Fog-assisted Blockchain Radio Access Network for Web3

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***Abstract*—Recently, Web3 has received extensive attention as the next generation Internet and is in rapid development, which can highly integrate the physical world with the digital world. The blockchain that can build trust and fog computing with distributed computing mode can fit well with the decentralization idea of Web3. The combination of the two can provide an effective solution for the implementation of Web3. This paper proposes a new network architecture, fog-assisted blockchain radio access network (FogBC-RAN), which supports stable and mutual trust connections on a global scale, and can smoothly coordinate multi-dimensional resources to support new services such as holographic communication, digital twin, and sensory interconnection. With the interconnection of ten thousand chains in the future Web3, the cross-chain information transfer process based on Polkadot for charging sharing is presented, which can realize flexible cross-chain transactions. Meanwhile, for the mainstream computing-intensive applications of Web3, considering the latency, energy consumption and transaction cost, a computing offloading strategy based on matching game is proposed to minimize the system cost. Finally, the simulation results demonstrate the effectiveness of the offloading mechanism proposed in FogBC-RAN.**

***Index Terms*—Web3, blockchain, fog computing, cross-chain service.**

I. Introduction

With the emergence of the metaverse, cryptocurrencies, and non-fungible tokens (NFTs), Web3 has once again become the focus of attention. The concept of Web3 was proposed by Gavin Wood, the famous CTO of Ethereum [1], in 2017 at the earliest. Web3, defined by Gavin, is an extensible series of technology frameworks that create applications in a new way, through which everyone can have their own digital identity in the network, be able to fully control their own data, and have corresponding digital assets. To date, Web3 is proposed as a typical user-centric Internet to open the new generation of World Wide Web that describes an open, collaborative, secure and trustworthy high-dimensional digital world jointly created by source developers and users.

Different from Web1 and Web2, Web3 represents a new Internet. There is no doubt that Web3 can inherit the original applications of Web1 and Web2 involving social networking, payment, entertainment, education and many other fields, and further upgrade the underlying technology and personal data autonomy on this basis. The application of Web3 will also extend to areas that were not covered in Web1 and Web2. For example, it is believed that the current prototypes of metaverse will develop rapidly in Web3 era. However, to truly usher in the Web3 requires high-quality distributed physical infrastructure on a global scale, deep integration of a series of cutting-edge information technologies such as B5G, artificial intelligence [2], Internet of Things [3], and blockchain [4], as well as a mature business model and a sound policy supervision mechanism.

Although there is no standard definition for Web3, it has some obvious features, including: decentralization, trustlessness and permissionlessness, artificial intelligence and machine learning, connectivity and ubiquity. At present, Web3 is conceived as a new, open consumer-centred value Internet, which can realize the value transformation of data, and provide safe and efficient digital asset management solutions for users.

However, the existing information technologies can not make users hold the ownership of personal data and safeguard digital assets. As a zero-trust/low-trust interaction protocol, the unique distributed ledger of blockchain makes it possible to capitalize digital content and achieve the exchange of value [5]. Blockchain can be regarded as the cornerstone of Web3, based on which the mapping of the physical world into the digital world can be gradually realized.

Distributed storage technology, cryptography, smart contracts and consensus mechanisms are the four key technologies in blockchain [6]. With the support of these key technologies, blockchain as a distributed shared ledger manages to eliminate the existence of centralized institutions, which is tamper-resistant, traceable, collectively maintained, open and transparent etc. With the use of blockchain, trust can be established between different devices and even between mutually independent systems so that all kinds of transactions can be conducted safely and securely [7]. When facing the more sophisticated application scenarios of Web3, blockchain can address information asymmetry and achieve collaborative trust and consistent action among multiple subjects.

Meanwhile, it is noticeable that Internet platforms try to simulate the real physical world in the era of Web3. With the combination of wearable devices, extended reality [8] and holographic technologies [9], users are allowed to immerse themselves in a digital world. It can be imagined that these computing-intensive applications will gradually rise and dominate the market, which have higher requirements for latency and reliability. To cope with the more demanding requirements

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of these mainstream applications in Web3, it is urgent to improve the computational performance of system, particular the margin coverage area. Fog computing is a distributed computing model with vast geographical distribution, which is in line with the decentralized characteristics of Web3 [10]. Fog computing performs storage, communication, control, configuration, measurement, and management operations at edge nodes close to users, which makes it a good fit for applications with very low latency, real-time, and large-scale distribution. Fog computing allows devices to process, analyze, and store data locally or in the network edge when not connected to the cloud.

Thus, the coordination among blockchain and fog computing can provide an effective solution for the implementation of Web3. Specifically, blockchain builds a trust mechanism infrastructure that guarantees the ownership of individual digital assets and safeguards online digital asset transactions, and fog computing provides distributed storage, computing and communication infrastructure, which significantly increases the density of network computing power. Based on the combination of blockchain and fog computing, a secure and trustworthy distributed wireless communication network can be established, which can break the trust and data barriers between people, machines, things and networks, and provide the seamless collaboration of communication, storage and computing resources to support heterogeneous services of Web3.

In this article, we firstly propose a novel architecture of FogBC-RAN for the implemention of Web3, which supports stable and mutual trust connections on a global scale and maps out digital universe. FogBC-RAN permits any FogBC-UE anywhere to enjoy digital life by using its generic, independent and private digital identity. While the progressive realization of Web3 will inevitably result in the coexistence of ten thousand blockchains. Moreover, these blockchains have different properties for being applicable in various applications of Web3. It is essential to find the proper solutions of blockchain interoperability, which is a technical bottlenecks in realizing the circulation of value in scale worldwide and seamless collaboration of multiple resources. Thus, a cross-chain transaction process based on Polkadot for charging sharing is presented to realize the flexible data interaction and asset flow, which improves the expansibility and the application scale of system. Based on the multi-chain collaboration, FogBC-UEs can adopt much more agile data processing mode by computation offloading among the whole system, which especially works for the mainstream computing-intensive applications of Web3. The minimization problem of the total costs of all FogBC-UEs for computation offloading is investigated. A matching strategy based on bidirectional preference sequences is proposed for FogBC-UEs, with the consideration of energy consumption, latency, system rewards and expenses. Finally, the simulation results demonstrate the effectiveness of the proposed architecture and mechanism.

II. FogBC-RAN Architecture for Web3

The Fig. 1 shows the architecture of FogBC-RAN that works in Web3, which is a decentralized mutual trust interconnection network and supports worldwide radio access. With the help of satellites, UAVs, ground and maritime communications, etc., FogBC-RAN further expands the coverage of geographic space, realizes full-area coverage, and meets the connection needs of various users in various scenarios. It is obvious that massive highly heterogeneous blockchains coexist in FogBC-RAN, which can interoperate with each other through the cross-chain protocol. The central relay chain in Fig.1 guarantees the shared security of FogBC-RAN and cross-chain interoperability. The application of blockchain and cross-chain protocol enables efficient and orderly large-scale distributed collaboration, ensuring secure and robust data interaction and providing converged services.

The fog-assisted blockchain user (FogBC-UE) is an intelligent device with computing, storing, perceiving, and communicating capabilities. The massive distribution of FogBC-UEs with different computing power in a vast geographical area effectively improves the computing connection density of the system, and thus significantly enhances the local processing capability of the network edge. Due to the size of the device, hardware technology and other reasons, the computing and storage capabilities of FogBC-UEs are limited. In contrast, the fog-assisted blockchain access point (FogBC-AP) is equipped with super computing capability and data storage capacity. FogBC-APs discretely distributed in FogBC-RAN can significantly increase the computing power density, that is, the computing power that can be provided per unit coverage area of the system. In the collaborative and mutual trust environment, different operators from around the world will not have to worry about security, and can collaboratively dispatch multi-dimensional network resources. To be specific, FogBC-UEs can transfer task of the computing-intensive applications to FogBC-AP of any operator with higher computing power according to offloading strategy, which effectively improves the peak computing power available to a single FogBC-UE and reduces the response latency.

Web3 can bulid a digital world that greatly extends the physical world, creating many scenarios for future life such as smart cities [11], health monitoring, smart traffic, and satellite Internet. Each FogBC-UE has its own digital wallet and the ability to issue and trade fungible token and NFT. All social actions will be recorded on the blockchain. Taking establishing a connection as an example, FogBC-UEs and FogBC-APs are wirelessly connected, and data can be transmitted between FogBC-APs and the cloud at high speed through super optical cable or wireless access. The establishment of connections is a transaction about spectrum resources and time resources. It is supposed that FogBC-UEs and FogBC-APs have unanimously agreed terms for such transactions as connection, and these terms are fully recorded in the smart contract authorized by the digital signatures of both parties. When the FogBC-UE want to connect a FogBC-AP, the transaction will be carried out automatically if the balance of the FogBC-UE is enough to pay for this transaction, and FogBC-AP can also provide enough spectrum resources, and meet other application requirements, such as connection speed and link capacity. When the contract conditions are met, a FogBC-UE uses time-limited spectrum resources to connect with a FogBC-AP, and pays the asset

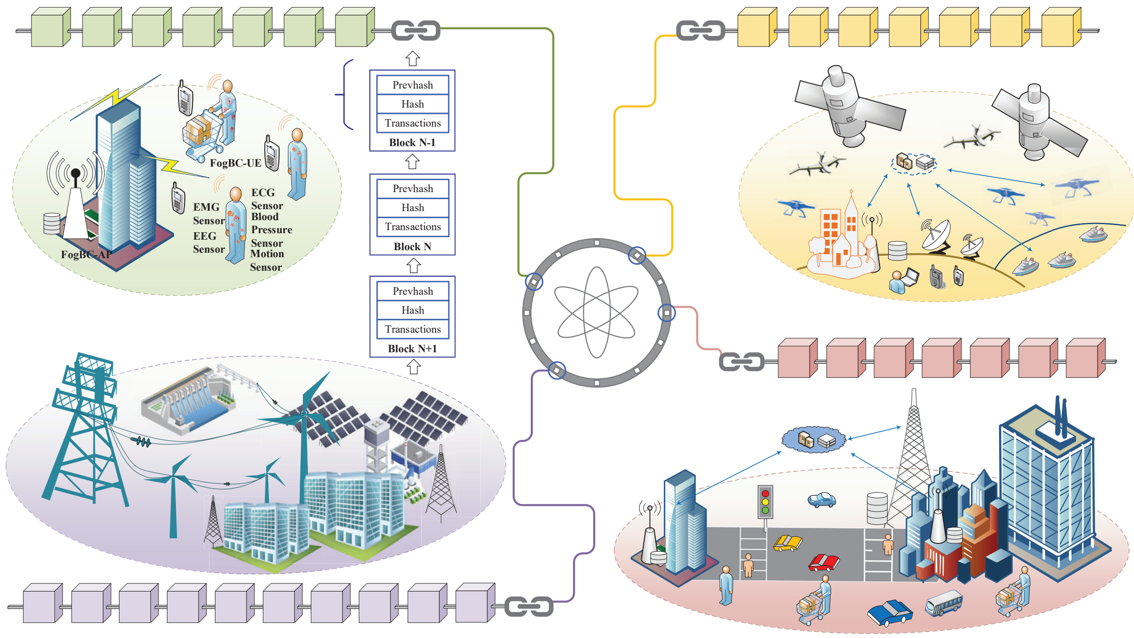

Fig. 1. The FogBC-RAN Architecture.

to the FogBC-AP at the agreed price. Then a new block is generated according to the above transaction process and added to the existing blockchain. After the transaction is done, FogBC-UE will also receive rewards from the system. The open and transparent records of the blockchain ensure that these connections are safe and reliable.

If a FogBC-UE is within the coverage of multiple FogBC-APs, after a transaction request is sent, FogBC-APs of different operators may provide offers according to the service. Then the FogBC-UE can make the optimal choice according to the requirements and its assets. Not limited to wireless connection, FogBC-UEs and FogBC-APs in different applications of Web3 will have various transaction requests. Every transaction that FogBC-UEs and FogBC-APs participate in will be recorded, and according to the specific circumstances of each accumulated transaction, a exclusive reputation record will be formed, showing their own reputation value and abilities. For the FogBC-UE, the record includes wireless transmission capability, computing capability, storage capability, perception capability, etc., and for the FogBC-AP, the record shows supportable wireless access scale, computing power density, storage capacity, and so on. After each transaction, the respective reputation records of the FogBC-UE and the FogBC-AP will also be updated. The reputation value will affect the rewards issued by the system after each successful transaction. Usually, FogBC-UEs or FogBC-APs with higher reputation value will get higher system rewards, which is conducive to energizing FogBC-UEs and FogBC-APs and promoting flexible sharing of resources.

III. Polkadot-based cross-chain transaction

In Web3, different application scenarios and organizations will generate dedicated blockchains accordingly. However, these blockchains may be completely heterogeneous and independent with different data types, security mechanisms, etc., which makes it difficult to directly exchange data between chains. For Web3, the Internet of Value, the greatest vitality lies in the circulation of value. As chains become increasingly specialized, the transaction demand will only increase steadily with the development of human society, and the strong demand for safe and accurate cross-chain technology is growing rapidly.

At present, there are several types of cross-chain technologies. As the blockchain technology gradually comes of age, many cross-chain projects have been launched around the world, the most notable being Cosmos and Polkadot [12]. Nevertheless, Cosmos is a protocol focusing only on asset transfer, not the arbitrary information. Through Polkadot, a large number of heterogeneous chains are connected together and allowed to process transactions in parallel, realizing asset flow, information exchange, and application collaboration [13].

Polkadot is an architecture integrating parachains and relay chains, including multi-layer relay chains and multiple parachains. Polkadot's unique heterogeneous sharding model enables each chain to be improved and optimized according to specific scenarios, which is in line with the development trend of diversified applications of Web3. These settings of Polkadot can fundamentally guarantee obvious superiority in terms of scalability, extensibility, interoperability and security. Meanwhile, more professional blockchains can also bring more innovations, creating some unimaginable new applications for Web3 in the future.

In this section, charging sharing for unmanned driving is considered to demonstrate Polkadot-based cross-chain collaboration in Web3. The market share of electric vehicles has been increasing, but the limitation of their batteries makes charging a regular behavior of electric vehicles. However, most of the traditional charging facilities are placed and independently operated by centralized institutions such as operators, with

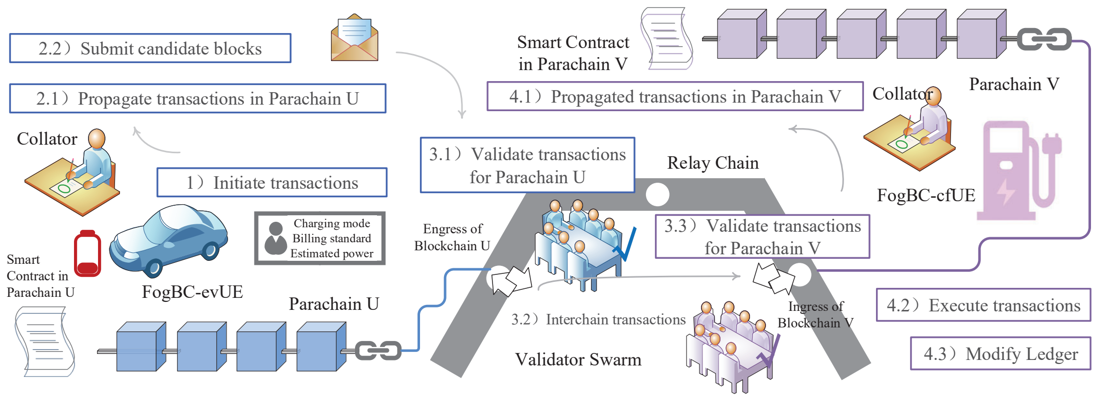

Fig. 2. The Polkadot-based cross-chain transaction of charging sharing in FogBC-RAN.

their own charging protocols and billing models. Privately installed charging facilities are exclusive to the owners, and most of them are put into idle, resulting in a waste of resources. Due to the mobility of electric vehicles and the uneven and discrete distribution of charging facilities, how to flexibly realize timely charging becomes a challenge, presenting an urgent need for shared charging. The discretely distributed entities in Web3 can be connected point-to-point to perform data exchange and support shared charging. FogBC-RAN provides a safe and reliable charging transaction environment for electric vehicles.

Fig. 2 describes the cross-chain process in FogBC-RAN where FogBC-evUE, an electric vehicle user in a blockchain U of smart car networking, successfully has the vehicle charged through the charging facilities in a blockchain V of a new energy company. The smart car networking blockchain U to which FogBC-evUE belongs and the new energy company commercial blockchain V are two parallel chains connected to the relay chain by renting two slots of Polkadot respectively. To meet the specific needs of their respective scenarios, these two parachains have their own economic model and governance model designed based on Layer-1 customized through Polkadot's blockchain development framework substrate. Parachains U and V developed using substrate can directly share the consensus mechanism of the relay chain after connecting to it, because Polkadot will assign them a certain number of validators to help with verification. For heterogeneous chains not developed by substrate, the existing chains can also be connected to Polkadot through corresponding bridges, such as bridge contracts and in-built bridging modules, to achieve interoperability of heterogeneous chains. After connected to the relay chain through the slot, the parachains U and V share trust, and they communicate with each other through the cross-chain message passing protocol. The specific cross-chain transaction steps of charging sharing in FogBC-RAN are as follows: (1) The FogBC-evUE in Parechain U sends a charging transaction request, signs and broadcasts the transaction; (2) The collator in Parechain U collects transaction information (including charging mode, estimated power required this time, acceptable billing standards, etc.), and verifies this transaction information. If it is valid, the collator organizes transaction-related data, packs it into candidate blocks, and puts them at the egress of parechain U; (3) the corresponding validator of parechain U in the relay chain selects the candidate block and verifies whether the block contains only valid transactions. The Validator cluster in the relay chain runs the consensus algorithm to confirm the transaction. After consensus is reached, the validator will move the transaction from the egress of parechain U to the ingress of parechain V to complete the message transmission; (4) The FogBC-cfUE in parechain V receives the charging transaction request from the FogBC-evUE in parechain U, automatically gets configured to provide charging services, and modifies its own ledger according to the payment.

The digital wallet of FogBC-evUEs and FogBC-cfUEs can accept tokens payment and transfer. The multi-chain collaboration mechanism provided by Polkadot enables FogBC-evUE to obtain charging services from different charging operators and private charging facilities without barriers, realizes safe and reliable transaction transfers, and effectively improves resource utilization. This convenient and safe cross-chain operation provides a huge and scalable application space for Web3 in many fields.

IV. Computation Offloading Requests Matching in FogBC-RAN

Web3 supports people to get the sensory experience closest to the real world by wearing a series of wearable devices to extend visual, auditory, and tactile senses, etc. The implementation of these new services relies on massive amounts of text, images, video, and 3D scene data. Judging from the current development of the equipment market, such computing requirements exceed the capabilities of most smart devices.

The computing capability, storage capability and the electric power of FogBC-UEs are all limited. For computing-intensive applications, to effectively relieve the processing burden, FogBC-UEs can trust FogBC-APs with greater computing power and send offloading requests. The delay, energy consumption and transaction cost of offloading are comprehensively considered for minimizing the total cost of all FogBC-UEs.

When sending an offloading request, the FogBC-UE will report the information about the task offloading, including the size of the input data D_n, and the processing densities μ_n

required to execute the application. The task of a FogBC-UE can be offloading to a FogBC-AP by wireless access. The transmission time should be the data volume D_n divided by the wireless link capacity. The task completion time is equal to the amount of computation over the computing capability f_n^m the FogBC-AP m provided, and the amount of computation to accomplish the task is the product of the data volume D_n and the processing densities μ_n. After completing the calculation, the FogBC-AP will send back information to the FogBC-UE, which is the transaction record. But compared with the size of the task, the data volume of this record, offloading requests and calculation results is extremely small, and so usually these times are ignored. And, the verification of calculation results and a consensus can be completed in a very short time. Thus multi-tier validation time is not included in the total time cost.

Therefore, the delay of completing the task is the sum of the transmission time and the processing time. The energy consumption in the transmission phase and in the calculation phase is related to the transmission power of the FogBC-UE and the power during idle waiting, respectively. The total cost for OFCOM (offloading and computing) the task is the weighted sum of the time cost and the energy cost, and the weight factors are the unit price of the time cost (tokens/s) and the unit price of the energy cost (tokens/joules), respectively. At the same time, since the resources of the system are limited and valuable, a FogBC-UE needs to pay the corresponding rental fee to the FogBC-AP to complete the task, which is proportional to the unit CPU cycle price of the FogBC-AP. Of course, when a FogBC-UE successfully complete the task via offloading, the FogBC-UE will also receive rewards from the system. In order to ensure the fairness of the system rewarding for each successful transaction, the reward is related to the proportion of the computing power of the FogBC-AP leased and its reputation value. For FogBC-UEs, the total cost of completing an task offloading gives a comprehensive consideration of the latency, energy consumption, revenue and expenditure during the transaction process. To minimize the total cost in FogBC-RAN, matching game theory [14] is applied to coordinate the mutual selection between FogBC-UEs and FogBC-APs.

For FogBC-APs, FogBC-UEs with faster task data upload are preferred, which can avoid the long-term idleness of computing resources, and provide more efficient services for more FogBC-UEs. Therefore, the utility function of a FogBC-AP is defined as the duration of task offloading. While the FogBC-UE want to be connected with a FogBC-AP with higher transmission rate as soon as possible, stably and economically to complete data transmission and obtain computing results. This reduces the transmission delay as well as the energy consumption. Although there are rewards after the transaction is done, FogBC-UEs still prefer FogBC-APs with the smallest total cost of offloading. According to their respective preference utility functions, FogBC-UEs and FogBC-APs can generate their own preference sequences.

When the matching process starts, each FogBC-UE first sends an access request to the FogBC-AP ranked first in the sequence according to its own preference series. For FogBC-UE m, if the offloading cost to FogBC-AP k is less than that to FogBC-AP k^*, then FogBC-AP k ranks before FogBC-AP k^* in the preference sequence. Considering that the computing capability of FogBC-APs is limited, and also to avoid the situation that some FogBC-APs are overloaded while other FogBC-APs are idle, we limit the number of FogBC-UEs that can be simultaneously accepted by one FogBC-AP. When the number of requested FogBC-UEs exceeds the maximum acceptable value, only the top FogBC-UEs in the preference list are accepted. The rejected FogBC-UEs will continue to send a offloading request to the subsequent preference FogBC-APs according to its preference sequence. When all FogBC-UEs find a suitable FogBC-AP to help complete the task, the dynamic matching process ends.

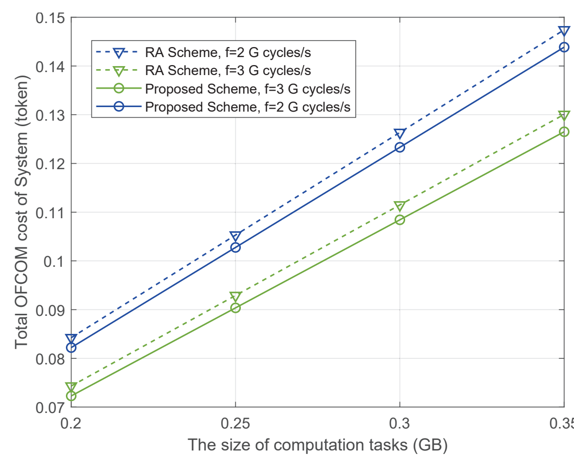

Fig. 3. The total OFCOM cost with the different computation capability of FogBC-APs versus the size of task D_n.

We perform simulation to evaluate the performance of the proposed offloading algorithm. Fig. 3 demonstrates the relationship between the OFCOM cost and the size of task D_n of each FogBC-UE, for the different computation capability of FogBC-APs. The total OFCOM cost increase, with the increasing of the size of task D_n. This is because that the bigger D_n results in the longer transmission delay and the computation time. Compared with the random (RA) offloading, the matching scheme outperforms the RA scheme.

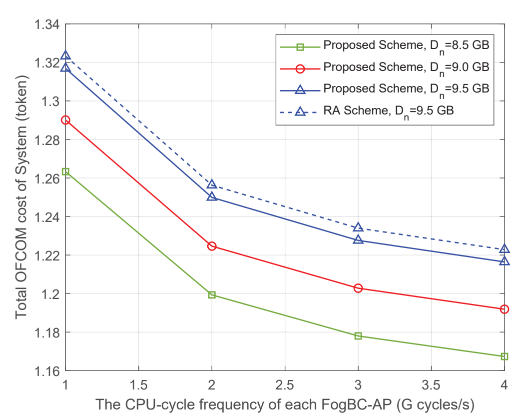

Fig. 4. The total OFCOM cost with different size of task D_n versus the computation capability of FogBC-AP.

In Fig. 4, the relationship between the OFCOM cost and the computation capability of a FogBC-AP under different data volumes is presented. The computation capability of FogBC-APs changes from 1 Gcycles/s to 4 Gcycles/s. As Fig. 3, the performance of the proposed scheme is better than the RA scheme. And it can be seen from Fig. 4 that when the computation capability of FogBC-APs is the same, the smaller the size of task is, the smaller the total OFCOM cost becomes. As the computation capability of a FogBC-AP gradually increases, the computing time decreases, and the total OFCOM cost also decreases, but the decrease will gradually become gentle.

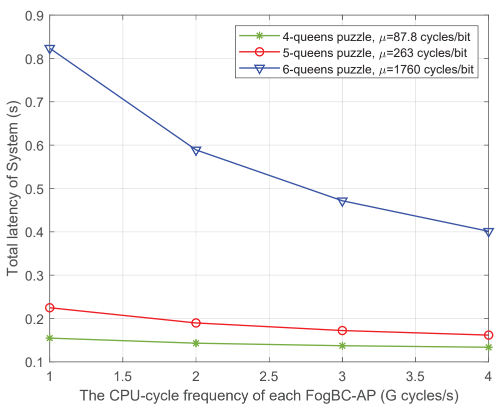

Fig. 5. The total latency with different processing density μ versus the computation capability of FogBC-AP.

Fig. 5 depicts the relationship between the total latency and the computation capability of a FogBC-AP for different applications which varies from 0.5 Gcycles/s to 4.5 Gcycles/s. The application considered is the m-queens puzzle [15], where k takes the values 4, 5, and 6. Three applications have the same size of data D_n but with different processing density μ_n, 87.8, 263, and 1760, respectively. Applications with greater processing density lead to greater overall cost of processing tasks. Likewise, as the computation capability of the FogBC-AP increases, the total latency of the system decreases.

V. Conclusion and Futhur

In this article, the FogBC-RAN is proposed for Web3, which effectively combines blockchain and fog computing to build a decentralized, safe and reliable system. When dealing with converged applications, the produce of cross-chain transactions with Polkadot is described in detail. Then, for FogBC-UEs requiring offloading, suitable FogBC-APs are selected based on the matching game, which effectively relieves the processing burden of FogBC-UEs and minimizes the total cost. The effectiveness of the proposed system architecture and offloading mechanism are verified by the simulation results.

At present, although Web3 has received unprecedented attention, it is still in the early stage of development, and the current industry's understanding of Web3 varies in many aspects. For example, how can Web3, as the technical framework of the metaverse, effectively combine spatial computing, social experience, economic system, creator economy, etc. to successfully build a metaverse still needs to be further explored. User identity is also very important in Web3. How to accurately map users from the physical world to the digital world and how to deal with the identities of users on multiple chains or on the same chain need to be improved. Furthermore, how to provide reliable cross-chain services in the future when numerous chains coexist remains to be explored. Polkadot can connect its parachains through slots, but the number of slots is also limited, which contains the scalability of Polkadot to a certain extent. This is just the beginning, and we look forward to the real arrival of the Web3 era in the future that is believed to bring unprecedented future experience to human society.

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