Neutral Host Technology: The Future of Mobile Network Operators

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This work was supported in part by the Ministry of Science and ICT (MSIT), South Korea, through the National Research Foundation of Korea (NRF) under Grant 2020H1D3A1A02080428 and Grant NRF-2022R1A4A3035401; and in part by the Ministry of Education and NRF under Leaders in INdustry-university Cooperation (LINC) 3.0 Project.

ABSTRACT The neutral host network (NHN) is a new self-contained network envisioned by fifth generation (5G) of cellular networks, which offers wireless connection to its subscribers from a variety of service providers, including both conventional mobile network operators and non-conventional service providers. The NHN infrastructure, which is operated and maintained by a third neutral party, is rented or leased to network operators looking to scale up their network capacities and coverage in a cost-effective way. This paper highlights NHN as an emerging communication technology for private networks and discuss its opportunities and challenges in realizing multi-tenanted space such as factory, hospitals, stadiums, and universities. The paper also investigates the current state of the art in NHN and elaborates on the underlying enabling technologies for the NHN. Lastly, an efficient radio access network (RAN) slicing scheme based on the multi-arm bandit approach has been proposed to allocate radio resources to various slices, which maximizes resource utilization while guaranteeing the availability of resources to meet the capacity needs of each multi-tenanted operator. The simulation results show that the proposed Thompson’s sampling (TS)-based approach performs best in finding the optimal RAN slice for all the operators.

INDEX TERMS Multi tenancy, neutral host network, RAN slicing, wireless infrastructure.

I. INTRODUCTION

The sixth generation (6G) of cellular networks envisions the hyper-connected world consisting of an enormous network of connected devices, that can communicate with each other anywhere and at any time. In addition, it will be supported by ultra-fast data speeds, on-demand service-oriented resource allocation, and automated control [1]. These factors necessitate a significant transformation in mobile network infrastructures such that traditional data transmission methods should be replaced by intelligent systems with virtualized computation and storage capabilities. The reasons for this paradigm shift in telecommunication networks can be uncovered through trend analysis of data traffic and customer behavior. According to Cisco [2], 80% of all mobile data traffic is generated indoors from crowded areas such as concerts, sports, hospitals, universities, stations, shopping malls, enterprises, and is rising at a pace of 20% every year. On the other hand, user behavior is shifting away from traditional services including text messaging and voice calls towards high computational and data-intensive activities such as there-dimensional (3D) gaming, networking sites, 4K and 360-degree video streaming, augmented reality (AR) and virtual reality (VR) experiences. Similarly, the introduction of the industry 4.0 campaign has completely revolutionized the industries and factories towards cyber-physical systems...
and Internet of things (IoT) systems [3]. As a result, one of the most enticing features of 6G will be the ability to provide seamless high-quality multimedia content even under adverse network conditions. Several studies [1], [4], [5] have focused their attention on these issues. Network densification has been one of the common choices to mitigate such issues, however, giving uniform cellular coverage for diverse users (i.e., subscribers of different wireless network providers) is still challenging as the number and location of cell site deployment may be limited due to infrastructural and regulatory restrictions. Moreover, these situations may correspond to inefficient and complicated arrangements, caused by duplicate infrastructure deployments by multiple operators. Thus, a more appealing solution would be to establish a single shared network infrastructure that could be utilized by all wireless carriers. In addition, an independent access provider that is not aligned with any of the specific wireless carriers acting as a host for wireless connectivity is one of the prominent solutions to these problems.

Small cells coordination for multi-tenancy and edge services (SESAME) [6], 5G ESSENCE [7], and 5GCity [8] under 5G Public-Private Partnership (5GPPP) [9] have been proposed to enable small cell (SC) intelligent multi-tenancy network operators. In this context, a socio-techno-economic assessment of the neutral host business strategy and market adoption determinants have also been researched on [10], [11], and [12] as a first stage of development of the multi-tenancy technology. Similarly, various research projects on the multi-tenancy approach are carried out both in academia and industry, as in [13], [14], [15], [16], [17], and [18].

The term, neutral host (NH), has been popular for representing the multi-tenancy approach in 5G communication. In the 5G research, the NH is a connectivity solution that allows multiple tenants (for example, conventional mobile network carriers or non-conventional service vendors) to access and utilize the shared resources based on an agreement with a third-party infrastructure owner, operator, and maintainer. NH is commonly used to improve wireless coverage and capacity in big events or other congested areas. The main goal of NH is to achieve deployment flexibility and enhance spectrum efficiency, while curtailing the deployment costs of the systems. In addition, NHN has been also considered as an additional model to the “pure” private networks, often managed by a corporation for internal IoT or telephony applications. For instance, a 5G-enabled factory may be primarily focused on machine vision and robotics, but it may also permit smartphone roaming by staff members and guests onto the coverage of the local network. The rural/remote areas, metropolitan areas, workplaces, arenas, and hotels, roadway and rail track coverage, industrial plants and major transport hubs, short-term events and gatherings (for example, festivals, huge construction projects), and some types of residential and business venues are the primary applications for neutral host network (NHN) deployment. In Fig. 1, we have categorized NHN applications into four categories, namely, indoor, rural, roads and rails, and dense urban areas. The most significant benefit of an NH is that its primary service is the infrastructure itself, which allows the fixed expenses of installations over as many operators as possible. Moreover, when a single network is constructed, wastage of resources is prevented, and space/area is utilized properly. There are, however, difficulties that must be overcome in order to build a model that can serve these capabilities while ensuring that mobile network operators (MNOs) can continue to provide the same or higher service quality compared to what they would if they installed their own networks while retaining network neutrality. Shared spectrum management, seamless integration between the MNOs slice in the NH and their own network, interoperability, security considerations, common standardization, billing, etc are some challenges that need to be solved for NH implementation.

The remainder of this paper is organized as follows. In Section II, we start with an NH technology definition and discuss its state of the art. In Sections III and IV, we elaborate on various opportunities and challenges in realizing the multi-tenanted space such as factories, hospitals, stadiums, and universities. Then, the enabling technologies are presented in Section V, whereas the framework that are already present in the 5G is briefly described in Section VI. In Section VII, we propose an efficient radio access network (RAN) slicing scheme based on the multi-arm bandit approach, which allocates radio resources to various slices to maximize resource utilization while guaranteeing the availability of resources to meet the capacity needs of each RAN slice. In the simulation, we consider an extremely dynamic environment, in which Thompson’s sampling
multi-arm bandit scheme is used for maximizing cumulative rewards over time. Finally, the paper is concluded in Section VIII.

II. DEFINITION AND ITS STATE OF ART

As expected from its name, neutral host is a term that combines two concepts: host and neutrality. The host component signifies an entity that makes a pool of resources accessible to users so that the hosted clients can continue to deliver connectivity services. The “neutrality” component refers to the host’s ability to serve diverse clients as a shared platform. The resources made available to each client are governed by a commercial agreement as well as policy-based administration between the NH and the hosted client. The connectivity services offered by an NH should always be accessible without any user intervention, and they must be seamless and indistinguishable to the host client as if the services have been provided by its subscribed conventional operators. In other words, when a host client of a tenant network operator enters the NH coverage area, the NH should provide radio access services to the subscriber as if the user had direct access to its host network. The general architecture of NHN is shown in Fig. 2. An NHN is consisting of the following core and RAN network elements [19]:

- NH Mobility Management Entity (NH-MME): The primary control node in the NH Evolved Packet Core (EPC) is NH-MME. It is in charge of monitoring and verifying subscriber mobile devices. In addition, it saves location data and decides which gateway to pair with user devices upon registration.
- Local Authentication, Authorization and Accounting (AAA)/Proxy server: The local or distant AAA server, where the user device credentials are registered, is in charge of data service authentication, authorization, and accounting.
- NH Gateway (NH-GW): Data communications between the user and the SP’s PDN GW2 are facilitated by NH-GW. To access the participating SP’s ePDG3 for subscription services, NH-GW creates a secure IPsec tunnel thru the Internet in “untrusted” configuration. By utilizing the 3GPP S2a interface, the NH-GW creates a connectivity in “trusted” mode between the user and the PDN-GW of the SP.
- Small Cell Access Points: These SCs allow NH shared RAN connectivity for subscribing service providers’ user devices at specific indoor locations.

Companies, venue owners or administrators, or even other commercial operators and entities who offer network infrastructure as a service are considered as NHs. There are various types of NHN models evolving, concurrently with a few other options, such as wholesale cellular networks that are managed or sponsored by the government, network sharing, or national roaming. Table 1 gives a brief comparison of the different types of NHs and their applications. The most significant NH variants are as follows:

- Multi-Operator Small Cell as a Service (SCaaS): This type of NHN does not have its spectrum. However, the NHN function is accomplished by clustering numerous SCs together and sharing backhaul, or by using one SC which has the capability of virtualization and the radios that support various MNOs’ channels. There are currently numerous SCaaS providers on the market such as TowerCo, ClearSky, Virgin Media, and Colt Telecom [20].
TABLE 1. Application of various types neutral hosts [21].

| Applications          | Neutral host (with spectrum) | Neutral host (without spectrum) | Private network | MNO sharing | Roaming |
|-----------------------|------------------------------|---------------------------------|----------------|-------------|---------|
| Rural                 | Best                         | Unsuitable                      | Unconceivable  | Best        | Best    |
| Indoor                | Best                         | Best                            | Best           | Best        | Unsuible|
| Industrial            | Suitable                     | Best                            | Best           | Unconceivable| Unsuible|
| Urban area            | Suitable                     | Best                            | Unconceivable  | Unsuital    | Unsuible|
| Road/Rail            | Best                         | Suitable                        | Best           | Best        | Unsuible|

- Spectrum-based NHNs: This type of NHN is a full-fledged local MNO, which has full right and has its own radio resources (shared or dedicated) and network that also hosts other diverse MNOs and service providers (SPs) as roaming or tenant partners. This is being investigated for rural mobile deployment and is on the high priority list of some major property owners who can purchase the spectrum. These days CBRS spectrum for the NH is one of the example spectrum-based NHNs that are being more popular.

The term “neutral host” first appeared in the mid-2000s in the context of passive infrastructure sharing operations, in which distributed antenna systems (DAS) required an operator-independent entity to improve the infrastructure [22], [23]. In 2012, Mobile infrastructure sharing Global System for Mobile Communications (GSMA) [24] analysis reported on the benefits of infrastructure sharing and its acceptance or even encouragement from the regulators. The analysis reports were on different levels of infrastructure sharing, especially for 2G and 3G networks at the time. The lack of available sites in urban areas has highly motivated operators to sign infrastructure sharing agreements between operators, though infrastructure sharing results in increased competition. Since then, there have been several studies on infrastructure sharing, in which the key contextual component was highly influenced by the spatial factors. With the advent of 5G cellular communication, Enhanced mobile broadband (eMBB) has gained great attention for network densification with the deployment of SCs to handle this traffic heterogeneity and increase capacity in already crowded spaces. The International Mobile Telecommunication (IMT), the International Telecommunication Union (ITU) and the 5G Infrastructure Public Private Partnership (5G PPP) are sponsoring technology and development initiatives to solve difficulties in 5G technology implementation [9]. However, there are still only a limited number of initiatives in the ecosystem that are concentrating on infrastructure sharing and organizational modifications to enhance, integrate, and showcase 5G neutral hosting capabilities in a hyper-connected city infrastructure with actual use cases. An innovative 5G-enabled NH framework, 5GCity project [8], was designed, developed, deployed, and validated for usage in three European cities: Barcelona, Bristol, and Lucca as part of the 5GPPP and European Commission (EC) Horizon 2020 (H2020) programs. Many other projects have also been carried out which have put a lot of effort into these issues. Among them, SESAME [6] and 5G ESSENCE [7] are the projects that mainly contribute to the innovation of the SC concept and “SC-as-a-Service” paradigm, respectively. Also, the focus on three important components [25]:

- The adoption of the edge computing architecture, which places network applications and intelligence at the edge of the network.
- The SC idea, which is now used in 4G technology but is projected to reach its full potential in ultra-dense 5G settings;
- Communication infrastructures’ multi-tenancy is being consolidated, letting various MNOs to share an SC network’s accessibility and edge computing capabilities.

The presented platforms, however, limit the control over the shared resources by presenting the infrastructure at the orchestration level and, the former does not tackle the inter-connection with the communication service provider’s (CSP’s) wider network. Moreover, the majority of research efforts are concentrated on urban regions, which have the largest population density [25], [26], [27]. Through the NH approach, special regions and venues have been investigated with the highest priority [13], [28]. There are only a few studies that focus on rural areas [29].

On the other hand, economic studies on the investment in NH business strategy have drawn a lot of interest. In [11] and [12], the authors present analysis of the main technological and economic factors influencing the adoption of NH 5G networks in the Netherlands and UK, whereas the authors [10] analyze the key technological and socio-economic factors, such as the usage of NH SCs for network densification, that affect the market’s adoption of 5G networks. An NH operator model is being developed as part of the LuxTurrim 5G initiative to drive a business environment with the goal of installing 5G microcells on light poles all over the city [14].

III. NHN OPPORTUNITIES

NHN has a wide range of applications and benefits. In an NH, a common infrastructure is shared so a single access site can serve the subscribers of multiple MNOs, thus reducing deployment costs, and increasing efficiency and network flexibility. Local authorities are in a privileged position to become an NH as they own multiple assets spread across cities (lampposts, street cabinets, etc.) that would accelerate
TABLE 2. Opportunities of neutral hosts.

| Opportunities                  | Details |
|-------------------------------|---------|
| One-box solution for Enterprises | • A single infrastructure for all operators.  
|                               | • Cellular connectivity to all the visitors from various network providers.  
|                               | • The owner will have access to full control over the NH infrastructure.  |
| Cost-effective alternative     | • A single network is built under shared infrastructure and wastage of resources is avoided.  
|                               | • Space is used more optimally.  
|                               | • Offers a more affordable option for network deployments compared to DAS or operator-specific SC.  |
| Indoor coverage                | • Eliminate traditional “Outside-in” coverage which has usually inadequate wireless coverage indoor and limited bandwidth.  |
| Eliminates regulatory constraints | • Solution for the local limitation of infrastructure installation due to space.  
|                               | • Use of an unlicensed and shared band eliminates licensing requirements.  |
| Traffic offloading             | • Capacity and coverage improvement to neighboring MNOs by offloading the traffic nearby NH SC private network.  
|                               | • Improves the QoS of end-user.  |
| Easy deployment                | • Need well-planned separate installations for each cellular service to provide.  
|                               | • Plug and play deployment.  
|                               | • A neutral spectrum, there is no need to coordinate RF network architecture with a macro network.  |

the deployment phases. We have listed the key opportunities of NH in Table 2 and described them sequentially in the following sections.

A. ONE-BOX SOLUTION FOR ENTERPRISES

When placing SCs wireless connectivity inside a managed area such as stadium, mall, or office buildings, the venue owner is obliged to provide connectivity to the visitors, who might have signed up with a variety of wireless network providers. Small cells from all major providers must be installed in addition to Wi-Fi and other unlicensed access technologies to guarantee consistent cellular coverage for all staff members, clients, and visitors [30], [31], [32]. However it can be fully eliminated by NH architecture. Moreover, there are outdoor tough conditions, such as remote and difficult-to-reach places, railroad connectivity, and even urban densification in support of 6G deployment. An NH provides an attractive chance to service at such locations with a single infrastructure for all operators. Further, the venue owner will have access control over the infrastructure.

B. COST-EFFECTIVE ALTERNATIVE

The congested area necessitates the multi-operator capabilities which are provided by DAS, but DAS installation is costly for operation, and complex business arrangements are required to secure signal sources from major operators. On the other hand, traditional SC is operator-specific and provides a built-in signal source. As a result, they need many SC deployments at each site, which quickly drives up the cost. The shared network infrastructure of the NH provides low-cost solutions. When only a single network is built under shared infrastructure, wastage of resources is avoided, and, at the same time, space is used more optimally. NH deals with complicated business models related to multi-operator support and offers a more affordable option for network deployments to enable both customers and businesses to achieve better wireless performances at a great value as shown in Fig. 3 [33].

C. INDOOR COVERAGE

The traditional “outside-in” coverage from neighboring cellular macro towers effectively serves many indoor areas. Thus, many venues have unstable wireless coverage and
limited bandwidth, which leads to a highly unsatisfactory indoor user experience. Modern construction materials, such as low-emissivity glass, worsen this indoor coverage difficulty by inhibiting outdoor mobile signals from infiltrating inside buildings. Another impending concern is the increased use of high-band frequency spectrum for 5G, such as mid-band and millimeter-wave (mmWave) bands, which would decrease the reach of outside cell signals even further as signals with higher frequencies travel farther compared to lower frequencies. Hence, outer-in coverage from the macro station will be insufficient, and an in-building NHN cellular connectivity network would be required.

D. ELIMINATES REGULATORY CONSTRAINTS

Local rules may limit the amount of infrastructure that may be installed in the SC deployments. For instance, the number of installations near historical and cultural landmarks and museums is restricted, since these locations are susceptible to being ruined and damaged by cellular towers and antennas. Further, even if several different operators are interested in installing at an ideal SC location, there might only be enough room for one antenna assembly in the physical world. In this situation, NHN-shared infrastructure helps service provider to support its coverage in such areas. Moreover, the use of an unlicensed and shared band for NHN eliminates licensing requirements and supports an easy deployment process much “like Wi-Fi” while providing the capacity, coverage, seamless mobility, security, and reliability of cellular technology.

E. TRAFFIC OFFLOADING

The local spectrum licenses for NHN enable private networks for the enterprises with a major concern on their internal connectivity for voice and IoT applications. Hence, once set up, these private networks may also provide capacity and coverage improvement to neighboring MNOs by offloading the traffic to nearby NH SC private network. Traffic offloading can be of two types: one is data and the other is user. In both cases, traffic offloading can significantly improves the quality of service (QoS) of the end user of MNOs. At the same time, venue owners can benefit from free data service or billing for offloading, when sharing its infrastructure to MNO.

F. EASY DEPLOYMENT

Traditional SC systems need well-planned separate installations for each cellular service provider. The NHN SC solution provides a straightforward and cost-efficient deployment alternative driven by venue/enterprise owners that serve customers from several cellular service providers. Given that these NHN SC networks operate in a neutral spectrum, there is no need to coordinate radio frequency (RF) network architecture with a macro network of the MNO. This technology also delivers wireless wide area network (WWAN) range and QoS level that unlicensed technologies such as Wi-Fi cannot provide.

IV. NHN CHALLENGES

NHN provides significant market potentials for service providers, venue owners, businesses, and traditional operators. There are, nonetheless, issues that need to be resolved, so that design model can deliver services with guarantees to the host client. NHN should be able to continue offering the same or better service quality that host client would if they deployed their own networks, while maintaining the network neutrality towards host client. In this context, we discuss some of the major challenges as follows.

A. SECURITY CONSIDERATIONS

The NHN environment may be required to serve several 3GPP/ non-3GPP use cases, including IoT, private industrial networks, and other access methods. Security at many levels from physical access to SCs to authentication and fraud management is needed [34]. Flexible authentication methods supporting different device types that support a wide variety of standardized and proprietary authentication methods are required. Moreover, subscriber confidentiality as well as encryption are mandatory for NH solutions.

B. SUBSCRIBER IDENTITY MODULE (SIM) PROVISIONING AND MANAGEMENT

Typically, an MNO offers individual SIM cards to its customers from which MNO manages SIMs/eSIMs profiles of the customers. However, in the case of an NHN, the responsibility for SIM provisioning and profile management questioning whether the MNO would need their own SIMs/eSIMs profiles, or this would be the NH operator’s responsibility. Furthermore, a surge in network devices could put a strain on the current capacity for numbering and mobile network codes (MNC) addresses.

C. COMMON STANDARDIZATION

The network equipment of the operator is subject to various tests and certifications, including security, integration, and performance to meet their operation standard. In an NH scenario, a single standardized method is needed that incorporates all of the requirements and standards of various operators’ types of equipment. Moreover, it can be complicated to bring together the various actors to establish the ecosystem of consultants, mobile carriers, device manufacturers, regulators, cloud service providers, and end users.

D. INTEROPERABILITY

The NHN user needs to be supported by seamless and continuous coverage going in and out of NH connectivity sites. To allow for movement between NHN and public cell coverage, inter-connectivity and roaming mechanisms would need to be in place, so that the NHN could assist automated network selection without user intervention. Moreover, the NH may be required to facilitate international roaming traffic in specific instances [31].
E. INNOVATIVE BILLING APPROACH
NHN is still in the preliminary phase. Tools for planning and design are not yet centralized on NHN installations, particularly when several frequency bands are employed. Furthermore, there is a need for NHN-friendly billing and charging software. The NH provider will charge for access services depending on a sophisticated set of rules linked to network resource utilization. Innovative pricing solutions will be required to accomplish a quick market adoption while maintaining high levels of automation and performance [17], [35].

F. QoS GUARANTEE
Guaranteeing QoS of connectivity to its customer is very difficult, if it involves servicing its users on another infrastructure. Likewise, the user of the NHN must be supported with emergency services. This can be extremely challenging when utilizing unlicensed air interfaces and services. Also, NH is a small coverage area, so it is likely that the NH coverage area’s emergency service centers will be in the hosted client network [36].

G. LIMITATION DUE HIGH FREQUENCY
An NHN must give its users superior performance capabilities. As a result, the use of a very high-frequency band known as the mmWave spectrum (30 to 300 GHz) is essentially required. However, a mmWave system cannot penetrate the buildings effectively. This means that NH infrastructures based on mmWave will require a large number of tiny nodes to be placed throughout an urban environment. If these nodes require the technical skills of professional contractors to be deployed, the initial deployment costs will be considerably increased [37].

H. SLICING
An NH should create the process to start and close new slices for exiting and new operators in real-time. Moreover, resource management is another big challenge for NH. As host clients share a common infrastructure, it is important to ensure that the operation of host clients is not affected by the traffic of others. In other words, there should be isolation between distinct slices and the ability for different slice owners to use their resources simultaneously without interfering with one another [38].

V. ENABLING TECHNOLOGIES
In this section, we present various enabling technologies that support NHN architecture, promoting operators to in-cooperate an NH infrastructure into their larger networks [15].

A. NETWORK SLICING
Network slicing is a revolutionary network design that allows physical resources to be shared by splitting them into multiple logical networks and allocating them to various users in mutual isolation. Each network slice can specify its logical topology, service level agreements (SLAs), reliability, and security level in several ways to fulfill the needs of different services, industries, or subscribers. Hence, each logical network can be dedicated to a certain service or industry user providing network services that are very flexible and
can be planned and allocated on-demand based on service requirements [39].

An automatic and flexible network slice allocation is a fundamental enabler of the NH paradigm. This allows policy programmability per defined SLAs, while enforcing dynamic up/down scaling decisions of infrastructure resources given to service providers. As a result, a tenant utilizes the NH architecture to create end-to-end segmented slices that reflect network, storage, and compute resource divisions. The slices are then leased to service providers who use them to run assigned resources to map out their services. Nevertheless, by integrating a wide range of well-known technological enablers such as network function virtualization (NFV), virtualized RAN solutions, and cloud/edge computing via end-to-end network slicing, an NH network may provide automatic or dynamic multi-tenancy [40].

B. MOBILE EDGE COMPUTING

Multi-Access Edge Computing (MEC) is self-contained software that is supported by a virtualization architecture. MEC shifts traffic and computational service from centralized accessed resources to the network edge, bringing it closer to the user. Rather than transmitting all the data to the centralized accessed resources for processing, the network edge analyzes, processes, and stores data locally. Data gathering and processing information closer to the user minimizes latency and gives high-bandwidth applications real-time performance. Moreover, it also helps to reduce network congestion by lowering the user’s dwell time in the network [32], [41], [42].

The NH approach can make use of numerous MEC deployments to fully meet 6G bandwidth, coverage, and latency requirements. Indeed, NHN networks can deploy end-to-end services over-dispersed pools of edge resources, ensuring ultra-low latency and high bandwidth through access to radio network information, location and traffic management in real-time. Moreover, the centralized orchestration of MEC can boost the dynamic operation of the life-cycle of edge computing applications using distributed cloud resources, eliminating the challenge of limited local resources.

C. VIRTUALIZED MULTI-RADIO ACCESS NETWORK

The virtualized RAN (vRAN) strategy enables the NH scenario to share the radio access component by dividing its resources among numerous tenants, each of which is run by a distinct Mobile Virtual Network Operator (MVNO). The projects such as Cloud Radio Access Network(C-RAN) [43], Open RAN (O-RAN) Alliance [44], and Next Generation RAN (NG-RAN) architecture [45] are focused on the splitting and virtualization of radio functions to integrate with software-defined network (SDN) and NFV platforms for slicing.

Furthermore, due to the flexibility of the NH framework, multiple sharing and architecture models (e.g., Multi-operator Radio Access Network (MORAN) and Multi-operator Core Network (MOCN)) can be achieved, providing a diverse set of deployment options. Network slicing between Multi-radio access technologies (Multi-RAT) will be critical for the NH. Hence, industry and research initiatives are focusing on integrating LTE and 5G New Radio (5G NR) technologies with various slicing methodologies (e.g., allocating shares of available airtime to different customers) from various wireless technologies (e.g., Li-Fi, Wi-Fi 6). The NH framework goes beyond a novel RAN controller supporting LTE and Wi-Fi by adding capabilities to multiple RAN controllers from multiple vendors and radio technologies.

D. SOFTWARE DEFINED NETWORKS (SDNs)

SDN is an architecture that gives networks more programmability and flexibility by separating the control and data plane from physical hardware such as routers and switches. It is becoming more common in research to refer it as network automation and programmable entity. SDN simplifies the management of infrastructure through network configuration and monitoring. It enables direct programmable network control for applications and network services, which may be exclusive to one organization or shared so that it can be used by several other entities. There are three key parts of SDN, which may or may not be physically close to one another, are as follows: the first is applications that communicate network information or requests for the allocation or availability of particular resources. To ascertain the final destination of data packets, the second SDN controllers, which has visibility and authority over the whole controlled network, interact with the applications. Within SDN, the load balancers are also the controllers. Lastly, the networking component is the third part that takes instructions on packet routed from the controllers.

In the case of an NH deployment, it is not enough for the SP to maintain control over coexisting with multiple tenant deployments on the data plane. Multiple control plane instances must also be created to present an abstract view of the resources that make up the logical network and provide control mechanisms. This control must be carefully coordinated to ensure isolation and avoid resource overlap between the various networks.

E. NETWORK FUNCTION VIRTUALIZATION (NFV)

NFV is a network architectural idea utilizing virtualization technology to virtualize functions of the entire classes of network nodes into linkable building blocks or chained together to create and deliver communication services. This implies that virtual machines utilize software to carry out the same networking tasks as conventional hardware. Software, rather than hardware, handles load balancing, routing, and firewall security. An SDN controller enables network engineers to program every different component of the virtual network, and even automate the network provisioning. NFV enables NH virtual network functions to run on a normal generic server under the management of an SDN, which is significantly cheaper compared to buying specialized hardware devices. A virtualized network makes NHN network configuration and management considerably easier. Best of all,
because the network is run on virtual machines that are easily supplied and managed, NHN network capabilities may be altered or added on the fly. The European Telecommunications Standards Institute (ETSI) NFV standard presents a framework consisting of VNFs, NFV infrastructure (NFVI), and NFV orchestrator (NFVO). It allows a network operator to programmatically construct and manage networks built on these virtual entities. The proposed framework’s primary features are interoperability between different function providers and the ability to programmatically install them on diverse infrastructures.

F. 5G NEW RADIO IN UNLICENSED BAND (NR-U)
The DAS-based NH paradigm solves carrier Wi-Fi’s issues with network security, performance, user mobility, interference, and service degradation brought on by unlicensed spectrum for industrial networks. Moreover, the traditional approach for performance improvements across wireless generations include simply deploying more spectrum, particularly in bands with bigger channel bandwidth, and utilizing spectral efficiency-boosting approaches such as higher modulation schemes. However, this approach is no more feasible in the current 5G NR world; thus, the recent technology NR-U, an alternative to carrier-deployed Wi-Fi systems, broadens the cellular ecosystem. Therefore, enhancing new deployment options will be available, which are ideal for Nhs. NR-U opens new opportunities for NHN by operating cellular technology in the unlicensed spectrum such as the global 5GHz band.

- NR-U provides the best of two world-leading technologies that are cellular-like performance and Wi-Fi-like deployments simplicity to an NHN.
- NR-U brings cellular benefits to NHN to a larger eco-system through enabling deployments such as indoors, in venues, enterprises, managed services, etc.
- NR-U is self-contained, self-organizing, and suitable for high-capacity dense plug-and-play deployments.
- NR-U enables the NH to serve multiple use cases at the same time such as augmenting mobile networks, enhanced local broadband access, and IoT verticals.
- NR-U helps the NH to share a wide channel on multiple deployments with better spectrum utilization and peak rate support through 3.5GHz General Authorized Access (GAA) scaling.
- NR-U is designed to share the spectrum fairly, which helps the NHNs to harmoniously coexist with other incumbent technology in the same shared band through the air contention mechanism.

VI. NEUTRAL HOST FRAMEWORK
The NH framework shown in Fig. 5 is proposed for 5G in [15] which enables NH tenants to produce and acquire slices utilizing a collection of virtualized resources across a shared infrastructure in city-wide deployments. The designed framework of the NHN is vertically divided into three layers: the infrastructure layer, the orchestration and control layer, and the service/application layer. The computing, network, and radio resource components are under the infrastructure layer. Here, NH uses NFVI for distributed computing and radio management. The edge computing capabilities also lie in this layer, which provides real-time access to radio network information. The second layer, the orchestration and control layer serves as the logical core of the whole system. It is further subdivided into several functional blocks for management, control, and orchestration. To make communication between infrastructure owners and tenants easier and to enforce the necessary security and billing, a dashboard with a graphic user interface (GUI) and an AAA component are implemented. For security purposes, network slices from various tenants are securely isolated, and maximum data and information segregation is maintained. A crucial function of the platform is played by the slice manager, who provides the necessary logic for the creation and administration of slices on-the-fly. There is also a resource placement component that is used to determine the best distribution of VNFs to be deployed over a particular slice. By combining the NFVO with MEC components that manage mobile edge (ME) applications, the orchestration capabilities of the platform are increased to facilitate NFV/MEC integration following the ETSI MEC specification. The multi-tier orchestrator component gives an abstracted view in front of multiple underlying orchestrators. SDN-based RAN controllers manage the radio components and enforce RAN slicing and RAN function virtualization for 5G NR, LTE, and Wi-Fi. The infrastructure abstraction entity helps to support multi-RAT controllers and technologies. Lastly, a service or an application layer constitutes a set of tools aimed at facilitating service design and composition to the service providers, tenants, and any other associated third-party groups. Here, the software development kit (SDK) for network function developers and service providers allows combining several functions for new service deployments. This part is also in charge of adding new features and services to the NFVO. A 5G Service & Apps index is offered to hold previously produced and published network services [15].

VII. DYNAMIC RAN SLICING FOR NHN
We have learned from the above discussions that network slicing is one of the primary functions that will enable an NHN with the required flexibility through the creation of several logical networks, known as network slices, on top of a single shared physical infrastructure. Using certain control plane (CP) and/or user plane (UP) functionalities, each network slice can be utilized to provide services for a specified operator or service category. In this section, we discuss RAN slicing schemes that enable radio resources from across the whole spectrum to be assigned to the host clients from various slices [46], [47]. In multi-tenant NH settings, three important requirements should be considered while allocating the slice resources to each hosting client such as isolation, customization, and resource utilization.
1) Isolation: It is important to keep network resources consistent across slices. Any alteration in one slice should not adversely affect other slices. The activities such as the addition of a new host client, the movement of existing host clients, inter-cellular interference, and changing channel conditions are the main cause of disturbance in between the slices.

2) Customization: Flexible spectrum sharing between the several tenant operators is necessary to meet the traffic requirements of each hosting client in real-time.

3) Spectrum Efficiency: The growth of new services and traffic volume are thought to be constrained by the lack of spectrum due to the increasing mobile cell-phone usage patterns and the increasing importance of higher-speed data. Regulators have already been investigating pertinent ways to increase the availability of spectrum, by promoting spectrum sharing among operators. Maximizing radio resource use is one factor that must be considered by not only NH but any wireless platform.

In this regard, we propose an effective RAN slicing approach, which dynamically distributes radio resources to various host clients intending to increase resource consumption, while assuring the availability of resources to meet the traffic requirements of each RAN slice. We consider the dynamic environment, where the NH must make slice decisions quickly and nearly continuously. In addition, we also consider that the NH cannot be fully informed of each subscriber of the tenant operator’s preferred slice option in real-time, which includes estimating each subscriber’s preferable slice category, assessing slice elasticity between tenant operators, and determining the best slice option for the subscriber of tenant operators. In this situation, we require a real-time dynamic network slicing algorithm that automates the optimal RAN slice for frequent and randomized environments to maximize spectrum efficiency and slice isolation over time. The algorithm must monitor the real-time effect of the slice decisions and incorporate this additional information into the future RAN slicing decisions (i.e., an “explore-and-exploit” strategy). We model our slicing problem as a bandit problem, a well-known dynamic optimization technique in reinforcement learning. In this approach, the NH agent is given a variety of slice options, often known as the arm. In most cases, each arm has an unknown reward distribution to the agent, who must select arms to maximize cumulative reward over time. Hence, we model this problem as a multi-armed bandit problem, as shown in Fig. 6. The MAB model for the RAN slicing of NH consists of the following entities.

- An agent is the NH access point.
- Arms correspond to different values of resource that splits between \( M \) number of the hosting clients or slices total of denoted by \( a_N \), where \( N \) is a total set of actions.
- Reward is a utility function that ensures that the appropriate action is taken. In our model, when an agent, NH, splits the available RAN resources among the \( M \) hosting clients at time steps \( t \), it is rewarded with

\[
\text{Reward}_t = \begin{cases} 
\text{Th}_t \times \exp^{-|1-F|}, & \text{for } x_t \geq x_{\text{min}} \\
0, & \text{for otherwise,}
\end{cases}
\]
where $T_h$ is a normalized total throughput obtained from the available spectrum (i.e., total throughput achieved from each hosting client). Further, $F$ is the Jain fairness index between achieved QoS of each slice and can be calculated using

$$\text{Jain Fairness}(F) = \frac{(\sum x_m)^2}{\sum x_m^2},$$

where $x_m$ is the QoS of each slice. The range of the factor $F$ is $[0,1]$, and the closer it is to 1, the better the QoS fairness between slices. The arm selection strategy is determined by the strategy that optimizes its objectives. Considering the performance of the total network and QoS in between the RAN slices, the reward function tries to maximize the system throughput, while keeping the QoS fairness factor between the slices as close to 1 as possible. Under this reward function, the agent selects a policy that iterates toward high throughput utilization and QoS fairness between the slice.

Hence, the NH agent repeatedly interacts with the environment as follows:

- NH agent enters the environment with zero knowledge about the density of the operator.
- Relying on the learned knowledge over time, the NH selects an arm $a \in N$, from the space possible actions and obtain reward $R$.

Thompson’s Sampling (TS) is a Bayesian method that sets a prior distribution to the reward of the arms, which is then updated utilizing Bayes’ theorem, as feedback from past actions is obtained. The TS algorithm operates by matching probabilities, which means that an arm is chosen with a probability equal to the likelihood that the arm is optimal. The fundamental concept behind TS is to apply a simple prior distribution to the fundamental parameters of each arm’s reward distribution. It then plays an arm based on its posterior probability of being the best arm at each sampling time. The Thompson’s multi-arm bandit-based algorithm proposed for NH is stated in Algorithm 1 and summarised as follows. The algorithm begins by establishing a uniform prior distribution between 0 and 1 for each variant $n$’s RAN slice option, with values $\text{Success}(n)$ and $\text{Fails}(n)$ equaling zero, as shown in algorithm steps 1 to 3. Then, in step 7, $\text{betarand}(\text{Success}(n) + 1, \text{Fails}(n) - \text{Success}(n) + 1)$ is used to generate a random probability from each $n$’s posterior distribution. Then, using $n^* = \max p(n)$, we choose the variant with the highest success probability. Then, in step 11, we observe and collect the reward for the chosen action before updating the distribution parameters $\text{Success}(n^*) = \text{Success}(n^*) + \text{rew}$ and $\text{Fails}(n^*) = \text{Fails}(n^*) + 1$ in steps 13 and 14.

We develop an NH system-level simulation platform using MATLAB. The RAN slicing decision observations are modeled and generated using a set of random multi-objective bandit cases, in which multi-dimensional reward distributions (i.e., throughput and QoS of each slice) follow finite trials with different mean distribution values, Success, of each reward. It should be noted that Success is independent for each trial and follows the uniform distribution between 0 and 1. We create $M = 5,000$ samples of RAN slices for various sizes (4 and 8) of the tenant operators. To analyze the performance, we compare popular multi-arm bandit approaches, Upper Confidence Bound (UCB), and eGreedy approaches. In the simulations, we observe how performance changes with time (i.e., time steps) for $N \in \{4, 8\}$, which corresponds to the number of arms (i.e., operators).

**Algorithm 1 Thompson Sampling-Based Dynamic Network Slicing for NHN**

1: Input: $n$ = number of slice option, $M$ = total number of slice accesses, $\text{rew} = \text{equation (1)}$
2: Initialize:
3: $\text{Success}(n) = \text{Fails}(n) = 0$;
4: for $m = 1, \ldots, M$ do
5: Sample posterior probability:
6: for $n = 1, \ldots, N$ do
7: $\text{p}(n) = \text{betarand}(\text{Success}(n) + 1, \text{Fails}(n) - \text{Success}(n) + 1)$;
8: end for
9: Choose action and collect reward:
10: $n^* = \max \text{p}(n)$;
11: $\text{rew} = \text{reward}(n^*)$;
12: Update success probability:
13: $\text{Success}(n^*) = \text{Success}(n^*) + \text{rew}$;
14: $\text{Fails}(n^*) = \text{Fails}(n^*) + 1$;
15: end for

---

**FIGURE 6. Multi-arm bandit model.**
The algorithm then attempts to assign the highest UCB value to the optimal arm.

Figs. 7 and 8 illustrate the simulation results of the proposed scheme (i.e., TS) and the two comparison targets (UCB and eGreedy). The values of spectrum efficiency and QoS are normalized by the optimal values of all slice categories. Fig 7 shows the spectrum efficiency achieved using the TS algorithm is significantly higher compared to the other schemes. This is because TS is able to more quickly converge to the optimal slice option based on a posterior probability distribution over all operators, as compared to the other schemes. Similarly, UCB takes more time to build UCB confidence over the optimal slice category and hence needs a long convergence time to select the optimal slice category. As a result, UCB shows lower spectrum efficiency compared to Thompsons sampling. Moreover, the eGreedy approach achieves the lowest spectrum efficiency, since it continues to explore the random slice option half of its given time. A similar conclusion can also be drawn for the average achieved QoS by the tenant operators, as shown in Fig 8. We can observe that all four operators have high QoS satisfaction for the TS approach (98%) and lower for UCB (87%) and lowest for eGreedy (78%). It is noted that the QoS unfairness across the slices is more severe in UCB and eGreedy, because they are highly subject to the high spectrum efficiency configuration rather than the fairness of each slice category.

VIII. CONCLUSION

An NH access mode is one of the new network architectures envisioned by 5G and beyond, where a third neutral party builds and operates part of the network offering private and public connectivity. It is a cost-effective alternative to provide better mobile performance to both, individual customers and enterprises, in remote and hard-to-reach areas or occasional high-density areas as NH serves such areas with only one infrastructure for all operators. We have discussed NHN as a next-generation communication technology for smart private network communication and presented its opportunities and challenges in realizing the multi-tenanted space and its enabling technologies. In support, we have proposed an efficient RAN slicing scheme based on the multi-arm bandit approach, which allocates radio resources to various slices to maximize resource utilization, while guaranteeing the availability of resources to meet the capacity requirement of each RAN slice. Through the simulation, we have shown that the proposed TS multi-arm bandit algorithm, which maximizes the cumulative rewards over time, can provide higher spectral efficiency and average QoS, compared to the UCB and eGreedy approaches.

REFERENCES

[1] W. Saad, M. Bennis, and M. Chen, “A vision of 6G wireless systems: Applications, trends, technologies, and open research problems,” IEEE Netw., vol. 34, no. 3, pp. 134–142, May 2020.
[2] U. Cisco, Cisco Annual Internet Report (2018–2023) White Paper. San Jose, CA, USA Cisco, Mar. 2020.
[3] R. Bajracharya, R. Shrestha, and H. Jung, “Future is unlicensed: Private 5G unlicensed network for connecting industries of future,” Sensors, vol. 20, no. 10, p. 2774, Mar 2020.
[4] W. Wu, C. Zhou, M. Li, H. Wu, H. Zhou, N. Zhang, X. S. Shen, and W. Zhuang, “AI-native network slicing for 6G networks,” IEEE Wireless Commun., vol. 29, no. 1, pp. 96–103, Feb. 2022.
[5] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, “The road towards 6G: A comprehensive survey,” IEEE Open J. Commun. Soc., vol. 2, pp. 334–366, 2021.
[6] [Online]. Available: https://5gcity.eu/
[7] [Online]. Available: http://www.5g-essence-h2020.eu/
[8] 5GCity. (2022). A Distributed Cloud & Radio Platform for 5G Neutral Hosts. [Online]. Available: https://www.5gcity.eu/
[9] 5G-PPP. (2022) The 5G Infrastructure Public Private Partnership. [Online]. Available: https://5g-ppp.eu/
[10] I. Neokosmidis, T. Rokkas, M. C. Parker, G. Koczian, S. D. Walker, M. S. Siddiqui, and E. Escalona, “Assessment of socio-techno-economic factors affecting the market adoption and evolution of 5G networks: Evidence from the 5G-PPP CHARISMA project,” Telematics Informat., vol. 34, no. 5, pp. 572–589, Aug. 2017.
[11] E. J. Oughton, Z. Frias, S. van der Gaast, and R. van der Berg, “Assessing the capacity, coverage and cost of 5G infrastructure strategies: Analysis of The Netherlands,” Telematics Informat., vol. 37, pp. 50–69, Apr. 2019.
[12] E. J. Oughton and Z. Frias, “The cost, coverage and rollout implications of 5G infrastructure in Britain,” Telecommun. Policy, vol. 42, no. 8, pp. 636–652, Sep. 2018.

[13] M. G. Kibria, G. P. Villardi, K. Nguyen, W.-S. Liao, K. Ishizu, and F. Kojima, “Shared spectrum access communications: A neutral host micro-operator approach,” IEEE J. Sel. Areas Commun., vol. 35, no. 8, pp. 1741–1753, Aug. 2017.

[14] J. Benseny, J. Walia, B. Finley, and H. Hännäinen, “Feasibility of the city-driven neutral host operator: The case of Helsinki,” in Proc. 30th Eur. Conf. Int. Telecom. Soc. (ITS), Towards Connected Automated Soc., Helsinki, Finland, 2019.

[15] A. Fernández-Fernández, C. Colman-Meixner, L. Ochoa-Aday, A. Betzler, H. Khalili, M. S. Siddiqui, G. Carrozzo, S. Figuerola, R. Nebajati, and D. Simeonidou, “Validating a 5G-enabled neutral host framework in city-wide deployments,” Sensors, vol. 21, no. 23, p. 8103, Dec. 2021.

[16] X. Foukas, M. K. Marina, and K. Kontovasilis, “Iris: Deep reinforcement learning driven shared spectrum access architecture for indoor neutral-host small cells,” IEEE J. Sel. Areas Commun., vol. 37, no. 8, pp. 1820–1837, Aug. 2019.

[17] J. Lähteennäki, “The evolution paths of neutral host businesses: Antecedents, strategies, and business models,” Telecommun. Policy, vol. 45, no. 10, Nov. 2021, Art. no. 102201.

[18] V. Vasconcellos and H. P. de Carvalho, “A framework for evaluating 5G infrastructure sharing with a neutral host,” in Proc. Conf. Open Innov. Assoc. (FRUCT), no. 28, Jan. 2021, pp. 659–663.

[19] K. Mung, (2018). Making Neutral Host a Reality With OnGo. [Online]. Available: https://ongoalliance.org/wp-content/uploads/2018/12/Neutral-Host-with-OnGo-WP-Final1.pdf

[20] J. Man-Kentadh and A. Ghanbari, “Smaller smallcell networksmultioperator or third party solutions or both?” in Proc. 11th Int. Symp. Workshops Modeling Optim. Mobile, Ad Hoc wireless Netw. (WiOpt), May 2013, pp. 41–48.

[21] D. Bubley, (2019). Neutral Host Networks for 4G & 5G Latest Learnings. [Online]. Available: https://disruptivewirless.blogspot.com/2019/07/neutral-host-networks-for-4g-5g-latest.html

[22] S. Muir, J. Chapin, V. Bose, and J. Steinreiber, “Distributed antenna systems plus software radio: Range extension and other benefits,” in Proc. Vehicular Tech., vol. 7, pp. 44771–44782, 2019.

[23] S. Y. Zhang, Y. Li, D. Jin, L. Su, S. Ma, and L. Zeng, “OpenRAN: A software-defined ran architecture via virtualization,” ACM SIGCOMM Comput. Commun. Rev., vol. 43, no. 4, pp. 549–550, 2013.

[24] L. Bonati, S. D’Oro, M. Polese, S. Basagni, and T. Melodia, “Intelligence and learning in O-RAN for data-driven NextG cellular networks,” IEEE Commun. Mag., vol. 59, no. 10, pp. 21–27, Oct. 2021.

[25] H. D. R. Albonda and J. Pérez-Romero, “An efficient RAN slicing strategy for a heterogeneous network with eMBB and V2X services,” IEEE Access, vol. 7, pp. 44771–44782, 2019.

[26] Y. Liu, X. Yang, and K. S. Chou, “Flexible spectrum sharing in OFDMA cellular networks,” in Proc. 14th ACM Int. Symp. Mobility Manage. Wire less Access, Nov. 2016, pp. 67–74.

R. Bajracharya et al.: Neutral Host Technology: The Future of Mobile Network Operators

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