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An Efficient Resource Management Mechanism for Network Slicing in a LTE Network

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ABSTRACT The proliferation of mobile devices and user applications has continued to contribute to the humongous volume of data traffic in cellular networks. To surmount this challenge, service, and resource providers are looking for alternative mechanisms that can successfully facilitate managing network resources in a more dynamic, predictive, and distributed manner. New concepts of network architectures, such as software-defined network (SDN) and network function virtualization (NFV), have paved the way to move from static to flexible networks. They make networks more flexible (i.e., network providers capable of on-demand provisioning), easily customizable, and cost effective. In this regard, network slicing is emerging as a new technology built on the concepts of the SDN and NFV. It splits a network infrastructure into isolated virtual networks and allows them to manage resources allocation individually based on their requirements and characteristics. Most of the existing solutions for network slicing are computationally expensive because of the length of time they require to estimate the resources required for each isolated slice. In addition, there is no guarantee that the resource allocation is fairly shared among users in a slice. In this paper, we propose a network slicing resource management (NSRM) mechanism to assign the required resources for each slice in a LTE network, taking into consideration the isolation of resources among different slices. In addition, NSRM aims to ensure isolation and fair sharing of distributed bandwidths between users belonging to the same slice. In NSRM, depending on requirements, each slice can be customized (e.g., each can have a different scheduling policy).

INDEX TERMS LTE network, network slicing, wireless virtualization, wireless resource management.

I. INTRODUCTION

Today's network providers contend with the exponential growth of network traffic due to the proliferation of network users and bandwidth-hungry services. The unprecedented growth of mobile networks and the intelligence of smart mobile devices push resource providers to look for more efficient management mechanisms for radio and core network resources in order to improve the users' Quality of Experience (QoE) and enhance the efficiency of traffic management. According to CISCO, because of the increasing appetite of mobile users for network resources, the mobile network traffic has increased and it is expected to grow to around 70% by 2021 [1], [2]. Taking into account the stupendous growth of traffic, it is timely to redesign the networks in order to meet Quality of Service (QoS) of different applications [3].

To date, many research efforts have been conducted aiming to provide better resource management models in mobile networks (e.g. [4], [5]). Some of these works proposed resource allocation mechanisms based on assigning a number of Physical Resource Blocks (PRBs) to each user's request in a cellular network. We can broadly classify a resource management mechanism into two levels: a low-level management model and a high-level management model. The advantage of applying a low-level model is that it is easy to implement because any requested resource gets resource allocation in units (e.g. a user in cellular network could get 10 units of PRBs). By utilizing a low-level model, it provides accuracy of allocating resources to each resource demand in units. However, it is hard for the high-level management

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entities (e.g. operators and service providers) to adopt a low-level management mechanism, because resources in the high-level management model are allocated in portion (e.g. 30% of total available PRBs).

Looking at the research focus from industries and academia, we envision that the future network will solely embrace network virtualization. The major factors that have resulted in rapid adoption of network virtualization are: cost-effective sharing of network resources and high network utilization. In order to gain synergistic benefits of network virtualization, along with designing efficient network architectures, a research effort should focus on an effective resource management mechanism in a virtual network. Future virtualized networks need a new management mechanism that would provide accuracy of resource allocation and guaranteed resource isolation. In order to accomplish these objectives, a novel resource management mechanism is required that will take into consideration both the low and high-level management models for resource allocation. The major role of the low-level model would be providing PRB based resource allocation in number of units, thereby ensuring high accuracy in resource allocation. On the other hand, the high-level model should be capable of ensuring isolation among the dedicated resources.

In order to facilitate such flexible resource allocation, dynamic network configuration and cost effective operation in a network, Software Defined Network (SDN) and Network Function Virtualization (NFV) open up new opportunities [6]. SDN is an emerging technology where a control plane is decoupled successfully from a data plane, making a network programmable and cost effective. SDN offers several advantages over conventional hardware-centric networks, including on-demand traffic forwarding policy, reduced cost and better QoS. NFV is a revitalizing technology in future networks. This allows a physical network infrastructure to be shared among coexistence of multiple network instances simultaneously. SDN and NFV partition the traditional networks into virtual elements, which are logically linked together [7].

To enable multiple virtual elements to share a common physical network, the network slicing mechanism comes into play. Network slicing enables to slice a virtual network across a Radio Access Network (RAN) and a Core Network (CN). It is a conceptual architecture that aims to share a common physical infrastructure among multiple virtual networks using the same principles applied in SDN and NFV [8], [9]. In particular, there are some important requirements which should be met when applying network slicing. These requirements are summarized as follows:

- Isolation among slices: isolation means the ability of restricting the impact of a slice on other slices in the same network, even if they share the same infrastructure. That is to say, if there is any change of resource status in a slice (e.g. traffic load change), such a change should not influence the allocated resources of other slices.
- Customization: resource management of each slice can be operated independently. That is, the admission control policy of a slice can be different from the other slices.
- Efficient resources utilization: maximizing the utilization of channel resources as much as possible would in turn allow increasing the capacity of a base station and efficiently utilizing a channel transmission.

Taking into account the aforementioned requirements, for a LTE network, we propose a Network Slicing Resource Management (NSRM) mechanism. NSRM aims to ensure the isolation of allocated resources, fair resource sharing and customized slice configuration. Most of the existing network slicing research (e.g. [10]–[12]) demonstrate performance gain using mathematical analysis. Unlike those research efforts, in this paper, we evaluate our NSRM in a realistic simulation environment (we use the OPNET Modeler to simulate the NSRM proposal). Results obtained through simulation delineate that NSRM can run different customized traffic for different slices simultaneously. Additionally, the results exhibit that, in a LTE network, the solution presented in this paper can successfully isolate distributed resources of an eNodeB (base station of a LTE network) among different slices and increase utilization of network resources.

The rest of the paper is organized as follows. Section II provides some background information and reviews some of the existing research on virtual resource allocation using network slicing. Section III describes the system model and proposed solution. Section IV provides detailed simulation results. In Section V, we conclude this paper and present a future research direction.

II. RELATED WORK

In this section, first we briefly summarize Medium Access Control (MAC) of a LTE network. Next, we discuss the existing research efforts in network slicing.

A. MEDIUM ACCESS CONTROL (MAC) IN LTE NETWORK

This sub-section describes the two types of LTE frame structure. Then, we introduce some of the existing research efforts in virtualization of network resources in cellular networks.

1) LTE FRAME STRUCTURE

MAC is a layer 2 protocol-stack of a LTE air interface, which processes the uplink and downlink flows [13]. LTE applies Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier-Frequency Division Multiple Access (SC-FDMA) for downlink and uplink communications, respectively. OFDMA divides the available spectrum into sub-carriers and allocates these sub-carriers to each user in the coverage area. The reader is refereed to [14], [15] for more discussion on the process assigning PRBs and different scheduling schemes.

2) LTE TRAFFIC SCHEDULING

The LTE standard classifies network services into nine classes, such that four of them are handled as Guaranteed Bit Rate (GBR) services, whereas the other five classes are handled as None Guaranteed Bit Rate (NGBR) services [16]. The LTE scheduler uses these classes to prioritize flow services. An operator sets a scheduling scheme for its eNodeBs. A scheduling scheme should take into consideration different QoS associated with the LTE service class attributes and it is very strict to the priority of flow of services. Due to this strict priority, it would result in either starving of NGBR (best effort) class or in some cases the GBR themselves would face lack of resources when wireless channel condition is less suitable [17].

3) VIRTUAL RESOURCES ALLOCATION IN CELLULAR NETWORKS

We have witnessed many research efforts on wired network virtualization; for example, wired network virtualization for a distributed cloud data center in order to maintain desired Service Level of Agreement (SLA) [18]–[20]. The wired network virtualization is accomplished at different levels of a network such as processor, memory, ports connection and physical link layer. Unlike wired network virtualization, a wireless network requires virtualization in both the CN and RAN. Note that, the concept of wired network visualization could be applied on the CN. However, accomplishing virtualization in RAN is relatively challenging due to two important reasons: i) a radio link connection is affected by stochastic fluctuation of wireless channel quality, and ii) the wireless networking protocols are completely different from the wired network [21].

In cellular networks, a user may have many flows (user bearers) associated with different applications running at the user's mobile device. User bearers may share network resources with other bearers of different users through a virtual layer, which is mapped to physical network resources (infrastructure) [22], [23]. In [24], the authors propose a virtual cellular network architecture based on SDN. This architecture facilitates resource virtualization across the CN and RAN for all the packet flows in order to maximize network resources utilization. In their proposals, the authors apply the concept of Virtual Bearer (VB), which has been popularly used in wired networks. The concept of a VB is similar to the PRBs in the LTE architecture. However, there are two basic differences between them. First, they differ in time scale. In case of a PRB, the length of a slot is fixed at 0.5 ms in LTE. On the other hand, in a VB, the length of a slot may be negotiated between the service provider and the network operator depending on requirement(s). Second, in terms of ownership, a VB is owned by a service provider who lacks the knowledge about the wireless resources allocation (a service provider has a concern on meeting QoS requirements of the end users). Whereas, in the case of PRBs, they are owned by a physical Infrastructure Provider (InP).

Next, we introduce the concept of network slicing in brief. Then, we present some of the existing research efforts in network slicing.

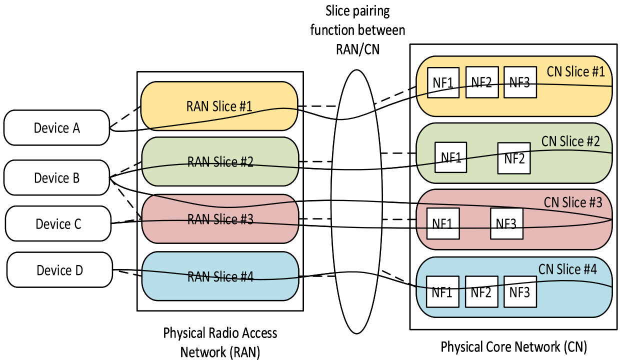


FIGURE 1. **Conceptual diagram of network slicing.**

B. NETWORK SLICING IN BRIEF

Network slicing is a structure of a virtual network architecture that allows sharing a common physical infrastructure among different virtual networks. It enables a cellular system to share network physical resources residing in CN and RAN among the virtual networks [25]. Figure 1 demonstrates a generic conceptual diagram of network slicing. Generally, cellular networks are composed of two different segments: RAN and CN. However, in the case of network slicing, we need an additional logical functional entity (i.e. Slice pairing function) which facilitates resource mapping between RAN and CN slices, as depicted in this figure. Each network slice is logically composed of one or more Network Functions (NFs) of CN and RAN. Note that, a NF can be occupied by a single slice or shared across multiple slices.

C. EXISTING RESEARCH EFFORTS IN NETWORK SLICING

A large and growing body of literature has investigated architectures for cellular networks slicing. In [10], the authors introduce a Karnaugh-Map algorithm in order to facilitate multiple users access in a virtualized embedded wireless network. This algorithm allows the network to handle real time resource requests. In this work, the authors did not provide an explanation how their proposed mechanism can be implemented in a real hardware, such as in a LTE scheduler.

Authors in [11] extend the work introduced in [10] by considering a case of a dynamic embedded system that rearranges the requests that have already been rejected due to the static nature of the network topology. One major drawback of this mechanism is that its calculation of each scheduling time is too complicated.

The solution proposed in [5] aims to slice the resources of a LTE eNodeB into several virtual networks (slices) so as to allocate each of the slices to different Service Providers (SPs). Each SP has a number of users with different SLAs. The scheduler in an eNodeB assigns a PRB to a user based on the SLA between the user and the SP. For instance, the eNodeB scheduler guarantees that the minimum PRBs that should be allocated to a user. However, it is beyond the scope of this work to ensure isolation among the slices explicitly.

This could result in not ensuring SLAs of all the users. This in turn will result in degrading QoE of some users.

The authors in [31] introduce Network Virtualization Substrate (NVS). The architecture and algorithm of this proposal are designed considering a WiMAX network architecture. The proposal devises a slice scheduler (a slice pairing function), which allows simultaneously coexistence of two kinds of resource allocation mechanisms: resource-based and bandwidth-based reservation mechanisms. In [31], the authors highlight that, flow isolation in WiMAX could be challenging. This is due to the fact that, according to the WiMAX standard, if a flow of a user requires more bandwidth than the initially allocated amount, the scheduler could allow the flow to occupy bandwidth of other flows belonging to the same user. Therefore, in order to ensure flow isolation, the authors propose to modify MAC of WiMAX in their solution. This solution introduced in [31] could be adapted to LTE with some modifications.

A heuristic-based admission control mechanism is proposed in [12]. The proposed idea mainly focuses on prioritization of the slices and users. A RAN scheduler takes into account a user's satisfaction while scheduling downlink transmission, resulting in improving overall QoE of users. Authors in [12] evaluate their solution based on a mathematical model.

In [26], the authors address the slicing of radio resource allocation among Multi-Tenants where each tenant represents a network operator, and they propose a criterion for dynamic resource allocation based on the weighted proportional fair to achieve the fairness of distributed resources between the tenants and their users.

The authors in [27] consider different traffic classes to forecast on-demand network capacity to accommodate network slice requests based on different SLA, where they are using penalty history and consider one-step training for forecasting error. Unlike the solution provided in [27], we consider a weighted historical value to forecast the resource for each slice which provides more accuracy for resource allocation of slices, also they do not consider the intra slice resource allocation.

In [28], authors introduce a novel network architecture for 5G networks that enables third parties to lease a mobile virtual network from infrastructure providers with the help of a network slice broker. Besides, this architecture provides signaling protocols and interfaces to run a new 5G network slice broker, meaning that the network needs to update the network interfaces to provide admission control and optimize network resources. The research effort in [28] discusses the concept of slice isolation and customization; however, detailed procedures on how to actualize such concept in a 5G network have not been stated. Furthermore, [28] does not provide any performance evaluation results.

In [29], the authors focus on virtualizing the LTE base stations, where the proposed solution (Orion) groups the PRBs convert into virtual Resource Blocks (vRB) groups via a set of abstractions, and supports only relevant information to the corresponding slice. Additionally, it does not consider intra slice isolation and any customization or multiplexing opportunities.

Our previous work [30] introduces a framework showing how LTE and WiFi network can be virtualized. The framework allows both LTE and WiFi networks to slice their network resources and maintain IP-flow mobility for the users. A user can connect with both LTE and WiFi slice when one of them alone is not sufficient to meet QoS requirements. Our work [30] does not present any performance evaluations results of the proposed framework. Furthermore, similar to many other existing works (e.g. [29]), we do not provide any solution for slice customization and intra slice isolation in [30].

The research efforts discussed above are promising. However, they all have one weakness or another. Unlike the existing proposals, the solution we introduce in this paper is not computationally intensive—that is, the solution does not require a long time to estimate resources required in each Transmission Time Interval (TTI). Additionally, in our solution, the user bandwidth request is met with regard to fair sharing of resources among the users belonging to the same slice. It is worth highlighting that our proposed work is capable of optimizing resource allocation in case a slice needs an extra bandwidth in each TTI scheduling time. Finally, it must be noted that most of the existing solutions are evaluated based on mathematical analysis. Unlike the existing solutions, we use the OPNET modeler in order to demonstrate the effectiveness of our solution in realistic scenarios. In Table 1, a qualitative comparison among NSRM and the solutions proposed in [12], [26]–[30] is presented.

III. PROPOSED NETWORK SLICING RESOURCE MANAGEMENT (NSRM)

This section explains the NSRM solution. NSRM presents three main contributions: (i) a novel architecture framework for virtualizing (network slicing) the LTE network in order to maximize network resources utilization; (ii) a novel algorithm which is capable of dynamically distributing bandwidth among different slices within an eNodeB to maximize resources utilization; and (iii) a Max-Min model that ensures isolation of slice resources across flows and secures a fair share of minimum bandwidth among users. The prime objectives of NSRM are twofold: (i) satisfying the requirements of slices in order to meet the users' QoE, which in turn will lead to maximize revenue of both InP and a slice owner (e.g. SP); and (ii) meeting QoS requirements for all the flows belonging to the same slice.

Figure 2 illustrates the network slicing concept along with the physical entities in RAN and CN of a LTE network. The physical entities shown in this figure take part in forming all the logical entities of the network slices. We would like to clarify here that, in this paper, we assume the core network slicing approach relies on the solution we proposed earlier in [30].

At this point, we need to highlight that in our solution, a slice owner is responsible for scheduling slice resources.

TABLE 1. Qualitative comparison among some of the recent research efforts on network slicing and proposed NSRM.

Solution proposed in	Criteria					Performance evaluation approach
	Bandwidth reservation	Inter slice isolation	Intra slice isolation	Slice customization	Dynamically reallocation of released resources	
[12]	✓	✓	✓	x	x	numerical analysis
[26]	✓	✓	✓	x	✓	simulation
[27]	✓	x	x	x	x	numerical analysis
[28]	✓	✓	x	✓	x	none
[29]	✓	✓	x	x	✓	prototype implementation
[30]	✓	✓	x	x	x	none
this paper (i.e. proposed NSRM)	✓	✓	✓	✓	✓	simulation (using OPNET modeler)

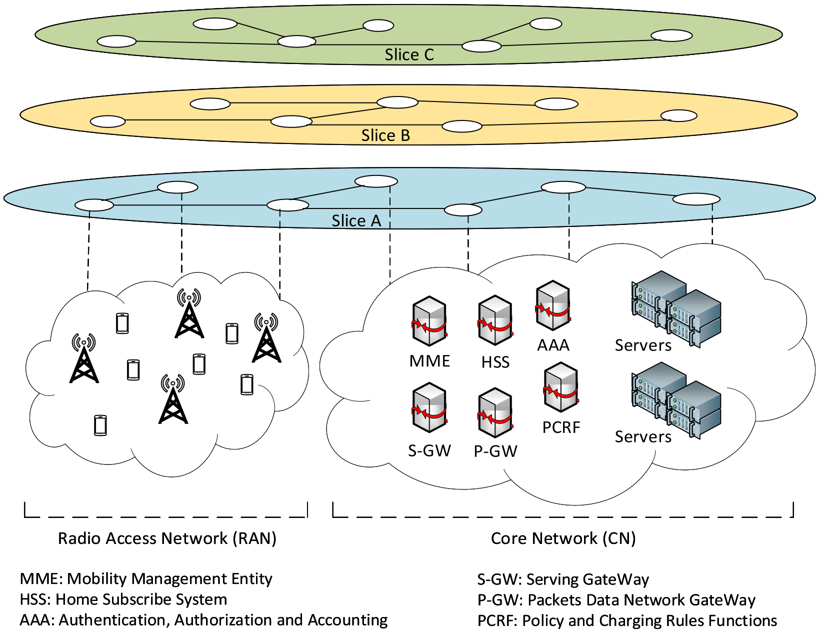

Slice C
Slice B
Slice A
MME
HSS
AAA
Servers
S-GW
P-GW
PCRF
Servers
Radio Access Network (RAN)
Core Network (CN)
MME: Mobility Management Entity
HSS: Home Subscribe System
AAA: Authentication, Authorization and Accounting
S-GW: Serving GateWay
P-GW: Packets Data Network GateWay
PCRF: Policy and Charging Rules Functions

FIGURE 2. LTE physical resources with network slices.

It allocates the required resources to each user's flows according to a predefined SLA. The following sub-section presents the NSRM system model.

A. NSRM SYSTEM ARCHITECTURAL MODEL

In our NSRM architecture, the network slicing is actualized based on SDN and NFV. As mentioned in our previous work [30], all the LTE core network nodes are hosted in a server and each of these nodes is represented by a VNF. We could represent a slice in the core network as a set of VNFs link together as a chain form [32], [33]. Therefore, a slice resource allocation could be represented as a forwarding graph, which refers to the sequence of executions for different VNFs. The conceptual architecture of the NSRM for the network slicing based LTE network is depicted in Fig. 3. This architecture is broadly segmented into three layers: Slice layer, LTE Slice Controller Manager (LSCM) layer, and Slicer layer. Moreover, the architecture facilitates slicing a virtual network into a number of slices each of which is configured based on the service requirements of an operator.

To present our system model, we consider that in a LTE network there are three slices (slice A, slice B and slice C), as shown in Fig. 3. We consider that each slice belongs to an operator and it is managed by its controller (Slice pairing function). The controller is in charge of maximizing utilization of the slice resources (all the virtual resources).

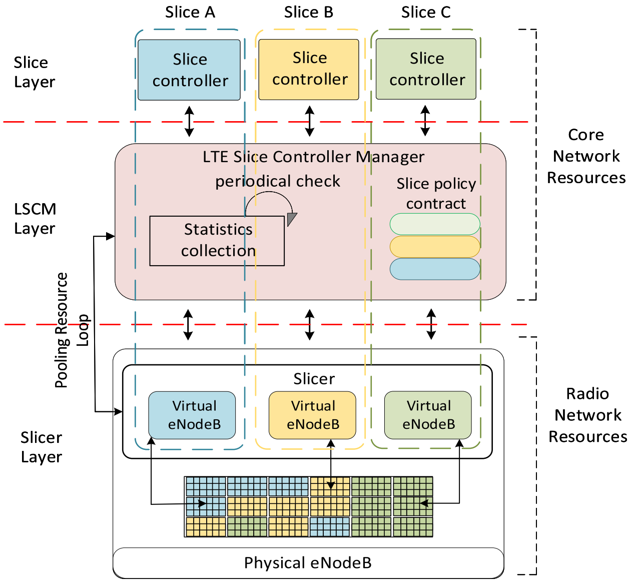


FIGURE 3. Conceptual a LTE network slicing architecture.

Generally, a user may have one or more flows. These flows might belong to the same slice or different slices [34]. In case when the flows belong to the same slice, in our proposal, the controller needs to manage intra slice resources in order to allocate required resources to each flow. Besides, it should ensure the isolation between the flows in a slice. To make sure that each of the slices can have predefined allocation, we need to have inter slices isolation. In our proposal, the Slicer layer is responsible of inter slices isolation (we provide more details in the subsequent part of this section).

As mentioned in [31], slice resource isolation can be classified into three general categories depending on: (i) group of users with the same type of application, (ii) end-to-end networking (different end-to-end flows), and (iii) resources allocated across different slices (the amount of allocated resource is predefined according to a policy). In our work, we consider that the type (i) and (ii) fall under intra slice isolation. Whereas, the type (iii) requires inter slice isolation.

We assume that a policy administrator (see Fig. 4) negotiates with a SP and settles the contract. Besides, it configures the LSCM layer in order to meet the slice requirements defined in the contract.

The elements of Slice layer, LSCM layer and Slicer layer are presented in Fig. 4. In this figure, these elements are logically interconnected to illustrate the main functionalities of the proposed logical framework architecture. The slice layer is a logical layer where each slice controller manages the intra resources of its slice. A slice controller has knowledge on the amount of resources required in a slice. The slice controller would pass the resource requirement information to the LSCM layer where the SGI element stores all the resource requirements of different slices requested by their controllers. Besides, the policy administrator has a set of suitable policies for all the slices. Therefore, the SGI and policy administrator provide information (policy and resource requirements) to the slice layer in order to assign resources to each of the slices accurately. Next, we provide a detailed explanation on how these elements under each layer function.

1) SLICE LAYER

As we mentioned earlier, each slice in this layer is owned by a slice owner and a slice controller is in charge of managing resources of a slice, as we can notice from Fig. 3. The controller coordinates the interaction among slice elements and stores all slice information, such as users information and resource requirements, in the User Information Database (UID), as depicted in Fig. 4. The following are the main elements of the slice layer:

- User Requests (UR): this element holds user requests. When a user wants to have a service from a slice, first, it needs to invoke the associated UR element of the slice. The user then sends a request message to the slice controller mentioning the service (e.g. video steaming service) it requires. Next, the slice controller determines the amount of required resources (e.g. PRBs) to meet the requirements of the service. Upon receiving this information from the user, the UR stores the information in the UID. The slice controller retrieves user requirements from the UID whenever required.
- User Policy (UP): this element handles a policy for each user (i.e. each user is associated with a policy). The policy is defined by the policy administrator. The slice controller uses the policy defined for a user while processing any requests from the user.
- Resource Computing Per User (RCPU): RCPU computes the resource requirement in order to satisfy the request of a user. The slice controller of a slice uses RCPU to know the exact number of slice resources required to meet a user's request. The RCPU retrieves a user's information from the UR and UP before computing the resource requirement for the user.
- User Status: a user could be in an active or idle mode at a given time [35]. This element periodically tracks the status of a user (i.e. active or idle). This facilitates the controller to release the allocated resources of a user if the user is found in idle mode at a given time.
  In our MAX-MIN model (section III-B.1.d), when a user with allocated resources moves from active mode to idle mode, it releases assigned resources. The slice controller then will redistribute the released resources to the remaining users which are in active mode within the slice. This approach will maximize the utilization of slice resources. In case when the user returns from idle to active mode, the slice controller will reassign the released amount of resources to the user. It is possible because all this process occurs within the same TTI. On the other hand, after leaving idle mode, if the slice controller does not have required amount of resources for allocating the user, it will invoke the Slicer to assign

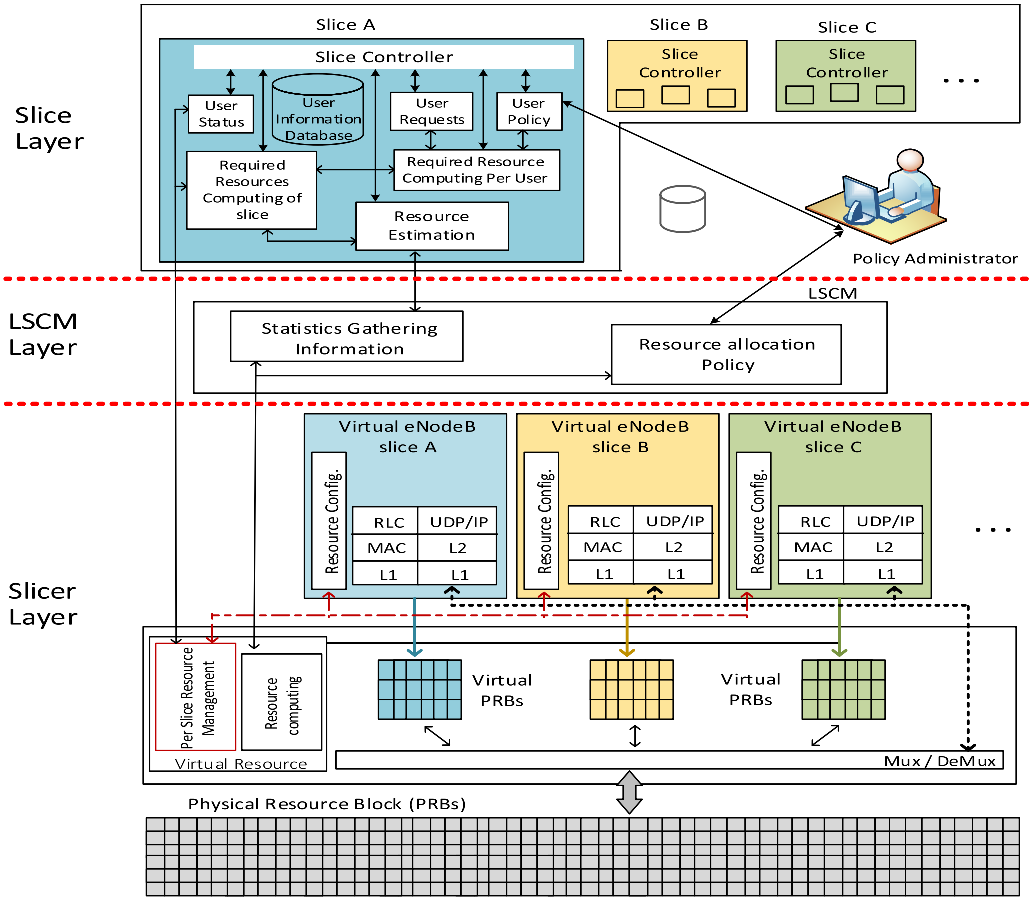


FIGURE 4. **Logical interconnections of three-layer elements.**

additional resources for the slice. The slice controller then updates the slice resource allocation in the next TTI.

- Slice Resource Tracker (SRT): this element has the global view of the slice resources. It periodically observes overall resource utilization of a slice and notifies the slice controller.
- Resource Estimation (RE): this element is responsible for estimating the future expected amount of resources that would be required based on the users' demand within a slice.

2) LSCM LAYER

In our architecture, the LSCM layer manages the LTE core network (it facilitates communication among the CN entities). Additionally, the LSCM has a global view of network resources requirements. It dynamically monitors the status of the network resources through the statistics of required resources and policies of assigning these resources. The following are the main two elements of this layer:

- Statistics Gathering Information (SGI): the task of SGI is to obtain statistics of the resource required for each slice. Periodically, the SGI collects and stores an estimated resource for each slice through the RE element. Therefore, it has a historical statistics of resources for each slice. Based on these statistics, the mean value of required resource is measured in order to realize the exact resource requirement of a slice.
- Resource Allocation Policy (RAP): RAP element holds all the policies between the SP and InP. The policy administrator places these polices in RAP. This will allow the Slicer to get policy associated information before allocating resources to each slice (see Fig. 4). Mainly, there are two different categories of slice allocation depending on the type of contract (SLA): Guaranteed bandwidth and Best effort [36]–[38]. We explain them briefly below:
Guaranteed bandwidth is categorized into two subcategories, as explained below:
   - Fixed Guaranteed (FG): in this type of contract, the SP will request the Slicer to allocate a fixed amount of bandwidth all the time (this bandwidth may or may not be 100% utilized).
   - Dynamic Guaranteed (DG): in this case, the bandwidth allocated to a SP is dynamically changed. The Slicer guarantees bandwidth allocation with the change of a SP's bandwidth requirement. The SP will pay to the InP depending on the usages.

Similarly, best effort bandwidth is classified into two subcategories, as presented below:

- Best effort (BE) with no guarantee: this type of bandwidth request has less priority than DG and FG. That is, in absence of high priority bandwidth requests (i.e. DG, FG), BE bandwidth request is accepted if the network has available bandwidth.
- BE with Minimum Guarantee (BEMG): in this type of contract, a SP can mention the lower and upper limit of its bandwidth requirement. The Slicer would ensure the lower limit of bandwidth request and the upper limit of a request will be satisfied in presence of abundant bandwidth.

3) SLICER LAYER

As shown in Fig. 4, we introduce a virtual layer (called Slicer layer) on the top of an eNodeB physical resources. The Slicer concept introduced here is similar to the Flowvisor concept, which is designed for wired network virtualization [39].

The Slicer is in charge of virtualizing the eNodeB by creating several virtual eNodeBs where each of this eNodeB represents a network slice. It schedules eNodeB physical resources among slice instances. That is, the Slicer allocates bandwidth resources (PRBs) to each slice using a bandwidth allocation algorithm after taking into account predefined contracts between an SP (slice owner) and InP. Note that it is challenging for the Slicer to allocate PRBs to the slices in a fair manner. To obviate this, in this paper, we come up with an algorithm, which is referred to as a simple exponential smoothing model, to measure the number of PRBs required for each slice (Section III-B.1.c presents this model in details). The following are the main elements of the Slicer layer:

- Virtual Resources (VRs): the task of VRs is to create a logical platform and divide this platform into different logical instances, where each logical instance represents a slice. Moreover, the VRs have two components running the functionality of this platform (see Fig. 4):
  - Per Slice Resource Management (PSRM): PSRM controls a configuration of slice resources between users of a slice. Additionally, PSRM with the slice controller enables distribution slice of resources among the users of slice in a fair manner utilizing the concept of Max-Min model.
  - Resource Computing (RC): RC is responsible of computing the estimated resource of each slice. RC utilizes the exponential smoothing model to calculate required physical resources in PRBs for each slice in every Round Trip Time (RTT). Moreover, SGI and RAP of LSCM layer are providing the RC with required statistics and policy rules to complement a process of slice resource allocation.
- Multiplexing/DeMuliplexing (Mux/DeMux): it is responsible for managing multiple data streams coming from/to different slices over eNodeB channel. Moreover, the Slicer uses this element in order to facilitate mapping between virtual and physical resources (see Slicer layer in Fig 4).

TABLE 2. Notations used in this paper.

Symbol	Explanation
X	A set of base stations and each base station denoted as x
V	A set of slices and each slice denoted as v_i
U	A set of users and each user denoted as u_i
B_x	The base station spectrum bandwidth
$\eta_{u_i x}$	The spectrum bandwidth for user within x
S and N	Represents the average signal and noise power
$L_{u_i\ x}$	The indication of user associated to x
$Y_{u_i\ x}$	The percentage of radio resources allocated to user u_i by BS x
$R_{u_i\ x}$	The instantaneous user u_i data rate
δ_{u_i}	The total number of virtual bearers assigned to a user
ΔT	Observation period
ρ_{u_i}	The total user bearer data rate over the period ΔT
$Q_{u_i x}$	The actual data rate load of a user bearer in a slice
$(\rho_{u_i})_{t+1}$	The next time round of scheduling allocation to a user data rate
v_B	A slice bandwidth capacity over base station x
V_B	The total slices bandwidth in the base station x
λ_{t+1}	The estimate PRBs of a slice during the $(t+1)$ interval time
α	A smoothing constant
FF_v	The fairness factor of a slice v
ω	The total estimated bandwidth of all slices
φ_v	The total number of PRBs allocated for each slice v
n	The number of users in a slice v
z	Represents the excess bandwidth for individual user u in a slice v

B. NSRM SOLUTION

In this sub-section, we present our NSRM solution. Before we delineate the proposed solution, we present mathematical models which assist the algorithms introduced in NSRM for making a decision in network resources allocation. We devise two mathematical models: the exponential smoothing model and the Max-Min model. The first model has the objective to quantify resource allocation among slices. The second model is formulated with the objective of fair resource allocation among the users in a slice. Our proposed NSRM presents two algorithms: (i) Resource estimation algorithm, which uses the estimation model we derive in this section and (ii) Fair resource sharing algorithm that uses the Max-Min model.

1) MATHEMATICAL MODELS FOR ESTIMATING RESOURCE ALLOCATION OF NETWORK SLICES

The resource allocation for slices using exponential smoothing model is presented. In addition, we provide a solution based on user's fairness and isolation using Max-Min model. The notations used in the paper is given in Table 2.

a: LTE NETWORK VIRTUALIZATION

In LTE, the RAN consists of a number of Base Stations (BSs). Let $X = (x_1, x_2, ..., x_n)$ denote as a set of BSs. We would highlight that, in our propose solution we consider individual BS (x) to show the strength of our solution in terms of allocating different slices in one corresponding physical BS, therefore, for each base station x there is a set of slices $V = (v_1, v_2, v_n)$ with a set of users $U = (u_1, u_2, u_3)$ for each v. In BS, the spectrum bandwidth allocated to x is B_x

(as described in Section II-A.1). By using Shannon bound, we can define the spectrum bandwidth efficiently for user u_i associated with BS x as shown in (1) [40].

$$\eta_{u_i x} = \log_2\left(1+\frac{S}{N}\right), \tag{1}$$

where S and N represent the average signal and noise power, respectively.

Let $L_{(u_i x)}$ be a pointer that indicates the user u_i is associated with BS x or not, where if the $L_{(u_i x)} = 1$ means u_i is connected to BS x; otherwise $L_{(u_i x)} = 0$ means it is not. $Y_{(u_i x)}$ represents the percentage of radio resources allocated to user u_i by BS x, where $Y_{u_i\,x} \in [0, 1]$ and notes that:

$$\sum_{x_i\in X, v_i\in V, u_i\in U} Y_{u_i x} \leq 1. \tag{2}$$

Such that, the instantaneous user u_i data rate is defined by:

$$R_{u_i\,x} = \sum_{x\in X} L_{u_i\,x}\, B_X\, Y_{u_i\,x}\, \eta_{u_i\,x}. \tag{3}$$

b: RESOURCES SLICING

Usually the PRB is assigned to a bearer as a pair of sub-frame in the time domains (described in Section II-A). Thus, we consider one Virtual Bearer (VB) to be equal to pair of PRBs sub-frames representing the resources of a slice in Slicer. Let δ_{u_i} represents the total number of VBs that the Slicer actually assigns to a user bearer u_i over some observation period T. Therefore, the total user bearer data rate ρ_{u_i} over this period is given as illustrated in (4).

$$\rho_{u_i} = \frac{\delta_{u_i}}{\Delta T}. \tag{4}$$

Thus, we can formulate the actual data rate load ($Q_{u_i x}$) of a user bearer in a slice over a base station from (3) and (4):

$$Q_{u_i x} = \rho_{u_i} R_{u_i\,x}. \tag{5}$$

The slice has to allocate and prepare required resources by the Slicer to satisfy a user data rate each time trip as shown in (6):

$$(\rho_{u_i})_{t+1} \geq (\rho_{u_i})_t. \tag{6}$$

At least the minimum value of the current $(\rho_{u_i})_t$ total user bearer data rate ρ_{u_i} at a time t is required in the next t time trip $(\rho_{u_i})_{t+1}$ of scheduling allocation to satisfy the requirements of a user data rate. Notice that, sometime user data rate in $(\rho_{u_i})_{t+1}$ is greater than the user data rate in $(\rho_{u_i})_t$ to satisfy the user demands (described in Section III-B.1.d).

Therefore, the $(v_{B_i})_t$ is the total slice bandwidth capacity (v_{B_i}) at a time t over the base station x is:

$$(v_{B_i})_t = \sum_{v_i\in V} (\rho_{u_i})_t. \tag{7}$$

Therefore, the total slices bandwidth $(V_B)_t$ at a time t in the base station x is:

$$(V_B)_t = \sum_{v_i\in V} (v_{B_i})_t, \quad \text{where } (V_B)_t \leq (B_x)_t. \tag{8}$$

The $(B_x)_t$ represents bandwidth capacity B for base station x at a time t.

c: SLICER'S RESOURCE ALLOCATION USING EXPONENTIAL SMOOTHING MODEL

PRBs in a BS need to be allocated and shared between slices based on resource requirements of each slice (as shown in Fig. 4). Thus, each slice should provide an estimated value of the required resources and periodically send them to the Slicer. In order to achieve this, a slice controller needs to calculate required bandwidth of the slice periodically as shown in (7). The LTE Slice Controller Manager (LSCM) collects all estimated bandwidth values from slices and sends them to the Slicer. The Slicer uses these values to allocate PRBs for each slice efficiently. To enable this, we utilize the simple exponential smoothing model as shown in (10).

$$\lambda_{t+1} = \alpha \times v_{Bt} + (1-\alpha) \times \lambda_t, \tag{9}$$

where λ_{t+1} indicates the estimate of PRBs for each slice during the $(t+1)$ interval time. The λ_{t+1} describes slice status where it either requires additional PRBs or the slice needs to release some PRBs. λ_t refers to the current estimate amount of PRBs during $TTI(t)$ interval. t is the Slicer interval, which consists of a number of $TTIs$. α is a smoothing constant, which serves as a weighting factor. Taking consideration α, we reformulate (9) as follows:

$$\lambda_{t+1} = \alpha v_{B_t} + \alpha\,(1-\alpha)\, v_{B_{t-1}} + \alpha(1-\alpha)^2 v_{B_{t-2}} + \ldots + \alpha(1-\alpha)^{t-1} v_{B_1} + (1-\alpha)^t \lambda_1, \tag{10}$$

where λ_1 represents a simple average of the $\sum_{t=1}^{n} v_{Bt}$, and α has a value between (0 and 1) where $(0 < \alpha < 1)$. In (10), too large value of t would result in making value of $(1-\alpha)^t$ close to zero.

Generally, λ_{t+1} has either positive or negative values when compared with λ_t. In the case of a positive value, the slice needs more PRBs, whereas in the case of a negative value, the slice operator satisfies the current state of allocation PRBs. The Slicer utilizes these values to calculate and allocate PRBs to each slice (virtual network). Moreover, this type of calculation is especially useful for network slicing within a contract from type DG, BE or BEMG. The DG contract represents the actual allocated bandwidth to slice operator for serving users requirements, and the maximum bandwidth by the terms of contract. With types BE and BEMG contracts, the Slicer determines the minimum requirements for the BEMG slice operator and the remaining PRBs will be assigned to BE contracts.

The isolation between slices is based on the fairness factor as calculated in the following (11):

$$FF_v = (\lambda_{t+1})_v / \omega. \tag{11}$$

FF_v is the fairness factor of slice v; $(\lambda_{t+1})_v$ is the estimation value of PRBs for slice v; ω is a total PRBs over all BE slices.

The ω is computed using the following equation.

$$\omega = \sum_{v=1}^{\forall BE\ x\ slices} (\lambda_{t+1})_v. \tag{12}$$

The total number of PRBs (φ) allocated for each BE slice v is described as in (13).

$$\varphi_v = int\ (FF_v{*}\Upsilon), \tag{13}$$

where the Υ is the remaining PRBs after allocating guaranteed bandwidth to slices.

d: MAX-MIN MODEL FOR USERS FAIRNESS AND ISOLATION IN SLICE

Generally, the scheduling mechanism should be fair and it should isolate the bandwidth between users in the same slice. To realize this, we use the Max-Min fairness model. The Max-Min fairness means maximizing the minimum fair share of the bandwidth for each user within a certain slice. Three principal steps have to be considered in the Max-Min mechanism:

1- Resource allocation is in increasing order of their demands.

2- No user gets a share larger than its demands.

3- Users with unsatisfied demands get equal shares.

Let U_P be a set of users U with their bandwidth demands p in v such that these users are arranged in ascending order, which we formally define as follows:

$$U_P = \{\rho_1, \rho_2, \ldots, \rho_N\}, \quad \text{such that } \rho_1 < \rho_2\ \ldots < \rho_N. \tag{14}$$

To equally share slice's resources (bandwidth) between users, let's consider u_E is the bandwidth share of individual user u in slice v. u_E gets as follows:

$$u_E = v_b/N, \tag{15}$$

where v_b is the total bandwidth of a slice v and n is the number of users in v. So that, the user will be protected by allocating the same bandwidth as other users. Not only that, allocated bandwidth represents the minimum satisfied requirement of a user service in slice v.

In some cases, the user's demands ρ is greater than the allocated bandwidth u_E, which means that the user is unsatisfied. In such a case, for all unsatisfied users, they will get the same (equally) extra bandwidth from the slice controller if it is available. In the slice, not all the users are unsatisfied. Some of them have more bandwidth than they actually need. Therefore, we can calculate the excess bandwidth and equally distribute it between unsatisfied users. Thus, assume that z represents the excess bandwidth for an individual user u, we compute the value of z as illustrated in (16):

$$z = u_E\ - \rho. \tag{16}$$

Now, for each unsatisfied user in slice v, it will get z/x bandwidth, if we assume that x represents the number of unsatisfied users in v. The slice operator repeats this process by the slice controller each time if excess bandwidth is available. As a result, no users will get more allocated resources (bandwidth) than they need.

2) NSRM ALGORITHMS

From the previous discussion on how the estimated resource model and the Max-Min model influence the resource allocation, we conclude that both models work in different tiers (intra, inter). In inter-tier resource allocation, the estimated resources are allocated among different slices, whereas the intra-tier resource allocation is a process in which the resources of a slice are allocated among different users in the slice. Here, we propose two algorithms for resource allocation namely, NSRM inter-tier resource allocation (Algorithm 1) and NSRM intra-tier resource allocation (Algorithm 2). Both algorithms are implemented in the Slicer.

Algorithm 1 NSRM Inter-Tier Resource Allocation

```
INPUT: $V$, $B_x$. /*set of slices in a base station*/
OUTPUT: $(\lambda_{t+1})_v$. /*PRBs for each slice within the base station*/
  for all $v = 1$ to $V$ do
     $\omega_V = \omega_{V-1} + call\ (GET - PRBs)_v$. /* invoke GET-PRBs to get PRBs for a slice $v$ */
  end for
  if $\omega_V \leq B_x$ then
     $v = 0$
     for all $v = 1$ to $V$ do
        $(\lambda_{t+1})_v/\omega_V$
     end for
  else
     $(\lambda_t)_v/\omega_V$
  end if
  if $(\lambda_t)_v > (\lambda_{t+1})_v$ then
     release $PRBs = (\lambda_t)_v - (\lambda_{t+1})_v$
  end if
```

GET-PRBs Sub-Algorithm to Assign PRBs to a Slice

```
INPUT: $\alpha$, $v_B$, $\lambda_1$
OUTPUT: return value of $(\lambda_{t+1})_v$ for the calling function.
  /* Using (10) calculate $(\lambda_{t+1})_v$ */
  /* Where $v_B$ is calculated using (7) */
```

As mentioned earlier, Algorithm 1 allocates resources among different slices. For that, it needs the required resource of each slice (v_B) and the total PRBs of an eNodeB (B_x). The algorithm invokes the GET-PRBs function to calculate the estimated resources of each slice according to (10). Then, it finds a value of the total estimated resources of all slices. This algorithm checks whether the total value of slices is less than or equal the total PRBs of the eNodeB. If so, the algorithm assigns a required resource to each slice, otherwise, all the slices continue with the same currently allocated resources until more resources are available in the Slicer. That is, sometimes the estimated forecasting of resource allocation of a slice is less than the current resource allocation. In such a case, Algorithm 1 will release the surplus resources to allocate to other slices that are unsatisfied with a current resource allocation.

Algorithm 2 NSRM Intra-Tier Resource Allocation

```
INPUT: $(\lambda_{t+1})_v, N, U_P$ /* $U_P$ set of users demand $p$ in a slice */
OUTPUT: $u_E$ /* the bandwidth for each user in a slice */
  $v_b = (\lambda_{t+1})_v$ /* resource allocation for a slice v by the Slicer */
  $u_E = v_b/N$
  $x = 0$
  for all $i = 1$ to $N$ do
    if $p_i > u_{E_i}$ then
      $U_E[x] = u_{E_i}$ /* all unsatisfied users will store in $U_E$ set */
      $X = X + 1$
    end if
  end for
  $i = 0$
  while $u_{E_i} > p_i$ do
    $z = u_{E_i} - p_i$
    $z/x$ /* for all the users in $U_E$ get $z/x$ share resources */
    $i = i + 1$
  end while
```

In Slicer, the Algorithm 2 is responsible for intra-tier resources allocation. This algorithm requires to know the number of users (N) in the slice along with their resource demands (U_P) and the overall resources allocated to the slice (λ_{t+1_v}) from the Slicer.

According to the Algorithm 2, initially, all N users get equal share of resource u_E. Then, the algorithm checks whether a user demand p_i is greater than u_E or not. If p_i is greater than u_{E_i} (i.e. the assign resource for a user is unsatisfied), the algorithm will add the user to a list of unsatisfied users. This process will continue until all users are checked. Moreover, the algorithm will check if there is any user whose u_{E_i} is greater than p_i. If so, this will distribute equally the surplus resources from the user among the all users in the unsatisfied list. This process continues until all the users in the slice are checked. Following this processes mentioned above, the algorithm meets demand of resources of all the users as much as possible.

IV. PERFORMANCE EVALUATION

This section is divided into two parts: the simulation configurations and simulation results. The configuration of the simulation explains the topology of the network used in the simulation. In the second part, we present the simulation results and explain the significance of our results. For validation purposes, we evaluated our proposed solution in different scenarios as presented in the next sub-sections.

TABLE 3. Simulation parameters.

Parameter Name	Value
Simulation run time	720 (in seconds)
Mobility model	Random Way Point (RWP). Users are initially distributed uniformly in a cell
Channel model	Path loss: 128.1 + 37.6 log10 (R), R is in km [41]. Slow fading: Correlated Log normal, zero mean, 8db, std. and 50 m correlation distance. Fast fading: Jake's like model.
Users speed	5 km/h
Total number of PRBs	99 (corresponds to about ∼ 20 MHz)
CQI reporting	Ideal
Modulation schemes	QPSK, 16 QAM, 64 QAM
eNodeB coverage area	Circular with one cell, R = 300 meters
Link-2-system interface	Effective Exponential SINR mapping [42]
FTP traffic model	File size: constant 3 MByte, Inter-arrival time: exponential (20s)
Video traffic model	24 Frames/sec, frame size: 1562 bytes (300 kbps)
VoIP traffic model	Encoder Scheme: G. 711 (64 kbps) Talk period / Silence period: exponential (3s)

A. SIMULATION CONFIGURATIONS AND SCENARIOS

To validate the proposed models in this paper, we use the OPNET Modeler to investigate different scenarios (the network topology in our simulation is presented in Fig. 5). This topology illustrates a LTE network with one eNodeB and 10 mobile nodes. In the topology, all the wired connections nodes are linked through 100BaseT cable. The scenarios we consider over this topology are based on a comparison study of the performance between the standard LTE network (a legacy network) and the proposed network slicing mechanism (NSRM). The simulation configuration parameters considered in the OPNET modeler in order to compare these two solutions are shown in Table 3. Additionally, in our simulation, for the proposed NSRM we assume that the smoothing constant (α) is 0.5 and the number of slices is 2.

B. SIMULATION RESULTS

First of all, we would like to state that in our performance evaluation all the users and operators in the core network slicing are satisfied, therefore, we are focusing on the performance evaluation of radio access network part.

In this performance evaluation, we aim to evaluate how the proposed NSRM performs in front of a legacy network in terms of three important aspects: bandwidth reservation, flow isolation and slice customization. In sub-section IV-B.1, through simulation, we impart how NSRM ensures effective bandwidth reservation for coexisting slices. With this, we will highlight the effectiveness of the proposed exponential smooth model that takes into account predefined agreements in measuring allocated bandwidth. Following this, in sub-section IV-B.2, we demonstrate how the proposed solution can successfully manage flow isolation (both inter and intra slices). In particular, from the results, we demonstrate how the proposed algorithms (Algorithm 1 and 2) come into play in realizing this. Additionally, this sub-section illustrates how the proposed NSRM can dynamically reallocate bandwidth when network condition changes (e.g. a user releases bandwidth). Finally, we present performance results in

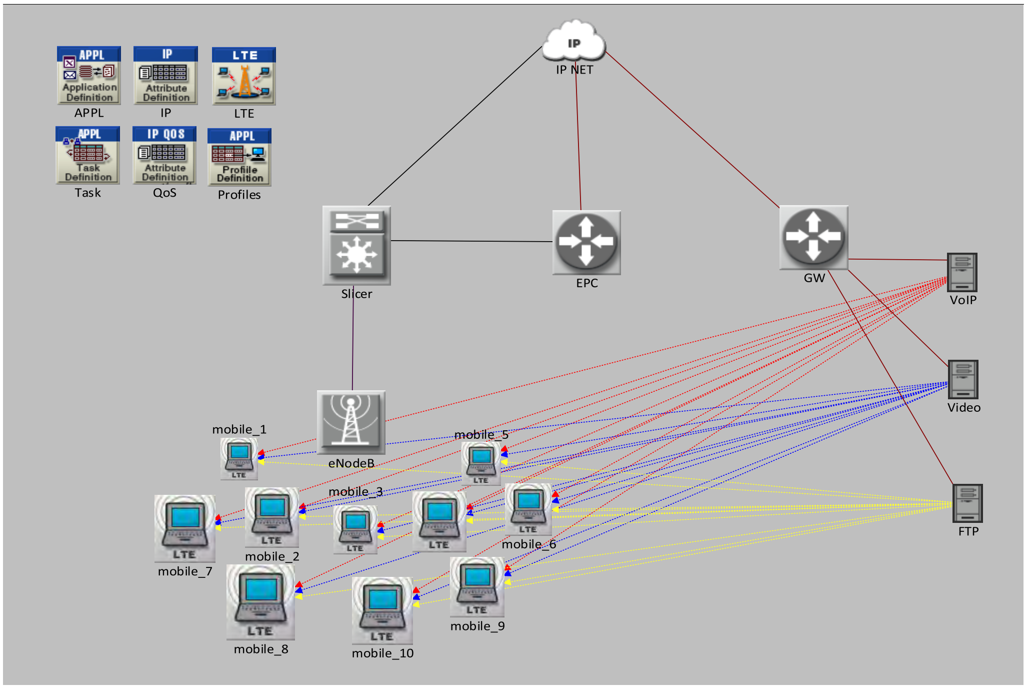


FIGURE 5. Network topology considered for simulation in the OPNET Modeler.

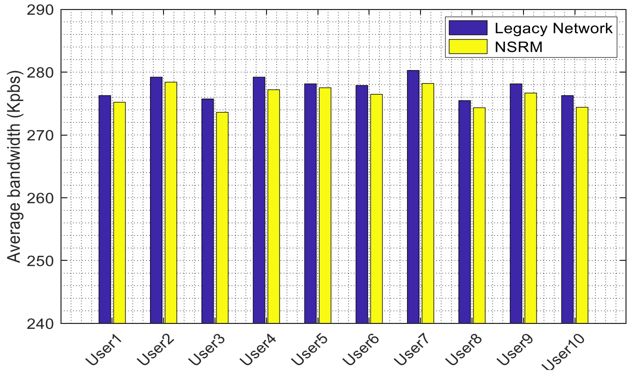


FIGURE 6. DL fixed guaranteed average per-user throughput.

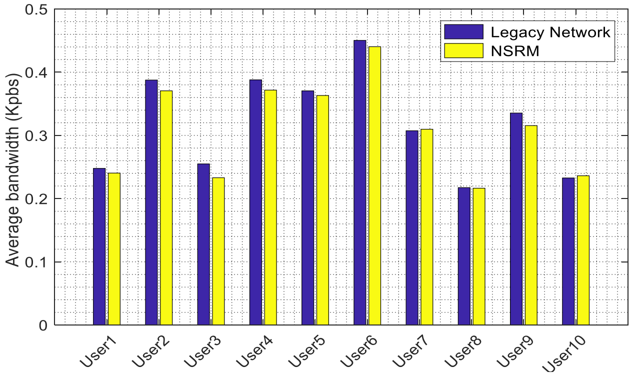


FIGURE 7. DL average per-user application end-to-end delay.

sub-section IV-B.3 showing how effectively each of the slices can be customized under the proposed NSRM.

1) BANDWIDTH RESERVATION

This sub-section presents different scenarios of bandwidth reservation based predefined contracts of slices with an InP as follows:

For the fixed guaranteed bandwidth contract, we consider a video traffic model. In this scenario, we assume that the downlink (DL) of an eNodeB provides 30 PRBs (a fixed guaranteed user data rate).

Figure 6 shows the average user throughput under a legacy LTE network and the proposed NSRM. As depicted in the figure, both networks show approximately the same per-user throughput performance. This happens because in the case of fixed guaranteed bandwidth both solutions follow the same mechanism, as we mentioned before. Unsurprisingly, due to the same reason, both of the solutions present similar average end-to-end delay performance (see Fig. 7).

The next scenario is based on a dynamic guaranteed bandwidth contract with the VoIP traffic model application. In this scenario, the DL user data rate dynamically changes based on users' requirement and the maximum guaranteed boundary of resource reservation is 30 PRBs. Figure 8 demonstrates throughout performance comparison between these two solutions. The result shows that the average throughput per user in both networks is similar. The reason for this is that under both solutions the bandwidth reservation is guaranteed even with dynamic changes of user throughput. This scenario proves that the NSRM solution is able to dynamically reserve PRBs of a slice according to users' requirements.

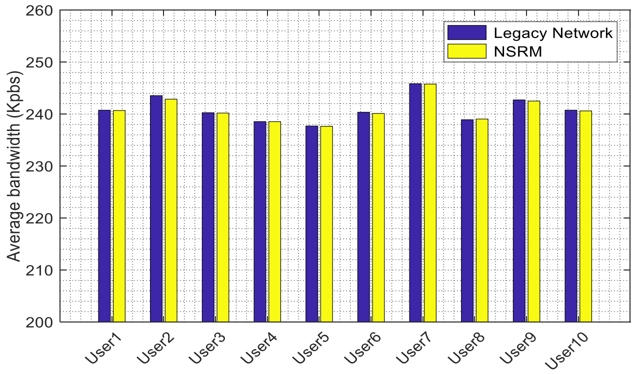


FIGURE 8. DL dynamic guaranteed throughput average per-user.

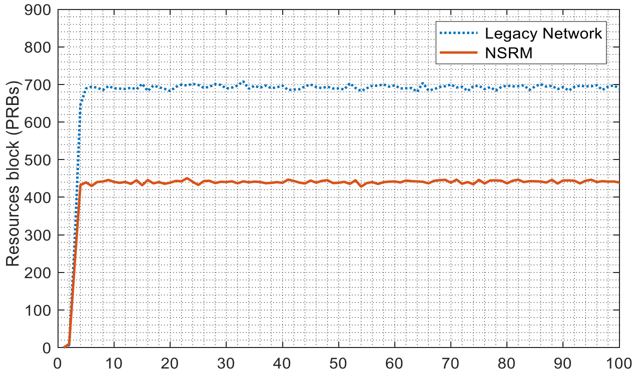


FIGURE 9. Bandwidth reservation in both scenarios.

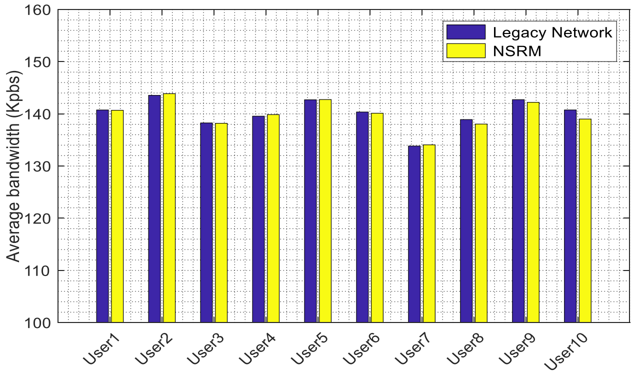


FIGURE 10. DL best effort average bandwidth of VoIP service per-user.

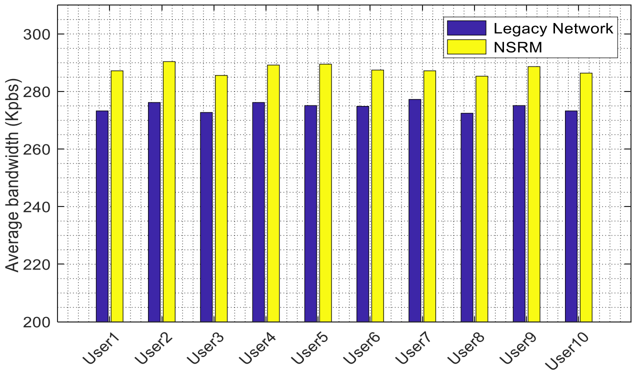


FIGURE 11. DL best effort average bandwidth of video service per-user.

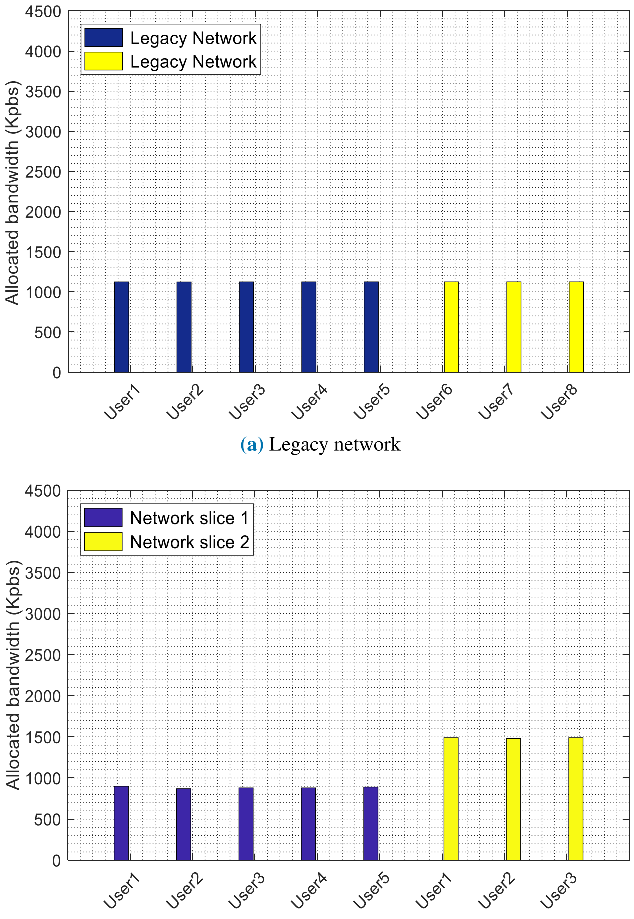
At this point, we are interested to observe how the proposed solution can contribute in maximizing utilization of radio resources. Figure 9 demonstrates resource blocking performance comparison between the two solutions. The results depicted in this figure confirms that in NSRM resource blocking is approximately 35% less compared to the legacy LTE network. The rationale for this result is that unlike the legacy LTE (see LTE bandwidth allocation mechanism in Section II-A.2), our proposed NSRM allocates bandwidth based on slice requirement, resulting increasing utilization of PRBs (i.e. there would not be any unused PRBs). Consequently, in NSRM, the resource blocking would be less compared to the legacy LTE network.

In addition, we are interested in observing the importance of the proposed solution when a network has best effort traffic. In our simulation, in this case, we consider three types of traffic: best effort, guaranteed bandwidth and dynamic guaranteed bandwidth. Traffic of VoIP and video application services is considered as best effort in our simulation. Both of these applications have a minimum and maximum guaranteed data rates of 30 PRBs and 50 PRBs, respectively.

Figure 10 shows the average bandwidth of VoIP service per-user in a legacy network and NSRM solution. In this figure, we can note that both networks have the same performance per user bandwidth. Note that both networks assign the remaining PRBs to the best effort applications after satisfying resource demand of the guaranteed bandwidth applications. In case of VoIP traffic, both solutions can meet the bandwidth requirement. Consequently, their performance for VoIP service is the same. However, the results for average bandwidth allocation for a video service depicted in Fig. 11, show that the NSRM outperforms the legacy LTE network. It needs to highlight that VoIP traffic is given more priority than the video traffic in a LTE network [14]. Therefore, after meeting the VoIP traffic bandwidth requirement, the legacy network allocates the residual bandwidth to the video services. The NSRM does the same; however, the amount of residual bandwidth in NSRM is larger than a legacy LTE network due to applying the dynamic bandwidth allocation mechanism. Consequently, in NSRM, a user gets more bandwidth compared to a user in a legacy LTE network (a user approximately gets 15 Kbps more bandwidth in NSRM).

2) EVALUATION OF ISOLATION MODEL

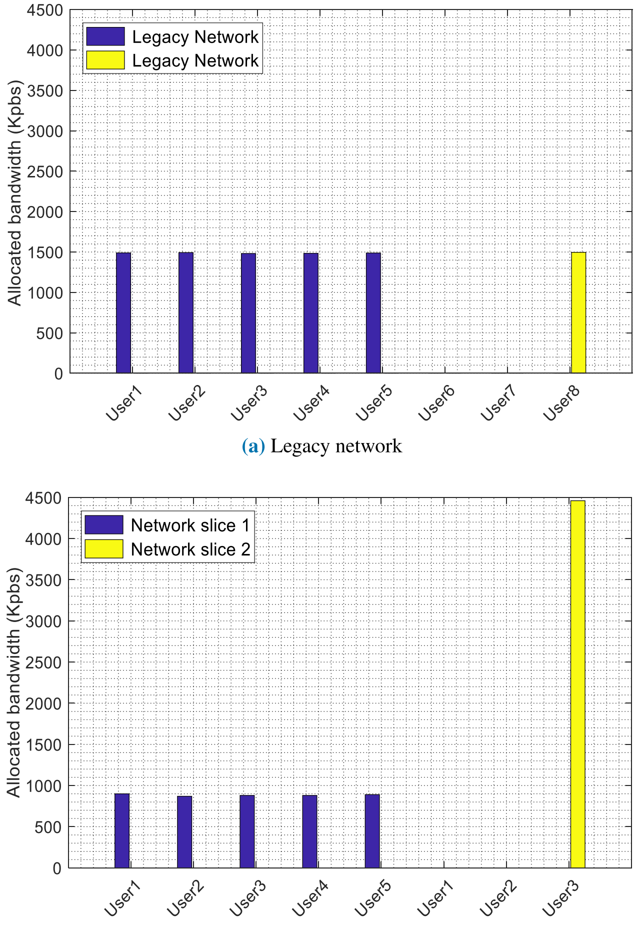
In this section, we demonstrate how our solution can successfully maintain the isolation for both inter slice (among the slices) and intra slice (among the users belong to the same slice). Under the same scenario, we compare NSRM's results in front of a legacy network. In this simulation scenario, we consider FTP traffic flows. Here, we consider two groups of users. The first group (*slice 1*) and the second group (*slice 2*) has 5 users and 3 users, respectively.



(a) Legacy network

(b) NSRM

FIGURE 12. **Bandwidth isolation performance evaluation: a) Legacy network; b) Proposed NSRM.**



(a) Legacy network

(b) NSRM

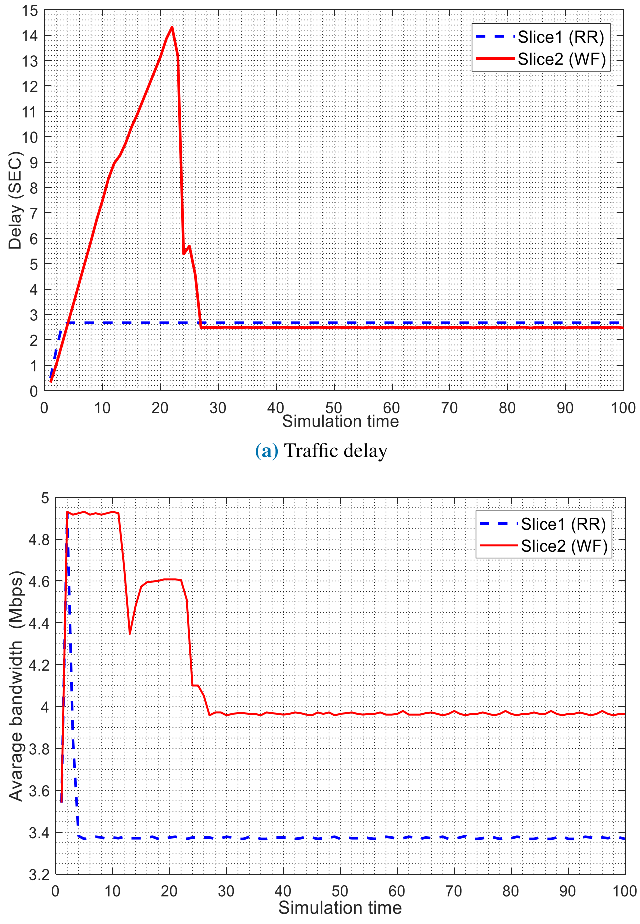
FIGURE 13. **Isolation scenarios when the bandwidth increasing: a) Legacy network; b) Proposed NSRM.**

All the users in our simulation are located at equal distance from an eNodeB, which applies 64 QAM for Modulation and Coding Schemes (MCS). Furthermore, we assume as an aggregation, bandwidth requirement is 9 Mbps and each of the slices needs 4.5 Mbps. Additionally, in this performance evaluation, we assume all the users in a slice have the same bandwidth requirements. Simulation results are presented in Fig. 12 (a) and (b) for a legacy network and NSRM, respectively.

Looking at Fig. 12 (b), we observe that NSRM successfully isolates resources between the two slices. That is, NSRM provides both of the slices an equal amount of bandwidth (each slice gets 4.5 Mbps). From the same figure, we can also realize that, under each slice all the users are provided almost the same amount of bandwidth. These results clearly highlight that NSRM can successfully isolate not only the inter slice bandwidth but also it can isolate users' bandwidth within a slice (e.g. in case of *slice 1*, each of the five users gets around 0.9 Mbps).

In the next simulation scenario, we aim to illustrate how our proposed NSRM can dynamically reallocate bandwidth and successfully isolate resources with the change of network conditions. We narrate the scenario as follows. In this case, our assumptions are the same as the previous scenario. Further, in this simulation, we consider, initially, each of the 8 users connected with an eNodeB is allocated 1.125 Mbps (i.e. the eNodeB provides total 9 Mbps to these users). After 200s from the simulation starting time, two users (users 6 and 7 in Legacy LTE, and 1 and 2 of *Slice 2* in NSRM) turn off their mobile, releasing around 2.25 Mbps bandwidth in each scenario. In case of Legacy LTE, the scheduler will redistribute the released bandwidth equally to the remaining users. However, for the NSRM, the slice controller (scheduler) of the slice will reallocate the released resources of the slice and distribute them to the users according to their current requirements. The simulation results from this scenario are presented in Fig. 13 (a) and (b).

Looking at Fig. 13 (a), we observe that in a legacy network overall bandwidth of each user is increased by 0.375 kbps after two users left the network (see Fig. 12 (a)). It happens because, in a legacy network, the eNodeB redistributes the released bandwidth across the users equally. In case of NSRM, as we notice from Fig. 13 (b), the user 3 of *Slice 2* is reallocated the released bandwidth (See Fig. 13 (b)). However, the bandwidth allocated to each user in *Slice 1*



(a) Traffic delay

(b) DL traffic received

FIGURE 14. Flow schedulers performance of different slices in NSRM: a) Traffic delay; b) Downlink traffic received.

remains the same (i.e. the change of bandwidth allocation in *Slice 2* does not influence the users of *Slice 1*). This result clearly proves that NSRM does not only successfully isolate resources between the slices but that it can also dynamically reallocate the resources.

3) CUSTOMIZATION

In this sub-section, we want to demonstrate that in our NSRM each slice can have its own scheduling policy (i.e. different slices can have different scheduling policies). Let us assume that *Slice 1* and *Slice 2* each has 4 users with heavy video traffic flows. In this simulation scenario, we consider that the *Slice 1* uses a Priority Round Robin (PRR) and the *Slice 2* applies Weighted Fair (WF) scheduling policy. Moreover, we suppose that all users in both slices have the same configuration setup (see video traffic model in Table 3). Simulation results are presented in Fig. 14 (a) and (b) for traffic delay and DL traffic received.

Figure 14 (a) shows the delay performance for each slice in NSRM. From this figure, we can realize that despite having the same number of users with the same configuration in both slices, their delay performances are not identical. In fact, this result is quite obvious. As these two slices have two different scheduling policies, their delay performance is not the same. And due to some reasons, they have different downlink throughput performances, see Fig. 14 (b). Therefore, these findings delineate that the proposed NSRM can allow dispensing different scheduling policies for each of the slices in an eNodeB. Note that the explanation of the performance of these two scheduling polices is not in the scope of this paper.

V. CONCLUSION AND FUTURE WORKS

In this paper, a network slicing mechanism for resource allocation in LTE networks has been presented. The proposed mechanism is based on a simple exponential smoothing model that takes into consideration the estimated bandwidth that each slice needs periodically. In addition, we propose a Max-Min fairness mechanism for isolating and fair sharing of a distributed bandwidth between users. Our simulation results show that the proposed mechanism satisfied the user service requirements and that it can implement different customized flow traffic for different isolated slices simultaneously.

In our future research, we are aiming at investigating how network slicing can be actualized in order to share resources from different heterogeneous access networks (develop a unified network slicing platform). In this unified network slicing platform, among the important resources issues, we are planning to study: (i) QoS aware mobility management, and (ii) energy efficient dynamic network slice selection for user devices.

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