Energy-Efficient RRH Sleep Mode for Virtual Radio Access Networks

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***Abstract*—Network functions virtualization (NFV) has become a strategic tool that facilitates mobile network resource sharing and management by mobile network operators (MNOs). Cloud radio access network (C-RAN) virtualization allows agglomeration of multiple radio access networks (RANs) functions in a single resource pool. In this paper, Virtualized Radio Access Network (VRAN) is utilized as the enabler of inter-operator traffic offloading. To explore the energy saving potential of sleep mode scheme in base stations of cooperating MNOs, we leverage on inter-band non-contiguous carrier aggregation and put forward spectrum sharing into private and shared bands. We formulate an optimization problem to obtain the optimal intra-operator and inter-operator beamforming design for realizing energy-efficient virtual RAN. Inter-operator base station load transfer algorithm is proposed as well as inter-operator BS sleep-mode energy saving algorithm. Simulations results show a significant reduction of total inter-operator power consumption as compared to other algorithms.**

***Index Terms*—Network Function Virtualization; Base station sleep-mode; Energy savings; Inter-operator Spectrum Sharing**

I. Introduction

The continued energy demand resulting from explosive growth in mobile traffic has led to ongoing studies and algorithms from researchers. With inundated data demand, mobile operators are faced with the need to increase data throughput. However, the growth in delivery of data rate is not without a cost. Operational expenses (OPEX) increase has accompanied the mobile broadband growth. Incidentally, the largest part of electricity bills faced by mobile network operators (MNO) emanates from energy consumed at the base stations [1].

The surge of mobile data traffic has also necessitated the need for more radio spectrum allocation for cellular networks to meet the growing capacity needs. In response, MNOs are demanding additional spectrum to improve their service delivery [2]. Acquisition of more spectrum, however, is expensive. In meeting the emerging market capacity demand while minimizing the OPEX on energy and spectrum costs, MNOs can be motivated to share spectrum [3]. Since savings from energy costs can serve as a motivation to share bandwidth, it is imperative to investigate BS power consumption reduction in a multi-operator spectrum sharing scenario.

A. Network Function Virtualization in Cellular Networks

NFV is an emerging technology that enables network functions to run on industry standard hardware through software virtualization techniques. NFV Industry Specification Group of the European Telecommunications Standards Institute (ETSI) proposes NFV use cases for cellular networks [4]. The cases relevant to this study are Virtualized Radio Access Network (VRAN) and Virtualized Evolved Packet Core (VEPC). The VRAN is conceived from the C-RAN architecture and it provides virtualization of baseband unit (BBU) pool running in the data centers, and remotely located BSs' radio head units (RRHs). In addition, the NFV can enable multiple operators to share resources [5]. Fig 1 shows VRAN and VEPC of two cooperating MNOs sharing network resources and UEs access.

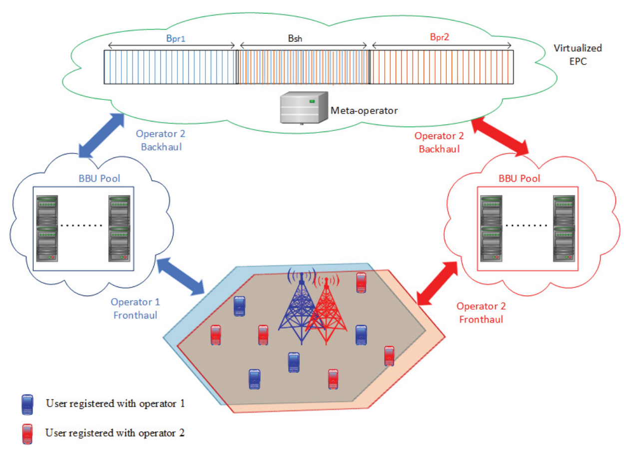

Fig. 1. Virtualized RAN and EPC of two cooperating operators with co-located BSs

B. Inter-operator Spectrum Sharing

The aforementioned dramatic increase in mobile traffic has led to a demand surge in spectrum. Inter-operator spectrum sharing is one of the areas researchers, such as in [6]–[10], are looking into for supplementary spectrum access. A complementary spectrum access method, called co-primary shared access (CoPSS) has been introduced to enable multiple MNOs fully or partly share their licensed spectrum [11].

The technology of carrier aggregation introduced in LTE-Advanced is also a harbinger to inter-operator spectrum sharing. The scenarios of the use of carrier aggregation are intra-band contiguous, intra-band non-contiguous and inter-band non-contiguous. 3GPP release 13 allows inter-band non-contiguous carrier aggregation in 18 pairs of LTE bands [12]. For the use case of UEs in the multi-operator shared spectrum, inter-band non-contiguous aggregation can be harnessed. In this study, we conceptualize a cooperation between multiple MNOs where their carrier components are dynamically shared

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into inter-band non-contiguous aggregated private and shared spectrum sub-bands.

C. Related Work

The benefits of NFV in communication networks, such as remote deployment, flexibility, and relatively shorter service delivery time, has incited studies on its feasibility in cellular networks. The power saving potential from NFV of cellular networks major use cases (VRAN, VEPC, and VCPE) is investigated in [13]. The estimation results from Bell Labs GWATT tool show higher power reduction in a network with NFV than in traditional networks.

In a SAPHYRE European project study [14], the researchers conceptualize cooperation between MNOs where their processing units are pooled centrally in the fashion of C-RAN. Spectrum sharing, between two co-located BSs of different MNOs, into private and shared frequency sub-bands is studied in [15]. The study is extended to user grouping such that some UEs are supported in the private spectrum and the rest in the shared spectrum. These aforementioned studies on spectrum sharing do not consider energy savings at the base stations. In one of the multi-operator spectrum sharing cases presented in [16], BS power consumption reduction is considered. However, the work solely relies on access by time, not by traffic variation. Our work is applicable to spatial and temporal traffic changes.

In this work, we explore the energy saving potential of VRAN in cooperating operators. Spectrum sharing into private and shared frequency sub-bands is considered. The optimal beamforming vectors, which minimize total inter-operator energy consumption in both sub-bands are determined. BS power consumption reduction algorithm in an inter-operator cooperation scenario is proposed by BS sleep mode strategy and inter-operator load sharing. The rest of this paper is organized as follows. Section II describes the spectrum access and sharing, and the inter-operator power consumption models. In Section III, the optimization problem is formulated to find the power efficient private and shared networks beamforming vectors. In the same section, the algorithm for inter-operator load transfer condition and energy saving by BS sleep-mode algorithms are proposed. Simulation results and analysis of the proposed algorithms are presented in section IV. Finally, in section V the conclusion is provided.

II. System and Power Model

A. Spectrum Access and Sharing Model

We consider M closely located identical cellular network systems based on LTE/LTE-Advanced network, with identical spectrum license, RANs, fronthaul and backhaul infrastructure. Each considered network belongs to a different operator. Following [17], network virtualization is applied to their backhauls for mutual cooperation. Thus, their backhauls lead to a joint Virtualized Evolved Packet Core (VEPC). We follow the concept of [9], [10] in which a certain number of component carriers are available for inter-operator dynamic sharing. To forestall inter-band interference, we submit that each operator has its carrier components laid on inter-band non-contiguous pair bands to enable dynamic spectrum partitioning into private and shared sub-bands. Thus, interference between private and shared sub-bands is ignored in this model. For the M cooperating operators each having an original licensed spectrum allocation of B_m, the operator's shared spectrum sub-band is $\frac{\mathrm{B}_m}{M}$ and the private sub-band is $\mathrm{B}_{pr}^{m} = \mathrm{B}_m - \frac{\mathrm{B}_m}{M}$. This interprets that $\mathrm{B}_{sh} = \sum_{m=1}^{M} \frac{\mathrm{B}_m}{M}$ is the shared spectrum.

B. System Model

Each operator exclusively uses its private spectrum, while all cooperating operators can access and utilize the shared band. A UE's access is mutually exclusive. For example, a UE registered with operator 1 is served in B_{pr}^{1} when served by its MNO. When served by other operator's BS, B_{sh} is utilized. Consequently, the received signal by a UE could be emanating from intra-RAN or inter-operator RAN. Inter-operator RAN backhaul routing is not discussed in this work as the focus is on energy efficiency.

Let the region of interest consist of A identical remote radio heads (RRHs) belonging to different operators. Each RRH is equipped with N antennas. The set of operator m's RRH is denoted by L_m such that $ML_m = A$. Our objective is to switch off some BSs and transfer their loads to other active BSs. When sleep-mode strategy is applied, the active BSs set is denoted with V and the ones in sleep-mode is Z such that $V \cup Z = A$ and $V \cap Z = \emptyset$. The active RRH of operator m is represented with RRH_m^v, and the inactive with RRH_m^z. We assume close proximity of BSs in subsets V and Z for feasibility of load transfer. Since the UE's access is mutually exclusive, when operator m's UE is served by RRH_m^v private spectrum is utilized and intra-RAN precoding is considered. Inter-RAN precoding is imperative when UE associated with RRH_m^z is transferred to any other MNO in subset V. In inter-operator routing, data symbols and CSI will be shared [17].

The signal received by the registered k-th user registered with operator m in the private spectrum is

$$y_k^{pr} = \sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{pr} s_k + \sum_{i \neq k} \sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{pr} s_i + \eta_k \quad (1)$$

where the complex scalar s_k represents the k-th user data symbol and $\mathbf{w}_{vk}^{pr} \in \mathbb{C}^N$ denotes the intra-operator beamforming vector at RRH_m^v for the k-th UE. $\mathbf{h}_{kv} \in \mathbb{C}^N$ is the channel vector responsible for CSI from RRH_m^v to user k and $\eta_k \sim \mathbb{CN}\left(0, \sigma^2\right)$ is zero mean i.i.d complex-symmetric additive Gaussian noise at the receiver.

When served by RRH_m^v in the shared spectrum, received signal served by the k-th UE originally associated with the switched off BS is

$$y_k^{sh} = \sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{sh} s_k + \sum_{i \neq k} \sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{sh} s_i + \eta_k \quad (2)$$

We note that the inter-operator beamforming vector $\mathbf{w}^{sh}$ is obtained from inter-RAN precoding and backhaul routing. Essentially, utilization of $\mathbf{h}$ and $\mathbf{w}^{sh}$ is facilitated by the virtualized backhaul pooling.

It follows from (1) and (2) that the corresponding signal-to-

TABLE I
NOTATION

Notation	Definition	Notation	Definition
M	Number of cooperating operators	y_k^{pr}	The signal received by the k-th UE using private spectrum
B_m	Operator m total allocated bandwidth	y_k^{sh}	The signal received by the k-th UE using shared spectrum
B_{pr}^m	Operator m private bandwidth	$SINR_k^{pr}$	SINR ratio for the k-th UE served in private spectrum
B_{sh}	Combined shared bandwidth of cooperating operators	$SINR_k^{sh}$	SINR ratio for the k-th UE served in shared spectrum
K	The set of UEs in the region	R_k^{pr}	Achievable data rate of the UE served in the private spectrum
A	Total number of RRHs in the region	R_k^{sh}	Achievable data rate of the UE served in the spectrum spectrum
N	Number of RRH antennas	P_v	RRH transmission power
V	The set of active RRHs	P_v^{rrh}	RRH power consumption
Z	The set of inactive RRHs	$P_{v,static}^{rrh}$	Static power consumption of RRH
s_k	the k-th user data symbol	$P_{v,sleep}^{rrh}$	The power consumed by RRH in sleep mode
$\mathbf{h}_{kv}$	Channel vector from v-th RRH to the k-th UE	P_v^f	The power consumed in the fronthaul link of the RRH v
$(\cdot)^{\mathsf{H}}$	Hermitian transpose	$P_{v,static}^f$	The power consumed in the fronthaul link when RRH v is active
$\mathbf{w}_{vk}^{pr}$	Intra-operator beamforming vector	$P_{v,sleep}^f$	The power consumed in the fronthaul link when RRH v is inactive
$\mathbf{w}_{vk}^{sh}$	Inter-operator beamforming vector	P^{bh}	The backhaul power consumption
η_k	Zero mean i.i.d complex-symmetric additive Gaussian noise	P_m	The total BS power consumption of operator m
a_m	RRH mode indicator	P_T	The joint total BS power consumption of the cooperating operators

interference-plus-noise ratio (SINR) for the k-th UE is given by

$$\text{SINR}_k^{pr} = \frac{\left|\sum_{v\in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{pr}\right|^2}{\sum_{i\neq k}\left|\sum_{v\in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{pr}\right|^2 + \sigma_k^2} \tag{3}$$

$$\text{SINR}_k^{sh} = \frac{\left|\sum_{v\in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{sh}\right|^2}{\sum_{i\neq k}\left|\sum_{v\in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{sh}\right|^2 + \sigma_k^2} \tag{4}$$

Therefore the achieved data rate of the UE served in the private sub-bands is

$$R_k^{pr} = B_{pr}\log_2(1+\text{SINR}_k^{pr}) \tag{5}$$

Similarly, the UE served in the shared spectrum achieves a data rate of

$$R_k^{sh} = B_{sh}\log_2(1+\text{SINR}_k^{sh}) \tag{6}$$

C. Power Consumption Model

To conceptualize the energy saved by cooperating operators, we factor in the power consumption at the RRHs of each operator. In addition, we consider the power dissipation in the fronthaul links of each operator's CRAN following [18], and [19] for the power consumed in the backhaul.

1) RRH Consumption Model

We propose a mutually exclusive network access for the users in the coverage area of the closely located inter-operator base stations. For two MNOs, for example, when RRH1 is transmitting RRH2 is on sleep mode and vice versa. Each RRH has the transmit power constraint

$$P_v = \sum_k \|\mathbf{w}_{vk}^{pr}\|_2^2 + \sum_k \|\mathbf{w}_{vk}^{sh}\|_2^2 \leq P_v^{max} \tag{7}$$

We use the following empirical model for RRH power consumption:

$$P_v^{rrh} = \begin{cases} P_{v,static}^{rrh} + \frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{pr}\|_2^2 + \frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{sh}\|_2^2, & P_v \neq 0 \\ P_{v,sleep}^{rrh}, & P_v = 0 \end{cases} \tag{8}$$

where P_{static}^{rrh} is the static power consumption of RRH. η is the efficiency of the RF power which is dependent of the number of transmitter antenna [20]. The RRH power consumed in sleep mode is denoted by $P_{v,sleep}^{rrh}$.

2) Fronthaul Consumption Model

The virtualized RAN legacy C-RAN architecture introduces location separation for RRHs and BBUs. The BBUs are combined into a centralized BBU pool at the data center, creating fronthaul links between the pool location and the multiple remote RRHs. The power consumed in the fronthaul link is represented as:

$$P_v^f = \begin{cases} P_{v,static}^f & P_v \neq 0 \\ P_{v,sleep}^f & P_v = 0 \end{cases} \tag{9}$$

where $P_{v,static}^f$ captures the power consumed in the fronthaul link while conveying RRH transmission and $P_{v,sleep}^f$ is the fronthaul link power when idle.

3) Intra-operator Power Consumption Model

When RRH v of operator m is transmitting, the private sub-bands are used for its UEs, while the shared sub-bands are used for the UEs belonging to other operators. Therefore the power consumed by RRH v is evaluated as follows.

- When active:

$$P_m = \frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{pr}\|_2^2 + \frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{sh}\|_2^2 + P_{active} + P_m^{bh} \tag{10}$$

  where $P_{active} = P_{v,static}^{rrh} + P_{v,static}^f$. The backhaul power consumption is represented by P_m^{bh}.
- When in sleep mode:

$$P_m = P_{sleep} + P_m^{bh} \tag{11}$$

  where $P_{sleep} = P_{v,sleep}^{rrh} + P_{v,sleep}^f$.

The total BS power consumption at any mode can be expressed as:

$$P_m = a_m\left[\frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{pr}\|_2^2 + \frac{1}{\eta}\sum_k \|\mathbf{w}_{vk}^{sh}\|_2^2 + P_{active} - P_{sleep}\right] + P_{sleep} + P_m^{bh} \tag{12}$$

where $a_m \in \{0,1\}$ is a mode indicator. $a_m = 1$ when RRH v is transmitting, and 0 if otherwise.

4) Inter-Operator Power Consumption Model

For the collective power consumption of the cooperating operators, we consider a scenario of a group of cooperating operators having closely located BSs (one for each operator) in the region of interest. The inter-operator total power consumption of the BSs is:

$$P_T = \sum_{m=1}^{M} P_m \tag{13}$$

Since identical networks is assumed, $P^{rrh}_{static} = P^{rrh}_{v,static} = P^{rrh}_{z,static}$ is the static power of the transmitting RRH encompassed in the P_{active}. Similarly, $P^{rrh}_{sleep} = P^{rrh}_{v,sleep} = P^{rrh}_{z,sleep}$ is the power of a BS in sleep mode included in P_{sleep}. It can also be assumed that $\sum_{m=1}^{M} P^{bh}_m = MP^{bh}_m$ because identical networks are considered. However, $\sum_k \|\mathbf{w}^{pr}_{vk}\|^2_2 \neq \sum_k \|\mathbf{w}^{sh}_{vk}\|^2_2$ due to difference in inter- and intra-operator precoding.

III. Beamforming Vectors Optimization and Energy Saving Algorithms

A. Power Optimization

As mentioned earlier, inter- and intra-operator precoding implementation are required for the system model. Our aim is to find respective optimal inter- and intra-operator beamforming vector to minimize inter-operator total power consumption while satisfying some network constraints.

$$\begin{aligned}
\min_{\mathbf{w}^{pr}_{vk},\mathbf{w}^{sh}_{vk}} \quad & \sum_{m=1}^{M} P_m(\mathbf{w}^{pr}_{vk}, \mathbf{w}^{sh}_{vk}) \\
\text{s.t.} \quad & R^{min}_k \leq R^{pr}_k, \forall k \in K_m \\
& R^{min}_k \leq R^{sh}_k, \forall k \in K_{-m} \\
& a_m \left[\sum_k \|\mathbf{w}^{pr}_{vk}\|^2_2 + \sum_k \|\mathbf{w}^{sh}_{vk}\|^2_2 \right] \leq P^{max}_v \\
& a_m \in \{0,1\}
\end{aligned} \tag{14}$$

The first and second constraints represent the minimum user data rate in private and shared spectrum, respectively. The RRH power requirement is stated in the third constraint. The UE registered with the transmitting BS's operator is $k \in K_m$. The user receiving service from other operator's BS is $k \in K_{-m}$. In addition, $K_m \cup K_{-m} = K$ represents the total number of UEs in the considered region.

B. Problem Reformulation

In the power optimization problem (14), R^{pr}_k and R^{sh}_k are non-convex. Since the phases responsible for the complex components of $\mathbf{w}^{pr}_{vk}$ and $\mathbf{w}^{sh}_{vk}$ have no effect on the objective function [21] and the constraints, only their magnitude parts are considered. Thus we take the approach of [18], [21] to obtain the convex form:

$$\|\mathrm{r}^{pr}_k\|_2 \leq \sqrt{1 + 1/(2^{R^{\min}_k/B_{pr}} - 1)}\mathrm{Re}\{D^{pr}_{kk}\}, \forall k \tag{15}$$

where $r^{pr}_k = [D_{k1}, D_{k2}, ..., D_{kk}, \sigma_k]^T$,
$D_{ki} = \sum_{v \in V_m} \mathbf{h}^{\mathsf{H}}_{kv} \mathbf{w}^{pr}_{vi}$.

Similarly for the rate with the shared bandwidth,

$$\|\mathrm{r}^{sh}_k\|_2 \leq \sqrt{1 + 1/(2^{R^{\min}_k/B_{sh}} - 1)}\mathrm{Re}\{D^{sh}_{kk}\}, \forall k \tag{16}$$

where $r^{sh}_k = [D_{k1}, D_{k2}, ..., D_{kk}, \sigma_k]^T$,
$D_{ki} = \sum_{v \in V_{-m}} \mathbf{h}^{\mathsf{H}}_{kv} \mathbf{w}^{sh}_{vi}$.

Therefore the optimization problem becomes:

$$\begin{aligned}
\min_{\mathbf{w}^{pr}_{vk},\mathbf{w}^{sh}_{vk}} \quad & \sum_{m=1}^{M} P_m(\mathbf{w}^{pr}_{vk}, \mathbf{w}^{sh}_{vk}) \\
\text{s.t.} \quad & \|\mathrm{r}^{pr}_k\|_2 \leq \sqrt{1 + 1/(2^{R^{\min}_k/B_{pr}} - 1)}\mathrm{Re}\{D^{pr}_{kk}\}, \forall k \in K_m \\
& \|\mathrm{r}^{sh}_k\|_2 \leq \sqrt{1 + 1/(2^{R^{\min}_k/B_{sh}} - 1)}\mathrm{Re}\{D^{sh}_{kk}\}, \forall k \in K_{-m} \\
& \sum_k \|\mathbf{w}^{pr}_{vk}\|^2_2 + \sum_k \|\mathbf{w}^{sh}_{vk}\|^2_2 \leq a_m P^{max}_v \\
& a_m \in \{0,1\}
\end{aligned} \tag{17}$$

The reformulated problem can be solved by a typical convex optimization tool as the problem is a second order cone programming (SOCP).

C. Load transfer Criterion Algorithm

A load transfer criterion is determined before the users of an MNO are transferred to others. Here, we assume each MNO has one BS in the considered region. The steps of the condition are shown in Algorithm 1. The combined load is evaluated to compute the required number of BS N capable of supporting the loads efficiently. This is computed with respect to the individual BS load limit L_{max}. The BSs in the area are sorted into set A, in descending order, according to their current associated users. A matrix of dimension K (number of UEs) and N(number of the selected BS) is formed. Along the row, the channel power gain, $|h_{nk}|^2$, is checked against the minimum required threshold, $|h_0|^2$. The channel power gain is chosen as the channel quality indicator because when it declines below the threshold, the transmitter does not send any bits and outage ensues [22]. A good UE–BS channel state is indicated by 1 in matrix H, and 0 if otherwise.

From matrix H, a $K \times 1$ vector U is generated whose each element correspond to a l_0-norm sum of the corresponding row of matrix H. If the product of array elements of vector U is 1 the load transfer criterion is satisfied. If otherwise, an additional BS is added to N until the channel quality check is affirmed. If the condition is not met until $N' \subset A$, the criterion is not satisfied.

D. Inter-operator BS sleep-mode Power saving Algorithm

We propose a BS sleep mode algorithm based on multi-operator spectrum sharing to put the least loaded BS(s) to sleep mode depending on the current traffic demand and channel quality. An inter-operator load threshold L_{th} is set among the cooperating MNOs. The steps are presented in Algorithm 2. When the combined loads fall below the threshold, the load transfer criterion of Algorithm 1 is checked. If satisfied, spectrum partitioning into private and shared bands for the selected operators is initiated. The intra- and inter-operator beamforming vectors are obtained by solving the optimization problem (17). Then the BSs not selected have their load transferred to others and (the unselected BSs) are powered off.

Algorithm 1: Load Transfer Condition Algorithm

1 Evaluate the load of every BS in the area. Form a sorted set A containing the BSs in descending order of their load weight.
2 Compute the total load L_T and calculate $N = ceil\left(\frac{L_T}{L_{max}}\right)$
3 Select N BSs, descending order of their load weight, from set A
4 **if** $N' \subset A \neq \emptyset$ **then**
5 Generate matrix H with dimension $K \times N$, with K being the total number of UEs and N the number of selected BSs in step 3.
6 **for** *each UE(rows)* **do**
7 check the channel power gain requirement for each BS (columns) and evaluate each element $H_{k,n} = \begin{cases} 1 & |h_{nk}|^2 \geq |h_0|^2, n \in N, k \in K \\ 0 & \text{otherwise} \end{cases}$
8 Generate a vector U (with dimension $K \times 1$), whose each element is the l_0-norm of the sum of corresponding row of matrix H, i.e, $U_k = \|\sum_n H_{k,n}\|_0$
9 **if** $\prod_{k=1}^{K} U_k = 1$ **then**
10 Load transfer condition is met
11 **end**
12 **else** Add one additional BS from subset $N' \subset A$, i.e $N = N + 1$, and go to step 3
13 **break**
14 **end**
15 **end**
16 **else**
17 Load transfer condition is not met
18 **end**

Algorithm 2: Inter-operator BS sleep-mode Power saving Algorithm

1 Evaluate the total load L_T in the region
2 **if** $L_T < L_{th}$ **then**
3 **if** *Load transfer condition (algorithm 1) is met* **then**
4 Initiate spectrum partitioning into B_{pr}^m and B_{sh}^m
5 Set a_m in (13) of the selected BS to 1 and $a_m = 0$ for other BSs.
6 Obtain $\mathbf{w}_{vk}^{pr}$ and $\mathbf{w}_{vk}^{sh}$ by solving optimization problem (17)
7 Selected BSs support their registered UEs on their respective licensed spectrum B_{pr}^m, and support other load on B_{sh}.
8 **end**
9 **else**
10 Go to step 14
11 **end**
12 **end**
13 **else**
14 Each BS continue to support its associated UEs on its respective licensed spectrum
15 **end**

If the load transfer condition is not met, each BS continues to support its respective associated UEs.

IV. Simulation and Analysis

The energy saving performance of the proposed algorithm for multiple cooperating MNOs is evaluated. We consider 10 identical RRHs (representing 10 MNOs) closely deployed in the region area. Each RRH is equipped with 4 transmit antennas, and one antenna to every UE. The total bandwidth of each MNO's BS is 10 MHz. The P_{static}^{rrh}, and P_{static}^{f} is 22.5 Watts and 3.5 Watts, respectively. The power values of 12 Watts and 1.2 Watts are used for P_{sleep}^{rrh} and P_{sleep}^{f}. 10 Watt is taken as the maximum transmit power of the RRH. The η value of 0.36 is used. The noise power is $\sigma^2 = -94$ dBm. We adopt the pathloss model of $140 + 36.7\log_{10}(d)$ for distance d, as in [15], [18], to give attenuation between the RRH and UE. The required minimum UE data rate is 0.5 Mbps.

The default bandwidth partition into private and public sub-bands are as discussed in section IIA. The maximum RRH power is chosen to be 10 Watts. The default number of UEs is 10. A coverage radius of 200 meters is chosen for each RRH. The UEs are randomly distributed in the area.

To evaluate the relative performance of the proposed algorithm, we performed comparative simulations with respect to some network schemes. The schemes are defined below.

- *Sleep-mode with No Cooperation (SNC)*: In this scheme, the MNOs are not in cooperation. There is no shared bandwidth. Each MNO solely uses its license bandwidth. However, sleep mode is applied to a BS with no load. An idle BS only becomes active at an arrival of a user.
- *No Sleep-mode and No Cooperation (NSNC)*: Similar to SNC, there is no inter-MNO cooperation. No spectrum sharing. In contrast to SNC, this scheme does not include putting the BS with no load on sleep-mode. All BSs are in active mode all the time.

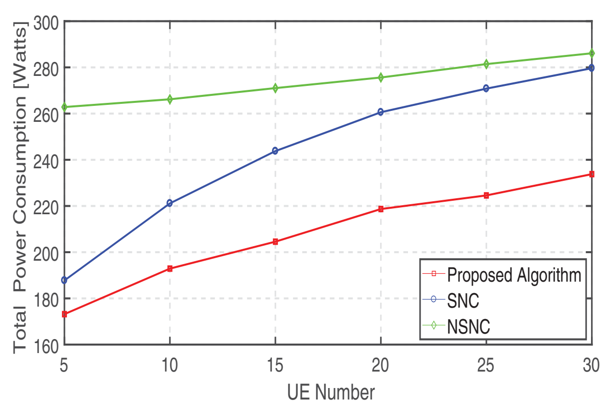

Fig. 2. Total inter-operator Power Consumption versus number of UEs

Fig. 2 shows the higher energy saving performance of the proposed algorithm over non-cooperative schemes. NSNC reminds of the waste of power without a sleep-mode strategy in cellular networks. The power consumption is evidently high

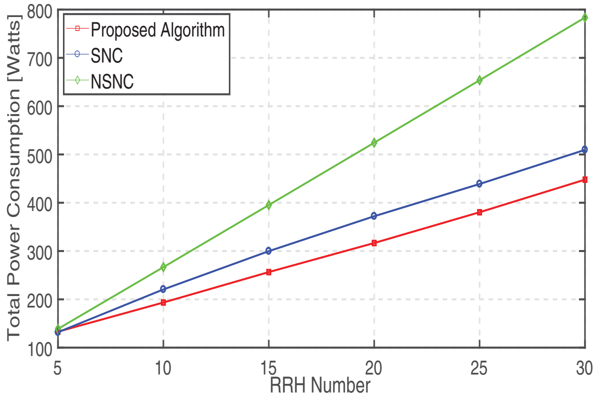

Fig. 3. Total inter-operator Power Consumption versus number of RRHs

even at low load. Despite the inclusion of BS sleep-mode in SNC, the proposed algorithm yields better energy efficiency due to inter-operator cooperation. Moreover, the rate of power dissipation in SNC as the traffic grows is higher than that of the proposed algorithm. The rate is due to relatively less number of BSs put to sleep mode in SNC as the traffic increases. More power is consumed in SNC than in the proposed algorithm as the traffic grows. The growth of traffic load as evident by the increase in the number of UEs causes the total power consumption to rise. At low load more BSs can be switched off, which implies the proposed algorithm gives the best performance at low load.

The algorithm is also evaluated with increases in each MNO BS number, with each belonging to different operators. The UE number is fixed at the default value. The objective is to assess the impact of the number of the cooperating MNOs on the amount of energy saved. The result of the evaluation is shown in Fig. 3. With a few number of cooperating BSs, all the schemes seem to converge as all the BSs are engaged; none is lightly loaded to be put on sleep-mode. As expected, increasing the number of BSs raises the total power consumption. However, increasing BS number creates an opportunity for load transfer from some BSs and hence the power consumption of the proposed algorithm is clearly lower than the other schemes. Even with sleep-mode strategy in SNC, the proposed algorithm is still more energy efficient.

V. Conclusion

In this work, we harness the VRAN use case to investigate energy saving feasibility for multiple cooperating MNOs. We utilize the concept of dynamic spectrum allocation and carrier aggregation to partition an operator's licensed bandwidth into private and shared bands in which UEs access is mutually exclusive. To achieve energy efficient inter-operator precoding, we formulated an optimization problem to obtain optimal intra-and inter-operator beamforming vectors while taking the maximum RRH power limit, and minimum data rates in private and shared spectrum into consideration. We proposed inter-operator load transfer condition algorithm, which considers the channel quality and current traffic load of the cooperating BSs. The second proposed algorithm, energy saving by sleep mode scheme in inter-operator power consumption shows a high reduction in the total power consumed in the RANs.

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