

**5.2%**





























Resultsofplagiarismanalysisfrom2022-07-2623:35CEST

Bakalarska\_Praca\_Text (6).pdf












Date:2022-07-2623:22CEST

\*Allsources 89 | Internetources 39 | PlagiarismPreventionPool 50 |

✓ [0]	<a href="#">arxiv.org/pdf/1805.02707</a> 0.6% 17matches
✓ [1]	<a href="#">fromaPlagScandocumentdated2020-11-1809:41</a> 0.5% 14matches
✓ [2]	<a href="#">eprint.iacr.org/2021/911.pdf</a> 0.6% 14matches
✓ [3]	<a href="#">dspace.vutbr.cz/bitstream/handle/11012/191485/final-thesis.pdf?sequence=3</a> 0.7% 10matches
✓ [4]	<a href="#">dspace.vutbr.cz/bitstream/handle/11012/200157/final-thesis.pdf?sequence=3</a> 0.5% 9matches
✓ [5]	<a href="#">www.vutbr.cz/www_base/zav_prace_soubor_verejne.php?file_id=216137</a> 0.5% 12matches
✓ [6]	<a href="#">fromaPlagScandocumentdated2022-07-1815:16</a> 0.3% 8matches
✓ [7]	<a href="#">arxiv.org/pdf/2003.09262</a> 0.4% 7matches
✓ [8]	<a href="#">fromaPlagScandocumentdated2017-12-0721:34</a> 0.3% 7matches
✓ [9]	<a href="#">dspace.vutbr.cz/bitstream/handle/11012/201270/final-thesis.pdf</a> 0.4% 8matches 1documentswithidenticalmatches
✓ [11]	<a href="#">fromaPlagScandocumentdated2022-06-2210:43</a> 0.3% 9matches
✓ [12]	<a href="#">fromaPlagScandocumentdated2019-01-2917:50</a> 0.2% 5matches
✓ [13]	<a href="#">www.mdpi.com/2073-8994/13/8/1363/htm</a> 0.3% 8matches
✓ [14]	<a href="#">arxiv.org/pdf/1902.01457</a> 0.4% 8matches
✓ [15]	<a href="#">www.hindawi.com/journals/scn/2021/6693731/</a> 0.3% 7matches
✓ [16]	<a href="#">fromaPlagScandocumentdated2020-03-0506:17</a> 0.2% 6matches
✓ [17]	<a href="#">fromaPlagScandocumentdated2022-06-2009:38</a> 0.2% 7matches
✓ [18]	<a href="#">research.aalto.fi/files/67183114/ELEC_Feng_etal_Blockchain_based_data_transmission_control_DCAN_2021.pdf</a> 0.2% 7matches
✓ [19]	<a href="#">fromaPlagScandocumentdated2022-02-2006:42</a> 0.1% 4matches
✓ [20]	<a href="#">fromaPlagScandocumentdated2021-11-1606:50</a> 0.2% 5matches
✓ [21]	<a href="#">www.slideshare.net/JonasMercier/wp-blockchain-ilnaseversion</a> 0.2% 5matches
✓ [22]	<a href="#">fromaPlagScandocumentdated2018-04-1114:53</a> 0.1% 4matches
✓ [23]	<a href="#">arxiv.org/pdf/1809.01620</a> 0.2% 5matches
✓ [24]	<a href="#">fromaPlagScandocumentdated2020-11-1717:50</a> 0.1% 3matches
	<a href="#">fromaPlagScandocumentdated2019-03-2203:36</a>

✓ [25]	 fromaPlagScandocumentdated2019-03-2200:00 0.2% 5matches
✓ [26]	 fromaPlagScandocumentdated2021-11-2014:22 0.1% 3matches
✓ [27]	 fromaPlagScandocumentdated2020-03-1710:09 0.1% 4matches
✓ [28]	 fromaPlagScandocumentdated2015-10-2510:13 0.1% 4matches
✓ [29]	 dl.acm.org/doi/10.1145/2968215 0.2% 5matches
✓ [30]	 fromaPlagScandocumentdated2021-12-2716:07 0.1% 4matches
✓ [31]	 drops.dagstuhl.de/opus/volltexte/2017/8016/pdf/LIPics-DISC-2017-1.pdf 0.2% 5matches
✓ [32]	 www.sciencedirect.com/science/article/pii/B9780444516084500110 0.1% 3matches
✓ [33]	 www.sciencedirect.com/science/article/pii/S0957417419308310 0.2% 4matches
✓ [34]	 fromaPlagScandocumentdated2020-11-1605:55 0.1% 4matches
✓ [35]	 fromaPlagScandocumentdated2020-10-0615:43 0.1% 3matches
✓ [36]	 fromaPlagScandocumentdated2019-01-2220:05 0.1% 2matches
✓ [37]	 fromaPlagScandocumentdated2019-04-1110:16 0.1% 3matches
✓ [38]	 citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.588&rep=rep1&type=pdf 0.1% 4matches
✓ [39]	 fromaPlagScandocumentdated2021-04-1315:09 0.1% 2matches
✓ [40]	 fromaPlagScandocumentdated2022-02-0811:16 0.1% 3matches
✓ [41]	 fromaPlagScandocumentdated2020-05-0109:51 0.1% 4matches
✓ [42]	 fromaPlagScandocumentdated2017-07-1107:56 0.1% 3matches
✓ [43]	 fromaPlagScandocumentdated2020-11-0907:21 0.1% 3matches
✓ [44]	 fromaPlagScandocumentdated2017-11-2110:34 0.1% 2matches
✓ [45]	 en.wikipedia.org/wiki/Biometrics#:~:text=Thefirsttimeanindividual,atthetimeofenrollment. 0.1% 3matches
✓ [46]	 www.academia.edu/23704409/Biometric_cryptosystems_A_new_biometric_key_binding_and_its_implementation_for_fingerprint 0.0% 3matches
✓ [47]	 fromaPlagScandocumentdated2018-10-1810:57 0.1% 3matches
✓ [48]	 silo.tips/download/consistency-in-the-identity-management 0.1% 2matches
✓ [49]	 www.ncbi.nlm.nih.gov/pmc/articles/PMC9027738/#:~:text=3.,StudyofBlockchainTechnology,NetworkLayerandDataLayer. 0.1% 3matches
✓ [50]	 pixelplex.io/blog/best-blockchain-consensus-algorithms/ 0.1% 1matches
✓ [51]	 www.mdpi.com/2073-8994/13/5/910/pdf 0.1% 2matches
✓ [52]	 appinventiv.com/blog/blockchain-consensus-algorithms-guide/

✓ [52]	0.1% 1 matches
✓ [53]	<a href="#">arxiv.org/pdf/cs/0109111</a> 0.0% 2 matches
✓ [54]	from a PlagScan document dated 2021-10-02 14:45 0.1% 2 matches
✓ [55]	from a PlagScan document dated 2020-03-12 05:45 0.1% 2 matches
✓ [56]	from a PlagScan document dated 2019-05-22 10:40 0.1% 2 matches
✓ [57]	from a PlagScan document dated 2022-05-19 03:23 0.1% 1 matches
✓ [58]	from a PlagScan document dated 2021-06-30 15:13 0.1% 2 matches ⊕ 1 documents with identical matches
✓ [60]	<a href="#">citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.51.5282&amp;rep=rep1&amp;type=pdf</a> 0.1% 2 matches
✓ [61]	<a href="#">link.springer.com/chapter/10.1007/978-981-15-1301-5_46</a> 0.1% 2 matches
✓ [62]	<a href="#">www.gemini.com/cryptopedia/blockchain-consensus-mechanism-types-of-algorithm</a> 0.1% 1 matches
✓ [63]	from a PlagScan document dated 2021-07-13 13:00 0.1% 2 matches
✓ [64]	<a href="#">www.sciencedirect.com/science/article/pii/S2352864819302913</a> 0.1% 2 matches
✓ [65]	from a PlagScan document dated 2018-03-28 07:24 0.1% 1 matches
✓ [66]	from a PlagScan document dated 2017-07-07 07:40 0.0% 1 matches
✓ [67]	<a href="#">core.ac.uk/download/pdf/30301981.pdf</a> 0.1% 1 matches
✓ [68]	from a PlagScan document dated 2022-06-03 21:10 0.1% 1 matches
✓ [69]	from a PlagScan document dated 2021-07-22 09:05 0.1% 1 matches
✓ [70]	from a PlagScan document dated 2021-07-05 11:11 0.1% 1 matches
✓ [71]	from a PlagScan document dated 2021-05-22 06:20 0.1% 1 matches
✓ [72]	from a PlagScan document dated 2020-12-28 11:53 0.1% 1 matches
✓ [73]	from a PlagScan document dated 2018-06-28 13:16 0.0% 1 matches
✓ [74]	from a PlagScan document dated 2018-01-31 10:13 0.0% 1 matches
✓ [75]	from a PlagScan document dated 2017-10-21 01:42 0.0% 1 matches
✓ [76]	<a href="#">publons.com/journal/51381/international-journal-of-scientific-and-research-p/</a> 0.1% 1 matches
✓ [77]	<a href="#">www.researchgate.net/post/Can_you_recommend_International_Journal_of_Scientific_and_Research_Publications_IJSRP</a> 0.1% 1 matches
✓ [78]	from a PlagScan document dated 2021-11-11 09:35 0.0% 1 matches ⊕ 2 documents with identical matches
✓ [81]	from a PlagScan document dated 2020-07-05 22:28 0.1% 1 matches

✓ [82]	 fromaPlagScandocumentdated2019-02-1208:46 0.0% 1matches
✓ [83]	 fromaPlagScandocumentdated2018-10-2109:07 0.0% 1matches ⊕ 1documentswithidenticalmatches
✓ [85]	 www.eurecom.fr/publication/6492/download/comsys-publi-6492.pdf 0.0% 1matches
✓ [86]	 fromaPlagScandocumentdated2022-02-0305:01 0.0% 1matches
✓ [87]	 fromaPlagScandocumentdated2018-09-2807:29 0.0% 1matches
✓ [88]	 fromaPlagScandocumentdated2017-04-0608:21 0.0% 1matches
✓ [89]	 laclavik.sk/publications/EntityRelationsTextGraphs_habilitation_thesis.pdf 0.0% 1matches
✓ [90]	 www.sciencedirect.com/science/article/pii/S2405959521000916 0.1% 1matches
✓ [91]	 ieeeexplore.ieee.org/document/6994220 0.1% 1matches
✓ [92]	 www.researchgate.net/publication/353904397_Securing_biometric_authentication_system_using_blockchain 0.1% 1matches
✓ [93]	 www.researchgate.net/publication/274404081_Hill-Climbing_Attacks_on_Multibiometrics_Recognition_Systems 0.1% 1matches

52 pages, 16321 words

 A very light text-color was detected that might conceal letters used to merge words.

PlagLevel: 5.2% selected / 5.4% overall

121 matches from 94 sources, of which 40 are online sources.

#### Settings

**Data policy:** *Compare with web sources, Check against my documents, Check against my documents in the organization repository, Check against organization repository, Check against the Plagiarism Prevention Pool*

**Sensitivity:** *Medium*

**Bibliography:** *Consider text*

**Citation detection:** *Reduce PlagLevel*

**Whitelist:** --

[3] ▶

**BRNO UNIVERSITY OF TECHNOLOGY**

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

**FACULTY OF INFORMATION TECHNOLOGY**

FAKULTA INFORMAČNÍCH TECHNOLOGIÍ

**DEPARTMENT OF INTELLIGENT SYSTEMS**

ÚSTAV INTELIGENTNÍCH SYSTÉMŮ

## **BIOMETRIC SYSTEM SECURITY USING BLOCKCHAIN TECHNOLOGY**

ZABEZPEČENÍ BIOMETRICKÉHO SYSTÉMU POMOCÍ TECHNOLOGIE BLOCKCHAIN

**BACHELOR'S THESIS**

BAKALÁŘSKÁ PRÁCE

**AUTHOR**

AUTOR PRÁCE

**MAREK ŽIŠKA**

**SUPERVISOR**

VEDOUCÍ PRÁCE

[3] ▶  
**Ing. PETR MALANÍK**

**BRNO 2022**

## Bachelor's Thesis Specification

**Student:** Žižka Marek  
**Programme:** Information Technology  
**Title:** <sup>[7]</sup> **Biometric System Security Using Blockchain Technology**  
**Category:** Security

**Assignment:**

1. Get familiar with principles of decentralized systems and systems which are commonly used for biometric security and biometric data storage.
2. Identify weak points of traditional biometric systems and propose a variant of a decentralized biometric system based on blockchain technology.
3. Implement the proposed system and demonstrate his <sup>[25]</sup> behavior and communication.
4. Evaluate results against traditional biometric systems. **Discuss the advantages and disadvantages of such a system as well as possible extensions.** Identify primary security threats.

**Recommended literature:**

Cachin, C., & Vukolić, M. (2017). <sup>[2]</sup> **Blockchain consensus protocols in the wild.** arXiv preprint arXiv:1707.01873.  
Narayanan, A., Bonneau, J., Felten, E., Miller, A., & Goldfeder, S. (2016). <sup>[5]</sup> **Bitcoin and cryptocurrency technologies: a comprehensive introduction.** Princeton University Press.  
<sup>[3]</sup> **Detailed formal requirements can be found at <https://www.fit.vut.cz/study/theses/>**

**Supervisor:** Malaník Petr, Ing.  
**Consultant:** Januš Filip, Ing., UITS FIT VUT  
**Head of Department:** Hanáček Petr, doc. Dr. Ing.  
**Beginning of work:** November 1, 2021  
**Submission deadline:** July 29, 2022  
**Approval date:** <sup>[3]</sup> **November 3, 2021**

## Abstract

Blockchain is characterized as a system of recording information that assures security, immutability, and transparency in a distributed network. The direct use of blockchain to secure sensitive data, such as biometric data, is not expected to be the most appropriate use, but its integration within the processes of individual components of biometric systems appears to be a good option. This work analyzes existing protocols used to reach consensus in blockchain technologies, describes the concepts of biometric systems, analyzes and identifies their security threats, presents existing solutions using blockchain technology in biometric systems, and, based on these findings, designs, and demonstrates a concept that makes use of the characteristics of the blockchain to improve their security.

## Abstrakt

Blockchain je charakterizovaný ako systém zaznamenávania informácií, ktorý zaisťuje bezpečnosť, nemennosť a transparentnosť v distribuovanej sieti. Priame využitie blockchainu na zabezpečenie citlivých údajov, akými sú aj biometrické údaje, sa nepredpokladá ako najvhodnejšie využitie, no jeho integrácia v rámci procesov jednotlivých komponentov biometrických systémov sa javí ako dobrá možnosť. Táto práca analyzuje existujúce protokoly používané na dosiahnutie konsenzu v technológiách blockchain, popisuje koncepty biometrických systémov, analyzuje a identifikuje ich bezpečnostné hrozby, predstavuje existujúce riešenia využívajúce technológiu blockchain v biometrických systémoch a na základe týchto zistení navrhuje koncept, ktorý by mohol využiť vlastnosti blockchainu na zlepšenie ich bezpečnosti.

## Keywords

blockchain, cryptography, biometric systems, security, distributed systems, consensus, decentralized systems, byzantine fault tolerance, practical byzantine fault tolerance

## Klíčové slová

blockchain, kryptografia, biometrické systémy, bezpečnosť, konsenzus distribuované systémy, decentralizované systémy, byzantská tolerancia chýb

## Reference

ŽIŠKA, Marek. Biometric System Security Using Blockchain Technology. Brno, 2022. Bachelor's thesis.<sup>[3]</sup> [Brno University of Technology, Faculty of Information Technology](#). Supervisor Ing. Petr Malaník

## Rozšířený abstrakt

Blockchain a biometria sú dve z najzaujímavejších technológií nedávnej éry. Pôvod technológie blockchain má korene vo vynáleze bitcoinu v roku 2008 od Satoshi Nakamota, kde je bitcoin opísaný ako systém platobnej siete navrhnutý tak, aby sprístupnil a sprehladnil platby pre každého so zárukou, že ich prevody nemožno vrátiť späť. akýmkoľvek spôsobom. S odhalením bitcoinu sa začali preteky o ďalšie možné prípady použitia, ako je doprava , maloobchod, zdravotníctvo alebo správa nehnuteľností.

Biometrické systémy môžu byť tiež oblasťou, ktorá môže ťažiť z ich integrácie s technológiou blockchain. Biometrické systémy sú technologické systémy, ktoré umožňujú rozpoznanie jednotlivca podľa daných vlastností, ako je odtlačok prsta, hlas alebo dúhovka. Existujúci výskum zabezpečenia biometrických systémov s využitím technológie blockchain sa zameriava najmä na bezpečnosť šablón. Táto práca skúma možnosti zabezpečenia komponentov "Matcher" a "Feature Extractor" v biometrickom systéme distribúciou ich vykonávania v peer-to-peer sieti biometrických zariadení. Každé zariadenie samostatne vykoná, porovná a spoločne sa dohodnú na výsledku operácie, ktorý je následne uložený v blockchaine. Týmto spôsobom je vykonávanie systémových procesov systému decentralizované medzi viacero účastníkmi, čo vedie k odstráneniu zraniteľnosti <sup>[1]</sup> "single point of failure", bežného pre tradičné biometrické systémy. Použitie blockchainu buduje dôveru v sieť a umožňuje auditovateľnosť vykonaných postupov v predchádzajúcich komponentoch so zámerom minimalizovať možné útoky na prenosové kanály (napr. pri "replay attacks") alebo odhaliť incidenty, kde sa určitý útočník pokúsil narušiť bezpečnostné mechanizmy systému za určitým zlomyseľným dôvodom alebo incidenty keď prišlo k poruche systému.

Komunikácia a základné funkcionality navrhovaného systému boli demonštrované a implementované ako konzolový program, ktorý simuluje určité scenáre špecifikované podľa predaných argumentov. Každý scenár predstavuje určitý typ útoku na systém a ten demonštruje ako sa s tým vie vysporiadať pomocou ukážky komunikácie. Rozšírený výpis programu umožňuje detailný náhľad na komunikáciu v sieti a taktiež aj možnosť zobrazenia obsahu blockchainu alebo šablónovej databáze.<sup>[4]</sup>



# Biometric System Security Using Blockchain Technology

## Declaration

I hereby declare that this Bachelor's thesis was prepared as an original work by the author under the supervision of Mr. Petr Malaník. The supplementary information was provided by Mr. Filip Januš<sup>[4]</sup>. I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

.....  
[3] Marek Žiška  
July 26, 2022

## Acknowledgements

I would like to thank Ing. Peter Malaník for leading me during this work, for all the useful advice that was given to me during consultations, and for professional and willing help despite the more demanding conditions due to my Erasmus. Additionally, I would like to thank all of my colleagues from my Erasmus stay in Dornbirn that I can now proudly consider as my dear friends for all their professional insights, the endless psychological support, and most importantly for always being there for me.

# Contents

1	Introduction	3
2	Theory	5
2.1	Biometric systems	5
2.1.1	History	5
2.1.2	Authentication	6
2.1.3	Structure of biometric system	8
2.1.4	Biometric traits	9
2.1.5	Biometric stages	10
2.1.6	Biometric system's security	12
2.1.7	Countermeasures to prevent attacks	14
2.2	Decentralized systems and blockchain	15
2.2.1	Blockchain	15
2.2.2	Smart contracts	17
2.2.3	Practical byzantine fault tolerance	18
3	Design	20
3.1	Consensus mechanism	20
3.1.1	Private vs public blockchain	20
3.1.2	Private blockchain protocols	21
3.2	Weighted PBFT	21
3.3	Biometrics on blockchain	23
3.4	Securing the transmission	24
3.5	Description of the proposed system	24
3.6	Scenarios of system's operation	25
3.6.1	Enrollment	25
3.6.2	Identification and Verification	27
4	Implementation	28
4.1	Main module	28
4.2	Biometric system's operation	29
4.3	Cryptographic operations	31
4.3.1	Wallet	31
4.3.2	Blockchain and transactions	31
4.4	Consensus system	32
5	Evaluation and testing	34
5.1	Testing scenarios	34

5.1.1	Expected behavior . . . . .	34
5.1.2	Unknown user authentication or identification . . . . .	35
5.1.3	Feature extractor compromised . . . . .	36
5.1.4	Node malfunction . . . . .	37
5.1.5	Channel interception . . . . .	37
5.2	Evaluation . . . . .	38
6	Conclusion and future work	40
	Bibliography	41
A	Contents of the included storage media	46

# Chapter 1

## Introduction

Blockchain and biometrics are two of the most exciting technologies of the recent era. Blockchain technology is still considered to be in its early stages, but some scientists and experts are already comparing it with the revelation of the Internet in the late 20th century [29]. Just as the Internet revolutionized the way we share information, blockchain technologies have the potential to transform/evolve the way we exchange, store and authenticate information [29].

The origin of blockchain technology is rooted in the invention of Bitcoin in 2008 by Satoshi Nakamoto [34], where Bitcoin is described as a payment network system designed to make payments accessible and transparent to everyone with the guarantee that their transfers cannot be reversed in any way. With the Bitcoin revelation, a race for the other possible use cases began. It is currently one of the leading innovations in the finance industry [40], where the blockchain is the backbone of a new type of monetary system known as cryptocurrencies. Through the use of advanced cryptography, cryptocurrencies similar to Bitcoin promise to reduce fraud, ensure fast, secure, and transparent transactions, lower overall costs, and eventually help manage risk within the joint global financial system. With market capitalization reaching as far as trillions of dollars<sup>1</sup>, its experiencing a rapid upward popularity trend. The financial sphere use case is not blockchain's only limitation. In addition to monetary transactions, nothing prevents other digital data from being stored on the blockchain [12]. This aspect opens up the potential to enable a transformation of entire operational models in well-established fields such as transportation [48], retail[41], healthcare[2] or real estate management [35]. Biometric systems might also be a field that can benefit from their integration with blockchain technology. Biometric systems are technological systems that allow recognition of an individual by given characteristics such as a fingerprint, voice, or iris. Existing research on the security of biometrics with the use of blockchain technology focuses mainly on the security of templates [31, 12, 20].

This thesis investigates the possibilities of securing the biometric system's components of Matcher and Feature Extractor by distributing their execution among a peer-to-peer network that settles on the given operation outcome that is afterward stored in a blockchain. In this way, the execution of the system's processes is decentralized among more participants, resulting in the elimination of a single point of failure vulnerability, common for traditional biometric systems. The use of blockchain builds trust in the network and allows for auditability and traceability of executed procedures in previous components, with the intention of minimizing possible attacks on transmission channels (e.g., „replay attacks“) or

<sup>1</sup><https://coinmarketcap.com/charts/>

to reveal incidents of attempted security breaches. The communication and fundamental functionalities of the proposed system were demonstrated and implemented as a console program.

# Chapter 2

## Theory

### 2.1 Biometric systems

Day in and day out, we use our senses to recognize others by our visual characteristics, such as facial looks, voice, or even the style and cadence of walking. Due to this fundamental ability, we can build relationships and trust, which is the essential function of our being. <sup>[12]</sup> This natural fact was one of the reasons why scientists back in the 1960s started to research automated personal identification.

Biometrics or biometric technologies represent procedures that observe, recognize, and measure selected attributes and characteristics of a living individual or group of individuals to identify their unique properties. These characteristics are not stored in their pure form, but in the form of preselected features also called templates(i.e., selected features, mathematical model, or the biometric sample by itself). They represent a persistent bond between a person and his identity. The standardized definition according to ISO/IEC 2382-37 [1] is <sup>[32]</sup> “the automated recognition of individuals based on their biological and behavioral characteristics,..”. Biometric systems can greatly increase security and convenience, compared to traditional recognition systems based on passwords, pins, or smart cards [37]. They might prevent impostors from accessing restricted areas or resources or reveal criminals trying to hide their real identities. With advances in their research, real-world use cases of biometric systems are becoming more frequent. They are used in many sectors, such as airport security, mobile access and authentication, building access control, law enforcement, or banking.

Biometric systems usually have two phases of operation: enrollment and recognition[25]. To register new users, the enrollment phase ensures that the system stores and logically links individuals to their biometric data(template, mathematical model, or biometric sample by itself) in a database. In recognition, previously-stored reference information is compared with the user's newly acquired biometric data, and the authentication result is determined.

Although the leakage of original biometric information is minimized by using templates, it can still be estimated by reverse engineering<sup>[12]</sup>[24]. <sup>[12]</sup> This fact is especially important to keep in mind when researching options for biometric integration with immutable data structures such as the blockchain [20].

#### 2.1.1 History

The term “Biometrics“ consists of two separate words, each with its roots in Greece. The first part „Bio“ originated from bios, as in „living constituents“ or „biological“, which

refers to living organisms and their physiological or behavioral traits. Although the word „metrics“ comes from *métrique*, it refers to measurements or quantitative analysis. Historically, the term „biometrics“ has been known to be a field of biology focused on the measurable analysis of statistical biological data. Today, a more frequent interpretation of „biometrics“ is „biometrics authentication“[45], mainly due to its use in the security field.

The first developments of systems with automatic human recognition(authentication) date back to the early 1960s. The very first biometric research appeared in the journal *Nature* published by Mitchell Trauring in 1963. Instead of referring to „biometrics“, the paper mentions only „automatic fingerprint recognition“. The article states that automatic fingerprint recognition could provide personal verification with faster operational times or lower expenses, since no skilled operating personnel is needed. In the 1970s, the field was already known as „automatic personal identification“. The U.S. National Bureau of Standards (NBS) put a great emphasis on its research, and in 1970 started formal testing of fingerprint systems. Later on, other U.S. organizations including the U.S. National Academy of Sciences (NAS, today NIST) or the U.S. Air Force followed suit. The first reference to the term „biometrics“ was found in the 1981 newspaper article in *The New York Times* [36], where the potential utilization of physiological traits to verify a person's identity was discussed. It is intended to improve existing security systems by replacing the standard authentication methods, which depend on something you possess(plastic cards, keys, etc.) or something you remember(passwords, pins, etc.), with biometrics that do not require such methods. Instead, it introduces a much more convenient method, which depends on who you are or what you do. This brought many advantages as you don't have to remember the passwords or you are not being forced to carry a special object with you to get verified. But it also has its downsides(e.g., data breaches, privacy issues). In the 1990s, the greatest progress was made by developing improvements in iris recognition [43]. During those years, the biometric community began to grow, new organizations were created, and conferences were held presenting new research. In 1991 the first European organization called Association for Biometrics(AFB) was founded. In the 21st century, biometrics has attracted great interest in passenger applications. Countries such as the United States, the UK, and Germany piloted their projects for air travelers, and several countries plan to issue passports with chips that hold biometric data.

### **2.1.2 Authentication**

Biometric systems are a single special instance of systems that execute user authentication. Other authentication systems (access control systems) use methods such as passwords, one-time passwords, or radio frequency identification (RFIDs). All of these systems operate with similar fundamentals of authentication. Bishop in his book[5] defined authentication as “authentication is the binding of an identity to a subject...”. The authentication process is then a security process that identifies subjects who request access to the secure system, network, or device. The management of access control determines the subject's identity using information that the subject knows (username and password), something that the subject owns (USB, mobile phone, or smart card), or something that qualifies the subject (biometrics such as face, fingerprint), or something that the subject can do(signature, walk)[25]. All this information must be stored and managed in the system. Authentication systems can be modeled as a signal-based model consisting of three components[42]: the human subject, the authentication system, and the reference storage. Components communicate through

certain transmission channels, each with its purpose.<sup>[5]</sup> The visualized model can be seen in Figure 2.1.

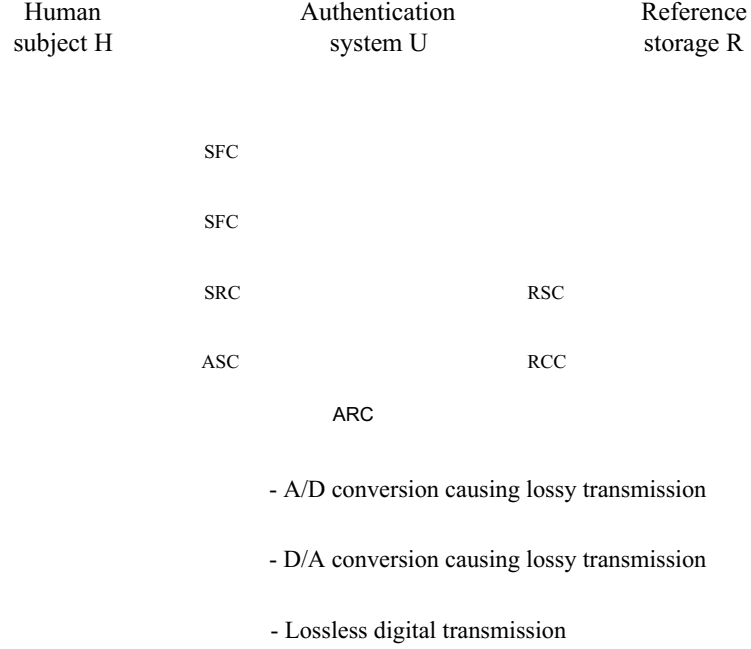


Figure 2.1: Generic signal model for authentication systems.

The human subject or user is the individual trying to access the system by authenticating its identity. To do so, the individual provides the requested authentication information to the authentication system. The authentication system then processes the provided data and, depending on the execution process, the components communicate, exchange information, and transmit data with each other. The model presents all data flow channels between those components needed for classical authentication systems or response-based systems(the user authenticates on a challenge from the system, e.g. biometric authentication). Because the subject's entered data are transferred to the system from the real world, the transmitted information is subject to analog-to-digital or digital-to-analog conversion, and thus loss of information may occur. Communication channels between authentication systems and reference storage are considered to be lossless due to transmitted information being digital. Each of these channels and components may be vulnerable to attacks and therefore their protection is required(as discussed later in section 2.1.6), the role of the channels is described below.

- Authentication submission channel(ASC) - Transmission of the authentication information from human subject to authentication system(use of this channel is mandatory in all authentication cases, for authentication by identification it's even sufficient).
- Synchronization forward channel(SFC) - Transmission of accompanying additional information from authentication system to human subject(required for verification or challenge-response authentication systems).



- Synchronization reverse channel(SRC) - Authentication system requests human subject to provide certain information.
- Reference information control channel(RCC) - Authentication system requests storage for reference information(eg. username and password).
- Request information submission channel(RSC) - The reference storage transmits requested information to authentication system.
- Authentication result channel(ARC)- Delivers the authentication result(eg. user access denied).

### 2.1.3 Structure of biometric system

A Biometric system can be considered as a pattern-matching system that operates by picking up biometric raw data from an individual, extracting distinguishable feature sets from this data, comparing the extracted feature sets against previously-stored feature sets, and providing the result of the comparison to the external application. Conventional biometric systems are described as a model consisting of five modules each executing one of these operations: a sensor module, feature extractor module, matching module, and a template or feature set database [26]. Sometimes, the application module is left out of the models representing the biometric system, but for the sake of showcasing all possible weak points later on, we kept it here. The modules and their communication hierarchy are modeled in a figure 2.2 and their roles are described in the list below [28, 26, 44].

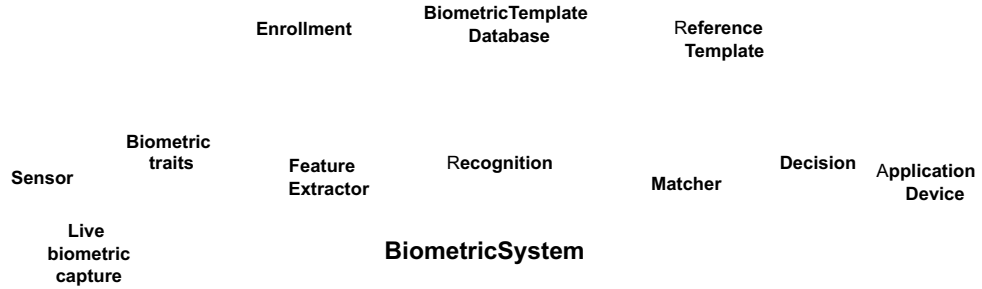


Figure 2.2: Schema of biometric system and it's processes.

1. Sensor module - Processes the raw biometric data of an individual and converts them into digital form (e.g., the image of a fingerprint or face). After the conversion, the acquired data are transmitted to the feature extraction module. The sensor module is the point of human-computer interaction; therefore, it must define a suitable user interface according to the acceptability criteria to lower the failure rate with biometrics collection.
2. Feature extraction module - Within feature extraction, several filters and quality enhancement algorithms preprocess the raw data to simplify extraction. If the received features are of deficient quality, the feature extractor might ask the individual

to use the sensor again. Otherwise, the data are processed to search for compact distinctive characteristic points known as features. These features can be incorporated into templates (that is, features on their own, parameters of a mathematical model characterizing the features [25]). During the identification or verification process, the templates are transmitted to the matching module to complete the recognition. In the case of enrollment, the extracted features are transmitted and stored in the database module.

3. Matching module - The received template is compared with previously stored reference templates, to generate scores that are used for the verification/identification decision. The variance of biometric data requires the execution of “fuzzy comparisons,” by using predefined thresholds determined by score distributions between authentic and artificial subjects. Depending on the execution mode, the matcher either: (1) compares the received features with all the templates stored in the database (identification) to search for an enrollee with the highest score; if the score is below a predefined threshold, the identification failed. (2) compares the received features with the template of the claimant. The predefined threshold is used again to determine the genuineness of the claimed identity. In some articles, this module is separated into matching and decision modules, where the matching module generates scores, and the decision module applies the threshold to determine the authentication outcome.
4. Template database - Also known as data storage, is responsible for saving references to biometric information (i.e. templates, samples, or models) paired with some biographic information (e.g., ID, PIN, or name) about enrollees. Data storage can be centralized (server or a computer).
5. External application - Application (e.g., entrance to secure area, e-Commerce or mobile phone) that is secured by the biometric system.

#### **2.1.4 Biometric traits**

Biometric systems use a variety of inherent physiological or behavioral characteristics such as fingerprints, palm-print hand geometry, veins in hand, gait (gait is a way or style of walking or moving on foot), iris, retina, voice, face, signature, or even keystrokes [11] to perform real-time biometric authentication and identification of an individual [14].

Biometric systems differ in their capabilities, complexity, and performance according to the type of biometric trait used. Some traits are more efficient, some are more reliable than others, but all have to conform to set properties (see the list below). The choice of biometric trait depends on the requirements and criteria of the given application. The main properties of the biometric traits evaluated are [9]:

- Uniqueness: Biometric traits must be different enough to be distinguishable between any individual.
- Permanence: The trait should remain the same despite the influence of other factors, such as aging, etc.
- Collectability: The trait should be able to be captured easily by anyone and anywhere.
- Acceptability: The selected trait should be socially acceptable to capture.

- Convenience: The collection of the trait should be convenient and methodical.
- Exclusivity: The standalone trait should be sufficient for the entire process of identification.
- Cost: The capture, measurement, and evaluation process should be designed in a cost-effective way.

Figure 2.3: Images showcasing physiological and behavioral biometric traits [11].

Biometric systems that use a single biometric trait are called “Unimodal”. Biometric systems could also utilize more biometric traits, these systems are called “Multimodal”, or alternatively “Multibiometric” [11]. To acquire multiple or complementary traits “Multimodal”, systems employ a combination of sensors, algorithms, procedures, and modes simultaneously. Compared to “Unimodal”, the use of “Multimodal”, systems provides increased security. They are less prone to spoofing attacks and offer better reliability and robustness. Capturing two (or more) different biometric traits could cause discomfort, as each needs to be acquired by a different sensor. The usual solution is to pick traits that are in the same body part.

### 2.1.5 Biometric stages

Depending on the context of the system, a biometric system generally runs in two stages of operation: enrollment and recognition. The recognition stage requires a prior enrollment of users to perform their expected execution. Historically, the recognition stage has been classified into two types: identification and verification. The distinction was made according to the mode of execution of the biometric system: it either authenticates claimed

identity(verification); or it identifies individuals without the claimed identity (identification) [44]. Both verification and identification stages can be classified by their outcome as a two-class problem: for verification, the subject gets authenticated by having his claim successfully verified or rejected[17], in identification, the subject's identity gets recognized or classified as unknown to the system. Today, use cases (for example, modern “few-to-many matching,”) and ongoing research of biometric systems have reached the point where the classification of verification/identification is no longer apparent[44].

### Identification

Identification mode tries to establish a person's identity without any entered claim. This is achieved by performing a one-to-many comparison of newly captured data with all previously stored data in the system database. In simple terms, the individual asks the system the question “Who am I?” or “<sup>[16]</sup>Am I already stored in the database?,”[25]. Identification is essential in negative recognition applications, where the system concludes whether the individual is who he denies being. These applications verify the absence of previous enrollment and aim to prevent the use of multiple identities by the same user. Negative recognition systems are limited to biometrics, as there is no other alternative automatic method to verify a claim of unknown identity[26].

### Verification

Verification mode tests the hypothesis that “the submitted traits are from an individual already stored in the system“ and validates a person's identity by doing a one-to-one comparison of newly captured data and claimed identity (e.g., with a PIN, magnetic stripe, user name, or smart card) with a previously stored template in the system database. In basic terms, the individual asks the system the question “Am I the one who I claim to be?,”[25].<sup>[45]</sup> Verification is often used in applications that perform positive recognition, where the aim is to prevent more users from using the same identity. The use of biometrics in positive recognition systems is voluntary, as there are many alternative methods to verify identity claims (e.g., <sup>[45]</sup>simple passwords, PINs, or keys)[26].

### Enrollment

During this procedure, the trait is acquired by the hardware sensors and then transmitted to the feature extraction module, where feature measurements are taken to create a template that is eventually stored in the database. Within enrollment, biometric information of an individual is linked to his identity (e.g., by ID, PIN, or name). In certain applications, the enrollment process may be supervised by a human. For example, a person who registers a new computer account on his biometric-enabled system can enroll his biometrics without any supervision. In another instance, an application where a person needs to use an ATM with biometric authentication will have to go through biometric enrollment in the presence of a bank official[26]. Due to human certification of credentials during enrollment, these applications might additionally store biographic information(such as name, address, phone number, etc.).

### 2.1.6 Biometric system's security

Biometric systems have a great reputation and offer various advantages compared to traditional authentication systems. However, they can still be vulnerable to various attacks. These attacks can be grouped according to their target into four categories: processing and transmission level attacks, input level attacks, back-end attacks, and enrollment attacks[3]. Transmission-level attacks exploit the fact that the transmission of sensitive data in biometric systems is usually done in networks of local or remote machines. The channels connecting the system thus might be intercepted, and the data may be used for various malicious attacks. To prevent data alteration, interception, or leakage in transit, biometric systems adopted security aspects such as data encryption, anti-spoof measures, and appropriate fall-back techniques [3]. In communication channels where transmission is done through wired cables, improving physical connections in the real world increases transmission security. In input-level attacks, the attacker might replace or interfere with hardware or software and gain access to processing modules of the biometric system (for example, implementing spyware). The established measures to prevent such attacks include improving the physical protection of devices, integrating mechanisms to prevent software modification, and intrusion detection methods[21]. Back-end attacks consist of attacks on matching, database, or combination of both modules, targeting modification or replacement of the templates themselves or the authentication decision of the system. Enrollment attacks target the enrollment stage, where the goal is to fool the identity management system of the biometric system by enrolling as someone else with their biometrics or the other way around. The authenticity of the enrollment process should be handled within the organization's procedures. As Figure 2.4 shows, there are generally eight weak points that are vulnerable to attacks [28]. From another point of view, attacks can be classified into two types [28]:

1. direct attacks - referring to attacks that do not require any knowledge of how the authentication system operates internally, they aim at the system interface.
2. indirect attacks - in contrast to direct attacks, here the knowledge of inner operations is required to be successfully performed.

Security vulnerable points

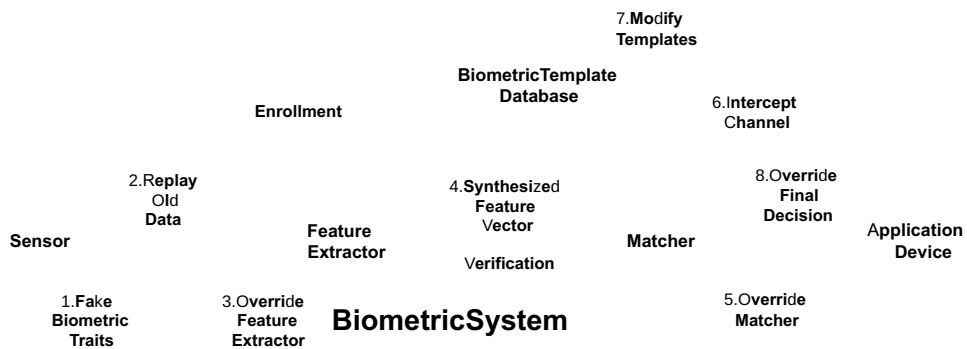


Figure 2.4: Security weak points in biometric system.

1. Type 1 attacks. Usually targets the sensor module and the authentication submission channel. The sensor could be replaced or integrated with an additional sensor controlled by the attacker to forge biometric authentication. Spoofing is the most common attack. Here, the attacker acts as an imposter and presents artificial biometric data to deceive the biometric system. Other known problematic attacks are “Overloading“, “Flooding„ or denial of service(DOS). “Overloading“ is an attempt to circumvent a system by damaging it or overwhelming the sensor to generate errors.
2. Type 2 attacks. Attacks aimed at the channel used for the transmission of raw biometric data to the feature extraction module. This channel can be intercepted and transmitted data could be stored for subsequent replay to bypass the sensor. These attacks are known as replay attacks[15]. In addition to replay attacks, this channel is vulnerable to three other attacks: the eavesdropping attack, the man-in-the-middle attack (MITM), and the brute-force attack.
3. Type 3 attacks. Also known as attacks on the feature extractor. Here, the attacker might gain control over the feature extractor module, and instead of producing legitimate features, it produces chosen features by him. The feature extractor component might as well as the sensor be replaced, resulting in feature processing being done according to the attacker's intentions.
4. Type 4 attacks. Attack on the communication channel between the feature extractor and the matching module is similar to the second type of attack, vulnerable to replay, MITM, eavesdropping, and brute-force attacks. Again, there is a risk that the attacker can replay intercepted data, in this case, feature values of legitimate users.
5. Type 5 attacks. In an attack on the matcher module, the attacker can override the automatic process of generating valid match scores and exchange them with an artificial score chosen by the attacker, ignoring the data received from the feature extractor. The hill climb attack is also one of the potential threats; it is a form of brute-force attack, and in this case the attack is carried out by iterative submission of synthetic features until a successful match is achieved[32]. Component replacement is again a vulnerable possibility.
6. Type 6 attacks. Attack aiming at intercepting the communication channel between the template database and the matcher. The attacker might manipulate, steal, or replace the transmitted data(again threats of MITM, replay and eaves-dropping attacks).
7. Type 7 attacks. Attack on the template database is the most apparent type of back-end attack. The main threat posed by this attack comes from possible modifications, enrollments, or replacements of templates in the database. The attacker may become registered in the system by injecting his templates into the database, or he may hijack the identity of an appropriately enrolled user by replacing the original template with their own.
8. Type 8 attacks. Attacks the biometric system's result channel to the external application. Regardless of the information exchanged and the operations performed on the components of the system, the attacker may have complete control over the authentication result.

Major vulnerability that is important to consider is caused by the disadvantage of biometric traits that cannot be easily revoked when compromised. Compromised biometric traits might be used in different applications or systems. There are only one biometric traits and unlike passwords, you cannot ask for a change of biometrics.

### 2.1.7 Countermeasures to prevent attacks

As can be seen in Section 2.1.6, most threats in biometric systems are directed at the biometric templates themselves. They must be secured accordingly, so all biometric systems must incorporate techniques for the protection of the biometric template.

Currently, the most widespread biometric template protection techniques are using schemes such as liveness detection, fake finger detection, biometric cryptosystems(also known as helper data-based schemes) and data authentication methods(such as digital watermarking, fingerprint embedding in images), or cancellable biometrics [28]. All of these techniques must find an acceptable trade-off among three template protection requirements [27].

1. Noninvertibility - It must be difficult to reverse engineer the biometric features of the stored template.
2. Discriminability - The technique should not harm the authentication accuracy of the biometric system.
3. Revocability - It should be possible to create multiple templates of the same biometric features without the possibility of linking them together.

#### Liveness detection

Liveness detection is any technique that can distinguish between the input of an artificial biometric sample and the input of a biometric sample from a real human being. It accomplishes this by measuring life signs such as sweat glands, pulses, or blood pressure. This technique is practical because of its ability to prevent some of the presentation attacks(attacks on the sensor).

#### Biometric cryptosystems

Biometric cryptosystems(BSC) make use of digital keys generated from biometrics or use digital keys bound with biometrics. These digital keys are used for an indirect biometric comparison of subject authorization. Since the comparison is carried out in the encrypted domain, BSCs are used as a means of protecting biometric templates. Based on the way helper data are obtained, BSCs can be divided into key-generating and key-binding schemes [38]<sup>[46]</sup>. In the key-generating scheme, the helper data is acquired from the biometric template only and then used to generate keys. In contrast to the key-binding scheme, where the keys are selected and bound to the biometric template and eventually stored in the system as helper data.

#### Watermarking

Watermarking techniques make use of watermarks, which are additional invisible information embedded in the structure of the image by some strong and appropriate algorithm

[33]. This information should be robust enough for various signal processing operations and should be easily recoverable by other software programs.<sup>[47]</sup> The use of watermarks in biometric systems improves their security and reliability and plays a key role in the authentication of ownership claims. The attacker may acquire or dismantle the secret information only if he knows which watermarking algorithm was used. Watermarks are used to prove the ownership of the watermarked data. It prevents attacks on channels between the sensor module and the feature extractor and between the matching module and the external application (weak points 2,8 in Figure 2.4) [28]. Additionally, these data do not require any additional storage, as watermarked data are already integrated into the host data.

## 2.2 Decentralized systems and blockchain

Decentralized systems are defined as a variation of a distributed system in which multiple authorities control different components and no single authority is fully trusted by all others[39]. Due to the close relationship between decentralized and distributed systems, misinterpretations are common and often cause confusion. Decentralized and centralized systems are a subset of distributed systems; the distinction between them was established by the way decisions are made in the system and by the way the system shares data through the nodes. In the decentralized system, there is no single controlling entity where the decision is made. On the contrary in the centralized version, the system's orchestration is done by a central trusted authority(see visualization in Figure 2.5).

Centralized                      Decentralized                      Distributed

Figure 2.5: Overview of distributed network architectures.

Figure 2.5 visualizes the differences between the network architectures. In a centralized system, there is a single node(red color) with authority connected with all the other nodes(blue nodes). In decentralized systems, there is no single authoritative node. In distributed systems, each node in the system can be interconnected. The blockchain network is designed to be decentralized, as it is not maintained by a single controlling entity, but rather by a group of peers.

### 2.2.1 Blockchain

Blockchain is a distributed ledger or linked data structure replicated and distributed over a peer-to-peer network connected in a private, secure, and independent manner [23].<sup>[1]</sup> The block structure consists of two parts:<sup>[6]</sup> the block header and the block itself. The block contains ordered data, called transactions, placed into time-stamped blocks by achieving distributed consensus of the participants in the system. Each participating peer on the



network validates transactions and keeps a copy of the blockchain. Consensus is an algorithm or mechanism that governs the behavior of the distributed system to remain correct. Bitcoin's "Proof of Work,"(PoW) protocol is among the most popular, where nodes follow an algorithm that uses computation power to calculate the hash value of a newly composed block until a target value is reached; then the whole network can verify the block and reach an agreement.<sup>[50]</sup> Other examples of consensus mechanisms are Proof of Stake(PoS), Proof of Authority(PoA), Proof of Elapsed Time(PoET), etc. [6]. Transaction records can be of various types: currency transactions, health data, system logs, or traffic information [10].

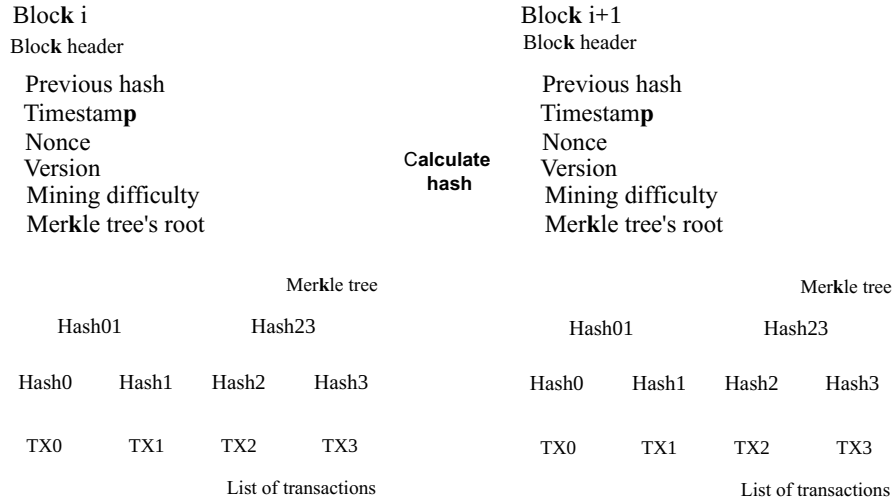


Figure 2.6: Block structure in “Proof of work” blockchains.

<sup>[6]</sup> A list of transactions stored in the blocks is bundled together and each is stored as a hash. The block header is made public and accessible to anyone. In blockchains with a proof of work, the consensus mechanism block header contains two sets of metadata(see Figure 2.6). One is associated with mining and is composed of timestamps, mining difficulty target, and “nonce.”<sup>[1]</sup> The second, associated with the block itself, consists of the hash of the previous block, the current version, and the Merkle tree root[23].<sup>[1]</sup> Merkle tree is a tree of hash values of transactions(Merkle tree leaves), and the leaves are linked into a tree structure by recursive calculation of hashes of two adjacent transactions stored in the block until there is only one left(Merkle tree root).<sup>[1]</sup> Each block in the chronological chain references the prior block by its cryptographic hash and every block validates transactions up to the present moment, so if the previous block is modified or not validated, any new block proposed to the existing chain gets rejected[23]. This is the key factor in achieving the immutability and permanency of blockchains, which ensures the authenticity of data on the network and is one of the strongest characteristics of blockchain technologies.<sup>[1]</sup> This means that modification of the data by an individual is very difficult;<sup>[2]</sup> one would have to corrupt the majority of the nodes in the network to do so(e.g., in Bitcoin an individual would have to control 51% of the computational power[12]). The blockchain network can be configured according to the use case and expected requirements in four categories [22]: public blockchains, private blockchains, consortium blockchains, and hybrid blockchains.

## Public blockchains

Most popular cryptocurrencies, including Bitcoin and Ethereum, are public blockchains.<sup>[35]</sup> Sometimes they are referred to as “Permissionless blockchains” since anyone without permission can access the blockchain network and become an authorized peer, trade monetary value, participate in consensus and “write” to the shared state by invoking new transactions[6]. Therefore, a user or node can view all current or past records, examine executed computations, verify transactions, and participate in finding consensus among peers for the new incoming block.<sup>[6]</sup> As a result, the blockchain is a self-governed network. To encourage peers to join and participate, these networks operate an incentive scheme that rewards them in return.

## Private blockchain

Some organizations may not be interested in sharing their confidential information (for example, sensitive records in private blockchain healthcare applications[2]) with anyone on the Internet, but at the same time they still want to collaborate and share data. They are controlled by a single authority, so they are also referred to as “permissioned blockchains,” since in this type of blockchain network only a limited amount of peers can participate and be authorized. This way the information transmitted through the private blockchain stays within the network. Private blockchains are more centralized due to the limited group of participants.<sup>[7]</sup> They are usually used in applications where users must be fully identified and trusted. Examples of such a blockchain are Ripple (XRP) and Hyperledger[6].

## Consortium blockchain

Consortium blockchains are sometimes considered as an intermediate access control architecture between private and public blockchains. They are similar to the previous type of “permissioned blockchains”, still relatively private with semi-decentralized architectures. But compared to private blockchains, the difference is that now there is a consortium of authoritative individuals(organizations) instead of one authority.<sup>[7]</sup> The usual elements of their application are businesses and financial scenarios with a limited number of participants. Examples of such blockchains are Tendermint, Quorum, and Multichain[6].

## <sup>[20]</sup>Hybrid blockchain

Hybrid blockchains are a unique type of blockchain that combines the best parts of both private and public blockchain architectures. The right combination of private and public blockchain protocol can optimize system throughput, latency, and scalability [46]. They are flexible, as they allow users to decide which information remains private and which information is made public. Compared to private blockchains, they are also not accessible to everyone, but features such as integrity, transparency, and increased security still remain.

### 2.2.2<sup>[7]</sup> Smart contracts

The smart contract is essentially a piece of code written in Turing-complete language that runs in a secure environment(blockchain) that controls digital assets[12]. Many public blockchains support smart contracts, but the most widely used framework is Ethereum. Ethereum offers the possibility of writing your own smart contracts with its own high-level programming language. By sending transactions to the Ethereum network, users can create

new contracts, request the execution of a certain function in a contract, or transfer digital assets(Eth) to other users or to other contracts. To guarantee the correct execution of smart contracts, each transaction is processed and resolved by the large pool of nodes running the “Proof of Work,, consensus [6]. To send a transaction, the user must pay execution fees, which are paid to the nodes that run the consensus as an incentive to remain honest<sup>[78]</sup>. This is one of the drawbacks of the Ethereum blockchain that its users must count on.

### 2.2.3<sup>[2]</sup> Practical byzantine fault tolerance

Practical byzantine fault tolerance(PBFT) is a consensus algorithm that was developed to withstand Byzantine nodes (this comes from a family of Byzantine fault-tolerant protocols(BFT)) in a distributed network to ensure its integrity [47]. All nodes must communicate and exchange messages until a two-thirds majority of votes is received, then the next block may be added. PBFT is a state machine replication algorithm that allows for the replication of complex operations over a network of clients with incorporated defense mechanisms against Byzantine faulty clients. The algorithm expects minimal participation of the  $n$  nodes of Equation 2.1<sup>[16]</sup>, where  $f$  is the number of fault nodes, and  $n$  is the number of all nodes in the network<sup>[8]</sup>. Based on this equation, we can also derive the equation for the fault tolerance  $f$  of the PBFT algorithm for the number of nodes  $n$  (see Equation 2.2).

$$f = \frac{n - 1}{3} \quad (2.1)^{[8]}$$

$$n = 3f + 1 \quad (2.2)^{[0]}$$

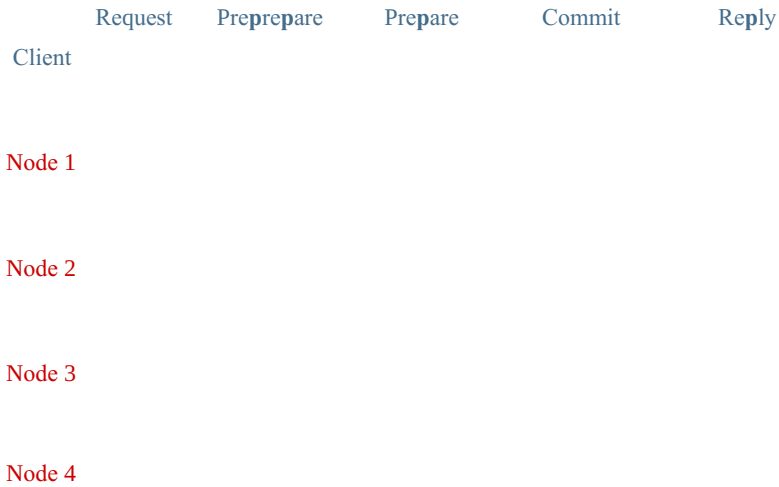


Figure 2.7:<sup>[0]</sup> Practical byzantine fault tolerance architecture.

<sup>[2]</sup> PBFT's three-phase protocol consists of three phases: preprepare, prepare, and commit to [7]. Phases are needed to order requests sent in the same view or across views, even when the primary node is faulty. The protocol between four nodes with one of them faulty is described in Figure 3.5. There are many alterations to this protocol that are being developed. Each is trying to optimize the original protocol in some aspects; for example, some works are focused

on structural optimizations that may introduce a hierarchical structure to the network [19]. Others are trying to simplify the overall process, for example, a work that incorporates reputation into the voting mechanism promises to reduce communication time, increase transaction throughput, and improve system efficiency and security [8].

## Chapter 3

# Design

This chapter first analyzes existing consensus protocols and provides an overview of existing blockchain solutions for the security of biometric systems and explains the essential design principles of biometrics and blockchain. Subsequently, it describes the security of communication between nodes in the system. Finally, it introduces the proposed proof-of-concept design of our solution and demonstrates its functionality by describing scenarios of established biometric processes in our system.

### 3.1<sup>[6]</sup> Consensus mechanism

The selection of the consensus mechanism depends on the type of blockchain used. As stated in Section 2.2.1<sup>[65]</sup> above, there are four types of blockchain, each with its advantages and disadvantages. We needed to select one of them that best fits our proposed system. Table 3.1 presents the categorization considered for our chosen consensus mechanism.

Table 3.1: Blockchain technology taxonomy [13].

#### 3.1.1 Private vs public blockchain

The first criterion that we must take into account is the privacy and accessibility of the system. We either might have the system publicly available for reading to anyone with Internet access by using the public blockchain, or we want to preserve the data by restricting access with the use of a private blockchain.<sup>[16]</sup> We assume that the proposed system will be used within a single organization that demands private storage of their data, so the use of a private type of blockchain seems more fitting. By choosing a private blockchain, we also avoid the fees associated with the private blockchains (e.g., paying the gas fee for Ethereum transactions or execution of smart contracts). But we lose on the higher level of security associated with public blockchains because, for example, the consensus that uses the

mining process is much more robust against collusion attacks [13]. Another criterion is the processing capacity and scalability. Private blockchains are typically much faster to process a transaction than public blockchains. For example, Ethereum can process only a dozen transactions per second compared to PBFT, where transactions have very high throughput and low latency. It is a great advantage of private blockchains, as the waiting time for transaction processing, for example, in Ethereum, is usually in the range of minutes [6]. This is a key factor for instant request-response-based systems, such as biometrics systems. Scalability is equally important. In public blockchains, all nodes must keep a copy of the blockchain. With each added block, the size of the blockchain increases (the size of the Ethereum and Bitcoin blockchains is hundreds of gigabytes [13]), which can be a problem for a variety of applications. From these criteria, we chose to design our system based on a private blockchain. Our system also assumes that the participating nodes are the terminals of the biometric system. Therefore, every new terminal added must be controlled, trusted, and identified. Thus, we examine consensus protocols that utilize “permissioned” access control.

### 3.1.2 Private blockchain protocols

Among the most prominent candidates for such protocols are Clique, Aura, PBFT, or its modifications (e.g., IPBFT [8], weighted PBFT [18]). All of these protocols are from a family of BFT protocols, which means that all of them can withstand subverted and faulty nodes. By choosing a protocol that tolerates subverted nodes, the proposed system addresses the single point of failure. In a recently published study [4], these protocols were qualitatively compared applying the CAP theorem (in the distributed system only two of consistency, availability, and partition tolerance can be ensured at the same time), with results showing that the PBFT protocol maintains the blockchain consistent compared to Clique and Aura, where consistency was given up for availability. This means that PBFT makes it a priority to maintain the integrity of transactions. This is a desired characteristic for our use case, where the order of the transactions determines if the user will get authenticated or not. PBFT is known for its high reliability, security, high throughput, and low latency [19]. Furthermore, it is feasible to implement the PBFT-based system from scratch. It comes at a cost of PBFT performing and scaling slightly worse than its Clique and Aura counterparts, caused by its high communication overhead [4]. These drawbacks may be solved by using some alterations that improved, modified, and optimized some of these shortcomings. In our proposed system, we chose to work around PBFT due to the characteristics mentioned above and due to the possible future development allowed by extensive research on PBFT modifications aimed at optimization or extension of the system. Inspired by the work of blockchain-based data transmission control in tactical data link [18], we modified the classical PBFT, where each of the nodes is treated equally by the introduction of weights into the system that allows the customizability of trust in certain nodes.

## <sup>[8]</sup> 3.2 Weighted PBFT

Modifying PBFT protocol with weights allows custom weight specification of the nodes in the system according to the probability that the node is compromised or defective. In practice, a biometric terminal close to the entrance of the building with access control and without many security mechanisms in place (e.g. camera, proper lightning, or security guard

checks) would have a much higher probability of being attacked and compromised than a terminal in the center of the building with proper security mechanisms. Thus, the vote from the less secure terminal should have lower “weight,” than the vote from the properly secured terminal. The details and phases of the weighted PBFT protocol are described below.

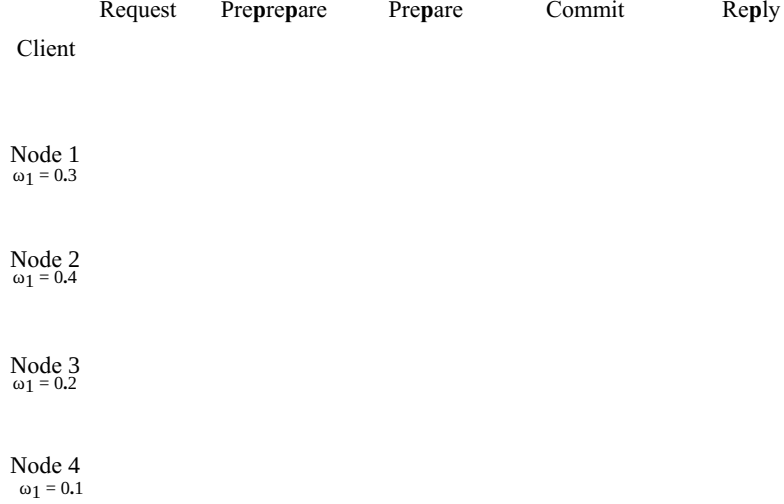


Figure 3.1: Weighted PBFT communication.

1. Setup: <sup>[60]</sup> Here establishment of all parameters in the system is performed, every node in the system generates its public/private key pair and gets its weight specified by the central authority in a way that corresponds to Figure 3.1. Initially, the node with the highest weight is chosen as the primary node (see Node1 in Figure 3.1).

$$\sum_{i=0}^N \omega_i = 1 \quad (3.1)$$

Figure 3.2: Sum of all the weights  $\omega$  in of  $N$  nodes equals to one.

2. Request: When node requests a block proposal or transaction validation, it first generates a signed request message that is transmitted to all consensus nodes. All nodes verify the signatures of that message and store it in their log. When the current primary node receives and verifies the request, it will also transmit a Preprepare message to all the nodes. The Preprepare message contains a hash value of the initial request and other values (view, sequence number) associated with the vote for a new primary node.
3. Preprepare: Message and the validity of the sender node are verified, and the existence of the received hash value of the initial request is checked in the log. If everything is as expected, the Prepare message is broadcasted.

4. Prepare: Same process of conducting the verification of each message as previously is performed again. Subsequently, the node in the Prepare phase waits for the Prepare messages received from the other nodes. <sup>[26]</sup> For each node sender of the received Prepare message, the node makes a request to the central authority that regulates the weights of the nodes. To broadcast the Commit message and enter the Prepared phase, the node waits until a sufficient number of Prepare messages are received. The sufficient requirement is that the weights of the received Prepare messages are in accordance with Figure 3.2.

$$\sum_{j=0}^N \omega_{m_j} \geq \frac{2}{3} \quad (3.2)$$

Figure 3.3: Sum of the message's weights  $\omega_m$  in network must be more than  $\frac{2}{3}$ .

5. Commit: Verification of the message and sender is executed again. The node waits and collects the Commit message until the sufficient weight according to Figure 3.2 is reached. After reaching the Committed phase, the node is prepared to execute the requested operation(block proposal or transaction validation) from the locally stored data. Subsequently, the operation is executed, a Reply message containing the result of the operation is constructed and transmitted to the current primary node. In case the node does not reach the sufficient weight in a certain timeout, the node does not transmit the Reply message.
6. Reply: Here primary node collects all the Reply messages and waits until the weight threshold from Figure 3.2 is reached again. When the primary node has enough Reply messages, according to the agreement of the result, the operation is performed globally (e.g. storing template in database or adding block to the blockchain).

### 3.3 Biometrics on blockchain

Blockchain offers characteristics such as immutability, auditability, availability, or universal access. These characteristics are desirable for biometric systems. Blockchain technologies require the distribution of data among peers participating in the network to achieve consensus. <sup>[12]</sup> As a result of this single fact, it is important to follow the design convention when it comes to applying biometrics to the blockchain: "Biometrics, in its raw or derived form(templates), should never be stored(plain or encrypted) on a public distributed ledger system(such is blockchain)."[20]. According to European regulations, it is even prohibited to store raw biometric data centrally (Regulation (EU) 2016/679[16]), so distribution in the network is entirely out of the question. Encryption of stored templates is not the solution to this problem. There are no guarantees of safety and privacy for such data in the future(for instance, due to rapid ongoing development of quantum computing).

Some works solved this with a segmentation mechanism that splits the templates into fragments, independently managed by each client. During authentication, this system runs a smart contract on a permissioned blockchain to find clients who manage the requested fragments[31]. Others applied distributed identifiers or keys that are stored on a blockchain and also linked to a biometric template stored in the database [20]. Person biometrics



remain privately stored in the secure database, and the identifier/key is universally discoverable and reachable for biometric authentication.

Since our work aims to secure the operation of certain components, resolving the issue with direct storage of biometrics on the blockchain through fragmentation could be excessive. The choice of identifier/key and biometric template pairs is more fitting.

### 3.4 Securing the transmission

Since the biometric data transmitted on the network is sensitive, it is necessary to encrypt them prior to transmission.<sup>[86]</sup> The solution for this problem is to use hybrid cryptography. It combines the convenience of asymmetric cryptography, where it is not required to share the same secret(key) in order to communicate securely, with symmetric cryptography, which is much more efficient in its computations. Many applications are avoiding asymmetric cryptography, as its application on long messages causes high costs.

### 3.5 Description of the proposed system

With the use of the weighted PBFT protocol, the proposed system incorporates a biometric system with blockchain technology while performing biometric authentication operations. This incorporation extends the security mechanisms of classical biometric systems to make them more resilient against known issues such as a single point of failure, the unreliability of the authentication process, and channel vulnerabilities against interceptions. Additionally, weights in the PBFT protocol allow for a custom distribution of voting power between nodes based on the security confidence of the given node.<sup>[27]</sup> Organizations that will potentially apply the proposed system can customize it according to their needs and the security analysis of the environment in which the biometric system will be deployed.

<sup>[22]</sup> The goal of our design of the decentralized biometric system is to ensure that the matching and feature extraction components are not executed on their own. Using the blockchain as an interface for the transmission of operational data, secure the communication “channels,” connected with those components as well. Figure 3.4 presents a partial graphic representation of our proposed system, where the integration of the blockchain is shown only with the matching component. The red dots show the traditional weak points from the previous sections and the green dots show the weak points that are tackled with our design. The decentralized manner of execution of the matching operation secures weak point number five. The blockchain can also be used to inspect operations performed in the decentralized biometric system as a way to verify the final decision received in the external application, thus securing the weak point number eight as well. With similar principles, our design is also used to secure the feature extraction component.

Every process is identified with a universal unique identifier (UUID) [30], which is used to link the partial operations that make up the process.<sup>[40]</sup> Since the results and metadata of the partial operations are stored on the blockchain in the form of transactions, this identifier enables the possibility to search for each operation that constitutes the given process. For example, to examine a failed process, you can search for a given process UUID to see which of the particular operations has malfunctioned or got overridden. In our design, the template database remains centralized, where each template is paired with a key of a given user that is used as an identifier in the blockchain domain to meet the privacy requirements of sensitive biometric data. Each node keeps the received requests with the data in their

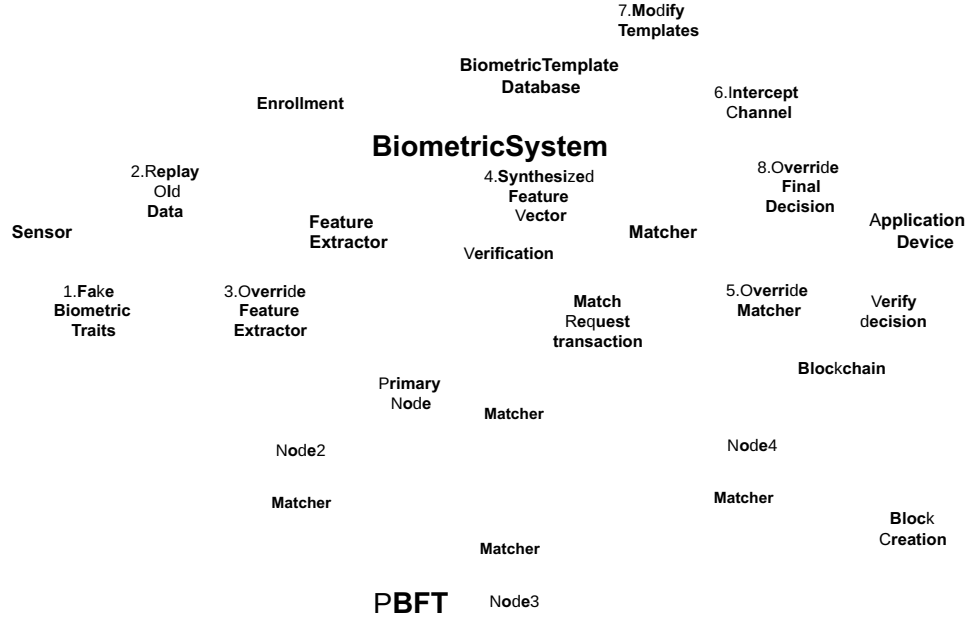


Figure 3.4: Incorporation of blockchain to biometrics in Matching component.

<sup>[58]</sup> logs, to be able to serve more requests at the same time. After a certain time period passes, the given log is deleted.

### 3.6 Scenarios of system's operation

As previously mentioned in Section 2.1 the classical biometric systems usually perform enrollment, identification, and verification processes. Their execution and the components responsible for their orchestration in a classical biometric system were described in 2.1.3. <sup>[39]</sup> For a better understanding of the inner functioning of the proposed system compared to the conventional biometric system, we describe our methodology behind each of these processes.

#### 3.6.1 Enrollment

During enrollment the key objective is to register a new template record in the database. For this process, the participation of the sensor and the feature extractor is required. At the initial point of authentication, the sensor module operates in a standard way, collecting the raw biometric data in a single terminal/node of the biometric system and converts and transmits it to the feature extraction module. After receiving the digital biometric data, the feature extractor processes the data to form them into a template.

The security of feature extraction is already included in our proposed system design. Its execution may end in success or failure. Therefore, the template is not stored in the template database, or the user is not asked to repeat the biometrics collection immediately, as would be the case in the classical biometric system. Both outcomes will be validated first in the distributed network of authorized nodes. After feature extraction's classical operation, two data collections are assembled: the operational data(transaction) about the

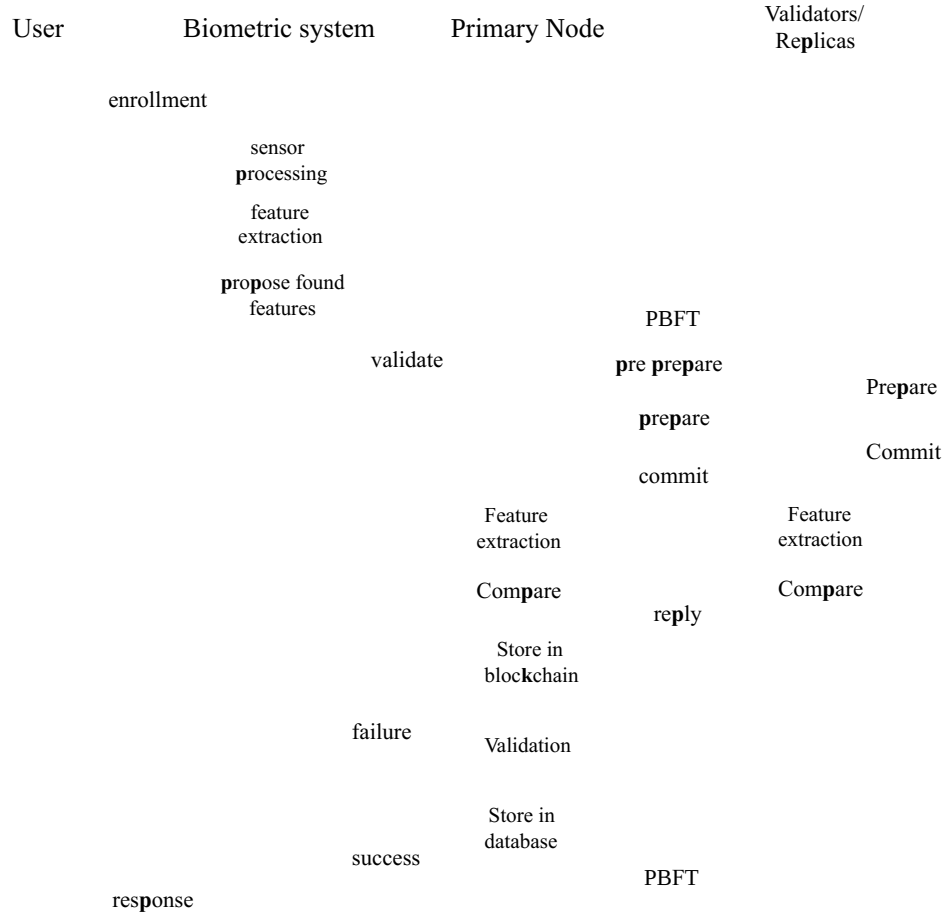


Figure 3.5: Communication in process of feature extraction during enrollment.

feature extraction (outcome, timestamps, etc.), and the sensitive data (biometrics and the extracted template)<sup>[21]</sup>. The node requests validation of its feature extraction and broadcasts a message with the beforementioned data collections over encrypted channels to other nodes in the network. All receiving nodes verify this message and store the data in their log. When the primary node in the PBFT protocol receives the request message, it starts a new round of the PBFT protocol.<sup>[1]</sup> Here, the nodes exchange messages and verify the operation by executing it with the request data in their log and comparing it with the data stored inside the transaction. The result of the comparison is then transmitted to the primary node. After the primary node receives enough replies, and in case of a positive result validation, it stores the template paired with the user identifier from transaction in the database and the transaction into local queue.<sup>[6]</sup> Furthermore, if the transactions in the

queue reach a threshold or timeout, the primary node proposes a new block containing the transactions that will be added to the blockchain and must be agreed upon by the network, according to the PBFT protocol.<sup>[6]</sup> When the block is proposed and added to the blockchain, all transactions contained in this block are deleted from the log.

### 3.6.2 Identification and Verification

In this two scenarios, additionally to the feature extraction, it is required to perform a comparison with the templates stored in the template database. The feature extraction is performed as in the enrollment scenario. After receiving the template from feature extraction, the blockchain is searched for the transaction of current identification/verification process, and the result is inspected. If the feature extraction operation was successful, matching can be performed. The matching of the templates is executed and the data split into two collections again, with the exception that sensitive data now hold only compared template and the operational data in addition contain user identifier that corresponds to the matched template. The node assesses the blockchain to determine whether the feature extraction was previously successfully performed. If the assessment was positive, the node requests validation of the performed matching over encrypted channels to other nodes, where the matching is performed and validated. Each node first examines the blockchain for a successful prerequisite feature extraction and performs the matching. In case of positive matching of the templates, the identifier of the matched user is compared with the identifier received in the transaction identifier. The result is transmitted again to the primary node. In case of enough positive validation responses, the user is successfully identified/verified. The transaction for matching validation request is stored again in queue and waits for the block proposal.

## Chapter 4

# Implementation

This chapter describes the details of the implementation of the demonstrator program, shows its representative architecture, and describes the role of each module (see Figure 4.1). All modules of the program are implemented in Python language and are documented dynamically by the Sphinx library, which generates webpages from annotated comments of given classes, functions, or variables. This choice of technologies allows for ease of implementation for the proof-of-concept demonstrator of messages in the proposed system. All modules are written from scratch, using only publicly available standard, cryptographic, or asynchronous libraries. For ease of use and to guarantee correct versions of the libraries, the program was developed using a virtual environment and all required libraries are specified in `requirements.txt`.

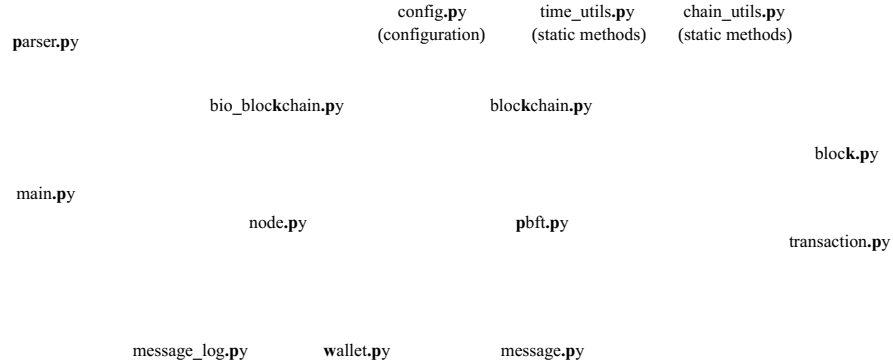


Figure 4.1: Dependency architecture of the demonstrator proof-of-concept program.

### 4.1 Main module

The `main.py` module orchestrates the execution of the demonstration scenarios in the bioblockchain program. Firstly, it instantiates the Parser class that processes the passed arguments and on their basis determines the execution scenario of the simulator to be demonstrated. Within the demonstration program, we implemented five scenarios. Each can be invoked by its corresponding argument. Additionally, the demonstrator program supports a verbose mode that gives more information about the communication and the

data stored in the system. Arguments from given scenarios are not combinable. Only combinations of verbose mode and a certain scenario are allowed. Without specifying the arguments, the program's default phase of operation is the successful enrollment of a new user and his subsequent verification and identification. The list of all supported arguments is as follows.

- **Help(-h)** - Provides information on the options to run the demonstrator program.
- **Verbose(-v)** - Provides extended information on network communication and makes it possible to view the contents of the blockchain or the template database after running a certain scenario.
- **Unknown individual verification(-uiv)** - Demonstrates a scenario in which an unknown individual claims to be verified as someone known to the system.
- **Unknown individual identification(-uii)** - Demonstrates a scenario of identification of an individual who is unknown to the system.
- **Feature extraction malfunctioned(-fem)** - Demonstrates a scenario in which feature extraction was compromised by an adversary who modified the extracted template in a way he has chosen.
- [ 1 9 ] ▶ • **Node malfunction returns always true(-nmat)** - Demonstrates a scenario in which one of the nodes in the network is compromised or malfunctioning and always returns a positive response to the request.
- [ 1 1 ] ▶ • **Node malfunction return always false(-nmaf)** - Opposite scenario to the previous, now one of the nodes in the network is compromised or malfunctioned and always returns a negative response.
- **Feature extraction and matcher channel interception( -femi)** - In this scenario the attacker intercepted the channel between the matcher and the feature extraction module, and attempted to replay the captured data of the legitimate user to the matcher module, with the goal of authenticating himself.

## 4.2 Biometric system's operation

It is handled with the BioBlockchain and Node modules. The module **Node** represents a single terminal/node in the system and contains methods that simulate the operation of standard modules in the biometric system 2.1.3. The BioBlockchain is a container or interface of the proposed system. It contains a list of all nodes participating in the network, its primary template database, and the blockchain.

According to the scenario specified in the main module, the corresponding calls are made to the class methods of BioBlockchain.<sup>[0]</sup> At first, a node in the network is randomly selected using the `get_random_node` method. This node represents a single terminal that was approached to perform biometric authentication / enrollment as described in Section 2.1. In addition to that, the BioBlockchain class implements two methods, each simulating a standard biometric process of:

- Enrollment (`run_enrollment`) - manages the standard operation of the enrollment process in the proposed system. It starts by identifying the process with UUID, retrieved from the static method `ChainUtils.id` with the use of the `uuid` standard

library. Then the acquisition of biometrics through the sensor is simulated using the `get_sensor_data` method of the randomly selected terminal/node. For the purposes of the demonstrator, the biometric collection is simplified to the generation of hashes with MD5 from `hashlib`. The hash is returned and passed to `feature_extractor`. Here, extraction is performed with the MD5 hashing function in a similar way as before. <sup>[22]</sup> In this way, the same hash("template"<sup>[46]</sup>) is generated from the same input("biometrics,"<sup>[0]</sup>), thus it is possible to simulate successful feature extraction. Afterward, the method creates two data dictionaries: sensitive data with biometric data paired with the extracted template and operational data. The contents of the operational data are shown in the list 4.1. In addition to basic information on the execution of the feature extraction and the outcome, the operational data dictionary also contains the identifier of a "user" who is enrolled. These dictionaries are passed to the `validate_decision` method of the `pbft.py` module, where the data will be evaluated in the distributed network of nodes and eventually the operational data will be stored on the blockchain. In case of successful validation, the extracted template will be stored in the template database as a pair of user's identifier and the extracted template.

```
"data": {
    "approached_node": "NODE2",
    "match_timestamp": "12.07.1999",
    "operation": "Feature Extraction",
    "process_id": "ef41d358-0617-11ed-a56b-8c85906ae247",
    "process_type": "enrollment",
    "success": true,
    "user": "6c18ffb87da096bb36fb5b58450e0efa33e0b49e9e0d552f0bad"
},
```

Listing 4.1: Transaction data of feature extraction in enrollment.

**Authentication (`run_authentication`)** - This method simulates both identification and verification depending on the passed `process` argument. For verification, it is also required to pass an argument with `claimed_identity`. The initial phase of the authentication process(feature extraction) remains the same as in enrollment. After the network in the PBFT module reaches consensus and stores the result of the feature extraction operation on the blockchain, the data matching can be performed with the node's `matcher` method. Here, depending on the type of process, the extracted template is compared with every template stored in the database (identification) with the `features_in_database` method, or only compared to the claimed identity (verification) with the `claimed_identity_in_database` method. The result of this comparison is the user identifier or `None`. Here again, all operational data is saved in a dictionary shown in Listing . The template and operational data are then passed to `validate_decision`, where the matching result will be evaluated and the operational data will be stored on the blockchain.

```

    "data": {
        "approached_node": "NODE2",
        "match_timestamp": "12.07.1999",
        "operation": "Matching",
        "process_id": "295cee12-068e-11ed-82c8-8c85906ae247",
        "process_type": "identification",
        "score": 87,
        "success": true,
        "user": "6c18ffb87da096bb36fb5b58450e0efa33e0b49e9e0d552f0bad"
    },

```

Listing 4.2: Transaction data of feature extraction in enrollment.

## 4.3 Cryptographic operations

Cryptographic functionalities are implemented with the easy-to-use Python library `ecdsa` that supports the creation of key pairs (signing / private key and verifying / public key) and with the Python standard library `hashlib` that provides a common interface to many different secure hash and message digest algorithms. All cryptographic operations are implemented statically in the `ChainUtils` module. The proof-of-concept program does not contain an implementation of hybrid cryptography that is part of our design, all the exchanged messages are encrypted only with use of asymmetric cryptography.

### 4.3.1 Wallet

This module is the foundation for most of the cryptographic mechanisms implemented in the program. It contains two parameters that store the public and/or private keys of some entity in the system (the nodes participating in the network or enrolled users in the biometric system). The private key / signing is acquired from a static function `generate_key_from_seed` that takes a certain `seed` as argument. The seed is needed to generate a secret exponent `secexp` by calling a `randrange_from_seed_tryagain` method with two arguments: the seed and the NIST256p curve used to generate the secret exponent. Subsequently, the secret exponent is used to instantiate a `SigningKey` class by invoking the method `from_secret_exponent`. The `SigningKey` class then allows the creation of the associated `VerifyingKey` that is used to verify the signatures made by the `SigningKey`. Data signing is performed in `ChainUtils.sign`. To sign the data we need its digital hash digest representation. The hash digests are calculated in `ChainUtils.hash` with the `sha256` method from `hashlib`. The data signature is then obtained with the `SigningKeys` method `sign_digest_deterministic`. Verification of signatures is done using the static method `ChainUtils.verify_signature`. This method takes two arguments: signed data, signature, and verifying key. The signed data must first be converted to the `bytes` data type. Subsequently, the previously created `VerifyingKey` provides a method for verifying the signature of the given data.

### 4.3.2 Blockchain and transactions

The `Blockchain` class has a list of blocks and provides methods for the creation, verification, and addition of blocks to the blockchain. Since blocks are cryptographically bound



together, the blockchain is initialized with the genesis block.<sup>[13]</sup> The `Block` class represents a single block on the blockchain, each having its own hash value, hash of the previous block, the proposer's public key, signature, data/transactions payload, and other accompanying information (see Listing 4.3). All cryptographic operations are implemented using methods previously described in Section 4.3, and timestamps are acquired with the library `datetime`.

```

- - - - - Block - - - - -
Timestamp : 18/06/2022 16:16:18
Last Hash : dda9024382573e0a13da84e1e2f3ab7d5a614296ad3edeb79b2a4c366abe
Hash : f513c5701029be442c24035b9c210a2d594f5ee245d4ee7c98902a76ca05
Data : "Genesis"
Proposer : 54bffd9ef9cf0a1a7d013b476c558e466cc73cc
Signature : 0a473767eea58c61b0e4e66969c26b9e8068b7d3fe141
Sequence No : 1
- - - - -

- - - - - Block - - - - -
Timestamp : 18/06/2022 16:16:18
Last Hash : f513c5701029be442c24035b9c210a2d594f5ee245d4ee7c98902a76ca05
Hash : 27176b5db0c16c9acc0f177592ca0fc664a9f19a0d7a9e70d906a5cbc45d
Data : Transactions
Proposer : 54bffd9ef9cf0a1a7d013b476c558e466cc73cc
Signature : a45c55478caa1d993848d48d85d85a66b34e8d9e944bb
Sequence No : 2
- - - - -

```

Listing 4.3: Two blocks chained together to form blockchain.

Each transaction in the system is represented by the `Transaction` class. Transactions have parameters and methods similar to those of the `Block` class. With one exception, the absence of a hash reference to the previous transactions.

## 4.4 Consensus system

The orchestration of communication between nodes that try to reach consensus is handled in the `PBFT` class with the transmission of messages represented in the `Message` class. Messages exchanged in the original protocol are asynchronous. Therefore, we use an asynchronous Python library `asyncio` that allows for a more accurate simulation of communication in the demonstrator program. The proof-of-concept implementation of the system does not contain all the mechanisms (view changes, key exchanges) in the `PBFT` protocol.

Every message exchanged in the protocol is first verified, and then, depending on the phase, certain operations are performed. The round of consensus starts in `validate_decision` or `validate_block`. Here, the transaction or block is constructed and subsequently transmitted to other nodes with a validation Request message.<sup>[1]</sup> The receiving node verifies the content transmitted in the Request message and stores the hash value of the message in the log of the given node as a pair with the message contents.<sup>[1]</sup> If the node that received the request message is primary, it transmits the Preprepare message, containing the hash value of the initial request, to other nodes and begins another phase.

After the node has received the Preprepare message, it inspects if the received hash value is already stored in its log. Subsequently, it transmits a Prepare message containing the hash value of the request to other nodes. Every node that receives the Prepare message increases the corresponding counter until a threshold from Equation 3.2 is reached. Then sends a Commit message using the `broadcast_commit` method.

In the Commit phase, the nodes increase the counter of the received Commit messages. When the threshold is reached again, the operation is performed and verified using the `verify_block` or `verify_decision` method. The result of the validation and the hash of the original request are composed of the Reply message and transmitted to the primary node.

The Reply phase consists of collecting validation results until the threshold of 3.2 is reached again and, based on those results, execute the given operation.<sup>[35]</sup> The execution of the operation is performed using the `execute_operation` method.<sup>[13]</sup> Here, the primary node, depending on the request, either stores the template into the database or adds a new block to the blockchain. The network may instead of agreeing on the proposed request, agree on a different result (for example, the proposed extracted template for given biometrics is artificially produced, and the system agreed on a legitimate template).

## Chapter 5

# Evaluation and testing

Firstly this chapter tests the behavior of the implemented system's demonstrator by executing prepared scenarios of successful or unsuccessful execution. Then based on these scenario results and our presumed effect of our design, we evaluate the security of the proposed system, deciding which weak points are addressed and which are still present, what did the system solve and what are the drawbacks the system still suffers with.

### 5.1 Testing scenarios

Within each testing scenario, the system is first set up according to the settings specified in the configuration file. Then the given scenario is performed, and the program shows the communication and the result of the system. All scenarios are available to be demonstrated in our program, by passing the arguments specified in Section 4.1. The purpose of the given scenarios is to demonstrate the decentralized manner of the proposed biometric system and its ability to function under expected and also malicious conditions. For ease of demonstration purposes, the system is configured to consist of four nodes, where each node has the same weight plus the node requesting validation. The following listings in testing scenarios do not contain the whole output of the program but just a key part of them.

#### 5.1.1 Expected behavior

This scenario tests the system on the expected and successful execution of the enrollment process and its subsequent authentication of the enrolled user. The node approached by the user in this test is honest, so requests for validation of the executed feature extraction and matching are agreed upon (see Listing 5.1). After transmitting the request to the network and enough nodes respond with a successful response, the primary node successfully stores the extracted template in the database and the user is authenticated.

```

- Sensor scanning raw biometrics...
- Feature extractor processing raw data...
- Extracted features requesting to be validated...
- Creating new request for extraction validation of SUCCESS enrollment!
-----PBFT START-----
- NODE2 executing feature extraction
- NODE2 validated!, sending „REPLY" message!
- NODE0 executing feature extraction
- NODE0 validated!, sending „REPLY" message!
- NODE1 executing feature extraction
- NODE1 validated!, sending „REPLY" message!
- Enough replies have been received!
- Feature extraction result has been validated!
- Storing features into database!
- NODE3 executing feature extraction
- NODE3 validated!, sending „REPLY" message!
-----PBFT END-----

```

Listing 5.1: Terminal output for enrollment.

### 5.1.2 Unknown user authentication or identification

Here, the testing scenario consists of a successful execution of the enrollment process and a subsequent malicious attempt to authenticate an unknown attacker who has overridden the matching module. Validation of feature extraction in both the enrollment and authentication process is successful (as seen in ??). In the authentication process, in which the compromised matcher component participates, the attacker attempts to verify himself as a previously enrolled user by overriding the matching decision. However, the request for the validation of the positive authentication to the network is disagreed on, and the outcome on the majority of the peers is different. The network concluded that the request was a failed verification, and thus the attacker's attempt to impersonate the enrolled user was unsuccessful. A similar scenario would occur when the unknown attacker would attempt to successfully identify himself as someone known to the system ().

```

- Creating new request for matching validation of SUCCESS verification!
-----PBFT START-----
- NODE2 executing matching verification
- NODE2 failed validation!, sending „REPLY" message!
- NODE0 executing matching verification
- NODE0 failed validation!, sending „REPLY" message!
- NODE1 executing matching verification
- NODE1 failed validation!, sending „REPLY" message!
- Enough replies have been received!
- Verification result has been disagreed with, other outcome determined!
- NODE3 executing matching verification
- NODE3 failed validation!, sending „REPLY" message!
-----PBFT END-----

```

Listing 5.2: Terminal output for failed verification.

### 5.1.3 Feature extractor compromised

Within this test scenario, the attacker compromised the feature extraction component with the intention of inserting his template. During the enrollment of a legitimate enrollee, the feature extractor ignores received biometric raw data, and the attacker inserts his own template instead of producing a legitimate one. When the approached node requests validation of such extraction, in order to get them stored in the database. The rest of the nodes with the uncompromised feature extractor disagree and store a legitimate template extracted from the received biometric data.

```

- Sensor scanning raw biometrics...
- Feature extractor processing raw data...
- Extracted features requesting to be validated...
- Creating new request for extraction validation of SUCCESS enrollment!
-----PBFT START-----
- NODE2 executing feature extraction
- NODE2 failed validation!, sending „REPLY" message!
- NODE0 executing feature extraction
- NODE0 failed validation!, sending „REPLY" message!
- NODE1 executing feature extraction
- NODE1 failed validation!, sending „REPLY" message!
- Enough replies have been received!
- Feature extraction result has been disagreed with, result determined!
- Storing features into database!
- NODE3 executing feature extraction
- NODE3 failed validation!, sending „REPLY" message!
-----PBFT END-----

```

Listing 5.3: Terminal output for enrollment from compromised node.

### 5.1.4 Node malfunction

In this scenario, a situation where one of the nodes on the network is defective and responds or proposes incorrect decisions.<sup>[34]</sup> For example, in the case of enrollment, incorrect responses from the defective node have no effect on the result of feature extraction (see Listing 5.4).

```
- Creating new request for extraction validation of SUCCESS enrollment!
-----PBFT START-----
- NODE2 executing feature extraction
- NODE2 validated!, sending „REPLY“ message!
- NODE0 executing feature extraction
- NODE0 validated!, sending „REPLY“ message!
- NODE1 executing feature extraction
- NODE1 failed validation!, sending „REPLY“ message!
- NODE3 executing feature extraction
- NODE3 validated!, sending „REPLY“ message!
- Enough replies have been received!
- Feature extraction result has been validated!
- Storing features into database!
-----PBFT END-----
```

Listing 5.4: Terminal output for enrollment with one malfunctioning node.

### 5.1.5 Channel interception

The attack on the transmission channels is also a common problem. Here, we demonstrate a scenario where the attacker intercepted the channel between the feature extractor and the matching module and performed a “replay attack,”. The attacker collected and stored the real data collections of the user identifier and his template transmitted through the channel. Later on he attempted to replay these data collections in hope that he could authenticate himself. The node serving this request executes the matching, which has a positive result, but afterwards the blockchain was inspected to determine if a feature extraction was previously executed. The node finds that there was no feature extraction in recent blocks or with a given process identifier, thus the matcher module concludes the request as a failed verification (see Listing 5.5).<sup>[21]</sup> The rest of the nodes in the network conclude the same and validate the verification as failed, thus the attempt of “replay attack” was unsuccessful.

```

- Creating new request for extraction validation of FAILED verification!
-----PBFT START-----
- NODE2 executing matching verification
- NODE2 failed validation!, sending „REPLY“ message!
- NODE0 executing matching verification
- NODE0 failed validation!, sending „REPLY“ message!
- NODE1 executing matching verification
- NODE1 failed validation!, sending „REPLY“ message!
- Enough replies have been received!
- Matching result has not been validated, failed verification!
- NODE3 executing matching verification
- NODE3 failed validation!, sending „REPLY“ message!
-----PBFT END-----

```

Listing 5.5: Terminal output for enrollment with one malfunctioning node.

## 5.2 Evaluation

All the methodologies presented in the proposed system are very innovative and therefore cannot be certified by any authority. The system was designed to secure the feature extraction and matching modules, which are vulnerable to direct attacks at points 3 or 5 and to channel attacks at points 2, 4, 6, 8 from Section 2.1.6. Our decentralized design of the biometric system eliminates the “single point of failure”, vulnerability known in classical biometric systems and mitigates direct attacks on the feature extraction and matching module (vulnerable point 3 or 5 of 2.1.6), as demonstrated in Section 5.1.2. The attacker would need to control the majority of the nodes (weight evaluation of the controlled nodes would have to be higher than the set threshold in Equation 2.2) to successfully override these components. In addition to tolerance of the subverted nodes, the system can withstand defective nodes, as demonstrated in Section 5.1.4.

In terms of securing the channels connected with the matcher and feature extraction modules, our proposed system can mitigate attacks on the channels between these two modules and between matcher and external application. Storage of the outcome and accompanying data of executed operations data on the blockchain allows for trusted backward checks. As demonstrated in Section 5.1.5, blockchain was used to detect “replay attack” on matching module by determining whether the prerequisite feature extraction was successfully executed and stored in the blockchain before. The channel between the matcher module and the external application can be secured in a similar way, just with the exception that the external application would search the blockchain for the prerequisite matching operation outcome as well.

From a privacy point of view, we successfully avoided storing sensitive biometric data such as templates or raw biometric data on blockchain by storing the user identifiers that are paired with the biometrics instead (as discussed in Section 3.3). Even though the communication and all the exchanged sensitive information is encrypted, the biometric data is transmitted in the network and for some time period stored in the node's log. This may cause bigger risks of biometric data leakage than would be the case in a single biometric terminal.

The PBFT protocol made it possible to withstand the subverted and defective nodes mentioned above. In addition, it ensures that the integrity and order of the transactions will be kept (as argued in Section 3.1.1. With the use of weighted modification of PBFT, we made it possible to customize the distribution of voting power based on the confidence in their security. A downside of this work is the unsolved problem with known scalability and communication overhead issues of PBFT.



## Chapter 6

# Conclusion and future work

The goal of this thesis was to study decentralized systems, classical biometric systems, blockchain technologies, and their existing consensus protocols.<sup>[12]</sup> With the information obtained, identify the weaknesses in the security of biometric systems and design a decentralized variant of the biometric system that would be able to make the system more secure. Then implement the proposed system with the aim of demonstrating the communication and behavior.

In summary, we proposed a decentralized version of biometric system, where operation of matching and feature extraction components is distributed among more nodes.<sup>[27]</sup> As a result of the incorporation of the PBFT protocol into the message exchanges between nodes, we found a solution on how to ensure a consensus on the results between the nodes executing the operation of these components. We have presented how this protocol may be used to propose and add new blocks to the blockchain, which can be afterwards used to provide a trusted source of proof that certain previous operations were executed. We made sure that none of the sensitive biometric data will be stored on the blockchain. We further modified the PBFT protocol used for consensus by introduction of the node “weights,, this way we made it possible to customize the voting power of certain nodes according to the security trust or probability that the node may get compromised/defective.

Our evaluation and testing shown that our decentralized design eliminates the “single point of failure” vulnerability and is able to minimize the threat of security weak points, where the feature extraction and matching module might get overridden by the attacker. In addition, the use of blockchain made it possible to withstand attacks on channels (such as “replay attack,,) between the feature extractor, matching and external applications modules.<sup>[0]</sup>

For future work, the scalability issue of PBFT could be investigated and optimized.<sup>[0]</sup> I propose incorporating load-balancing methods that would lessen the overall bandwidth and communication overhead of the consensus nodes in the current system. Another possible solution could be the combination of public blockchain with private blockchain (in our case PBFT), which would integrate advantages of both and optimize the throughput, latency, and scalability of the system. For example, a combination of Proof of Stake and PBFT, where the number of consensus nodes is dynamically selected according to their equity and verifiable cryptographic sortition algorithm [46].

# Bibliography

- [1] ISO/IEC 2382-37:2022(en), Information technology — Vocabulary — Part 37: Biometrics. Available at: <https://www.iso.org/obp/ui/#iso:std:iso-iec:2382:-37:ed-3:v1:en>.
- [2] AGBO, C. C., MAHMOUD, Q. H. and EKLUND, J. M. Blockchain Technology in Healthcare: A Systematic Review. Healthcare. firstth ed. 2019, vol. 7, no. 2. DOI: 10.3390/healthcare7020056. ISSN 2227-9032. Available at: <https://www.mdpi.com/2227-9032/7/2/56>.
- [3] ALASWAD, A. O., MONTASER, A. H. and MOHAMAD, F. E. Vulnerabilities of Biometric Authentication “Threats and Countermeasures”. p. 12.
- [4] ANGELIS, S. D., ANIELLO, L., BALDONI, R., LOMBARDI, F., MARGHERI, A. et al. PBFT vs Proof-of-Authority: Applying the CAP Theorem to Permissioned Blockchain. p. 11.
- [5] BISHOP, M. Computer security: art and science. Boston: Addison-Wesley, 2003. 415–416 p. ISBN 978-0-201-44099-7.
- [6] CACHIN, C. and VUKOLIĆ, M.<sup>[0]</sup> **Blockchain Consensus Protocols in the Wild**. arXiv:1707.01873. ArXiv, july 2017. ArXiv:1707.01873 [cs] type: article. Available at: <http://arxiv.org/abs/1707.01873>.
- [7] CASTRO, M. and LISKOV, B.<sup>[0]</sup> **Practical byzantine fault tolerance and proactive recovery**.<sup>[0]</sup> **ACM Transactions on Computer Systems**. november 2002, vol. 20, no. 4, p. 398–461. DOI: 10.1145/571637.571640. ISSN 0734-2071, 1557-7333. Available at: <https://dl.acm.org/doi/10.1145/571637.571640>.
- [8] CHEN, J., ZHANG, X. and SHANGGUAN, P. Improved PBFT Algorithm Based on Reputation and Voting Mechanism. Journal of Physics: Conference Series. april 2020, vol. 1486, no. 3, p. 032023. DOI: 10.1088/1742-6596/1486/3/032023. ISSN 1742-6588, 1742-6596. Available at: <https://iopscience.iop.org/article/10.1088/1742-6596/1486/3/032023>.
- [9] CLARKE, R. Human Identification in Information Systems: Management Challenges and Public Policy Issues | Emerald Insight. Information Technology & People. MCB UP Ltd. december 1994. Available at: [https://www.emerald.com/insight/content/doi/10.1108/09593849410076799/full/html?casa\\_token=f6kSycmUQUwAAAAA:to670F1j-QBeVYDxJbfp7z3FcrdYqhBxGC9Jvc6qDhAsX7DHkXsb\\_uSDqqt\\_SnqlphRZ-KHPdKRIhhm5Uwq0zKCA3nsmvNjgzZ38IqpuVQXCffiw7jI](https://www.emerald.com/insight/content/doi/10.1108/09593849410076799/full/html?casa_token=f6kSycmUQUwAAAAA:to670F1j-QBeVYDxJbfp7z3FcrdYqhBxGC9Jvc6qDhAsX7DHkXsb_uSDqqt_SnqlphRZ-KHPdKRIhhm5Uwq0zKCA3nsmvNjgzZ38IqpuVQXCffiw7jI).

- [10] CUI, Z., XUE, F., ZHANG, S., CAI, X., CAO, Y. et al. A Hybrid Blockchain-Based Identity Authentication Scheme for Multi-WSN.<sup>[9]</sup> **IEEE Transactions on Services Computing**. march 2020, vol. 13, no. 2, p. 241–251. DOI: 10.1109/TSC.2020.2964537. ISSN 1939-1374. Conference Name: IEEE Transactions on Services Computing.
- [11] DARGAN, S. and KUMAR, M.<sup>[33]</sup> **A comprehensive survey on the biometric recognition systems based on physiological and behavioral modalities**.<sup>[2]</sup> **Expert Systems with Applications**. april 2020, vol. 143, p. 113114. DOI: 10.1016/j.eswa.2019.113114. ISSN 0957-4174. Available at: <https://www.sciencedirect.com/science/article/pii/S0957417419308310>.<sup>[33]</sup>
- [12] DELGADO MOHATAR, O., FIERREZ, J., TOLOSANA, R. and VERA RODRIGUEZ, R. Biometrics: A First Look into Opportunities and Challenges. March 2019.
- [13] DELGADO MOHATAR, O., FIERREZ, J., TOLOSANA, R. and VERA RODRIGUEZ, R. Blockchain meets Biometrics:<sup>[7]</sup> **Concepts, Application to Template Protection, and Trends**. arXiv:2003.09262. ArXiv, march 2020. ArXiv:2003.09262 [cs] type: article. Available at: <http://arxiv.org/abs/2003.09262>.
- [14] DRAHANSKÝ, M. Biometrie. 1. vyd.th ed. Brno: M. Drahanský], 2011. ISBN 978-80-254-8979-6.
- [15] EDITOR, C. C. Replay attack - Glossary | CSRC. Available at: [https://csrc.nist.gov/glossary/term/replay\\_attack](https://csrc.nist.gov/glossary/term/replay_attack).
- [16] EUROPEAN PARLIAMENT, C. o. t. E. U.<sup>[24]</sup> **REGULATION (EU) 2016/679 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL**. L 119. may 2016, vol. 59. ISSN 1977-0677. Available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32016R0679>.
- [17] FEMILA, M. D. and IRUDHAYARAJ, A. A. Biometric system. In: 2011 3rd International Conference on Electronics Computer Technology. April 2011, vol. 1, p. 152–156. DOI: 10.1109/ICECTECH.2011.5941580.
- [18] FENG, W., LI, Y., YANG, X. and CHEN, L.<sup>[18]</sup> **Blockchain-based data transmission control for Tactical Data Link**.<sup>[18]</sup> **Digital Communications and Networks**. june 2020, vol. 7. DOI: 10.1016/j.dcan.2020.05.007.
- [19] GAN, B., WU, Q., LI, X. and ZHOU, Y. Classification of Blockchain Consensus Mechanisms Based on PBFT Algorithm. In:<sup>[25]</sup> **2021 International Conference on Computer Engineering and Application (ICCEA)**. 2021, p. 26–29. DOI: 10.1109/ICCEA53728.2021.00012.
- [20] GARCIA, P. Biometrics on the blockchain. *Biometric Technology Today*. may 2018, vol. 2018, no. 5, p. 5–7. DOI: 10.1016/S0969-4765(18)30067-5. ISSN 0969-4765, 1873-1880. Available at: <http://www.magonlinelibrary.com/doi/10.1016/S0969-4765%2818%2930067-5>.
- [21] GRIFFIN, J.<sup>[2]</sup> **What Is an Intrusion Detection System (IDS)?** Definition and Software. July 2021. Available at: <https://logicalread.com/intrusion-detection-system/>.

- [22] GUPTA, K. and SAM, A. Blockchain in Operations Management.<sup>[41]</sup> **International Journal of Scientific and Research Publications (IJSRP)**. november 2019, vol. 9, no. 11, p. p9551. DOI: 10.29322/IJSRP.9.11.2019.p9551. ISSN 2250-3153. Available at: <http://www.ijsrp.org/research-paper-1119.php?rp=P959332>.
- [23] HUGHES, A., PARK, A., KIETZMANN, J. and ARCHER BROWN, C. Beyond Bitcoin: What distributed ledger technologies mean for firms. *Business Horizons*. may 2019, vol. 62, no. 3, p. 273–281. DOI: 10.1016/j.bushor.2019.01.002. ISSN 00076813. Available at: <https://linkinghub.elsevier.com/retrieve/pii/S0007681319300023>.
- [24] JAIN, A., NANDAKUMAR, K. and NAGAR, A. Biometric Template Security.<sup>[29]</sup> **EURASIP Journal on Advances in Signal Processing**. march 2008, vol. 2008. DOI: 10.1155/2008/579416.
- [25] JAIN, A. K. Biometric authentication. *Scholarpedia*. june 2008, vol. 3, no. 6, p. 3716. DOI: 10.4249/scholarpedia.3716. ISSN 1941-6016. Available at: [http://www.scholarpedia.org/article/Biometric\\_authentication](http://www.scholarpedia.org/article/Biometric_authentication).
- [26] JAIN, A. K., FLYNN, P. and ROSS, A. A. Handbook of Biometrics.<sup>[29]</sup> **Springer Science & Business Media**, october 2007. ISBN 978-0-387-71041-9. Google-Books-ID: WfCowMOvpioC.
- [27] JAIN, A. K. and NANDAKUMAR, K. Biometric Authentication: System Security and User Privacy. *Computer*. november 2012, vol. 45, no. 11, p. 87–92. DOI: 10.1109/MC.2012.364. ISSN 0018-9162. Available at: <http://ieeexplore.ieee.org/document/6353458/>.
- [28] JAIN, R. and KANT, C. Attacks on Biometric Systems: An Overview. *International Journal of Advances in Scientific Research*. september 2015, vol. 1, no. 7, p. 283. DOI: 10.7439/ijasr.v1i7.1975. ISSN 2395-3616. Available at: <http://ssjournals.com/index.php/ijasr/article/view/1975>.
- [29] KREMENOVA, I. and GAJDOS, M. Decentralized Networks: The Future Internet.<sup>[8]</sup> **Mobile Networks and Applications**. Dec 2019, vol. 24, no. 6, p. 2016–2023. DOI: 10.1007/s11036-018-01211-5. ISSN 1572-8153. Available at: <https://doi.org/10.1007/s11036-018-01211-5>.
- [30] LEACH, P. J., SALZ, R. and MEALLING, M. H. A Universally Unique IDentifier (UUID) URN Namespace [RFC 4122]. RFC Editor, july 2005. DOI: 10.17487/RFC4122. Available at: <https://www.rfc-editor.org/info/rfc4122>.
- [31] LEE, Y. K. and JEONG, J.<sup>[90]</sup> **Securing biometric authentication system using blockchain**. *ICT Express*. september 2021, vol. 7, no. 3, p. 322–326. DOI: 10.1016/j.ict.2021.08.003. ISSN 24059595. Available at: <https://linkinghub.elsevier.com/retrieve/pii/S2405959521000916>.
- [32] MAIORANA, E., HINE, G. and CAMPISI, P.<sup>[91]</sup> **Hill-Climbing Attacks on Multibiometrics Recognition Systems**. May 2015. DOI: 10.1109/TIFS.2014.2384735.
- [33] MODI, H. and MISTRY, D. Security on Fingerprint Data Transfer System. *International Journal of Advance Computer Technology*,. may 2014, III, p. 783–787.

- [34] NAKAMOTO, S. Bitcoin:<sup>[0]</sup> **A peer-to-peer electronic cash system**. 2009. Available at: <http://www.bitcoin.org/bitcoin.pdf>.
- [35] PANKRATOV, E., GRIGORYEV, V. and PANKRATOV, O. The blockchain technology in real estate sector: Experience and prospects. IOP Conference Series: **Materials Science and Engineering**. IOP Publishing. jun 2020, vol. 869, no. 6, p. 062010. DOI: 10.1088/1757-899x/869/6/062010. Available at: <https://doi.org/10.1088/1757-899x/869/6/062010>.
- [36] POLLACK, A. Technology; Recognizing The Real You.<sup>[45]</sup> **The New York Times**. 1st ed. New York: [b.n.]. september 1981, p. 2, [cit. 2022-03-22]. ISSN 0362-4331. Available at: <https://www.nytimes.com/1981/09/24/business/technology-recognizing-the-real-you.html>.
- [37] PRABHAKAR, S., PANKANTI, S. and JAIN, A. Biometric recognition: **security and privacy concerns**.<sup>[21]</sup> IEEE Security & Privacy. march 2003, vol. 1, no. 2, p. 33–42. DOI: 10.1109/MSECP.2003.1193209. ISSN 1558-4046. Conference Name: IEEE Security & Privacy.
- [38] RATHGEB, C. and UHL, A.<sup>[29]</sup> **A survey on biometric cryptosystems and cancelable biometrics**.<sup>[29]</sup> **EURASIP Journal on Information Security**. september 2011, vol. 2011, no. 1, p. 3. DOI: 10.1186/1687-417X-2011-3. ISSN 1687-417X. Available at: <https://doi.org/10.1186/1687-417X-2011-3>.
- [39] TRONCOSO, C., ISAAKIDIS, M., DANEZIS, G. and HALPIN, H. Systematizing Decentralization and Privacy: Lessons from 15 Years of Research and Deployments.<sup>[0]</sup> **Proceedings on Privacy Enhancing Technologies**. october 2017, vol. 2017, no. 4, p. 404–426. DOI: 10.1515/popets-2017-0056. ISSN 2299-0984. Available at: <https://www.sciendo.com/article/10.1515/popets-2017-0056>.
- [40] VARMA, J. Blockchain in Finance. Vikalpa. march 2019, vol. 44, p. 1–11. DOI: 10.1177/0256090919839897.
- [41] VERMA, K.<sup>[6]</sup> **Blockchain Technology and its application in Retail**. In:. January 2018.
- [42] VIELHAUER, C. and KALKER, T. Security for biometric data. In: DELP III, E. J. and WONG, P. W., ed. San Jose, CA: [b.n.], June 2004, p. 642. DOI: 10.1117/12.528261. Available at: <http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.528261>.
- [43] WAYMAN, J. L.<sup>[32]</sup> **10 - The scientific development of biometrics over the last 40 years**. In: LEEUW, K. D. and BERGSTRA, J., ed.<sup>[32]</sup> **The History of Information Security**. Amsterdam: Elsevier Science B.V., 2007, p. 263–274. DOI: <https://doi.org/10.1016/B978-044451608-4/50011-0>. ISBN 978-0-444-51608-4. Available at: <https://www.sciencedirect.com/science/article/pii/B9780444516084500110>.<sup>[33]</sup>
- [44] WAYMAN, J. L., JAIN, A. K., MALTONI, D. and MAIO, D. Biometric Systems: Technology, Design and Performance Evaluation. Springer Science & Business Media, december 2005. ISBN 978-1-84628-064-1. Google-Books-ID: LkHHDZtQwG0C.

- [45] WAYMAN, J., JAIN, A., MALTONI, D. and MAIO, D. Biometric Systems: Technology, Design and Performance Evaluation. 1st ed. London: Springer London, 2005. 1-2 p. ISBN 9781846280641. Available at: <https://books.google.at/books?id=LkHHDZtQwG0C>.
- [46] WU, Y., SONG, P. and WANG, F. Hybrid Consensus Algorithm Optimization: A Mathematical Method Based on POS and PBFT and Its Application in Blockchain. <sup>[41]</sup>[Mathematical Problems in Engineering](#). april 2020, vol. 2020, p. e7270624. DOI: 10.1155/2020/7270624. ISSN 1024-123X. Publisher: Hindawi. Available at: <https://www.hindawi.com/journals/mpe/2020/7270624/>.
- [47] WĄCHAL, M. Private Blockchain not only for FinTech. October 2021. Available at: <https://softwaremill.com/private-blockchain-not-only-for-fintech/>.
- [48] YUAN, Y. Towards Blockchain-based Intelligent Transportation Systems. In:. November 2016. DOI: 10.1109/ITSC.2016.7795984.

## Appendix A

# Contents of the included storage media

```
/
LICENSE
Makefile
README.md
bioblockchain
  __init__.py
  bioblockchain.py
  block.py
  blockchain.py
  chain_utils.py
  config.py
  main.py
  message.py
  message_log.py
  node.py
  parser.py
  pbft.py
  template_database.py
  time_utils.py
  transaction.py
  utils.py
  wallet.py
docs
  Makefile
  bioblockchain.rst
  conf.py
  index.rst
  make.bat
  modules.rst
requirements.txt
test
  __init__.py
```

```
all_tests.py
test_block.py
test_transaction.py
test_utils.py
test_wallet.py
```

- README.md - manual for setting up the virtual environment, installing needed packages and running the code.
- LICENSE - thesis licensing.
- Makefile - makefile containing rules for execution of unit tests, installing packages, cleaning directory and executing the program.
- bioblockchain - directory containing all the source codes of implemented demonstrator program.
- requirements.txt - description of all the packages needed to execute the program or compile the documentation.
- test - directory containing used unit tests (used mainly on cryptographic operations).