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Energy-efficient Virtual Radio Access Networks for Multi-Operators Cooperative Cellular Networks

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***Abstract*—5G networks will be characterized by massive densification of base stations (BSs). To minimize the network power consumption due to the increased BS deployment, we leverage emerging paradigms to propose BS energy-saving strategies applicable to 5G networks. We explore the potentials of virtualized radio access and core networks to enable spectrum sharing among mobile network operators (MNOs) by harnessing inter-band non-contiguous carrier aggregation. We propose the Sleep-mode with Efficient Beamformers and Spectrum-sharing (SEBS) strategy, which minimizes BS power consumption of cooperative MNOs. The licensed bandwidth of each MNO is partitioned into private and shared bands to provision active BSs with sufficient spectrum resources for serving all UEs. Moreover, an optimization problem is formulated to obtain the optimal intra- and inter-RAN beamforming vectors for efficient BS transmission power and improved user signal reception. Numerical simulations show that the proposed strategies yield significant reductions of total power consumption as compared to other schemes. We present different bandwidth sharing ratio formulations to motivate the cooperation among MNOs by the spectrum–user support trading. We also show that the trading does not always yield a higher spectral efficiency in the cooperative cellular network.**

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

I. Introduction

As we are on the brink of manifestation of 5G networks where at least 100 billion devices will be supported with a 1,000-fold surge in capacity as compared to the legacy networks, the trade-off between the imminent spectral increase and energy efficiency (EE) has become one of the main focuses of 5G network research. The increased capacity demand is in response to the continued rise in the mobile traffic. The global mobile data traffic is forecasted to reach 49 exabytes per month, or a run rate of 587 exabytes annually [1]. On the part of mobile network operators (MNOs), the massive densification of base stations (BSs) is one of the capacity building measures to satisfy the coverage need of the mobile traffic growth. However, since most power consumed in cellular networks occurs in the BSs, the densification will tremendously inflate the energy consumption of cellular networks. Consequently, such high energy consumption results in substantial energy bills that constitute a significant part of MNOs' operational expenditures (OPEX). Moreover, the BS deployment expansion will yield increased CO_2 emission since fossil fuels are the primary source for powering the BS sites. Therefore, there is a need to minimize the base station energy consumption to achieve OPEX savings and CO_2 emission reduction.

In the first two decades of cellular mobile network roll-out, the network infrastructure was based on exclusive ownership and utilization by individual mobile network operators [2]. The RF planning and locations of BSs of different operators are usually implemented independently of each other. However, the market coverage competition and increased number of subscribers sometimes lead to colocation of BSs within an overlap region of coverage for different MNOs. The participation of third-party mobile tower companies has also led to increased incidence of the BS colocation. In the US for instance, a strong presence of colocation is fostered by companies which sublease space from independent landlords to deploy BSs belonging to more than one MNO at a single location [3]. While the colocation helps an individual MNO to hold its share of subscribers in the region, there are redundancy and under-utilization of power-hungry BS components, especially at low traffic [4].

Recent studies have focused on minimizing OPEX resulting from under-utilization and high power consumption of colocated BSs belonging to different operators. Many works mainly centered on infrastructure sharing, such as site sharing, tower sharing, Radio Access Network (RAN) sharing, and core network sharing [5]. The RAN sharing approach to energy saving has received much research attention because BSs are an integral part of RAN. A study on the adoption of active RAN sharing in [6] reveals potential savings up to $60 Billion in 5 years. The drawback of the inter-operator spectrum sharing through the active RAN sharing is the constraint in separating both data and control planes among the different participating operators, and the flexibility of inclusion of individual operator's requirements [7]. Network virtualization is introduced to address these needs such that services are separated from their underlying infrastructure [8]. In this paper, we posit MNOs to pool their RAN resources to form a virtual network, and a mobile operator can rely on the coverage of other operators' networks to serve its users in the region of overlapping coverage. Therefore, in the low traffic scenario, some MNOs can switch off their BSs to conserve

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power while other operators support the users of all MNOs in the region.

A. Contributions

We propose the SEBS strategy, which reduces the power consumption of colocated BSs of multiple cooperative operators. Given the BS maximum transmission power limit and target data rate per UE, SEBS partitions each operator's spectrum into private and shared bands, finds the intra- and inter-RAN beamformers, and puts lightly loaded BSs into the sleep-mode. The SEBS scheme involves four steps. First, when the traffic in the region falls below a certain threshold, the number of BSs required to support the traffic is optimally determined. Second, the joint MNOs' BS power consumption is formulated into a convex optimization problem, which is solved to obtain efficient intra- and inter-operator beamforming vectors. Third, the bandwidths are partitioned into private and shared bands, and all the shared bands are pooled together for joint access. Finally, the selected BSs support their own UEs on their private bandwidths, and other UEs are served in the pooled shared bandwidth. The remaining BSs are put into the sleep-mode. To motivate MNOs to cooperate, SEBS is extended to accommodate the spectrum–power consumption trading, where an operator can trade part of its licensed spectrum for serving its UEs. The main contributions of this paper are summarized as follows.

1) We propose a sleep-mode and spectrum-sharing strategy to minimize the BS power consumption for cooperative multiple operators by leveraging on virtualized radio access and core networks. Besides the conference version of this work [9], to our best knowledge, this paper is the first to proffer a BS energy-saving scheme that jointly considers inter-operator spectrum sharing, optimization of intra-and inter-RAN beamforming vectors, and sleep-mode control.
2) We present multiple methods for dynamic inter-operator spectrum sharing cognizant of inter-RAN traffic support volume to motivate MNOs to cooperate to achieve energy efficiency in their RANs. Based on the proposed spectrum–sharing formulations, inter-operator joint optimization problem is formulated to obtain power efficient intra- and inter-RAN beamforming vectors for supplementary energy gains and improved UE signal reception.
3) We prove, by numerical simulations, the better energy efficiency performance of the SEBS strategy as compared to the non-cooperative scheme. We also show that the EE by spectrum trading may not always boost the spectral efficiency. When the bandwidth allocated for inter-RAN UE support exceeds a specific ratio, the intra-RAN UE support bandwidth is reduced, thus resulting in lower UE data rates.

B. Organization

The rest of this paper is organized as follows. In section II, we present the related works, and the proposed approach. Section III describes the spectrum access and sharing, and the inter-operator power consumption models. In Section IV, the optimization problem is formulated to find the power efficient private and shared networks beamforming vectors. The algorithm for determining the inter-operator load transfer condition, and several BS sleep-mode algorithms are proposed in Section V. We present the spectrum–power consumption trading formulations in Section VI. Simulation results and analysis of the proposed algorithms are presented in Section VII. Finally, in Section VIII, the conclusion is provided. Selected notations are given in Table I.

II. Related Works and The Proposed Approach

A. Related Works

The BS energy saving by the sleep-mode technique is hinged on the cooperation among BSs either in a single-operator network or a multi-operators network. When some BSs are put into the sleep-mode, these inactive BSs release their spectrum resources for the active neighboring BSs to be utilized for the coverage expansion to support all users [10]. Among existing works on BSs energy saving in cellular networks, most of them focus on a single MNO. The studies [11]–[13] focus on the user association, where an optimal association of users and BSs is sought to yield the required number of BSs to support the users, and then to switch off other BSs. In [14], a sleep-mode strategy is used to improve the energy efficiency of a wireless network, where an interference alignment technique is used to manage interference among users. Energy saving is further enhanced by the introduction of transmission-mode adaptation, which implies reallocation of transmitted power of active users following user sleep-mode control. However, the sleep-mode strategy is only applied to the users.

The BS sleep-mode by self-organizing network, where BS configurations can be automatically adjusted to adapt to traffic condition, was applied in [15], [16]. In [17], energy efficiency (EE) of a network is improved via zero and partial zero forcing based approaches, where beamforming and power allocation are jointly optimized in the presence of inter- and intra-cell interference. However, most of the proposed single operator strategies are targeted and applicable to the pre-5G legacy networks. 5G networks will be characterized by a reshape of network functionalities, which include the potentials of advanced technologies like the network function virtualization, network slicing, and resource sharing among multiple operators [18]. It is imperative to develop BS energy-saving schemes compliant with the emerging 5G network paradigms. Therefore, recent research directions are geared towards multi-operators cellular networks.

Collaboration among wireless network operators has been shown to reduce OPEX as elicited in cooperation between a cellular operator and Internet Service providers (ISPs) [19]–[21], and in multi-operators cellular networks [22]. Cooperation among multiple operators for the goal of energy saving has been researched in recent studies. In [23], the BS sleep-mode strategy based on a game theory algorithm has been proposed to select active BSs between two cooperating MNOs while incorporating the fairness concerning the inter-operator roaming cost. The drawback of this work is the limitation to two network operators. Multi-operators cases are studied in [24]–[26]. In [24], a 24-hour time profile BS switch-

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off pattern has been proposed for cooperating MNOs. The pattern, however, may not be feasible in practice as all but one network are switched off at a time. Consequently, the only active BS may be overburdened at the expense of network QoS. BS sleep-mode schemes using game theory are also studied in a cooperative multi-operators network, such as in [25], [26], where network stability is considered. The schemes are extended to a heterogenous multi-operators network in [27]. Most of the discussed works mainly focus on optimized solutions solely based on network dynamics akin to the case of a single operator. However, to be feasible in 5G networks, a step further is required to capture the integration of modern paradigms, such as the network virtualization and dynamic resource pooling, in actualizing collaborative BS energy saving. In the comparative study on multi-operator systems done in [4], the BS sleep-mode strategy in a virtualized network has achieved significant energy savings as compared to the conventional network. However, the scheme is applicable for offline applications in a region where the number of BSs and user statistics are known *a priori*.

B. Our Approach

In this paper, we present the Sleep-mode with Efficient Beamformers and Spectrum-sharing (SEBS) strategy for energy-efficient BS operations in the collaborative multi-operators cellular system. Specifically, based on the traffic condition, an optimal number of BSs is selected to serve the users in the region, and other BSs are put into the sleep-mode. We leverage the network virtualization to facilitate the inter-operator spectrum resource pooling and access for mutual users support with the ultimate goal of joint network energy savings. The virtualized RAN (VRAN) applied in our work evolves from the cloud-RAN (CRAN) architecture. In CRAN, the traditional RAN is decoupled into centralized BBU and the RRH at the network edge. These centralized BBUs can be pooled and used as shared resources, providing gains in energy efficiency and statistical multiplexing. The BBU/RRH network functions can be implemented on commodity HW and executed on a virtualized environment. In VRAN, centralization of BBU/RRH provided by CRAN is leveraged by implementing the BBU/RRH network functions on commodity hardware based on the principles of Network Functions Virtualization (NFV), and executing them on a virtualized environment [28]. Thus, with virtualized BBUs, operators can dynamically allocate resources to different (virtualized) base stations. In addition, operational efficiencies of advanced features such as carrier aggregation and CoMP (Coordinated Multipoint) in LTE-Advanced are facilitated by the virtualized BBUs.

In contrast to other works, the spectrum pooling in our work serves two purposes. The first objective is to avail the active BSs with sufficient resources to serve their own and inter-operator handed over users. The second objective is to motivate the MNOs to cooperate. This motivation is a form of incentive for lightly loaded MNOs to trade the spectrum for the users support. Moreover, to accommodate a system of more than two participating MNOs, we model the spectrum band of each MNO as a combination of spectrum blocks based on the carrier aggregation model introduced in LTE-Advanced. In 3GPP release 13, 18 pairs of inter-band non-contiguous carrier aggregation of LTE bands are facilitated [29]. For the use case of user equipment (UEs) in the multi-operators shared spectrum in particular, the inter-band non-contiguous aggregation can be utilized. Therefore, our inter-operator model is conceptualized on the cooperation among multiple MNOs where their carrier aggregated components are dynamically shared into inter-band non-contiguous aggregated private and shared spectrum sub-bands.

In addition to energy gains achieved by switching off some BSs, energy is further saved by optimizing the transmission power of the active BSs. An optimization problem is formulated to obtain optimal beamforming vectors for power efficient transmissions. The optimal beamforming vectors also ensure a better signal reception by all UEs; thus, the coverage is improved. Since the active BSs are to serve their own and other inter-operator UEs, both intra- and inter-operator beamforming vectors are optimized.

III. System Model

A. Spectrum Access and Sharing Model

Consider a region consisting of M colocated cellular mobile networks. The considered MNOs are assumed to have equal spectrum bandwidths. Their RANs are also assumed identical for tractable power consumption modeling. Each network is owned by a different MNO. The multi-operators system leverages the virtualized RAN and core networks for spectrum sharing and inter-RAN UE support. Virtualization of RAN and core networks facilitates shared network by allowing capacity and resources, such as spectrum, to be decoupled from the underlying physical resources. Therefore, the work relies on the assumption that the radio resources are virtualized. The system model is illustrated in Fig. 1 with an example of 4 cooperating MNOs, each having a BS colocated with others in the region of interest. We follow the concept of [30], [31] in which a certain number of component carriers in the licensed spectrum are available for inter-operator dynamic sharing. To preclude inter-band interference, we propose that each operator has its carrier components composed of inter-band non-contiguous bands. Thus, the spectrum can be dynamically partitioned into private and shared sub-bands with non-contiguous bands. Since there is no contiguity between private and shared bandwidths, interference between private and shared sub-bands is inconsequential in this model, and thus ignored.

B. Transmission Model

Each operator has exclusive access to its private spectrum after partitioning. On the other hand, the pooled shared bands can be accessed and utilized by all the MNOs in cooperation. Only one BS supports one UE at a time, and the UE's access to the partitioned bandwidths is mutually exclusive. That is, a UE is served in its MNO's private spectrum when its BS is active. While the BS whose MNO the UE is registered with is in the sleep-mode, the UE is supported in the pooled shared spectrum by another active BS. Therefore, a signal received by a UE in the region could be emanated from intra-RAN or inter-operator RAN. In our work, an ideal case of full CSI sharing

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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	Υ_k^{pr}	SINR ratio for the k-th UE served in private spectrum
B_{sh}	Combined shared bandwidth of cooperating operators	Υ_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 UE data symbol	$P_{v,sleep}^{rrh}$	The power consumed by RRH in sleep-mode
$\mathbf{h}_{kv}$	Channel vector from the 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 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
δ_m^d	Numeraire of spectrum demanding MNO	L_m^d	Number of inherited UEs by an active BS
δ_m^s	Numeraire of spectrum supplying MNO	L_m^s	Number of traded UEs by an inactive BS

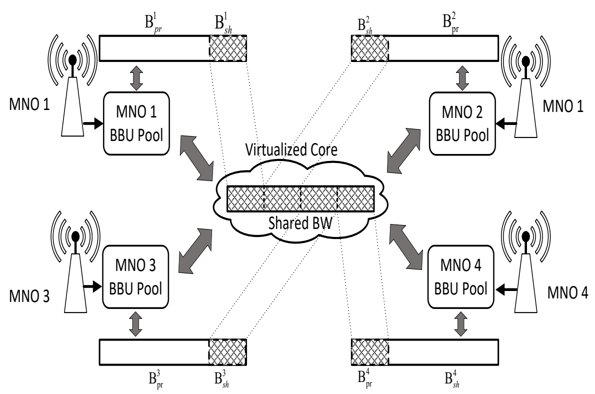

Fig. 1. Virtualized RAN and Core of 4 cooperating operators with colocated BSs

amongst MNOs, similar to other studies of multi-operators MIMO systems [32], [33], is assumed. We, however, note that in practice full CSI sharing amongst multiple operators is not easily realizable due to the extra transmission overhead [34], the requirement of high data rate backhaul links [33], and the need to exchange the information at a reasonable time scale smaller than the channel coherence time [35], [36]. The signal processing theories of inter-operator RAN backhaul routing are not discussed here as the energy efficiency is the focus of this work.

Let the region of interest consists of $|A|$ identical and colocated remote radio heads (RRHs), each belonging to a different operator. Each RRH is equipped with N antennas. Our objective is to minimize joint operators' power consumption by switching off some BSs with low traffic and transferring their UEs to other active BSs. When the sleep-mode strategy is applied, the set of active RRHs is denoted by V and the ones in the sleep-mode are depicted by Z, such that $V \cup Z = A$ and $V \cap Z = \emptyset$. The cardinality of set V is denoted by $|V|$. Since a UE can either be supported in the private bandwidth B_{pr}^m or shared bandwidth B_{sh}^m, both intra- and inter-RAN precoding are considered.

The signal received by the k-th UE registered with MNO 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 UE 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 UE k and $\eta_k \sim \mathbb{CN}\left(0, \sigma^2\right)$ is the zero mean i.i.d complex-symmetric additive Gaussian noise at the receiver.

A UE k registered with $m \in Z$ when served by $m \in V$ in the shared spectrum receives the signal

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

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

It follows from (1) and (2) that the corresponding signal-to-interference-plus-noise ratio (SINR) for the k-th UE served in the private and shared bandwidth are respectively given by

$$\Upsilon_k^{pr} = \frac{\left|\sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{pr}\right|^2}{\sum_{i \neq k} \left|\sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{pr}\right|^2 + \sigma_k^2}, \quad (3)$$

$$\Upsilon_k^{sh} = \frac{\left|\sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vk}^{sh}\right|^2}{\sum_{i \neq k} \left|\sum_{v \in V_m} \mathbf{h}_{kv}^{\mathsf{H}} \mathbf{w}_{vi}^{sh}\right|^2 + \sigma_k^2}. \quad (4)$$

Therefore, the achievable data rate of the UE served in the private bandwidth is

$$R_k^{pr} = B_{pr} \log_2(1 + \Upsilon_k^{pr}). \quad (5)$$

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

$$R_k^{sh} = B_{sh} \log_2(1 + \Upsilon_k^{sh}). \quad (6)$$

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C. Power Consumption Model

To capture the joint energy consumption of all cooperating MNOs, we consider the power consumption at the RRHs of each operator. Also, power dissipation in the fronthaul links of each operator's Cloud Radio Access Network (C-RAN) follows that in [37], and power consumed in the backhaul follows that in [38].

1) RRH Power Consumption Model

An active RRH supports both UEs from its own MNO and others. Thus, the transmission power is a function of intra-RAN as well as inter-RAN precoding. Each active RRH has the following transmission 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 on the number of transmitter antennae [39]. The RRH power consumed in the sleep-mode is denoted by $P_{v,sleep}^{rrh}$.

2) Fronthaul Power Consumption Model

The virtualized RAN hinges on the legacy C-RAN architecture, which introduces physical location separation between RRHs and BBUs. The BBUs are combined into a centralized BBU pool at the data center, creating fronthaul links between the pool data center location and the multiple remote RRHs. The power consumed in each fronthaul link is expressed 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 in provisioning RRH transmission and $P_{v,sleep}^f$ is the fronthaul link power when its BS is in the sleep-mode.

3) Intra-operator Power Consumption Model

Here, we present the outlook of power consumed by an individual MNO entity in the region of interest. When RRH v of operator m is active, its private bandwidth is used for its UEs, while the pooled shared bandwidth is used for the UEs belonging to other operators. The power consumed by a BS 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 the 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 otherwise.

4) Inter-Operator Joint Power Consumption Model

To obtain the overall power consumption of the colocated BSs of the cooperating operators in the region, we consider the summation of individual total BS power consumption. The inter-operator joint power consumption is

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

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

IV. Transmission Power Optimization

A. Optimization Formulation

As mentioned in the previous section, intra- and inter-operator precoding implementation is required for intra- and inter-operator UE support, respectively. All active MNOs have access to the shared spectrum to support users whose RRHs are on the sleep-mode. Significant inter-operator interference is experienced when multiple operators operate on a shared spectrum [33], [34], and optimizing beamforming mitigates such mutual interference [32], [33]. Also, optimal beamforming vectors through efficient transmission power enhance seamless coverage and signal reception of users. Since transmission power is a component of network power consumption, optimizing beamforming improves the energy efficiency of the joint network. Therefore, the intra- and inter-RAN beamforming vectors are optimized in the work. Seeking the intra-RAN and inter-RAN optimal beamforming vectors of BS transmission in private and shared bandwidths, respectively, can be formulated as an optimization problem. The objective is to find respective optimal inter- and intra-operator beamforming vectors which minimize inter-operator total power consumption while satisfying relevant network

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constraints.

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

The required minimum UE data rates in private and shared spectrum are stated in the first and second constraints, respectively. The third constraint gives the RRH power limit. A registered UE of active operator m is $k \in K_m$. A UE belonging to another operator, but being served by MNO m, is $k \in K_{-m}$. Thus, $K_m \cup K_{-m} = K$ represents the total number of UEs in the considered region.

B. Optimization Problem Reformulation

The power optimization problem (14) is non-convex due to non-convexity of R_k^{pr} and R_k^{sh}. Since the phases responsible for the complex components of $\mathbf{w}_{vk}^{pr}$ and $\mathbf{w}_{vk}^{sh}$ have no effect on the objective function [40] and the constraints, only their magnitudes are considered. Thus, we take the approach of [37], [40] to obtain the convex form:

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

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

Similarly, for the rate with the shared bandwidth,

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

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

Therefore, the optimization problem becomes:

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

Problem (17) can be solved by a typical convex optimization tool, such as CVX, since the problem is now a second order cone programming (SOCP) problem.

V. SEBS Algorithms

In this section, we present the algorithms that make up the proposed SEBS strategies. The outline of SEBS is shown in Fig. 2. Based on the agreed spectrum sharing formulation among operators, one of the joint energy saving algorithms, sleep-mode with equal spectrum pooling (SESP) or sleep-mode with spectrum–power trading (SSPT), is chosen. In SESP, the shared bandwidth is obtained from individually licensed bandwidth by equal spectrum pooling (ESP). Spectrum–power trading (EPT) is applied for spectrum partitioning in SSPT for trading between spectrum demanders set D and suppliers set S. It is noteworthy that for the ESP option, $\alpha_m = \delta_m = 0$ and $D = S = \emptyset$. The load transfer condition (LTC) algorithm is triggered by load threshold L_{th} to ascertain UE–BS channel quality relative to the required minimum channel gain L_{th}. With the active set V and inactive set Z determined, the inter-and intra-operator beamforming vectors for the optimal transmission power are obtained, as discussed in Section V, while taking R_k and P_{max} into consideration. The SESP/SSPT algorithm is invoked with an active BS set, the optimal transmission power, and partitioned bandwidths.

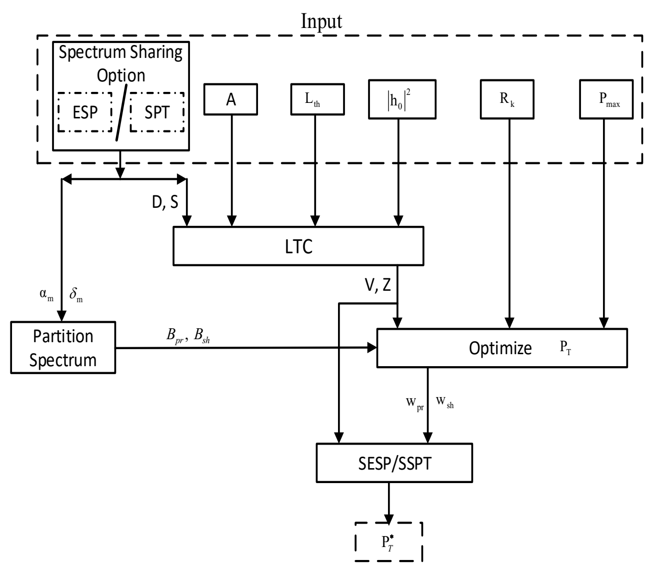

Fig. 2. Outline of SEBS scheme

A. Load Transfer Condition Algorithm

A load transfer condition is checked to ensure that all UEs in the region have good channel quality with the associated active BSs, as depicted in Algorithm 1. The combined UE traffic L_T in the region is evaluated and used to compute the required number of BSs, $|V|$, to support the UEs efficiently. The individual BS load limit L_{max} is taken into consideration in calculating $|V|$. Since the BSs are identical, L_{max} is assumed equal for all BSs. The BSs are sorted into set A, in descending order, according to their current associated traffic.

A $K \times |V|$ dimension matrix H is formed with K depicting the total number of UEs and $|V|$ the number of active BSs. The UE–BS channel quality is checked exhaustively between each UE and BS by comparing the channel power gain, $|h_{nk}|^2$, against the minimum required threshold, $|h_0|^2$. When the channel power gain declines below the threshold, the transmitter does not send any bits and outage ensues [41]. A good UE–BS channel state is indicated by 1 in matrix H, and

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0 otherwise. A l_0-norm of each row of matrix H is computed to yield a $K \times 1$ dimension vector U. A product of all array elements of vector U indicates the load transfer check result. $\prod_{k=1}^{K} U_k = 1$ means the load transfer criterion is satisfied. Otherwise, an additional BS is added to set V, and the steps are repeated until $V' \subset A \neq \emptyset$.

Algorithm 1: Load Transfer Condition Algorithm

```
1  Form a sorted set A containing the BSs in descending
     order of their load weights.
2  Compute the required number of active BSs
     |V| = ceil(L_T / L_max)
3  Select the first |V| BSs from set A to form set V
4  if V' ⊂ A ≠ ∅ then
5      Generate matrix H with dimension K × |V|.
6      for each UE (row) do
7          Check the channel quality for each UE against all
             BSs (columns) and and note in matrix H, i.e
             H_{k,v} = { 1   |h_vk|^2 ≥ |h_0|^2 , v ∈ V, k ∈ K
                       { 0   otherwise                         .
8          Generate a vector U = [U_1, U_2, ···, U_K], where
             U_k = ||Σ_v H_{k,v}||_0.
9          if ∏_{k=1}^{K} U_k = 1 then
10             Load transfer condition is met
11         end
12         else Add an additional BS from subset V' ⊂ A,
             i.e |V| = |V| + 1 , and go to Step 3.
13         break
14     end
15 end
16 else
17     Load transfer condition is not met.
18 end
```

where

$$|V| = ceil\left(\frac{L_T}{L_{max}}\right)$$

$$H_{k,v} = \begin{cases} 1 & |h_{vk}|^2 \geq |h_0|^2, v \in V, k \in K \\ 0 & \text{otherwise} \end{cases}.$$

$$U_k = \|\textstyle\sum_v H_{k,v}\|_0.$$

B. Power Savings with Equal Spectrum Pooling (ESP)

We propose the SEBS algorithm where cooperative colocated BSs conserve joint power consumption by putting the least loaded BS(s) into the sleep-mode. The algorithm is contingent on spectrum pooling, traffic demand, and channel quality, as presented in Algorithm 2. Each of the M cooperating operators with B_m contributes an equal amount of bandwidth to the shared bandwidth pool. That is, individual MNO apportions

$$\mathrm{B}_{sh}^{m} = \frac{\mathrm{B}_m}{M} \tag{18}$$

to the pool. The private sub-band is therefore

$$\mathrm{B}_{pr}^{m} = \mathrm{B}_m - \frac{\mathrm{B}_m}{M}. \tag{19}$$

This implies that the total pooled shared bandwidth is $\mathrm{B}_{sh} = \sum_{m=1}^{M} \frac{\mathrm{B}_m}{M}$.

The scheme is triggered by traffic demand. A combined load threshold L_{th} is determined. When the joint traffic falls below the threshold, the load transfer criterion of Algorithm 1 is checked to ascertain a good channel quality for each UE. If the criterion is met, the optimal number of active BSs to support the load is computed. Each MNO partitions its private and shared bands according to (18) and (19), respectively. The efficient transmission power optimization problem (17) is solved to obtain the optimal intra- and inter-operator beamforming vectors. The BSs not selected to be active have their UEs transferred to the active BSs, and they are therefore put into the sleep-mode. The active BSs support their own UEs on their respective private bands, while they support the UEs of the inactive BSs using the pooled shared spectrum. On the other hand, if the load transfer criterion is not met, each MNO maintains the status quo, which is to continue to support its respective associated UEs in its full unpartitioned bandwidth.

Algorithm 2: Sleep-mode with Equal Spectrum Pooling (SESP) 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          Partition spectrum into B_pr^m and B_sh^m using (18)
             and (19).
5          Set a_m in (12) for all selected active BSs in set
             V to 1 and a_m = 0 for other BSs.
6          Obtain w_vk^pr and w_vk^sh by solving optimization
             problem (17).
7          BSs in set V support their registered UEs on
             their respective licensed spectrum B_pr^m, and
             other UEs on B_sh.
8      end
9      else
10         Go to step 14.
11     end
12 end
13 else
14     Each BS continues to support its associated UEs on
         its respective licensed spectrum B_m.
15 end
```

VI. Spectrum–Power Consumption Trading (SPT)

Although Algorithm 2 proves to save energy considerably, some operators may not be willing to participate due to unequal gains from the scheme. All operators contribute equally to the shared spectrum. However, the MNOs with fewer subscribed UEs may benefit more from the joint energy-saving scheme. They are less likely to be selected (from the sorted BS list in Algorithm 1) to support the joint UEs, thus saving more power. The spectral efficiency of the active BSs may also negatively impact BSs with high traffic due to the release of a part of their spectrum for sharing.

Many authors [42]–[44] have validated the tradeoff between spectral and energy efficiencies in mobile cellular networks. The EE–SE (or EE–throughput) tradeoff has also been pertinent in resource sharing in cellular networks [45], specifically when a spectrum is shared [46]. In this section, we utilize this trade-off as an incentive to motivate MNOs to cooperate for the overall power consumption reduction.

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A. Spectrum Trading Sharing Model

In this section, we take advantage of the trade-off between spectrum and power consumption to create an incentive for cooperation for spectrum sharing, and ultimately power saving. We propose dynamic partitioning of B_{pr}^{m} and B_{sh}^{m} based on symmetric fair spectrum–power consumption trading model. The amount of traffic belonging to a BS embarking on the sleep-mode is used as the *numeraire* for spectrum trading with the supporting BSs. The operators are categorized into two: spectrum donors are the *Suppliers*, while those accepting spectrum in exchange for UE support are the *Demanders*.

Let the fraction of the individually licensed spectrum allocated to the shared spectrum based on trading for each operator be denoted by δ_m. Since the number of associated UEs per operator may not be equal, δ_m may differ across MNOs. For clarity, δ_m is further denoted as δ_m^d for a demander and δ_m^s for a supplier.

BS power consumption, however, does not solely depend

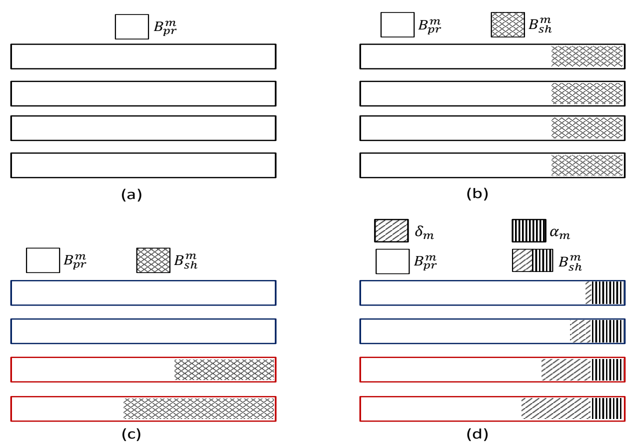

Fig. 3. Spectrum Sharing partitioning scenarios. (a) No spectrum sharing; each MNO exclusively uses its licensed spectrum. (b) All operators contribute equally to the shared bandwidth. In this case, α_m is fixed. The spectrum pooling scheme is used in SESP where $\alpha_m = \frac{B_m}{M}$. (c) Spectrum sharing here is based on Spectrum–Power consumption Trading as in SSPT. Bandwidths belonging to demanders are in red, and the suppliers are delineated in blue. Here, $\alpha_m = 0$. (d) This is also a SSPT scheme with $\alpha_m \neq 0$.

on the number of UEs served. For example, power is also consumed by an active fronthaul regardless of the number UEs. Moreover, the BS power consumption in varying traffic is not the same for all BS types. The impact of the number of UEs on BS power consumption is higher in a macro BS than a micro BS, even much higher than in pico and femto [39]. We represent the factors that cannot be captured by δ_m by a flexible constant α_m.

Therefore, $\alpha_m \geq 0$ represents the agreed spectrum fraction each operator m contributes to the shared spectrum regardless of current and future traffic condition. This amount is equal for all operators, i.e $\alpha_1 = \alpha_2 = ... = \alpha_M$. In this work, we take the total pooled shared bandwidth to be $B_{sh} = B_m$, and hence $B_{sh} \geq M\alpha_m$. For demander $m \in V$, the inherited traffic load to be supported is L_m^d such that the combined load of all demanders is depicted as $\sum_{m=1}^{Z} L_m^d$. The spectrum numeraire of demander m is

$$\delta_m^d = \frac{L_m^d}{\sum_{m=1}^{Z} L_m^d} \left(B_{sh} - M\alpha_m \right). \tag{20}$$

The private bandwith of demander m becomes

$$B_{pr}^{m,d} = (B_m - \alpha_m) + \delta_m^d, \tag{21}$$

and its total contribution to the pooled shared bandwidth is simply

$$B_{sh}^{m,d} = B_m - B_{pr}^{m,d}. \tag{22}$$

For each supplier, the spectrum numeraire in exchange for UE support is

$$\delta_m^s = \frac{L_m^s}{\sum_{m=1}^{Z} L_m^s} \left(B_{sh} - M\alpha_m \right), \tag{23}$$

where L_m^s is the number of other operators $m \in Z$ with their traffic supported by the active BSs. Therefore, its contribution to the pooled shared bandwidth is

$$B_{sh}^{m,s} = \alpha_m + \delta_m^s, \tag{24}$$

and the private bandwidth of supplier m can be simply expressed as

$$B_{pr}^{m,s} = B_m - B_{sh}^{m,s}. \tag{25}$$

The illustration of various spectrum sharing and partitioning methods is shown in Fig. 3. The ESP is described in Fig. 3(b), while SPT methods are depicted in Fig. 3(c) and (d). The simplified steps of the ESP and SPT spectrum sharing approaches are shown in Fig. 4.

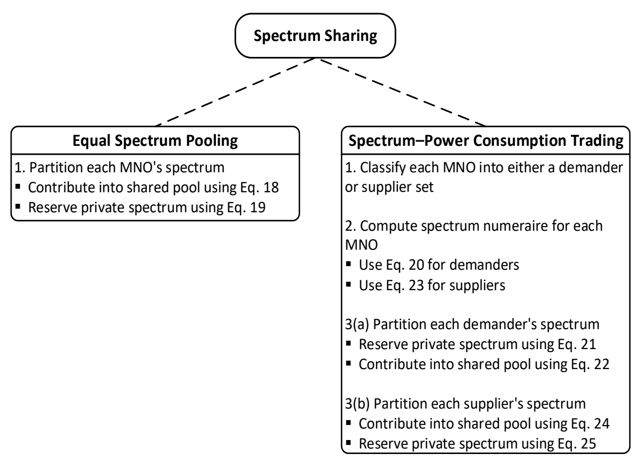

Fig. 4. Simplified illustration of the spectrum sharing algorithms.

B. Joint Power Savings by Spectrum–Power Consumption Trading

Here, we present the energy-saving strategy by BS sleep-mode based on spectrum trading for UE support. The scheme is illustrated in Algorithm 3. While the strategy can be extended to be triggered by a joint load threshold, the algorithm allows MNOs to make desired trade side requests. Both sets of demanders and suppliers are sorted in descending order of their associated traffic. The set of potential active BSs, V, is initialized by the demanders and the UE–BS channel quality is

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checked by Steps 5 – 11 of Algorithm 1. A bad overall channel condition outcome leads to rejection of the first supplier's request and inclusion in set V. The step is repeated until a good channel quality is attained for all UEs.

Algorithm 3: Sleep-mode with Spectrum–Power consumption Trading (SSPT) Algorithm

---

1 Group the BSs based on requests: set of spectrum demanders and set of suppliers.
2 Sort the 2 BS sets in descending order of their load weight; D= sorted spectrum demanders and S = spectrum suppliers.
3 Concatenate sets D and S to form set A, i.e $A = \{D, S\}$.
4 Form set $V \subset A$ and initialize V with subset D.
5 **while** $V' \subset A \neq \emptyset$ **do**
6   Check for all UE–BS channel quality using **Algorithm 1** Steps 5–11.
7   **if** *channel condition is satisfied* **then**
8   For $\forall m \in V$ apportion $B^m_{pr} = B^{m,d}_{pr}$ using (21) and $B^m_{sh} = B^{m,d}_{sh}$ using (22). For $\forall m \in V'$ partition $B^m_{sh} = B^{m,s}_{sh}$ using (24) and $B^m_{pr} = B^{m,s}_{pr}$ using (25).
9   Solve problem (17) to obtain the optimal $\mathbf{w}^{pr}_{vk}$ and $\mathbf{w}^{sh}_{vk}$.
10   Each BS $\forall m \in V$ supports its own UEs in B^m_{pr} and offloaded UEs from any V' on B_{sh}, and put $V' \subset A$ into sleep-mode.
11   **end**
12   **else**
13   Include the most loaded BS from suppliers, i.e $|V| = |V| + 1$ from $V' \subset A$, and go to Step 6.
14   **end**
15 **end**
16 Each BS supports own UEs on its respective licensed spectrum B_m.

VII. Numerical and Simulation Results

In this section, we evaluate the performance of the proposed schemes. We show SEBS strategies can achieve power savings and sum rate increase in multiple operator scenarios.

In the simulation, the following are utilized as the default scenarios and parameters. 10 identical colocated RRHs are deployed, each belonging to a separate MNO and a uniform distribution of UEs in the region of interest of coverage radius of 200 meters. Each RRH is equipped with 4 transmit antennas, and one antenna to every UE. We adopt the pathloss model of $140 + 36.7\log_{10}(d)$ for distance d, as in [37], to give attenuation between the RRH and UE. Other simulation parameters are presented in Table II. For SSPT, the number of intitial spectrum demanders and suppliers are $|D| \sim \left(\left[ceil\left(\frac{|A|}{4}\right), ceil\left(\frac{3|A|}{4}\right)\right]\right)$ and $|S| = |A| - |D|$, respectively. 200 simulation runs are performed for all schemes.

TABLE II
Simulation Paramters

Parameter	Value
Coverage radius	200 meters
Original MNO bandwidth	10 MHZ [47]
Minimum achievable data rate	0.5 Mbps
Pathloss model	$140 + 36.7\log_{10}(d)$ [37]
Noise power, σ^2	-94 dBm
RRH maximum transmission power	10 W
RRH static power, P^{rrh}_{static}	22.5 W
RRH sleep-mode power, P^{rrh}_{sleep}	12 W
Fronthaul link static power, P^{f}_{static}	3.5 W
Fronthaul link sleep-mode power, P^{f}_{sleep}	1.2 W

A. Benchmarks

To evaluate the relative energy efficiency performance of the proposed schemes, we performed comparative simulations of some network BSs operation in cooperative and non-cooperative modes. The comparative schemes are defined below.

- *Sleep-mode with No Cooperation (SNC)*: In this scheme, BS sleep-mode strategy is employed. BSs with no loads are switched off, but powered on upon arrivals of UEs. However, the MNOs are not in cooperation. Thus, there is no inter-operator bandwidth sharing. Each operator solely uses its total licensed bandwidth exclusively for its UEs.
- *No Sleep-mode and No Cooperation (NSNC)*: Unlike the SNC, this scheme does not incorporate the sleep-mode strategy. All BSs are in the active mode all the time. Also, there is no inter-operator cooperation in this scheme, hence no spectrum sharing.

B. Performance Evaluation with Traffic Variation

The performance of SEBS schemes is evaluated in various traffic scenarios. The schemes are compared with the benchmarks mentioned above in the simulation. The number of RRHs is held constant at 10, while the number of UEs in the region is varied.

In the SESP strategy, the cooperating MNOs partition their licensed spectra into shared bands according to (18), and private bands using (19). For fair inter-operator spectrum sharing by the SEPT scheme, $\alpha_m = 0$ is used to model the BS's contribution to the shared bandwidth for power consumption analysis since identical BSs are assumed. Therefore, spectrum pooling is only dependent on the number of UEs traded.

Fig. 5 shows the higher energy saving performance of the proposed schemes over non-cooperative benchmark schemes. The inter-operator joint power consumption increases with traffic in all schemes. The non-cooperative strategies, NSNC and SNC, exhibit smaller EE than the proposed cooperative schemes. NSNC confirms the energy inefficiency of BS operation without a sleep-mode strategy in cellular networks. The power consumption is undoubtedly high even at low traffic loads. Despite the inclusion of the BS sleep-mode in SNC, the proposed algorithms yield better EE due to inter-operator cooperation. Moreover, SNC yields a higher rate of power dissipation as the traffic grows than the proposed schemes. The rate is due to the relatively less number of BSs put into the sleep-mode in SNC as the traffic increases. SSPT is more power efficient than the other proposed cooperative scheme, SESP. Unlike in SESP where the active BSs are

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constrained to support UEs with the fixed pre-apportioned shared bandwidth, SSPT allows some spectrum slices from the inactive BSs to be used to support UEs. More availability of spectrum to active BSs results in the edge in EE over SESP.

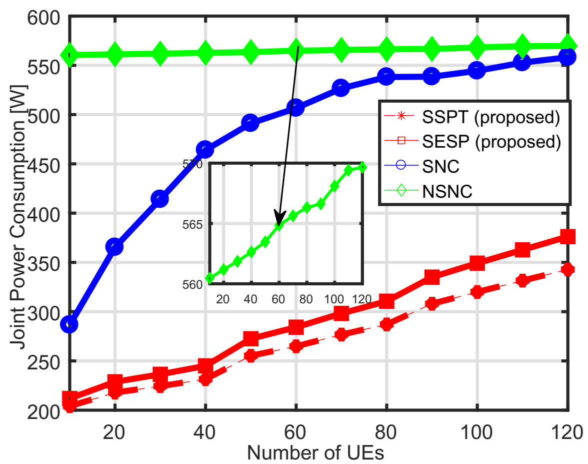

Fig. 5. Total inter-operator power consumption versus number of UEs

C. Impact of the Number of Cooperative MNOs

The number of participating MNOs is modeled here with the variation in the number of RRHs since each RRH may belong to a separate operator. The UE number is fixed at the default value of 10. Shared bandwidth pooling is facilitated by $\alpha_m = 0$ for the fair spectrum-sharing of the SSPT scheme. The objective is to assess the impact of the number of cooperating MNOs on the amount of energy saved. The simulation of the performance is shown in Fig. 6.

With a few RRHs, all the schemes seem to converge as all the RRHs are actively engaged; none is lightly loaded to be put into the sleep-mode. Increasing the number of RRHs raises the total power consumption in all the schemes mainly from P^{rrh}_{static} for the active RRHs, and $P^{rrh}_{v,sleep}$ for RRHs on the sleep-mode. On the other hand, the increase in the number of MNOs creates an opportunity for traffic handover from some BSs. Thus, the power consumption is lower in sleep-mode strategies than NSNC. However, with sleep-mode strategy in SNC, the proposed schemes (SESP and SSPT) are still more power efficient. This validates that inter-operator cooperation is more energy efficient even with the increase in the number of participants. Similar to the previous analysis, fair spectrum-sharing of the SSPT scheme provides better energy-saving performance than SESP.

D. Impact of Channel Power Gain

The BS–UE channel quality evaluation of the LTC (Algorithm 1) is the pivot of the two proposed algorithms. Therefore, this evaluation tests the performance of SEBS in different channel states conditioned on the threshold $|h_0|^2$.

Fig. 7 shows the power consumption incurred by the SEBS schemes for different channel conditions while the numbers of UEs and RRHs are held constant. Similar to the previous results, SSPT yields higher EE than SESP. However, the power

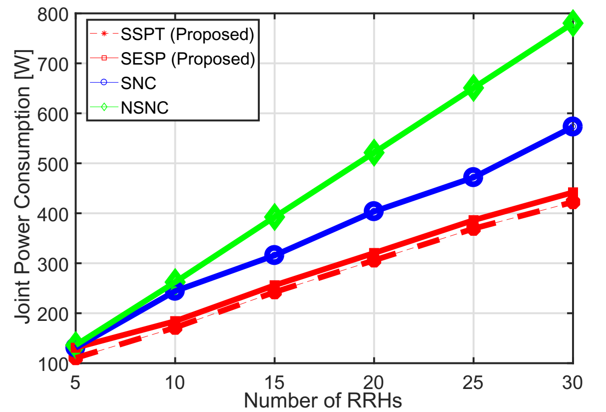

Fig. 6. Total inter-operator power consumption versus number of RRHs

consumed, in both schemes, is not linear as the channel threshold increases. At lower thresholds, fewer BSs are engaged, but heavily laden. This results in increasing the dynamic power part, and the evident initial surge in power consumption. The system energy consumed drops with the channel threshold increase to some optimal point. However, as the threshold is tightened, it becomes more difficult for more BSs to satisfy LTC, thus leading to an increase in more active BSs. With more BSs in operation, the aggregate of more P^{rrh}_{static} and $P^{f}_{v,static}$ causes the system energy consumption to rise.

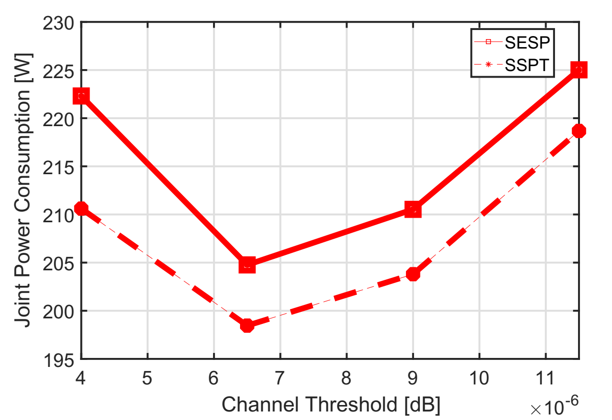

Fig. 7. Channel quality threshold versus power consumption

E. Impacts of Sharing Ratios on Sum Rate

Spectrum Efficiency (SE) - EE tradeoff is one of the fundamental tradeoffs in wireless networks [48]. In this subsection, we validate the performance of SEBS on the sum rate of all UEs of all the colocated BSs. For a critical evaluation, we examine various spectrum sharing scenarios depicted in Fig. 3. This avails the opportunity to examine the impact of different bandwidth sizes on the SE–EE relationship.

Different shared bandwidth partitioning ratios characterize the various SSPT curves in Fig. 8. Strictly equal spectrum sharing is represented by SESP, and SNC is the non-cooperative scheme. All schemes involve the sleep-mode strategy for unbiased analysis. SNC clearly results in a relatively much

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lower sum rate.

A further probe into the result shows that not all sharing methods outperform the fixed spectrum sharing method as per spectral efficiency. This also provides an insight on the impact of support of inherited UEs on the SE. Specifically, at $\alpha_m = 0$ and $\alpha_m = 0.5B_m/M$, more bandwidth is available to support the inherited UEs. This ultimately yields a higher sum rate than the fixed equal spectrum sharing method, SESP. However, a lower sum rate is achieved at $\alpha_m = 1.5B_m/M$. Here, inherited UEs are supported with less bandwidth, thus culminating in a lower sum rate.

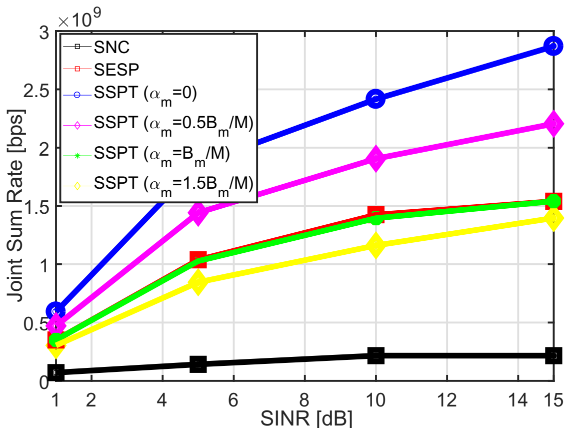

Fig. 8. Joint sum rate of various SEBS schemes

VIII. Conclusion

In this work, we have presented the Sleep-mode with Efficient Beamformers and Spectrum-sharing (SEBS) strategy, which reduces the power consumption of colocated BSs of multiple cooperative operators. We have utilized the concept of dynamic spectrum allocation and carrier aggregation to partition an operator's licensed bandwidth into private and shared bands in which a UE's access is mutually exclusive. To achieve energy efficient transmission power, we have formulated an optimization problem to obtain the optimal intra- and inter-RAN beamforming vectors while taking the maximum RRH power limit, and intra- and inter-operator UE minimum data rates into consideration. We have also proposed Sleep-mode with Efficient Beamformers and Spectrum-sharing (SEBS) strategies based on the load transfer condition algorithm to achieve gains in energy efficiency. The load transfer condition algorithm considers the channel quality and current traffic load of the cooperating BSs. The proposed inter-operator joint energy saving schemes include a spectrum–user support trading to motivate cooperation among identical operators. We have also analyzed the impacts of the schemes on the joint sum rates of UEs by exploring different bandwidth sharing formulations. The results show that SEBS strategies achieve significantly a higher energy efficiency than non-cooperative schemes. It is also revealed that spectrum–user support trading yields higher joint sum rate than in equal spectrum sharing when appropriate bandwidth sharing ratios are used.

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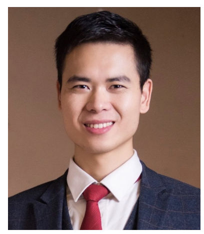

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