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On Fairness in Network Sharing

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***Abstract*—Network Sharing (NS) has gained increasing interest for Mobile Operators (MOs) because of the high investment costs of 5G combined with a period of low return of investment. The benefits that NS can offer include reduced capital and operational expenditures, because of fewer equipment, and lower energy consumption, possibly combined with higher network resiliency. While these aspects have been investigated in the literature, in those works more attention was paid to the overall benefits, disregarding asymmetries between the involved MOs. In this paper we address the issue of fairness in sharing network infrastructure among MOs and we introduce a Fair Cooperative Network Sharing (FCNS) framework that dynamically offloads traffic among co-located BSs owned by different MOs with two primary objectives: distributing active operational time more equitably between BSs in a pair, and significantly decreasing the failure rate of BS pairs. Simulation results based on empirical mobile traffic data demonstrate that the proposed FCNS framework effectively balances the BS active time across operators. In addition, FCNS achieves energy savings of up to 38% for each MO within a BS pair and reduces the failure rate by approximately 20%. These findings highlight the potential of cooperative network sharing as a feasible and sustainable solution for resilient 5G deployments.**

I. Background

5G networks are expected to deliver higher Quality of Service (QoS), support to continuous mobility, and improved energy efficiency relative to earlier generations [1], [2]. Despite early commercialization [2], 5G faces challenges from demanding service categories and edge-supported smart mobility [3], that require enormous bandwidth and strict delay constraints. Extensive Radio Access Network (RAN) densification is typically used to cope with rapidly increasing traffic, but it also leads to rising capital expenditure (CAPEX) as well as higher energy consumption, and may result in underutilized infrastructure during off-peak periods. Our previous paper [4] introduced data-driven network infrastructure sharing (NS) strategies that offload traffic between co-located BSs owned by different MOs. Based on real-time traffic demand variations, these strategies allow one BS to remain active at all times, while the other can modulate its power state by periodically entering sleep mode to save energy, as long as the other BS can handle its traffic demand. Although simulations indicate energy savings of over 40% in certain scenarios, the benefits stem from switching off the lower capacity BS, forcing the always-on BS to bear full energy consumption and creating unfairness among MOs. While the issue of fairness in NS has largely been overlooked in existing literature, reducing asymmetries between the involved MOs is key to promoting the practical adoption of NS, as balanced contributions and equitably shared benefits between MOs increase operator willingness to adopt such solutions. Moreover, repeated state transitions, combined with prolonged sleep mode periods, may variably subject sensitive components to thermal cycling and electrical stress, potentially leading to premature wear and reduced lifespan of one BS compared to the other. Degradation models based on the Arrhenius law [5] and related frameworks [6] show that excessive switching can increase failure rates by 30–50% compared to steady-state operation, leading to significant financial implications; industry analyses report annual maintenance costs of $10,000 to $20,000 per macro BS [7]. Conversely, sleep mode periods preserve BSs from degradation, hence reducing the failure rate. Notably, no previous research has specifically addressed infrastructure sharing in relation to BS degradation —a key focus of this article. We present a Fair Cooperative Network Sharing (FCNS) framework, based on [4], that integrates energy efficiency, fairness among MOs, and hardware lifespan improvement into NS strategies. We design and evaluate the performance of various NS strategies with the following objectives:

- Enhance RAN energy efficiency by reducing overall consumption, thereby lowering the associated OPEX;
- Balancing the MO contribution to NS, to ensure a fair share of NS benefits among MOs;
- Extend BS lifespan by managing sleep mode transitions, thereby improving RAN resilience.

Focusing on a densely populated urban environment and leveraging realistic traffic data from the NetMob23 Dataset [8], our study evaluates the performance of these NS strategies in terms of fairly balancing energy savings among MOs, lowering BS switching frequency, and improving BS failure rate.

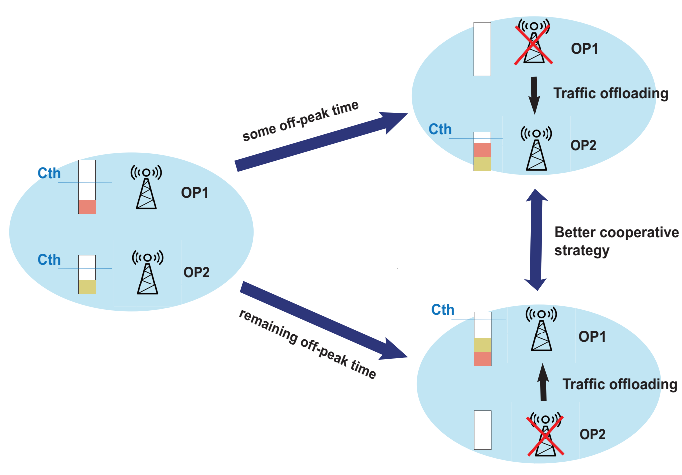

Fig. 1: Fair Cooperative Network Sharing

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II. Fair Cooperative Network sharing

We assume that a subset of network operators agree to share the capacity of their BSs to support offloaded traffic from neighboring cells. As shown in Fig. 1. BSs are grouped into pairs, each comprising BSs at the same installation site and operated by at least two different MOs. The traffic load at each BS, estimated from historical data or predicted using machine learning techniques, leads to a dynamic offloading algorithm. Within each pair, if a BS with available capacity can accept traffic from the least loaded active BS, this traffic is offloaded and the idle BS is switched off.

Building on this NS framework, this paper further explores network sharing between pairs of BSs with distinct capacity configurations, introducing Fair Cooperative Network Sharing (FCNS). Our objective is to design a cooperative strategy such that when both BSs in a pair can accept offloaded traffic from the other BS, a decision is made on which BS should handle traffic, while reducing sleep mode transitions. We aim to ensure fairness between MOs in terms of active time – which, in turn, may positively affect OPEX and CAPEX fairness– enhancing energy efficiency and promoting equitable utilization. By reducing activation cycles and ensuring that BSs function in the appropriate sleep mode, thermal stress on metal components is diminished, extending equipment lifespan, reducing hardware replacements and maintenance, thus lowering CAPEX, and enhancing network stability. Our work focuses on the design and implementation of FCNS management strategies to achieve energy savings while ensuring fairness among MOs, thereby facilitating sustainable BS resource management, and enhancing network resilience. We evaluate the performance of the proposed NS algorithms through simulations, quantifying energy savings and the impact on BS failure rate relative to a baseline scenario in which network resources are not shared among MOs.

III. Methodology

We consider a portion of the RAN in the city center of Paris, France, in which two MOs provide mobile access within the same coverage area, where a number of LTE BSs are installed. Real data are used to define the geographical locations of sites hosting BSs [9]. As depicted in depicted in Fig. 1, we focus on pairs of co-located BSs, owned by two different MOs, Op_1 and Op_1, having capacity C_1 and C_2, respectively, resulting in a capacity ratio, C_r, defined as $C_r = C_1/C_2$. We use real-world traffic traces with a 15-minute time slot granularity [8], processed according to the methodology outlined in [4].

a) NS traffic offloading strategy

To enable the sharing of network infrastructure between Op_1 and Op_2, a traffic offloading strategy is applied to each pair of co-located BSs owned by different MOs. BSs located within 50 meters of each other are considered suitable candidates for NS. A preliminary agreement between MOs is assumed, which allows traffic offloading in either direction (i.e., from Op_2 to Op_1, or vice versa) and deactivating the unused BS to save energy. At every time slot, the system checks whether the current aggregate traffic volume of the two BSs remains below a predefined saturation threshold, denoted C_{th}, which is set to 80% of the capacity of each BS in a

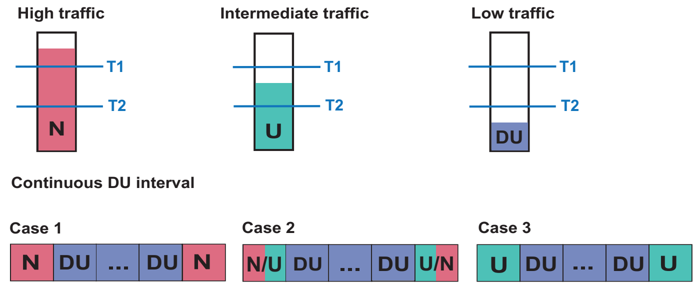

Fig. 2: NS states and three types of DU interval

pair. The condition is verified for both BSs individually, to determine if either or both are eligible to receive offloaded traffic from the other. Thus, the NS saturation threshold for BS_1, which represents the maximum aggregated traffic that BS_1 can handle if BS_2 is deactivated under NS, is defined as $T_1 = C_1 \cdot C_{th}$. Similarly, for the BS owned by Op_2, the traffic threshold is given by $T_2 = C_2 \cdot C_{th}$.

b) Fairness model

The aggregated traffic volume of BS_1 and BS_2, denoted as S_{tr}, determines the *NS state*, which characterizes the BS pair at a given time slot. Let us assume $C_1 \geq C_2$. As depicted in Fig. 2, the following NS states are defined:

(1) **No Network Sharing (No-NS –** N **for short):** If $S_{tr} > T_1$ (*high traffic* condition), the aggregate traffic demand is so high that both BSs must remain active to avoid overload.

(2) **Unilateral Network Sharing (UNS –** U **for short):** If $T_2 < S_{tr} \leq T_1$ (*intermediate traffic* condition), the traffic load allows NS, but only the lower-capacity BS_2 can be deactivated without exceeding the saturation threshold of the other BS that remains active, i.e., BS_1.

(3) **Dual-Usable Network Sharing (DUNS –** DU **for short):** If $S_{tr} \leq T_2$ (*low traffic* condition), both BSs have sufficient capacity to individually handle the aggregate traffic of the BS pair. Hence, during DU time slots, either BS_1 or BS_2 can be deactivated as needed without any risk of traffic loss.

To ensure fairness among MOs, we aim at balancing the time spent in sleep mode by each BS under NS. We introduce the *Network Sharing Duty Cycle - D*, which is the average daily fraction of time slots during which a BS in a pair is deactivated under NS [10]. Furthermore, let us denote as f_N, f_U, and f_{DU} the fractions of time slots in which the BS pair is in state N, U, or DU, respectively, such that $f_N + f_U + f_{DU} = 1$. The values of these fractions depend on the temporal variations in the aggregate traffic profile of the two BSs in a pair. The duty cycles of the two BSs, in turn, depend on both the frequency of time slots of type U and DU, as well as the specific strategy implemented to determine which BS to deactivate under NS in each time slot. They can be derived as follows:

$$\begin{aligned} D_1 &= \alpha f_U + \beta f_{DU} \\ D_2 &= (1-\beta) f_{DU} \end{aligned} \tag{1}$$

where α is the fraction of U time slots in which BS_2 is deactivated, whereas β is the fraction of DU time slots in which BS_2, rather than BS_1, is deactivated under NS. In our scenario, given the traffic profiles of the considered BS pairs and the predefined setting of the NS saturation threshold, all analyzed BS pairs are characterized by $f_{DU} \geq f_U$, thus falling into the case where $\alpha = 1$. Each BS i in a pair is thus active for a time $T_{a_i} = (1 - D_i) \cdot T$, where T represents the number of time steps in the entire operation period. To enforce fairness, ensuring that both BSs are active for an equal share of time, we impose $T_{a_1} = T_{a_2}$, which entails $D_1 = D_2$:

$$\alpha f_U + \beta f_{DU} = (1-\beta) f_{DU} \tag{2}$$

where:

$$\begin{cases} \alpha = 1, \quad \beta = \frac{f_{DU}-f_U}{2f_{DU}} & \text{if } f_{DU} \geq f_U \\ \alpha = \frac{f_{DU}}{f_U}, \ \beta = 0 & \text{if } f_{DU} < f_U \end{cases}$$

A fair share of the active time between the two MOs is hence ensured under the following condition:

$$T_{a_1} = T_{a_2} = \left(1 - \frac{f_U + f_{DU}}{2}\right) \cdot T \tag{3}$$

c) BS failure rate and Accelerator Factor

The failure rate of a BS follows the Arrhenius law and depends on its operating temperature [5]. When a BS is in sleep mode, its temperature drops, which improves its lifetime and lowers its failure rate [11], [5]. However, switching power states increases the failure rate because temperature changes can harm metal parts. The BS failure rate has two components, depending on the failure rate in active and sleep modes (weighted by the time spent in each state), and on the effect of power state transitions. According to [11], [12], any hardware event that interrupts BS operation is considered a failure. Therefore, the failure rate of a BS i is given by:

$$\gamma_i = (1-\tau_{\text{sleep}_i})\gamma_{\text{on}_i} + \tau_{\text{sleep}_i}\gamma_{\text{sleep}_i} + \frac{f_{\text{tr}_i}}{N},$$

where $\tau_{\text{sleep}_i} = 1 - T_{a_i}$ is the fraction of time the device is in sleep mode. γ_{on_i} and γ_{sleep_i} (failures/hour) are the failure rates in active and sleep modes respectively (both computed using the Arrhenius law [5]), f_{tr_i} is the BS switching frequency (cycles/hour). One cycle is counted when the BS switches from active to inactive and back to active state. N (cycles/failure) is the number of cycles the device can undergo before a failure. To assess how switching affects the device's lifetime, we use the *Accelerator Factor (AF)*, defined as the ratio of the BS failure rate observed under NS to the failure rate when the BS is always on. An AF greater than 1 implies a higher failure rate, while an AF less than 1 indicates an improvement. The overall AF is influenced by the time spent in sleep mode (which reduces the failure rate, lowering AF) and the frequency of state transitions (which increases the failure rate, raising AF). The AF for BS i over a period T is given by:

$$AF_{i,T} = \frac{\gamma_i}{\gamma_i^{\text{on}}} = 1 - (1 - AF_{\text{sleep}})\tau_{\text{sleep}} + \chi f_{\text{tr}},$$

where AF_{sleep} is the AF under the assumption that the BS constantly remains in sleep mode, resulting in a value always below 1 [5], and χ (in h/cycle) is defined as follows:

$$\chi = (\gamma_b^{\text{on}} N)^{-1},$$

which weights the switching frequency. Assuming LTE technology, we set $AF_{\text{sleep}} = 0.5$ and $\chi = 0.2$.

IV. Network Sharing resource management

We now present two FCNS methods under perfect NS state knowledge of the NS state at each time slot: a computationally simple, fairness-driven approach, and a more sophisticated strategy to jointly fairness and BS switching frequency.

a) Halfday Block Alternation (HBA)

A very simple approach to fairness improvement consists in segmenting the daily network management into two 12-hour periods. In any time slot of type U, NS is enabled by deactivating BS_2. In contrast, in DU time slots, BS_1 and BS_2 alternate their roles over successive periods Specifically, in a given 12-hour period j, during DU slots NS is applied by putting BS_1 into sleep mode, while in the following 12-hour period $j+1$, BS_2 is deactivated during DU slots. By selecting which BS remains active between BS_1 and BS_2 during DU time slots fairness is improved. Conversely, during U and N time slots, the offloading decisions are constrained by the available BS capacity. We also introduce an offset ω to shift the transition time between the 12-hour blocks$j$ and $j+1$ by ω time steps. We hence evaluate the NS performance under varying values of ω to determine whether a balance point of active time exists between the two BSs such that $T_{a_1} = T_{a_2}$, and to analyze how the frequency of BS power state transitions fluctuates in relation to the block transition time.

b) Heuristic Optimum (HO)

We now present a heuristic NS strategy aiming at ensuring the fairness condition between the two BSs in a pair, while minimizing the overall frequency of switch operations of the two BSs under NS, that we denote $f_P = f_{tr_1} + f_{tr_2}$. We focus on efficiently managing periods of consecutive time slots in the DU state, where NS enables the deactivation of either BS. The aim is to make appropriate offloading decisions that balance the active times of BS_1 and BS_2, i.e., T_{a_1} and T_{a_2}. Let us denote by I_D an interval consisting of consecutive DU time slots, with duration $L_D > 0$, and analyze the boundaries of this interval. As shown in Fig. 2, each interval I_D is categorized into one of three cases based on the NS states of the immediately preceding and subsequent time slots. These categories impacts the NS decisions and the resulting number of switching operations within I_D interval:

Case 1 – DU interval with boundary Type $(\mathbf{N}, \mathbf{N})$: When both the time slots immediately preceding and following an interval I_D are in the N state, it is required that both BS_1 and BS_2 remain active at these boundary points. In this case, there is no distinction between utilizing BS_1 or BS_2 for NS within the interval I_D, as either choice results in two switching transitions —one at the start and one at the end of the interval— without any additional BS transitions. This condition is optimal for balancing the active time of the two BSs pairs, as either BS can be freely selected for deactivation during I_D with a minimal cost of only two switching operations.

Case 2 – DU interval with boundary Type $(\mathbf{N}, \mathbf{U})$ or $(\mathbf{U}, \mathbf{N})$: When one boundary time slot is in state N and the other in state U, the U state forces the deactivation of BS_2 under NS. In such cases, the algorithm prioritizes applying NS by keeping BS_1 active during I_D to minimize transitions. If deactivating BS_1 during all available I_D intervals of type (N,N) does not suffice to meet the fairness requirement for equal active time between the two BSs, a subset of DU intervals of type $(N,U)/(U,N)$ can be selected to activate BS_2, while putting BS_1 in sleep mode during D time slots. This incurs two additional transitions: one to put the active BS into sleep mode and another to reactivate the other BS, which was in sleep mode, either at the beginning or at the end of I_D, depending

Algorithm 1 Heuristic Optimum with Combined Logic

Require:
- System operation time: T
- NS state of each time slot: N, U, DU
- Frequency of each NS state: f_N, f_U, f_{DU}
- Duration of I_D intervals: L_D
- Fairness gain per transition for each I_D interval with Boundary Type (N,U), (U,N): Ex_{tr}
- Fairness target: $D_1 = D_2 = \frac{f_U + f_{DU}}{2}$

Ensure: For each DU interval, the appropriate BS is selected for deactivation so as to minimize the overall BS transitions in a pair, f_P, while satisfying the fairness target for the BS active time.

Initialize: $D_1 \leftarrow f_U$ (BS_2 is deactivated during all time slots of type U)
if $D_1 < \frac{f_U+f_{DU}}{2}$ **then**
  Sort intervals $I_D \in I_1$ –i.e., with boundary type (N,N)– in descending order by duration, L_D
  for each $I_D \in I_1$ **do**
    if $D_1 \geq \frac{f_U+f_{DU}}{2}$ **then**
      Break (fairness target reached)
    else
      Enforce BS_2 deactivation during the current I_D
      Update: $D_1 \leftarrow D_1 + \frac{L_D}{T}$
    end if
  end for
  if $D_1 < \frac{f_U+f_{DU}}{2}$ **then**
    Sort intervals $I_D \in I_2 \cup I_3$ in descending order by k
    for each interval in sorted list **do**
      if $D_1 \geq \frac{f_U+f_{DU}}{2}$ **then**
        Break (fairness target reached)
      else
        Enforce BS_2 deactivation during the current I_D
        Update: $D_1 \leftarrow D_1 + \frac{L_D}{T}$
      end if
    end for
  end if
end if
Result: BS_1 and BS_2 are balanced in active time over the long term and the cost for switching operations, C_{ex}, is minimized. =0

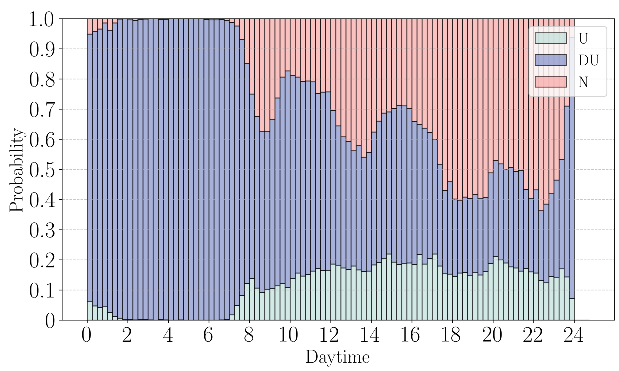

Fig. 3: Different NS state distribution during the day for all pairs of BSs in the selected Paris region.

on the location of the boundary time slot of type U.

Case 3 – DU interval with boundary Type $(\mathbf{U},\mathbf{U})$: When both boundary time slots are in state U, BS_2 is deactivated for NS in these time slots. In this case, keeping BS_2 in sleep mode over interval I_D avoids additional transitions. If needed for fairness purposes, BS_2 can be activated while putting BS_1 into sleep mode during I_D, though this incurs 4 additional transitions at the beginning and end of I_D.

Finally, we introduce the parameter k for I_D intervals with boundary types $(N,U)/(U,N)$ and (U,U), to quantify the amount of active time T_{a_2} under NS potentially gained by BS_2 due to the deactivation of BS_1 during I_D. Let Ex_{tr_j} denote the number of additional transitions required to apply NS by deactivating BS_1 during the I_D interval j when its boundary type is either $(N,U)/(U,N)$ or (U,U). The value of k_j is thus derived as L_{D_j}/Ex_{tr_j}, with L_{D_j} representing the duration of I_D. In our heuristic approach, I_D intervals with higher k values are prioritized for applying NS based on BS_1 deactivation, with the goal of equalizing the duty cycles –and consequently the active times– of the two BSs (as in Equation 3), while simultaneously minimizing the number of additional BS switching operations. We define the cost for extra switching operations, denoted as C_{ex}, as follows:

$$C_{ex} = \sum_{j \in I_2 \cup I_3} Ex_{tr_j} \cdot x_j \tag{4}$$

where I_2 is the set of I_D intervals with boundary type (N,U) or (U,N), I_3 is the set of I_D intervals with boundary type (U,U), x_j is a binary variable which is set to 1 if NS is applied by deactivating BS_1 during the I_D interval j, and 0 if NS is instead applied by deactivating BS_2. Algorithm 1 summarizes this heuristic approach. The proposed algorithm first processes the I_D intervals with boundaries (N,N), where BS_1 can be deactivated without any impact on the cost for additional switching operations, C_{ex}. Subsequently, if needed to satisfy the fairness condition, additional I_D intervals with boundary type (N,U), (U,N), or (U,U) are selected for applying NS by deactivating BS_1. The selection is guided by the sorted k values, prioritizing intervals with the highest k to minimize the cost C_{ex}, and continues until the fairness condition is met, i.e., $D_2 = \frac{f_{DU}+f_U}{2}$, as derived from Equation 3.

V. Performance analysis

A. Fair Network Sharing potential

We conduct our performance analysis considering all the BS pairs eligible for NS in the considered Paris area, assuming time slots of 15 minutes and an operation time T of one month. Before investigating the performance of the proposed NS strategies, which aim to achieve fairness among MOs, we analyze how the different types of time slots, N, U, and DU, are distributed during the day. Fig. 3 reports the average probability distribution per time slot of states N, U, and DU. N state is observed during peak periods –morning work hours, lunch time, dinner time, and evening entertainment– accounting for roughly 40% to 60% of the overall time. U time slots occur uniformly from 8 a.m. to 11 p.m. and cover about 10% to 20% of the time. However, since $f_U < f_D$, keeping BS_1 active and BS_2 idle exclusively during U time slots may lead to an imbalance between T_{a_1} and T_{a_2}, thereby penalizing Op_1. In this regard, DU time slots offer the flexibility to choose which BS should remain active under NS, providing an opportunity to balance utilization between the two BSs under NS. Notably, during the night and early morning hours (2 a.m. to 7 a.m.), the DU potential approaches 100%, suggesting that a portion of these time slots can be effectively exploited to apply NS by deactivating BS_1 while keeping the lower-capacity BS_2 active. This approach helps compensate the fairness imbalance constrained by the U states.

B. Halfday Block Alternation Analysis

Fig. 4 reports for three BS pairs (represented by different colors) characterized by different capacity ratio, C_r, the active time, T_{a_1} and T_{a_2} (upper plot), and the aggregated switching frequency, f_P (lower plot), versus the time in which the transition between the 12-hour block periods j and $j+1$

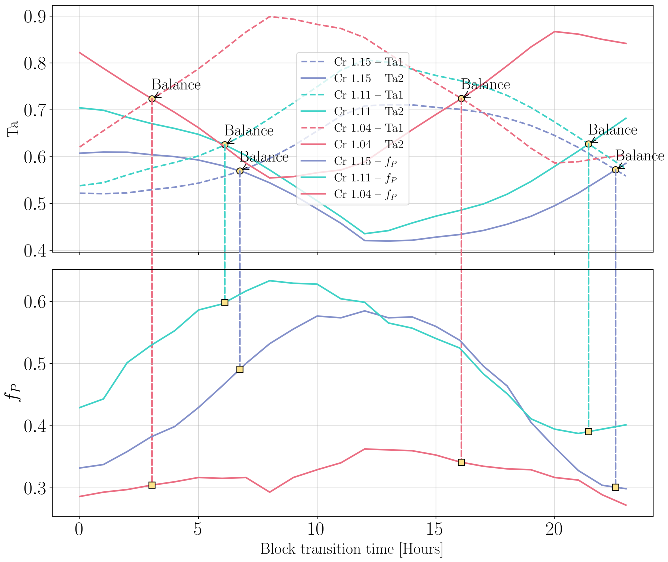

Fig. 4: Halfday Block Alternation performance

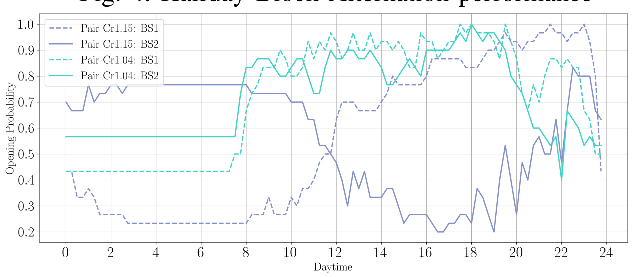

Fig. 5: Probability of keeping BS_1 or BS_2 active under HO for two BS pairs with different C_r values.

occurs, depending on the varying offset ω, under HBA. We remark that during DU time slots, BS_1 is deactivated in block period j, while BS_2 is put into sleep mode in the subsequent block period $j+1$. We observe that each BS pair exhibits two balance points (shown in yellow) for the active time (T_{a_1} and T_{a_2}), corresponding to the configurations of ω that allow to satisfy the fairness condition. With a higher capacity ratio increases (C_r=1.15), the balance points become more distant in time, with one crossing occurring earlier in the morning (before 7:00) and the other closer to midnight. These two crossings serve as critical balance points, indicating under which ω configurations the NS strategy allocates the active time fairly between both base stations, such that $T_{a_1} = T_{a_2}$. A greater capacity gap between the two BSs increases not only the separation between these crossings, but also the amplitude of f_{P}, as forced transitions occur more frequently. Notably, under higher C_r, although both balanced block transition points meet the fairness requirement, the second crossing point shows a f_{P} that is approximately 20% lower than the first crossing. This means that deactivating BS_1, rather than BS_2, during DU time slots in the night period is more effective to reduce the AF, thereby enhancing the resilience of the communication infrastructure. These findings can serve as a guideline for deducing the optimal cooperative NS strategy.

C. Heuristic optimum Analysis

Fig. 5 illustrates the average probability of keeping active BS_1 or BS_2 under the NS optimal strategy (Alg. 1) throughout the day for two different BS pairs, which are characterized by different C_r. For $C_r > 1$, deactivating BS_2 is the only feasible option for applying NS under high traffic conditions. Under higher capacity ratio ($C_r = 1.15$, purple curves), during peak periods (12:00-20:00) BS_2 is generally deactivated under NS, with active probabilities ranging from 20% to 45%, while during off-peak periods (about midnight), BS_2 operates for approximately 80% of the night time to reach fairness between the two MOs in terms of active time. Under lower capacity ratio $C_r = 1.04$ (azure curves), the similar capacities allow the smaller capacity BS_2 to more frequently handle the aggregated traffic load during the daily peak (11:00–20:00) while BS_1 remains switched off, with T_{a_2} resulting only about 5% less than that of BS_1. However, during the evening peak, the difference between active probabilities increases to around 25%. At night, the T_a disparity between BS_1 and BS_2 is about 10%, compared to almost 50% for a larger capacity gap. These findings show that C_r directly influences the likelihood of each BS being active at various times, thus suggesting that NS performance is shaped by both C_r and traffic demand patterns.

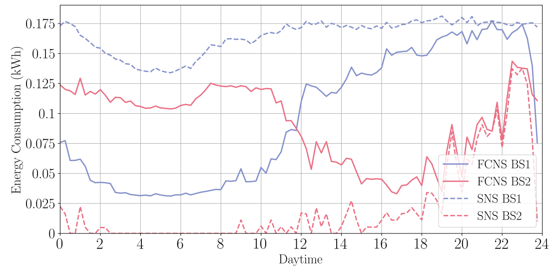

Fig. 6: Average BS energy consumption under SNS and FCNS.

D. Comparing cooperative NS against baseline benchmark

We now compare the performance of the FCNS approach with the single-NS (SNS) strategy, as presented in [4]. The SNS strategy serves as a baseline benchmark, where the same BS, specifically the one with the largest capacity (BS_2), is always deactivated during NS periods. In contrast, the FCNS approach provides a trade-off in the NS contribution between the two MOs, by shifting some load -and consequently energy consumption- from BS_1 to BS_2 during off-peak times. As shown in Fig. 6, which reports the energy saved by each BS in a pair under NS, a significant disparity is observed under SNS (dotted curves) between the energy savings of BS_1 and BS_2, with BS_1 obtaining much higher savings. Conversely, the FCNS strategy (continuous curves) achieves significant energy reductions for BS_1 (up to 100 Wh) during the overnight and morning hours (00:00–12:00), while during afternoon and evening traffic peaks, the energy reduction for this BS is smaller, ranging from 25 Wh to 50 Wh. This suggests that part of the energy savings achieved by BS_1 under SNS are shifted to BS_2, under FCNS, leading to a more balanced and cooperative scenario. Furthermore, as shown in Fig. 7, which compares the aggregated energy consumption of all BS pairs in the case when no NS is applied with the cases of FCNS and SNS, the overall energy gain under SNS, relative to the case without NS, is less than one percentage point higher than that of FCNS. Under FCNS, for several BS pairs energy savings exceed 30% and can reach up to 38% compared to scenarios

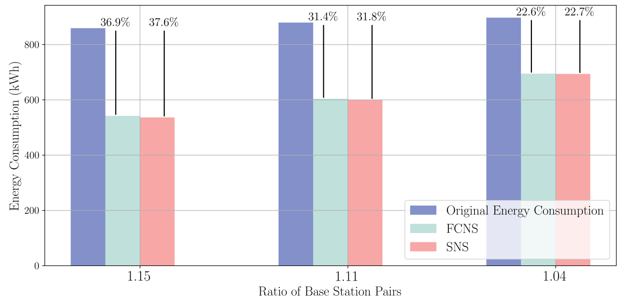

Fig. 7: Monthly energy consumption for various BS pairs with different capacity ratio, C_r, without NS and under NS.

TABLE I: Performance metrics under different NS strategies

	AF	**f$_{tr}$**	**Energy saving**
SNS BS_1	1	0	-10.3%
SNS BS_2	0.606	0.207	85.4%
HBA BS_1	0.801	0.077	38.7%
HBA BS_2	0.831	0.224	35.1%
HO BS_1	0.794	0.064	35.4%
HO BS_2	0.819	0.175	38.4%

without NS. Thus, a BS pair could save up to 300 kWh per month under FCNS, which translates to 720 €/year (based on the France electricity rate of 0.2 €/kWh), with savings equally shared by the two MOs. These findings indicate that FCNS is much more effective than SNS, since it allows both BSs in an NS pair to save energy, leading to reductions in OPEX for both MOs, at the price of negligible loss in energy efficiency.

E. Fair enhancement of network resilience between two BSs

The results in Table I, which summarizes performance indicators comparing various cooperative and non-cooperative NS strategies, show that HBA reduces AF for both BSs, approaching the AF values observed under the heuristic optimal strategy. Under HBA, the f_{tr} value of BS_2 is 0.05 higher than the heuristic optimum, which corresponds to an AF increase of 0.02. Such a 2% difference in AF has only a minor impact on the overall resilience of the base station infrastructure. Moreover, although the HBA strategy tends to favor BS_1 in terms of energy saving, it does not compromise the total energy saving compared to the heuristic optimum. In contrast to SNS, where only BS_2 experiences an AF reduction, FCNS leads to a lower failure rate for both BSs, enhancing network resilience and higlighting the potential benefits of FCNS for both sustainability and financial savings. Compared to FCNS strategies, SNS is clearly unfair in terms of energy saving and AF, as BS_1 remains active all the time. Since BS_1 must handle more traffic load than no-NS condition, its energy consumption increases by approximately 10%, while BS_2 saves around 85% of its energy consumption. Such a disparity would likely be unacceptable in practical scenarios. In contrast, FCNS achieves a more balanced distribution of energy savings and AF benefits between the two MOs, thereby forming a win-win and sustainable cooperative framework. Both FCNS strategies can be applied in practical situations to ensure fairness, but they offer distinct advantages and challenges. HO, while providing the best minimization of $f_P = f_{tr_1} + f_{tr_2}$, may require more accurate traffic predictions, making it potentially more complex to implement. In contrast, HBA simplifies operations with a fixed daily schedule that makes it easier for MOs to allocate operating times, although not achieving an optimal performance in minimizing f_P.

VI. Conclusion

Our study highlights that cooperative network sharing can significantly reduce both energy consumption and the failure rate of base station infrastructure in mobile networks. By comparing the baseline SNS strategy with our two proposed FCNS approaches, we show that FCNS achieves comparable energy savings —up to 38% in some scenarios— while enabling a more equitable distribution of energy benefits between MOs, exceeding 35% for both BSs, and decreasing the failure occurrence rate by 20% for both MO BSs compared to the always-on condition. This balanced allocation not only supports sustainable development of more resilient RANs, leading to lower carbon emissions, but also facilitates mutually beneficial economic collaboration agreements among MOs.

As future work, we plan to employ machine learning techniques to dynamically determine the optimal NS decisions by combining traffic demand forecasts and predictions of NS states. Additionally, from a microeconomic perspective, we will integrate game-theoretic approaches to determine the Nash equilibrium in the current scenario. By incorporating diverse parameters such as served demands, offloaded volume, penalty factors, and degradation factors, the resulting equilibrium strategy is designed to maximize utility for both MOs, thereby offering an economically optimal solution for NS.

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