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# Radio Access Network Cooperation with the Smart Grid: bandwidth limitation or sleep mode?

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***Abstract*—In this paper, we consider a Radio Access Network (RAN) powered by the Smart Grid (SG), which provides monetary incentives to users who respond to the grid's explicit requests to increase or decrease their energy consumption. The typical solution for reducing the RAN's power needs is to employ Base Station (BS) sleep modes, but this may lead to a drop in user coverage. For this reason, we propose dynamically adjusting the bandwidth allocated to users in response to SG requests. Our study considers a realistic urban RAN and evaluates the effectiveness of bandwidth limitation in meeting the SG's power reduction requests. Results indicate that this approach is particularly effective in high-density user environments, reducing power requirements by up to 20% while maintaining sufficient bandwidth for essential applications such as audio and video streaming. In contrast, BS deactivation can lead to substantial coverage losses, with user coverage falling below 90%.**

***Index Terms*—Radio Access Network, Smart Grid, Base Station, Demand Response**

## I. Introduction

The growth of population, urbanization, and economic development is leading to an increasing standard of living, whose energy requirement has been increasing, a trend that is expected to continue in the coming years [1]. While global electricity demand grew by 2.2% in 2023, slightly less than the 2.4% growth seen in 2022, it is projected to rise more rapidly, with an average annual growth of 3.4% through 2026, driven by improving economic conditions. This growth will occur in both advanced and emerging countries [2]. Meanwhile, in 2023, the International Panel on Climate Change reported that to limit global warming to 1.5°C, global carbon emissions must be halved by 2030 and reach net zero by around 2050, in line with the Paris Climate Agreement.

To meet these targets, many countries have significantly increased their adoption of Renewable Energy Sources (RES) in recent years. For example, 167 GW of distributed photovoltaic (PV) panel systems were installed globally between 2019 and 2021 [3]. However, due to the intermittent, unpredictable nature of RES production, managing the balance between electricity demand and supply has become extremely challenging. To adapt energy demand to supply availability, SG have implemented a bidirectional communication channel to manage energy optimally, using Demand Response (DR) strategies. DR requests users to reduce energy consumption during peak demand periods and increase usage when demand is low, offering monetary incentives to those who comply. In this context, large consumers, such as telecommunications mobile operators, can significantly contribute to DR objectives by adjusting their energy demand, while benefiting from substantial incentives. Currently, operators face enormous costs to power their infrastructure, and these costs are expected to rise, as they are directly affected by traffic demand, which is projected to grow at an annual rate of around 55% between 2020 and 2030, reaching 5,016 EBytes in 2030 [4]. Consequently, responding to SG requests by dynamically modulating network power requirements may help reduce operators' Operational Cost (Opex) while earning monetary rewards from the SG.

Since BS in the RAN are the most energy-intensive segment, accounting for 73% of the network's overall energy consumption, surpassing the energy needs of edge networks, data centers, and core services, reducing RAN power demand has been a major focus for many years [5]–[7]. One promising solution is to put BSs into sleep mode during periods of low traffic, significantly reducing RAN power requirements [8]. In [9], the authors propose a greedy policy to decide when to switch a BS off, aiming to balance power reduction with Quality of Service (QoS), measured by latency. Other works, in [10], [11], leverage machine learning models to determine the optimal sleep mode for power reduction.

While reducing RAN power by putting BSs into sleep mode during low traffic periods is promising, it can create coverage gaps in the network. To address this, we propose reducing RAN power consumption in response to SG requests by limiting the bandwidth allocated to users, rather than deactivating BSs. In our study, we consider a realistic urban RAN located in Zurich, Switzerland. To comply with SG requests for power reduction, based on the DR mechanism, the RAN dynamically adjusts the bandwidth allocated to each user according to their required bit rate and SG needs. Our results show that limiting bandwidth is particularly effective in high-density user environments for small power reductions, while still providing sufficient bandwidth for applications like audio and video streaming. In contrast, BS switching can reduce user coverage to below 90%.

The rest of the paper is structured as follows. Section

II motivates the bandwidth limitation for energy saving. The energy reduction strategies proposed and studied in this paper are described in Section III. Section IV presents the simulation framework used. In Section V, we present our results, followed by the conclusion in Section VI.

## II. Bandwidth Limitation for Energy Saving

In this part of the work, we discuss the motivations behind implementing bandwidth limitations to reduce RAN power needs.

Power consumption models show that the power usage of a BS consists of a fixed cost and a contribution dependent on the BS load [12], [13]. Thus, the BS power need, in watts, can be formulated as:

$$P_b = \bar{P}_b + K_b \cdot \rho_b \qquad (1)$$

where $\bar{P}_b$ represents the fixed cost for BS $b$, $\rho_b$ is the load at BS $b$ and $K_b$ is the factor that linearly scales the load, with parameters $\bar{P}_b$ and $K_b$ that depend on the technology of the BS. This means that the power consumption of a given portion of the RAN is the sum of the power requirement of each active BS in the considered area:

$$P = \sum_{\forall\ b \text{ active}} \left(\bar{P}_b + K_b \cdot \rho_b\right) \qquad (2)$$

Assuming that the BSs in the considered area are homogeneous in technology, the expression can be rewritten as:

$$P = N_A \bar{P} + \frac{K}{N_{RB}} \sum_{\forall\ \text{b active}} r_b \qquad (3)$$

where $N_{RB}$ is the number of available Resource Blocks (RB), per BS, $N_A$ is the number of active BSs, $\bar{P}$ and $K$ are the fixed cost and the linear factor of the load, respectively, and $r_b$ is the number of allocated RB on BS $b$.

Observe from this expression that, to reduce the RAN power requirements, two possible approaches can be used: (i) reducing the number of active BSs that reduces the fixed component of the power, and (ii) limiting the bandwidth occupancy, i.e., reducing the number of used RBs, that acts on the second term. As mentioned above, deactivating some BSs is a solution widely investigated in the literature, providing significant power needs reduction. However, it reduces coverage, creating holes and leaving some users disconnected. For this reason, in this work, we aim to reduce the RAN power requirements by reducing the allocated RBs. Assuming that the desired RAN power requirements must not exceed $\Theta$, from (3) the following condition that determines the maximum amount of used RBs, $R$, must be satisfied:

$$R = \sum_{\forall\ \text{b active}} r_b \leq \frac{N_{RB}}{K}\left(\Theta - N_A \bar{P}\right) \qquad (4)$$

This expression drives the strategy proposed in this paper; indeed, from the derivation of the number of RBs that can be used while guaranteeing a desired power provided by (4), our strategy defines the number of RBs to allocate to each user and, hence, the bandwidth it can use.

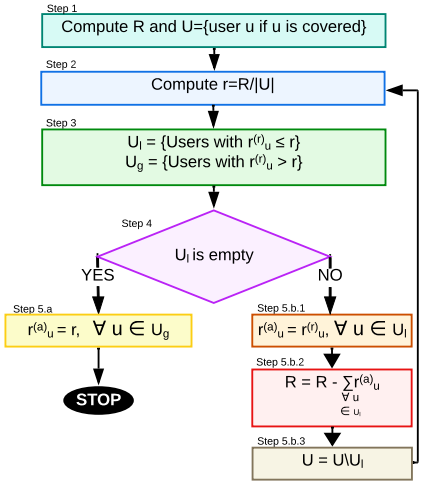


Fig. 1: Flow chart with the different steps of our bandwidth limitation approach.

## III. Energy Reducing Strategy

In this section, we describe the energy reducing strategy that the operator can use to respond to a possible smart grid request to reduce RAN power usage. As mentioned above, the smart grid typically employs DR approaches to align energy demand with supply availability. For example, these approaches can reduce energy consumption during peak demand periods, preventing demand from exceeding available energy.

*Bandwidth Limitation (B-L):* To reduce the RAN power needs, the RAN reduces the used bandwidth. This means that to each user $u$ that requires $r_u^{(r)}$ RBs the allocated bandwidth is set to $r_u^{(a)}$ RBs that can be smaller than what requested. To do this, the algorithm computes the usable RBs, $R$, as in (4), given the power requirement imposed by the smart grid, $\Theta$, in watt (Step 1 in Fig. 1). Given $R$, the algorithm computes the average number of RBs that each covered user can use as $r = \frac{R}{|U|}$, where $|U|$ is the cardinality of the set of covered users (Steps 1 and 2 in Fig. 1). An iterative procedure follows, in which the number of RBs is distributed to maximize the number of users that receive what they have requested and evenly distribute the rest to others. The procedure works as follows. The users are grouped into two sets: the ones who request an amount of RBs lower than $r$, denoted as $U_l$, and the ones who request an amount of RBs greater than $r$, denoted as $U_g$ (Step 3 in Fig. 1). If the set $U_l$ contains at least a user (Step 4), for each user $u$ in $U_l$, the algorithm allocates what is requested, i.e., $r_u^{(r)}$ (Step 5.b.1). Then, the algorithm computes the number of RBs that can be still allocated without violating the SG requirement (Step 5.b.2) and it also updates the set of users $U$ removing those whose number of allocated RBs has been already set

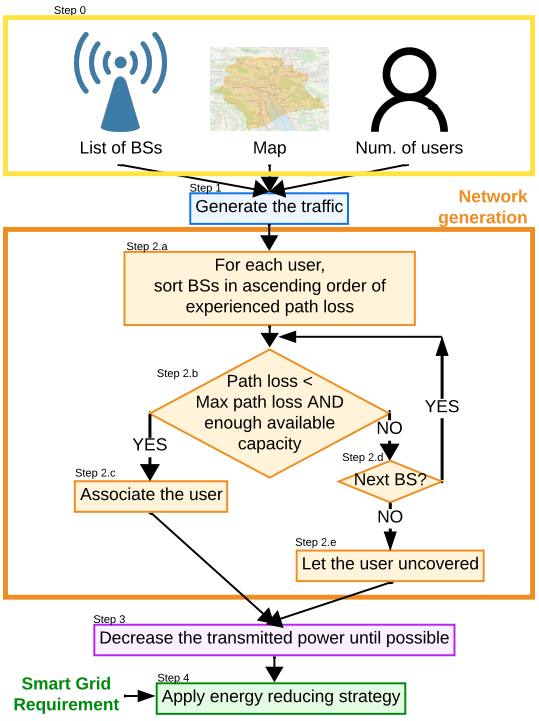


Fig. 2: Flow chart with the different steps of the simulation framework.

(Step 5.b.3). The procedure is repeated up to when the set $U_l$ is empty, meaning that the remaining users require a larger amount of RBs than the one that the RAN can provide them and the number of RBs that are allocated to them is set to the current $r$ (Step 5.a in Fig. 1).

*BS Switching (B-S):* Used as a benchmark in our work, the RAN switches some BSs to sleep mode, to cope with the SG requirement. In particular, given $\Theta$, the maximum allowable power need for the RAN, the least loaded BSs are iteratively deactivated until the requirement is met.

## IV. Simulation Framework

To evaluate our proposed strategy, we use a simulation framework that considers the urban area of Zurich, in Switzerland, similar to [14]. The area covers 70.4 km$^2$ and its population density is 5 897 people/km$^2$. In the area, there are 102 BSs, whose position is obtained from [14]. These BSs support the 5G New Radio technology, using 800 MHz as the frequency band. The used link budget parameters are reported in Table I [14].

### A. Input

The simulation framework requires the inputs described below:

TABLE I: Link Budget [14]

| **Parameter** | **800 MHz** |
|---|---|
| Frequency (MHz) | 800 |
| Bandwidth (MHz) | 120 |
| Used Subcarriers | 7680 |
| Total Subcarriers | 12288 |
| Sampling Factor | 1536 |
| TDD Duty Cycle DL (%) | 75 |
| TDD Duty Cycle UL (%) | 25 |
| Spatial Duty Cycle (%) | 0 |
| BS Transmit Antenna Gain (dBi) | 16 |
| BS Transmit Array Antenna Feed Loss (dBi) | 2 |
| BS Ratiated Power (dBm) | 46 |
| BS Number of Antenna Elements | 1 |
| User Antenna Element Gain (dBi) | 0 |
| User Transmit Power (dBm) | 23 |
| User Antenna Height (m) | 1.5 |
| User Number of Antenna Elements | 1 |
| RX Noise Figure (dB) | 8 |

- A shape file contains detailed 3D information about the buildings in Zurich, Switzerland (see Step 0 in Fig. 2)
- A file containing the positions of the BSs, as depicted in Step 0 in Fig. 2. As mentioned above, they are obtained from [14], where a total of 102 BSs is considered, whose link budget is reported in Table I.
- The number of users in the simulated scenario (see Step 0 in Fig. 2). The number of users matches the data gathered by operators in 2021. During peak times, there are 1,984 concurrent active users. To project traffic growth from 2021 to 2030, we use a compound annual growth rate of 2.2% [15]. For determining the user count for a particular operator, we rely on Swiss Market Distribution data, which shows that the operator's market share is 15.31%. Thus, the number of users is estimated to be 2 466. In our simulations we further increase the number of active users to investigate its impact.

### B. Generation of Traffic and Network Operation

The simulator starts with the generation of the traffic, see Step 1 in Fig. 2. For each user $u$, we determine its position as a 3D coordinates $(x^{(u)}, y^{(u)}, z^{(u)})$ within the designated area. The coordinate is generated by a uniform distribution, assuming that there are no hot spots such as tourist attractions or parks, ensuring equal probability for each location [14], [16]. The requested bit rate is determined using a uniform distribution between 1.0 Mbps and 20 Mbps.

Once the users are generated, the association process starts (depicted by the orange rectangle in Fig. 2). Each user is associated with the BS that yields the lowest path loss. For doing this, we create the list of potential BSs (Step 2.a in Fig. 2), that are the BSs that (i) can provide the amount of RBs necessary for satisfying the requested bit rate and (ii) provide an experienced path loss lower than a maximum (Step 2.b in Fig. 2). From the list of BSs, we pick the one that provides the lowest path loss (Step 2.c in Fig. 2). If the list is empty, the user remains without coverage (Step 2.e).

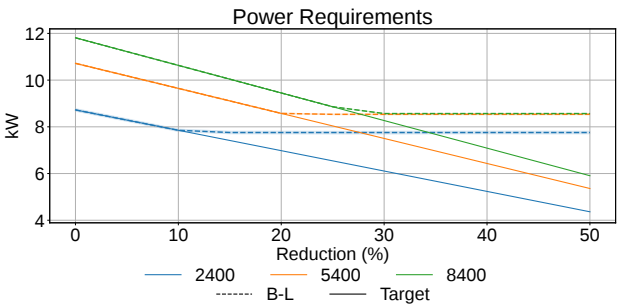


Fig. 3: Power Requirements for different numbers of users.

To determine the experienced path loss, the direct line between the user and the considered BS is established and we determine if the user is in Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS), accounting for the presence of existing buildings, whose 3D data are provided as input to the framework. For modeling the signal propagation in this environment, we use the specification of the Urban Scenario of the 3GPP TR 38.901 [17], while for the penetration loss of the buildings, we consider both low and high building loss values obtained from the ECC report 302 and ITU-R P.2109 recommendation [18], [19].

Once each user is associated with a BS, if possible, the transmitting power of each BS is decreased until it reaches the minimum required, i.e., until the path loss experienced by its users does not exceed the allowable maximum (Step 3 in Fig. 2). In case a BS has no users, that BS is switched off.

Once the network has been created one of the energy reducing strategies described in Section III is used (Step 4), to meet the SG requirement.

### C. Key Performance Indicators (KPI)

To assess the effectiveness of the strategies, we consider the following KPIs.

- *Power Requirement [W]* is measured as the sum of the power consumed by each BS in the network, in watt, computed as in (2). The power requirement of a BS is modeled as in [12].
- *User Coverage [%]* represents the percentage of users that are served by the RAN.

## V. Results and Analysis

In this section, we analyze the performance of our proposed methodology. As in [20], we conduct 30 simulations to obtain accurate estimations of the KPIs, calculating the mean and confidence interval, reported in the plots discussed below.

### A. Bandwidth Limitation Strategy

Fig. 3 reports the potential power consumption reduction that the *B-L* strategy can achieve. For given values of the smart grid's requests for power consumption reduction reported on the x-axis in relative terms, the solid line indicates the corresponding maximum power that the RAN can use to satisfy the requests. The different colors refer to different values of the number of users in the considered area. The dashed lines indicate which reduction the *B-L* strategy can actually achieve. When the requested reduction is 0%, actually no energy reducing strategy is applied. In this case, increasing the number of users means increasing the power requirements, due to the growth of the traffic that the RAN manages that rises the BS load and the number of active BSs. From the figure, we notice that when the requested reduction is low, the strategy can satisfy the request by limiting the amount of RBs that are allocated to users, and the dashed lines overlap with the solid lines. After some point, however, no further reduction is possible and the dashed curves become flat. The regions with flat curves correspond to extreme cases of maximum bandwidth limitations in which no service is provided. This means that the power requirements are due to the fixed contribution of the BSs (see Eq. 1). When a larger number of users are active, larger bandwidth (and hence energy) reductions are possible.

The bit rate assigned to users versus the requested one is reported in Fig. 4 for different values of the SG's power reduction request. As previously, different colors of the lines correspond to different numbers of users in the considered area. The black dashed, dash-dotted, and dotted lines indicate the needed bit rate for the Speech/Audio (S/A), the Video Streaming (VS) Basic 360 VR, and the VS High Definition (HD) 360 VR, respectively, as in [21]. When the reduction request is large, as in Fig. 4a, most of the users undergo a bit rate reduction and the VS can not be provided. Conversely, for small reduction requests like in Fig. 4d, the actual bit rate is slightly reduced and only for those users demanding large bit rates, but the RAN can provide sufficient bit rate for the VS Basic 360 VR applications, as well as the S/A ones. Notice that when there are many users the effort to reduce consumption is distributed among the several users and smaller reductions per user are needed to satisfy the smart grid's request.

### B. Comparison with BS Switching

The power requirement of a BS is composed of a fixed cost needed to keep active the BS and a factor that is load dependent. The latter is the part on which the *B-L* can act for reducing the BS consumption. In Fig. 5 each circle marked dashed curve represents the maximum allowable energy consumption of the RAN for different numbers of users in the network, increasing on the x-axis the requirement for power needs reduction. The solid lines represent the fixed component of the energy consumption, which grows with the number of users due to the increasing number of BSs that are needed in the area. Since for the moment we consider no BSs sleep mode, this component remains constant despite

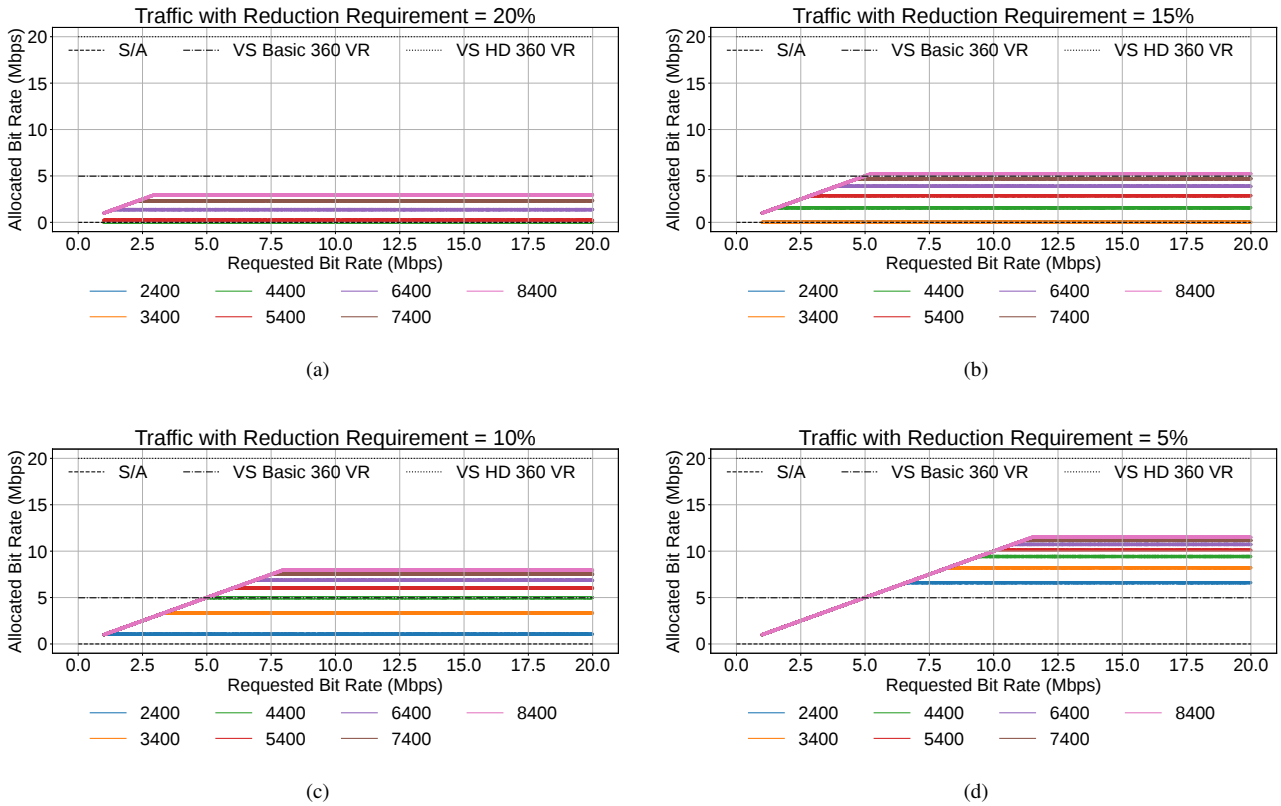


Fig. 4: Required Bit Rate vs Allocated Bit Rate with the *B-L* approach, varying the number of users in the considered area, with power reduction requirement equal to: (a) 20%, (b) 15%, (c) 10% and (d) 5%.

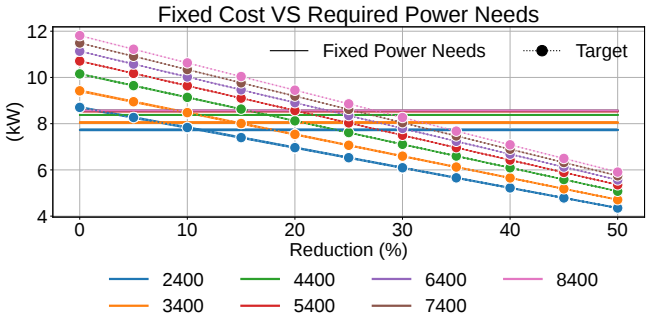


Fig. 5: Fixed component of BS power requirements versus requested power requirements reduction.

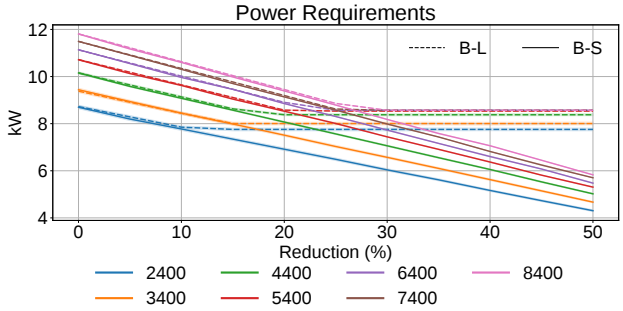


Fig. 6: Power Requirements, in kW, for different energy reducing strategies.

the changing energy consumption requirements. From the figure, we observe that when the smart grid's requirements are stringent, the RAN must reduce its energy consumption below the constant contribution level. When this occurs, the bandwidth limitation alone cannot meet the smart grid's demands, and some BSs must be switched off.

Fig. 6 shows the power requirements with the *B-L* and the *B-S* approaches, dashed and solid curves, respectively, for different numbers of users, in different colors, increasing on the x-axis the requirement for the reduction of the RAN power needs. From the figure, we notice that the *B-S* is always able to satisfy the power requirement. The situation is different for the *B-L* approach: after a given threshold it is not able to satisfy the SG requirements and the RAN power needs remain constant, while the needed reduction grows. This is because, dropping the power needs through the reduction of the bandwidth occupancy may be not always sufficient (see Fig.5).

To assess the QoS achieved with the considered strategies,

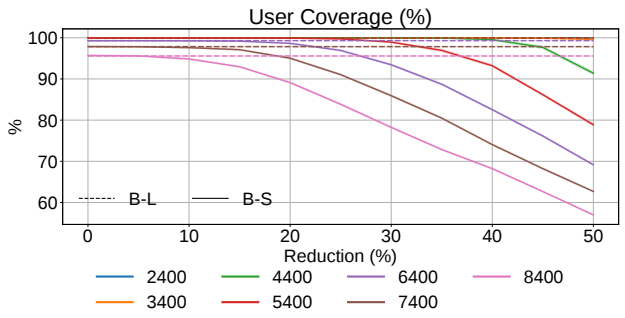


Fig. 7: User Coverage, in %, for different energy reducing strategies.

Fig. 7 illustrates the user coverage, in percentage, as the power reduction from the SG varies along the x-axis, for different values of the number of users in the considered area. The solid and dashed lines correspond to the *B-S* and *B-L* approaches, respectively. The figure illustrates that when *B-S* is employed, the user coverage significantly drops, if the power needs reduction is larger than 10%, since many BSs are switched off and the number of BSs that remain active is not enough to serve all the users.

## VI. Conclusion

In this work, to reduce the RAN power requirements and meet the SG's explicit requests for decreased power usage, we dynamically adjust the bandwidth allocated to each user based on their required bit rate and the SG's needs. By simulating a realistic urban RAN, our results reveal that this approach is particularly effective in high-density user environments. It can reduce the RAN power needs by up to 20% while guaranteeing sufficient bandwidth for essential applications such as audio and video streaming. In contrast, BS switching significantly reduces user coverage to less than 90%.

In future work, we plan to evaluate our proposed methodologies in urban, suburban, and rural contexts, with varying user densities. Additionally, we aim to combine the bandwidth limitation approach with BS switching to optimize QoS while further reducing RAN power requirements.

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