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Framework for Multi-Operator Collaboration for Green Communication

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ABSTRACT Network infrastructure sharing has been recently introduced as a promising solution toward energy reduction in cellular networks. In this paper, a framework for the potential power saving inherent in the network sharing approach is provided in multi-operator mobile networks. The overall downlink transmitted power consumption is derived in closed form expression as a function of relative inter-base stations (BSs) distance of cooperative operators. In addition, the optimal inter-BSs distance is deduced to obtain minimum power consumption in multi-operator networks. The proposed model is evaluated and compared with non-roaming scenario in order to provide an apparent vision for saving in power in mobile network operators networks. The proposed model provides a framework to guide the operators whether to roam the user equipment or not.

INDEX TERMS Green communication, mobile networks operators, power saving.

I. INTRODUCTION

Driven by the exponentially increasing in wireless network infrastructure, an enormous growth of energy consumption of wireless networks arises [1]. More specifically, the global mobile data traffic is expected to reach 69 exabytes per month by 2022 at a compound annual growth rate of 45 percent [2]. The huge expansion of mobile network infrastructure leads to high energy consumption. In particular, some analysis shows that for the worst-case scenario, and if sufficient improvement is not adopted in electricity efficiency of wireless access networks and fixed access networks/data centers, information and communication technology (ICT) could use as much as 51% of global electricity in 2030 [3]. In addition, ICT industry is responsible for 2% of global CO_2 emissions, but this percentage is increasing as rapidly as the number of connected devices increase. Moreover, it is foreseen that 75% of the ICT sector will be wireless by 2020 [4], thus implying that wireless communications will become the critical sector to concern.

In the context of green cellular networking, the macro base stations (BSs) consume relatively high operational power. More specifically, approximately 80-90% of the total network energy is consumed to run the radio sites, taking into consideration that there is about more than 5 million deployed BSs worldwide [5].

Network infrastructure sharing has been introduced as a promising viable solution for the operators for the sake of reducing the deployment of capital expenditures (CAPEX) and the operation expenditures (OPEX) associated with the cellular networks [5]. The coexistence of multiple MNOs in the same geographical area motivates the research community to shift towards a new promising sharing model based on MNOs collaboration: roaming based infrastructure sharing. In this model, the MNOs use their resources jointly to achieve their common goal, which is to achieve energy and cost reduction while guarantee UE service [6].

Infrastructure sharing is classified into three scenarios [7]: 1) passive sharing of sites components, towers, masts, and building premises; 2) active sharing of the active network components, such as backhaul equipment, switches and antennas; and 3) roaming-based sharing, where the cell coverage is shared by the MNOs according to a pre-negotiated sharing deal. In this paper, motivated by the aforementioned issues, a framework for roaming-based infrastructure-sharing scheme is modeled and investigated in multi-operator mobile network. In spite of the technical and regulation challenges that might appear in such sharing scenarios, the potential benefits of infrastructure sharing between MNOs have been recently estimated to reach to about € 2 billion [5], further motivate the MNOs in sharing their devices.

Recently switching off schemes is studied to exploit unused resources during light traffic hours per day in order to achieve drastic energy efficiency gains.

Switching off schemes can be adopted in multi-operator network if BSs of collaborating operators are installed at the same location and have the same coverage area for their cells which is not applicable in many cases. Practically, the location of BSs depends on many considerations which are not similar for each operator. In such case, switching off BSs with different cell coverage generates dead zone and if the active BS of one operator extends its radiation to cover the generated dead zone, it may interfere with its own neighbor's cell.

In addition, in 5G environment where wideband small cells are deployed inside the coverage area of a macro cell in order to support huge traffic demands of 5G. Based on this network architecture, a separation between user plane and control plan is adopted where the macro BS's control plane manages the operation of all small cells as well as the access of all UEs in a centralized manner [8]. Even if the UE is in idle state, it is connected to the macro BS for controlling session initiation. So it is appropriate to keep the macro BS active in order to manage the control plane of all UEs in the cell. On the other hand, switching off BS of specific operator enforces the control plane of all UEs to be transferred to the active BS of associated operator which generates huge processing overhead and complicated scheduling algorithms. It can be concluded that Switching off BS is applicable with BSs which are located at the same location and in region with low traffic demands.

Hence in general case, where BSs of different operators are not located together, a practical assumption is proposed in this paper that the BS is always active so as to provide management of control signal of all UEs and avoid generating a dead zone due to deactivating some BSs [9], [10].

According to [11] and [12], power consumption rate at the BS increases exponentially with its traffic load in terms of the number of served UEs given that each UE has a constant rate requirement. The power consumption of the BS starts from a base level when there is no traffic load then it increases with its downlink transmitted power [12].

Data roaming between different operators thus may help in saving the BS's power consumption by dynamically control UE's association with suitable BS in order to reduce the overall downlink transmitted power for each operator. Each operator should be aware of this in designing the traffic sharing with other operators, and should also consider the heterogeneity of sharing BSs in location and cell coverage.

This thus motivates this paper to investigate the dynamic association between UEs and BSs of different operators to save the overall power consumption in the 5G mobile network while meeting all UEs' service requirements.

This paper studies the overall power consumption when roaming is adopted between operators whose BSs are not located together. This paper answers the question whether the operator should roam its UEs with cooperative operator whose BS is located at specific distance from its own BS or not. The roaming based overall power consumption is derived in closed form manner as a function of the relative distance between BSs. The decision is taken per BS based according to the distance with nearest BS. So some BSs may roam their UEs to nearest BS and some other may not. Switching off BSs is still an option in some BSs if no dead zone will be generated and if the active BS can process the control signal of both BSs.

The main contributions of this paper are summarized as follows:

1. A framework for the roaming based overall power consumption in multi-operator mobile network: As a part of an integrated roaming-based infrastructure sharing scheme for multi-operator mobile networks, a closed form expression for overall power consumption as a function of inter-BSs distance is introduced.

2. Novel multi operator cooperation and dynamic user association to minimize the overall power consumption: the multi operators cooperation and dynamic users' association are studied with the sake of serving roaming traffic between operators and minimizing the overall power consumption of the MNOs. The different power consumption patterns for each operator are modeled with respect to their traffic load, where the relative BSs' location between operators and their UEs' coverage areas is considered.

3. Optimal separation between different BSs: A novel algorithm to find the optimal separation between BS of different operators is provided in order to achieve optimal power saving.

4. Network performance evaluation in power saving, coverage and capacity: the impact of roaming between MNOs in overall power consumption is evaluated and compared with non-roaming case and the saving in power is depicted in several scenarios. It can be observed from the results that the roaming between operators provides more flexibility in achieving green performance compared to the traditional scenario. In addition, the results indicate that the benefit of roaming is not only in form of saving in power but also in form of increasing in UEs' densities and cell coverage for both operators.

The remainder of this paper is organized as follows.

Section II briefly reviews the related works. The system model is described in section III and optimal setting for network roaming parameters is introduced in section IV. Section V presents optimal roaming strategy for each operator. Numerical analysis and results are provided in section VI. Finally, the paper is concluded in section VII.

II. RELATED WORKS

Ideas and proposals of network sharing started to appear in Europe in the 2000s after the universal mobile telecommunications system (UMTS) licenses were granted [7]. A drafted report on the state of shared 3G network infrastructure is declared by Telecommunications Industry Association (TIA) Europe in 2001 [13]. In 2009, the North Stream report analyzed the competitive and practical effects of network sharing [14].

Infrastructure sharing is investigated in literature with all levels of sharing starting from sharing passive elements in network like mast and towers to sharing spectrum between MNOs. Many researches deal with protocols and algorithms that organize network sharing. Some literatures suggest a common pool for resources and small cells (SCs) to be shared between operators. Others study the existence of third part that provides infrastructure to network operators.

Francesco *et al.* [15] present a framework to model infrastructure sharing planning process while taking into account both the ability to share resources and the constraints imposed by competition regulation.

The existence of a third party that provides a common SCs infrastructure for the operators is proposed in [16] and the authors suggest an accurate cost model for the SCs.

Doyle *et al.* [17] present virtual network operators which construct their networks from a pool of shared resources (e.g. base stations, spectrum, core network components, cloud resources, processing capabilities etc.). The resources will be sourced from traditional industry players as well as crowd sourced from individuals.

Spectrum sharing is introduced to tackle the challenge of providing higher data rates within limited spectral resources. Many literatures deal with the required algorithms and protocols to coordinate the actions of spectrum sharing between operators [12], [13]. A survey for licensed spectrum sharing schemes for mobile operators is presented in [18] and [19].

The problem of underutilization of the dedicated, licensed spectrum of network operators is discussed in [20]. To tackle this problem, they study the spectrum assignment with the goal of maximizing the social welfare of the network between operators by adopting many-to-one stable matching game framework.

Luoto *et al.* [21] considered mobile network where operators are sharing a common pool of radio resources. Long term fairness of spectrum sharing is ensured without coordination among small cell base stations.

Kibilda and DaSilva [22] study efficient coverage provisioning in mobile networks under an inter-operator infrastructure sharing regime. Two cases are studied in this work: real state and state from Poland.

Resource sharing in heterogeneous cloud radio access networks (H-CRANs) is investigated in [23] at three levels: spectrum, infrastructure, and network. For each level, the authors discuss the challenges and benefits, highlighting key enabling technologies that make resource sharing feasible in H-CRANs.

A mathematical framework is introduced in [24] for analyzing and optimizing multi-operator cellular networks that are allowed to share spectrum licenses and infrastructure elements. The proposed approach exploits stochastic geometry for modeling the locations of cellular base stations and for computing the aggregate average rate.

Cano *et al.* [25], [26] analyze the strategic situation in which MNOs have to decide whether to invest in long term evolution (LTE) pico-cell BSs and whether to share the investment with other MNOs. The infrastructure sharing problem in this work is formalized through a Mixed Integer Linear Programming to maximize the quality of service and includes techno-economic parameters.

Most research works in field of power saving have focused on switching off BS during periods of low traffic as it the most power-hungry element in mobile networks. It depends on deactivated some BSs and the active BSs extend their radiation to cover switched off BSs area.

Oh and Son [27] studies the dynamic operation of macro base stations (BSs) for potential energy savings by considering not only downlink traffic but also uplink traffic as well.

The Strategies for Switching off Base Stations in heterogeneous networks in 5G systems are surveyed in [28].

Switching small cells is also considered [9], [29], [30]. A coverage probability, average achievable rate, and energy efficiency in heterogeneous K-tier wireless networks with different sleep modes is derived in [29] using a stochastic geometry-based heterogeneous cellular network (HCN) model. While in [9] a location based strategy is introduced to dynamically switch of small cells.

The appearance of infrastructure sharing between operators leads the research from traditional switching-off schemes to one step further by considering the emerging business model of roaming-based infrastructure sharing among MNOs offering service to the same geographical area. In this area the research community takes attention in switching off BSs among multiple MNOs.

Marsan and Meo [31] investigate the potential energy saving inherent in the network sharing approach. They show that in most European countries the amount of energy necessary to run mobile networks can be reduced by 35 to 60% with respect to the case in which each operator manages a separate network infrastructure.

Oikonomakou *et al.* [32] propose a cooperative switching off scheme at which the MNOs cooperate during the low traffic hours so as to save energy by switching off BSs, regardless of the BS type, i.e., Evolved Node B (eNB) or SC. Antonopoulos *et al.* [5] present network deployments scenarios and possible architectures of MNOs.

Many literatures use the game theoretic strategy in BS switching off between operators [5], [6], [33]. An innovative distributed game theoretic to decide the best suitable BSs to remain active is proposed in [5] and [33].

Bousia *et al.* [6] introduce a game-theoretic framework that enables the MNOs to individually estimate the switching-off probabilities that reduce their expected financial cost. While Ghazzai *et al.* [1] study the interactions among competitive mobile operators collaborating together in order to achieve green goals without compromising their profits and QoS.

In [34], several alternatives are studied, as regards the switch-off pattern: the one that balances the switch-off time periods, the one that balances roaming costs, the one that balances energy savings, and the one that maximizes the amount of saved energy.

According to the best of our knowledge, no one tackles the collaboration between MNOs who's offering service to different coverage area.

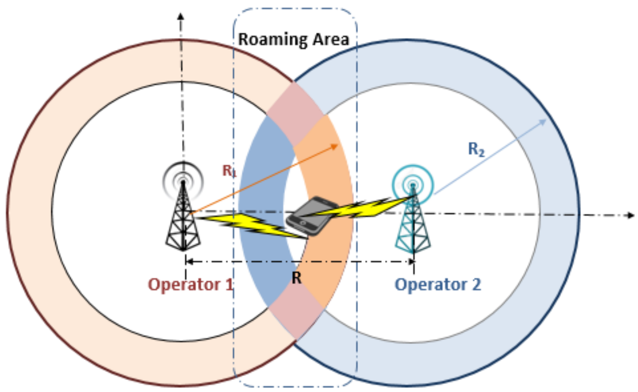

FIGURE 1. MNO system model with two operators.

III. SYSTEM MODEL

As shown in Figure. 1, a MNO is considered where two operators are deployed at the same geographical area. The first is operator 1 or host operator and the second is operator 2 or guest operator. Each operator dynamically adjusts its users' association with the more suitable BS in MNO in order to reduce the total power consumptions across the entire MNO networks. In the following, the network model of MNO is introduced. Then the power consumption model of operator 1 is deduced with different roaming scenarios with operator 2.

Since the transmitted power of the BS is directly proportional with its served traffic load, the expected traffic load at the BS is considered at first then its downlink transmitted power is derived.

A. MNO NETWORK MODEL

This subsection introduces the dimensions of the MNO network components at the space in the proposed model. Denote the coverage radius of the cell of each operator as R_1 and R_2, respectively. The BS of each operator is assumed to be located at the center of their respective coverage area. Throughout the paper, the BS of operator 1 will be called as home BS.

Without loss of generality, in the two dimensional plan R^2, let the BS of the first operator is located at the origin o, given by $(0, 0)$, and the BS of the second operator is located at $(R, 0)$ where R is distance between the two BSs. The cell coverage areas of both operators are A_1 & A_2 respectively.

To model the UE location in MNO, the spatial randomness is taking into consideration. The widely accepted Poisson point process (PPP) is used to model the UE location.

For each operator, a homogeneous PPP with density λ_i is used to model UE distribution at the cell area where $i = 1$ & 2 according to operator identity. Under this model, the UEs are independently and uniformly distributed over the cell area. In addition, the PPP of each operator are mutually independent. However, due to the non-identical UE densities between operators in general, UEs' distributions are not uniform over different operators. This is reasonable as some operators may have more customers than others due to marketing considerations.

All BSs are divided into three sectors; each sector is equipped with single antenna. The home BS of the operator 1 is surrounding with many BSs of operator 2. Each UE of each operator is equipped by a single antenna and may be associated to its nearest home BS of its own operator or roamed to nearest BS of other operator BSs according to applied roaming strategy.

The cell spatial structure of the proposed model is regular hexagonal lattice which helps in providing theoretical insights in closed form expressions. In reality, the BSs are not deployed so ideally, due to environmental constraint and shrinking cell sizes, which is more suitably modeled randomly [35]. PPP is the most frequently model used to model this randomness. As [36] proves, PPP and lattice structure provide a lower and an upper bound on the coverage probability respectively. In this paper, we focus in lattice structure and the other distributions which capture the randomness behavior of the BSs structure are left for future extension for this work.

In the following, the power consumption model for each sector is introduced, then the overall power consumption for the entire BS in the MNO network is deduced.

B. POWER CONSUMPTION MODEL

This subsection presents the downlink power consumption model for the BS. The consumed power at the BS is directly proportional to the traffic load as the load-dependent power amplifier is the main power-consuming component at the BS [12]. The consumed power starts from a base level $P_b > 0$ and increases linearly with its downlink transmitted power P_t [21]. So

$$P = P_b + k_u P_t \tag{1}$$

where P is the consumed power at BS, and $k_u > 0$ is the power utilization coefficient for the BS. A typical example for P_b and k_u in Europe are $P_b = 712$W and $k_u = 14.5$ [12].

According to (1), if BS traffic is roamed to cooperative operator, its downlink transmitted power P_t decreases and so the total consumed power P decreases as well. On the other hand if the cooperative operator roams its traffic to the home BS, then the BS's downlink transmitted power increases and the total consumed power increases as well. In the following, the downlink transmitted power for all UEs within the BS respective area is deduced whatever those UEs belong to BS's operator or are roamed from the cooperative operator.

C. BS TRANSMITTED POWER P_t FOR ALL UEs

In this section, the overall downlink transmitted power is derived based on the PPP UE location model. The BS's transmitted power for each individual UE is derived at first. Then the transmitted power P_{ts} for all UEs at BS's sector are aggregated at the coverage region of each sector, whatever this UE belongs to this operator or are roamed from another operator. Finally the overall downlink transmitted power P_t at the entire cell is calculated by aggregating the downlink transmitted power for all cell sectors. It supposes that the BS's downlink power for each individual UE to be sufficient to satisfy the UE's QoS requirement regardless of his location within cell area.

1) BS ALLOCATED POWER PER UE P_{TN}

For a given UE n which is located from a distance r_n of BS, considering at first distance-independent path loss, if the UE is located within a circle of radius $r_0 > 0$ (i.e. $r_n < r_0$), the UE experiences a fixed path loss $D > 0$. On the other hand if the UE is located at distance $r_n > r_0$, the path loss increases and the power attenuates along the distance it travels according to path loss exponent α [12]. In addition, the short-term Rayleigh fading for the wireless channel is considered where h_n is the Rayleigh fading from the serving BS to UE n, and it follows exponential distribution with unit mean.

If the BS's transmitted power to UE n is P_{tn}, then the received power, denoted by P_{rn}, is obtained as

$$P_{rn} = \begin{cases} P_{tn}h_nD; & if \ \ r_n \leq r_0 \\ P_{tn}h_nD\left(\frac{r_n}{r_0}\right)^{-\alpha}; & otherwise. \end{cases} \quad (2)$$

Let C bits/sec be the minimum data rate to satisfy the QoS requirement for UE n. The operating bandwidth for the BS is B and there are N UEs in its coverage area. So the allocated bandwidth for UE n is B/N. Recall the Shannon's formula

$$C = \frac{B}{N}log_2\left(1 + \frac{P_{rn}}{\Gamma N_0 B}\right) \quad (3)$$

where N_0 is the noise power density and $\Gamma \geq 1$ is used for capacity loss due to practical coding and modulation. In order to achieve C bits/sec for UE n, the outage probability should not be more than a given threshold $\varepsilon \ll 1$.

By substituting P_{rn} from (2) and solving for P_{tn}, the required downlink transmitted power to achieve predefined QoS for UE n is

$$P_{tn} = \begin{cases} \frac{\Gamma N_0 B}{-Dln(1-\varepsilon)} \times \frac{2^{\frac{NC}{B}}-1}{N}; & if \ \ r_n \leq r_0 \\ \frac{\Gamma N_0 B}{-Dln(1-\varepsilon)} \times \frac{2^{\frac{NC}{B}}-1}{N} \times \left(\frac{r_n}{r_0}\right)^{\alpha}; & otherwise. \end{cases} \quad (4)$$

Remark 1: with the same data rate requirements between UEs, the downlink transmitted power P_{tn} depends on the number of UEs in the cell N and the distance between UE and BS r_n. So P_{tn} can be rewrite to be $P_{tn}(N, r_n)$ as a function of r_n and N.

Remark 2: it can be noticed from (4) that the downlink transmitted power exponentially increases with the distance between the UE and BS. Consequently the BS needs more power to support UE in cell edge. So from power saving point of view, it is more likely for BS to serve the UE at cell core than the one at cell edge. Thus with uniformly distributed UEs and identical traffic load, the relative distance between the UE and the serving BS is considered an important factor in roaming decision between operators.

Proposition 1: In the case of identical system parameters and power model between UEs, if UE i is located at distance r_i from the BS and the operator decides to roam this UE, then UE j which is located at distance r_j where $r_i < r_j$ should be also roamed. On the other hand, if the operator decides not to roam UE i, then UE k which is located at distance r_k where $r_i > r_k$ should not be roamed either.

According to proposition 1, there is a distance d from the BS separates between the UEs according to roaming decision. If the UE is located at distance r_n then

$$U_n = \begin{cases} 0 & if \ \ r_n \leq d \\ 1 & if \ \ r_n > d \end{cases} \quad (5)$$

where $U_n \in \{0, 1\}$ is the roaming mode of the UE n, and $U_n = 0$ if the UE is served by his own BS while $U_n = 1$ if the UE is roamed to another operator. So the cell UEs can be divided according to roaming decision to cell edge UEs who are more likely to be roamed to cooperative operator and cell core UEs who are more likely to be served by the operator itself.

The power saving based roaming decision not only depends on the distance between the UE and the BS from which the UE is roamed but also depends on distance between the UE and the BS to which the UE is roamed. So if the UE is located in the cell edge of the cooperative operator, then roaming this UE will not lead to reduce the consumed power. Thus the relative distance between the BSs of the cooperative operators is the main factor in determine the roaming decision.

2) BS TRANSMITTED POWER P_{TS} TO ALL UES PER SECTOR

In this subsection, the downlink transmitted power P_{ts} for all UEs of different operators in BS's sector coverage area is considered. This allows us to develop a mathematical framework that can be used for MNO networks.

In the MNO network, according to PPP model, the UEs of each operator are identical and independently distributed at each area with mean μ being equal to the average number of UEs at the corresponding area.

So by summing up $P_{tn}(N, r_n)$ for all the UEs in the sector whatever those UEs are from the same operator or roamed from other operator over the corresponding coverage area of cell, the BS transmitted Power P_{ts} can be obtained.

The UEs from different operators who are roamed to the home BS should be added to the total downlink transmitted power, while the home BS UEs who are roamed to the cooperative operator should be excluded from the total downlink transmitted power. So the roaming criteria that control the roaming between cooperative operators should be considered.

In the following, the roaming criterion is introduced to determine UE's association with each BS. Then the average number of UEs who are served by the home BS from different operators is deduced.

- ***Roaming criterion***

According to (4) and subsequent remarks, the following roaming criteria are assumed in order to minimize the power consumption in MNO networks:

Given UE i belongs to operator 1. The UE i is then roamed to operator 2 according to the following criterion:

1. The UE i is roamed if (and only if) it is located at cell edge area of BS of operator 1 and it is located at the cell core area of operator 2 as well.
2. The UE i is not roamed if :
   a. It is located at cell core area of operator 1.
   b. It is located at cell edge area of operator 1 but it is not located at cell core area of operator 2.

So there are three groups of UEs who are distributed at different areas of the cell. Those groups are considered in downlink transmitted power calculation for each BS for both operators:

1. The cell core UEs.
2. The cell edge UEs of operator 1 who are not located at cell core area of operator 2
3. The cell edge UEs of operator 2 who are located at cell core area of operator 1. Those UEs are roamed to operator 1 in order to reduce the overall power consumption in MNO network.

The BS transmitted Power P_{ts} depends on the number of UEs in the BS sector. In addition, the average distance between UE and the serving BS affects on the required power to compensate the path loss impact.

In the following, the average number of UEs from the three groups is derived. Then the average distance between the user and the serving BS is deduced.

- ***Derivation of average number of UEs at each group***

In order to calculate the average number of UEs of each group who are served by the home BS, the area over which those UEs are distributed is deduced.

Let A_{gn} be the area over which the UEs of group n are distributed in the cell sector where $n = 1, 2$ or 3. For example the UEs of group 1 (cell core UEs) are distributed in the area A_{g1} at cell core.

According to Fig. 2, the area of each group is as following:

$$A_{g1} = \frac{\pi}{3} R_{c1}^2 \tag{6}$$

$$A_{g2} = \frac{\pi}{3}\left(R_1^2 - R_{c1}^2\right) - \frac{R_2^2}{2}(\eta - sin\eta) + \frac{R_{c2}^2}{2}(\xi - sin\xi) + \frac{R_{c1}^2}{2}(\psi - sin\psi) + \frac{R_{c2}^2}{2}(\omega - sin\omega) \tag{7}$$

$$A_{g3} = \frac{R_{c1}^2}{2}((\theta - sin\theta) - (\psi - sin\psi)) + \frac{R_2^2}{2}(\varphi - sin\varphi) - \frac{R_{c2}^2}{2}(\omega - sin\omega) \tag{8}$$

where R_{c1} & R_{c2} are the radii of the cell core areas of operators 1 & 2 respectively. The angles ξ, η, θ, φ, ω & ψ are illustrated in Fig. 2. The UEs who are covered by angles ξ & η are located at intersection between cell edge area of operator 1 and cell core area of operator 2. While the UEs who are covered by angles θ & φ are located at intersection between cell core area of operator 1 and cell edge area of operator 2. Finally the UEs who are covered by angles ω & ψ are located at intersection between cell core areas of both operators.

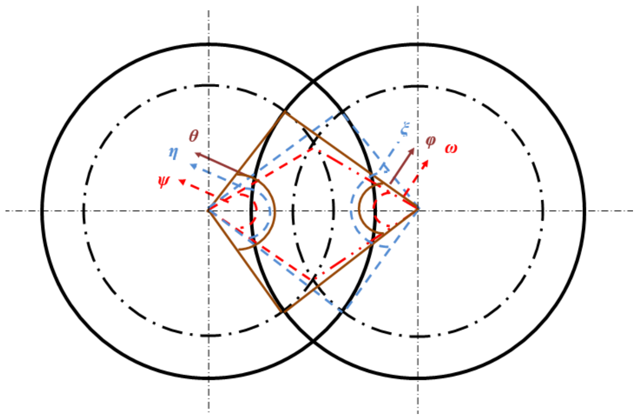

FIGURE 2. Intersection areas between the two operators cells and related angles.

Then the average number of UEs at each cell sector who belong to operator 1 & 2 and is served by home BS is

$$\mu = \lambda_1 A_{g1} + \lambda_1 A_{g2} + \lambda_2 A_{g3}. \tag{9}$$

- ***Derivation of BS power consumption*** p_{ts}

The UEs of both operators are randomly distributed at the corresponding areas according to PPP model. So the number of UEs at each area as well as the distance between each UE and the BS are both random variables.

Let the number of UEs of operator 1 be N_1. Some of them (N_{r1}) are roamed to operator 2, while the remainder ($N_{o1} = N_1 - N_{r1}$) are served by their own BS. While N_{r2} are UEs from operator 2 who are roamed to BS of operator 1.

All cell UEs of each operator are identically and independently distributed in the BS's coverage area. Let the distance between BS of operator 1 and its corresponding UE n is r_{n1}, while the distance between BS of operator 2 and its corresponding UE n is r_{n2}. Therefore, by taking expectation over the number of UEs at each area and distance between each UE and BS, the downlink transmitted power for all UEs per sector can be obtained.

$$P_{ts} = E_{N_{o1},N_{r2}}\left[E_{r_1,\ldots\ldots r_{N_{o1}},\ldots\ldots r_{N_{r2}}}\left[\sum_{n=1}^{n=N_{o1}} P_{tn}(N_{o1}, r_{N_{o1}}) + \sum_{n=1}^{n=N_{r2}} P_{tn}(N_{r2}, r_{N_{r2}})\right]\right]. \tag{10}$$

Following [12], the inner expectation of the distance between each UE and the BS, as well as the outer expectation of the number of UEs at each area are executed respectively. Then by substituting the transmitted power of each UE $P_{tn}(N, r_n)$ from (4), and making the summation on the expected value of r_n & N over the corresponding area, an explicit expression for the downlink transmitted power for all UEs is obtained as

$$P_{ts} = \left(\frac{\Gamma N_o B}{-Dln(1-\varepsilon)}\left(exp\left[\left(2^{\frac{C}{B}-1}\right)\mu\right]-1\right)\right) \times \sum_{n=1,2,3}\frac{1}{\mu}\int_{A_{gn}} L\left(r\right) dA_{gn} \quad (11)$$

where

$$L\left(r\right) = \begin{cases} 1; & if\ r_n \le r_0 \\ \left(\frac{r_n}{r_0}\right)^{\alpha}; & otherwise. \end{cases}$$

The downlink transmitted power in (11) is multiplication of two factors:

- The traffic load which is function of average number of UEs.
- The path loss factor which mainly depends on the distance between each UE and the BS, as well as the area which UEs is distributed. The path loss factor can be obtained by averaging the path losses of the UEs over their corresponding area. By definition, each group has its own path loss factor.

In the following, the path loss factor of UEs at each group over the corresponding area is studied.

a: PATH LOSS FACTOR OF UEs OF GROUP 1

In this part, the path loss factor of UEs of group 1 is obtained. Recalling the path loss model in equation (2), the UEs of group 1 are located in cell core area of the BS.

The path loss factor is obtained by integration of path loss of individual UE over area of A_{g1} as

$$\int_{A_{g1}} L\left(r\right) dA_{g1} = \frac{\pi}{3\left(\alpha+2\right) r_o^{\alpha}}\left(2R_{c1}^{\alpha+2}+\alpha r_o^{\alpha+2}\right). \quad (12)$$

b: PATH LOSS FACTOR OF UEs OF GROUP 2

In general, the cell edge UEs are more likely to be roamed if they are located at the cell core area of the BS of operator 2 in order to reduce the overall power consumption. The UEs of group 2 are the remaining cell edge UEs who are not roamed to operator 2 as they are not located at the cell core area of operator 2. Hence the coverage area of UEs of group 2 can be obtained by excluding the part that is located at cell core of operator 2 from cell edge area of operator 1.

Then the path loss factor of UEs of group 2 is

$$\int_{A_{g2}} L\left(r\right) dA_{g2} = \frac{\pi}{3\left(\alpha+2\right) r_o^{\alpha}}\left(R_1^{\alpha+2}-R_{c1}^{\alpha+2}\right) - \left(\frac{1}{\left(\alpha+2\right) r_o^{\alpha}}\left(R_1^{\alpha+2}\left(\eta-sin\eta\right)-R_{c1}^{\alpha+2}\left(\psi-sin\psi\right)\right) + \left(\xi-\omega\right)\left(H\left(R,R_{c2}\right)-\frac{R^{\alpha+2}}{\left(\alpha+1\right)\left(\alpha+2\right) r_o^{\alpha}}\right)\right) \quad (13)$$

where

$$H\left(R,R'\right) = \frac{\left(R-R'\right)^{\alpha+1}\left(R+R'\left(\alpha+1\right)\right)}{\left(\alpha+1\right)\left(\alpha+2\right) r_o^{\alpha}}$$

and R_1 is the radius of the cell.

Proof: Please refer to Appendix A.

Remarks on equation (13)

- The first part of equation (13) is the path loss factor of cell edge UEs while the second part is the path loss factor of cell edge UEs who are located at cell core of operator 2 and so they are not served by home BS.
- The angles ξ, η, ω & ψ are function of inter-BSs distance R. If the inter-BSs distance is smaller than $R_{c1}+R_{c2}$, then there is intersection between cell core areas of the two operators. This intersection is determined by angles ω & ψ. On the other hand, if $R_1+R_2 \ge R \ge R_{c1}+R_{c2}$, then there is no intersection between cell core areas of both operators and the angles ω & $\psi = 0$, then equation (13) is simplified to (14). Finally if $R \ge R_1+R_2$, then the angles ξ & $\eta = 0$ as well and the two BSs are far away to roam their UEs between each other, so the second part is then omitted from (13) and all UEs at cell edge area are served by their own BS:

$$\int_{A_{g2}} L\left(r\right) dA_{g2} = \frac{\pi}{3\left(\alpha+2\right) r_o^{\alpha}}\left(R_1^{\alpha+2}-R_{c1}^{\alpha+2}\right) - \left(\frac{1}{\left(\alpha+2\right) r_o^{\alpha}}\left(R_1^{\alpha+2}\left(\eta-sin\eta\right)\right) + \left(\xi\right)\left(H\left(R,R_{c2}\right)-\frac{R^{\alpha+2}}{\left(\alpha+1\right)\left(\alpha+2\right) r_o^{\alpha}}\right)\right). \quad (14)$$

Equation (13) and its corresponding remarks imply that when the BSs of the cooperative operators are too close to each other, the downlink transmitted power increases due to decreasing the roaming area (at $R = 0$, there is no roaming area between operators and so the transmitted power reaches its peak). On the other hand when the distance between the BSs increases, the roaming area increases and so the downlink transmitted power from UEs of group 2 decreases as well. At specific distance between the BSs, the downlink transmitted power reaches its minimum value with largest roaming area between operators. Finally the transmitted power increases again when the distance increases because the BS of operator 2 becomes far away to roam cell edge UEs of operator 1 and all cell edge UEs with high power requirements are served by their home BS.

c: PATH LOSS FACTOR OF UEs OF GROUP 3

The UEs of group 3 are roamed from operator 2 to the home BS in order to reduce the consumed power in BS of operator 2. Those UEs are located at cell edge of operator 2 and at the same time are located at cell core of operator 1. So if they are roamed to nearer BS, a less transmitted power is required to provide them their service. As a result, the coverage area of UEs of group 3 is the intersection of cell core area of operator 1 and the cell edge area of operator 2.

By integrating of path loss of individual UE who is located at this area, we can obtain the path loss factor of UEs distributed over this area in theorem 1.

Let

$$G(\tau, \upsilon) = (\tau - sin\tau) - (\upsilon - sin\upsilon). \quad (15)$$

Theorem 1: In the multi-operator network, given the distance between two BSs R, and cell core radius of both BSs R_{c1} & R_{c2}, the path loss factor of UEs of operator 2 who are roamed to operator 1 is

$$\begin{aligned}\int_{A_{g3}} L(r)dA_{g3} &= \left(\frac{2R_{1c}^{\alpha+2} - \alpha r_o^{\alpha+2}}{2(\alpha+2) r_o^{\alpha}}\right) \times G(\theta, \psi) \\ &+ \frac{1}{2} r_o^2 G(\varphi, \omega) + (\varphi - sin\varphi)\left[H(R, r_o) - H(R, R_2)\right] \\ &- (\omega - sin\omega)\left[H(R, r_o) - H(R, R_{c2})\right]. \quad (16)\end{aligned}$$

Proof: Please refer to Appendix B.

Remarks on equation (16)

- As in equation (13), the angles θ & φ, ω & ψ are function of inter-BSs distance R. If the inter-BSs distance is smaller than $R_{c1}+R_{c2}$, then there is intersection between cell core areas of both operators. UEs who are located at this intersection are not roamed as they are close enough to be served by their own BS. This intersection is determined by angles ω & ψ. On the other hand, if $R_1+R_2 \geq R \geq R_{c1}+R_{c2}$, then the angles ω & $\psi = 0$ and (16) is simplified to (17). Finally if $R \geq R_1 + R_2$, then the angles ξ & $\eta = 0$ as well and the two BSs are far away to roam their UEs between each other:

$$\begin{aligned}\int_{A_{g3}} L(r)dA_{g3} &= \left(\frac{2R_{c1}^{\alpha+2} - \alpha r_o^{\alpha+2}}{2(\alpha+2) r_o^{\alpha}}\right) \\ &\times G(\theta, \psi) + \frac{1}{2} r_o^2 G(\varphi, \omega) \\ &+ (\varphi - sin\varphi)\left[H(R, r_o) - H(R, R_2)\right]. \quad (17)\end{aligned}$$

- If $R = 0$, then there is no cell edge UEs of operator 2 are located at cell core of operator 1, then there is no consumed power for serving UEs of group 3. With increasing R, the downlink transmitted power for UEs of groups 3 increases due to increasing the roaming area between operators. The transmitted power continues to increases with increasing the roaming area till it reaches its peak, then it starts to decrease with R when the cell edge area of operator 2 becomes far away from cell core of operator 1.

It is observed from (12-17) that the distance between the BSs of the operators is a tiebreaker in determine the roaming strategy of each operator.

3) OVERALL BS TRANSMIT POWER P_T TO ALL UES AT THE WHOLE CELL

In this section, we aim to study the overall downlink BS transmitted power at the whole cell. So we include any other BSs of operator 2 that may roam their UEs to the home BS.

In order to consider the cooperation between home BS and all surrounding BSs of associated operator, we have to extend the analysis in the previous section at one sector to the other two sectors. So we need to consider not only the relative distance between the home BS with only one BS of cooperative operator but also with all other BSs which have roaming area with the other two sectors. Let S_1, S_2 & S_3 be the three sectors of the home BS, while the surrounding BSs of guest operator of these sectors are BS_1, BS_2 & BS_3 respectively. To be compatible with the previous analysis, R is the distance between the home BS and guest BS_1. The relative inter-BSs distance at each sector is not identical, so the area of each group is different per sector.

Let R_{s2} & Rs_3 be the distance between home BS and BS2 & BS3 respectively. In the following analysis, we assume that the azimuth of the sectors of both operators is identical. This assumption can be simply relaxed by considering the difference in azimuth angles between operators in roaming area calculation. Also we have $R_{s2} = R_{s3} = R$'.

Then we can simply deduce that[1]

$$R' = \left(4R_2{}^2 - 2\sqrt{3}R_2 R + R^2\right)^{1/2}. \quad (18)$$

The average number of UEs that is served by the whole cell of the home BS is

$$\mu = \lambda_1 \mathbb{A}_{g1} + \lambda_1 \mathbb{A}_{g2} + \lambda_2 \mathbb{A}_{g3} \quad (19)$$

where

$$\begin{aligned}\mathbb{A}_{g1} &= \pi R_{c1}^2 \\ \mathbb{A}_{g2} &= \pi\left(R_1^2 - R_{c1}^2\right) - (A_{re1} + 2A_{re2}) \\ A_{re1} &= \frac{R_2^2}{2}(\eta - sin\eta) + \frac{R_{c2}^2}{2}(\xi - sin\xi) - \frac{R_{c1}^2}{2}(\psi - sin\psi) \\ &+ \frac{R_{c2}^2}{2}(\omega - sin\omega) \\ A_{re2} &= \frac{R_2^2}{2}\left(\eta' - sin\eta'\right) + \frac{R_{c2}^2}{2}\left(\xi' - sin\xi'\right) \\ &- \frac{R_{c1}^2}{2}\left(\psi' - sin\psi'\right) + \frac{R_{c2}^2}{2}\left(\omega' - sin\omega'\right) \\ \mathbb{A}_{g3} &= \frac{R_{c1}^2}{2} G(\theta, \psi) + \frac{R_2^2}{2}(\varphi - sin\varphi) - \frac{R_{c2}^2}{2}(\omega - sin\omega) \\ &+ 2 \times \left(\frac{R_{c1}^2}{2} G\left(\theta', \psi'\right) + \frac{R_2^2}{2}\left(\varphi' - sin\varphi'\right)\right. \\ &\left. - \frac{R_{c2}^2}{2}\left(\omega' - sin\omega'\right)\right)\end{aligned}$$

[1]This relation is valid in hexagonal cellular system structure. A future extension may consider more practical cellular system like different spatial stochastic models.

where $\mathbb{A}_{g1}$, $\mathbb{A}_{g2}$ & $\mathbb{A}_{g3}$ are the areas of UEs of group 1, 2 &3 respectively at the whole cell. While the angles θ', φ', ξ', η', ω' & ψ' are corresponding to angles θ, φ, ξ, η, ω & ψ at the other two sectors.

The overall expected transmitted power is multiplication of traffic load by path loss factor. Similar to the previous analysis, the path loss factor differs according to the group that each UE belongs.

In the following, the path loss factor of all UEs of each group over the corresponding area is studied.

a: PATH LOSS FACTOR OF UEs OF GROUP 1

The UEs of group 1 are located in cell core area of BS. The path loss factor is obtained by integration of path loss of individual UE over cell core area surrounding the BS at all sectors

$$\int\limits_{\mathbb{A}_{g1}} L(r)d\mathbb{A}_{g1} = \frac{\pi}{(\alpha+2)\, r_o^{\alpha}}\left(2R_{1c}^{\alpha+2} + \alpha r_o^{\alpha+2}\right) \tag{20}$$

b: PATH LOSS FACTOR OF UEs OF GROUP 2

The cell edge UEs of second and third sectors are roamed to BS_2 & BS_3 respectively. So the path loss factor of cell edge UEs over all cell edge area is

$$\int\limits_{\mathbb{A}_{g2}} L(r)d\mathbb{A}_{g2} = \frac{\pi}{(\alpha+2)\, r_o^{\alpha}}\left(R_1^{\alpha+2} - R_{c1}^{\alpha+2}\right) - (r_{e1} + 2r_{e2}) \tag{21}$$

where

$$r_{e1} = \frac{1}{(\alpha+2)\, r_o^{\alpha}}\left(R_1^{\alpha+2}(\eta - sin\eta) - R_{c1}^{\alpha+2}(\psi - sin\psi)\right) + (\xi - \omega)\left(H(R, R_{c2}) - \frac{R^{\alpha+2}}{(\alpha+1)(\alpha+2)\, r_o^{\alpha}}\right)$$

and

$$r_{e2} = \frac{1}{(\alpha+2)\, r_o^{\alpha}}\left(R_1^{\alpha+2}(\eta' - sin\eta') - R_{c1}^{\alpha+2}(\psi' - sin\psi')\right) + (\xi' - \omega')\left(H(R', R_{c2}) - \frac{R'^{\alpha+2}}{(\alpha+1)(\alpha+2)\, r_o^{\alpha}}\right).$$

Remarks on (21)

- The angles ξ' & η' is dependent on R' which in turn is function of R, so the roaming area of UE of group 2 at the whole cell is dependent on R.
- The distances between home BS and both BS_2 & BS_3 are inversely proportional to R according to (18). So the roaming areas of operator 1 with BS_2 & BS_3 decrease with increasing the roaming area with BS_1.
- The roaming area at all sectors are identical at $R = R' = 2/\sqrt{3}$. At this point the path loss factor to UEs of group 2 at the three sectors are identical and equal to

$$\int_{\mathbb{A}_{g2}} L(r)d\mathbb{A}_{g2} = \frac{\pi}{(\alpha+2)\, r_o^{\alpha}}\left(R_1^{\alpha+2} - R_{c1}^{\alpha+2}\right) - 3r_{e1}. \tag{22}$$

- If the two BSs of both operators are located at the same location i.e. the two cells are confined ($R = 0$), all cell edge UEs of the operator 1 are located at cell edge area of operator 2, then there no cell edge UEs are roamed and $r_{e1} = r_{e2} = 0$. So maximum overall downlink transmitted power is required to compensate the increase in path loss of UEs of group 2.

Equation (21) and its corresponding remarks imply that starting from $R = 0$, the maximum downlink transmitted power is required to serve UEs of group 2. With increasing of R, some edge UEs are roamed and as a result, the transmitted power decreases. When the roaming area between the two BSs reaches its peak, the transmitted power reaches its minimum value. Then it starts to increase again if the host BS approaches another BS.

c: PATH LOSS FACTOR OF UEs OF GROUP 3

By considering UEs from BS_2 and BS_3 who are roamed to home BS, the Path loss factor of UEs of group 3 is as stated in theorem 2.

Theorem 2: In the multi-operator network, given the relative distance between the home BS and corresponding BSs of operator 2 are R, R'& R' and the cell core radius of both operators are R_{c1} & R_{c2}, the path loss factor of UEs of operator 2 who are roamed to operator 1 at the entire cell is

$$\int_{\mathbb{A}_{g3}} L(r)d\mathbb{A}_{g3} = r_{c1} + 2r_{c2}$$

where

$$r_{c1} = \left(\frac{2R_{1c}^{\alpha+2} - \alpha r_o^{\alpha+2}}{2(\alpha+2)\, r_o^{\alpha}}\right) \times G(\theta, \psi) + \frac{1}{2} r_o^2 G(\varphi, \omega) + (\varphi - sin\varphi) \times [H(R, r_o) - H(R, R_2)] - (\omega - sin\omega) \times [H(R, r_o) - H(R, R_{c2})] \tag{23}$$

and

$$r_{c2} = \left(\frac{2R_{1c}^{\alpha+2} - \alpha r_o^{\alpha+2}}{2(\alpha+2)\, r_o^{\alpha}}\right) \times G(\theta', \psi') + \frac{1}{2} r_o^2 G(\varphi', \omega') + (\varphi' - sin\varphi') \times \left[H(R', r_o) - H(R', R_2)\right] - (\omega' - sin\omega') \times \left[H(R', r_o) - H(R', R_{c2})\right].$$

The same remarks of (16) on cell edge UEs to be roamed to operator 2 are hold for (23) for cell edge UEs to be roamed from operator 2 as the angles θ', φ', ω' & ψ' are dependent on R' which in turn is function of R.

In the following, in order to probably investigate the power consumption minimization problem, we provide an algorithm to find the optimal inter-BSs distance R_{opt} that provides minimum downlink transmitted power. According to this investigation, we deduce a framework for determine the optimal strategy that each operator may take to roam their UEs to minimize its overall power consumption.

IV. OPTIMAL SETTING FOR NETWORK ROAMING PARAMETERS

From the previous sections, it can be deduced that the inter-BSs distance has a great impact on the roaming between operators and consequently the total reduction in power consumption. In addition, the boundary between cell edge and cell core of each operators affects on the number of UEs to be roamed between operators and so it should be carefully adjusted.

In the following, the optimal inter-BSs distance as well as the optimal choice for boundary between cell edge and cell core is presented.

A. OPTIMAL INTER-BSS DISTANCE OF DIFFERENT OPERATORS

In this section, we provide an algorithm to deduced optimal inter-BSs distance to minimize overall power consumption in MNOs. Equations (13) & (16) imply that the path loss factor and consequently the overall downlink transmitted power of UEs of groups 2 & 3 depends on the distance between BSs.

Equation (13) implies that the consumed power for serving cell edge UEs *decreases* from its peak (non-roaming case) because some cell edge UEs are roamed to operator 2. This variation is function of distance between BSs. On the other hand, equation (16) implies that the consumed power for serving cell core UEs *increases* from its minimum value (non-roaming case) because some UEs are roamed from operator 2. This variation is function of distance between the BSs as well.

In order to study the relation between decreasing in consumed power for cell edge UEs with increasing in consumed power for cell core UEs, proposition 2 is presented.

Proposition 2: With uniform UE distribution, and identical UE's densities and power model for both operators, the increase in number of UEs to be roamed to the BS in cell core area as a result of change in inter-BSs distance is equal to decrease in number of UEs to be roamed from BS in cell edge area, hence the total number of UEs in the cell is constant regardless of the distance between BSs.

Proof: please refer to appendix C

According to proposition 2, the roaming based power saving depends on decreasing the transmitted power by roaming UEs who are located at cell edge and consequently consume relatively high power to operator 2, while the same number of UEs from operator 2 who are located at cell core, and consequently consume less power, are roamed to operator 1. So this act as transferring some cell edge UEs with high power consumption to cell core area with less power consumption.

Proposition 2 implies that there is only one point of R at which maximum number of cell edge UEs are roamed and so minimum power is consumed at this point.

Theorem 3: In hexagonal cellular system and in case of uniform UE distribution, if the overall downlink transmitted power of BS is P_t and the inter-BSs distance is R, then there always exists an optimal inter-BSs distance R_{opt} that consumes least power in MNOs, which is the unique solution to equation $P_t{'}(R_{opt}) = 0$.

Let $P|_{R=x}$ be the overall transmitted power of the home BS when the BS of operator 2 is located at $x = (0, x)$.

$$P|_{R=x} = P_b + k_u\, P_t|_{R=x} \tag{24}$$

while $P|_{R=y}$ be the overall transmitted power when the BS of operator 2 is located at y where $y = (0, x + \Delta R)$ and ΔR is unit area

$$P|_{R=y} = P_b + k_u\, P_t|_{R=y}\,. \tag{25}$$

Finally let ΔP be the difference in transmitted power when the BS changes its location from $x = (0, x)$ to $y = (0, x+\Delta R)$ due to variation in roaming area. So

$$\Delta P = \left| P|_{R=y} - P|_{R=x} \right|. \tag{26}$$

Then we can find the optimal distance R_{opt} as illustrated in algorithm 1 by gradually increasing R and then calculating the difference in transmitted power ΔP at each point. The optimal distance R_{opt} that minimize the total power consumption is reached when $\Delta P = 0$.

If we start the algorithm with $R\_lower = 0$ (i.e. $R = 0$), then there is no roaming area for both operators, and maximum power is consumed by each BS. Practically there is a constraint in the maximum power that each BS can transmit. If the power consumption exceeds this constraint, no more UEs are admitted. This value is referred as maximum allowable power consumption P_{tmax}.

Table 1 provides numerical examples for running algorithms 1 with practical setting parameters.

B. GIDE LINES FOR ADJUSTING BOUNDARY BETWEEN CELL CORE AND CELL EDGE

The boundary between the cell core and cell edge is the border line between the UEs to be roamed to or from the operator. If the UE exists in cell edge area, the UE is more likely to be roamed to operator 2 and if the UE exists at cell core area, it is more likely to be served by its home BS. So the radius of the cell core affects in transmitted power of the BS and consequently the overall power consumption in MNOs.

In order to study the impact of d (or R_{c1} & R_{c2} of operators 1& 2 respectively) in the transmitted power, the following remarks can be highlighted.

- Proposition 2 and subsequent remarks implies that when cell edge area increases, more cell edge UEs (with relatively high power consumption) are roamed from the BS, so the overall power consumption decreases. On the other hand when cell core area increases, more cell edge UEs can be roamed to the BS.
- In case of non-identical UEs' densities between operators, and with cooperative MNOs, in order to reduce the overall power consumption, it is preferable to operator with higher UEs' densities to increase its cell edge area in order to roam more UEs. While it is preferable to operator with lower UEs' densities to increase its cell core area in order to receive more UEs.
- In case of identical UEs' densities between operators, the same cell core radius is used for both operators,

Algorithm 1 To Determine R_{opt}

Input $A_1, A_2, \lambda_1, \lambda_2$
Initialize $R_{lower} = R\_lower$,
$N = No\_of\_stebs$
Calculate $R_{upper} = R_1 + R_2$,
$\Delta R = (R_{lower} + R_{upper})/N$
Initialize $P(0) = P_b + k_u\ P_t|_{R=R_{lower}}$
For $n = 1 : N$
  $R(n) = R_{lower} + n\Delta R$
  Calculate $P(n) = P_b + k_u\ P_t|_{R=R(n)}$
  $\Delta P(n) = P(n) - P(n-1)$
  If $\Delta P(n) \geq 0$
    $R_{opt} = R(n-1)$
    break
  End if
End for
Return R_{opt}

TABLE 1. Optimal Inter-BS distance using algorithm 1*.

A_1 (10^5) m^2	2.83	5.0	7.85	11.3	15.4	20.1	25.4
A_2 (10^5) m^2	2.83	5.0	7.85	11.3	15.4	20.1	25.4
λ_1(10^{-3}) /m^2	5.0	3	1.7	1.2	0.8	0.6	0.15
λ_2 (10^{-3}) /m^2	5.0	3	1.7	1.2	0.8	0.6	0.15
R_{opt} m	347	461	578	692	809	923	1040

*The network setting parameters for these examples are the same as used in numerical analysis and results section. Also we let R_lower = 50m, step size ΔR = 3m.

so increasing cell edge area to roam more cell edge UEs implies decreasing cell core area which reduces the number of roamed UEs. So there is an optimal point at which the maximum number of cell edge UEs can be roamed.

V. OPTIMAL ROAMING STRATEGY FOR EACH OPERATOR

Each operator should take the decision of roaming their UEs or not. The decision is taken by compromise roaming cost and profit. The roaming cost is in the form of processing overhead due to a complicated scheduling and ppsignaling which is generated because of roaming between operators. On the other hand, the roaming profit is in the form of reduction in overall power consumption. Therefore, in case of suffering of large roaming cost, the operator would prefer not to roam their UEs. According to the previous analysis, the power consumption depends on the relative Inter-BSs distance of both operators and so the roaming decision is taken per BS and not with whole network. The BS of the cooperative operator can be located in one of three cases:

1. $P_t(R_{opt}) \leq P_t \leq \sigma P_t(R_{opt})$: The overall power consumption, resulted from roaming with the cooperative operator, does not exceed the minimum power consumption with a pre-defined value σ ($\sigma \geq 1$). The pre- defined value σ is defined as the point at which the roaming cost exceeds roaming profit. It occurs if the associated BS is located in the area surrounding the optimal inter-BSs distance R_{opt}. The overall power consumption of this case is the least. So the roaming profit at this area is greater than roaming cost and it is preferable that the operator roams its UEs.
2. $P_t > \sigma P_t(R_{opt})$: The overall power consumption exceeds the minimum power consumption with a pre-defined value σ. This region includes area where the saving in power due to roaming is not larg enough to exceed the roaming cost. In this case, it is not preferable that the operator roams its UEs with associted BS.
3. *Switching off Case:* if the two BSs are located together and they both have the same coverage area. In this case, it is preferable to switch off one of them during low traffic periods.

VI. NUMERICAL ANALYSIS & RESULTS

In this section, we introduce the simulation results to investigate the impact of roaming between operators in BS power consumption. In the first, the model is compared with non roaming case in order to validate and evaluate roaming impact. The comparison is adopted in two cases: the first is with constraint in the consumed power in BS by adopting maximum BS transmitted power P_{tmax}. The second is without constraint in power consumption. The roaming and non-roaming model are compared with different UEs' denisties and different coverage areas.

The percentage of power saving in the proposed model is calculated with different distance between BSs'. With practical setup parameters, we apply algorithm 1 in order to find optimal distance between operators to minimize overall power consumption. In addition, the effect of cell core radius in roaming area between operators is illustrated. The optimal cell core radius is shown as well.

For the total power consumption of BS, which is given in (1), the setting parameters are $P_b = 712$, $k_u = 14.5$ [9], [12]. The remaining parameters for simulation are as follows.

- The fixed path loss $D = -35$ dB.
- The reference distance $r_0 = 10$ m.
- The capacity loss $\Gamma = 1$.
- The path-loss component $\alpha = 2.5$.
- The maximum allowable outage probability $\varepsilon = 0.05$.
- The noise power $N_0 = -174$ dBm/Hz.

and the allocated bandwidth for each operator is $B = 10$ MHz, and the required data rate for each UE is $C = 0.1$ Mb/s.

This section is divided into two parts: the first is model evaluation and the second is model optimization.

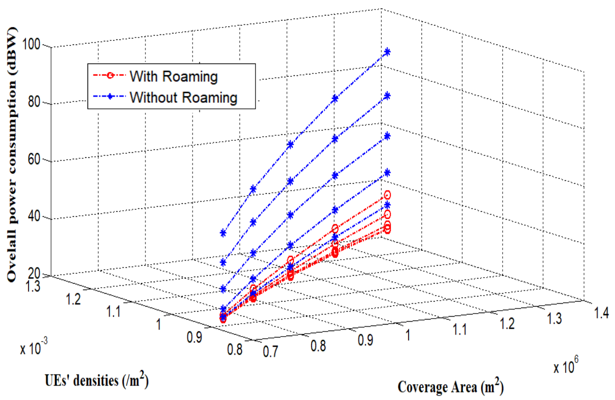

FIGURE 3. Overall power consumption (dBW) as a function of coverage area of the cell at x-axis and UE densities at y-axis.

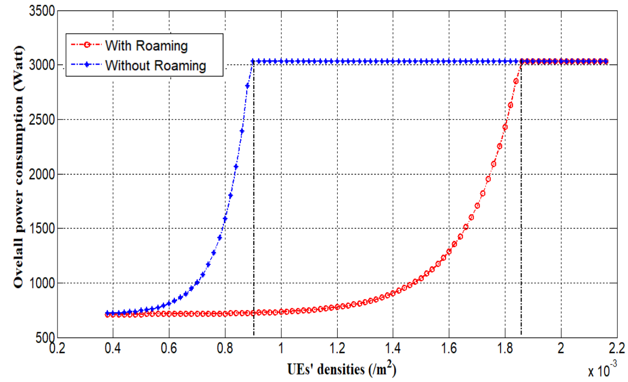

FIGURE 4. Overall power consumption (dBW) as a function UEs' densities with practical maximum BS power P_{tmax} = 160 watt.

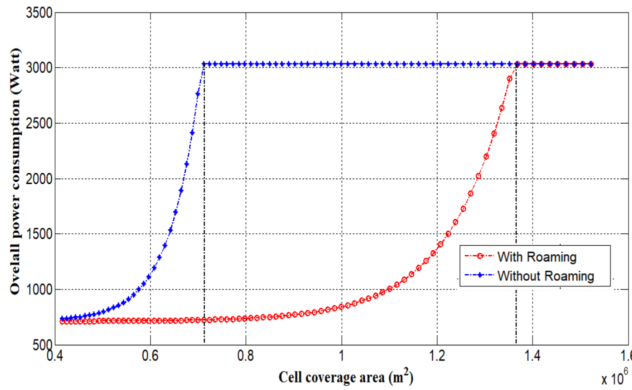

FIGURE 5. Overall power consumption (dBW) as a function cell coverage area with practical maximum BS power P_{tmax} = 160 watt.

In model evaluation, a comparison between roaming and non-roaming case is introduced, while in model optimization, both of optimal inter-BSs distance and cell core radius are obtained.

A. MODEL EVALUATION

In this part, the performance of the roaming based multi-operator power saving scheme is compared with benchmark scheme to further illustrate the roaming effect in overall power consumption. The benchmark scheme is a mobile network with non-cooperative operators where no roaming is adopted between operators and each operator supports its UEs. In both schemes, the same power allocation method is adopted at BS, which is discussed in the system model, to assure the macro-cell UEs' QoS.

It is assumed that the cell radius is identical for both operators. The inter-BSs distance is proposed to be greater than cell radius by one tenth. While the cell core radius to cell radius is taken as 1:2.

The comparison is based on two criteria: the first is the impact of UEs' densities in power consumption in roaming and non-roaming case (capacity perspective). The second is the impact of coverage area in power consumption for the two cases as well (coverage perspective).

In Fig. 3, the transmitted power is scanned with different coverage areas at x-axis, and with different UEs' densities at y-axis. In general, it is observed that the overall power consumptions are increasing over covered area and UEs' densities as expected. This can be considered an evidence for the stability of the proposed model.

As explained earlier in this paper that the overall power consumption is a mutiplication of traffic load factor which index to the cell capacity and path loss factor which index to the cell coverage.

It can be seen also that roaming scheme consumes less power than non-roaming scheme especially at higher densities and larger coverage areas. More specifically, It can be noted that there is more than 30% saving in power with roaming schemes at $\lambda = 0.8 \times 10^{-3}/\text{m}^2$ and coverage area which not exceeds 6.36×10^5 m^2. The saving in power increases to 51% with increase in UEs' densities to $0.9 \times 10^{-3}/\text{m}^2$. It also increases to 45% with increasing the coverage area to 6.8×10^5 m^2. The practical maximum BS power P_{tmax} is not adopted at this comparison, so all UEs will obtained their QoS at both schemes but with more power consumption with non-roaming case.

In Fig. 4 & 5, a practical maximum BS transmitted power P_{tmax} is adopted at both schemes. So when the consumed power exceeds the constraint of P_{tmax}, the call admission control randomly rejects some UEs in order to satisfy the QoS of the remaining UEs.

Fig. 4 depicts the power consumption with different UEs' densities (capacity perspective). It is observed that the maximum UEs' denisities λ_{th} at roaming case is larger than at non-roaming case, so more UEs can properly access the BSs for both operators when roaming is adopted, where λ_{th} is the maximum UEs' densities that can be supported by BS which guarantees that each UE gets its QoS. On the other hand, Fig. 5 illustrates the impact of power transmission in cell coverage range (coverage perspective). It is observed that maximum cell range R_{th} at roaming scheme is larger than at non-roaming scheme, so larger area can be covered for both operators, where R_{th} is the maximum coverage range that can

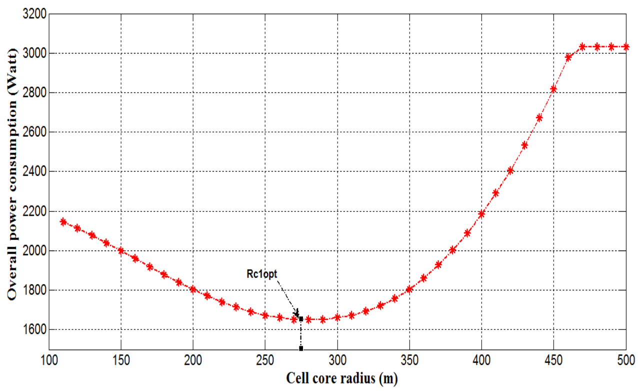

FIGURE 6. Overall power consumption (dBW) as a function cell core radius, the cell area of both operators $A_1 = A_2 = 7.85 * 10^5$ and the distance between the BSs $R = 550$ m, while the UE densities are λ_1 & $\lambda_2 = 0.17 * 10^{-3}/m^2$.

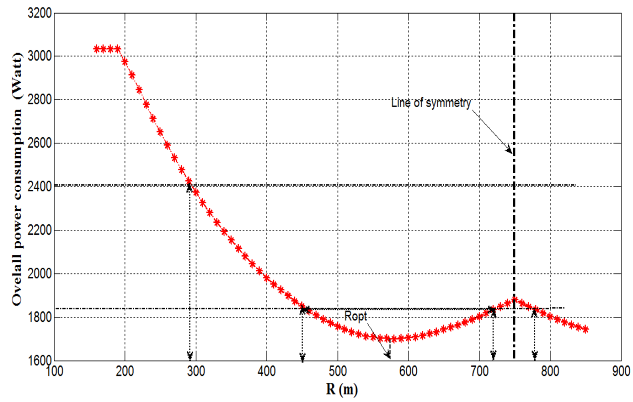

FIGURE 7. Overall power consumption (dBW) as a function of inter-BSs distance R, the cell area of both operators $A_1 = A_2 = 7.85 * 10^5$ and the cell core radius is 325 m, while the UE densities are λ_1 & $\lambda_2 = 0.17 * 10^{-3}/m^2$.

be covered by the BS due to power constraint. The maximum BS power P_{tmax} at Fig. 4 & 5 is taken as 160 watt [12].

B. MODEL OPTMIZATION

In this part, the optimal network parameters to minimize the overall power consumption are studied. The optimal cell core radius and optimal inter-BSs distance is shown in figures 6 & 7 respectively.

The cell core radius affects on the area of cell edge which controls the UEs who properly are roamed to operator 2 as well as the area of cell core which controls the UEs who properly are roamed from operator 2. From Fig. 6, the power consumption decreases with increasing of cell core radius till it reach its minimum value at $R_{c1} = R_{clopt}$. Then it starts to increase with increasing the cell core radius.

The setting parameters are as follows: the cell areas of both operators are $A_1 = A_2 = 7.85 * 10^5$ m^2 and the distance between the BSs is $R = 550$ m, while the UE densities are λ_1 & $\lambda_2 = 0.17 * 10^{-3}/m^2$.

Fig. 7 illustrates the impact of inter-BSs distance on the overall power consumption for both operators. The setting parameters are hold as those of Figure. 6. While the cell core radius is 325m.

It is observed that when the BSs are too close to each others ($R \ll R_1$), the power consumption increases. This as a result of small roaming area, hence small number of UEs may be properly roamed between the two operators (the maximum value at $R = 0$). At this region, the required power to support UEs' QoS exceeds P_{tmax}, so the BS can not admite the required UEs' denisities. When the inter-BSs distance increases, the power consumption decreases.This is as a result of increasing of roaming area between operators and the UEs with larger distance with their home BS are roamed to the nearer BS.

It can be seen from the figure that the BS can admite the required UEs' denisities. The power consumption reaches its minimum value at $R = R_{opt}$, so this distance is the optimal distance for roaming between operators. With increasing the inter-BSs distance, the power consumption tends to increase again due to decreasing the roaming area between operators. This behavior is repeated along the line of symmetry as shown in Fig. 7 since the BS approaches from another BS.

The optimal distance can be obtained using algorithm 1 as well. By tuning the network parameters to the same setting parameters of Fig. 7, then gradually increasing R (starting from $R_lower = 50$m, $R_upper = R_1 + R_1 = 1000$m, step size $\Delta R = 3$) and measuring the variation in the transmitted power at each point. The optimal distance ($R_{opt} = 578$m) is reached at $\Delta P = 0$ when the overall transmitted power reaches its minimum value ($P = 1690$ watt).

Fig. 7 illustrates the cases that the BSs of cooperative operator can be found with respect to home BS as well as the corresponding strategy the operator may adopt. The figure shows the distance over which the operator should take the decision of roaming at two values of σ. At $\sigma = 1.1$, if the associated BS exists at distance from 450m to 725m from home BS, the operator should roam its UEs. While if the associated BS exists at distance smaller than 450m, the roaming cost exceeds the roaming profit and so the operator should not roam its UEs. Finally at distance $R = 0$, a suitable switching off algorithm should be adopted between operators. The same details can be deduced at $\sigma = 1.4$ as shown in the figure.

VII. CONCLUSION

In this paper, a framework for roaming-based multi-operators' collaboration in MNOs is introduced. A closed form expression for overall downlink transmitted power consumption is derived with respect to relative distance between BSs. In addition, we studied dynamic UE's association based on his location and relative distance with serving BS to serve roaming traffic between operators. In order to achieve optimal power saving, we introduced an algorithm to find the optimal separation between BSs of different operators. A numerical analysis is provided for model validation and giving more inspection on the impact of roaming between operators in minimizing overall power consumption.

APPENDIX A

In this part, the path loss factor of UEs of group 2 is derived. Recalling the path loss model in (2), the distance between the UE n and the BS is the main factor in the path loss factors. The path loss factor of UEs of group 2 is derived by excluding the part that is roamed to operator 2 from cell edge UEs. At first we obtain the path loss factor of cell edge UEs per sector

$$\int_0^{2\pi/3}\int_0^{R_1}\frac{r^{\alpha+1}}{r_o^\alpha}drd\theta-\int_0^{2\pi/3}\int_0^{R_{c1}}\frac{r^{\alpha+1}}{r_o^\alpha}drd\theta = \left(\frac{2\pi}{3r_0^\alpha(\alpha+2)}\right)\left(R_1^{\alpha+2}-R_{c1}^{\alpha+2}\right) \quad (27)$$

where r, as mentioned before, is the distance between the UEs and the serving BS. If the cell edge UEs are located at cell core area of operator 2, then those UEs are roamed to operator 2 (N_{r1}). Those UEs are cover by angles ξ & η in Fig. 2 as

$$N_{r1}=\int_0^{\eta}\int_0^{R_1}\frac{r^{\alpha+1}}{r_o^\alpha}(1+cos\eta)\,drd\eta - \int_0^{\xi}\int_0^{R_{c2}}\frac{r^{\alpha}}{r_o^\alpha}\ell(1+cos\xi)\,dld\xi \quad (28)$$

where ℓ is the distance between UEs of operator 1 and their home BS. As those UEs are roamed to the BS of operator 2, so the effective distance which should be considered in path loss factor is the distance with BS which they are roamed to. So the integration should be with respect to r. From Fig. 1, we have $\ell = R - r$ and $d\ell = -dr$. So

$$N_{r1}=\left(\frac{(\eta-sin\eta)R_1^{\alpha+2}}{r_0^\alpha(\alpha+2)}\right)-\left(\frac{\xi-sin\xi}{r_0^\alpha(\alpha+1)(\alpha+2)}\right)\times\left(R^{\alpha+2}-(R-R_{c2})^{\alpha+1}(\alpha R_{c2}+R_{c2}+R)\right). \quad (29)$$

If $R \le R_{c1}+R_{c2}$, then the cell core area of both operators intersects and the UEs who are located at this area are not roamed. Those UEs are covered by angles ω & ψ as illustrated in (30), as shown at the bottom of the this page.

By combining (29) and (30), we get the general form for the part that is roamed to operator 2 from cell edge UEs.

By subtraction this part from cell edge UEs of (28), we get path loss factor of group 2 UEs in (13).

APPENDIX B

In this part, the path loss factor of UEs of group 3 is derived. The UEs of group 3 are located at cell edge area of operator 2 and are roamed to operator 1. Those UEs are covered by angle φ in (31), as shown at the bottom of the this page.

ℓ' in (31) is the distance between UEs of operator 2 and their home BS. The UEs of this group are roamed to operator 1, so the integration should be with respect to r.

Then we have $\ell' = R - r$ and $d\ell' = -dr$.

According to roaming criteria, those UEs are located at cell core area of operator 1, so they are covered by angle θ as well, as shown in (32), as shown at the bottom of the this page.

$$\int_0^{\psi}\int_0^{R_{c1}}\frac{r^{\alpha+1}}{r_o^\alpha}(1+cos\psi)\,drd\psi-\int_0^{\omega}\int_0^{R_{c2}}\frac{r^{\alpha}}{r_o^\alpha}\ell(1+cos\xi)\,d\ell d\omega = \left(\frac{(\psi-sin\psi)R_{c1}^{\alpha+2}}{r_0^\alpha(\alpha+2)}\right)+\left(\frac{\omega-sin\omega}{r_0^\alpha(\alpha+1)(\alpha+2)}\right)\left(R^{\alpha+2}-(R-R_{c2})^{\alpha+1}(\alpha R_{c2}+R_{c2}+R)\right) \quad (30)$$

$$\int_0^{\varphi}\int_0^{R-r_o}\ell'(1-cos\varphi)\,d\ell'd\varphi-\int_0^{\varphi}\int_{r_o}^{R_2}\frac{r^\alpha}{r_o^\alpha}\ell'(1-cos\varphi)\,d\ell'd\varphi = (\varphi-sin\varphi)\left(\frac{1}{2}r_0^2+\frac{1}{r_0^\alpha}\left(\frac{(R-r_0)^{\alpha+1}(R+r_0(\alpha+1))-(R-R_2)^{\alpha+1}(R+R_2(\alpha+1))}{(\alpha+1)(\alpha+2)}\right)\right) \quad (31)$$

$$\int_0^{\theta}\int_0^{r_o}r(1-cos\theta)\,drd\theta+\int_0^{\theta}\int_{r_o}^{R_{c1}}\frac{r^{\alpha+1}}{r_o^\alpha}(1-cos\theta)\,drd\theta=(\theta-sin\theta)\left(\frac{2R_{c1}^{\alpha+2}-\alpha r_o^{\alpha+2}}{2(\alpha+2)r_o^\alpha}\right) \quad (32)$$

$$\int_0^{\psi}\int_0^{r_o}r(1-cos\psi)\,drd\psi-\int_0^{\psi}\int_{r_o}^{R_{c1}}\frac{r^{\alpha+1}}{r_o^\alpha}(1-cos\psi)\,drd\psi + \int_0^{\omega}\int_0^{R-r_o}\ell'(1-cos\omega)\,d\ell'd\omega+\int_0^{\omega}\int_{r_o}^{R_{c2}}\frac{r^\alpha}{r_o^\alpha}\ell'(1-cos\omega)\,d\ell'd\omega = (\psi-sin\psi)\left(\frac{2R_{c1}^{\alpha+2}-\alpha r_o^{\alpha+2}}{2(\alpha+2)r_o^\alpha}\right) - (\omega-sin\omega)\left(\frac{1}{2}r_0^2+\frac{1}{r_0^\alpha}\left(\frac{(R-r_0)^{\alpha+1}(R+r_0(\alpha+1))-(R-R_{c2})^{\alpha+1}(R+R_{c2}(\alpha+1))}{(\alpha+1)(\alpha+2)}\right)\right) \quad (33)$$

If $R \leq R_{c1} + R_{c2}$, then the cell core area of both operators intersects. This intersection is covered by angles ω & ψ as shown in (33), as shown at the bottom of the previous page.

By combining equation (31) and (32), then excluding (33), we obtain theorem 1.

APPENDIX C

In this part, proposition 2 is proved. At specific inter-BSs distance R, the number of UEs to be roamed from operator 2 at any sector (to cell core area of operator 1) is equal to

$$\lambda_2 A_{g3} \tag{34}$$

while the number of UEs to be roamed to operator 2 at the same sector (from cell edge area of operator 1) is equal to

$$\lambda_1 (A_e - A_{g2}) \tag{35}$$

where A_e is the cell edge area of cell sector. With uniform UE distribution for both operators, let $\lambda_1 = \lambda_2 = \lambda$ then the variation in numbers of UEs to be roamed to or from operator 1 with respect to distance R is

$$\frac{\delta\lambda \left(A_{g3} - (A_e - A_{g2})\right)}{\delta R} = \frac{\lambda\delta \left(A_{g3} - (A_e - A_{g2})\right)}{\delta R} \tag{36}$$

Also we have

$$A_{g3} - (A_e - A_{g2}) = \frac{R_{c1}^2}{2}(\theta - sin\theta) + \frac{R_2^2}{2}(\varphi - sin\varphi) - \frac{R_2^2}{2}(\eta - sin\eta) - \frac{R_{c2}^2}{2}(\xi - sin\xi). \tag{37}$$

Proposition 2 is valid with identical power model and UEs' densities for both operators. Hence by applying the path loss model for the transmitted signal from both operators, the cell coverage range for both operators is the same. So $R_1 = R_2$, then $\theta = \xi$. Also we have $R_{c1} = R_{c2}$, then $\eta = \varphi$. So

$$A_{g3} - (A_e - A_{g2}) = 0. \tag{38}$$

So the numbers of UEs to be roamed to operator 1 is equal to the number of UEs to be roamed from operator 1. So the total number of UEs in the cell is constant regardless of the distance between BSs.

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