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Research advances on blockchain-as-a-service: architectures, applications and challenges

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Abstract

Due to the complexity of blockchain technology, it usually costs too much effort to build, maintain and monitor a blockchain system that supports a targeted application. To this end, the emerging "Blockchain as a Service" (BaaS) makes the blockchain and distributed ledgers more accessible, particularly for businesses, by reducing the costs and overheads. BaaS combines the high computing power of cloud computing, the pervasiveness of IoT and decentralization of blockchain, allowing people to build their own applications while ensuring the transparency and openness of the system. This paper surveys the research outputs of both academia and industry. First, it introduces the representative architectures of BaaS systems, and then summarizes the research contributions of BaaS from technologies for service provision, roles, container and virtualization, interfaces, customization and evaluation. The typical applications of BaaS in both academic and practical domains are also introduced. At present, the research on blockchain is abundant, but research on BaaS is still in its infancy. Six challenges of BaaS are concluded in this paper for further study directions.

KEYWORDS:
Blockchain as a service, Blockchain, Service, Internet of things, Cloud computing

1. Introduction

A blockchain [1] can be referred to as a distributed ledger, where data and transactions are not under the control of any third party. Compared with the traditional distributed database, the blockchain has drawn intense attention from academic communities to industries because of its decentralization, persistency, anonymity and auditability. However, the barrier of developing a blockchain-based application is high [2]. For example, Dubai's government wants a single system on which agencies launch different blockchain projects. Illinois's government designed an experimental process for individual projects to test different types of blockchain platforms and applications to find the best fit for their particular needs [3]. The implementation of a blockchain is a complex and error-prone process, in which components such as P2P interconnection, file storage, smart contract and consensus mechanism should be elaborately developed and tested. To address the challenge of complexity, tech giants have jumped on the bandwagon and started providing "Blockchain as a Service" (BaaS) since 2017 [4]. BaaS provides blockchain services in cloud computing or edge computing environments, such as network deployment and system monitoring, smart contracts analysis and testing. Based on these services, the developers can focus on the business code to explore how to apply the blockchain technology more appropriately to their business scenarios, without the bother of having to maintain and monitor the blockchain platform [5]. BaaS is a promising solution to improve the productivity of blockchain application development, and it is the latest revolution that initiates the mass adoption of blockchain technology. BaaS has rapidly developed on a global scale with the rapid transformation of blockchain applications from system development to services utilization. BaaS is proposed as a blockchain platform integrating cloud computing, Internet of Things (IoT) and edge computing. BaaS can manage blockchain consensus [6], forking, node validity, commodity exchange, backup, off-chain and on-chain synchronization, all by itself. Similar to cloud services, BaaS can also manage resource, bandwidth, Internet connection and other associated services.BaaS provides enterprises with the flexibility to focus on the business logic and functional needs of a blockchain. BaaS helps to create, develop, test, host, deploy and operate blockchain related applications on the cloud infrastructure. The BaaS implementation fully outsources the technical overhead to the cloud service provider. At present, the research on blockchain is abundant, but research on BaaS is still in its infancy.We have searched more than 30 BaaS related publications from Digital Bibliography and Li-

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brary Project (DBLP)and Google Scholar with the key words "BaaS" or "Blockchain Service". Based on our examination of the existing research papers including, but not limited to, the well-known systems such as IBM Blockchain, Microsoft Azure Blockchain and AWS Blockchain, we conclude that current BaaS studies focus on four aspects and present them in out papaer as follows: Section 2 investigates commercial and academic BaaS systems with various representative architectures. Section 3 studies the service technologies of BaaS but not the blockchain itself. Section 4 applies BaaS to different domains, such as machine learning, Software Defined Networking (SDN), data and transaction services, IoT in the academic domain, as well as applications in the commercial domain.As far as we know, there is no comprehensive survey that focuses on BaaS. Although some surveys on blockchain have mentioned BaaS, they did not go into further details.The main contributions of this paper are a detailed survey on the research results of the aforementioned aspects, and the proposition on the future challenges and research trends related to BaaS, as described in Section 6.

2. Architectures

Among the academic and industry reports of BaaS, a frequently covered topic is the architecture. The architecture is the most representative characteristic of a BaaS system. In this section, the architectures of some famous commercial BaaS systems and novel academic systems are discussed.

2.1. Commercial systems

(1) Alibaba

Alibaba's BaaS system is built on Kubernetes.It supports three different blockchain technologies:Hyperledger Fabric, Enterprise Ethereum and Quorum.It also supports Ant Blockchain, which is a proprietary financial-grade blockchain.As shown in Figure 1, the system's architecture is divided into four layers:

- Infrastructure layer: The layer presently supports both public and private cloud offerings of Alibaba Cloud and will support the hybrid cloud in the future.
- Cloud resource layer: The layer provides basic cloud resources for blockchain services and upper-layer applications.
- Platform service layer: The layer is built on "Alibaba Cloud Container Service Kubernetes". The platform supports multiple basic BaaS services, including resource creation, resource management, resource operation, and security management.
- Mid-layer application: This is a reference architecture that is used to connect BaaS with business applications. It is usually implemented in the form of blockchain business solution or blockchain middleware.

(2) IBM

IBM's ADEPT system that is built on Bluemix is an excellent example of the early blockchain use within the IoT sup-portion. IBM's blockchain structure and components are based on the underlying infrastructure and Hyperledger Fabric.As shown in Figure 1, the system architecture includes three layers:

- Infrastructure layer (IBM cloud): It supports IBM cloud services. LinuxONE mainframes are used as the base of this layer to provide better performance and securer environment.
- Middle layer (Hyperledger Fabric): This layer is composed of three parts, namely, certificate authority, peers and ordering service. It is used to create and manage the blockchain components that are based on Hyperledger Fabric.
- Top layer (Hyperledger composer): This layer grants the user an ability to create and manage blockchain components and deploy solutions. It provides the ability to create smart contracts instead of writing them by providing a simple layer, and business level abstraction to implement smart contracts rather than writing them from scratch.

(3) Microsoft

Microsoft's BaaS system [7] supports different blockchain protocols. It is built on top of Microsoft Azure cloud platform. As shown in Figure 1, the system architecture includes three tiers.

- Base platform tier: This layer includes the smart contract implementations, such as Ethereum and Hyperledger, etc. It is occupied by the blockchain node which could be a consortium or public one regardless of the node location, such as Azure, datacenter and other cloud services.
- Middleware tier: This layer provides the core like the identity and operations management, in addition to data and intelligence services like the analytics and machine learning. A new concept called Cryptlets will enable secure interoperation and communication between Microsoft Azure the ecosystem middleware and customer technologies.
- Industry solutions: This layer includes user solutions either by deploying first party solutions or integrating third party ones. It contains the "smart contract market place" where for example a user can create a smart contract then list it on the marketplace to get paid for each instance it has created.

(4) Oracle

Oracle's BaaS system, named Oracle Blockchain Cloud Service (OBCS) [8], is based on Hyperledger with a number of enhancements for better performance, scalability, security, etc. Its architecture is shown in Figure 1. The architecture is divided into three layers and five core components:

- Infrastructure and PaaS(Platform as a Service) services: This component incorporates the underlying infrastructure dependencies through existing Oracle Cloud Services.
- Blockchain nodes and containers: This component incorporates the Hyperledger Fabric framework for its peer nodes and ordering service, smart contracts containers, membership services, and basic APIs. It configures and runs the blockchain software on the provisioned infrastructure.
- Data services: OBCS uses its own block and object store. The key/value world state is stored using the NoSQL DB cloud service, whereas the ledger is stored using the Object Store Cloud Service.
- Administration services: This component offers a management/operations console that automates many administrative tasks, allows dynamic configuration with (automatic) server restart, and makes it easy to monitor transactions.

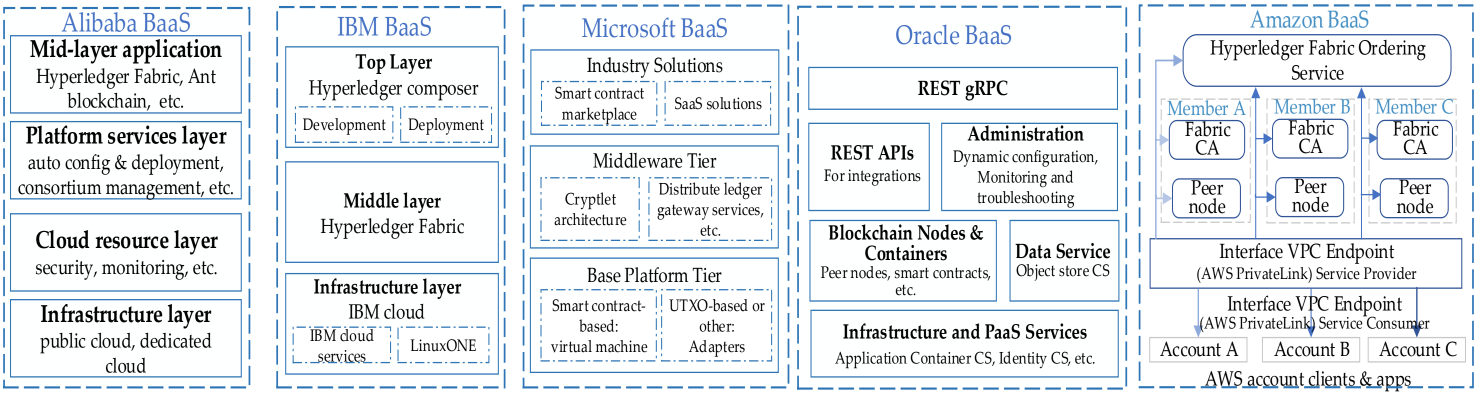

Figure. 1: The architectures of Alibaba's, IBM's, Microsoft's, Oracle's and Amazon's BaaS

- REST Gateway/APIs: It is a REST gateway that supports a subset of common Fabric APIs and enables synchronous invocation of these APIs.

(5) Amazon

Amazon's BaaS platform [9] does not use a layered architecture but a component-based one, as shown in Figure 1. The basic components include the Hyperledger fabric ordering service, members, each member fabric certificate authority and peer node, and the AWS (Amazon Web Services) clients and apps. The creator also must create the first "managed blockchain" network member. Additional members are added through a proposal and voting process. The blockchain network remains active as long as there are members. The network is deleted only when the last member deletes itself from the network. Each user peer node contains a local copy of the ledger and a global state of the network for the channels in which they participate, which gets updated with each new transaction.

(6) Comparison and discussion

Despite common points, the aforementioned systems provide their unique features and tools, respectively. Table 1 compares eight aspects of them.

2.2. Academic systems

(1) NBaaS

NBaaS (Novel BaaS) [2] is a proposed paradigm that helps to improve some limits of PaaS-based BaaS. The authors argue that BaaS systems could take away the decentralization and auditability of the blockchain. However, NBaaS provides the ability of adding deployable components which in turn help assure decentralization and auditability. The main architecture of each blockchain instance in NBaaS consists of members of the network, peers where the ledgers and smart contracts of each member are hosted, orders which do the transactions ordering, the client side where the users of the network operate, and deployable components which are the add-on components that can be added to the blockchain instance. All the deployable components of a blockchain instance are released as a part of the blockchain service. Clients have the ability to deploy any component to any computing environment.

(2) uBaaS

uBaaS (Unified Blockchain as a Service) [10] is the solution of vendor locked deployment which means that the applications belong to either a specific cloud provider or a specific blockchain platform. Users can build up a blockchain environment and design blockchain-based applications via the uBaaS front-end user interface, which interacts with the back-end services through an API gateway. The uBaaS architecture provides various back-end services, in which the deployment as a service includes the blockchain deployment service and the smart contract deployment service; the design pattern as a service consists of data management services and smart contract design services; the data management services include on-chain and off-chain services, data encryption service, and hash integrity service; the smart contract design services comprises multiple authorities service, dynamic binding service, embedded permission service; the auxiliary services support two auxiliary services, key management service and file comparison service; and the key management service is used to generate key pairs for data encryption, while the file comparison service is to validate the authenticity of a file such as any type of certificates.

(3) FBaaS

FBaaS (Functional BaaS) [11] adopts the micro-service to implement blockchain services and services composition to implement the business logic. A micro-service provides less functionality than a monolithic system. In other ways, it provides a higher level of abstraction for the service they provide. Decomposing a micro-service into several functions can be similar, where Function as a Service (FaaS) is commonly seen as the one with the ultimate level of abstraction. The architecture consists of nine sub-layers and four main layers. As shown in Figure 2-(a), the main four layers are:

- Infrastructure layer, which includes FBaaS layers 1 and 2, which include the physical clusters and operating systems.
- Component layer, which includes FBaaS layers 3. The basic functions are implemented inside this layer. For example, authentication functions and authorization functions are developed here to be frequently reused in the upper layer.
- Services layer, which includes FBaaS layers 4 and 5. This layer implements the majority of functions of BaaS.
- Business logic layer, which includes the APPs and large-scale services. To establish the blockchain and the com-

Table 1: The comparison among the five commercial BaaS systems

Providers \ Aspects	Authentication & Authorization	Blockchain type	Development facility	Scalability	Blockchain frameworks	Other features	Pricing	Architectural styles/properties
Alibaba	Access Key and Access Key Secret generated with Alibaba Cloud	Permissioned& Consortium	Alibaba Cloud Container Service	with a wide range of Alibaba Cloud services	Hyperledger Fabric and Ant Blockchain.	Chaincode Management	Subscription plan and pay as per use	Layered Architecture: Four layers
IBM	IBM Secured Services Containers	Permissioned	IBM Bluemix development platform	IBM Smart Cloud only	Hyperledger Fabric	Red Hat CodeReady Workspaces	Monthly Subscription, Free trial	Layered Architecture: Three layers
Microsoft	Active Directory	Permissioned& Consortium	High with Microsoft development kit	High with all Microsoft products	Hyperledger and Ethereum	Built-in Consortium Management	Subscription plan and pay as per use	Layered Architecture: Three tiers
Amazon	Identity and Access Management	Permissioned	Medium, limited only with AWS kit	Provide API for quick node creation	Hyperledger fabric and Ethereum	Pre-built templates to develop a blockchain.	Pay as per use	A component based architecture
Oracle	Identity federation	Permissioned& Consortium	Hyperledger Fabrik SDK	with all Oracle SaaS and third party SaaS	Hyperledger	Multiple identity support	$0.75 pay as you go	Layered Architecture: Three layers and five corecomponents

plicated services, the functions of layer three are grouped together.

(4) NutBaaS

NutBaaS [5] is a new BaaS system that is directed to help developers focus on the business code and how to apply the blockchain into their business scenarios without the bother of maintaining and building a blockchain. The name“nut” means providing developers with a “hard” barrier like the nut shell to protect their blockchain applications. NutBaaS provides a number of blockchain services such as network deployment and system monitoring, smart contracts analysis and testing. As shown in Figure 2-(b), the architecture of NutBaaS consists of the following four layers:

- Resource layer, which provides the infrastructure, such as storage, databases and networks, needed for blockchain services.
- Service layer, where all blockchain basic services and advanced services are implemented.
- Application layer, which is conducive to the overall ecological development and includes some applications like DApp store, contract center as well as some general industry solutions, those apps being constructed by integrating layer two services.
- Business layer, where some mature solutions and corresponding application examples are shown and people can find and explore those solutions and examples.

(5) FSBaaS

FSBaaS (Full-Spectrum Blockchain as a Service) [12] is built on top of a high-performance centralized private blockchain platform called Blockchain Lite and a Hyperledger Fabric blockchain. It is an integration of private and consortium blockchain [13] services. FSBaaS is presented to help the user to get the benefits of two worlds, instead of restricting the user to choose either a centralized, private blockchain system or a consortium blockchain network. FSBaaS helps provide a unified interface for the two blockchain runtimes from programing model and RESTful APIs to the tenant model. A BaaS tenant can subscribe to the two runtimes simultaneously and migrate data from one to the other as needed. As shown in Figure 2-(c), the main architecture of FSBaaS consists of:

- Blockchain tenants, which are the users of the blockchain.
- Blockchain nodes, which include the nodes of the blockchain. The nodes are divided into two types, in which the lite-node is a private centralized type, and the fabric node is a decentralized consortium. A bc-lite tenant can host one or more centralized business networks. A bc-fabric tenant can host one or more decentralized business networks, or let the node join existing (decentralized) business networks of others. A hybrid blockchain tenant can do both what a bc-lite tenant and a bc-fabric tenant can do.
- Business networks, where the business network solutions can be deployed.
- Business network solutions, which are developed following the FSBaaS programming model.

(6) Comparison and discussion

The aforementioned five systems address the difficult shortcomings of the commercial BaaS systems. If they are compared, no challenges they studied are overlapping. However, these studies have the same goals. On one hand, they try to maintain the four key characteristics of the blockchain: decentralization, persistency, anonymity and auditability. On the other hand, they try to improve the generality and universality of the BaaS systems, but not the performance. For example, FSBaaS and uBaaS have the similar idea, i.e., how to enable the user to deploy a blockchain solution without the worry of choosing a specific infrastructure or vendor. In FBaaS and NutBaaS, the authors enhance the environments and features of BaaS, respectively, to popularize BaaS systems. In brief, these studies promote the popularization and utilization of BaaS.

3. Services technologies

A service, as a new dominant logic, is defined as the application of specialized competences (knowledge and skills) through deeds, processes, and performances for the benefit of another entity or the entity itself. The blockchain technology creates a trusted environment through its transparent nature, making information publicly available throughout its entire network, while also assuring the integrity and immutability of the data [14]. In this section, we discuss the services-related technologies of BaaS.

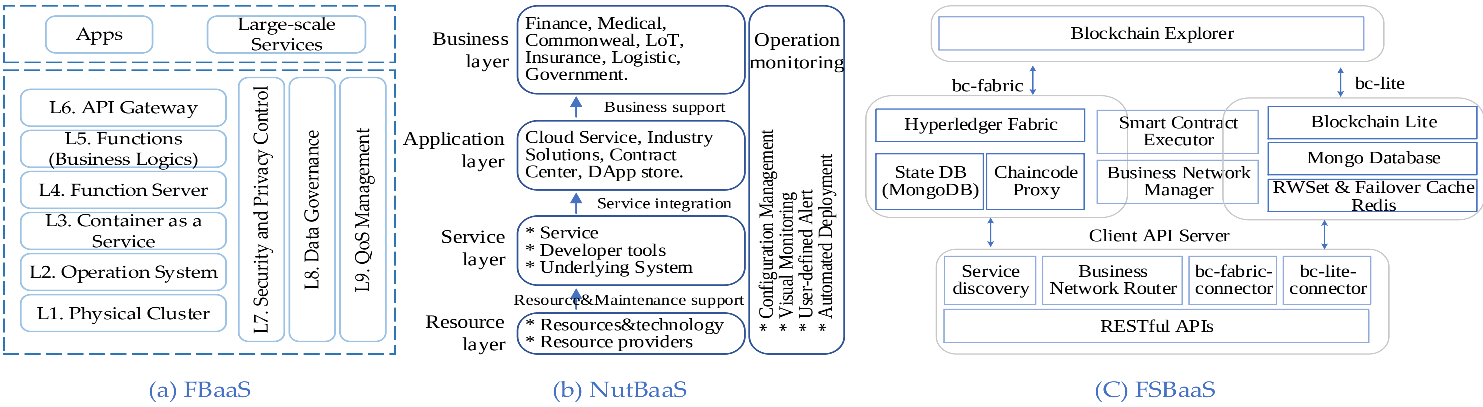

Figure. 2: The Architecture of FBaaS, NutBaaS and FSBaaS

(1) Service provisions

Cloud computing offers services such as Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS). Inheriting from the concept of cloud computing service, BaaS refers to on-demand provisioning of blockchain capabilities and functionalities. Compared with the none-BaaS ones, BaaS nodes provide the developers with services such as customizable development environment, blockchain-based search queries, transaction submission, data analysis and so on. These services, which can be both centralized and decentralized, hide the complexities of the blockchain platform from the developers. In our literature review, we found that BaaS can be classified into the following two categories: PaaS-based encapsulated Blockchain as a Service (eBaaS) and SaaS-based domain-oriented Blockchain as a Service (dBaaS). eBaaS is the most common form of BaaS. It relays on the enterprise-grade blockchain platform/middleware, encapsulates the blockchain capabilities and functionalities in terms of services, and provides such services to developers through APIs. The API-driven integration simplifies and accelerates the application development and integration using the built-in REST proxy for invoking smart contract transactions from the cloud-based or on-premises applications. Developers could also invoke blockchain operations from Java, GO or JavaScript SDKs (Software Development Kit). The eBaaS offerings are offered by big technology companies, such as IBM, Microsoft, Alibaba, and Oracle, including blockchain implementations specific to these companies. The implementations are based on open source projects such as Hyperledger Fabric and Ethereum. The technology companies add their own special features, such as enhanced security, easy integration via APIs, and ease of distribution of nodes, and then sell them as a service. The typical eBaaSs include Microsoft Azure which hosted R3's distributed ledger platform, Corda and R3Net, Ethereum and Amazon AWS which hosted many kinds of blockchain applications. Tencent is more aggressive and its TrustSQL [15] is committed to providing an enterprise-class blockchain infrastructure that supports secure, reliable and flexible eBaaS. TrustSQL provides SQL-like interface for user access. It is a kind of database as a service system with blockchained functions. A dBaaS focuses on certain business domains, and is based on SaaS applications that are incorporated with the blockchain platform. These are ready to use with little or no technical overhead. Built with traditional web application technologies, they wrap themselves around BaaS in a way that is highly transparent to the user. Actually, when using a dBaaS, the blockchain capabilities are hidden from the clients, clients and admin requests all go directly into the cloud service. The domain oriented applications are accessed with a web or mobile client, where tenants may customize the applications according to their business requirements, but not blockchain requests, while blockchain capabilities are naturally inherited from dBaaS and seldom customizable. The users of a tenant may have no perception about the blockchain. These applications are industry-specific, and like SaaS applications, follow the pay-as-you-go model. The typical dBaaSs include IBM's Bluemix-based Hyperledger with GUI to deploy the blockchain instance. Some application examples of subscription services from IBM are IBM Food Trust and IBM Trade Lens. The former, which is made famous by Walmart, connects many different participants to make the food data traceable, and the latter facilitates international trade by providing a single source for the shipping data. Since the dBaaS offerings have the highest level of transparency and knowledge of special business domains, they are constantly changing. Before undertaking a blockchain development project, it may be wise to research current offerings to determine if there is a dBaaS that already meets the needs [16]. An IaaS is defined as moving the blockchain nodes to the cloud infrastructure and make them cloud hosted. A eBaaS provides extra unified interfaces of the cloud hosted blockchain platform to clients, while a dBaaS additionally offers the customizable business logics for a special domain. The three approaches meet different requirements due to the fact that not all features of a blockchain are needed for all applications, and even so, not all the blockchained applications need to be built from the ground. There are fine lines between dBaaS, eBaaS and IaaS. dBaaS represents the industry-specific, cloud-based applications that drive the workflow of an industry process and include the blockchain as a feature. A dBaaS is often the frontend of an eBaaS. While an eBaaS is normally based on one of the most well-known blockchain platforms and provides the general and careful-designed APIs for developers.

(2) Roles

A BaaS system contains three customizable functions, which can be abstracted as roles. They are participants, assets and transactions. Participants are people and systems generating transactions within the blockchain network. Multiple participants share an organization's nodes [17]. In most business applications, participants have no awareness of this when using a blockchain. An asset is a type of goods that has some value, and its activities are recorded on a blockchain. Transactions are generated when participants have some impact on assets, which means there is complex connections between these three roles [16]. When clients define their requirements to a BaaS provider, that along with the business logic which will drive smart contracts, information about participants, assets, and transactions is helpful. Meanwhile, there are some researchers who add a fourth role as "service providers" [18], which is reasonable from the BaaS research point of view. Of course, participants are the "tenants". For example, in [17], tenants are patients and providers are healthcare centers. Roles are assigned not only to the servers, but also to the nodes of the BaaS system. For example, in [5], the nodes are divided according to four roles: the Jaeger client is for passing the tracing information, the Jaeger agent is for listening and receiving the span data, the Jaeger collector is for receiving data from the Jaeger agent and then writes the data to the backend storage, i.e., the Jaeger store. In [19], the nodes include IoT servers, peers, MEC network and blockchain server.

(3) Container and virtualization

When implementing any service technology, the container and virtualization required by the service are also essential. Typically, these blockchain nodes, including both the blockchain files and the world state database, are distributed to peers in a network via containers such as Docker or Kubernetes. These containers run the nodes in cloud-based environments, so physical equipment is not required by each organization. Because of this, even though the network is distributed, each node is running from a separate container that could reside on the same cloud instance. For developers, containers can be very helpful when prototyping because multiple containers, which represent multiple nodes, can run at the same time on a single system. For containers, it is widely accepted that the Docker container is one of the best technologies as a BaaS container [2, 5, 20] not only in the runtime environment, but also in the development environment [21]. For example, IBM's BaaS has its unique IBM secured services container. Nova et al. [22] uses Docker as virtualization. Chen et al. [11] proposed a function of container as a service in the service layer, which takes the container as a service and also uses the idea of container. Lu et al. [10] mentioned in the evaluation section that the inspector seals the containers if the process of on-site loading complies with the regulations and adopted the containers, but did not specify. For virtualization, Singh et al. [18] introduced the coming AMD secure encrypted virtualization in silicon-based trust. Melo et al. [20] explained that Docker can not only be used as a necessary tool to run the system, but also can virtualize the software and apps over the host operating system's kernel. Bose et al. [23] pointed out that the transaction or flow table entries are checked by the virtual controller when introducing DDoS. Therefore, virtualization is a good solution. When introducing BaaS applications on Industry 4.0, Petroni er al. [24] pointed out that the CPS (Cyber Physical Systems) layer is interconnected to the physical elements through sensors and actors, so that the monitoring and control of the physical environment can be performed from the environmental environment. Aujla et al [25] describeed the virtual environment and introduced the virtual switch, which can also confirm the existence of virtualization. Asherieva et al. [19] pointed out that the virtual processor queue can represent the processing of tasks when analyzing the proposed system, and the virtual processor queue can also verify the existence of virtualization.

(4) Interfaces

An interface is a key component of the service-oriented system. In BaaS, the clients access the blockchain functions through interfaces. The rare existing research about BaaS interfaces mostly just mentioned the types and functions of interfaces, but did not conduct any further study. Among those interfaces, the SDK is a commonly used interface in [2, 10, 12, 21–23, 25–28], of which Java, Python and Go are the most popular programming languages. Besides, the most widely used interface is the RESTful API, such as in [2, 5, 12, 21]. Also in [11] and [10], interfaces are in the shape of API gateway, which is easy for the caller to perceive the existence of various back-end services. Unlike the academic, the commercial BaaS systems offer both SDK and RESTful API as interfaces. For example, Microsoft's BaaS offers both ABDK (Azure Blockchain Development Kit) and RESTful API. IBM's BaaS also provides both types of interfaces. SaaS-based BaaS systems provide graphical user interfaces for tenants. Similarly, Al-Zaharani et al. [28] adopted a web interface provided by Multichain blockchain to deploy a private blockchain network.

(5) Customization

As a service technology, customization is an essential function of BaaS. Many BaaS systems provide various customized services. When evaluating the trust of tenants, Singh et al. [18] proposed that the tenant can select and pay for the services consumed, and may have options to customize and configure the services. And when providing the duty of the provider, in a PaaS-like setting, the tenants can select, use, integrate and customize components according to their security and privacy needs. In NutBaaS [5], the automated deployment operated by the blockchain implements the customization of the app. While in the resource layer of NutBaaS, the combination of features provides some customized blockchain services, further reducing absorption barriers to the development. Besides, the identity-chain technology allows enterprises to customize the user account system, including the choice of encryption algorithm, etc. In the BaaS-HIE system [17], a patient can firstly create electronic health records collected from devices, then send them to the customized smart contract for a complete analysis. Lu et al.[10] proposed that users can set the blockchain setting, and also can use BaaS to set a customized blockchain network, but they do not provide enough details about the network customization. Al-Mamun et al. [29] used the customized consensus algorithm, which includes the customized PoW (Proof-of-Work), customized PBFT(practical Byzantine fault tolerance), etc., and these algorithms make the system perform better. The aforementioned customizations focus on the configuration, business function and core algorithms of BaaS, however, they are mentioned in the paper very briefly. There is no detailed studies about customization. Thus in section 6, we argue that BaaS customization still remains an unsolved question.

(6) Evaluation

Among the existing studies on BaaS, several have qualitatively or quantitatively evaluated the system. Melo et al. [20] took a modeling methodology based on Dynamical Reliability Block Diagrams (DRBD) to evaluate the reliability and availability of the system of a BaaS infrastructure. To evaluate the two dependability attributes, there are several steps, which are system understanding, metric definition, environment definition, input parameter survey, design dependability models, dependability evaluation and sensitivity analysis. At last, the reliability evaluation shows that the system has almost 100% chances to suffer from a failure in less than 31 days, so periodic maintenance must be done, and redundancy techniques can be applied to the proposed environment as an attempt to improve both the availability and reliability results. The similar work also evaluated the availability of BaaS over four different infrastructures hosting a blockchain [22]. They are baseline, double redundant, triple redundant, and hyper-converged. The obtained results demonstrate that the hyper-converged architecture has an advantage over a full triple redundant environment regarding the availability and deployment cost. Onik et al. [30] presented the evaluative judgement, by comparing various BaaS platforms, along with the trajectory of adoption, challenges and risk factors. The paper is titled as "performance comparison", but does not give any quantitative results, and the comparators are commercial systems which have been covered in section 3.1.

4. Known applications

As a service system, BaaS is famous in service provisions and applications. With the founding of IBM's and Microsoft's BaaS systems, BaaS entered the market of applications. Nowadays, BaaS is broadly used in various domains, such as machine learning, finance, data tracing, etc. This section introduces these applications in both academic and commercial prospectives.

4.1. Academic applications

In academia, many researchers combine BaaS with advanced research areas, and fully utilized its advantages to promote the current technologies. Considering from the state-of-arts researches, these areas mainly include machine learning, software defined networking, as well as data and transaction services. In this section, BaaS applications in these three fields are introduced and discussed.

(1) Machine learning

A blockchain is a method of storing a list of entries which cannot be changed easily after being created. While machine learning gives computers the ability to learn without being explicitly programmed. Intuitively, BaaS and machine learning are two disjoint domains. However, recent research has shown the application of BaaS on machine learning, and that BaaS can improve the defects of machine learning through its own advantages. Mendis et al. [26] defined two major problems in machine learning, which are the issues of privacy and the related concerns,namely, a huge demand on communication bandwidth and a dramatically increased attack surface when collecting tremendous raw data from multiple parties. For these problems, they designed a blockchain-powered decentralized computing paradigm for machine learning.Some disadvantages of BaaS can also be fixed by advanced machine learning methods. To enhance the performance of the blockchain-empowered MEC system, Nguyen et al. [27] proposed an optimization scheme which can maximize the edge service revenue and the blockchain mining reward while minimizing the service computation latency. For this problem, a novel Deep Reinforcement Learning (DRN) approach which uses a double deep Q-network (DQN) algorithm has been formulated. In this approach, there are several DRN's definitions of specific states, such as the state space and action space.The blockchain's immutability and decentralization may not promote machine learning's demands on performance and precision. Due to the rapid development of AI, machine learning has great research prospects in the future, and the emergence of BaaS makes the development of machine learning more diversified. The high security and high computational efficiency of BaaS can improve the security and learning efficiency of machine learning. Therefore, with the progress of BaaS, the application of machine learning and BaaS will also be well developed.

(2) Software Defined Networking

SDN is a new and creative network framework which can make the control of a net-work traffic flexible. In BaaS, there are several applications in the SDN scenario. The most common attack at the data plane is malware injection via a compromised switch that is part of the normal flow. The flow tables and packets of the flow are secured when using permissioned blockchain. Tasks like creating a new block and adding to a blockchain are limited to the controller in a permissioned blockchain manner. The consensus mechanism is realized using a proof of stake mechanism wherein the controller stakes its network topology repository [31]. Among various SDN attacks, DDoS/DoS is one of the most popular kinds. There are some BaaS applications which can solve or mitigate these attacks. Bose et al.[23] proposed a BaaS for the SDN which can reduce Distributed Denial of Service (DDoS) attacks. Although the SDN is a popular network technology, an attacker can easily capture any forwarding device and restrict the availability of the controller using different prevalent attacks, so the BlockchainSDSec model and BaaS to mitigate DDoS are proposed to solve the problem. In this solution, many features of BaaS have been considered, such as privacy and integrity. Also, the BlockchainSDSec model is based on the SDN model, which adds the data of more than one layer of the SDN architecture into blocks. It has phases of verification, flow table updating and block creation. Aujla et al. [25] introduced an application on smart city optimization. BlockSDN, a BaaS framework, for the SDN is proposed to solve the problem of SDN being attacked by various types of attackers. The architecture of permissioned blockchain is presented followed by two attack scenarios, a malware compromised switch at the data plane and a DDoS attack at the control plane, to demonstrate the applicability of the BlockSDN framework for various future applications. BaaS applications on SDN is a hot topic. As a new network framework, the SDN has advantages of high scalability, high network resource utilization, and support for multiple services. However, as mentioned in the previous application, the SDN is easily broken by DDoS, and the current SDN still has shortcomings such as high program complexity and high computational pressure. The computing power and security provided by BaaS can make up for these shortcomings. So in the long run, the application of SDN and BaaS has a good development prospect.

(3) Data and transaction services

Data and transaction services are the basic services of the blockchain. Although nowadays huge amounts of meaningful data are collected daily, but because of privacy and security problems, few people would like to share data with others. Therefore, it is a suitable approach to adopt a BaaS system to solve data security and privacy problems. The main application scenarios are data storage and data sharing. BaaS is naturally applied in both scenarios. Nevertheless, the related works are not plenty for BaaS, and they most concentrate on the blockchain itself [32]. Some researchers propose a subscription-based data-sharing model which contains data as a service and blockchain technologies [28]. This model consists of two main entities: the data provider and the data user/subscriber, and offers three elaborated models: business models, subscription-based data-sharing models and pricing models. Besides that, this model has a data access mechanism and authentication to enhance security. Through several simulated experiments, it is shown that the feasibility and rationality of the proposed model are demonstrated. When BaaS is applied in the cloud storage for data and transaction services, the main problem in the cloud is the security and privacy of data [33], and there is a huge possibility that the owner of the cloud would change the user's information. To avoid this situation, Singh et al.[33] proposed a BaaS system whose technology can be relied on in terms of data sharing and storage within the groups in the cloud. This system uses a key generation algorithm and other security technologies and methods to enhance the security of the cloud. Ochoa et al. [34] designed a BaaS for the Battery Energy Storage System (BESS), which is actually the storage of transactions. This BaaS application offers various services to BESS, including security, supply chain, health monitoring, data sharing, and energy transactions. Since BaaS is still a work in progress, the users can not fully benefit from the advantages of the blockchain until there is a massive adoption of the BaaS technology by companies and developers.

(4) Internet of Things

Edge computing and cloud computing are two equally suited hosting platforms for BaaS. Since although the existing solutions are mostly based on cloud computing, edge computing is a suitable infrastructure in terms of computational resources and latency [35]. Edge computing is a distributed computing framework that brings the enterprise applications closer to the data sources, such as IoT devices and local edge servers. There are many studies on combining BaaS and IoT on one hand, and developing IoT based BaaS on the other hand, BaaS being thought as a possible technique to improve IoT [36]. For example, by capitalizing on these promising properties, researchers and industries are trying to integrate the Blockchain technology into the IoT context. Some interesting results achieved so far refer to security functionalities (such as authentication, access control, and intrusion detection), lightweight implementations, and shared economy applications [37]. The integration of the blockchain and IoT ecosystems has become an overarching industrial and academic topic covering many use-cases: IoT access control [38], secure firmware updates [39], energy systems [40], dataset sharing [41] and so on. Concepts of collaboration frameworks for the blockchain and IoT have been of research interest in terms of digital asset management, IoT devices management and configuration, secure information distribution, and so on [42]. Samaniego et al. [43] first proposed the combination of BaaS and IoT. A key challenge in the deployment of BaaS for the IoT is the hosting environment. The authors evaluated the use of cloud and fog as the hosting platforms, and got a clear performance analysis which shows that network latency is the main factor and that fog outperform the cloud. With the development of IoT, the age of Industry 4.0 is coming. Petroni et al. [24] presented an architecture that enables the blockchain to verify certain services in Industry 4.0. There are 5 layers in this architecture, and the IoT layer works as a service bus which can combine, match, and integrate different services. Specifically, this architecture has been applied in an anonymous steel company. By Industry 4.0 structural elements and communication protocols, creating rules or smart contracts through the cyber physical systems has potential. Also the blockchain can protect the communication and data security of the IoT from malicious cyber-attacks [44]. Pesic et al. [21] presented a Hyperledger Fabric-based BaaS for addressing identified challenges. They show that the semi-automated blockchain deployment, business logic prototyping and integration with existing IoT systems can be easily managed through specifically tailored deployment workflows and mechanisms with the Hyperledger Fabric blockchain technology. Resource management and pricing can be well applied in the IoT system with BaaS and Mobile-Edge Computing (MEC) [19]. Some works not only combine BaaS with the IoT, but also apply them to special domains. The typical ones are symbIoTe [45] and BaaS-HIE [17]. symbIoTe [45] is a project funded by European Commission that aims to improve the interoperability between different IoT platforms. It provides a solution to federate IoT platforms so that they will be able to share resources between them, granting access to data of sensors, actuators, and virtual services to the users of any platform of the federation. The design work of BaaS-HIE (BaaS for Health Information Exchange) [17] involves the use of IoT technologies, a private blockchain and smart contracts as an access control manager to medical records. All of the health data is encrypted and stored into a decentralized Interplanetary File System (IPFS) and the hash of assets URI is stored in a blockchain. The proposed BaaS-HIE system enables the interoperability of HIE and the permission management in a secure, private and auditable way by leveraging unique properties of the blockchain technology in an IoT-EHRs/EMRs scenario.

4.2. *Commercial applications*

In industry, the first application of blockchain is the well-known Bitcoin. Examples of non-monetary applications of the blockchain include the settlement of securities , supply-chain, HR management, healthcare, decision making, personal data management and so forth. As far as BaaS is concerned, it replaces the blockchain platform and is used in many domains. There would be so many scenarios for applying BaaS. To what extend an application fits BaaS properly is determined by how many benefits it obtains from both blockchain technologies and services. The first domain is manufacturing with the demand of traceable products. For example, food tracing is a proper application of BaaS to ensure the origin and check-points the food has passed before reaching the end-consumers. In this case, BaaS could help provide information about the food source, and ensure that the food does not get contaminated during the transportation from the source to the destination [16]. For example, the VeChain organization food safety solution is based on their own BaaS system called ToolChain. The application helps provide full food traceability and improve trust and integrity. 71% of consumers are willing to pay an additional average premium of 37% for companies to offer full transparency and traceability [46]. The second domain is e-paying with predefined rules or contract. Taking paying royalties for publishers as an example. Paying royalties includes when and how these royalties are paid. This is a good BaaS application because the blockchain depends on smart contracts, so pre-defined stipulations could be written in the smart contract to help automate these payments.

Microsoft uses this particular system to pay Xbox games' publisher royalties. Since Microsoft implemented its BaaS system on these cases, the paying efficiency has been promoted from days to minutes, and 70% of the staff for accounting reconciliation have been reallocated to other projects [16]. The third domain is the financial management for a business. For example, BaaS systems that support finance management and product provenance. Alibaba's BaaS provides many applications on this case. It supports end-to-end traceability and counterfeiting services which help companies to solve issues concerning lack of information transparency and data tampering. Other usages include improving shipping time and delivery [16]. Workflow applications such as Microsoft workflow BaaS helps companies digitize all the trading work connected with other companies [30]. The fourth domain is the public ledger or information sharing system with immutableness, verification and authentication. For example, Leanne Kemp, a veteran supply-chain professional specializing in jewelry, diamonds, and insurance claims, had an idea in 2015 for a new way to finance and ensure of diamonds, namely, if a diamond's identification and transaction verification are available via an immutable ledger, fraud and theft would be exposed. So one of the oldest and most respected blockchain networks was born, and now it is also the best blockchain in the area of diamonds [16].

5. Challenges and opportunities

The blockchain technology has some drawbacks, including storage space, transaction throughput, accessibility, cost issues, network congestion, block size, or synchronization mechanism. Thus, the technology still needs improvement [47]. Some research mainly focused on blockchain optimization [17]. BaaS inherits the challenges of the blockchain, moreover, it also has its own challenges which are to be discussed in this section.

(1) IoT versus services

Integrating a full blockchain framework into an IoT system is a cumbersome task. It requires setting up an entirely separate infrastructure, which also often requires specific technologies, protocols, and hardware requirements in terms of storage space, CPU utilization and RAM consumption, as well as applications in IoT, systems, frameworks, and mechanisms. Providing IoT-based blockchain capabilities as services also brings new challenges. The service provision approaches for the cloud computing are not directly applicable to the IoT system. For example, BaaS requires greater processing capabilities than that of a typical node in an IoT ecosystem (e.g. smart watch, embedded device, Raspberry Pi), so does the service provision. Also IoT devices lack support for 64-bit operating systems, as nodes in most blockchain platforms require 64-bit OS. In summary, the IoT-based BaaS should enable most of IoT devices to participate in the blockchain ecosystem, through an IoT oriented blockchain framework, capabilities on deploying nodes at resource-constrained devices (embedded devices, sensors, etc.), tailored communication modules, re-designed workflow of transaction processing, and lightweight services API. Efforts in IoT-based BaaS must also be directed towards monitoring transactions, blocks, users, and device's health, as well as the topology changes capture, resource sharing and computational offloading and managing complex privacy models [21].

(2) Transparency versus customization

Increasing the transparency of blockchain deployment and runtime through BaaS could help reduce the technical barrier of a blockchain. Increasing the customization makes BaaS more adaptable and acceptable to the applications. Both two criterions are strongly related to the granularities of interfaces because clients see through, use and customize the system through service interfaces. Finer granularity of service interfaces promotes customization but breaks transparency, while the coarse granularity of service interfaces increases the transparency but leaves less space to the system to be customized. Current research about service interfaces mostly discusses the types rather than the granularities of interfaces (see section 4.3). The reason for such situation is the lack of taking both transparency and customization of BaaS into consideration. For the transparency, the BaaS provider may design it according to the known knowledge of cloud services, or inherit it from the blockchain framework. A careful study about the transparencies of two types of BaaS, i.e., eBaaS and dBaaS, is on demand. For the customization, according to section 4.3, related studies are also rare. Customization should include not only smart contracts, but also other mechanisms such as membership, authentication and authorization, consensus, data storage, node types and infrastructure. Some high-level customization even includes the criterions of SLA and QoS [48].

(3) Trustability versus privacy

In a blockchain, the history of transactions is immutable, namely, it can never be removed without breaking the chain. Blockchain transactions are stored in each peer's file system, but any data manipulation on a peer is detected because the hashes for the blocks containing changed data would no longer match the originals. However, BaaS re-introduces an intermediary in the form of a service provider, who often has a relationship with certain participants in the network. For example, some participants may have more power to control the infrastructure than others through their arrangements with the service providers. Thus, BaaS introduces new trust considerations concerning the providers. From this point of view, BaaS seems to run counter to the decentralized trust mechanism of the blockchain. The above situation brings new challenges, i.e., trustability versus privacy. BaaS trustability measures how much a system can be trusted under a BaaS provider. If it is poor, the privacy is critical so that the BaaS provider should offer a service to the clients to off-load parts of data and functions to their trusted location. For example, client machines or clients trust IaaS or PaaS providers. In other words, the BaaS should be securer and more private. We argue that, on one hand, trustability is naturally high for a blockchain system but not a BaaS system, and how to improve the trustability of BaaS remains a blank. On the other hand, privacy is the counterpart of a service based system, and it is a challenge to reach both service orientation and privacy. As BaaS might be applied to more sensitive domains, the trade-off between trustability and privacy remains to be studied. Similarly, the considerations and trade-offs concerning the adoption of cloud services are also relevant in a BaaS context. From security and governance perspectives, businesses relying on a BaaS solution may have less control over the application than when using their own in-house infrastructure. Meanwhile, businesses benefit from an established service provider's "best-in-class" security and resilience solutions, including identity management services [18].

(4) Data localization versus virtualization

"Data localization versus visualization" is a consideration extended from the "trustability versus privacy". Both blockchain and BaaS are distributed in nature, and they subject to data ownership and data privacy regulations [49]. In a blockchain platform, the block data is stored with each participant for the blockchain is a distributed and decentralized ledger. In other words, the data is localized. However, in a BaaS system, the block data is encouraged to be stored in the trusted cloud. The data is said to be virtualized because a participant may own the data and manipulate the data through the service interfaces, and the data is actually managed at the cloud side. Data localization is possible but very challenging for BaaS; if so, the system architecture and infrastructure basis need to be re-designed.

(5) Decentralization versus centralization

The blockchain has a hypothetical nature of the decentralized system [50]. Since it was born, it has always been associated with decentralization in people's mind. In some of the blockchain definitions [51], decentralization is even an essential characteristic of a blockchain system. But a decentralized blockchain platform also contains centralized parts. Actually, some blockchain platforms, like Hyperledger Fabric, have been criticized for including centralized components in a decentralized system. For example, Kafka, the ordering service typically used in Hyperledger Fabric, is currently under scrutiny due to a central point of failure in a decentralized system, as it runs on one node in one organization. On the other hand, the BaaS providers usually adopt APIs for user access or simply migrate the blockchain application to the cloud. Obviously these BaaS systems are provided in a centralized way which erodes the trustless mechanism and incurs the lock-in risk. Most blockchain applications require decentralization, however, there are groups of blockchain users who are not motivated to maintain a blockchain node for ephemeral business collaborations. It makes no difference for those users whether the underlying blockchain is decentralized or not. For example, it might be helpful to architect the BaaS application whose nodes are providers of virtual machines' by the same cloud providers, thus it is known as a centralized approach. Furthermore, the centralized collaboration and decentralized collaboration are often mixed together for a user in different business activities. Therefore,whether the BaaS is formed as decentralization or centralization is a trade-off between the two kinds of requirements. Some believe that BaaS introduces the role of a third-party service provider, which is contrary to the decentralization and trustless mechanism of the blockchain. Others believe that BaaS reduces the uptake barriers of development and improves the security and reliability of blockchain applications, thus would drive the development of blockchain technology [5].

(6) Performance versus energy

Most of blockchain consensus approaches, including the widely used PoW, demand a tremendous amount of power consumption. Thus, their antithetic stand against the notion of green computing has been strongly criticized. However, if tasks associated with consensus are outsourced to the cloud nodes via BaaS, which are already being used anyway, the "extra" demand of electricity for this purpose can be saved. A high-performance blockchain consensus algorithm means that the algorithm will consume as few computing resources and power as possible and achieve better performance during the execution. The relationships between performance, resources and energy consumption are complex and remain to be studied.

6. Conclusion

This paper surveys the recent research in BaaS, including the concepts and classifications, system architectures, service technologies, known applications and open issues. To further understand the intricacies of BaaS, the system architectures developed by both tech giants and research communities have been presented. As the key of BaaS is providing cloud-based services, the service provision, roles, container, interfaces, customization and evaluation are discussed as the service technologies. Moreover, emerging applications of BaaS, including both academic and commercial ones, are presented, among which, the BaaS studies associated with machine learning, SDN, data and transaction services and IoT are emphasized. Nevertheless, there are still a large number of challenges and open issues that need to be solved.

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References

[1] M. Crosby, P. Pattanayak, S. Verma, et al., Blockchain technology: Beyond bitcoin [online]. available, https://scholar.google.com/scholarhl=en&as_sdt=0,5&cluster=8252366061449166107.

[2] Z. Wan, M. Cai, J. Yang, X. Lin, A novel blockchain as a service paradigm. https://doi.org/10.1007/978-3-319-94478-4_20 (2018) 267–273.

[3] A. Nordrum, Govern by blockchain dubai wants one platform to rule them all, while illinois will try anything. https://doi.org/10.1109/MSPEC.2017.8048841, IEEE Spectrum 54 (10) (2017) 54–55.

[4] Blockchain as a service.[online]. available, https://en.wikipedia.org/wiki/Blockchain_as_a_service.

[5] W. Zheng, Z. Zheng, X. Chen, K. Dai, P. Li, R. Chen, Nutbaas: A blockchain-as-a-service platform https://doi.org/10.1109/ACCESS.2019.2941905, Ieee Access 7 (2019) 134422–134433.

[6] Zhang, Pengyi, and Song Jie. , Research advance on efficiency optimization of blockchain consensus algorithms. https://doi.org/10.11896/jsjkx.200700020, Computer Science 47.12(2020): 221-228.

[7] J. Philip, D. Shah, Implementing signature recognition system as saas on microsoft azure cloud https://doi.org/10.1007/978-981-13-1402-5_36 (2019).

[8] Leon johnson, what is a blockchain oracle? medium. [online].available. http://medium.com/@leon.johnson/what-isa-blockchain-oracle-8d7b94d55bf.

[9] Everything enterprises need to know about amazon's blockchain as a service. [online]. available. https://media.consensys.net/everything-enterprises-need-to-knowaboutamazons-blockchain-as-aservice-9bd740e09276.

[10] Q. Lu, X. Xu, Y. Liu, I. Weber, L. Zhu, W. Zhang, ubaas: A unified blockchain as a service platform https://doi.org/10.1016/j.future.2019.05.051, Future Generation Computer Systems 101 (2019) 564–575.

[11] H. Chen, L.-J. Zhang, Fbaas: Functional blockchain as a service https://doi.org/10.1007/978-3-319-94478-4_17 (2018) 243–250.

[12] Y. Chen, J. Gu, S. Chen, S. Huang, X. S. Wang, A full-spectrum blockchain-as-a-service for business collaboration https://doi.org/10.1109/ICWS.2019.00045 (2019) 219–223.

[13] Z. Zheng, S. Xie, H.-N. Dai, X. Chen, H. Wang, Blockchain challenges and opportunities: A survey https://doi.org/10.1504/IJWGS.2018.095647, International Journal of Web and Grid Services 14 (4) (2018) 352–375.

[14] S. Seebacher, R. Schüritz, Blockchain technology as an enabler of service systems: A structured literature review https://doi.org/10.1007/978-3-319-56925-3_2 (2017) 12–23.
[15] Trustsql. [online]. available.https://trustsql.qq.com/.
[16] Karen Kilroy., Blockchain as a service.[online]. available.https://www.oreilly.com/library/view/blockchain-as-a/9781492073475/.
[17] A. Buzachis, A. Celesti, M. Fazio, M. Villari, On the design of a blockchain-as-a-service-based health information exchange (baas-hie) system for patient monitoring https://doi.org/10.1109/ISCC47284.2019.8969718 (2019) 1–6.
[18] J. Singh, J. D. Michels, Blockchain as a service (baas): Providers and trust https://doi.org/10.1109/EuroSPW.2018.00015 (2018) 67–74.
[19] A. Asheralieva, D. Niyato, Distributed dynamic resource management and pricing in the iot systems with blockchain-as-a-service and uav-enabled mobile edge computing https://doi.org/10.1109/JIOT.2019.2961958, IEEE Internet of Things Journal 7 (3) (2019) 1974–1993.
[20] C. Melo, J. Dantas, D. Oliveira, I. Fé, R. Matos, R. Dantas, R. Maciel, P. Maciel, Dependability evaluation of a blockchain-as-a-service environment https://doi.org/10.1109/ISCC.2018.8538752 (2018) 00909–00914.
[21] S. Pešić, M. Radovanović, M. Ivanović, M. Tošić, O. Iković, D. Bošković, Hyperledger fabric blockchain as a service for the iot: proof of concept https://doi.org/10.1007/978-3-030-32065-2_12 (2019) 172–183.
[22] C. Melo, J. Dantas, R. Maciel, P. Silva, P. Maciel, Models to evaluate service provisioning over cloud computing environments-a blockchain-as-a-service case study http://dx.doi.org/10.22456/2175-2745.91814, Revista de Informática Teórica e Aplicada 26 (3) (2019) 65–74.
[23] A. Bose, G. S. Aujla, M. Singh, N. Kumar, H. Cao, Blockchain as a service for software defined networks: A denial of service attack perspective https://doi.org/10.1109/DASC/PiCom/CBDCom/CyberSciTech.2019.00166 (2019) 901–906.
[24] B. C. A. Petroni, J. Z. Reis, R. F. Gonçalves, Blockchain as an internet of services application for an advanced manufacturing environment https://doi.org/10.1007/978-3-030-29996-5_45 (2019) 389–396.
[25] G. S. Aujla, M. Singh, A. Bose, N. Kumar, G. Han, R. Buyya, Blocksdn: Blockchain-as-a-service for software defined networking in smart city applications https://doi.org/10.1109/MNET.001.1900151, IEEE Network 34 (2) (2020) 83–91.
[26] G. J. Mendis, M. Sabounchi, J. Wei, R. Roche', Blockchain as a service: An autonomous, privacy preserving, decentralized architecture for deep learning https://arxiv.org/abs/1807.02515, CoRR abs/1807.02515.
[27] D. C. Nguyen, P. N. Pathirana, M. Ding, A. Seneviratne, Blockchain as a service for multi-access edge computing: A deep reinforcement learning approach https://arxiv.org/abs/2001.08165, arXiv preprint arXiv:2001.08165.
[28] F. A. Al-Zahrani, Subscription-based data-sharing model using blockchain and data as a service https://doi.org/10.1109/ACCESS.2020.3002823, IEEE Access 8 (2020) 115966–115981.
[29] A. Al-Mamun, D. Zhao, Baash: Enabling blockchain-as-a-service on high-performance computing systems https://arxiv.org/abs/2001.07022, arXiv preprint arXiv:2001.07022.
[30] M. M. H. Onik, M. H. Miraz, Performance analytical comparison of blockchain-as-a-service (baas) platforms https://doi.org/10.1007/978-3-030-23943-5_1 (2019) 3–18.
[31] A. Jindal, G. S. Aujla, N. Kumar, Survivor: A blockchain based edge-as-a-service framework for secure energy trading in sdn-enabled vehicle-to-grid environment https://doi.org/10.1016/j.comnet.2019.02.002, Computer Networks 153 (2019) 36–48.
[32] X. Xu, Q. Liu, X. Zhang, J. Zhang, L. Qi, W. Dou, A blockchain-powered crowdsourcing method with privacy preservation in mobile environment https://doi.org/10.1109/TCSS.2019.2909137, IEEE Transactions on Computational Social Systems 6 (6) (2019) 1407–1419.
[33] M. Singh, J. Nirban, S. Singh, A. Raina, S. Oak, Blockchain as a service for cloud storage (baas) https://doi.org/10.1007/978-981-15-1420-3_58 (2020) 550–557.
[34] J. J. Ochoa, G. Bere, I. R. Aenugu, T. Kim, K.-K. R. Choo, Blockchain-as-a-service (baas) for battery energy storage systems https://doi.org/10.1109/TPEC48276.2020.9042496 (2020) 1–6.
[35] X. Xu, Y. Chen, X. Zhang, Q. Liu, X. Liu, L. Qi, A blockchain-based computation offloading method for edge computing in 5g networks https://doi.org/10.1002/spe.2749, Software: Practice and Experience.
[36] X. Xu, X. Zhang, H. Gao, Y. Xue, L. Qi, W. Dou, Become: blockchain-enabled computation offloading for iot in mobile edge computing https://doi.org/10.1109/TII.2019.2936869, IEEE Transactions on Industrial Informatics 16 (6) (2019) 4187–4195.
[37] Y. Li, H. Ma, L. Wang, S. Mao, G. Wang, Optimized content caching and user association for edge computing in densely deployed heterogeneous networks https://doi.org/10.1109/TMC.2020.3033563, IEEE Transactions on Mobile Computing.
[38] A. Ouaddah, A. Abou Elkalam, A. Ait Ouahman, Fairaccess: a new blockchain-based access control framework for the internet of things https://doi.org/10.1002/sec.1748, Security and communication networks 9 (18) (2016) 5943–5964.
[39] Y. Liu, Q. Lu, S. Chen, Q. Qu, H. O'Connor, K.-K. R. Choo, H. Zhang, Capability-based iot access control using blockchain https://doi.org/10.1016/j.dcan.2020.10.004, Digital Communications and Networks.
[40] Z. Li, J. Kang, R. Yu, D. Ye, Q. Deng, Y. Zhang, Consortium blockchain for secure energy trading in industrial internet of things https://doi.org/10.1109/TII.2017.2786307, IEEE transactions on industrial informatics 14 (8) (2017) 3690–3700.
[41] Banerjee, Mandrita , J. Lee , and K. K. R. Choo . , A blockchain future for internet of things security: a position paper., Digital Communications and Networks (2017):S2352864817302900.
[42] S. Huh, S. Cho, S. Kim, Managing iot devices using blockchain platform https://doi.org/10.23919/ICACT.2017.7890132 (2017) 464–467.
[43] M. Samaniego, U. Jamsrandorj, R. Deters, Blockchain as a service for iot https://doi.org/10.1109/iThings-GreenCom-CPSCom-SmartData.2016.102 (2016) 433–436.
[44] T. Faika, T. Kim, J. Ochoa, M. Khan, S.-W. Park, C. S. Leung, A blockchain-based internet of things (iot) network for security-enhanced wireless battery management systems https://doi.org/10.1109/IAS.2019.8912024 (2019) 1–6.
[45] P. Tedeschi, G. Piro, J. A. S. Murillo, N. Ignjatov, M. Pilc, K. Lebloch, G. Boggia, Blockchain as a service: Securing bartering functionalities in the h2020 symbiote framework https://doi.org/10.1002/itl2.72, Internet Technology Letters 2 (1) (2019) e72.
[46] Q. Lu, X. Xu, Adaptable blockchain-based systems: A case study for product traceability https://doi.org/10.1109/MS.2017.4121227, Ieee Software 34 (6) (2017) 21–27.
[47] X. Xu, I. Weber, M. Staples, L. Zhu, J. Bosch, L. Bass, C. Pautasso, P. Rimba, A taxonomy of blockchain-based systems for architecture design https://doi.org/10.1109/ICSA.2017.33 (2017) 243–252.
[48] W. Zhong, X. Yin, X. Zhang, S. Li, W. Dou, R. Wang, L. Qi, Multi-dimensional quality-driven service recommendation with privacy-preservation in mobile edge environment https://doi.org/10.1016/j.comcom.2020.04.018, Computer Communications 157 (2020) 116–123.
[49] X. Chi, C. Yan, H. Wang, W. Rafique, L. Qi, Amplified lsh-based recommender systems with privacy protection https://doi.org/10.1002/cpe.5681, Concurrency and Computation: Practice and Experience 1.
[50] M. Atzori, Blockchain technology and decentralized governance: Is the state still necessary? https://dx.doi.org/10.2139/ssrn.2709713, Available at SSRN 2709713.
[51] R. Marvin, Blockchain: The invisible technology that's changing the world [online]. available. https://www.pcmag.com/news/blockchain-the-invisible-technology-thats-changing-the-world, PC MAG Australia. ZiffDavis, LLC 30.

Conflict of interest statement

On behalf of my co-authors, we declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Research Advances on Blockchain-as-a-Service: Architectures, Applications and Challenges”

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