# Blockchain-enabled Reliable Osmotic Computing for Cloud of Things: Applications and Challenges

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***Abstract*—Cloud of Things (CoT) refers to an IoT solution consuming the cloud services of a single cloud vendor. In this paper, we have introduced the concept of a MultiCoT[1] solution which refers to the collaborative execution of an IoT solution by multiple cloud vendors. Cloudlets and ad-hoc clouds are the extensions of centralized cloud services, closer to the user, in the form of fog and edge computing layers respectively and the Osmotic Computing (OC) serves as a glue by accomplishing the seamless compute sharing across these layers. The OC can also be integrated within a MultiCoT solution for extending it across three computational layers of cloud, fog and edge. However, this can only be achieved after establishing enough trust among all the vendors that are working in collaboration to simultaneously serve a particular MultiCoT solution.**

**Blockchain has been already proven for establishing trust and supporting reliable interactions among independently operating entities. Hence, it can be used for establishing trust among the multiple cloud vendors serving a single MultiCoT solution. In this paper, we have presented the importance of using the proactive Blockchain-enabled Osmotic Manager (B-OM) for improving the reliability of OC. We have also highlighted the blockchain features that can improve the reliability of OC by establishing trust among the independently operating vendors of a MultiCoT solution, followed by the challenges associated with the integration of blockchain and OC along with the future research directions for achieving the proposed integration.**

***Index Terms*—Osmotic Computing, IoT, CoT, Blockchain, MultiCoT, Multi-Cloud of Things.**

## INTRODUCTION

The terms intercloud and "cloud of clouds" were introduced by the Vukolic [1] and are used for referring to the scenarios where multiple services of different cloud vendors are simultaneously serving the deployment of a single application. As the intercloud deployments are managed by multiple cloud vendors therefore, it is crucial to establish trust among each of the participants for maintaining the seamless execution of the deployed system. This need becomes more crucial when more vendors of fog and edge computing layers join the system for shifting computation closer to the user through cloudlets and ad-hoc clouds services respectively.

FaaS (Function-as-a-Service) is one of the ways of sharing the computation between cloud, fog and edge computing layers. However, it is highly optimized for stateless functions and is also managed by a single vendor. Hence, the concept of Osmotic Computing (OC) [2] was introduced for enabling the seamless spread of an application over the infrastructure of cloud, fog and edge, managed by multiple service providers. This is achieved by automatically shifting the load, based on the predefined policies, between different nodes of clouds, cloudlets and ad-hoc clouds of multiple vendors. The execution of operations based on the predefined policies require and a central entity and the Osmotic Manager (OM) [3] serves this purpose by executing the OC through the coordination of participating vendors. However, this approach confines all the participants to trust a centralized OM and the researchers have already highlighted the need for utilizing the blockchain to improve the reliability of the OC by removing the dependence

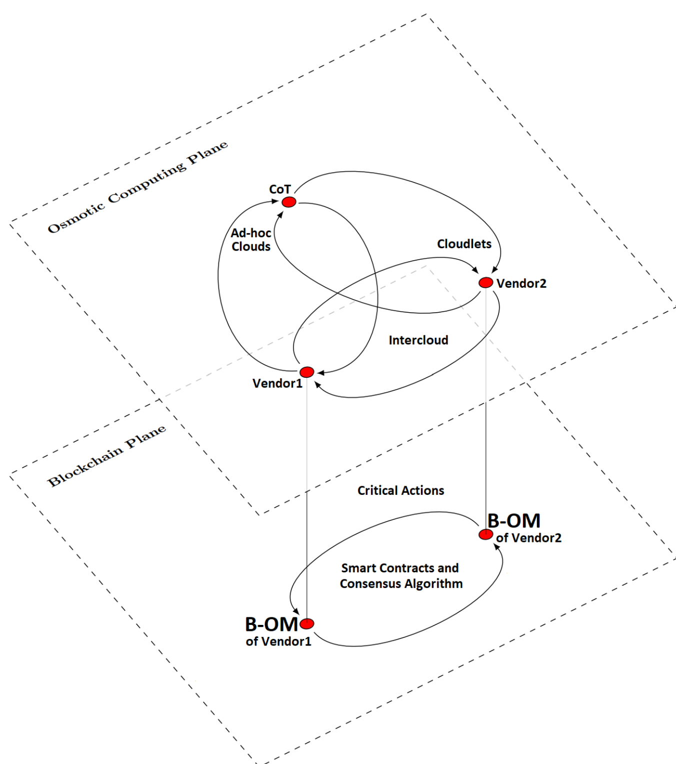


Fig. 1. Using the Blockchain-enabled Osmotic Managers (B-OM) in *Blockchain Plan* for achieving the reliable Osmotic Computing (OC) between the independently operating vendors of the *Osmotic Computing Plane*.

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[1]http://www.MultiCoT.com

on a centralized OM [4]. In this paper, we have extended the same idea of blockchain-based reliable OC by presenting.

Fig. 1 presents two distinct planes of blockchain and OC where the former plane establishes trust among the independently operating vendors in the latter plane. Both of the vendors in the OC plane owns one Blockchain-enabled Osmotic Manager (B-OM) in the blockchain plane for maintaining the blockchain ledger and executing the smart contracts and consensus algorithms. Details of each of the modules in the *blockchain plane* are covered in the third section of the blockchain plane. The OC plane refers to the three different computation levels of cloud, fog and edge and these are referred to the intercloud, cloudlets and the ad-hoc clouds [5] respectively. More details of each of these computational levels are covered in the next section of the *OC plane*.

The scenario in Fig. 1 presents two vendors that are offering cloud services. The given scenario also contains the ad-hoc cloud and cloudlets services where the former services are offered by the *Vendor 1* while the latter services are exhibit by the *Vendor 2*. If one of the vendors of OC plane needs the resources of the other vendor, this operation is labelled as the critical operation and it needs to be approved from the blockchain plane. For example, if *Vendor 1* needs to launch a new VM (Virtual Machine) in the cloud layer of *Vendor 2*, it will first request the underlying blockchain plane to trigger a *smart contract* on its corresponding B-OM. The invoked *smart contract* uses the predefined SLA (Service Level Agreement) for evaluating the legitimacy of the requested operation and approved requests are forwarded to the B-OMs of other vendors in the blockchain plane. The B-OMs of the blockchain plane executes the consensus algorithm for collectively evaluating the legitimacy of the received request for provisioning the requested resources. The *Vendor 1* will only be able to launch a new VM in the cloud layer of the *Vendor 2* after getting approval from the consensus algorithm.

The scenario discussed in the above example presents the feasibility of replacing the centralized authority of the Osmotic Manager(OM) with the distributed ownership through the B-OM of the blockchain plane for supporting the execution of Cloud of Thing (CoT) application hosted in the OC plane. The term CoT refers to the IoT applications consuming the cloud services [6] and in this paper, we have introduced the term of a MultiCoT( Multi-Cloud of Things) solution for such IoT applications that are consuming the services from multiple cloud vendors. The conventional approach of using the centralized OM for OC for MultiCoT is vulnerable to a single point of failure and it also bounds the participating vendors to trust on the centralized OM. However, the proposed B-OM can be used for solving both of these problems.

It has been already recommended by the researchers to incorporate the blockchain and OC for improving the reliability of the whole system [4]. However, a detailed survey on the OC [7] has reported only two papers that have discussed the OC and blockchain and out of these two, only a single study has presented the implementation of a very basic hyperledger based OC solution [8]. Hence, there is a dire need for extensive research on the integration of the blockchain and OC. This paper presents the application of blockchain features for improving the reliability of OC and also highlights the challenges associated with the proposed integrating of both.

## Osmotic Computing Plane: An Enabler for Seamless Compute Sharing

This section explains the different computation levels of cloud, fog and edge and how the single cloud vendor or multiple cloud vendors operate the services at these computational levels. It also elaborates the importance of OC for seamlessly sharing the computation among the computation levels of cloud.

### Computational Levels of Multi-Cloud of Things (MultiCoT)

A technical report by the University of California Berkeley stated the ability of the cloud to give the illusion of infinite resources as one of the main characteristics of the cloud computing [9]. About a decade ago, the cloud got traction as a platform for providing infinite server resources to the connected clients of client/server architecture. However, the growing number of internet-connected devices resulted in the tremendous growth of data generation capabilities and it also pushed the researchers and industry to find the possible extensions of the cloud services for CoT. Intercloud is one of the ways of elastically expanding cloud resources by combining the services of multiple cloud vendors and hence, we are referring the IoT devices connected with intercloud as Multi-Cloud of Things.

Intercloud can be constructed in two different ways of multi-cloud [10] or federation of clouds [11]. When multiple cloud service providers mutually agree on sharing the cloud resources, it is known as the federation of the cloud while the cloud vendors are not aware of each other in multi-cloud deployments. A multi-cloud is formed by the end-user which uses the services of more than one cloud vendor in a way that the vendors are not aware of this setup. Both multi-cloud and federation of cloud uses the services hosted in the centralized data centres and therefore, this approach can be considered as the horizontal resource sharing.

The centralized cloud services can be extended closer to the user through vertical resource sharing [5]. A cloudlet is an example of vertical resource sharing as it offloads the cloud burden by shifting it closer to the user in the form of a mini-cloud [12]. Multiple cloudlets of a single vendor may interact with each other to support the operations of a single application and this computation layer is known as fog computing layer. Fog computing layer not only reduces the cloud burden but also results in the reduction of latency for the CoT devices. However, multiple cloud vendors can also assist each other at the fog layer by offloading computation to the nearby cloudlets for supporting the sudden traffic spikes in MultiCoT solutions.

Ad-hoc Clouds are formed by shifting computation to the edge mobile devices [5]. These edge devices perform the computation for the betterment of themselves as well as the whole system. An important example is the incorporation of federated learning in the Gboard of Android where each mobile device performs the computation for training the predictive models to suggest the words during the typing on Gboard. The trained models are then merged by the centralized cloud and a globally refined model is again shared with the edge mobile devices. Previously this model was trained at the centralized data centres of Google or it was limited to the individual mobile devices through distributed learning. However, federated learning uses the mobile devices for performing the computation which was previously confined to the centralize clouds.

### Compute Sharing between Different Cloud Levels of MultiCoT through Osmotic Computing

The Fig. 1 shows the dispersion of computation at three different levels of intercloud, cloudlets and ad-hoc mobile clouds. OC serves as a glue between these computation levels and is derived from a natural phenomenon, known as osmosis. This phenomenon establishes the equilibrium between two liquids that are separated through a membrane. The movement of particles between both liquids is based on the chemical/physical principles.

Similar to the phenomenon of osmosis, OC also takes the predefined policies and shifts the computation from the cloud to the edge and vice versa through an Osmotic Manager (OM). Traditionally, a single OM is used for executing the policies and running the process of OC. However, it is not a reliable approach in the case of the MultiCoT because the multiple independently operating vendors are forced to trust a single OM. Moreover, it also becomes a single point of failure and the solutions of both of these problems are covered in the next section.

## Blockchain Plane: An Enabler for Reliable Osmotic Computing

Blockchain [13] has been already proven as a solution for removing the dependency on a single entity and distributing the authority among multiple independently operating entities. Bitcoin is the first and most popular application based on the blockchain. There are many important features in the blockchain that make it unique and effective in comparison to the other application development techniques. In this section, we have discussed the challenges of OC along with the corresponding features of blockchain that can be used for tackling these challenges.

### Openness through Shared Ledger

Openness is an important feature for supporting transparent coordination among multiple vendors running the same MultiCoT solution through OC. The integration of blockchain and OC can offer openness by sharing a common ledger among all the vendors operating the same MultiCoT solution. The sharing of distributed ledger is inherent in the blockchain and it will be shared with the B-OM of each participating vendor of MultiCoT. Fig. 1 shows one B-OM per vendor in the blockchain plane. These B-OMs will be having the complete blockchain ledger and will perform the blockchain related operations. The distributed ledger of the blockchain will contain the information of all the operations that have been approved by the B-OMs through the consensus algorithm that have been covered in the next section.

### Trust through Consensus Algorithms

One of the major reason for integrating blockchain with OC is to establish trust among the independently operating vendors of the MultiCoT. The consensus algorithms of the blockchain are used by the participants of the blockchain to collaboratively decide the evolving state of the blockchain and hence, it establishes trust among the independently operating participants of the blockchain. Proof of Work (PoW) is the first consensus algorithm that was introduced with the first blockchain-based cryptocurrency of bitcoin. However, it is a very resource-intensive algorithm as it requires the B-OMs to accept the transactions only after finding a nounce through a highly computational process. Hence, many variants of consensus algorithms have been produced for improving different aspects of consensus process [14]. Therefore, a detailed study needs to be performed for finding the most appropriate consensus algorithm for enabling the OC in the MultiCoT solutions.

### Reliability through Smart Contracts

The smart contracts are machine-readable policies that can be automatically applied against the events to convert these into the transactions for approval from the consensus algorithms. The term smart contract was first introduced by the Szabo in 1994 and the policies represented through smart contracts are mutually defined by the collaborating partners. Hence, the concept of smart contracts can be used for adding reliability to OC as it enables the independently operating vendors of the MultiCoT solutions to define the terms of cooperation in the form of smart contracts. The consensus algorithms execute the transactions defined through the pre-agreed policies in the form of smart contracts. Hence, the consensus algorithms establish trust through unbiased execution of transactions that are reliably defined through the transparent execution of mutually agreed policies in the form of machine-readable smart contracts.

### Agility-Trust Trade-off in Existing Solutions

Agility is the ability to understand the situation and quickly respond with an appropriate reaction Currently, two extremes

TABLE I
COMPARISON OF BLOCKCHAIN-ENABLED OSMOTIC MANAGERS (B-OM) WITH EXISTING SOLUTIONS OF MANUAL AND OSMOTIC MANAGER (OM)

| | **Manual** | **OM** | **Reactive B-OM** | **Proactive B-OM** |
|---|---|---|---|---|
| **Agility** | Low | High | Medium | **High** |
| **Trust** | High | Low | High | **High** |

are followed for supporting the agility feature in the OC. At one end, we handle the decision making manually and on the other hand, decision making is handed over to an autonomous Osmotic Manager (OM) [3] which can quickly respond based on the predefined policies. Former has low agility along with little to no chance of breach of trust while the latter has high agility that we can avail after compromising on trust. Hence, existing solutions bound us to trade-off between agility and trust.

## Reactive vs Proactive Blockchain-enabled Osmotic Manager (B-OM)

Blockchain-based Osmotic Manager (B-OM) solves the problem of agility-trust trade-off discussed in the previous section. A B-OM utilizes the smart contracts for improving the agility by automatically taking decisions (similar to the OM). However, the consensus algorithm, running on multiple B-OMs, verifies the transactions generated through the execution of the smart contract for establishing trust among the multiple collaborating vendors of the MultiCoT solutions. However, the execution of consensus algorithms may cause a delay in the approval of the decisions taken through the smart contract. Hence, we can get high trust through the smart contract-driven transactions of OC but the delay caused in the approval of transactions, through the consensus algorithm, reduces the agility from high to medium.

Table. 1 shows the solution for the agility problem by introducing two types of reactive and proactive B-OMs where a reactive B-OM is only equipped with smart contracts while the proactive B-OM is capable of performing predict analytics along with the execution of the smart contracts. Fig. 1 shows two B-OMs in the blockchain plane and both of these are working as the B-OM for their particular vendor. The push model is used by the reactive B-OM where the transactions are pushed from the OC plane to the blockchain plane and it gives the medium agility due to the delay caused by the execution of the consensus algorithm. However, the agility can be improved by following a pull model where the transactions will be automatically predicted, by the B-OM, after pulling the traffic patterns from the OC plane and using predictive analysis to formulate a transaction ahead of time. A detailed experimental study needs to be conducted for finding the optimal prediction-models for improving the agility by reducing the delay of different consensus algorithms.

## Autonomy with Responsibility

Autonomy is the ability and authority to take decisions flexibly. Autonomy can be introduced by allowing each proactive B-OM to freely define the architecture and policies for predictive analytics. However, this must be done with responsibility because if the decision of a predictive analysis process is not accurate then the corresponding B-OM will suffer the most. In case of a wrong prediction, other B-OMs may need to run the extra consensus algorithm but the corresponding B-OM will be allocated with surplus resources or will suffer from the shortage of resources.

The introduction of blockchain-enabled OC will not only give autonomy of using the proactive B-OM to each vendor but also confine the effects of the prediction algorithm to each of the vendors only. Hence, each participant of a MultiCoT solution can configure the predictive B-OM with full responsibility.

## Privacy through PoE and Access Control Techniques

Proof of Existence (PoE) ensures data integrity without sacrificing the privacy of the actual data and is achieved by passing the original data to a one-way hashing algorithm and using its output for representing the original data. Many blockchain-based projects [13] are already using the PoE, for various use cases, for preserving the privacy of the data stored on the ledger. Hence, the use of PoE can also be explored for supporting the use case of MultiCoT solutions. However, PoE is only one of the many proposed techniques of privacy-preserving in the blockchain. For example, the popular opensource project of the hyperledger uses the concept of channels for achieving privacy. Hence, a detailed research study needs to be conducted for finding the applications of different privacy-preserving techniques for supporting the MultiCoT solutions in future.

## Security through AAA Protocols

AAA refers to the Authentication, Authorization and Auditing and these three are very important for achieving the successful MultiCoT solutions. Specialized AAA protocols need to be defined for supporting the secure and reliable OC in the scenario of MultiCoT. The authentication will be required when a vendor wants to add its resources to the network pool. For example, a service provider wants to replace its malfunctioning hardware, this can only be accomplished after authentication to ensure that only a legitimate machine can be added in the network. However, if a service provider needs to offload its burden by requesting the resources of another service provider then the authorization protocol will decide if the requested operation needs to be executed or not. More details of this scenario are covered in the section of *Next Generation 5G and Tactile Internet.*

The smart contracts and consensus algorithms will be used for enforcing authentication and authorization. The details of all the operations executed after authentication or authorization will be stored on the distributed ledger of the blockchain. The analysis of data stored on the blockchain ledger will support the feature of auditing and the findings of this analysis will help in improving the authorization process. This improvement will occur after using the findings of the auditing process for populating more decision points in smart contracts and consensus algorithm. Hence, the development of a AAA protocol can play a key role in the realization of the reliable OC for the MultiCoT solutions.

### Ownership through Semi-private Blockchain

In contrary to create, read, update and delete operations of a database, a blockchain only supports the two operations of reading and writing and both of these are mentioned at the top and bottom of the Fig. 2 respectively [13]. The public and private blockchain networks are at the two extremes of the ownership and read access. A single owner can write data and can define the data access rules in a private blockchain solution and the authorized users can consider the ledger of a private blockchain as a read-only and append-only copy of a database. On the other hand, a public blockchain solution offers equal reading access to all the users that are interested in accessing the data of the blockchain ledger. The write access is also the same for all the members but the write operations need to be verified through a public consensus algorithm.

A consortium blockchain solution sits between the private and public blockchains as, in contrast to the former, it distributes the reading and writing access between the pre-defined consortium members and in contrary to the latter, it confines the reading and writing access only to the cofounders of the consortium blockchain and no new members can be added as the co-founders of a consortium blockchain solution. A semi-private blockchain sits between the private and consortium blockchains as, in contrast to the former, it gives the reading and writing access to the consortium members and in contrary to the latter, it supports the addition new consortium members. However, the right of adding the new consortium members is limited to a single owner and it makes the semi-private blockchain a better candidate for supporting the OC in the MutliCoT deployments.

In case of a MultiCoT solution, a single application owner distributes the application over different tiers of different service providers. For example, Fig. 1 presents a deployment scenario where an owner is availing the deployment services of two vendors. The vendor 1 is offering the cloud and edge computing services while the vendor two is offering the cloud and fog computing services. A semi-private blockchain solution can be used here where the ownership will remain intact to the owner of the application and both vendors can be added as the consortium members of the blockchain solution. Our proposed solution will also offer flexibility as the owner can very easily add new vendors for extending the application deployment to more vendors or can also remove any of the existing vendors or service providers.

This section has identified the requirements for reliable OC in the MultiCoT solutions and has also mapped the corresponding blockchain features for the realization of the proposed solution.

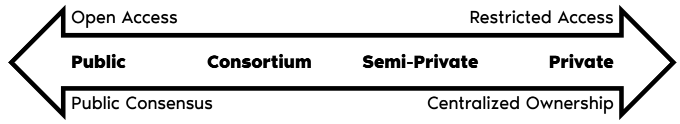


Fig. 2. Classification of blockchain networks

## Challenges and The Road Ahead

The previous section has highlighted many advantages associated with the integration of OC plane and blockchain plane given in Fig. 1. However, the proposed integration is a challenging task and it comes with many open research questions. This section highlights the future research directions that can help in the realization of reliable OC for the MultiCoT solutions.

### Centralized vs Distributed Control

In contrast to the fully centralized control in the database-driven solutions, a blockchain solution offers the decentralization of control by distributing it among the participants. Apart from the decentralization nature, there are some other benefits of the blockchain solutions that we have covered in the previous section. However, a database solution also has some advantages over a blockchain solution like better performance, more fine-grained access control etc. Fig. 2 presents four types of blockchain solutions where the private blockchain solutions are more like as a database solution and have the benefits similar to a database solution. On the other hand, public blockchain solutions purely exhibit most of the discussed benefits of blockchain solutions.

In this paper, we have proposed the semi-private blockchain solution for achieving the OC for MultiCoT solutions. However, there are many public blockchain-based projects that are offering internet services (for example IPFS and Maidsafe), DNS services (like Namecoin and DNSChain) and cloud-like data storage services (like Storj and Sia). All of these projects are supporting more features of the blockchain as compared to the proposed solution of the semi-private blockchain-based MultiCoT. Hence, more research needs to be conducted for finding the merits and demerits of using different types of blockchain solutions for offering reliable OC.

### Prediction Algorithms for Proactive B-OM

Prediction algorithms for proactive B-OM

Table 1 presents the concept of a proactive blockchain-enabled osmotic manager (B-OM) for achieving high agility and high trust. However, the effectiveness of the proposed B-OM is dependent on the prediction algorithm running on the particular B-OMs. Hence, it is very important to define different prediction algorithms against different scenarios for improving the effectiveness of proactive B-OM. Availability of different prediction algorithms will also facilitate the vendors in choosing the more appropriate prediction algorithm against their particular requirements. A detailed research study needs to be conducted for finding the correlation of the prediction algorithm and consensus algorithm to achieve the optimal deployment of OC for MultCoT.

### Improvements in the Consensus Algorithm

The OC involves three computation levels of cloud, fog and edge computing. Hence, the consensus algorithm must be designed in a way that it tries to perform the consensus from the peers from the same computational level. There are already many consensus algorithms available that give importance to particular users and some of these algorithms are the Proof-of-Importance, Proof-of-Authority, Proof-of-Stake, Proof-of-learning [14] etc. Similarly, few vendors are trust-worthy for each other and the consensus algorithm can also be improved by allowing the vendors to define different trust levels for the other participating vendors in a MultiCoT solution. The smart contracts can be used for defining the rank of operation before submitting it to the consensus algorithm and the ability to recognize the priority of an operation can be added in consensus algorithm to reduce the verification time for the high priority operations.

The consensus algorithm can also be equipped with the ability to evolve based upon the feedback of the auditing feature of AAA protocols. Realtime experiments need to be performed for finding the optimal size of a block in the blockchain along with details of data points, associated with an operation, that need to be stored in the ledger of the blockchain. The ability to truncate the extra blocks from the ledger can be added for hosting a stripped-down version of the main ledger on the edge devices and the consensus algorithm can be designed in a way that it can keep on truncating the older blocks from the edge devices while preserving the same blocks on the fog or centralized blockchain storage at the cloud of each vendor.

### On-chain vs Off-chain Transactions

Integration of blockchain with OC adds an extra layer of computation and data storage alongside the existing infrastructure. Experiments must be performed to analyze the overhead in terms of computation and memory so that the application owners can clearly understand the trade-off required for availing the reliable OC through blockchain. In order to reduce the computational overhead and improve the overall performance of the system, the blockchain operations can be further divided into two categories of the on-chain transactions and the off-chain transactions.

The on-chain transactions are recorded on the distributed ledgers after verifying through the consensus algorithm. However, as the consensus algorithms can take time and therefore, some of the operations can be shifted to the category of off-chain transactions. These transactions are not stored in the ledger and hence are not passed through the consensus algorithm. These factors tremendously improve the performance of a transaction which has been shifted from the category of on-chain transactions to the off-chain transactions. In this paper, we have proposed the execution of the prediction algorithm as an off-chain transaction which is proposed to be executed by the proactive B-OM. More operations need to be identified that can be shifted from the category of the on-chain transaction to the off-chain transaction without sacrificing the reliability of the whole deployment.

### Cell Breathing in 5G and Tactile Internet

The Next-generation 5G and tactile internet will be using many small cells, located near to the user, for improving the QoS. There are different types of small cells that are deployed in large number and are limited in computational capabilities. If a small cell encounters more traffic and/or users than its capacity, it offloads its burden to the neighbouring cells through a concept known as the cell breathing. In a real-world scenario, a single venue may have the small cells of many service providers and there are chances that the closer neighbouring cells can belong to some other vendor. In that case, the neighbouring cells of other vendors can support the cell breathing by helping in computational offloading for CPU intensive tasks. The proposed approach of blockchain-based reliable OC can also be adopted for achieving reliable cell breathing between small cells of different vendors in the next-generation 5G or tactile internet.

## Conclusion

In this paper, we have presented the effectiveness of semi-private blockchain for achieving reliable OC in the MultiCoT solutions. We initially identified the problems associated with the OC for MultiCoT solutions, followed by the mapping of the corresponding blockchain features for tackling the identified problems. We have also elaborated the challenges associated with the proposed integration along with highlighting the future research directions for the realization of achieving reliable OC in the MultiCoT solutions.

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