Energy-Efficient 5G Deployment in Rural Areas

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***Abstract*—Energy efficiency is of profound importance for prospective 5G wireless networks, especially in sparsely populated rural areas where broadband mobile services should be provided at a reasonable cost. In this paper the impact of beamforming (BF) and cell discontinuous transmission (cell DTX) technologies on the average area power consumption is studied. The required density of base stations for a 5G cellular system in a rural environment is also investigated. For this purpose, we propose a simple rural area model that captures a non-uniform distribution of users and employ the generalized Lloyd algorithm to determine the deployment of base stations. We assume a 5G system operating in mmWave band centered at 28 GHz with the bandwidth of 100 MHz, compared with existing LTE networks at 0.8 GHz with a 20 MHz bandwidth. Simulation results show that for the 5G network the density of base stations needed to provide 50 Mbps for 95% of users at the busy hour will be reduced by 8-9 times with the implementation of BF. It is also observed that BF has a greater effect on the energy saving of 5G networks in rural areas in comparison to the cell DTX.**

I. Introduction

Provisioning of a high data rate wireless connectivity in rural and remote areas has become a stringent challenge for perspective 5G wireless networks. The concept of the "broadband access everywhere" is a pillar of 5G service requirements, and the target performance of 50 Mbps everywhere is considered in terms of the experienced user throughput [1]. Since rural areas are characterized by very low population densities [2], the service providers look for solutions that are able to maintain this high quality of connectivity at a low cost. In this light, the energy efficiency of 5G networks in rural scenarios is an important problem since the energy bill accounts for a significant portion of operating expenses (OPEX) of mobile telecom operators [3].

Various approaches and solutions have been developed for energy efficiency of 5G. Among them is the concept of ultra-lean system design, especially the technology of cell discontinuous transmission (cell DTX) [4]. It refers to a hardware feature that deactivates certain functions of base stations (BSs) during non-transmission periods. Beamforming (BF) has also been studied as a way to increase the energy performance, either by itself [5] or in combination with cell DTX [6]. However, little attention has been paid to the energy efficiency of 5G in rural areas. Such a scenario is of significant difference in comparison to the urban one. Much lower population density poses a coverage requirement which is hardly an issue in urban areas. What is more, a high heterogeneity of inhabitant distribution creates a different traffic load profile for the BSs. Thus, the role of both BF and cell DTX will be changed as well. Energy efficiency of BF combined with cell DTX has not been thoroughly investigated for rural areas.

In this paper, we pursue a numerical simulation study in order to investigate how the implementation of both BF and cell DTX can reduce the energy consumption of 5G networks in rural areas. We assume that a hypothetical 5G network operates at 28 GHz with the bandwidth of 100 MHz. As a reference to the existing LTE systems, a similar analysis is made for the frequency of 0.8 GHz and 20 MHz bandwidth.

Our main contribution is that we numerically evaluate the energy saving effect of BF together with cell DTX in a rural environment. We estimate the number of BSs needed to provide a quality of service (QoS) requirements expected in the future (downlink throughput of 50 Mbps for 95% of the users). Moreover, to grasp the distinctive features of rural areas, we propose a simplified model of the heterogeneous user distribution where 80% of the population reside in 20% of the area. Also, a version of the generalized Lloyd algorithm [7] has been designed to provide a suboptimal scheme of BSs deployment that takes the non-uniform distribution of the population into account.

The remainder of the paper is structured as follows. In Section II the main assumptions and models that are used in numerical simulations are described. The method applied to solve the problem together with the simulation algorithms is given in Section III, while in Section IV results of the computer simulations are presented.

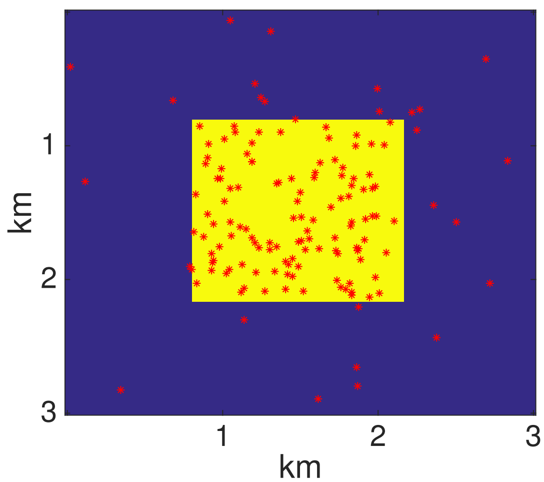

Fig. 1. The model of rural areas with two different population densities ("80/20" distribution).

Finally, the obtained result are concluded and directions of future research are identified in Section V.

II. System Model

A. Rural Environment

The environment under study is a typical 3 x 3 km^2 rural area in Europe with an average population density of 100 inhabitants/km^2 distributed non-uniformly [2]. To model the heterogeneity of the user distribution, we propose a simple model referred to as "80/20" distribution. In this model, 80% of the population is uniformly distributed in 20% of the simulated area as shown in Figure 1. The remaining 20% of the users are uniformly distributed over the rest 80% of the total simulated area. On average, the total population density is 100 inhabitants/km^2.

In Figure 1 the subarea with a higher user density is colored yellow, while the subarea with a lower population density is in blue. A realization of active users' positions at the busy hour is depicted by the red dots.

B. Radio Propagation

Due to the shortage of available spectrum at frequencies below 6 GHz, 5G is most likely to be deployed at higher frequencies, and mmWave band should be considered as a transmission medium. In this study, we consider a system running in 28 GHz with the bandwidth of 100 MHz. In [8] authors proposed the use of the power law propagation model for the mmWave for cellular networks deployed in urban environments. However, there is no clear mmWave propagation model available for the rural areas. To overcome this obstacle, our approach is to introduce a compensation factor of 20log$_{10}(f/f_{ref})$ to the existing empirical propagation model, where f is the carrier frequency in MHz. We employ the Okumura-Hata propagation model and the reference frequency f_{ref} of 800 MHz. Then, the path loss compensation factors for 28 GHz is calculated as 30.9 dB. The motivation for using the compensation factor is to reduce the computational complexity of the simulations. It exhibits a close match with the propagation model proposed in [8] for the case of the dense urban environments.

The Okumura-Hata propagation loss model with a compensation factor can be formulated as

$$\begin{aligned} PL[\text{dB}] =& 20\log_{10}(f/f_{ref}) + 69.55 + 26.16\log_{10}(f) \\ & - 13.82\log_{10}(H_b) - \alpha(H_m) \\ & + [44.9 - 6.55\log_{10}(H_b)]\log_{10}(d) \\ & - C_m + Y_\sigma, \end{aligned} \quad (1)$$

where f is the carrier frequency in MHz, H_b and H_m are the BSs and the MSs antenna heights in meters respectively; d is the distance from transmitter to receiver in kilometers, and Y_σ is a zero-mean Gaussian random variable with standard deviation σ in dB representing the shadow fading. The parameters in Okumura-Hata path loss model should be in the following ranges: H_b, H_m, and d should be between 30-200 m, 1-10 m, and 1-20 km, respectively.

For rural areas of small and medium-size we can say that

$$\begin{aligned} \alpha(H_m)[\text{dB}] = & [1.1\log_{10}(f) - 0.7]H_m \\ & -1.56\log_{10}(f) + 0.8, \end{aligned} \quad (2)$$

and

$$\begin{aligned} C_m[\text{dB}] = & 40.94 + 4.78[\log_{10}(f/28)]^2 \\ & -18.33\log_{10}(f). \end{aligned} \quad (3)$$

C. Cell Discontinuous Transmission

The power consumed by BS m during time t can be expressed as

$$E_m^t[\text{W}] = \zeta P_{tx}\eta_m^t + P_0, \quad (4)$$

where ζ is a factor representing feeder losses and amplifier power consumption, P_{tx} is the transmit power, $\eta_m^t \in [0,1]$ is the cell load and P_0 is the circuit power consumption. The BS will thereby consume P_0 watts even if the cell load is zero, i.e., all users are inactive. Cell DTX is a technology that aims to reduce P_0 by a factor of $\delta \in [0,1]$ when the BS is not being used, resulting in a lower average power consumption [4]. The power consumed by BS m during time t with cell DTX can then be expressed as

$$E_m^t[\text{W}] = \zeta P_{tx}\eta_m^t + (1-\delta)P_0\eta_m^t + \delta P_0 \ . \quad (5)$$

Note that (4) and (5) are the same when $\delta = 1$ (no cell DTX capability) or when $\eta_m^t = 1$ (full load). Thus, cell DTX is a feature that only saves power when the BS is idle, and the power saving will be more apparent during periods when the cell load is low. It is reported that the introduction of cell DTX in BSs can lead to significant energy reductions in LTE networks, and it is going to be a main feature of 5G cellular networks. It has been shown that it can save energy by up to 42% in urban areas [4], however at the cost of more dense deployment of the BSs.

D. Beamforming

Due to the small lengths of electromagnetic waves in mmWave band, 5G cellular systems can exploit the smaller antenna elements in geometrical size that can form arrays. It represents the multi-element antenna systems that can support a fully-directional communication by BF. It is a key technology to overcome the dramatic path loss in mmWave channels, to decrease intra-system interference and to reduce power consumption. However, fully-directional communication has two main problems [9]. The first problem is blockage that represents a significant attenuation due to obstacles on a propagation path. To overcome this negative situation, alternative reflected or retransmitted beam channels could be found together with new handover and mobile management strategies. Secondly, deafness i.e. narrow pencil beams of both BS and terminal should be pointed to each other.

For the sake of simplicity, we neglect the presence of blockage due to the small density of possible obstacles in rural areas and with an assumption of smart initial network planning plus implementation of techniques for alternative beam channels search. Moreover, we assume that the terminals are equipped with omnidirectional antennas, and therefore, the deafness problem can also be omitted from our analysis with another assumption that the BS knows the direction towards the user's terminal. According to this model, antenna gain within the main lobe, defined by $\theta-$azimuthal half-power beamwidth and $\varphi-$elevation beamwidth is constant and equals

$$G_{ML} = \frac{16}{sin(\theta^o).sin(\varphi^o)}. \tag{6}$$

Antenna gain for angles outside the main lobe is considered to be zero. We assume $\theta = \varphi = 10^o$, for all BSs. Therefore, the antenna gain within the main lobe is G_{ML} = 27.2 dBi. For BSs without BF functionality we assume that an omnidirectional antenna has a constant gain of 8 dBi in the azimuthal plane.

E. Radio Resource Allocation

In this study, the radio resource allocation is simplified with the following assumptions. Resources are divided in the time domain. Each user achieves the Shannon capacity (r_n), i.e. the data rate for user n, is calculated as in (7).

$$r_n[\text{bps}] = W\log_2(1+\gamma_n) \tag{7}$$

where W is the bandwidth, and γ_n is the signal to interference plus noise ratio (SINR) for user n calculated according to (8).

$$\gamma_n = \frac{P_{tx}G_{n,m}G_r g_{n,m}}{\sum_{i\neq m} P_{tx}G_{n,i}G_r g_{n,i} + N_p} \tag{8}$$

where P_{tx} is the BS's transmit power, $G_{n,m}$ is the transmit antenna gain between user n and BS m, $G_{n,i}$ is the antenna gain between user n and BS i, G_r is the receiver antenna gain, $g_{n,m}$ is the link gain between user n and BS m, $g_{n,i}$ is the link gain between user n and BS i, and N_p is the total noise power.

For the BF scenario the antenna gain is modeled as an ideal BF antenna with a 10^o beamwidth and 27.2 dBi gain as explained in Section II-D, for all frequencies. For the sake of comparison this includes the LTE band. Users outside the main lobe receive zero signal power. In the omnidirectional case the transmit antenna gain is 8 dBi for all users. Every user has a receive antenna gain of 0 dBi in all simulation scenarios. The noise power spectral density is assumed to be -174 dBm/Hz. The total noise power is increased by 7 dB in order to account for the receiver noise figure.

The performance of the different scenarios is estimated using Monte Carlo simulation method. The QoS requirement considered in this study is defined to be 50 Mbps per user with 95% user satisfaction at the busy hour. Only the downlink transmission is considered.

For the BF case, in each snapshot one user per cell is randomly selected and all users within the beam width of the BS in that cell are served. These are allocated a normalized time that is equal to the number of users within the beam width divided by the total number of users in the cell. This time allocation is then further divided among the users within the beam width in such a way that as many users as possible experience the throughput of 50 Mbps. This is done by allocating time to the user with the highest SINR until an experienced throughput of 50 Mbps is reached and then to the user with the second highest SINR and so forth until the time budget is spent. The number of users who achieved 50 Mbps is considered satisfied. The ratio of satisfied users over the total number of users within the beam width area is used as the metric for QoS for each BS. The total QoS is obtained by averaging the QoS over all BSs and all simulation runs.

In the omnidirectional case the time resource for each BS is divided between all its users such that as many users as possible experience a throughput 50 Mbps. This is again done by first allocating time to the user with the highest SINR, then to the second highest etc. until the normalized time budget of 1 is spent or all users are satisfied. As for the BF case the users that had an experienced throughput of 50 Mbps were considered satisfied and the ratio of satisfied users divided by the total number of users within the cell is used as the QoS metric.

In both cases no users are allocated more than 50 Mbps. If the whole time resource is not used, the BS is considered inactive for the remainder of the unused time. The activity or load of BS m at time t, denoted by η_m^t, is estimated as the portion of time the BS is active, i.e., in transmission.

III. Energy Efficiency Evaluation Methodology

A. Energy Efficiency Metric

The average daily area power consumption (ADAPC) has been used to evaluate the energy efficiency of the cellular network rather than bit/Joule, since it gives a better understanding of the achieved energy saving in the network level [10]. Calculation of the $ADAPC$ was performed as proposed in [10]. If we denote the total network area by A, the total number of BSs by M, and divide the day into H time slots then $ADAPC$ is given by

$$ADAPC[\text{W/km}^2] = \frac{\sum_{t=1}^{H}\sum_{m=1}^{M} E_m^t}{HA}, \tag{9}$$

where E_m^t denotes the power consumption by BS m during time t and is obtained from equation (5). The user activity profile used in this study is defined for each hour of the day based on the typical European user activity profile presented in [11].

B. Deployment of Base Stations

An important factor in estimating the $ADAPC$ is the placement of the BSs, since the γ_n in (8) increases as the distance to the nearest BS decreases. Thus, we propose a heuristic algorithm of BS deployment that attempts to minimize the sum of all possible distances to each BS in each cell.

The proposed scheme is based on a version of the generalized Lloyd algorithm. First, a selected number of BSs (M) are randomly distributed over the simulated area which is represented by an N by N matrix. The normalized coordinates of the BSs need not be integers of $1/N$ but can be any number in the interval $[0, N]$. Each element of the matrix is given a weight proportional to the expected user density at that area element. The area is then divided into M cells such that each cell contains one BS. The cell borders are drawn such that the Euclidean distance between the BS and the mid points of all area elements within the cell is smaller than the Euclidean distance between those subareas and any other BS. Each BS is then repositioned within its cell so that (10) is minimized for each cell. This is solved iteratively where each area element is given a complex number where the real and imaginary parts form a vector that points from the BS to the area element. All such vectors for the area elements within one cell are multiplied with the corresponding population density weight, w_i, and summed together to form one complex number referred to as a force vector. The BS is then moved in the direction of this force vector with an appropriate step length. In this case it is half the distance to the cell border. This process is then repeated until the magnitude of the force vector is below some threshold level.

After the optimization of all BS positions new cell borders are drawn with the same criterion as before and the process is repeated until the sum of all M objective functions, where the m'th objective function is shown in (10), converges. The criteria in (10) was selected as it was presumed that the energy consumption is proportional to the distance between the BS and the users to the power of the path loss exponent α as well as the number of users. For this reason a traditional hexagonal cell pattern was not considered since the user distribution is assumed to be highly non-uniform.

$$\begin{aligned} f(\mathbf{b}_m) &= \sum_{i \in C_m} w_i |\mathbf{b}_m - \mathbf{p}_i|^\alpha \\ C_m &= \{i \mid |\mathbf{b}_m - \mathbf{p}_i| < |\mathbf{b}_k - \mathbf{p}_i|, \ \forall \ k \neq m\}. \end{aligned} \tag{10}$$

In (10), $\mathbf{b}_m$ is the location of BS m, C_m is the set of elements belonging to cell m, $\mathbf{p}_i$ is the location of element i, α is the path loss exponent and w_i is the weight at element i. After the optimization new cell borders are drawn and the process is repeated until the sum of all M objective functions converges.

C. Simulation Algorithm

To answer the research questions and estimate $ADAPC$ for each combination of frequency band and antenna technologies, Algorithm 1 was used according to parameters in Table I.

IV. Numerical Results

In this section the results of the computer simulations are presented. All simulation parameters are listed in Table I.

Figure 2 shows the percentage of users that experience the throughput of 50 Mbps at the busy hour for the two frequency bands while using BF. The lower bandwidth of the 0.8 GHz band causes the BSs density required to satisfy 95% of the users to be significantly higher than that required for the mmWave band. For

Algorithm 1 Calculation of the area power consumption.

Find the number of BSs needed for the required QoS using the BS deployment scheme described in Section III and by estimating the user satisfaction as described in Section II-E.
for t = 1 to 24 **do**
  for r = 1 to R **do**
    Distribute a number of users according to the user activity rate for time t and the selected user distribution
    Calculate the activity rate η_m^t for all M BSs.
  end for
  Take the average of η_m^t over all R simulation runs
end for
calculate P_{area} from Equations (9) and (5) with cell DTX ($\delta < 1$) and without cell DTX ($\delta = 1$)

TABLE I
VALUES OF PARAMETERS USED IN SIMULATIONS.

Parameter	**Parameter Value / Description**
Area	3 km by 3 km
Population density	100 inhabitants/km^2
QoS requirements	50 Mbps for at least 95 % of the users
Users distribution	80 % of the population is uniformly distributed in the center of the simulation area covering 20 % of that area.
Frequency band and bandwidth	0.8 GHz (20 MHz), and 28 GHz (100 MHz)
Propagation model	Okumura-Hata propagation model for rural areas with compensation factor. Hb = 70 m, and Hm= 1.5 m
feeder loss, ζ	4.7
Transmission power, P_{tx}	40 W
Cell-DTX factor, δ	0.29
BS circuit power P_0	130 W
BF Beam width	ϕ = θ =10°
Antenna gain BF	27.2 dBi
Omnidirectional antenna gain	8 dBi
Mobile antenna gain	0 dBi
Noise power spectral density	-174 dBm/Hz.
Receiver noise	7 dB

the omnidirectional case, the difference is even severer as shown in Figure 3. Consequently, the lower number of BSs required when using BF will increase the cell load as illustrated in Figure 4. Table II summarizes the BSs densities needed to achieve the required QoS, if BF was incorporated with the 5G network deployment the number of BSs mandatory to fulfil the same QoS requirements will reduce by approximately 88%.

The ADAPC for LTE at 0.8 GHz and mmWave network at 28 GHz are presented in Figure 5 and Figure 6, respectively. We can see that for 28 GHz the

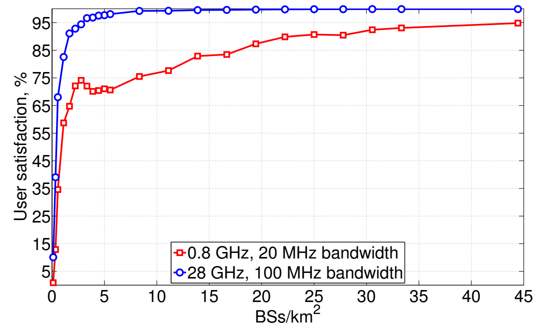

Fig. 2. The average user satisfaction with BF during the busy hour.

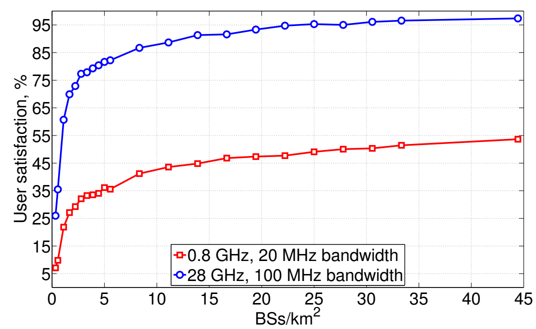

Fig. 3. The average user satisfaction without BF during the busy hour.

ADAPC saving due to the introduction of only cell DTX technology is 53% in comparison to 69% for 0.8 GHz carrier case. The amount of ADAPC savings due to the incorporation of BF only is approximately 83% for 28 GHz and nearly 94% for 0.8 GHz. Furthermore, incorporating both cell DTX and BF will reduce the ADAPC of the network by a total of 86% for the mmWave network and 97% for LTE network. This means that the additional benefit of cell DTX is not so significant when BF is already in place, and this effect is more obvious for LTE networks since for this frequency the effective propagation distance is larger and therefore less BSs are needed. The superior role of BF could be explained by the fact that BF significantly lowers the required BSs density, keeping the BSs busy. On the other hand, when no energy saving technologies are implemented, the LTE network is requiring an ADAPC that is 28 times higher than that for the 5G network. Nevertheless, when BF and cell DTX are both functional, the ADAPC for the LTE network is only 5 times higher than that consumed by the 5G network.

V. CONCLUSION

In this paper, we have evaluated the impact of BF and cell DTX technologies for the energy efficiency of

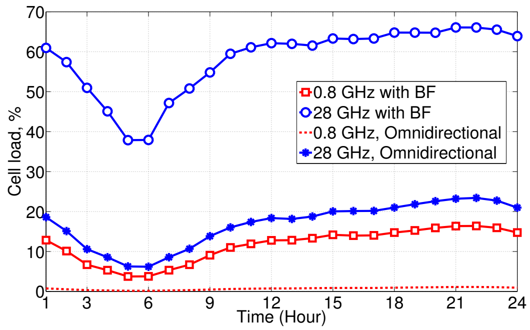

Fig. 4. Average cell load, η^t, for different hours of the day.

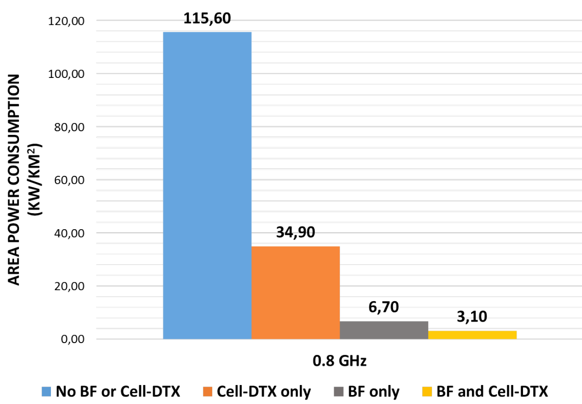

Fig. 5. Average daily area power consumption at 0.8 GHz for different energy-saving technologies.

5G wireless networks in rural environments. For this purpose, we proposed a simple rural area model reflecting highly non-uniform distribution of inhabitants, and then applied a version of generalized Lloyd algorithm to determine the BSs densities required to satisfy a QoS of 50 Mbps for 95% of users at the busy hour.

The simulation results show that BF significantly reduces the number of required BSs by enhancing the signal strength and suppressing the interference. It makes BF a key enabler of energy saving for 5G rural networks. BF makes the average cell load rather high because each BS serves many users. Consequently, the additional benefit of cell DTX is marginal if BF is already implemented.

Refinement of the simulation algorithms remains as an interesting area of future work. Particularly, more realistic modeling of rural environments and mmWave propagation are needed. Radio resource allocation mechanisms under a more realistic BF model are also to be investigated.

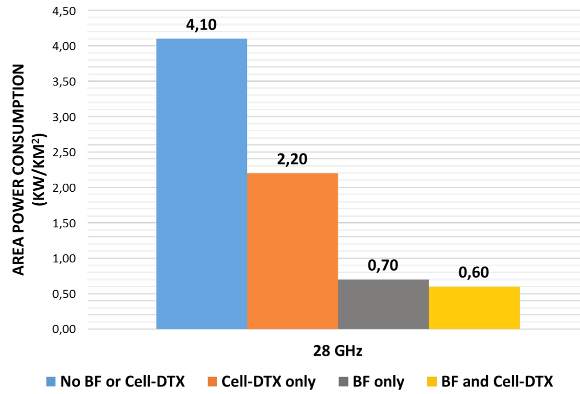

Fig. 6. Average daily area power consumption at 28 GHz for different energy-saving technologies.

TABLE II
THE REQUIRED BSS DENSITIES.

Frequency	BS/km^2 without BF	BS/km^2 with BF
0.8 GHz	880	44.4
28 GHz	25.6	3

ACKNOWLEDGMENTS

This work has been supported by Wireless@KTH, the center for wireless research at KTH Royal Institute of Technology.

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