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Greening the Airwaves with Collaborating Mobile Network Operators

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ABSTRACT: Base station sharing is currently considered one of the most promising solutions for reducing the energy consumption costs of cellular networks. This paper presents a game theoretic framework for the study of such cooperative solutions where different mobile network operators (MNOs) decide to switch OFF subsets of their base stations during off-peak hours and roam their traffic to the remaining stations. The solution is based on a detailed optimization framework that determines exactly which base stations should remain active and how much traffic each one of them should serve, so as to maximize the aggregate energy savings.

Accordingly, using the axiomatic Shapley value rule, it is determined how the benefits from the cooperation, i.e., the cost savings, should be dispersed among the cooperating MNOs. It is proved that this coalitional game with transferrable utilities has a nonempty core, and thus there exists a cooperation solution that incentivizes the participation of all operators. Moreover, using a thorough numerical analysis, it is shown that the benefits achieved with the implementation of the cooperation strategy depend mainly on the power consumption characteristics of the MNOs, which in turn are related to the number, type, and technology of their base stations. Overall, the energy savings are found to be most sensitive to the technology of the used base stations, and more precisely to the no-load base station energy consumption which defines the energy waste in a network.

KEYWORDS: Base station management, coalitional games, energy efficient networking, game theory, mobile network operators, wireless networks.

I. INTRODUCTION

According to the widely accepted recent forecasts by Cisco and Ericsson, mobile data is expected to increase with an annual growth rate of 60% in the next five years, reaching 25 Exabytes per month in 2020 [1], [2]. This explosive traffic growth places unprecedented strain on mobile network operators (MNOs), increases their operating and capital expenditures, and even challenges their economic viability. Today it is commonly agreed that one of the most critical cost factors for cellular networks is the energy consumption of their active network components [3], [4]. Up to 90% of this cost is realized at the Radio Access Network (RAN), and, specifically, it is induced by the power consumption of base stations (BSs). Indeed, a conventional macro BS (MBS) exhibits high power consumption ranging from 800 W to 2 kW (older models reached up to 3.5 kW), while a micro BS (mBS) requires 300 W even when it does not serve any traffic [5]. This creates on average an annual consumption of 15 MWh and 2 MWh, respectively. Therefore, a MNO with 5000 MBSs and 5000 m BSs has operating expenses (electricity) of the order of $8 million per year.

A large body of academic studies and industry activities [6], [7], [8] have recently focused on identifying effective approaches that will allow MNOs to reduce these energy costs. One of the first proposed methods were energy-prudent management techniques which switch off some base stations, putting them into a *sleep mode*, when the traffic in their area is relatively low and thus can be transferred to neighboring base stations (*intra-network sharing*). The key motivation for such sharing methods are that (i) cellular traffic follows mostly a periodic pattern1 while the network capacity is dimensioned based on the peak traffic value, and (ii) in many cases the base stations coverage areas overlap so that it is possible to use only a subset of them in off-peak hours. An even more radical solution is the cooperation among different MNOs so as to share their whole RAN infrastructure in some geographic area (*inter-network sharing* or MNO cooperation).

The main idea in this latter approach is to switch off at once multiple base stations of a MNO in a certain area, and serve its users by roaming their traffic to other MNOs that provide coverage in the same area. This idea is currently

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gaining increasing research interest and has been already adopted by several operators, e.g., see [9], which exploit the fact that often their BSs are very closely located or even co-located (*mast sharing*). Unlike with the intra-network sharing approach, in this case each MNO is not required to have overlapping BSs (over-provisioning) since the BSs of the remaining operators can directly serve the roaming traffic without having to increase their transmission power or adjust their antennas. In general, this approach offers a larger set of solutions with possibly higher benefits [10] especially when the networks are not always congested (varying traffic load), and the MNOs are diverse in terms of the deployment of their base stations.

II. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

1) RAN and Traffic Model:

We consider a geographical area A[$km2$] that is covered by a set J of |J| ≥ 2 MNOs. The operators offer services of similar quality2 (QoS) but may have different network planning strategies. The latter comprises decisions related to the deployment of BSs, such as their number, location, and their characteristics (antenna pattern, RF transmission power, etc.). We assume heterogeneous cellular architectures with different types of BSs, such as macro cell and microcell BSs. Namely, each MNO $i \in$ J has a set Mi = {1, 2, . . . , Mi } of macro cellular BSs (MBSs), and a set Ki ={1, 2, . . . , Ki } of microcellular BSs (mBSs). We denote with Ni = Ki ∪Mi the set of all BSs that are managed by operator $i \in$ J. Different operators have, in general, different BS deployment strategies, hence it can be |Mi | _= |Mj | and |Ki | _= |Kj |, ∀ $i, j \in$ J, i _= j . The general description of the system model and its parameters is depicted in Fig. 2. The planning of the MNOs is based on peak traffic conditions.

We denote with COn the coverage area (set of grid points in the area) of BS $n \in$ Ni of operator $i \in$ J. The BSs may have overlapping areas, but each user is associated to only one base station according to a best-server criterion (e.g., highest SNR rule). We assume that each MNO i has a subset of BSs $CBi \subseteq Ni$ that guarantee the coverage of area A. The BSs belonging to CBi are called *critical stations* and are usually MBSs, responsible to provide coverage. The remaining stations $FBi \subset Ni$, with $FBi \cup CBi = Ni$, are called *flexible stations.*

These can be MBSs or mBSs and are employed to satisfy the necessary capacity requirements. Flexible stations can be set in sleep mode when BS management schemes are implemented by a single MNO during low traffic periods. Clearly, whether a BS is flexible or critical depends on the network deployment strategy of the MNO (signal coverage) and the traffic demand (capacity coverage). In the analysis here we consider the type of each BS as given. Moreover, for the purpose of inter-network sharing, all BSs can be considered flexible since the access network of a MNO in a specific area can be entirely switched off during cooperation. In other words, inter-network sharing does not require that each MNO has overlapping BSs. Coverage and capacity in the service area is supported by the access network of other MNOs that remain active.

Every MNO $i \in$ J at time t = 1, 2, . . . , T which is slotted, has a set Ui (t) of Ui (t) = |Ui (t)| active users (or subscribers)on average, that globally generate an aggregate traffic fi (t) (in bps), with $t \in [0, T]$ spanning over T = 24 hours. We define the vector:

$$\boldsymbol{fi} = (fi\,(t) : t = 1, \ldots , T) ,\ i \in J \qquad (1)$$

This traffic follows a periodic pattern: it is high in certain peak hours and much lower during night or other time-windows within the day [5]. Note that we adopt a macroscopic point of view and study average traffic $\beta > 0$ per end-user, i.e. $fi\ (t) = \beta Ui\ (t),\ i \in$ J, t = 1, . . . , T , while we assume that the expected number of users for each MNO is known in advance based on collected statistics. In other words, due to the timescale of the problem we rely on expected averages3. Finally, we denote with $f\ ni\ (t)$ the traffic of operator i that is served by its base station $n \in$ Ni . This is the traffic generated at time t by users Uni (t) that are in range with BS n (belong in COn) according to a certain rule $Li\ (\cdot)$ such as the max-SNR criterion:

$$L_i\left(f_i(t)\right) : \mathbb{R} \rightarrow \mathbb{R}^{N_i}, \text{ with } \sum_{n=1}^{N_i} f_i^n(t) = f_i(t) \qquad (2)$$

We denote by *Ji (fi)* the servicing cost incurred by operator $i \in$ J when it serves traffic during the time period T. In general, the servicing cost may vary with time (e.g., due to variation of the energy prices), and thus it can be written:

$$J_i(f_i) = \sum_{t=1}^{T} J_i^t(f_i(t)) \tag{3}$$

here *J ti (·)* is the servicing cost per time slot. Here, we focus on energy costs. Namely, the operation of a BS is associated to electricity costs that are related to power consumption. Therefore, the monetary servicing cost, during each slot, can be written:

$$J_i^t(f_i(t)) = q^t \cdot \sum_{n=1}^{N_i} C_n(U_i^n(t)) \tag{4}$$

where *qt* is the cost per unit of consumed energy that in general can change with *t*, and *Cn(·)* is the function that yields the energy consumption (in KWatts) for the users that BS $n \in$ N*i* serves. Please note that because the roaming decisions are taken in practice per users, we modeled the energy cost with respect to their numbers. Specifically, as we will explain in detail below, this quantity depends on the type and the load of the BS and can be written,
$\forall n \in$ N, t = 1, 2, . . . , T :

$$C_n(U_i^n(t)) = \begin{cases} a_n \cdot \cdot U_i^n(t) + b_n, \; BS\ is\ on \\ 0, \; BS\ is\ off \end{cases} \tag{5}$$

Equation (5) is an empirical one and is derived according to the methodology described in the sequel. We assume that if the BS is set in sleep mode (is off) then the power consumption is zero. In practice, sleep modes refer to negligible consumption compared to active mode. Parameter *an* is a multiplication factor that depends on the type of BS. It is expressed in Watts per user and it is computed in the sequel to be in the order of *an* = 3 if $n \in$ M*i* and *an* = 0.7 if $n \in$ K*i* . Meanwhile, parameter *bn* is expressed in Watts and describes the no-load (i.e., redundant) power consumption that characterizes the operation of cooling units and power units in the BS. We assume *bn* = 450 if $n \in$ M*i* , and *bn* = 32 if $n \in$ K*i*

2) Power Consumption Model:

The consumption characteristic of the BSs may differ according to the used technology. For example, The Code of Conduct on Energy Consumption of Broadband Equipment of the European Commission JRC [18] mandates that 3G macro BSs (3 sectors, 2.1 GHz, 2 carriers per sector, with remote radio unit) released in 2016 should consume no more than 760 W at full load, and no more than 540 W at low load. In the case of LTE macro BSs (3 sectors, 2.6 GHz, 20 MHz, 2 × 2 MIMO) released in 2016, power consumption should be lower than 840 W at full load, and lower than 600 W at low load. Estimates of LTE macro BS power consumption in 2020 have been computed [19] in the framework of Green Touch [8], obtaining values 700 W - 750 W at full load (2 × 2, 4 × 4MIMO), and 120W- 140Wat low load. Interestingly, in the latter study it was estimated that the times necessary to enter and exit sleep modes in which the power consumption is below 10 W are extremely short, i.e., of the order of 10ms.

In more details, the power consumption is a function of the load of the BS. In the literature it is usually referred as a linear function of the transmitted RF power of the antenna, In general, the RF out power is computed according to the radio technology used. In UMTS networks, perfect Signal to Interference Noise Ratio (SINR) based power control is used to allocate the resources (power in that case) to each user and satisfy the demand [3,5]. In LTE networks, the power allocation is performed for each resource block and the aggregated power represents the power assigned to the user. The number of blocks is related to the requested user service. For the purpose of our investigation, we have expressed the power consumption of the BS as a function of the number of served users. In that way, the equation used to express power can significantly simplify simulation results for the computation of the network power consumption. Besides, the roaming decisions are taken in practice on a per-user basis. To achieve this, we have performed Simulations that capture a great diversity of randomly generated scenarios.

Let us focus on one operator $i \in J$ and consider a user $u \in U_i(t)$ served in slot t. The minimum transmit power per user according to SINR criteria is given by

$$P_u = P_0 - g_u - g_n + l_{n,u} + \psi_u + 10 \cdot \log10(M_u) \quad (6)$$

In the above equation P_0 is the receiver sensitivity for the specific service (here it is assumed $P_0 = -121dBm$), parameter $g_u = 2.14dBi$ represents the antenna gain of user u and $g_n = 2.14dBi$ represents the antenna gain of BS n, $l_{n,u}$ is the path loss between the BS n and user u, ψ_u is the shadow component derived by a log normal distribution with standard deviation equal to 8 dB and M_u is the number of resource blocks assigned to user u. The total RF out power of BS $n \in N_i$ at time t is given by

$$P_n(t) = \sum_{u=1}^{U_i^n(t)} P_u \quad (7)$$

Channel Model:

To compute the channel characteristics between a BS and a user we use an empirical formulation for urban environments. Based on [20] we use the average value of the Line of Sight (LOS) and Non Line of Sight (NLOS) models between user and MBS. We implement this model for all users connected to MBS or mBS to simplify computations. The path loss is given by

$$l_{n,u} = 16.8 + 33.2 \cdot \log10(d_{n,u}) \quad (8)$$

where $d_{n,u}$ is the distance (meters) between user u and BS n.

Other issues:

For the simulations, we assumed that all users require the same QoS and thus all active users in the network were assigned the same number of subcarriers. In order to define a relationship between the RF out power of the BS and the number of served users, we developed a stochastic model that randomly generates users around a BS. We generated 100 random scenarios with users spread uniformly on a disc of radius *3 km* around the BS. The independent scenarios were executed for 1 to 200 users. The relationship between the number of users served and the RF out power (in Watts) is shown in Fig. 3. A curve fitting approximation was used to derive the linear relationship. The vertical axis represents the RF out power P^{RF}_n of the BS $n \in N$, and the horizontal axis the number of users that are served.

As a next step, we incorporate this linear equation into the general BS power model that is given in [3,5], and correlates the power consumption of the BS with its RF out power, i.e.:

$$C_n^{RF} = \gamma_n P_n^{RF} + b_n \quad (9)$$

where $\gamma_n = 22.6$ if $n \in M_i$ and $P_{max} = 5Watts$, and $\gamma_n = 5.5$ if $n \in K_i$. Parameter b_n is the same as expressed in (5). Eq. (5) now describes the BS power needs as a function of the active users in the cell, rather than of the RF out power.

III. ALGORITHM

The main idea of the algorithm is to find the MNO with the lowest joint opening and servicing cost per unit of traffic, and assign to it as much traffic as possible6. When this MNO will be congested, the algorithm iteratively identifies the operator with the next smallest joint cost term, and assigns the remaining traffic until it reaches the capacity, or all the traffic is served. The detailed procedure is given in Algorithm 1 which follows the analysis. First, let us introduce the variable

$$Y_i(t) = \sum_{j\in\mathcal{J}} y_{ji}(t), \tag{10}$$

which indicates how much traffic operator *i* admits if it is open. One can observe that for any feasible solution ***(x, y)*** we can set ˆ *xi (t)* = *Yi (t)/Wi* , and obtain another feasible solution *(ˆ**x**, **y**)*. This means that we can omit the *xi (t)* variables and rewrite the objective of the above optimization
problem as follows:

$$\min_{\{Y_i(t),\, i\in\mathcal{J},\, t=1,\ldots,T\}} \sum_{i\in\mathcal{S}} \sum_{t=1}^{T} \left(\frac{B_i}{W_i} + A_i\right) Y_i(t) \tag{11}$$

Algorithm 1. Greedy Algorithm for Solving the Min-Cost MNO Cooperation Problem

Input: B_i, A_i, W_i, f_i, $i \in \mathcal{J}$;
Initialization: $x_i(t) = 0$, $y_{ij}(t) = 0$, $\forall i, j \in \mathcal{J}$, $t = 1, 2, \ldots, T$;
$t \leftarrow 0$; % Initialize the time
while $t < T$ **do**
  $t \leftarrow t + 1$;
  $\mathcal{B} \leftarrow \mathcal{J}$; $\mathcal{D} \leftarrow \emptyset$;
  while $\sum_{k\in\mathcal{D}} Y_k(t) < \sum_{i\in\mathcal{B}} f_i(t)$ **do**
    $k = argmin_{i\in\mathcal{B}}\{A_i + (B_i/W_i)\}$;
    $x_k^*(t) \leftarrow 1$; $Y_k^*(t) = \min\{W_k, \sum_{i\in\mathcal{B}} f_i(t)\}$;
    $\mathcal{D} \leftarrow \mathcal{D} \cup \{k\}$; $\mathcal{B} \leftarrow \mathcal{B} \setminus \{k\}$;
  end
  Find any roaming policy y^* that satisfies the following set of conditions $\forall i \in \mathcal{J}$:

$$\sum_{j\in\mathcal{J}} y_{jk}^*(t) = Y_k^*(t),\ \forall k \in \mathcal{D}, \text{ and } \sum_{k\in\mathcal{D}} y_{jk}^*(t) = f_i(t) \tag{22}$$

end
Output: x^*, y^*;

IV. CONCLUSION

The increasing volume of mobile data traffic calls for innovative solutions such as the inter-network sharing among different mobile network operators. Although such approaches have a huge potential in terms of cost savings, and despite the fact that related efforts already appeared in the market [9], they haven't received adequate focus from the research community. In this work we proved that, under some mild conditions, RAN sharing is an incentive compatible policy that allows all the co-existing operators to work together and reduce their servicing costs.

Moreover, we provided a detailed optimization framework for devising the minimum servicing cost policy for different network deployment and traffic scenarios. This policy dictates which operators should switch off their networks and how their traffic will be served by the remaining ones. We employed a coalitional game theoretic formulation and designed the roaming fees such that the cost benefits are dispersed among the participants in a fair fashion according to the Shapley value rule. The numerical analysis revealed that the profits generated by the cooperation strategy are very sensitive to the network technology as they heavily depend on the no-load power consumption of the base stations. Overall, the energy savings were found to be in the order of 40–50%.

In terms of actual implementation, cooperation can be supported by a ”horizontal” service provider that will coordinate the access network infrastructure of the different MNOs and will apply the proposed roaming and charging rules.

Moreover, our analysis can be applied in settings where the operators offer different QoS to their users. This diversity can be captured through the energy cost functions of the base stations, which yield higher operating expenses per user as the offered QoS increases. Therefore, our analysis is generic and can address a variety of different scenarios. Among them, of particular interest are settings where the MNOs rely on renewable energy resources with time-varying and random production [40], [41], and hence the inter-network sharing is even more crucial.

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