Wireless Resources Virtualization in LTE Systems

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***Abstract*—This paper proposes a framework for Wireless Resource Virtualization (WRV) in Long Term Evolution (LTE) systems. An shared radio access network connects Multiple Mobile Network Operators (MNOs) and allocates radio resources to their users. We formulate the WRV problem as a Binary Integer Programming (BIP) problem. Subsequently, a low complexity iterative algorithm is presented to solve the BIP problem. The proposed framework allows MNOs to customize their scheduling policies to fit their service requirements and business models. Essential considerations like isolation across MNOs, complexity, and efficient resource utilization are also considered and evaluated. The results show that the proposed framework can efficiently share the radio resources between MNOs while maintaining the sharing agreement conditions.**

I. INTRODUCTION

Within the last decade, the volume of mobile data traffic has increased rapidly. However, Mobile Network Operators (MNOs) profits are not growing at the same rate as the traffic volume [1]. Wireless resources are very scarce, and deploying wireless networks with higher capacities to handle this increase is costly and challenging. In this context, Wireless Resource Virtualization (WRV) has received much attention by network operators. Virtualizing the wireless resources of a cellular network enables MNOs to create multiple logical networks based on a single physical substrate. WRV reduces OPEX and CAPEX, facilitates new business models, supports higher peak rates, and contributes to better resource utilization.

WRV enables resource and infrastructure sharing, which can bring in substantial benefits to MNOs. A new study from ABI Research reported in [2] shows that MNOs that deploy active infrastructure sharing can potentially save as much as $60 billion in OPEX and CAPEX over a period of 5 years. In addition, infrastructure sharing would reduce the number of the network physical components (for example antenna masts), which leads to potential energy savings. Moreover, sharing the radio resources between multiple MNOs facilitates carrier resource aggregation and supports higher peak rates. Also, it introduces multi-MNOs multiplexing gain as a result of increasing the number of users in cells. For instance, in a Rayleigh fading channel, the aggregated capacity of a cell increases by $\ln(M)$ [3], where M is number of users in the cell. Furthermore, network sharing facilitates new business models in wireless market. For example, operators without Long Term Evolution (LTE) licenses, spectrum, or network resources would be able to provide LTE services by renting parts of the LTE radio resources from other MNOs.

Thus, three main requirements are needed to enable WRV as follows [4]:

1) Isolation among MNOs. Isolation is a capability of limiting the impact of one MNO on the other MNOs despite them sharing the same physical substrate. For example, any change in the traffic load or channel quality for any particular operator should not affect other operators.
2) Customization. MNOs should be able to implement different custom scheduling policies. MNOs target to maximize their revenues and satisfy user requirements. Thus, different MNOs may have different services, Quality of Service (QoS) requirements, and pricing models. Radio resources are allocated to users based on scheduling policies. Every MNO should be offered the flexibility to implement custom scheduling policy to achieve its goals.
3) Efficient radio resource utilization. To keep up with the demand for data on mobile devices, efficient use of the radio resources should be maintained. Besides, efficient radio resource utilization engages the scarce radio resources as much as possible, which increases the transmission capacity of cellular systems, and consequently offers the opportunity to MNOs to maximize revenues.

In this work, a framework that maintains the above WRV requirements is proposed for the LTE system. The rest of the paper is organized as follows. Section II discusses the related work and paper contributions, while sharing assumptions and system model are shown in Section III. A Binary Integer Programming (BIP) formulation of the problem is presented in Section IV. Section V presents an iterative approach to solve the BIP problem. Simulation results are shown and discussed in Section VI, and Section VII concludes the paper.

II. RELATED WORK

Network sharing has been proposed to be an integral part of the next-generation networking architectural. For example, The 3GPP LTE standard supports two network sharing configurations [5], namely Multi-Operator Core Network (MOCN) configuration, and Gateway Core Network (GWCN) configuration. In MOCN, MNOs share only the evolved Universal Terrestrial Radio Access (eUTRAN). While in GWCN, parts of the core network are shared in addition to the eUTRAN.

In the literature, there has been a recently increasing research interest in WNV [2], [4] [6], [7], [8]. For example, Zaki *et al.* in [6], proposed an LTE air interface virtualization scheme. A hypervisor is added on top of physical resources. This hypervisor virtualizes the evolved Node B

978-1-4799-3088-3/14/$31.00 ©2014 IEEE

(eNB) into a number of virtual eNBs, each is used by a network operator. The authors mainly focus on exploring the benefits and potential gains (in terms of capacity) that can be achieved by sharing the spectrum resources between different MNOs. Their results show that resource sharing introduces extra multiplexing gain by developing Multi-MNO Diversity (MD), and it enhances the resource utilization. As an extension to [6], more practical scenarios were investigated in [7] and [8], where MNOs share multiple eNBs. The sharing process is managed again by the so-called hypervisor. Two traffic models, namely best effort model and guaranteed bit rate model have been considered for resource sharing and load estimation. In addition, enhancements like load balance and safety margins are also investigated.

Kokku *et al.* [2], [4] proposed a flow-level virtualization of wireless resources in cellular networks. The radio resources of the base stations are sliced between different flow groups. Their virtualization scheme enables customized flow scheduling per slice, and takes into account the level of isolation and resource utilization trade-off. Each slice can be seen as a virtual MNO and contains a number of flows. Different utilities are mapped to different flows, where the objective function is to maximize the total sum of the flows utility. Admission control procedure is assumed to restrict the number of flows established, and to guarantee feasible solutions. Nevertheless, the random nature of the wireless channel is not considered in the design, where a single Modulation and Coding Scheme (MCS) is assumed for each flow, which leads to inaccurate bandwidth reservation for each slice. However, in real systems, different MCSs are used contingent on the channel quality. In addition, their scheme does not take into account the instantaneous channel quality for the mobile users in the scheduling decisions, which is an essential point of concern for efficient radio resource scheduling.

Another framework for wireless network virtualization that separates service providers from network operator is reported in [9]. The service providers are in charge of QoS management, while spectrum management is maintained by the network operator. The interactions among the service providers and the network operator is modeled as a stochastic game which is regulated by the network operator. The role of the SPs is to compete for the wireless resources for each of subscribed user.

Compared with previous works, this paper has the following key contributions: 1. Wireless Resource Virtualization that enabled isolation, customizable resource scheduling, and efficient resource allocation between multiple MNOs is formulated. 2. The proposed framework is able to control the sharing of MD gain between MNOs according to sharing agreements. 3. The dynamic behaviour of the wireless channel and adaptive MSC transmission are considered.

III. Sharing and System Model

A framework of WRV in the context of network consolidation is proposed, where MNOs have different spectrum bands, and agree to combine them on a single eNB. We consider an LTE downlink scenario, where an N MNOs share R radio Resource Blocks (RBs) over a single eNB. Each MNO has an associated Evolved Packet Core (EPC). The eNB can establish multiple radio bearers per user to support multiple traffic types. Each bearer is only associated to a user. The number of the established bearers is controlled by an admission control procedure. We assume that M_i bearers have been established for MNO-i, where i belonging to a set of MNOs $I = \{1, 2, \ldots, N\}$. Fig 1 shows an example of four bearers established for three users who belong to two MNOs.

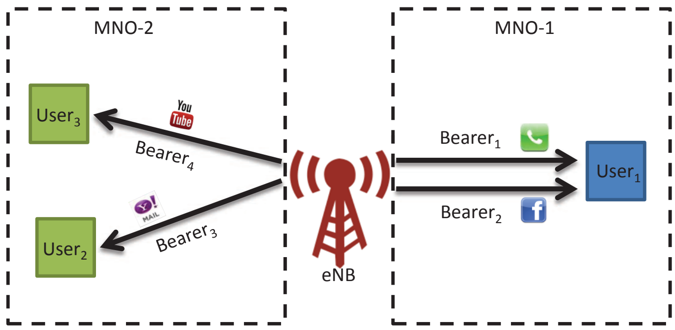

Fig. 1. LTE bearer establishment

Each MNO owns a set of RBs $\{R_i\}$ such that

$$R_i \cap R_j = \emptyset, \forall i, j \in I \quad \text{and} \quad R = \bigcup_{i \in I} R_i. \tag{1}$$

The total RBs set $\{R\}$ is assumed to be fully pooled and accessible to every MNO. RBs are shared in accordance to the following agreement:

1. Given that the bearer m receives a Level of Bearer Satisfaction (LS) of Ψ_m^{ws} in cases of no sharing. In this context, LS is typically defined in terms of throughput, minimum jitter, minimum delay, or a combination of two or more of them. In cases of sharing, the bearer i should at least receives LS greater than or equal to Ψ_m^{ws} . This condition guarantees isolation between MNOs on the bearer-level and protects their LS from other MNOs traffic fluctuations. For example, when an MNO has a high traffic load, the other MNO bearers would still receive at least the LSs that would be received without sharing the resources.

2. MNOs should be able to implement different scheduling policies to achieve their Service-Level Agreement (SLA). Different MNOs have different QoS requirements to satisfy as well as different billing and charging models. MNOs may apply different scheduling policies to meet their SLA, and to maximize their revenues. For example, if a particular MNO would care about fairness between users, it may apply Proportional Fair scheduling. However, if the MNO would care more about achieving maximum revenues by transmitting the maximum achievable data rates, Sum-rate Maximization

scheduling may be applied.

3. The MD gain should be distributed between MNOs based on sharing agreements. As the quality of the wireless channels are independent across users, the aggregated capacity of a cell increases with the increase in the number of users [3], which is referred to as MNOs multiplexing gain. Denote Ψ_m^s as the LS of bearer m that is achieved by sharing the radio resources, respectively. The MD gain of bearer m is expressed as

$$\Psi_m^g = \Psi_m^s - \Psi_m^{ws}, \tag{2}$$

Consequently, the total MD gain that MNO i achieves is expressed as

$$\Psi_i = \sum_{m=1}^{M_i} \Psi_m^s - \Psi_m^{ws}. \tag{3}$$

Without loss of generality, we assume that MNOs agree to share MD gains such as

$$\bar{\Psi}_i = \gamma_i \times \sum_{i=1}^{N} \bar{\Psi}_i \tag{4}$$

where , $\bar{\Psi}_1, \bar{\Psi}_2, \ldots, \bar{\Psi}_N$ are the expected values of $\Psi_1, \Psi_2, \ldots, \Psi_N$, respectively, and $\gamma_i \in [0,1], \forall i$ are constants and satisfy

$$\sum_{i=1}^{N} \gamma_i = 1. \tag{5}$$

Wireless channel model: the wireless channel between eNB and each user is modeled as a block Rayleigh fading. The channel is assumed to be constant over an RB bandwidth, but changes independently over RBs and users. The channel gain for user k over the RB r is denoted as $h_{k,r}$. The received Signal to Noise Ratio (SNR) over the RB r seen by user k can be expressed as

$$s_{k,r} = \frac{P \times h_{k,r}}{\sigma^2} \tag{6}$$

where σ^2 and P denote the noise variance, and the transmit power, respectively. In (6) we assume that fixed power allocation is applied and P does not vary across users nor RBs.

The LTE subframe has a duration of 1 ms and consists of 132 symbols [10], [11], [12]. The transport block size per subframe that can be transmitted over an RB can be calculated as

$$T_c = \lfloor 132 \times \zeta_c \rfloor \tag{7}$$

where ζ_c, is the spectral efficiency of the MCS c, and $\lfloor x \rfloor$ finds the largest integer number less than or equal to x.

The received SNR determines the MCS that should be used to deliver the data block T_c with a given Block Error Rate (BLER). A simple MCS selection scheme is performed using a lookup table which maps the received SNR to MCS [13]. Table I shows MCSs that are used in LTE and how they are mapped to the received SNR for BLER 10% [14].

For example, assume that the received SNR over the RB r seen by user k is $s_{k,r} = 5$ dB. The proper MCS would be

TABLE I
LIST OF MCS WHICH ARE USED IN LTE [14]

Index	Modulation	Coding Rate	ζ_c	SNR(dB)
0	—	—	0 bits	> -6.7536
1	QPSK	78/1024	0.15237	$-6.7536 : -4.9620$
2	QPSK	120/1024	0.2344	$-4.9620 : -2.9601$
3	QPSK	193/1024	0.3770	$-2.9601 : -1.0135$
4	QPSK	308/1024	0.6016	$-1.0135 : +0.9638$
5	QPSK	449/1024	0.8770	$+0.9638 : +2.8801$
6	QPSK	602/1024	1.1758	$+2.8801 : +4.9185$
7	16QAM	378/1024	1.4766	$+4.9185 : +6.7005$
8	16QAM	490/1024	1.9141	$+6.7005 : +8.7198$
9	16QAM	616/1024	2.4063	$+8.7198 : +10.515$
10	64QAM	466/1024	2.7305	$+10.515 : +12.450$
11	64QAM	567/1024	3.3223	$+12.450 : +14.348$
12	64QAM	666/1024	3.9023	$+14.348 : +16.074$
13	64QAM	772/1024	4.5234	$+16.074 : +17.877$
14	64QAM	873/1024	5.1152	$+17.877 : +19.968$
15	64QAM	948/1024	5.5547	$> +19.968$

$c = 7$, which delivers a data block of $T_c = 194$ bits with a BLER of 10%.

IV. BIP FORMULATION

In this work, a utility-based resource allocation is assumed. Utility function characterizes user satisfaction level with respect to the allocated bandwidth. In fact, Utility function varies across traffic types and applications. For example, utility function of the best effort applications depends on throughput, for delay-sensitive applications it depends on delay [15], and for constant bit rate traffic applications it is typically characterized by unit step function, where the utility maximizes if the achieved rate is greater than the required constant bit rate requirement, otherwise, it is zero [16]. In the literature, different utility functions have been proposed to describe different traffic types [15], [16], [17].

A utility-based scheduling algorithm aims at maximizing the aggregate utility. The scheduler objective is to optimally allocate RBs to each bearer such that the total bearer utilities are maximized. We assume each bearer is associated with a utility function. Also, we assume all utility functions are linear [3]. Denote the utility function of bearer m by U_m. If bearer m is assigned the RB r, the bearer utility is $U_m(r)$. Define R_m as the set of RBs that is assigned to bearer m. The LS of bearer m is denoted by $\mathbf{U}_m$, and is defined as a total utility achieved as follows

$$\mathbf{U}_m = \sum_{r \in R_m} U_m(r) \tag{8}$$

At every transmission time interval, which is 1 ms in LTE [11], the optimization problem can be formulated as BIP problem

$$\max \sum_{r=1}^{R} \sum_{i=1}^{N} \sum_{m=1}^{M} \alpha_i U_m(r) \beta_{m,r} \tag{9}$$

subject to:

$$\sum_{m=1}^{M} \beta_{m,r} \leq 1, \quad \forall r \in R \tag{10}$$

$$\Psi_m^s \geq \Psi_m^{ws}, \quad \forall m \tag{11}$$

$$\bar{\Psi}_i = \gamma_i \times \sum_{i=1}^{N} \bar{\Psi}_i \tag{12}$$

where α_i is a constant defined for each MNO, and is used as a reference point to fairly divide the MD gain between the MNOs based on (12), and $\beta_{m,r}$ is a binary number indicator defines as

$$\beta_{m,r} = \begin{cases} 1, & \text{if the RB number } r \text{ is assigned to bearer } m \\ 0, & \text{otherwise }. \end{cases}$$

It is worth pointing out that the constraints in (10) represent the allocation constraints; which ensure that each RB can be occupied at most by a single bearer, where the constraints in (11) represent the minimum LS bearers should receive as listed in the sharing agreement.

The setting of $\alpha_i, \forall i$ ensures that the constraint in (12) is satisfied, and determines the distribution of the MD gain among the MNOs. The values of $\alpha_i, \forall i$ either can be fixed and agreed upon by the operators or can be found iteratively. For example, MNO-i may choose a higher value of α_i to receive higher MD gain (higher γ_i) than the other MNOs. A simple way to find the proper values of $\alpha_i, \forall i$ iteratively is described as follows. Denote γ_i' the current achieved MD gain of MNO-i. If γ_i' is greater than γ_i, α_i increases to $\alpha_i + \delta$, where δ is a positive constant. Otherwise α_i decreases to $\alpha_i - \delta$.

Theorem 1: there is at least one feasible solution for the optimization problem in (9).

Proof: Suppose that the sets of RB $\{R_1\}$, $\{R_2\}$, ..., and $\{R_N\}$ are assigned to MNO-1, MNO-2, ..., and MNO-N, respectively. This implies that there is no sharing between MNOs, $\Psi_m^s = \Psi_m^{ws}, \forall m \in M$, and $\Psi_i = 0$, $\forall i$, which satisfies the constraints in (10-12).

V. Iterative Scheduling Algorithm

BIP problem is classified as an NP-hard [18], meaning that the computational time increases exponentially with the problem size. In cases of limited scheduling computational resources, less complex algorithms should be applied. In this section, an iterative algorithm is proposed to solve the BIP with considerably less computational complexity. The algorithm is described by Table II, and is divided into two sequential parts. Part one (lines 1-7) assigns RBs iteratively to bearers. In each iteration, one RB is assigned to the bearer that has the maximum difference between its minimum LS (Ψ_m^{ws}) and the current LS ($\mathbf{U}_m$). Assigning RBs stops when all bearers receive LSs greater than their minimum LS ($\mathbf{U}_m > \Psi_m^{ws}, \forall m$). Then part two of the algorithm begins (lines 8-11), where the leftover RBs from part one is assigned to the least satisfied MNO according to $\Gamma_i(R)$. The least satisfied MNO is defined as the MNO that has the maximum difference between the agreed MD gain ratio γ_i and the current one γ_i' (line 9), where the function $\Gamma_i(R)$ allocates the resources R according to MNO-i scheduling policy (line 10).

TABLE II
Iterative Allocation

1: **while** $|\mathcal{R} \neq \emptyset|$ and $\mathbf{U}_m < \Psi_m^{ws}, \forall m$ **do**
2: $\quad \mathcal{R} = \{1, 2, \ldots, R\}$
3: $\quad m^* = \arg\max_m (\Psi_m^{ws} - \mathbf{U}_m)$
4: $\quad r^* = \arg\max_r U_{m^*}(r)$
5: $\quad \mathbf{U}_m^* = \mathbf{U}_m^* \cup U_{m^*}(r^*)$
6: $\quad \mathcal{R}^* = \mathcal{R} \setminus r$
7: **end while**
8: **if** $|\mathcal{R} \neq \emptyset|$ **then**
9: $\quad i^* = \arg\max_i (\gamma_i - \gamma_i')$
10: $\quad \Gamma_i(R) \rightarrow \mathbf{U}_m, \forall m \in i$
11: **end if**

VI. Numerical Results

A. Experimental Evaluation Parameters

In this work, system throughput studies are performed to verify the proposed framework. Full-buffer traffic model is considered [19]. We consider a system with two MNOs which apply different resource schedulers. MNO-1 is assumed to apply Proportional fair (PF) scheduling, while MNO-2 applies Sum-rate Maximization (SrM) scheduling.

PF scheduling is a channel-aware scheduling. It aims to maximize the total throughput of the system while maintaining fairness between users at the same time. In PF scheduling, the utility function of bearer m is defined by the following [15]

$$U_m(r) = \frac{T_m(r)}{\bar{T}_m} \tag{13}$$

where $T_m(r)$ is the transport block size that can be transmitted by assigning the RB r to bearer m, which is computed from (7), and $\bar{T}_m$ is bearer m historical average transmitted data. PF scheduler aims to maximize the sum of the utility functions as follows

$$\begin{array}{c} \Psi^{PF} = \max \sum\limits_{r=1}^{R_i} \sum\limits_{m=1}^{M_i} \frac{T_m(r)}{\bar{T}_m} \beta_{m,r} \\ \text{such that} \sum\limits_{m=1}^{M_i} \beta_{m,r} = 1, \quad \forall r \in R_i \end{array}. \tag{14}$$

Maximizing Ψ_i^{PF} can be achieved using the following scheduling criterion

$$s(r, m) = \arg\max_{i \in M} \frac{T_i(r)}{\bar{T}_i}, \tag{15}$$

where $s(r, m)$ represents RB r to be assigned to user m.

However, SrM scheduling aims to maximize the total throughput of the system by assigning the following utility function to users [15]

$$U_m(r) = T_m(r). \tag{16}$$

SrM scheduler maximizes the sum of the utility functions

$$\begin{array}{c} \Psi^{SrM} = \max \sum\limits_{r=1}^{R_i} \sum\limits_{m=1}^{M_i} T_m(r) \beta_{m,r} \\ \text{such that} \sum\limits_{m=1}^{M_i} \beta_{m,r} = 1, \quad \forall r \in R_i \end{array}. \tag{17}$$

TABLE III
SIMULATION DEFAULT PARAMETERS

Parameter	Value	Parameter	Value
M_1	2	M_2	2
R_1	5	R_2	6
MNO-1 scheduler	PF	MNO-2 scheduler	MrS
Fading	Rayleigh	Iteration #	1e4
SNR_l	10 dB	SNR_h	15 dB
I	2	P	27dBm
δ	0.1	σ^2	1

Maximizing Ψ^{SrM} is performed by using the following scheduling criterion

$$s(r,m) = \arg\max_{i \in M} T_i(r). \tag{18}$$

MD Gain Sharing: in this work, the setting of α_1 and α_1 are found iteratively. The value of α_1 is fixed to one, while α_2 varies until the constraints in (12) are satisfied. The new value of α_2 (denoted as α_2') incrementally increases or decreases as follows:

$$\alpha_2' = \alpha_2 + \delta \times sign(\gamma_i - \gamma_i') \tag{19}$$

where

$$sign(\gamma_i - \gamma_i') = \begin{cases} +1, & \text{if } (\gamma_i - \gamma_i') > 0 \\ -1, & \text{otherwise} . \end{cases} \tag{20}$$

B. Experimental Evaluation Results and Discussion

We have evaluated the performance of the proposed BIP and the iterative approaches using simulations. The BIP problem is solved using *bintprog* optimization package from MATLAB. We assume that each MNO has two users; one user is close to eNB and receives average SNR of SNR_h dB, where the other user is far from the eBN and receives average SNR of SNR_l. Also, we assume that each user has only one bearer as illustrated in Table IV. The simulation default parameters are shown in Table III.

Fig. 2 compares the BIP and the iterative approaches for different γ_i values. The main observations are: first, WRV offers throughput gain to all bearers. Second, users with same channel quality are treated differently. This is because the MNOs apply different scheduling policies. For example, bearer-1 and bearer-3 experience similar channel conditions, but bearer-1 throughput is higher than bearer-3 throughput because of applying different scheduling policies. MNO-1 applies PF scheduler which fairly allocates the shared resources between users. However, MNO-2 applies SrM scheduler which tends to allocate more shared resources to users who have good channel quality. The third observation is seen from Fig. 2(d). For all values of γ_1 and γ_2, the proposed approaches maintain the agreed upon MD gain distribution between the two MNOs. For example, in the case of $\gamma_1 = \gamma_2 = 0.5$, MD gain of MNO-1 is equal to MD gain of MNO-2.

The distributions of the MD gain among the bearers are shown in Fig. 3(a), Fig. 3(b), and Fig. 3(c). For all sharing settings, MD gains are shared among bearers in line with the MNOs scheduling policy. MNO-1 shares its MD gain according to PF criterion, and maintains fairness between

TABLE IV
BEARER-USER MAP

User	Bearer	MNO	Average SNR
User-1	Bearer-1	MNO-1	SNR_l
User-2	Bearer-2	MNO-1	SNR_h
User-3	Bearer-3	MNO-2	SNR_l
User-4	Bearer-4	MNO-2	SNR_h

bearers. However, MNO-2 aims at maximising throughput regardless fairness between users, and allocates most of the MD gain to bearer-4. Thus, the main observation is that the proposed WRV approaches maintain isolation between MNOs, and each MNO distributes its MD gain according to its own scheduling policy.

Overall, the BIP approach outperforms the iterative approaches at the cost of complexity. Fig. 3(d) shows the average running time for both the BIP and the iterative approaches. The running time is measured by the MATLAB functions *tic* and *toc* for each iteration. As expected, the iterative algorithm has a significantly lower running time than the BIP.

Fig. 4 evaluates the performance of the iterative approach against the number of shared RBs. Because the computational time of the BIP increases exponentially with the problem size, the BIP performance is not included in this comparison. We assume that $R1 = R2 = R/2$. As the number of shared RBs increases, the MD gain per MNO increases. In addition, the MD gain is distributed in accordance with the values of γ_1 and γ_2.

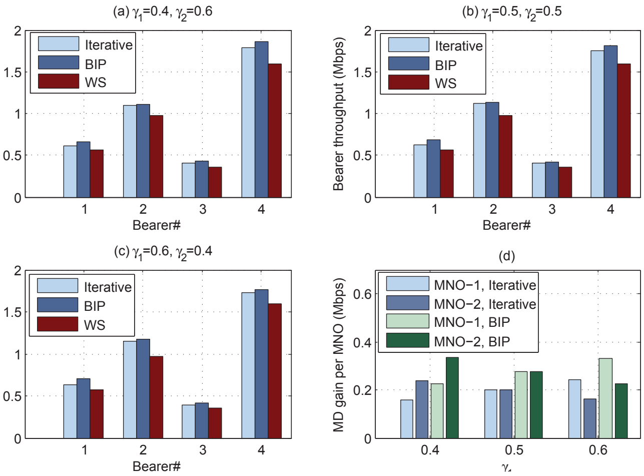

Fig. 2. Performance evaluation of BIP and Iterative approches. (a) Bearers throughput for $\gamma_1 = 0.4$ and $\gamma_2 = 0.6$. (b) Bearers throughput for $\gamma_1 = 0.5$ and $\gamma_2 = 0.5$. (c) Bearers throughput for $\gamma_1 = 0.6$ and $\gamma_2 = 0.4$. (d) MD gain per MNO.

VII. CONCLUSION

In this paper, a framework of wireless resource virtualization on a single eNB is presented. The proposed approaches allow operators to customize their schedulers and control distributing. The proposed framework considers fundamental WRV requirements in terms of isolation, complexity, and resource

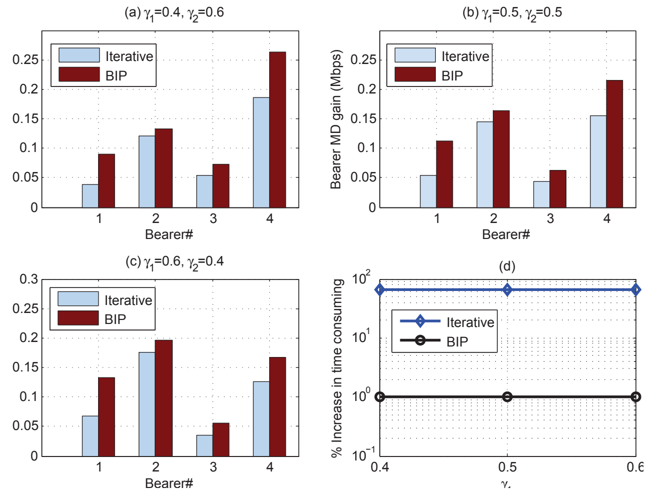

Fig. 3. Performance evaluation of the BIP and the iterative approches. (a) MD gain distrubition for $\gamma_1 = 0.4$ and $\gamma_2 = 0.6$. (b) MD gain distrubition for $\gamma_1 = 0.5$ and $\gamma_2 = 0.5$. (c) MD gain distrubition for $\gamma_1 = 0.6$ and $\gamma_2 = 0.4$. (d) Running time comparison for the BIP and the iterative approaches.

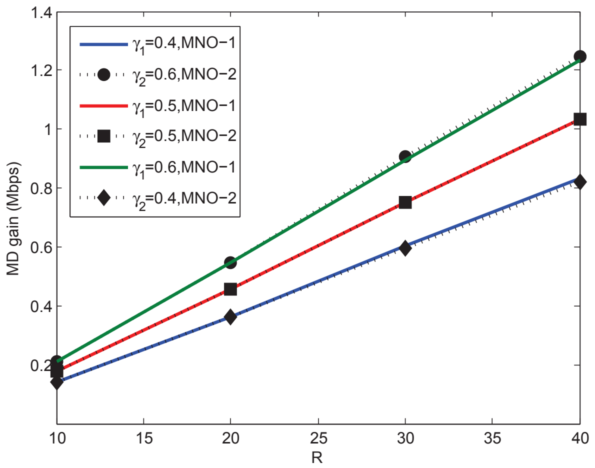

Fig. 4. MD gain per MNO for the iterative approach

utilization. The problem is formulated as a binary integer programming. Consequently, an iterative algorithm is derived to solve the BIP with less computational overhead. System throughput studies are performed to evaluate the proposed approaches. The results have shown that the proposed approaches increase bearers throughput and meet the sharing agreement. Also, the performance of the BIP approach outperform the iterative approach at the cost of complexity. However, both approaches maintain the WRV requirement.

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