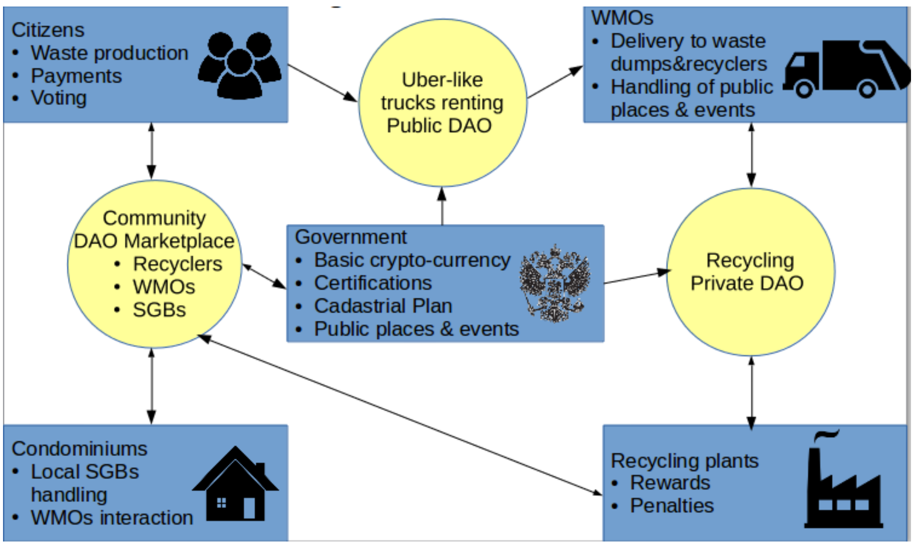


Figure 3. Example of DAO architecture

1.3 Problem Definition

Internet of Things and blockchain technology are two technologies that are accelerating upwards in Gartner's Hype Cycle [13] [14]. A lot of tools and technologies are build and are being built around Internet of Things. Likewise, blockchain technology is said to be in the same phase in which the Internet was during the 80's and 90's. Even though these techs are under rapid development, their possibility of impact and usefulness outbids their lack of maturity. [15].
Traditional waste management systems in practise serve their purpose by collecting the waste, transporting it to the facility and recycle or incinerate (most of the times) what could not be recycled. The problem of waste is addressed to some extent but, this kind of system does not encourage, motivate people to produce lesser waste than what they were producing. A solution

to this problem would be introduction of a flexible pricing. In such system of pricing, people would pay for the waste management services as per the amount of waste they produce. The limitation of this kind of implementation would be the availability of the data of waste generation. Another aspect of this problem is the lack of route optimization for the waste collection trucks. In many cases, there are several collection trucks overlapping in the same route. Had there been a way for these trucks to know before-hand, the level of waste in the waste bins, appropriate route planning could be done. This could reduce the overall fuel consumption leading to economic and environmental benefits.

The characteristic feature of Internet of Things, as mentioned above, is suitable to address such problem of related sensing, measurement and collection of waste related data. Use of IoT in waste bins could measure the level of waste which can be used to charge users with appropriate amount. The same data could be used to optimize the route of collection trucks, if the data is publicly available. The pervasive nature of IoT, of course, has it's advantages. On the other hand, the associated privacy concerns can lead to reluctance of acceptance of such system, thus, reducing its usability.

Blockchain provide an ideal solution to the privacy and security concerns by promising a highly available, secure, decentralized and public network. Furthermore, blockchain's support for payment services has been tested and verified for nearly a decade now. IoT and Blockchain together can address the drawbacks of traditional waste management system and has the potential to open new business models that could benefit society and environment.

The goal of this thesis to propose, develop, implement and validate a system that brings together Internet of Things and blockchain technology together, to provide a robust, sustainable, and efficient solution to overcome the problems of waste management system. One of the main challenge for this kind of system would be the evaluation and selection of appropriate technology stack that provides a balance between performance, security and rapid development. IoT and blockchain both are evolving technologies and hence the high frequency of updates of tools for development could be another challenge. This thesis aims to address the above described problems using the following two research questions:

- What are the requirements of an IoT based system to work together with concepts of blockchain technology like Smart Contract and Decentralized Autonomous Organization?

  To address this question, we have taken into account latest tools, protocols and technologies trending in both IoT and blockchain technologies. Justification of the use of particular library or protocol has been supported by the results of researches in those particular domain.

- What are the impacts of IoT, Smart Contracts and Decentralized Autonomous Organization in social, economical and environmental context?

  Smart Contracts and Decentralized Autonomous Organization representing a real world organizations that can has the capacity to interface with IoT devices has been proposed in this thesis. Though the concepts described in this thesis do not address all the requirements of such a system, it provides a good outlook and a general overview of such a system. This thesis, being a proof of concept, may not provide real data backed evidence to justify the direct impact of the proposed system in social, economic and environmental settings. However, through the use of simulation, analysis and performance evaluation in experimental settings, the advantages of this kind of system is highlighted.

Above mentioned research questions attempt to address the technological as well as non-technological but equally significant aspect of the problem. The research methodology followed to establish a road-map to solution can be divided into four phases, namely:

- Problem Definition

  Different aspect of the problem of waste management was studied and understood through a rigorous literature review. The socio-economic impact, effects to environment and gap between different proposed solutions was identified. This provided a reasonable problem space where the proposed system could have meaningful implementation.

- Requirement Analysis

  During this phase, different programming languages, tools and libraries were evaluated, keeping the focus on technological requirement. An outline of the ecosystem of the technological stack was developed that served as a blue-print for the next phase.

- Development and Testing

  Using Scrum, the requirements were divided into small user stories. The user stories were realized into actual implementation using rapid prototyping. In each iteration, a new user story was added to the previous prototype. Git was used for version control and Heroku was used for deployment.

- Implementation and Evaluation

  The entire ecosystem of the implementation comprises of a mobile application bot, a SGB simulation based on Python Django framework, a centralized server built with NodeJS and MongoDB and finally, the blockchain component. The overall performance evaluation of such ecosystem is a complex process and hence, is beyond the scope of this thesis. The performance of blockchain part of the system was measured in different settings. The measurements provide an overview of mining time of transactions in blockchain which is described in detail in the following chapters.

1.4 Research Contribution

The contribution of this research was to establish a proof of concept of a system combining Internet of Things with blockchain technology to address problems of Smart Cities. Waste management was selected as a reasonable area of application of this kind of system. This research proposes a Smart Waste Management System which includes simulated Smart Garbage Bins powered by Internet of Things that communicate with their blockchain components via one of the most popular IoT protocol. The implementation of blockchain was carried out in a private remote node and public test node and mining time were analyzed for each. This provides an insight on efficiency of the system in those two settings. Such a data-driven system could help provide a broader view of the waste problem and thus, better address the waste problem our society is facing. With the increasing interest of academia and industry in IoT and blockchain technology, this research could provide a sound over view of both of the technology as separate entities and as a single entity which combines the characteristics of both of these technology to provide solutions to social, economic and environment problems.

1.5 Scope

The scope of this thesis is to establish a general framework of technologies that can help bring together Internet of Things and blockchain technology. The combination of IoT and blockchain technology can give rise to new business models where blockchain can handle transaction and data management while IoT devices can become the point of contact to the real world [15]. As a proof of concept, this framework is implemented in developing a Smart Waste Management use case. A simulated Smart Garbage Bin, blockchain test network and private network (not the main Ethereum network) is used for the deployment. Test data are used to represent the waste and user related information. A custom cryptocurrency is used so that the flow of the currency in the system can be managed as per requirement. The pricing of the currency and regulation of its value is out of the scope of this thesis. Source sorting of waste has not been taken into account in the implementation. Security aspect of the implementation has not been taken into account.

1.6 Structure of Thesis

The following parts of this thesis is divided into different sections as follow:

1.6.1 Background and State of the Art

This sections describes about the current waste management practises in developed countries and developing countries and the problems they comprise. Though the implementation of this kind of waste management system would be mostly meaningful in developing countries, it's not limited only to developing countries, which is what we try to establish in this section. A thorough study and analysis of similar works in the domain of Smart Waste Management is described. How different sections of these different works add a building block in the implementation in highlighted. We also describe about the recent development in blockchain technology like Smart Contracts, and DAO, which forms the base of blockchain part of the implementation.

1.6.2 Research, Design and Implementation

This sections deals with the technical aspect of TAG. It describes in detail, the different components of TAG and the technology stack used. How data flows from user's mobile application to the SGB simulation to the blockchain. It also includes the snapshots of various components of TAG which helps to visualize the functionality of its components.

1.6.3 Evaluation and Discussion

This section describes about the deployment and performance of TAG. How does the change in hardware and network type affect the efficiency of the system is described in this section.

1.6.4 Conclusion and Future Work

This section is a summary of the entire thesis. We also describe about the short comings of TAG and what additional development can be assembled to overcome those shortcomings.

2 Background and State of the Art

This section provides an overview of waste management practises in developed and developing countries. Using data from World Bank (2012), European Union (2014) and study of waste management practices in Asia, the prevalent waste management practices are highlighted.

2.1 Waste Management Practises

The process of Solid Waste Management can be divided into two parts: 1. *Collection and Transport* 2. *Disposal and Recycle* World Bank describes Waste Management as the collection of solid wastes from the point of production to the point of treatment or disposal. In developed countries, most of the existing waste management systems include multiple third party waste collectors that transport the waste disposed in waste bins to a recycle plant or landfill sites. The major cost in waste management system in developed countries is spent in disposing of waste. In case of developing countries, this is the opposite. Most of the budget for waste management is spent on collection of waste and only a small fraction is spent on disposal. A report by European Union in 2014 [16] reveals that 2503 million tonnes of waste was produced on that year from household and other economic activities. Nearly, 47% of this waste was incinerated, 36% was recycled (not including energy recovery) 10.2% was landfilled and remaining was incinerated to recover energy. Contrary to this, in most of the Asian countries, most of the wastes were dumped in open and go untreated. Countries like Nepal, Bangladesh, India, Thailand and Vietnam had more than 60% of waste in open dump or untreated [17]. Japan and Singapore incinerate most of their waste while only Hongkong recycled more than 40% of its waste.

2.2 Pitfalls of prevalent practices

It can be inferred from data provided in previous sections that there is a high correlation between the level of income and the amount of waste generated. Large investments are made and huge budgets are being sanctioned anually to overcome this problem. However, the heart of the problem lies elsewhere. As long are common people are not motivated to change in the pattern of consumption, the curative measures are going to be a temporary fix.

Most of the existing systems use fixed cost pricing strategy i.e. whatever amount of waste the users produce, a fixed amount is charged to the users. There is no motivation whatsoever to produce lesser waste or even consider producing less waste. On top of this, the waste data is not reliable as well. A study conducted in the same domain in Sweden [18] reflects the data reliability problem. 30 waste management companies were keeping records of the waste data which amounted to 500,000 entries. Lack of quality control and appropriate pre-defined criteria to record the data resulted in usability of only a fraction of data from the data-set.

TABLE 1

Comparison of Solid Waste Management Practices by Income Level (adapted from *What a Waste 1999*)

Activity	Low Income	Middle Income	High Income
Source Reduction	No organized programs, but reuse and low per capita waste generation rates are common.	Some discussion of source reduction, but rarely incorporated into an organized program.	Organized education programs emphasize the three 'R's' — reduce, reuse, and recycle. More producer responsibility & focus on product design.
Collection	Sporadic and inefficient. Service is limited to high visibility areas, the wealthy, and businesses willing to pay. High fraction of inerts and compostables impact collection—overall collection below 50%.	Improved service and increased collection from residential areas. Larger vehicle fleet and more mechanization. Collection rate varies between 50 to 80%. Transfer stations are slowly incorporated into the SWM system.	Collection rate greater than 90%. Compactor trucks and highly mechanized vehicles and transfer stations are common. Waste volume a key consideration. Aging collection workers often a consideration in system design.
Recycling	Although most recycling is through the informal sector and waste picking, recycling rates tend to be high both for local markets and for international markets and imports of materials for recycling, including hazardous goods such as e-waste and ship-breaking. Recycling markets are unregulated and include a number of 'middlemen'. Large price fluctuations.	Informal sector still involved; some high technology sorting and processing facilities. Recycling rates are still relatively high. Materials are often imported for recycling. Recycling markets are somewhat more regulated. Material prices fluctuate considerably.	Recyclable material collection services and high technology sorting and processing facilities are common and regulated. Increasing attention towards long-term markets. Overall recycling rates higher than low and middle income. Informal recycling still exists (e.g. aluminum can collection.) Extended product responsibility common.
Composting	Rarely undertaken formally even though the waste stream has a high percentage of organic material. Markets for, and awareness of, compost lacking.	Large composting plants are often unsuccessful due to contamination and operating costs (little waste separation); some small-scale composting projects at the community/ neighborhood level are more sustainable. Composting eligible for CDM projects but is not widespread. Increasing use of anaerobic digestion.	Becoming more popular at both backyard and large-scale facilities. Waste stream has a smaller portion of compostables than low- and middle-income countries. More source segregation makes composting easier. Anaerobic digestion increasing in popularity. Odor control critical.
Incineration	Not common, and generally not successful because of high capital, technical, and operation costs, high moisture content in the waste, and high percentage of inerts.	Some incinerators are used, but experiencing financial and operational difficulties. Air pollution control equipment is not advanced and often by-passed. Little or no stack emissions monitoring. Governments include incineration as a possible waste disposal option but costs prohibitive. Facilities often driven by subsidies from OECD countries on behalf of equipment suppliers.	Prevalent in areas with high land costs and low availability of land (e.g., islands). Most incinerators have some form of environmental controls and some type of energy recovery system. Governments regulate and monitor emissions. About three (or more) times the cost of landfilling per tonne.
Landfilling/ Dumping	Low-technology sites usually open dumping of wastes. High polluting to nearby aquifers, water bodies, settlements. Often receive medical waste. Waste regularly burned. Significant health impacts on local residents and workers.	Some controlled and sanitary landfills with some environmental controls. Open dumping is still common. CDM projects for landfill gas are more common.	Sanitary landfills with a combination of liners, leak detection, leachate collection systems, and gas collection and treatment systems. Often problematic to open new landfills due to concerns of neighboring residents. Post closure use of sites increasingly important, e.g. golf courses and parks.
Costs (see Annex E)	Collection costs represent 80 to 90% of the municipal solid waste management budget. Waste fees are regulated by some local governments, but the fee collection system is inefficient. Only a small proportion of budget is allocated toward disposal.	Collection costs represent 50% to 80% of the municipal solid waste management budget. Waste fees are regulated by some local and national governments, more innovation in fee collection, e.g. included in electricity or water bills. Expenditures on more mechanized collection fleets and disposal are higher than in low-income countries.	Collection costs can represent less than 10% of the budget. Large budget allocations to intermediate waste treatment facilities. Up front community participation reduces costs and increases options available to waste planners (e.g., recycling and composting).

Figure 4. Waste Management Practices (Source : What a Waste)

To address these problems, different solutions using IoT devices have been forwarded (some discussed in literature review).But these solutions do not use IoT protocols designed for resource constrained environments. The use of proper IoT protocols designed for constrained environment like MQTT or CoAP could have enhanced the energy efficiency.
Also, if we consider the deployment of this kind of system in developing countries, there are many limiting factors. Many governments in developing countries do not even have funds to invest in developing a proper waste management system. Another hindrance would be the lack of proper payment infrastructure for the payment of waste management services. Department of Computer Science, Stanford University, outlines several technical, social and economic challenges in current micropayment systems [19]. One of the main barriers of explosion of micropayments structure is the incapability of minimizing the transaction cost in relation to the actual incurred cost. In case of cryptocurrencies, there are no third-party involvement and hence, the transaction overhead is minimal. Micropayments can be executed in a simplified, transparent way. A different approach to solve this can be local community coming together and raising fund to invest into solutions to their problems. DAO is a powerful concept of creating organization on top of blockchain technology using mere immutable computer codes. This bypasses the need of a third party or Government in general for lawful regulation and asset security. Because Smart Contracts always will behave the way they are designed to behave before execution. The codes cannot be tampered with or changed once its deployed on blockchain network. Changing the rules and objectives of DAO will be possible only by consensus (depending on the type of DAO). Like any normal organization, a DAO may need investment. The investments are all performed in cryptocurrencies. Cryptocurrencies can be purchased from different exchanges or can be generated using another DAO that can act as the central bank. TAG uses it's own cryptocurrency regulated by its own central bank. The bank can inflate or deflate the currency as per the need and consensus of its regulatory members.
For a common user, knowing all these technical terms in detail is not feasible and practical. In thsi subsection, TAG is presented in common user's perspective. A user who wants to dispose waste using TAG needs two things: A Telegram App and an Ethereum account. Ethereum account can simply be created by downloading an Ethereum Wallet. [20]. An alternative to use Ether or to buy crytocurrency would be minting, which is discussed in their Architecture section. TAG has an entire ecosystem of DAOs that runs using a common currency regulated by a central bank. Users then need to transfer some funds to this central bank account's address to use TAG's services. Once user has account with some balance in it, they can generate a QR-code using Telegram app by sending their account number to a Telegram Bot. The Telegram bot also sends the location of the SGB closest to user's location with information about the level of waste, the current exchange rate and the charging policies. User can open the SGB by scanning the QR-code. After disposing the waste, the system will measure the weight of the waste user deposited and transfer PercCoins from user's account in the central bank to the SGB owner's

account in the central bank, that equals to the amount 5% of the weight of the waste that user disposed. So, if user disposed 1000 grams of waste, the cost would be 50 (5% of 1000) cents converted in PercCoin. The pricing of PercCoin is beyond the scope of this research. We have used a constant rate of exchange for TAG to simplify things.

2.3 State of the Art

The State of the Art chapter is divided into five subsections. In the first section, the recent development in different approaches to Smart Waste Management systems is presented. Afterwards, popular IoT protocols are described and a comparison is made between them, outlining the advantages and disadvantages of each. The following subsections are dedicated to the detailed description of blockchain and related technologies.

2.3.1 Waste Management Systems

As a solution to this problem of Waste Management, a lot of projects using technologies like IoT, RFID, WSN etc are already in place. Junaith Ahemed Shahabdeen has patented a *Smart Garbage Bin* or *SGB* [21] that uses sensors mounted in the cover (range finder) or bottom (weight sensor) of the SGB that can sense the amount of items deposited in the SGB. This thesis takes into consideration this very approach for calculating the amount of waste present in the SGB. For the purpose of experimentation , a simulation of SGB is used. Above mentioned approach is suitable for deployment to real world. Another approach where selective sorting of different types of waste is enabled using RFID technology [22] is already in place. The quality of waste generated can be significantly improved by the use of this approach. To perform model sorting at source technologically in our system is currently not possible. Wireless Sensor Networks are used to check the filling of the bin by the use of sensors embedded in the SGB. These sensors feed data to Data Transfer Nodes which enables long range transmission of data to a Decision Support Server [23]. Apart from a combination of WSN and RFID technology, an approach based on image processing that takes timely snapshot of level of waste in SGBs and processes them using Microcontroller to identify the level of waste and send information to the central office using GSM module has been in place [24]. In [25], the authors propose a solid waste bin monitoring system using Zigbee and GSM / GPRS technologies. The entire architecture is divided into 3 tier. The lower tier consists of bins with sensors that feed the status of the bin to middle tier. The proposed model uses capacity, weight, temperature, humidity and chemical sensors. Middle tier acts as a liaison between upper tier and lower tier. The system uses energy efficient sensing algorithm that can help reduce the emission and operation cost. While [25] focused on the monitoring of solid waste in a waste bin, [26] proposes a system that forecasts the quantity and variance of solid waste using an intelligent, sensorized container. Weight and volume of waste in the sensorized container is taken as input parameter for the system. Pneumatic waste collection system is getting considerable interest in Smart Cities. In [27], the author compares pneumatic waste collection system with traditional door to door waste collection system and concludes that both are at a disadvantage in densely populated, urban areas. Pneumatic systems has high installation cost and large maintenance overhead while pick up trucks face traffic and space problems while operating in urban cities. Still, if only cost factos are taken into consideration, traditional pick up system are approximately six times more viable that pneumatic systems. The most interesting of all is a WSN and RFID based SGB which introduces the idea of HSGB (Head SGB) that monitors other SGB within its area using a mesh topology6 [12]. An edge-router is responsible to assign HSGB using the battery / power status of a particular SGB over the span of 7 days. This approach introduces an *"Adaptive User charge policy"* that motivates users to produce less waste by charging users with a rate based on the 10% of the total waste production by the user on monthly basis.

2.3.2 IoT Protocols

With the increasing attention towards Internet of Things, a number of protocols have been proposed to best support the IoT architecuture. MQTT, CoAP, Websocket and AMQP are the popular ones. IoT devices are resource constrained i.e. have very less storage, processing and memory capacity. Among the aforementioned protocols , MQTT and CoAP are considered most promising for resource contrained environment.

- MQTT

  MQTT was developed as bandwidth efficient and power economic protocol to monitor the oil pipeline through the desert as the devices were connected with expensive satellite link. It is a publish/subscribe based protocol where a node / device that has to send some data, pushes the data to a broker, which the broadcasts the received data to all subscribing devices. It uses TCP/IP protocol stack. Some of it's key features are asyncronicity, open standard and multiplexing multiple subscribers via a single channel. It also provides different level of QoS based on the type of message delivery service required. MQTT is comprised of 3 components, namely: Subscriber, Broker and Publisher. They are connected with each other over TCP.

  1. Publisher: This component comprises of the sensors or data generator along with a gateway / middleware like arduino / raspberry-pi that formats the message from sensors. The mechanism of message being sent by Publisher to MQTT broker is known as Publishing.
  2. MQTT Broker: MQTT Broker works as the bridge between the message source / sender and the rightful receivers. It collects the message from the sender, checks the rightful receivers of this particular message topic and makes necessary provisions to

send it. If the receiver is down or the channel is not functioning, the messages are stacked. Mosquitto Broker is used as the broker of choice for the MQTT implementation of this thesis.

3. Subscriber: Subscribers are those devices that subscribe to a particular type of message. Each client that wants to receive messages subscribes to a certain topic and the broker delivers all messages with the matching topic to the client. Therefore the clients don't have to know each other, they only communicate over the topic. This architecture enables highly scalable solutions without dependencies between the data producers and the data consumers.

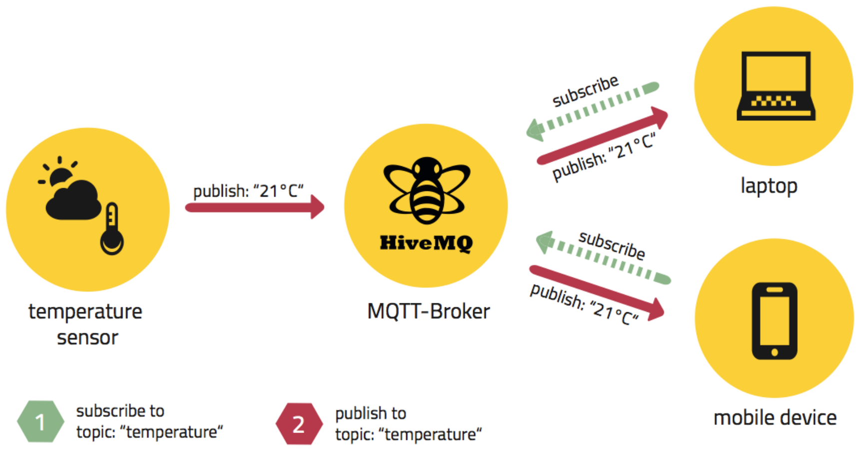


Figure 5. MQTT Components Architecture (Source : Eclipse Community)

- CoAP

  CoAP is another IoT protocol suitable for resource constrained environment. It also provides RESTful interfaces like GET, POST, PUT and DELETE. However, it runs on top of UDP and not TCP protocol, which makes it lightweight. The interaction between CoAP client and Server is connectionless due to the use of UDP protocol. Unlike MQTT, CoAP offers two levels of QoS: *Confirmable* and *Non-confirmable*. Acknowledgement from receiver is expected when Confirmable QoS is used.

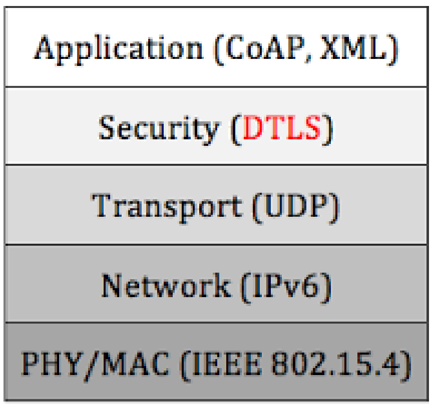


Figure 6. CoAP Protocol Stack Source: Dept. of Computer Science,Washington University in St. Louis

- Comparison between MQTT and CoAP

  Selecting the suitable protocol for the implementation of proposed system is important. CoAP enables client server communication and is best suited for transfer of state. MQTT is many to many protocol where different publishers and subscribers communicate with each other using a central broker. This architecture of MQTT is best suited for event based models. TAG needed to use a protocol to transfer the state of SGB or communicate with server based on certain events like Opening of SGB's lid, closing of lid etc. Plus, MQTT outperforms CoAP in terms of throughput and latency when high traffic links are used [28]. Since TAG can be implemented in community setting to metropolitan scale, high traffic scenario should be kept in priority. In terms of security, since CoAP runs on top of UDP, TLS/SSL support is not available. CoAP uses DTSL as security agent. But, DTSL still has some issues and is not know to provide best support in terms of security. MQTT brokers can be made secure by username and password authentication for clients to connect. To ensure privacy, the TCP connection may be encrypted with SSL/TLS. However, CoAP outperforms MQTT in terms of energy efficiency as CoAP does not need to spend energy in TCP connection handshaking. Except for this particular aspect, MQTT was a reasonable choice for TAG.

2.3.3 Blockchain

After Satoshi Nakamoto published the his famous paper in 2009 [6], Bitcoin and it's underlying technology i.e. blockhchain was introduced to the world. Bitcoin so far has been the most successful implementation of blockchain. Blockchain is a peer to peer distributed database system where a number of nodes interact with each other in order to maintain and record the transactions in a secure and chronological fashion. This kind of system removes the need of intermediaries for a transaction to take place in a secure and verifiable way, thus lower the cost of transactions significantly. The transactions once mined, are irreversible; this protects sellers from fraud. Another advantage of it's decentralized nature is that this kind of system does not have a single point of failure. If a node goes down due to some reasons (DDOS attack, node failure etc), there are other multiple nodes maintaining the state or data of the network. The mechanism by which this kind of network works, as mentioned in Satoshi's original paper, is as follows:

– New transactions are broadcast to all nodes.
– Each node collects new transactions into a block.
– Each node works on finding a difficult proof-of-work for its block.
– When a node finds a proof-of-work, it broadcasts the block to all nodes.
– Nodes accept the block only if all transactions in it are valid and not already spent.
– Nodes express their acceptance of the block by working on creating the next block in the chain, using the hash of the accepted block as the previous hash.

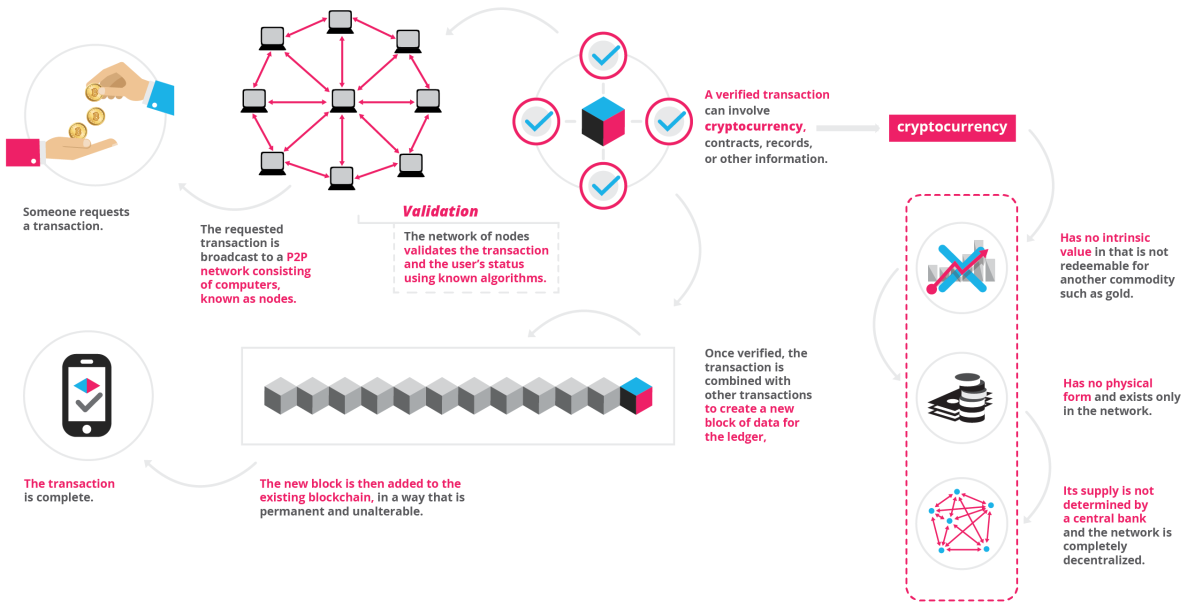


Figure 7. Inner working of blockchain (Credits: Blockgeeks)

1. Algorithm: Proof of Work Blocks in blockchains are collection of transactions. A block contains [29] [30]:
   - A version number - 4 bytes
   - A unix time stamp in seconds - 4 bytes
   - Hash of the previous block - 32 bytes
   - A current mining difficulty value - 4 bytes
   - A *Proof of Work* nonce - 4 bytes
   - A *Merkle Tree* root has that contains valid transactions included in that block - 32 bytes

   Miners can select which transactions to include and which not to based on the value / commission each transaction contains, so as to maximize their benefit. To mine a block in blockchain network, all the nodes compete to solve a computational problem. The first node being able to solve the problem gets the authority to mine the block. To prove that a particular node which claims it has solved the computational problem, has actually solved the computational problem, *Proof of Work* or *Pow* algorithm is used. *PoW* can have several kind of implementation. Bitcoin uses *Hashcash* variation of *PoW*.

   To form a block, all the mining nodes compete with each other to find a hash value derived from the block's header and a *nonce* value. This resulting hash value should be lower than a current *target*. A *target* is a 256-bit value known to all the nodes. It's a function of the blockchain network. The network uses this value to control the creation of new blocks. Each node starts the hashing processing with the initial value of *nonce* set to 0. If the resulting has does not satisfy the condition (lower than the *target*), then the nonce value is increased and the process repeats. The hashing process results in a random hash that can't be predicted. Calculating the hash is not very difficult. It's just that the probability of getting the hash value lower than current *target* is very low. Lower the *target*, lesser the probablility to generate a hash lower than the *target*. Therefore, this process is like a lottery where any node in the network can win, thus getting the authority to mine a block. This block contains the *nonce* value and the current *target* along with other above mentioned parameters. Hence, other nodes can easily verify if this particular node has generated the required hash value or not. In other words, the verification of the hash provides the *Proof of Work* done by this node.

2. Algorithm: Proof of Stake

   PoW algorithm is resource intensive. While one node gets the mining ticket for any particular block, all the processing of other nodes are wasted. Likewise, if an attacker owns 51% processing capacity of the entire network, the attacker can attack the system in ways like denial of service (not including transactions into blocks) or double spending. This however, is not practical, given the growing size of blockchain networks; however, they are a possibility. Bitcoin wiki [31] provides an in-depth analysis over this matter. To overcome the fallacies of *PoW*, a new concept of *PoS* or *Proof of Stake* is being discussed. While *PoW* is based on the computing capacity of nodes, *PoS* is based on the actual share of cryptocurrency. So, in a *PoS* system, the more stake one has in the network, the more can one mine the blocks. For example, if a miner holds 5% share of the total crytocurrencies in circulation, the miner can mine 5% of the blocks. In terms of security, attacking the network requires the attacker to own more crytocurrencies. The more the attacker purchases, the more the price might increase. Ultimately, when the attacker will have enough ownership to attack the network, it will be counter-productive as the attack will affect the attacker more since he/she is the owner of majority of the asset. Instead, playing by the rules would be a beneficial affair. At the time of writing, both the blockchains discussed here i.e. Bitcoin and Ethereum, use *PoW*. However, the community of developers are showing increasing interest in *PoS*. There is a strong possibility of shift in alorithm from *PoW* to *PoS* in future.

2.3.4 Ethereum Blockchain

Dr. Gavin wood introduced Ethereum in 2014, which is another implementation of blockchain technology that supports Smart Contracts (described below). The currency or medium of exchange in Ethereum blockchain is called Ether. For any transaction to be executed, it needs certain amount of *gas*. This prevents infinite loop of execution of contracts, as they will stop execution once they run out of *gas*. This gas can be purchased in exchange of Ether. To be more precise, the gas prices are fairly low and are purchased in *Wei* where 1 Ether = 10^{-10} Wei. The price of gas is floating and is governed by the law demand and supply in the Ethereum blockchain network. A transaction can be anything from transfer of funds between accounts to execution of smart contracts. So, if user X wants to send E amount of Ether to user Y, user X will send E + *default gas price* where *default gas price* is determined by a set of actions involved in the execution of transaction, like the SHA3 encryption and the amount of data present in the transaction. Each 256 bits of data that is to be hashed accounts for 6 gas units. This transaction cost can be understood as the purchase of space or inclusion price for this transaction to be included in a block that is being mined by a miner. The extra gas remaining after the execution of the transaction is provided to the miner by the network in addition to the mining reward. A miner has the freedom of choice to include a particular transaction in its block or not. Hence, more the extra gas sent with the transaction, higher the chances of the transaction to be mined early. Not sending enough gas with a transaction may demotivate the miners to include this transaction in their block, thus, resulting in long transaction time.

2.3.5 Smart Contracts

The term Smart Contract was coined by computer scientist Nick Szabo. Smart Contract can be understood as a set of rules that define how a transaction is supposed to take place in blockchain. Smart Contract extends the functionality of blockchain by modeling real world scenarios using Turing complete high level programming languages. Ethereum blockchain have their own set of programming languages which can be used to write these contracts. Smart Contracts extend the functionality of blockchain by modeling real world concepts in blockchain. Once deployed, the Smart Contract code cannot be tampered with.

Execution of a Smart Contract is also treated as a transaction. The default gas unit is needed to execute a Smart Contract is calculated based on the number of bytes the Smart Contract holds. Hence, the complex the contract (meaning more number of bytes) the higher the number of gas needed to execute the contract. By execution, it is meant that the state of blockchain is change i.e. data is either added to blockchain or data is removed from it. To simplify it further, write operations in blockchain cost gas while read operation does not cost anything. Write operations are relatively slower as the change of state of blockchain needs to be mined as any other transaction. Read operations on the other hand are performed in the copy of the global state or database in local node which receives the read call, hence it is relatively faster. *Figure* 8 provides a good overview of the schematic of Smart Contract [32].

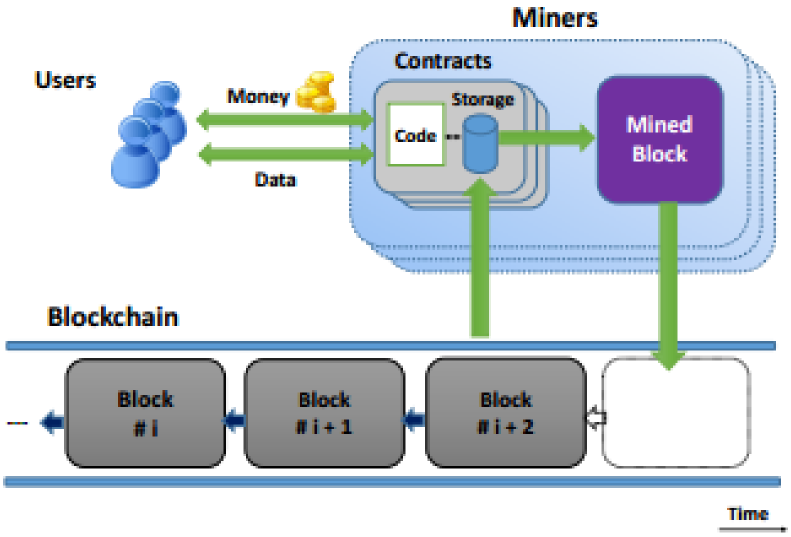


Figure 8. Schematic of a Smart Contract

2.3.6 DAO

Decentralized Autonomous Organization is a Smart Contract or a collection of Smart Contracts that can represent an organization in blockchain, automatizing the decision making process and the governance of the organization.A DAO, like any other real world organization, has members that have the ability to raise funds and propose different kinds of proposals. If passed by majority, these proposals can be executed. Proposals can be anything from transfer of funds to execution of other Smart Contracts. In this thesis, we have used such a DAO that represents a waste management organization. A proposal for transfer of funds to a SGB factory account for the purchase of SGB is passed using consensus of the members. The number of votes required, the time period of voting, majority margin etc are defined prior to the deployment of the DAO. These, of course, are subject to change even after deployment, with the consent of the members, through a transparent voting mechanism. *Figure* 9 (source: `https://slock.it/dao.html`) shows different components of DAO with description.

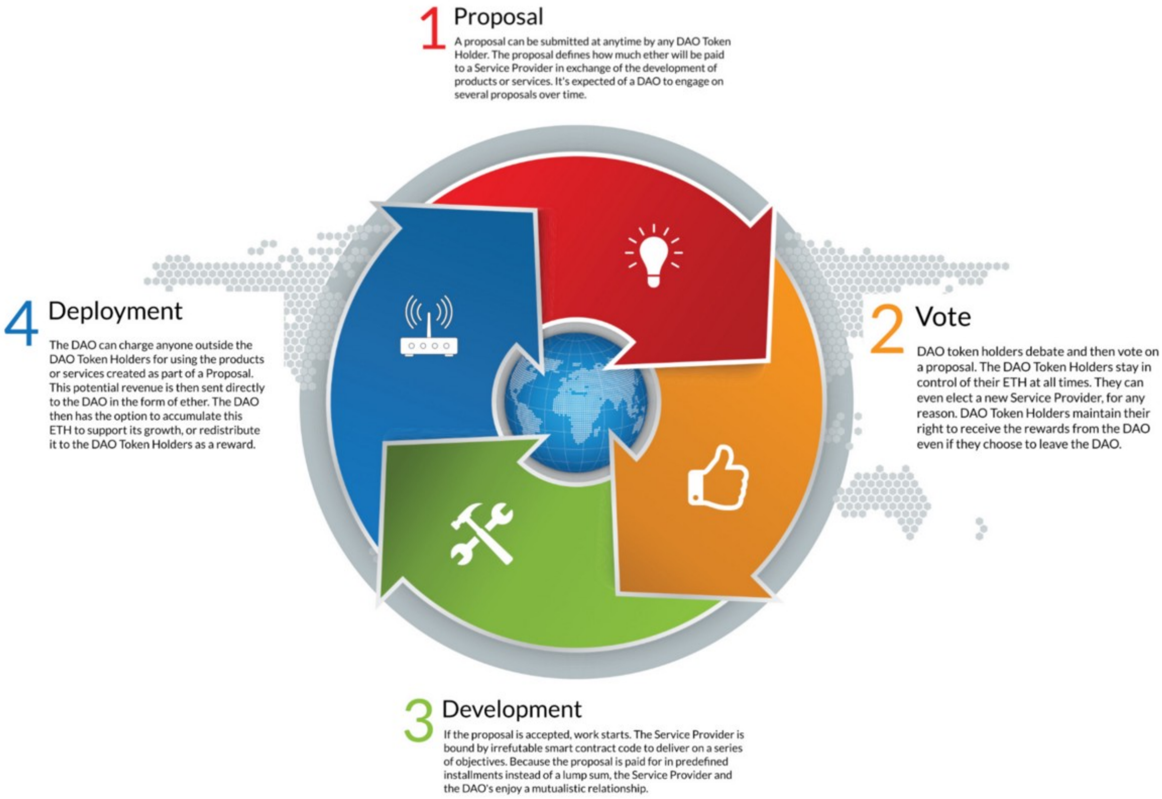


Figure 9. DAO: Proposals, Voting, Development and Deployment

2.3.7 Summary

This subsection provides a critical summary of the state of the art and descirbes how the state of the art has shaped the research for a reasonable solution to the problem presented in previous section.

This thesis takes into consideration the very approach as described in the patented SGB, for calculating the amount of waste present in the SGB. For the purpose of experimentation , a simulation of SGB is used which is based on the assumptions that the SGB calculates the weight of waste using similar methods. This kind of SGB can be suitable for deployment to real world of TAG in real world.

Sorting at source enhances the quality of waste generated significantly. Including this capability can enhance the impact and also pave way for a reward / reinforcement sytem, wher users can get some discount or rewards based on the quality of the waste they produce, from recycle plants. This aspect has been discussed in the conclusion section.

Using image processing techniques for the measurement of level of waste is a reasonable approach. From a sustainability perspective, this approach however, is not so appropriate as the SGB in case of TAG will already have a camera that acts as a QR-reader. Another camera for image processing could be very energy intensive. Also, MQTT protocol (discussed below) used for the communication with a central server is relatively battery intensive.

The concept of weight-rate based disposal system discourages people to produce more waste. People are liable to pay as per the amount of waste they produce. If this could be implemented in large scale, it can have sustainable impacts in community and society in general. This approach has been implemented in South Korea and has shown a significant reduction (33%) in the amount of waste produced by people, in a pilot run for 1 year. Also, since this kind of system requires payment for service, blockchain technology can be reasonably implemented by using weight-rate based system.

Blockchain technology provides security, high availability , privacy and low transaction cost. With recent developments in blockchain, specially in Ethereum blockchain, the reach and support to blockchain is increasing. Smart Contracts and DAOs are highly disruptive concepts as they make it possible to automate things in blockchain without human intervention. Internet of Things cab be the interface to the real world for blockchain technology. Sensing, measurement and communication of environmental parameters can provide contextual information to blockchain and changes undergoing in blockchain can be reflected in different ways using actuation.

3 Research, Design and Implementation

This section describes in detail, the architecture, components and the process flow of the implementation. First, different tools and technologies used in the implementation are described. Then, in architecture section, a most basic and simplest combination of IoT devices (which is a SGB here) and blockchain is described. In this type of architecture, blockchain is used as the backend of the implementation, where all the data are stored in blockchain. Then, a critical analysis of the efficiency of such system is done. A refined architecture that overcomes the drawbacks of this architecture is proposed in the following section.

3.1 Proposed Architecture

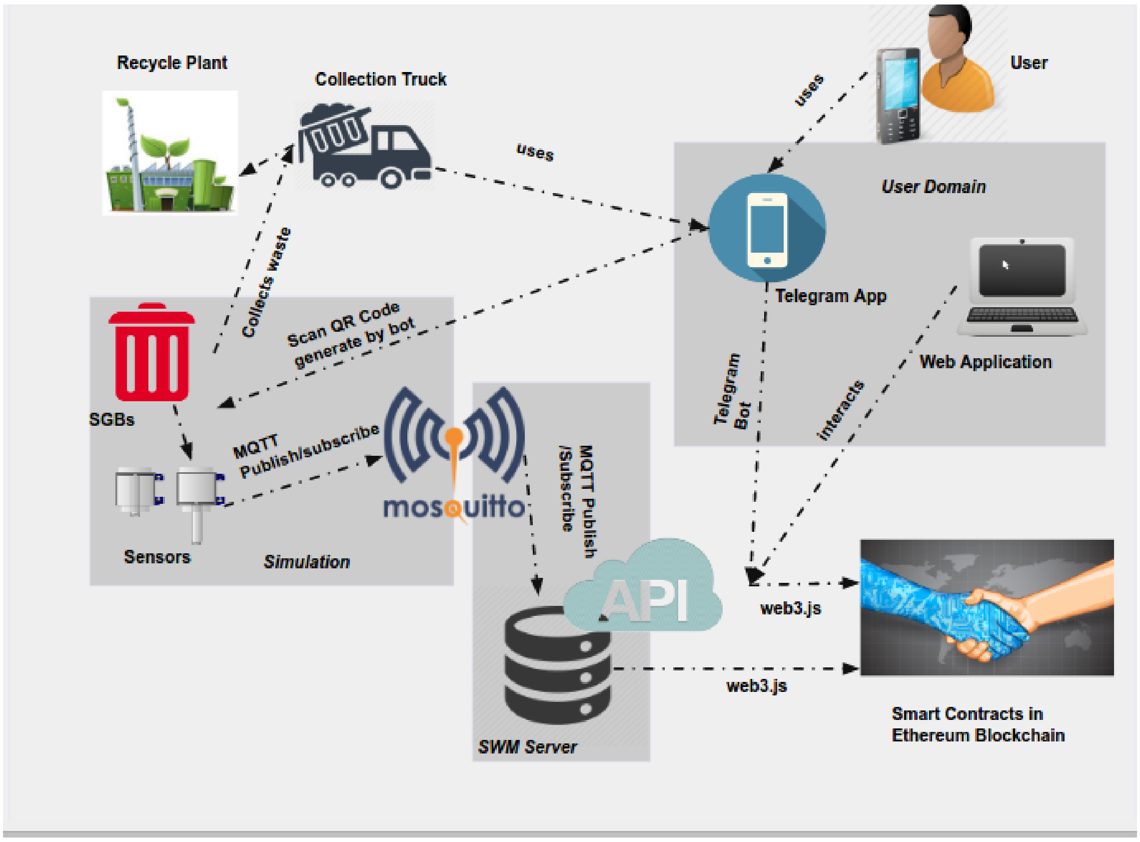


Figure 10. TAG Architecture

Following is the detail description of all the components:

3.1.1 Blockchain

TAG is powered by Ethereum blockchain. The main motivation behind this is the implementation of Smart Contracts and the concept of DAO provided by Ethereum. Ethereum provides

3 different languages to write smart contracts with, which can be compiled and deployed in Ethereum blockchain. The three languages are namely: Solidity, Serpent, and LLL. Solidity is a Java-like language, most developed and supported by the Ethereum community. Serpent is a Python-like implementation and LLL is Lisp-like implementation. Smart Contracts are written in Solidity 0.4.8 for TAG. Truffle and Embark are two frameworks to build applications on Ethereum. Truffle v2.1.2 is used to deploy Smart Contracts. TAG interacts with three Smart Contract. The detailed description of each is listed below:

- The Bank

  DAO is the representation of any real world organization on top of blockchain. One of the crucial aspect of it is, once it is deployed; the code can't be tampered with. Members can change the rules or objectives using the mechanism of voting. The Bank is one such smart contract which represents a Bank like organization from real world in blockchain. The Bank has a registry which is an array of array of addresses and balances. The addresses can be the account number of users or other DAOs. This bank can be understood as a Central Bank regulating the economy of an eco-system of DAOs. All other DAOs use a common currency of this central bank. The currency used by this central bank is named *"PercCoin"*. There can be two methods to create currency in The Bank, namely:

  External Transfer

  Exchange rates can be defined for different currencies to be used in the bank. The economics of the process is not within the scope of this research. For TAG, whenever certain amount of external transfer of Ether is made to The Bank, it records the sender account in it's registry and assigns an equivalent amount of PercCoin with an exchange rate 1 Wei = 1 PercCoin to this account. If it's an existing account, it adds the equivalent amount of PercCoin to the existing balance of the account.

  Minting

  Purchase of Ether or mining of Ether might not be a best idea in developing countries, specially in rural communities. It takes a lot of computing resources and the investment on devices can be substantial with the increase in time, as the difficulty of network also increases over time. Anything that is of value or even fiat currency can be used to buy PercCoin. The Bank can mint an equivalent amount of currency as per the provided asset of value and add it to the user's account.

Listing 1. TheBank Code

```
function() payable{

        balanceOf[msg.sender] += msg.value * exchangeRate;
        totalSupplyOfEther += msg.value;
        totalSupplyOfPercCoin += balanceOf[msg.sender];
    }

function mintCoin(address _receiver, uint _amt) onlyBank returns
    (bool success){
        totalSupplyOfPercCoin += _amt ;
        balanceOf[msg.sender] += _amt;
        NewPercCoinsCreated(_amt);

        return true;
    }

function transfer(address _to, uint256 _amt)
    onlyBankOrAccountHolder returns (bool success){
        /*check if sender has enough balance*/
        if(balanceOf[msg.sender] < _amt) throw;
        /*check if negative balance is sent*/
        if(balanceOf[_to] + _amt < 0) throw;

        balanceOf[msg.sender] -= _amt;
        balanceOf[_to] += _amt;

        /*Create an event of the transfer*/
        Transfer(msg.sender,_to,_amt);

        return true;
}
```

All the code for TAG are available in Github under a GPL license. The project components can be accessed at:
https://github.com/itmo-swm

- Community DAO

Community DAO can be understood as an organization running with the objective of investing and managing in Waste Management. Any member of this Community DAO can propose a proposal which is subjected to voting. The voting rules can be set during the first deployment and later a new proposal can be passed to change the voting rules, if necessary. Ethereum provides a couple of different templates [33] to form different type of democratic organizations. A Congress template provided in the Ethereum website is used here. The terms in the DAO template are also used *"as is"*. This type of organization is owned by the address that deploys it and thus is more like an authoritarian organization. The owning address can add and remove members, even though the members have voting capabilities. Since this thesis is a proof of concept, Congress template is simpler to use for this case. However, other different templates can be used to create a DAO which have different flavours of democracy. The main points to understand in this type of DAO, as mentioned in Ethereum website are:

minimumQuorum

It is the minimum number of votes required to pass a proposal. If there are 5 members and this parameter is set to 3, at least 3 people should vote to pass the proposal.

debatingPeriodInMinutes

It is the time window (measured in minutes) for the voting period. If set to 10, the members must cast their vote within these 10 minutes.

majorityMargin

A proposal passes if there are more than 50% votes plus the majority margin. If there are 4 members and this parameter is set to 1, then 50% of total possible votes would be 2 and majority margin = 1. So if 3 votes (50% of 4 + majorityMargin) are received, the proposal passes. It should be left to 0 for a simple majority and total possible votes -1 for absolute majority.

- SGB Factory

SGBFactory represents an account for SGB producers. It can be understood as a market place. The ComDAO can raise fund. The members can decide upon the investment amounts for SGB and pass a proposal to transfer fund to this SGBFactory. Upon reception of the fund, the SGB producers can deliver the SGB. This represents one of the fundamental capabilities of blockchain, i.e. movement of goods and services in real world based on the transaction in blockchain. Though a pretty straight forward concept is defined here, in actual implementation, an escrow fund can be created which can hold the transfer from ComDAO and only transfer the fund to SGBFactory account upon the reception of SGB by ComDAO members in real world.

3.1.2 SWM Server

Even though, blockchain have massive potential, it should be accepted that this technology is in its dawn. Due to delayed processing time, blockchain technology is not efficient enough to work with applications that need swift read write. Due to this very drawback of blockchain, TAG is designed as a hybrid system, where a central server, name Smart Waste Management Server or SWM handles components that need fast read write and blockchain technology to take care of the financial transactions. The SWM has following components:

- Telegram Bot

  A Telegram Bot named *"perccomanitmo"* is deployed in Telegram application. It can be searched in Telegram in the same way users look up to other users.Typing "/hello" will start the conversation. User can interact with it to find balance or to generate QR-code that is needed to open the SGB. If the users have enough balance in their account, this bot generates a QR code and asks for users location. Once the location is provided, it is considered as center of the circle and the closest SGB within a circular area with radius 3 km is returned to the user. MongoDB's geoJSON query comes in handy at this point. User can then go to the SGB and scan the QR-code generated earlier. If the QR-code is not re-used and has been generated by the Telegram bot, the SGB opens. See figure 12 and figure 14 on page 42 for further clarity.

- API

  SWM has an *Application Programming Interface* that provides a number of data end-points. Some of the fundamental ones are listed below:

  url**: **/api/info/:sgb_id
  ***description**: when a SGB id supplied as a parameter, different attributes of the SGB is returned*
  ***returns**: current_waste_amt,total_capacity, percent_used,rate*

  url**: **/api/filled_bins/:percent/:radius/:lat/:lon
  ***description**: when level of waste(%), radius , lat and lon is supplied as a parameter, all the SGB within range with the required level of waste is retruned*
  ***returns**: _id,current_state, location*

Figure 11. API: Bin Info

3.1.3 SGB Simulation

A SGB Simulator with QR code scanner and MQTT publishing and subscribing capability is developed for the convenience of experimentation. This simulator scans the QR code generated by the Telegram Bot in user's Telegram application and communicates with the server using MQTT protocol. If the decoded QR sent by this SGB is verified by the server, the lid of SGB opens. Figure

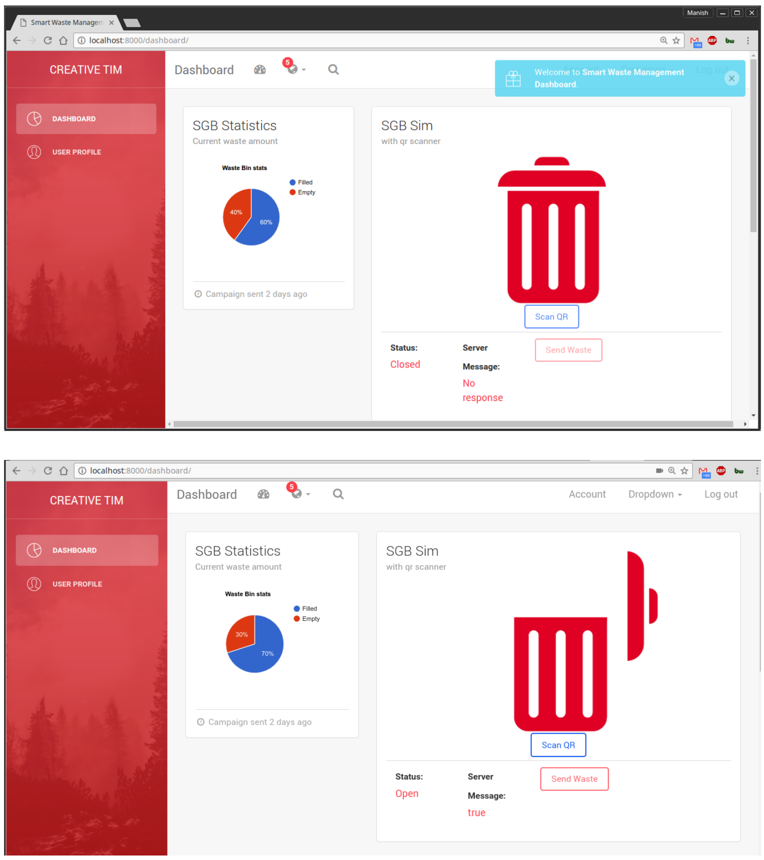


Figure 12. SGB Simulation

3.1.4 MongoDB

The SGB information like owner account, quantity of waste, location information etc is stored in the MongoDB. One of the advantage of using MongoDB is the easier processing of geoJSON data. When supplied with a location value and radius (in radian), MongoDB can return the location of all the SGB lying within the circular area of given radius. This information is requested by Telegram Bot when user selects to throw the waste, in Telegram Bot menu.

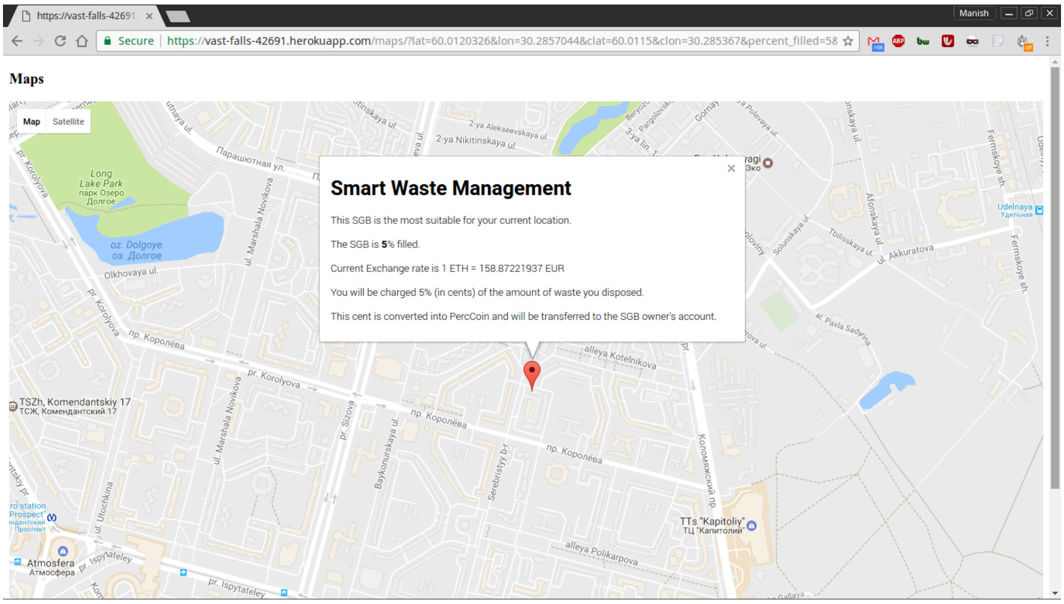


Figure 13. SGB Location Info

When the user provides permission to send location from Telegram application, the location data is sent by the Telegram application to NodeJS server. The latitute and longitude value is parsed by the server and a Point object is created using the latitude and longitude value. This Point object together with a distance metric is used to query the MongoDB database to obtain all the SGBs lying in a circular area. The center of the circle being the latitude and longitude received from User's Telegram application and radius of the circle being a constant defined in the server i.e. 3 km. The distance has to be in radian for MongoDB to be able to query the database. For this, the distance metric is divided by the radius of Earth to convert it into radian distance. Below is a snippet of the code that serve this purpose:

Listing 2. Snippet of geoJSON query for SGB lookup

```
function getSGBLocationsQuery(latitude,longitude,radiusInKM){
    var center = {"loc" : {
                    "type" : "Point",
                    "coordinates" : [
```

```
                                latitude,
                                longitude
                              ]
                        }
                }
        var query = {
                "location" : {
                    $geoWithin : {
                        $centerSphere : [center.loc.coordinates,
                            kmToRadian(radiusInKM) ]
                    }
                }
            };
        return query;
    }

function kmToRadian(distanceInKM){
  var earthRadiusInKM = 6371;
  return distanceInKM / earthRadiusInKM;
}
```

The transaction information is also stored in MongoDB in another collection. It contains information like user's account, who disposed the waste, the amount of waste disposed, the SGB in which the waste is disposed, the amount of PercCoin transferred from user's account to the SGB owner's account.

The SGB and the transactions done by user are represented in MongoDB using two data models. The SGB model stores the data of the bins using different attributes like location information and waste level. In the same way, the Transactions model stores the data about transactions made in the system using different attributes like user account, weight of waste, cost of transaction etc. Below is the description of each schema in detail:

- SGB Model

  Several attributes are taken into consideration to simulate a SGB in TAG. When a user makes a request to dispose waste, the server returns location and the amount of waste present in the SGB. To impose a restriction on use when user has no balance in his / her bank account, a minimum balance attribute is added to the SGB model. To prevent the overflow of waste and to provide data related to level of waste, a maximum capacity and a current level of waste attributes are used. When the payment is made by the user, the crytocurrencies are transferred to the owner account, which could be of different types like Private, Governmental, Community or Joint Venture. Following is the SGB Schema extracted from the prtotype of TAG.

Listing 3. SGB schema

```
var SGBSchema = new Schema({
                location : {
                        type : { type : String },
                        coordinates : [ Number, Number ]
                       },
                minimum_balance_required : { type : Number,
                   default: 0.05 },
                owner_type : {
                         type: String,
                        enum: ["PRIVATE", "GOVERNMENTAL",
                           "COMMUNITY" , "JOINT_VENTURE"]
                       },
                max_capacity  : { type: Number, required: true
                   },
                current_state : { type: Number, default: 0.00 },
                owner_account : { type: String, required: true
                   },
                fixed_unit_cost : { type: Number, required:
                   true}
              });
```

- Transaction Model

  In the same way as SGB model, six different attributes represent a transaction in TAG system. There are two entities involved in the transaction, namely: a) SGB, which receives the waste and payment of services, and b) User, who disposes the waste and pays for the services. The sgb attribute ties a particular transaction to a SGB. User account attribute represents the account number of user in The Bank *Smart Contract* in blockchain. QR code attribute represents the unique string which is used by the server to identify user / transaction. When user requests the disposal of waste, server generates a unique code, converts it into QR code and sends it to user. When user scans the QR code and sends the decoded value to server, the server queries the db to find out if there is such existing code. The weight of the waste represent the amount of waste disposed, for this transaction to take place. Finally, the cost of the transaction is the amount of *PercCoins* transferred from user's account to SGB owner's account.

Listing 4. Transaction schema

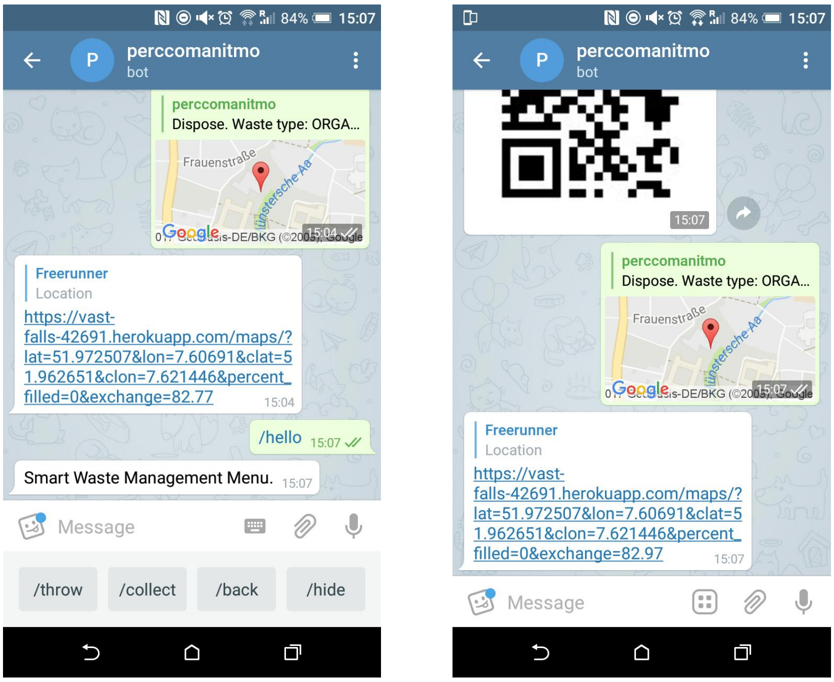
```
var TransactionSchema = new Schema({
  sgb : { type: Schema.ObjectId, ref: 'SGB' },
  user_account : { type: String, required : true },
  qr_code : { type: String, required : true },
  waste_type : {
       type: String,
       enum: ["ORGANIC", "PLASTIC", "GLASS" , "METAL"],
       required : true
    },
  waste_weight : { type: Number },
  transaction_cost : { type: Number, default : null}
});
```

3.1.5 User Domain

User domain consists of two components. A bot running in Telegram mobile application and a web application that users can use to interact with TAG. Following is the description and snapshot of the components respectively:

- Telegram

  Users can use features of TAG via Telegram Application. A Telegram bot named "perc-comanitmo" works as an intermediary between user's Telegram and TAG.



(a) Bot Menu (b) Bot Response

Figure 14. Telegram Bot Menu and Response

- Web Application

  Users can look up information about themselves (like the amount of waste they have produced, the amount of money they have spent) in a web application. Apart from this, the web application provides information about ways to reduce waste. It also shows different information to users that might motivate them to produce less waste in a responsible way.

3.2 Tools and Technology

This subsection provides a detail description of the implementation of different tools and technologies described in the previous sections. MQTT protocol provides a mechanism to logically separate messages based on hierarchy and category. For the simplification of communication between the server and SGB, two parent categories were created. Each category consisted of a sub-category that would uniquely identify what kind of message was being sent from which entity (server or SGB). The next subsections describes tools like Geth and Truffle which are used to run Ethereum node and deploy Smart Contracts to Ethereum blockchain, respectively. In the last subsection, an ideal blockchain IoT architecture is discussed about and it's critical analysis is done.

3.2.1 MQTT Topic hierarchy

The first level of topic hierarchy is classified according to the devices using them. Hence, the first level consists of: *SGB* and *Server*. The next level of classification of message is based on the action each device does. Each device uses MQTT for publishing and subscribing: (i) Authentication message, and (ii) Waste message. Following is the description of message exchange:

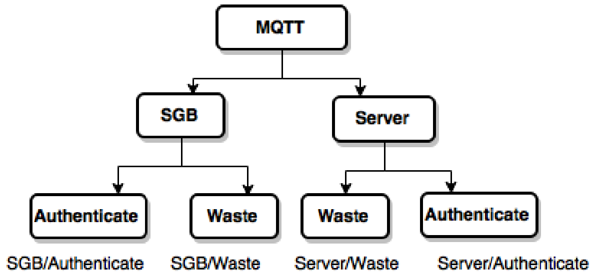


Figure 15. MQTT Topic Hierarchy

Authentication When SGB scans the QR-code, it publishes the decoded value to *SGB/Authenticate* topic. To receive this message, the Server is subscribed to *SGB/Authenticate*. Once the Server receives the message, it checks whether the decoded value is the same one that was generated by the Server when user requested to throw waste using the Telegram app. If verified, the Server will publish a JSON data with appropriate response to *Server/Authenticate* topic. The SGB is subscribed to *Server/Authenticate* topic to receive the message from the Server. If user is verified, the SGB opens.

Waste When the user puts the waste in SGB, the sensors calculate the total weight of waste in SGB (including the weight of waste generated by user). Upon closing of lid, the SGB publishes the waste information to *SGB/Waste* topic. The Server will receive the message by being subscribed to *SGB/Waste* topic. The amount of waste generated by user is calculated as the difference between the total waste amount sent by SGB and the total waste amount present in the Server's database. *PercCoin* equals to 5% of the waste amount generated by user is transferred from user's account to the SGB owner's account and the transaction information is updated in the Server's database. The status of this operation (successful or unsuccessful) is published by the Server to the topic *Server/Waste*. For simulation environment, SGB can be subscribed to *Server/Waste* topic, but it is not significant to real world deployment of SGB.
The blockchain component contains all the Smart Contract and DAOs, the details of which is explained in following subsections. The SWM Server consists of a Telegram Bot that users use to interact with the SWM system using *Telegram* [34] mobile application. Since blockchain

Device	Publish	Subscribe	Action
SGB	SGB/Authenticate	Server/Authenticate	Authenticate User
Server	Server/Authenticate	SGB/Authenticate	Authenticate User
SGB	SGB/Waste	Server/Waste	Send Waste Info
Server	Server/Waste	SGB/Waste	Sends Transaction success info

Figure 16. MQTT Topic Table

transactions are relatively slower compared to centralized databases, an MongoDB database is used to store SGB information and transaction information. All the financial information is segregated to blockchain. This enhances the efficiency of the system and keeps the financial data secure, powered by blockchain. *User domain* consists of the Telegram application and a web application. The Telegram application, as mentioned above is the means to interact with the Telegram Bot. The web application provides information about the user and system transactions, the amount of waste user produced, a *god-view* to see all the SGBs in a map with related information. In place of actual Smart Waste Bin, a simulation of waste bin is used, which consists of a QR scanner and a MQTT publish and subscribe client to interact with the SWM Server. *Figure* 10 shows the overview of different components of TAG.

3.2.2 Geth

Geth is the command line tool that runs an Ethereum node in any machine. Geth version 1.5.8 has been used in the implementation of this thesis. Geth provides several configuration options that can be used to configure the node. For our implementation, we have used two Ethereum blockchain network options:

Ethereum Private Network

An Ethereum Private Network is a kind of blockchain network which inherits all the properties of Ethereum but it's node are not connected to the main Ethereum Network or Test Network. Unlike the nodes of main network, the nodes in private network don't have to download all the blocks of main network. To try out Ethereum , run tests or run blockchain for internal purpose when having few machines to run the nodes, this can be a reasonable solution. However, while running a private node, all the configurations have to be done manually. In our implementation, we have used a single nodea and exposed a JSON-RPC interface which can be used by our server to execute Smart Contracts remotely.

The first block of a blockchain network is called a "Genesis Block". This is the only block that doesn't have a preceeding block in the blockchain network. This is where network options like *gasLimit*, *difficulty*, *coinbase* and other accounts can be defined. *gasLimit* is the maximum units of gas that this node can burn. This puts an upper limit to the computation time of any Smart Contract, preventing infinite loops. *difficulty* is the value of global block difficulty that represents mining difficulty for the network. The higher it is, the difficult it is to mine a block. Below is an example of genesis file used to create the Private Ethereum Network for our implementation.

Listing 5. Genesis File

```
{
"nonce": "0x0000000000000042",
"timestamp": "0x0",
"parentHash":
   "0x0000000000000000000000000000000000000000000000000000000000000000",
"extraData": "0x0",
"gasLimit": "0x8000000",
"difficulty": "0x400",
"mixhash":
   "0x0000000000000000000000000000000000000000000000000000000000000000",
"coinbase": "0x3333333333333333333333333333333333333333",
"alloc": {
         0x9f04760d4acc712d147f4cb98affe7bb59b72eba" : { "balance":
            "1000000000000000000000000000" }
       }
}
```

Ethereum Test Network

Ethereum Test Network can be understood as a sandbox Ethereum Network. The only requirement to run this network is Ethereum Wallet. It is node (Geth) to interact with which a GUI is available. Transactions can be minded like Main Ethereum Network and fake Ether can be earned as rewards for mining the blocks. The GUI tool is the best way to visualize and understand transactions and contract execution. The Smart Contract and DAO were deployed in both Private and Test Network to study the execution time in both the networks. *Figure* 17 shows a snapshot of Ethereum Wallet.

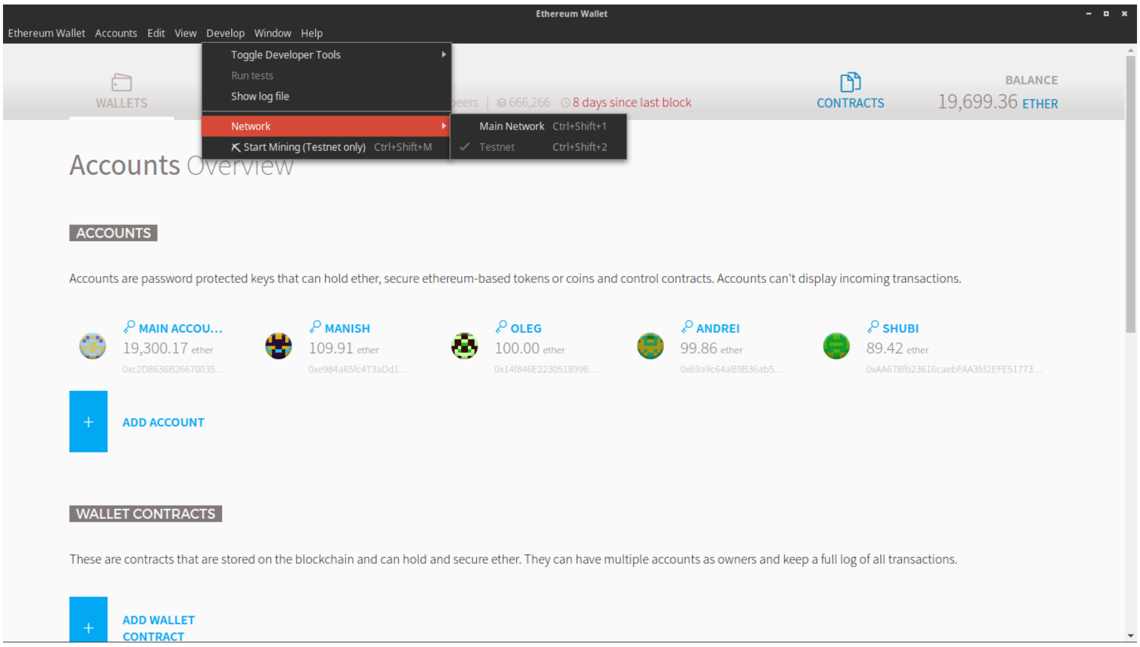


Figure 17. Ethereum Wallet

3.2.3 Truffle

Truffle is a development framework for Ethereum. It provides features like contract compilation, testing , console and deployment. Contracts can be deployed in local node or remotely by providing appropriate configuration options. Since we have used both remote and local node for the implementation and analysis, we have used Truffle for the deployment locally and in remote node. Truffle version 2.1.2 has been used for compilation and deployment.

3.3 Basic architecture

The simplest architecture that can support blockchain and IoT devices (weight sensor and range sensor) together would be to run an Ethereum node using geth in the SGB itself. In this kind of setup, the sensors send data to a Raspberry Pi. A program in Raspberry Pi can communicate with geth running in the Raspberry Pi using an RPC interface. In this kind of architecture, each SGB runs a full Ethereum node. Or if a private node is used, all these SGBs can run in a single private network. All the data (like user, payment, transaction, SGB) are stored in the blockchain. The addresses of the DAO and Smart Contracts can be stored in a file or any database from where the program can read the address and perform actions accordingly.

3.3.1 Critical Analysis

This kind of architecture adds security by running multiple nodes in a private Ethereum network. The simplicity of this architecture can reduce processing overhead and complies to the decentralization philosophy. However, write operations in blockchain requires gas and gas are not free. Just storing data in the blockchain increases the cost. On top of this, the state of the blockchain is not updated as long as the transactions are not mined into blocks by the nodes. Furthermore, PoW algorithm in itself is very resource intensive. Hashrate is directly related to the CPU capacity. If any feature in the proposed system has very high read and write requirement, blockchain cannot be a reasonable solution.

3.3.2 Conclusion

If, in future developments, the mining time and resources consumption of blockchain reduces significantly, then, this kind of simple architecture would be an ideal to use. However, for the time being, this architecture can be improved by adding features from a centralized system. In this kind of system, those data that are frequently accessed and updated can be added in a centralized database which is accesed using a centralized server. Blockchain can be ran remotely and accessed using RPC interface. However, security can be a concern while exposing RPC interface to outside network. Next section deals with the hybrid architecture that uses a combination of centralized and decentralized philosophy in detail.

3.4 Process Flow

Process Flow describes the sequence of flow of control within different component of TAG. This process flow represents the interaction between different component from when a user has some waste to dispose, The waste disposal process is divided into three distinct parts:

3.4.1 Disposal Request

The components involved in this process are User, Telegram Bot, SWM Server, blockchain and MongoDB. When a user has to dispose some waste, he/she will interact with the Telegram Bot *perccomanitmo*. A Telegram bot running in SWM server responds to the request and asks for user to enter Ethereum account number. This account should be registered in *The Bank* in blockchain. The details for having an account are described in 2 section. The SWM server checks if there is enough balance in the user's bank account or not. This minimum balance amount can be set in the SGB itself while registering it in the System. For test purpose, in the implementation, we check if the account has balance more than zero or not. If yes, the server generates a random number of 10 alphanumeric characters, generates a QR-code with it and sends it to user along with user's account information. At the same time, a transaction record with an *incomplete* status is added into the database. With the QR-code, a location request is sent. Once the user sends his/her location, all the SGB with a certain radius of user's location is returned as a Google map. *Figure* 18 shows the location of a SGB with related details.

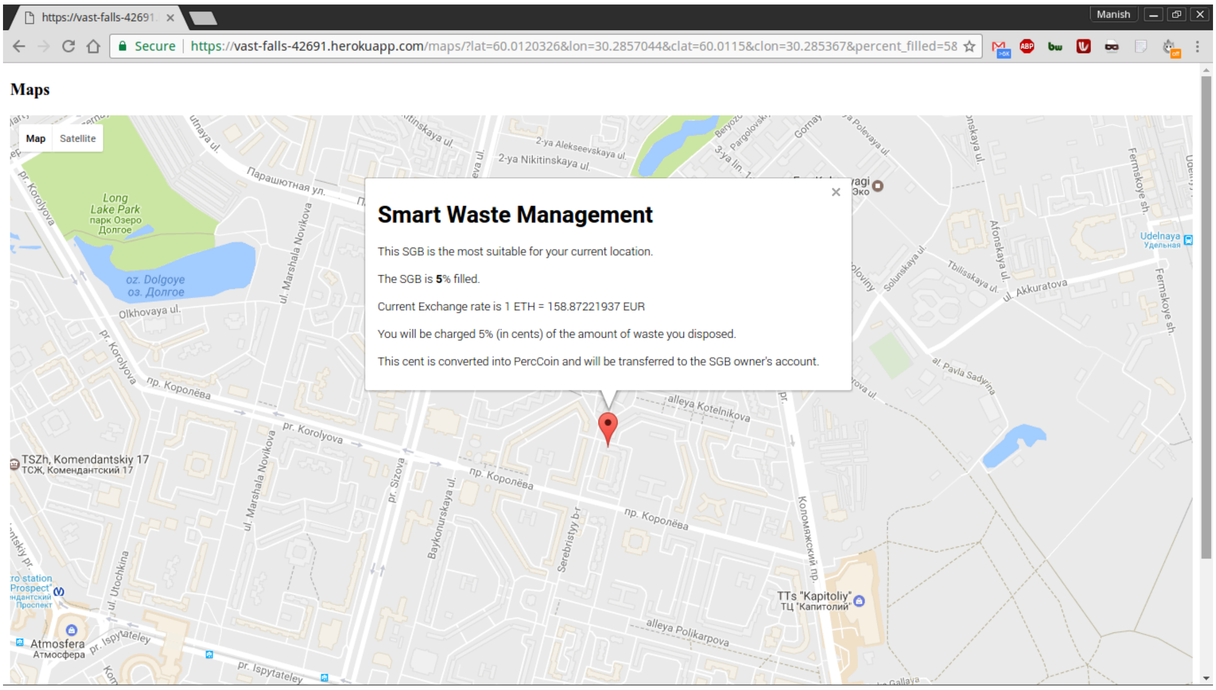


Figure 18. Location of SGB with details

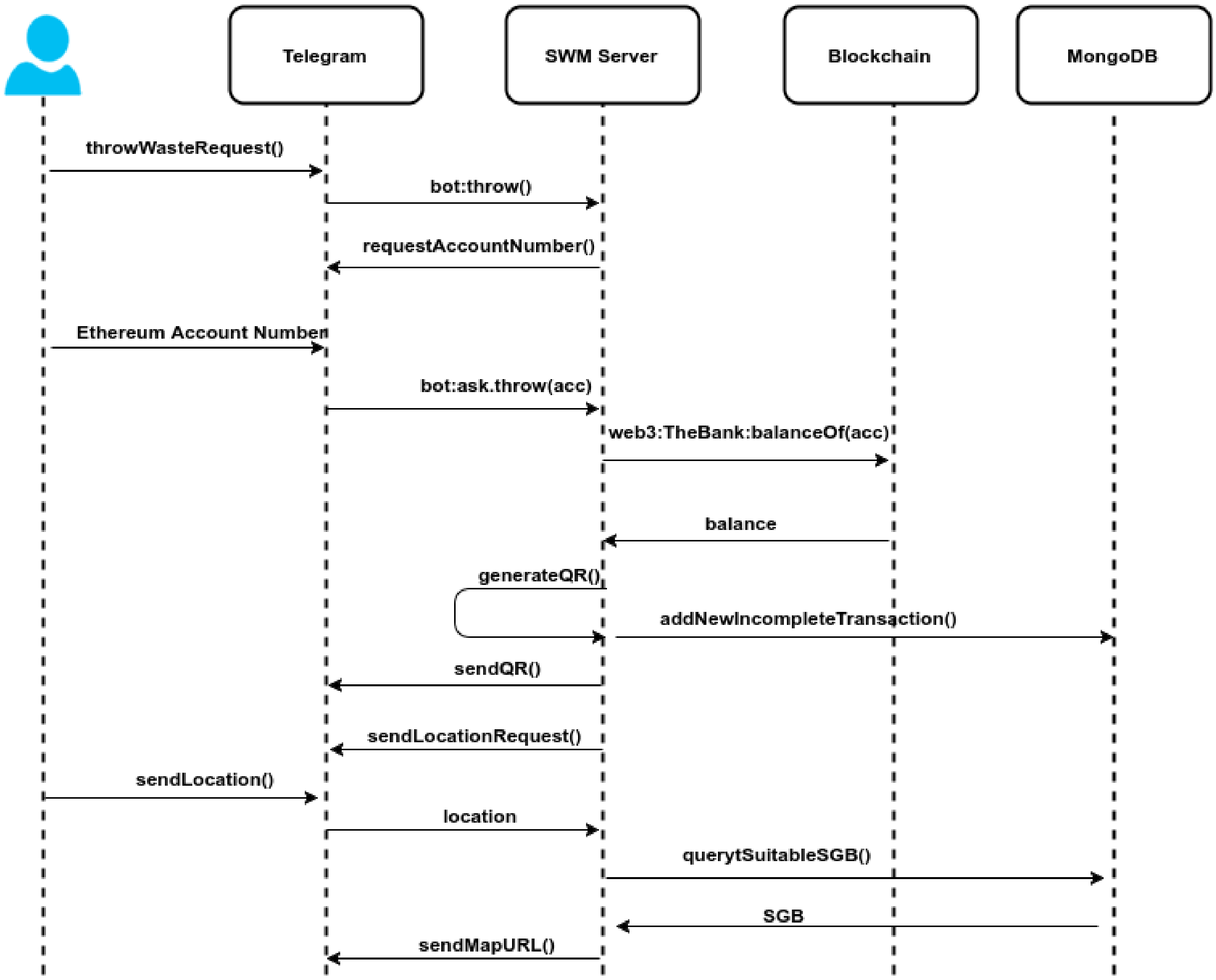


Figure 19. Process Flow: Dispose Request

3.4.2 Authenticate

After the user has received the QR-code and location from the previous process, the location SGB can be navigated using the Google Map. The SGB has a QR-reader that can scan the QR-code user received in Telegram application. Once the QR-code is scanned and decoded, the SGB publishes the decoded value to a MQTT broker to a topic to which the SWM Server is subscribed to. The SWM Server checks for the authenticity of the code and responds accordingly by publishing to MQTT broker to another topic to which the SGB is subscribed to. If the SWM Server acknowledges that it can verify the decoded value, the lid of SGB opens. For the details of MQTT messaging architecture, refer to sub-section 3.2.1.

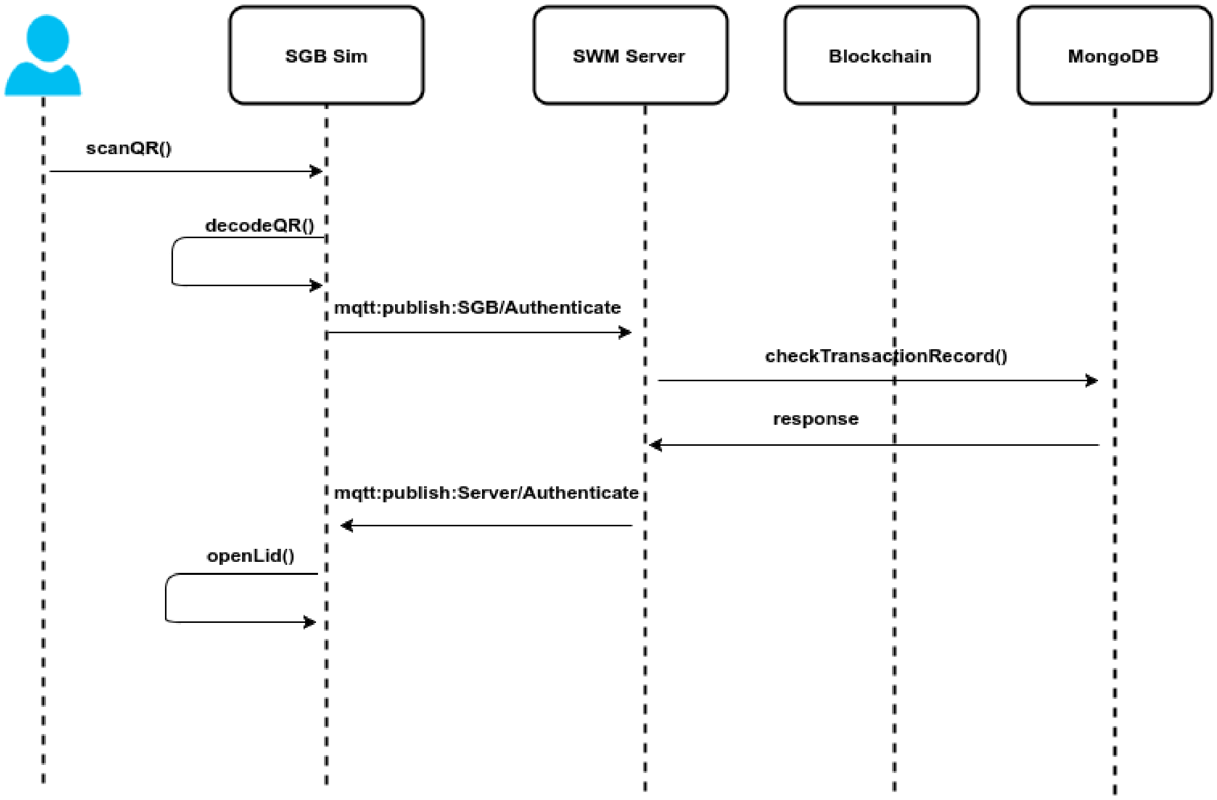


Figure 20. Process Flow: Authenticate

3.4.3 Dispose Waste

After the lid of SGB is opened as per the interaction with the SWM as mentioned in above processes, the user can dispose the waste into the SGB. When the lid of SGB is closed, the total weight of the SGB is calculated and publised to the SWM Server. The SWM Server calculates the difference between the previous weight and the current weight in SGB and finds out the amount of weight user deposited. Using weight-rate based calculation, the amount user needs to pay is calculated. First of all, the transaction record with incomplete status in database is set as *complete* and all the information (cost of service, user account, date, amount of waste etc) are updated in the record. Finally, a transfer request for the amount user is supposed to pay to the SGB owner is made to The Bank in blockchain is made via Web3 interface.

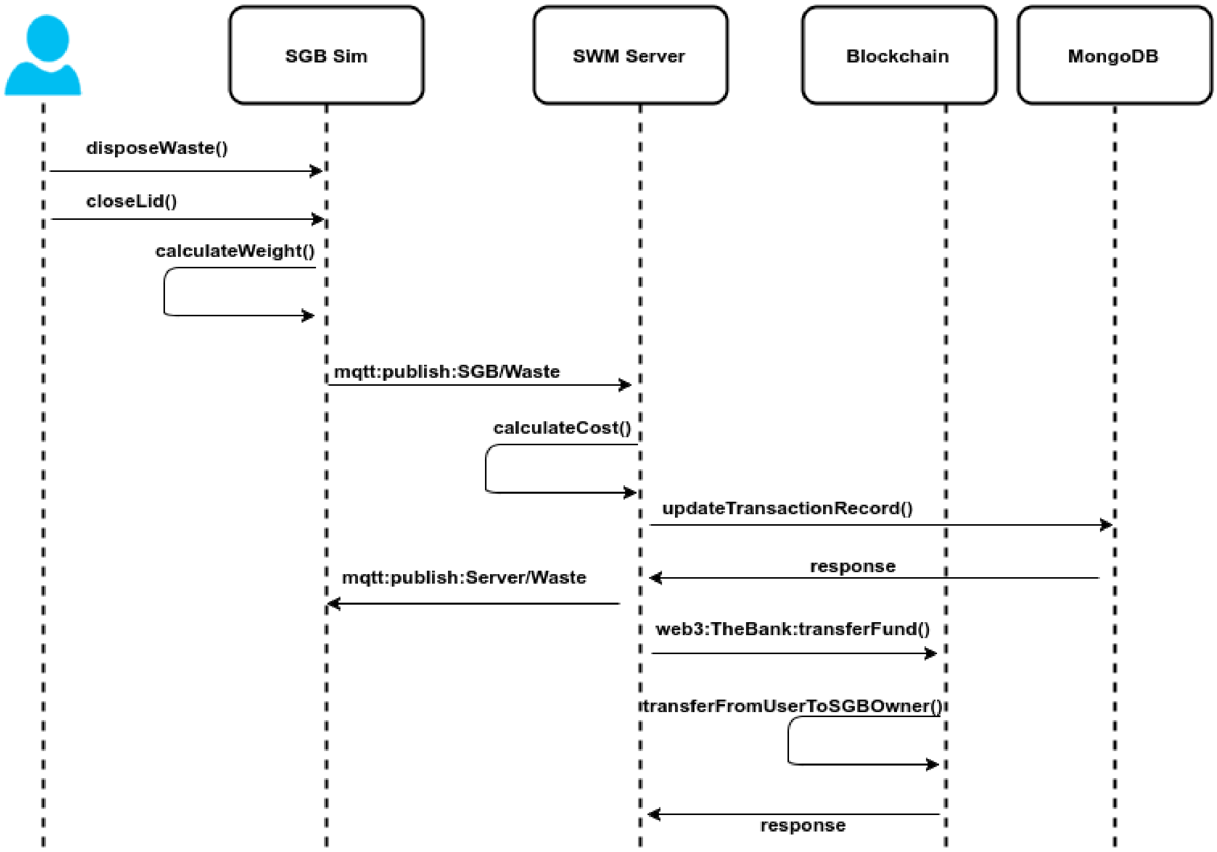


Figure 21. Process Flow: Dispose Waste

3.5 Summary

In this section, the implementation, technology and the flow of data between different components of system was described in detail. The first subsection highlighted the proposed architecture. Blockchain and the surrounding technology was dealt in great detail in the following subsection. *DAO* and a central bank regulating a custom cryptocurrency as implementation of *Smart Contract* was explained. Different components and their significance in the TAG was highlighted and finally using a process flow diagram, the flow of data from its generation stage (by user) to its processing and storage (MongoDB, blockchain) was described.

4 Evaluation and Discussion

Figures 22 23 24 show the time taken to mine a transaction in Private Ethereum Network and Ethereum Test Network. Having more number of nodes increases the security of network but it has no effect in the mining time. One mining thread generally needs 2 MB or 4096 KB. Hence, for a given CPU, the appropriate number of mining threads is determined as L2 cache of CPU (KB) / mining thread size [35] . So, if the L2 cache is 4096 KB (4 MB) then mining thread can be obtained as: 4096/2048 = 2 mining threads. The measurements are taken in milliseconds (ms). Private Network running single thread is represented a PN1T. Likewise, PN2T for 2 thread in Private Network and 2 thread in Test Network is represented as TN2T. By a transaction, we mean transfer of *PercCoins* from a test account to *Community DAO* account in *The Bank*.

4.1 Private Network

A Private Ethereum Network with a single node was run in Ubuntu 14.04 in Openstack cloud. It consisted of 1 VCPU and 2GB RAM. The SWM Server used Web3 interface to make RPC from local machine to this node running in Openstack. Web3 is a *JavaScript* library used to interact with Ethereum blockchain. 1 thread and 2 threads respectively to measure the mining time of transactions. A total of 10 transactions were taken into account for each variation of no of threads. On top of the actual CPU process used for mining, network latency also could have had some effects in the measurement as the transactions are fed to the remote node over the Internet using Web3 interface.

4.1.1 Mining with One Thread

Out of the 10 measurements taken using single thread in Private Network, there were some *perks* or sharp rise in mining time observed. Since the machine used for test was running multiple other processes, there could be any reason responsible for this rise. The average mining time of the transactions was calculated to be *29759.1321 milliseconds* which is heavily affected by the extreme values in the result.

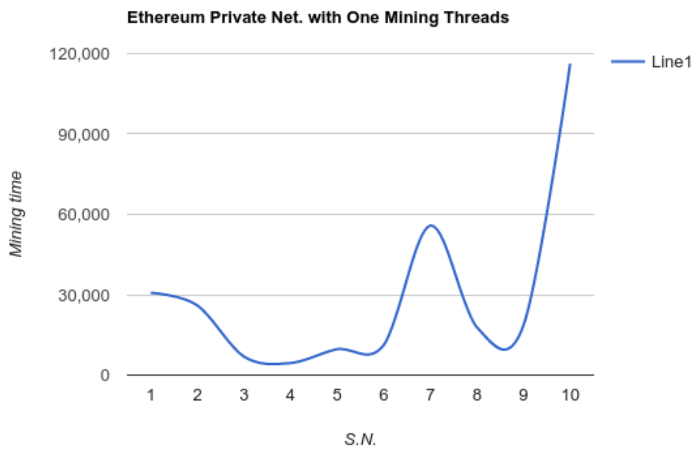


Figure 22. Mining in Ethereum Private Net. with 1 Threads

4.1.2 Mining with Two Threads

Using two threads in Private Network yielded better results. There were sharp decline in mining time observed. This phase of measurement was taken right after the previous one with single thread. The same process accountable for the steep rise in the mining time during previous measurement could be finishing during this reading resulting the steep reduction during first three readings. The average mining time for this phase was *17154.5816 milliseconds* which is relatively better than single thread mining.

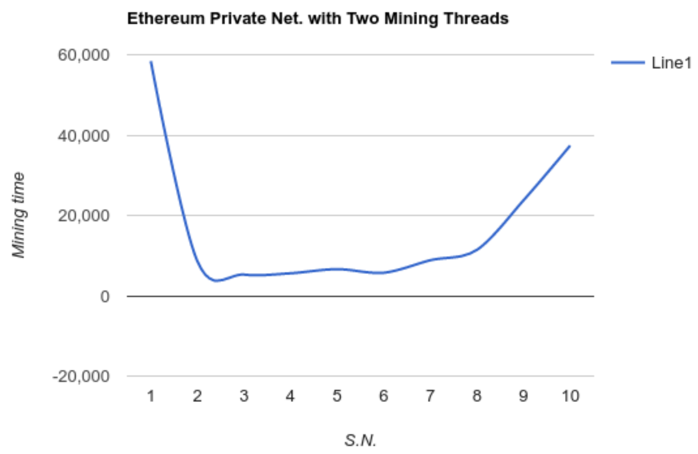


Figure 23. Mining in Ethereum Private Net. with 2 Threads

4.2 Ethereum Test Network

The test network was run locally in the same machine in which the SWM was running. Web3 interface was used this test as well but since the node was running locally, the network latency should not have any effect in the measurements in this case. The test machine consisted of 4 CPU's and 8 GB RAM. It can be seen that the speed of mining significantly increases when the node is running on a high-end hardware locally.

Mining with Two Threads

The mining speed is improved a lot with the use of high end hardware. The first three readings show steep decrease similar to two thread mining in Private Network. The average mining time is *1835.0843 milliseconds*. The graph shows steep decline in the mining speed, however the first three high values are affecting the average, increasing it significantly.

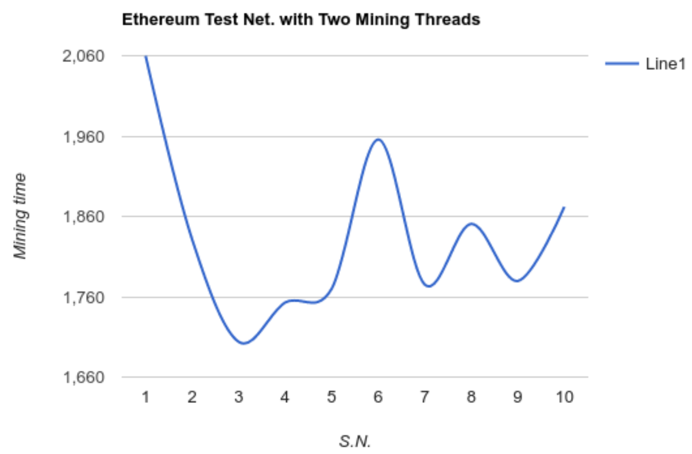


Figure 24. Mining in Ethereum Test Net. with 2 Threads

These measurements provide a general idea of execution of Smart Contracts in two different networks of Ethereum. These measurements are not to be taken as a comparison of execution time, since the conditions of experiments are not ideal and are effected by other unaccounted factors like network latency and difference in hardware used. However, they provide a good overview of how factors like executing contracts remotely or locally can affect the speed of execution or mining of transactions.

5 Conclusion and Future Work

The objective of this thesis was to evaluate, analyse and implement different technologies surrounding Internet of Things and blockchain technology and develop a smart waste management system suitable for future cities. This chapter concludes the work, presents limitations and opportunities for future improvements.

5.1 Conclusion

In this thesis, we have proposed a prototype of IoT and blockchain based smart waste management system. To the best of our knowledge, there has not been another implementation of similar kind, till date. We used an architecture including Smart Waste Bin simulation to help understand the requirement for deploying this kind of waste management system in real world. We have shown that blockchain technology can help create a payment infrastructure that can handle micropayments with least transaction overhead. Weight rate based system relies largely on stream of micropayments. The proposed smart waste management systems is able to handle micropayments by the virtue of blockchain and *Smart Contracts*. Furthermore, the thesis outlines that the concept of DAOs has strong possibilities to create different business models which can lower the penetration cost and boost innovation. People can come together, raise fund and invest into solutions that can address their problems and also can be sure that they are in control of their own investment.

5.2 Future Work

To increase the quality of waste generated, sorting of waste at source is vital. Users could be rewarded by recycle companies based on the quality and type of waste they produce, which in turn would motivate users to sort waste and check the waste they generate. For example, rewarding users for using more recycle-able products. For this feature to work, associating users with the waste they produced is becomes important. This is a challenge the proposed system cannot address as of now. We are looking for ways to address this scenario in TAG in such a way that the implementation will impose least technological complexity in part of users. Further development of TAG could also lead to a possibility of a *Uber-like Waste Management System* where anyone can collect rewards for delivering waste from SGB to a recycle plant. It could just be another organization represented in blockchain as a DAO.

The mining time in worst case took as long as 50 seconds. This means that ,for blockchain to validate the transaction, it could take as long as 50 seconds. While blockchain can handle the cases of duplicate payment very well, there is a possibility that a malicious user may be able to exploit the system within the time frame when the transaction is mined. Blockchain will obviously reject the duplicate payment but the system is not designed to take necessary step to punish the malicious user in this case. As an effort to further this work, a penalty system can be introduced. If a malicious user spends more that the amount present in his wallet (which is possible only under special circumstance mentioned above), the system should be able to flag the user and fine a penalty amount. Unless, the penalty is paid off, user should be barred from the use of system.

5.3 Challenges

Blockchain technologies are relatively new concept. Ethereum blockchain is gaining popularity but it is still a system under development and yet to be mature. One of the drawback it imposes is that, creating a system whose entire database is running on top of blockchain is not very applicable at the moment because of the processing time the network needs to mine data into blocks. Bitcoin's network alone consumes as much electricity as the country of Ireland as a whole [36]. A change of algorithm from *Proof of Work* or *PoW* to *Proof of Stake* or *PoS* might possible make the network less resource intensive and enhance the efficiency. Another drawback is the lack of knowledge of blockchain technologies among common population. With the increase in the amount of applications built on top of blockchain and the improvement of efficiency of the network, the appeal of blockchain might grow.

REFERENCES

[1] Alexandra Klimova, Eric Rondeau, Karl Andersson, Jari Porras, Andrei Rybin, and Arkady Zaslavsky. An international master's program in green ict as a contribution to sustainable development. *Journal of Cleaner Production*, 135:223 – 239, 2016.

[2] EU funded Horizon 2020 Program. biotope. Available at http://www.biotope-project.eu/.

[3] Daniel Hoornweg and Perinaz Bhada-Tata. What a waste : A global review of solid waste management. 2012. Available at https://openknowledge.worldbank.org/handle/10986/17388.

[4] Zoran Jovic, Goran Coric, and Igor Pejovic. Challenges of Modern Electronic Banking. *Sinteza 2016 - International Scientific Conference on ICT and E-Business Related Research*, 2016. Available at http://portal.sinteza.singidunum.ac.rs/paper/459.

[5] William Song, Weidong Kou, and CJ Tan. An Investigation on Multiple e-Payments and Micro-Payment. *Research gate*, 2016. Available at https://www.researchgate.net/profile/William_Song6/publication/220952197_An_Investigation_on_Multiple_e-Payments_and_Micro-Payment_-_A_Technical_and_Market_View/links/54d1319e0cf28370d0e02e20.pdf.

[6] Satoshi Nakamoto. Bitcoin: A peer-to-peer electronic cash system. 2008. Available at https://bitcoin.org/bitcoin.pdf.

[7] Vitalik Buterin et al. A next-generation smart contract and decentralized application platform. *white paper*, 2014. Available at https://www.weusecoins.com/assets/pdf/library/Ethereum_white_paper-a_next_generation_smart_contract_and_decentralized_application_platform-vitalik-buterin.pdf.

[8] Christoph Jentzsch. Decentralized autonomous organization to automate governance. *Final Draft-Under Review*, 2016. Available at https://download.slock.it/public/DAO/WhitePaper.pdf.

[9] Azni Idris, Bulent Inanc, and Mohd Nassir Hassan. Overview of waste disposal and landfills/dumps in Asian countries. *Springer-Verlag*, 322(6):104–110, 2004. Available at https://link.springer.com/article/10.1007/s10163-004-0117-y.

[10] Nir Kshetri. Will blockchain emerge as a tool to break the poverty chain in the Global South? *Third World Quarterly*, 28 Apr 2017. Available at http://dx.doi.org/10.1080/01436597.2017.1298438.

[11] The Independent. Sweden's recycling is so revolutionary, the country has run out of rubbish, 2016. Accessed: 2017-05-26, Available at http://www.independent.co.uk/environment/sweden-s-recycling-is-so-revolutionary-the-country-has-run-out-of-html, Independent.co.uk Article.

[12] Insung Hong, Sunghoi Park, Beomseok Lee, Jaekeun Lee, Daebeom Jeong, and Sehyun Park. Iot-based smart garbage system for efficient food waste management. *The Scientific World Journal*, 2014, 2014. Available at https://www.hindawi.com/journals/tswj/2014/646953/.

[13] Gartner Inc. Gartner hype cycle 2016. Accessed: 2017-05-24, Available at http://www.gartner.com/newsroom/id/3412017.

[14] Gartner Inc. Gartner hype cycle 2015. Accessed: 2017-05-24, Available at http://www.gartner.com/newsroom/id/3114217.

[15] Konstantinos Christidis and Michael Devetsikiotis. Blockchains and smart contracts for the internet of things. *IEEE Access*, 4:2292–2303, 2016. Available at http://ieeexplore.ieee.org/abstract/document/7467408/.

[16] European Union. Waste statistics, 2014. Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics.

[17] João Aleluia and Paulo Ferrão. Characterization of urban waste management practices in developing asian countries: A new analytical framework based on waste characteristics and urban dimension. *Waste Management*, 58:415 – 429, 2016.

[18] Hossein Shahrokni, Bram Van der Heijde, David Lazarevic, and Nils Brandt. Big data gis analytics towards efficient waste management in stockholm. In *Proceedings of the 2014 conference ICT for Sustainability*, pages 140–147. Atlantis Press, 2014. Available at https://lirias.kuleuven.be/bitstream/123456789/466195/1/209.pdf.

[19] Department of Computer Science Stanford University. Micropayments: A viable business model? Accessed: 2017-05-16, Available at https://cs.stanford.edu/people/eroberts/cs181/projects/2010-11/MicropaymentsAndTheNet/issues.html.

[20] Ethereum Foundation. Ethereum wallet (0.8.9), 2017. Available at https://github.com/ethereum/mist/releases.

[21] J.A. Shahabdeen. Smart garbage bin, June 23 2016. US Patent App. 14/578,184.

[22] Yann Glouche and Paul Couderc. A Smart Waste Management with Self-Describing objects. In Wolfgang Leister, Hoyoung Jeung, and Petri Koskelainen, editors, *The Second International Conference on Smart Systems, Devices and Technologies (SMART'13)*, Rome, Italy, June 2013. IARIA. Available at https://hal.inria.fr/hal-00924270.

[23] S. Longhi, D. Marzioni, E. Alidori, G. Di Buo, M. Prist, M. Grisostomi, and M. Pirro. Solid waste management architecture using wireless sensor network technology. In *2012 5th International Conference on New Technologies, Mobility and Security (NTMS)*, pages 1–5, May 2012. Available at http://dx.doi.org/10.1109/NTMS.2012.6208764.

[24] Gaikwad Prajakta, Jadhav Kalyani, and Machale Snehal. Smart garbage collection system in residential area. *IJRET: International Journal of Research in Engineering and Technology eISSN*, pages 2319–1163, 2015. Available at https://www.researchgate.net/publication/277908234_SMART_GARBAGE_COLLECTION_SYSTEM_IN_RESIDENTIAL_AREA.

[25] M. A. A. Mamun, M. A. Hannan, A. Hussain, and H. Basri. Wireless sensor network prototype for solid waste bin monitoring with energy efficient sensing algorithm. In *2013 IEEE 16th International Conference on Computational Science and Engineering*, pages 382–387, Dec 2013. Available at http://dx.doi.org/10.1109/CSE.2013.65.

[26] F Vicentini, A Giusti, A Rovetta, X Fan, Q He, M Zhu, and B Liu. Sensorized waste collection container for content estimation and collection optimization. *Waste management*, 29(5):1467–1472, 2009. Available at http://www.sciencedirect.com/science/article/pii/S0956053X08003735.

[27] Nea Teerioja, Katja Moliis, Eveliina Kuvaja, Markku Ollikainen, Henna Punkkinen, and Elina Merta. Pneumatic vs. door-to-door waste collection systems in existing urban areas: a comparison of economic performance. *Waste Management*, 32(10):1782 – 1791, 2012. Available at http://www.sciencedirect.com/science/article/pii/S0956053X1200236X.

[28] M. Collina, M. Bartolucci, A. Vanelli-Coralli, and G. E. Corazza. Internet of things application layer protocol analysis over error and delay prone links. In *2014 7th Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, pages 398–404, Sept 2014. Available at http://dx.doi.org/10.1109/ASMS-SPSC.2014.6934573.

[29] Ethereum Blog. Merkling in ethereum, 2015. Accessed: 2017-06-03, Available at https://blog.ethereum.org/2015/11/15/merkling-in-ethereum/.

[30] Bitcoin Stackexchange. What's the process of creating a block on the blockchain, 2016. Accessed: 2017-05-26, Available at https://bitcoin.stackexchange.com/questions/7330/whats-the-process-of-creating-a-block-on-the-blockchain.

[31] Bitcoin Wiki. Proof of stake, 2015. Accessed: 2017-06-03, Available at http://en.bitcoin.it/wiki/Proof_of_Stake.

[32] Kevin Delmolino, Mitchell Arnett, Ahmed Kosba, Andrew Miller, and Elaine Shi. Step by step towards creating a safe smart contract: Lessons and insights from a cryptocurrency lab. In *International Conference on Financial Cryptography and Data Security*, pages 79–94. Springer, 2016. Available at http://fc16.ifca.ai/bitcoin/papers/DAKMS16.pdf.

[33] Dao templates. https://www.ethereum.org/dao. Accessed: 2017-05-10, Available at https://www.ethereum.org/dao.

[34] LLP Telegram Messenger. Telegram. 2013. Accessed: 2017-05-10, Available at https://core.telegram.org/bots/api.

[35] Stack Exchange (Monero). Optimal number of threads when mining, 2017. Accessed: 2017-06-15, Available at https://monero.stackexchange.com/questions/328/optimal-number-of-threads-when-mining.

[36] Karl J O'Dwyer and David Malone. Bitcoin mining and its energy footprint. 2014. Available at http://ieeexplore.ieee.org/document/6912770/.