UNIVERSITY OF LEEDS

This is a repository copy of *Blockchain-Enabled Multi-Operator Small Cell Network for Beyond 5G Systems*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/164274/

Version: Accepted Version

Article:

Okon, A, Jagannath, N, Elgend, I et al. (3 more authors) (2020) Blockchain-Enabled Multi-Operator Small Cell Network for Beyond 5G Systems. IEEE Network. ISSN 0890-8044

https://doi.org/10.1109/mnet.011.1900582

© 2020 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Reuse
Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Blockchain-Enabled Multi-Operator Small Cell Network for Beyond 5G Systems

Asuquo Okon[1], Nishant Jagannath[1], Ibrahim Elgendi[1], Jaafar M. H. Elmirghani[2]
Abbas Jamalipour[3], Kumudu Munasinghe[1]
[1]Faculty of Education, Science, Technology and Mathematics, University of Canberra, ACT 2601, Australia
[2]School of Electronic and Electrical Engineering, University of Leeds, LS2 9JT, UK
[3]School of Electrical and Information Engineering, University of Sydney, NSW 2006, Australia
Email: {Alex.Okon, Nishant.Jagannath, Ibrahim.Elgendi, Kumudu.Munasinghe}@canberra.edu.au
j.m.h.elmirghani@leeds.ac.uk, a.jamalipour@ieee.org

Abstract— **Despite the huge deployment of Base Stations (BS), Mobile Network Operators (MNOs) are still faced with the daunting challenge of providing adequate coverage and capacity in indoor environments. Furthermore, the trust-less environment in which MNOs operate makes it even more difficult to achieve interoperability across carriers. Recently the concept of Micro-operators (uO) has emerged as a promising solution towards addressing this problem, through the deployment of small cells. However, their success has been severely hampered by the absence of a framework for creating and managing business agreements between key stakeholders - MNOs & uOs. This paper proposes a blockchain-enabled Software Defined Networking (SDN) approach for managing agreements and radio resources between MNOs over small cell networks. Specifically, our solution uses a smart contract to validate transactions between MNOs. Simulation results shows that our solution guarantees seamless handoff and high availability between different operators in contrast to a break in connectivity in the absence of an agreement.**

Index Terms— B5G, Multi-operator, MNO, SDN, Small Cell, Blockchain, Interoperability

I. INTRODUCTION

Beyond fifth-generation systems (B5G) are driven by diverse use cases which bring extreme requirements to the network. Some of the envisaged Key Performance Indicators (KPIs) include approximately 1000 times higher wireless area capacity, support for much higher data rates in excess of 10 Gbps, ultra-low latency of 1ms, very high reliability, and improved spectral and energy efficiency [1]. With about 50 billion devices expected to be connected to the Internet by 2020, studies have shown that about 80% - 90% of the traffic will be generated indoors [2]. This trend is now placing more demands on Mobile Network Operators (MNOs) to provide the much-needed coverage and capacity to handle this huge volume of traffic.

One key strategy in meeting the capacity requirements of B5G is through network densification or DenseNets [2]. This entails extreme exploitation of spatial reuse through increased deployment of Base Stations (BS) per unit area. Indeed the authors in [3] are of the view that contrary to BS densities of 8-10 BSs/km^2 in 4G cellular networks, the BS density of future networks are anticipated to be in the region of 40 – 50 BSs/km^2, and are expected to support large scale deployment of wireless devices which studies project will be in the region of 1,000,000 devices/km^2 [4]. However, for the MNO, the increased deployment of macro base stations (MBSs) may not be economically viable especially in terms of meeting the coverage and capacity requirements in indoor environments owing to building penetration losses (BPL) [2].

While it is well established that the majority of indoor mobile traffic today is carried by Wireless Local Area Networks (WLAN), these networks are increasingly becoming saturated [8],[9], making them unable to deal with the exponential increase in the number of devices and data traffic that will characterize future networks. This has created the need for the deployment of small cells in indoor scenarios to meet the demands of B5G use cases in terms of capacity and coverage requirements while also providing Quality of Service (QoS) guarantees for vertical industries.

Given the high density of devices expected to be connected over the wireless network, current research efforts are exploring novel techniques for addressing the critical problem of efficient radio spectrum management. One such very promising approach is the use of Blockchain technology – a distributed ledger technology (DLT), for recording a growing list of digital actions or transactions, chained to each other and distributed across nodes [5], [6]. Indeed, blockchain has been proposed by several authors as a facilitator for sharing spectrum assets among operators in a secure and trusted manner [7], [8]. Also recently, Micro-operators (uOs) have emerged as key industry players who through small cell deployments are able to provide not only capacity and coverage but also Quality of Service (QoS) guarantees to complement MNOs in locations that are technically difficult or commercially uneconomic to deploy BSs such as shopping malls, hospitals, campuses, sport arenas and enterprises [9], [10].

To this end, the main contribution of this paper is to present a framework for managing both the network operations and business agreements of multi-operator small cell deployments using blockchain. Specifically, we employ the smart contract feature of blockchain to realize an autonomous, distributed, and reliable architecture for small cell networks. The novelty of our solution lies in the unique value creation it brings to the key stakeholders which we present as follows:

- First our solution enables business agreements between MNOs for managing access to the radio network and network services. Here, the decision metric is the spectrum availability for enabling roaming user access across networks and operators over the small cell network. Our architecture employs smart contracts in managing the complexities of Service Level Agreements (SLAs) and enables radio spectrum negotiation between multiple parties to be automated and executed in a reliable and transparent manner.
- The blockchain layer sits as an overly on the Software Defined Network (SDN) layer and together they provide granular access control and network management at service and device levels respectively.

The rest of this paper is structured as follows. Section II provides a literature review of related work, highlighting key research efforts on small cell deployments as well as identifying gaps. In section III, we present our proposed architecture and the concept behind it. Section IV describes the operation of our model in achieving spectrum management and in Section V, our simulation platform and results are presented. Finally, in Section VI, we summarize our work and give directions for future research.

II. RELATED WORK

The research community is of the view that 5G networks and beyond will not just be an incremental improvement over their predecessors but rather a revolutionary leap forward in terms of data rates, latency, massive connectivity, network reliability and energy efficiency [4]. In meeting with the extreme networking requirement especially in indoor scenarios, densification of small cell network has emerged as a very promising solution. Small cells are low cost, low power base stations that have smaller coverage area relative to macro base stations and are often employed for offloading macro traffic or to complement macro cells in dense networks [9]. Two good examples of successful commercial deployments of small cell networks include Cloudberry, the first small cell operator in the world [11] and Denseair [12].

Following from the above, the emergence of Micro-operators (uO) [9] is receiving a lot of research interest, as it defines a concept where industry/business stakeholders can exploit their domain specific knowledge to establish local small cell networks where context related services and content can be offered with quality of service guarantees in high-demand areas. Such locations may include indoor facilities in high-demand areas such as shopping malls, hospitals, campuses, sport arenas and enterprises [8], [9]. While facility owners do not want a single operator to dominate capacity provision on one hand, on the other hand, they are opposed to the deployment and management of multiple physical indoor networks by different actors [11]. Therefore, in addition to providing the RAN for MNOs, uOs play a strategic role in managing business agreements between the various actors through the deployment of a single shared infrastructure.

In essence, the micro-operator acts as a carrier for carriers by providing services to MNOs under a neutral host arrangement. The two main benefits of this approach to the MNOs are (i) massive cost savings (CAPEX and OPEX) in terms of reduction in the cost of rolling out and managing new base station deployments which in turn reduces time to market and (ii) extension of the MNOs geographic coverage and network footprint thus allowing their subscriber to access network services and applications over a neutral operator's network, which in turn provides additional revenue streams to the MNO and uO.

Several studies have been conducted on small cell deployment for multi-operator or multi-tenancy support [8] – [11]. Some authors propose a framework for indoor small cell deployment managed by micro operators that leverages on network slicing to provide customized services. In their framework, the micro operator is responsible for virtualizing the small cell into network slices realized using Software Defined Networking (SDN) and Network Function Virtualization (NFV) [9]. The assumption that network slicing should be operated by the MNO while 3rd party service providers buy the network slices from MNOs was challenged by [10]. In their view, new stakeholders such as micro operators could deploy ultra-dense small cell Radio Access Network (RAN) for tailored service delivery to various infrastructure providers including MNOs by employing network slices and spectrum sharing techniques. However, network slices require radio resources for meeting agreed service quality, hence the authors are of the view that efficient deployment of ultra-dense small cell RAN calls for novel spectrum micro licensing models. The problem of small cell network sharing with a focus on the business model implications for different multi-operator deployment solutions for indoor scenarios has been discussed [11]. The authors noted that control of the spectrum is key to the business for the independent operator or neutral host, where the capacity to offload traffic and computationally intensive tasks is a vital service offering.

Recent studies have examined the concept of sharing network resources among operators in small cell networks and how blockchain can be used to achieve efficient management of network resources [7], [8], [13]. In [8] the smart contract feature of blockchain is used to manage the attach and detach procedures of a user equipment (UE) to mobile networks, such that the user subscription information and authentication keys are stored in a distributed ledger which replaces the centralized Home Subscriber Server (HSS) used in LTE networks. Authentication and security procedures are performed by communicating with this ledger. In the network sharing arrangement, multiple copies of the same ledger are distributed throughout the network and all nodes retain a copy of the entire blockchain. A proposal to adopt smart contract for the implementation of simple but effective Service Level Agreements (SLAs) between small cell providers and MNOs is presented in [13]. Similarly, blockchain and SDN are used in developing new techniques that remove re-authentication in repeated handoff among heterogenous cells.

From the works reviewed so far, one thing that has clearly not been addressed is how business agreements can be created between operators that will enable subscribers from one MNO to use the services of another MNO in a shared network. Such framework could enable MNOs to leverage on areas where each MNO has comparative advantage to provide value added services to their subscribers in a cost-effective manner, for example in locations where an MNO may have poor network coverage. To the best of our knowledge, our solution is the first to come up with an architecture for enabling both spectrum management and business agreements among MNOs. It will be interesting to develop an integrated framework that can efficiently manage network operations as well as negotiate business agreements between the various actors in a multi-operator small cell network. This gap provides the motivation for this research work as we propose a blockchain-based approach implemented on top of an SDN infrastructure for multi-operator small cell deployments.

III. THE PROPOSED BLOCKCHAN-ENABLED SDN ARCHITECTURE

In designing our architecture, we consider indoor scenarios such as shopping malls, hospitals and campuses, with high user traffic where radio signals from an MNO's macro base station may become severely attenuated, owing to BPL. The architecture is made up of two main tiers. At the lower tier is the Network Infrastructure domain, while the upper tier has the Mobile Network Operator Domain. The proposed architecture is shown in figure 1.

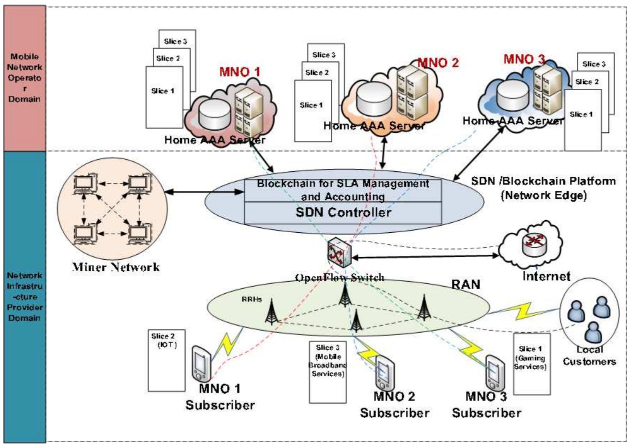

FIGURE 1. Proposed solution for supporting multi-operator small cell deployments in B5G

The Network Infrastructure Domain is owned and operated by the uO and comprises the RAN, the SDN controller and a Blockchain controller (BC). The uO is responsible for deploying the indoor small cell infrastructure following agreements with the facility owners. These indoor small cells are plug and play femtocell access points (FAP) capable of supporting higher data rates, higher number of concurrent users, higher processing power and storage capacity than Wi-Fi access points. The femtocells provide the primary access technology based on the 3GPP standards [14] and they are deployed extensively around the facility to provide adequate wireless coverage.

In our architecture, the SDN decouples network operations into the control and data planes to allow for ease of network management and programmability via software programs. Specifically, the SDN controller domiciled in the control plane is responsible for managing FAPs, UE management, and handling the allocation of traffic to the data plane. The data plane devices carry out packet forwarding based on rules provided by the SDN controller. Communication between the SDN controller and forwarding devices is established using programmable OpenFlow switches.

The blockchain layer is logically designed on top of the SDN layer and is responsible for verifying transactions and agreements between MNOs. Specifically, the blockchain controller serves as the repository for the SLA, which are contractual agreements between MNOs and their subscribers stipulating what customers can expect from the service but not how that service will be delivered. The SLA contains quantitative terms such as QoS metrics (e.g. transactions per second, delay, packet loss rate) for benchmarking network performance written into a smart contract. This smart contract is a computer program (code) that has embedded in it, contractual clauses that are automatically executed once the enforcing or triggering conditions are met.

Every UE negotiates access to the network by sending service requests to the SDN controller via the FAP. The SDN controller passes these service requests to the smart contract by making a transaction to the smart contract address to initialize and trigger the requested service. The transactions once confirmed as valid by the smart contract are broadcasted to the mining network nodes where miners compete to verify the transaction. Once the transactions have been verified by a miner, it is appended to the chain as a block using a harsh value.

The MNOs also communicate with the smart contract by writing transactions to the smart contract address and are made part of the private blockchain network to enable network interoperability. The source code for the smart contract is published in the blockchain, a copy of which is distributed to all participating nodes in the network. In that way, the blockchain platform guarantees immutability and a trustful payment system, ensuring that the integrity of the contract is always protected from dubious or suspicious activities.

Typical information contained in a smart contract include: Device ID, Device location, Subscription and billing information, Participating MNOs, Operating frequency, QoS Parameters (throughput, delay budget, packet losses, bandwidth, etc.), breach of contract clause and transaction history. A brief description of elements in the smart contract is given below.

Device ID: This is the identification number assigned to devices which uniquely identifies the device (such as the UE, core network nodes, blockchain controller etc.) in the network. The device ID is also used for authentication and authorization purposes.

Device Location: Gives the geographic location of nodes on the network. This is useful for mobility management in addition to providing targeted location-based services.

Subscription and Billing Information: Contains the service profile of users or subscribers on the network. Such information includes type and class of services subscribed to by the UE, the billing cycle, the charging rate as well as the validity period of those services.

Participating MNOs: List the MNOs participating in the contract and who have entered into agreements with their peers.

Operating frequency: Maintains information on the frequency bands currently used by each MNO to provide services to its subscribers for purposes of spectrum accountability.

QoS parameters: QoS parameters stipulate the performance metrics against which services provided by MNOs are monitored and evaluated. The services can be characterized in terms of priority, throughput, bandwidth to be provided, E2E packet delay, packet losses, availability etc. Failure to provide the prescribed levels of service amounts to a breach of contract and attracts a penalty (such as debit) which is automatically triggered by the corresponding clause.

Breach of Contract clause: This contains clearly defined thresholds that must be met and the penalties that will be incurred if those thresholds are not exceeded. It contains explicit information on the deliverables by all parties involved, the triggering conditions and how the penalties will be enforced. In scenarios where the contract has been breached after several consecutive billing cycles, the offending party is automatically delisted from the smart contract.

Transaction History: Contains information on all transaction history between participating parties in the network. This can be used for account reconciliation and billing settlements.

IV. NETWORK OPERATION AND MANAGEMENT

A. Radio Access Control and SLA Management

The novelty of our solution is the integrated SDN and blockchain architecture for facilitating business agreements between MNOs needed to manage radio access control in a shared network environment. Our framework seeks to answer a fundamental problem which is formulated as follows:

Supposing a certain MNO say MNO1 has very poor radio coverage and is unable to provide agreed levels of service to its subscribers within a facility as is common in indoor scenarios for example a basement of a large warehouse. However, another MNO say MNO2 has adequate coverage as well as the capacity to provide the prescribed levels of service to these subscribers within the same facility. How can subscribers of MNO1 leverage on the indoor femtocell network to access network services on MNO2 using their existing UE (mobile device and Subscriber Identity Module (SIM) card from MNO 1)?

To solve this problem, the SDN controller which is located at the network edge keeps a register of all UEs as well as their profiles or characteristics. UEs seeking to connect to the network must first be authorized by the SDN controller. Any device which is not registered with the SDN controller is denied access to the network. The BC on the other hand maintains a shared billing system of both MNOs as well as an SLA Manager which is implemented in the blockchain using a smart contract. With this configuration, the smart contract becomes responsible for coordinating and providing billing settlements and agreed levels of service to subscribers. Furthermore, service level authorization by blockchain ensures that only subscribers who have subscribed to a specific service have access to that service.

In terms of network operation, figure 2 illustrates the signaling sequence and transactions that occur between the different nodes and how the smart contract is used for access control and network management. First, the UE performs a radio frequency (RF) scan to discover the available networks within the vicinity. The UE uses the Received Signal Strength Indication (RSSI) values to identify the next available MNO with the strongest signal within its vicinity.

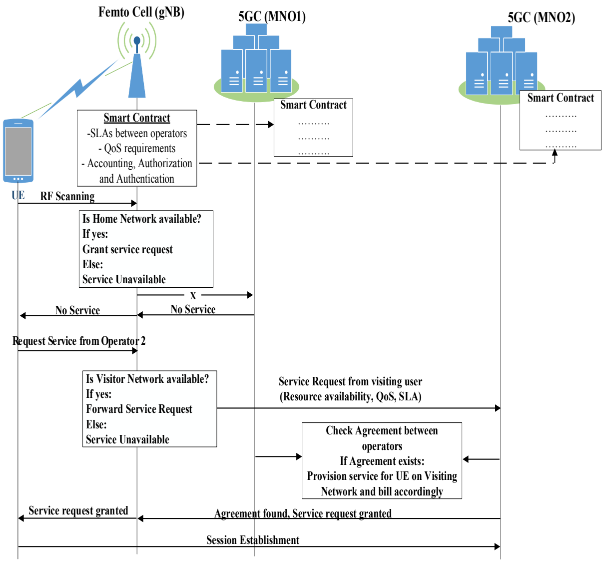

FIGURE 2. Network management signaling diagram using Smart Contract

Thereafter it sends a service request notification to the SDN controller via the FAP about its intention to connect to the new network. The SDN controller exchanges messages with the smart contract which checks if there is any pre-existing contract between MNO 1 and MNO 2. If there is, the controller forwards the request to the MNO 2 core network to confirm that the agreed QoS guarantees as stipulated in the SLA can be provided. Once MNO 2 confirms that it can provide the service, it sends a service grant notification to the SDN controller. Finally, the subscriber establishes a session with MNO 2 over the femtocell RAN and billing procedures are automatically initiated.

The logical centralized control provided by the SDN controller enables it to maintain a global view of the network allowing for efficient monitoring of spectrum usage, proper coordination of spectrum mobility and effective implementation of spectrum sharing strategies among MNOs. The blockchain controller advertises the service profile of the devices on the network to the SDN controller and enforcement of the terms of the contract which is translated into flow rules and made available to the SDN switches. These flow rules determine which devices should be granted access to the network and what type/class of service these devices can access. Thus, access to the network is controlled at two levels – service level using blockchain and device level using SDN. Furthermore, the blockchain layer facilitates a distributed peer-to-peer network where non-trusting members (MNOs) can interact with each other without a trusted intermediary, thus creating a framework for trusted interaction in a trustless environment.

Users carry out digital transactions when a phone call is made, text messages are sent or data is used on the network, leading to large amount of transactional information that has to be verified to ensure customers are billed correctly. In heterogenous networks consisting of diverse devices with different service profiles and service requirements, the lack of consistent billing records of network data could pose serious difficulties for network management and billing settlement.

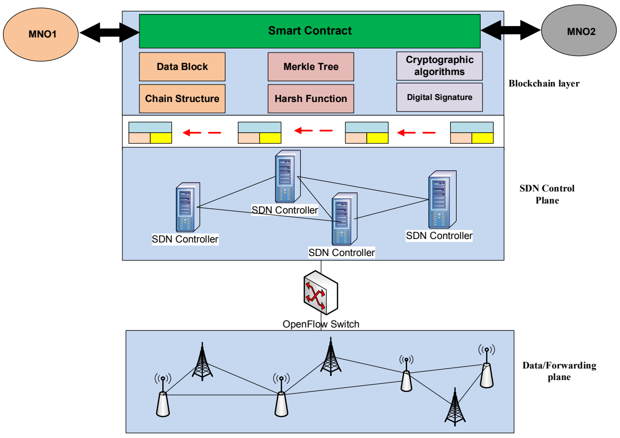

FIGURE 3. Smart Contract implemented in Blockchain layer as an overlay on SDN

Figure 3 shows how the smart contract in the blockchain layer can be implemented on top of the SDN layer. Our integrated SDN and blockchain architecture using smart contracts enables a distributed consistent record of network management data which ensures accurate billing and effective network management. Specifically, the smart contract helps maintain a record of which devices have access to what resources.

V. SIMULATION PLATFORM AND RESULTS

The architecture is modeled using a blockchain-enabled SDN platform consisting of an off-chain smart contract, Ethereum private blockchain and the simulation module. The consensus mechanism employed is the Proof of Work (PoW). The smart contract enables management of access rights needed to facilitate interoperability between multiple operators. The contracts are designed based on the different vertical services users subscribe to and serves as an interface between multiple operators. The private blockchain is initialized on a test-net using Geth (go-ethereum) software and thereafter the genesis file is set up. The genesis file is used to define the genesis block which is the first block of the blockchain [15], which gives information about specifications of the block including such variables as gas limit, difficulty level, coin-base, timestamp and transaction fee.

The simulation is carried out on fifteen (15) Ethereum Virtual machines (VM) in order to provide insight on the frequency of transactions between multiple users and the number of times users access services from the MNOs. The virtual machines run on a Dell Latitude 7400 with Intel(R) Core (TM) i7-8665U CPU @ 2.11 GHz, 16 GB of RAM, and 1 Gbps Ethernet connection. The difficulty level is set to 1 for every block and the approximate block processing time is set to about 10 seconds using the PoW consensus algorithm.

In this paper, our focus is on how the SDN controller and blockchain platform can be used to manage spectrum resources through access control of UEs to spectrum assets (RAN) as well as output from the blockchain. The overall impact of the SDN and blockchain controllers on network performance metric such as E2E delay, throughput and packet losses will be studied in future work.

In studying the impact of SDN and blockchain platform in radio access management, we assume that a contractual agreement between the MNOs is already in place. A UE seeking to access services on different MNO, first perform an RF scan to confirm spectrum availability of the intended the MNO (by virtue of a higher RSSI value) and notifies the SDN controller. The UEs and FAP both have a transmit power of 100mW with the FAP having a coverage range of 50m. Once access has been granted by the SDN controller to the RAN, the UE makes a transaction to the smart contract address to initialize and trigger the services specified in the contract.

Figure 4 shows how the SDN controller and blockchain are employed in the management of spectrum access between MNOs. As the UE moves within the facility, it carries out periodic RSSI measurements of the two operators. When the UE moves away from the coverage area of MNO1, its RSSI value drops over time until it reaches a threshold value called $RSSI_{th}$, beyond which the received signal strength becomes significantly attenuated that the UE initiates a switch to the next available operator. For the purpose of this simulation, we have set the $RSSI_{th}$ value as -73.8 dBm which also serves as the switching point to guard against total loss of connectivity. At this point, the UE sends a signaling request to the SDN controller notifying it of its intention to switch to MNO2 which is observed to have a higher RSSI value.

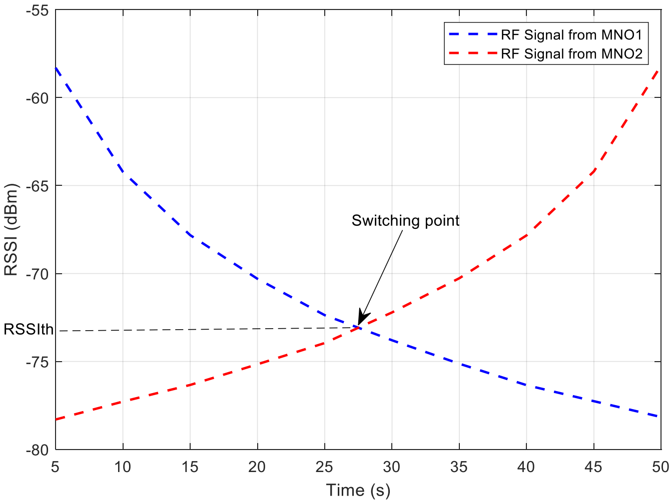

FIGURE 4. RSSI values measured across different networks before agreement

Following this request, the SDN controller initiates a switch between the operators, by writing to the smart contract to confirm availability of an agreement between both operators. With an agreement already in place, network connection is established between the UE and MNO2 and this is written as a transaction into the blockchain. Figure 5 shows network performance with and without blockchain agreement. In this scenario, the network performance is studied when 10 UEs move between 3 FAPS. From figure 5(a), it is observed that without blockchain, the stations experience a total break in connection characterized by a complete drop in throughput as they move from one FAP to another. This is due to the absence of an agreement between MNOs.

The scenario is however different in figure 5(b) where an agreement already exists between operators. Here the presence of an agreement which is enforced in the smart contract enables faster handoff between operators. The handoff delay in moving from one FAP to the next is equivalent to the roundtrip time of sending a transaction in blockchain which from our simulation equals 70ms. Since the service and device profiles of the stations are already known to FAPs through flow rules from the SDN and blockchain, the transition between FAPs is seamless.

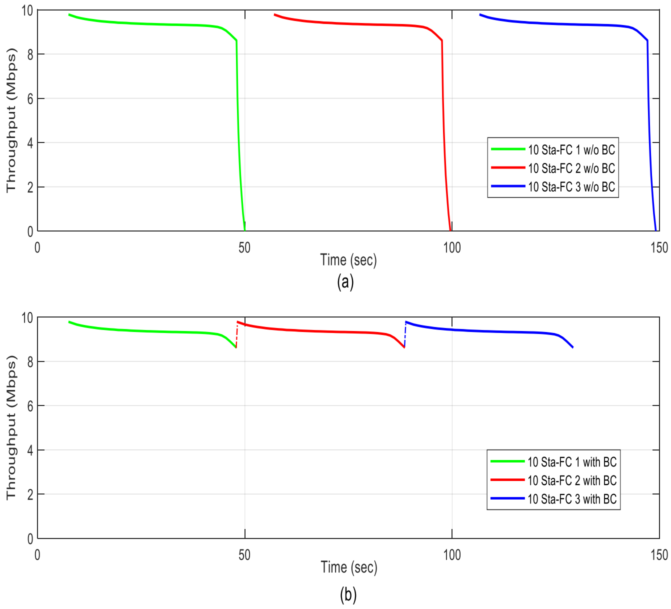

FIGURE 5. Network performance (a) Without blockchain (b) With blockchain

The blockchain performance was also evaluated across different instances with 1, 5, 15 and 25 users actively interacting with the smart contract, each instance was simulated for 600 seconds as shown below.

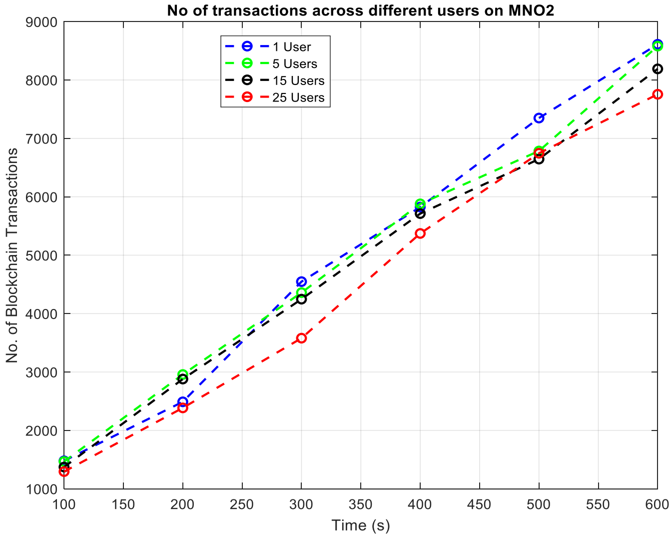

FIGURE 6. No of transactions across different users on MNO2

From figure 6, it is observed that the number of transactions increases over time across the different categories of users, however, the number of transactions mined decreases with increase in users. This is due to the increased number of blocks that have to be processed by miners which in turn increases the difficulty level culminating in a slow consensus. The huge number of successful transactions recorded across the different categories of users from the simulation results clearly shows how smart contracts can enable interoperability across network operators.

Our proposed multi-operator small cell solution very much aligns with provisions of the latest 3GPP Release 15 and beyond which allow support for Multi-operator Core Network (MOCN), whereby Radio Access Network (RAN) can be shared by multiple core networks [14].

VI. CONCLUSION AND FUTURE WORKS

This paper presents a model for multi-operator small cell deployment for 5G systems and beyond. The most important contribution of this work is the development of a framework that enables business agreements between MNOs for managing access to the radio network and network services using the smart contract feature of blockchains. Simulation results show that our platform enables users to access network service across operators.

Future research work includes consideration of additional decision metrics such as minimizing additional latency due to the blockchain, maximizing energy efficiency and maximizing resilience. Furthermore, the resource allocation problem will be extended into a Mixed Integer Linear Programming (MILP) optimization problem. The objective here is to find the optimum number of UEs from MNOs with limited resources that can be matched to MNOs with adequate resources based on some metrics (such as latency, power consumption, resilience). Finally, the effect of the SDN controller and blockchain operation on network performance indices such as E2E delay and packet loss will also be investigated.

VII. REFERENCES

[1] M. Peng, Y. Li, Z. Zhao, and C. Wang, "System Architecture and Key Technologies for 5G Heterogeneous Cloud Radio Access Networks," *IEEE Network* pp. 6-14, 2015.

[2] F. Hu, *Opportunities in 5G Networks: A Research and Development Perspective*, 1st ed. CRC Press Taylor & Francis Group, 2016.

[3] X. Ge, S. Tu, G. Mao, C. Wang, and T. Han, "5G Ultra-Dense Cellular Networks," *IEEE Wireless Communications,* pp. 72 - 79, 2016.

[4] M. Shafi *et al.*, "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," *IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS,* vol. 35, no. 6, pp. 1201 - 1221, 2017.

[5] X. Ling, J. Wang, T. Bouchoucha, B. C. Levy, and Z. Ding, "Blockchain Radio Access Network (B-RAN): Towards Decentralized Secure Radio Access Paradigm," *IEEE Access,* vol. 7, pp. 9714 - 9723, 2019.

[6] M. Saravanan, S. Behera, and V. Iyer, "Smart Contracts in Mobile Telecom Networks," presented at the 23RD Annual International Conference in Advanced Computing and Communications (ADCOM), 2017.

[7] H. Dai, Z. Zheng, and Y. Zhang, "Blockchain for Internet of Things: A Survey," *arXiv:1906.00245v2[cs.NI],* pp. 1-19, 2019.

[8] B. Mafakheri, T. Subramanya, L. Goratti, and R. Riggio, "Blockchain-based Infrastructure Sharing in 5G Small Cell Networks," presented at the 14th International Conference on Network and Service Management (CNSM 2018), 2018.

[9] J. Walia, H. Hämmäinen, and M. Matinmikko, "5G Micro-operators for the Future Campus: A Techno-

economic Study," presented at the Internet of Things Business Models, Users, and Networks, 2017.

[10] M. Matinmikko-Blue, S. Yrjölä, and M. Latva-aho, "Micro operators for ultra-dense network deployment with network slicing and spectrum micro licensing," presented at the IEEE 87th Vehicular Technology Conference (VTC Spring), 2018.

[11] J. Markendahl and A. Ghanbari, "Shared Smallcell Networks - Multi-Operator or Third Party Solutions – Or Both?," presented at the Fourth International Workshop on Indoor and Outdoor Small Cells 2013, 2013.

[12] Denseair. "Dense air." http://denseair.net/ (accessed August 9, 2019).

[13] E. Pascale, J. McMenamy, I. Macaluso, and L. Doyle, "Smart Contract SLAs for Dense Small-Cell-as-a-Service," *arXiv:1703.04502v1 [cs.NI],* pp. 1-2, 2017.

[14] 3GPP. "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Release 15 Description; Summary of Rel-15 Work Items (Release 15)." 3GPP. https://www.3gpp.org/release-15 (accessed August 17, 2019).

[15] S. Asharaf and S. Adarsh, *Decentralized Computing Using Blockchain Technologies and Smart Contracts: Emerging Research and Opportunities*. IGI Global, 2017.