Users Selection and Resource Allocation in Intelligent Reflecting Surfaces Assisted Cellular Networks

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***Abstract*—Satisfying the users' increasing demand and reducing the networks' energy consumption are among the most critical requirements of future cellular networks. In this paper, we exploit Intelligent Reflecting Surfaces (IRSs) to reduce the bandwidth required by users, which will allow more users to be served and/or reduce the energy footprint of cellular base stations. In contrast to most of the existing studies that focus on configuring the phase shifts of IRSs and/or the active beamforming of the base station, we consider that the IRS consists of blocks of resources that can be shared by several users. We formulate the problem of managing these resources as nonlinear integer problem. Then, we solve the optimization problem using exhaustive search, and propose two low complexity heuristic algorithms. The performance of the system is evaluated considering variable number of users, position of IRS, required bit rate and radius of the cell. Results show that using IRS can achieve significant bandwidth savings and important energy demand reduction when the IRS resources are well managed.**

***Index Terms*—Beyond 5G (B5G), Intelligent Reflecting Surface, Cellular Networks, Resource Allocation, Energy Efficiency**

I. Introduction

Cellular networks are witnessing huge increase in users' traffic with no sign of slowing down. Based on Ericsson's Mobility Report in November 2020 [1], mobile data traffic is expected to grow 7 times from 2020 to 2026. To satisfy this growing demand and reduce the corresponding increase in the energy footprint, several approaches have been proposed such as dense deployment of small cells, cognitive radio, massive Multi-Input-Multiple-Output (MIMO) and introducing of millimeter wave (mmWave) [2]–[4]. Deploying more active nodes, such as Base Stations (BSs) and distributed antennas, leads to higher energy consumption and significant increase in capital cost. Packing more antennas at the BSs demands more hardware and signal processing capabilities. Exploiting mmWave to utilize their large bandwidth requires additional deployment and is restricted by the behavior of these waves.

Intelligent Reflecting Surfaces (IRSs) have been recently introduced as a promising technology to achieve smart and re-configurable wireless channels [5], [6]. An IRS module consists of configurable sub-wavelength passive elements to reflect the incident waves from a source towards a desired destination. By adjusting the reflected signal, the IRS can alter the wireless channel to enhance the spectral and energy efficiencies of the network.

Several studies have been done to examine the usage of IRS in wireless network [5], [6]. The most common goals are to minimize the transmitting power at the BS, maximize the minimum user rate and maximize the system's energy efficiency. In [7], the authors minimize the transmitting power of an access point (AP) by jointly optimizing the transmit beamforming by active antenna array at the AP and the reflected beamforming by passive phase shifters at the IRS. In [8], the authors enhance the achievable rate of an orthogonal frequency division multiple access system using IRS. The problem is to maximize the achievable rate by jointly optimizing the transmit power allocation and IRS reflection coefficients based on the estimated channels. Point-to-point communication between a BS and a single user is considered in this paper.

The work in [9] aims to enhance the spectrum and energy efficiency by leveraging the passive IRS via smartly adjusting its signal reflection. More-specifically, the active transmit beamforming at the AP and passive reflect beamforming at the IRS are jointly optimized to minimize the transmit power. In [10], the authors develop energy-efficient design for both the transmit power allocation and the phase shifts of the IRS elements, by using different algorithms like Alternating Optimization and gradient descent for optimal transmit power allocation. In [11], the authors maximize the Weighted Sum-Rate of the IRS-aided downlink for a Multiple-Input Single-Output (MISO) system. They proposed an iterative algorithm to alternatively optimize the active beamforming at BS and the passive beamforming at IRS under the BS transmit power constraint using a fractional programming algorithm in an outdoor environment. In [12], the authors study the joint IRS reflection coefficients and the transmit covariance matrix optimization for maximizing the capacity of a point-to-point IRS-aided MIMO system.

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In [13], the authors compare the performance of IRS and repetition-coded relaying. They optimize both technologies by computing the optimal transmit power and the optimal number of elements in an IRS. Channel estimation and beamforming design for an IRS-assisted multi-user (MISO) communication system is considered in [14]. The authors focus on solving the maximization of the minimum signal-to-interference-plus-noise ratio (SINR) problem by jointly designing the precoding vectors and power allocation at the BS in addition to the phase shifts vector at the IRS.

In [15], the authors use stochastic geometry to study the effect of large-scale deployment of IRSs on the coverage of cellular networks. Similarly, in [16], the authors study the coverage of an IRS-assisted mmWave cellular network using stochastic geometry. Results show that deploying passive reflectors have the same effect as equipping BSs with more active antennas. In [17], power allocation and phasehift optimization is applied for the downlink IRS-assited heterogeneous network.

Although a lot of studies have been done on IRS-assisted wireless networks, few work consider the application of IRS in cellular networks especially on system level. In this paper, we study the effect of using IRS in an IRS-assisted cellular network scenario. In contrast to most of existing studies that focus on configuring the phase shift of the IRS and/or the active beamforming of the base station, we consider that the IRS consists of blocks of IRS elements. Each block can be controlled independently to assist a specific user. This will provide more flexibility and higher gain in case of multi-user cellular networks. We formulate the problem of managing the IRS resources as nonlinear integer problem. Then, we solve the optimization problem using exhaustive search, and propose two low complexity heuristic algorithms. The performance of the system is evaluated considering variable number of users, position of IRS, required bit rate and radius of the cell.

The rest of this paper is organized as follows. In Section II, we present the channel models without and with IRS, then explain the scenarios where the IRS assists several users. The problem formulation and proposed approach are presented in Section III. We present and discuss the results in Section IV before concluding in section V.

II. System Model

We consider a base station serving K users in a cell of radius Ra. Users are uniformly distributed in the cell, where each user requires a minimum bitrate R_{min}. We consider two cases without and with IRS:

1) The first case (without IRS) is used as a reference scenario, where all users equally share the available bandwidth. In this context, we calculate the required transmit power for each user to achieve a predetermined bitrate.
2) In the second case, an IRS module is added to the system. Assuming same transmit powers as in the first case, the IRS is used to enhance the spectral efficiency of certain users, denoted assisted users. The enhancement in the spectral efficiency is expressed as percentage of bandwidth savings, which can be translated into reducing the BS power demand or increasing number of users served by the BS.

A. First case: BS-user without IRS

As in [13], the received signal y_k by user k from the BS can be calculated as:

$$y_k = h_{s,k}\sqrt{p_k}s + n_k \tag{1}$$

where $h_{s,k}$ represents the channel between the user and the base station, p_k is the transmit power by the BS to user k, s is the unit signal information and $n_k \sim \mathcal{N}_{\mathcal{C}}(0, \sigma_k^2)$ represents the Additive White Gaussian Noise (AWGN) at the receiver. Note that the antenna gains are included in the channel. The Signal to Noise Ratio (SNR) at user k in this case is:

$$SNR_k = \frac{p_k \mid h_{s,k} \mid^2}{\sigma_k^2} \tag{2}$$

Also for a given bitrate, the required SNR by user k can be calculated by:

$$SNR_k = 2^{\frac{R_k}{B_k}} - 1 \tag{3}$$

where B_k represents the allocated bandwidth for user k and R_k is the required bitrate by user k . For the case of fair sharing of bandwidth among users:

$$B_k = \frac{B_T}{K} \tag{4}$$

where B_T is the total available bandwidth at the BS. From Eq. 2, the required transmit power, by the BS, for user k is:

$$p_k = SNR_k \frac{\sigma_k^2}{\mid h_{s,k} \mid^2} \tag{5}$$

B. Second case: IRS-supported transmission

In this case, we consider that an IRS module is added within the coverage of the base station. The channel between the BS and IRS with N elements is denoted by h_{sr}, while $[h_{sr}]_n$ represents the nth component. $h_{s,k}$ represents the channel between the base station and user k. The channel between IRS and the destination is denoted by $h_{r,k}$.

Each element in the IRS has a size that is smaller than the wavelength, thus it scatters the incident signal with approximately constant gain in all directions of interest [18]. Therefore, the IRS's properties are fully represented by the diagonal matrix:

$$\Theta = \alpha \times diag(e^{j\theta_1} \dots e^{j\theta_N}), \tag{6}$$

where $\alpha \in (0, 1]$ represents the amplitude reflection coefficient and $\theta_1 \dots \theta_N$ is the phase shift variables. Based on [18], the received signal at user k is:

$$y_k = (h_{s,k} + h_{sr}^T \Theta h_{r,k})\sqrt{p_k}s + n_k \tag{7}$$

where p_k and n_k are respectively the transmitted power and the noise. Note that the used transmitted powers are the same as calculated for the system without IRS. When user k is assisted by IRS the received power in function of the transmitted power is:

$$P_{R_I}^k = p_k \mid h_{s,k} + h_{sr}^T \Theta h_{r,k} \mid^2 \tag{8}$$

Note that $h_{sr}^T \Theta h_{r,k} = \alpha \sum_{n=1}^{N} e^{j\theta_n} [h_{sr}]_n [h_{r,k}]_n$. As in [13], the phase shifts of IRS variables can be optimized by selecting:

$$\theta_n = \arg(h_{s,k}) - \arg([h_{sr}]_n [h_{r,k}]_n) \tag{9}$$

For brevity, we introduce the notation:$\mid h_{s,k} \mid= \sqrt{\beta_{s,k}}$, $\mid h_{sr} \mid= \sqrt{\beta_{sr}}$, $\mid h_{r,k} \mid= \sqrt{\beta_{r,k}}$, and $\frac{1}{N} \sum_{n=1}^{N} \mid [h_{sr}]_n [h_{r,k}]_n \mid= \sqrt{\beta_{IRS}}$.
From Eq. 8, the received power is:

$$P_{R_I}^k(N) = p_k(\sqrt{\beta_{s,k}} + N\alpha\sqrt{\beta_{IRS}})^2 \tag{10}$$

The Signal to Noise Ratio with IRS (SNR_I^k) in this case is:

$$SNR_I^k = \frac{P_{R_I}^k(N)}{\sigma_k^2} \tag{11}$$

We can compute the new bandwidth required by user k as follows:

$$\mathcal{B}_I^k = \frac{R_I^k}{\log_2\left(1 + \frac{P_{R_I}^k(N)}{\sigma_k^2}\right)} \tag{12}$$

where R_I^k is the required bitrate by user k when assisted by the IRS.

For one assisted user k, the bandwidth saving using N elements of IRS is:

$$S_{B_k} = \frac{B_k - \mathcal{B}_I^k}{B_k} \tag{13}$$

C. IRS assisting multi-users

Knowing that the IRS consists of large number of elements, the IRS can assist several users. Choosing the users to be assisted depends on several factors such as the positions of the base station and the IRS and distribution of users. Knowing that the position of the base station is usually fixed, it is recommended to choose the position of IRS to be near the users or the base station [5]. Yet, the number of users to be assisted depends on the users' condition and the number of elements in the IRS.

Assisting several users by the IRS can be done by more than one approach. For example, it is possible to optimize the IRS phase shift to increase the SNR of all assisted users. Another approach is to focus on optimizing the phase shifts of IRS so that a target SNR is achieved by all assisted users [5].

Alternatively, it is possible to consider the IRS as resources that can be shared by users. For example, the IRS can be shared via time division. This is possible due to the real time switching (intelligence) of the IRS. From another perspective, it is possible to share the IRS by several users at the same time, where each user is allocated a certain number of elements. Given that the users are working on different frequencies, interference between signals at IRS can be neglected. Indeed,

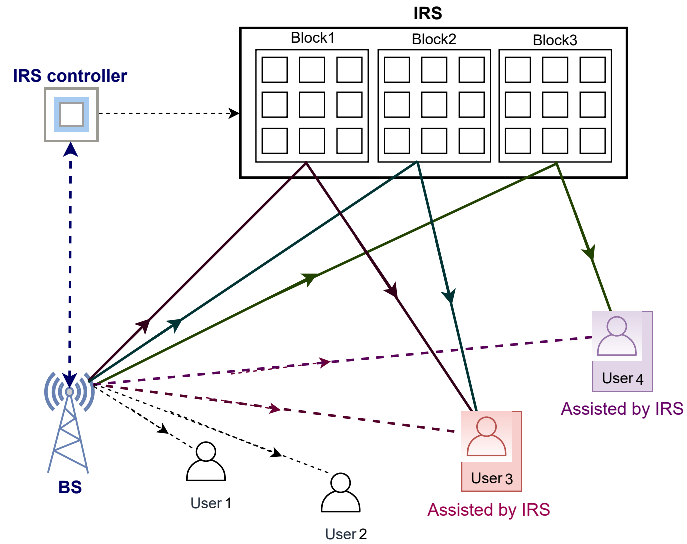

Fig. 1. An example of IRS module that consists of 3 blocks of IRS elements.

the number of elements to be allocated should not be small to ensure a minimum gain [13].

In this work, we consider that a minimum number of IRS elements can be allocated to a user, which is denoted N_a^{min}. On the one hand, a very small number of elements is not effective in terms of increasing the received power [13]. On the other hand, this will reduce the complexity of the allocation policy by reducing the number of possibilities. Furthermore, this will reduce the computation necessary for phase shift optimization.

III. Problem formulation

We consider a base station serving a number of users K. The IRS is assisting certain number of users by allocating block(s) of elements. The size of a block is considered as N_a^{min}. The number of IRS resources (blocks), denoted n_b is:

$$n_b = \frac{N_{tot}}{N_a^{min}} \tag{14}$$

where N_{tot} represents the total number of elements in the IRS module. Note that n_b also represents the maximum number of users that can be assisted by the IRS.

Assuming that the IRS is sufficiently far from both the users and the base station, the effect of assisting a user by any of the blocks is the same. Indeed, if the IRS is very close to the base station, e.g. near field, the position of the block should be considered. However, this is not in the scope of this work. Figure 1 presents an example of a base station serving 4 users, where only 2 of the users are assisted by the IRS. As shown in the example, a user might not be assisted by the IRS. More over, assisted users might have different number of allocated blocks.

Given that users equally share the bandwidth in case of not using IRS and that the transmit power remains the same despite using IRS, the problem can be formulated as determining the vector $X_K = [x_1, x_2, \ldots, x_K] \in \mathbb{N}^{1\times K}$ that represents the number of blocks assigned for each user as follows:

$$\max_{X_K} \sum_{k=1}^{K} (S_{B_k^{x_k}}) \tag{15}$$

where $S_{B_k^{x_k}}$ is the bandwidth saving of user k with x_k allocated blocks of IRS calculated using Eq. (13). Note that the number of elements of IRS allocated for user k is $x_k \times N_a^{min}$.

In addition, the optimization problem of the IRS blocks allocation is constrained by:

$$\sum_{k=1}^{K} x_k \leqslant n_b \tag{16}$$

$$0 \leqslant x_k \leqslant n_b \tag{17}$$

The constraints ensure that the number of allocated blocks for each user is positive and that the sum of allocated blocks for all users is equal to the available blocks. The non-linearity in the objective function (Eq. (15)) and the integer nature of the variables $x_1, x_2, \ldots, x_K$ lead to a Non-Linear Integer Problem (NLIP) [19] .

A. Proposed Algorithms

To evaluate the gain that can be achieved by sharing the IRS by several users, we evaluate the bandwidth saving for a certain number of assisted users. Assuming perfect knowledge of users' condition, we use exhaustive search to find the optimal combination of the allocated IRS blocks by examining the effect of all possibilities (users to be assisted and number of blocks allocated to each assisted user), and select the one with highest gain in terms of bandwidth savings.

For example, if we have 3 blocks and 4 users as in Figure 1, then the maximum number of users that can be assisted is 3. Assuming that we consider that 3 users are assisted with 1 block each, then the best case is selected form the 4 possible ones. Assuming that 2 users are to be assisted and 2 to rely solely on the base station, then the number of possibilities is 12.

Although exhaustive search gives the best possible solution, it requires high computation cost. Thus, we propose two low complexity algorithms as follows:

- **MAX-BS**: users with maximum distance from the BS will be selected and allocated with highest number of IRS blocks. This algorithm will give high priority to users with low SNR from the BS.
- **MIN-IRS**: users with minimum distance to IRS will be selected and allocated with highest number of IRS blocks. This algorithm will give high priority to users with best radio conditions with respect to the IRS.

IV. Simulation Results

We consider a Macro-base station serving a cell, where users are distributed randomly. The BS operates with 3 GHz carrier frequency and 10 MHz bandwidth. The channel gains are modeled using 3GPP Urban Micro (UMi) from ([20], Table B.1.2.1-1) while we utilize the line-of-sight (LOS) and non-LOS (NLOS) versions of UMi, which are defined for distances $\geq 10m$. G_s and G_d are the antenna gains (in dBi) at the source and the destination, respectively. Table I summarizes the parameters considered in the system.

TABLE I
VALUES AND ASSUMPTIONS

Parameters	Values and assumptions
Number of users	variable (6 to 30)
Cell radius in m	variable (125 to 1500)
Number of elements in IRS	150
number of antennas	1 at BS, 1 at user
G_s	15 dBi
G_d	0 dBi
Environment	Urban
Carrier frequency f_c	3GHz
Total Bandwidth B_T	10 MHz
BS power model	Earth [21]
$d_{(SR)}$	50 m, 200 m
α	1

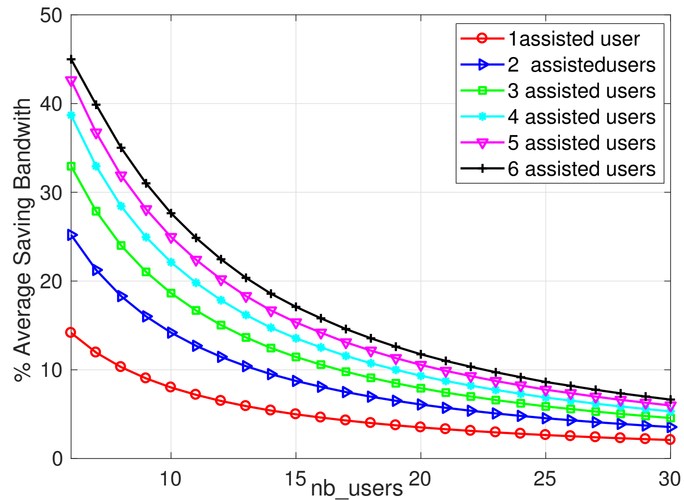

Fig. 2. Percentage of bandwidth savings with respect to number of served users for variable number of assisted users by the IRS (d_{SR}=50 m).

The channel gain β as a function of distance d is:

$$\beta(d)[dB] = G_s + G_d + \begin{cases} -37.5 - 22\log_{10}(d/1m) & \text{if LOS,} \\ -35.1 - 36.7\log_{10}(d/1m) & \text{if NLOS,} \end{cases} \tag{18}$$

The results presented in this section are obtained using Monte Carlo Simulation by simulating the environment 10000 times for different distribution of users. Although we present the result as average percentage of bandwidth savings it can be interpreted as the increase in spectral efficiency of the system, which can be translated into reducing the energy footprint of the base station.

Figure 2 shows the percentage of saved bandwidth with respect to the number of served users when exhaustive search is applied (required rate R_b =1Mbps, cell radius $Ra = 250m$, Algorithm: exhaustive search). The IRS is positioned at $d_{SR} = 50m$ from the BS, which corresponds to the case where the

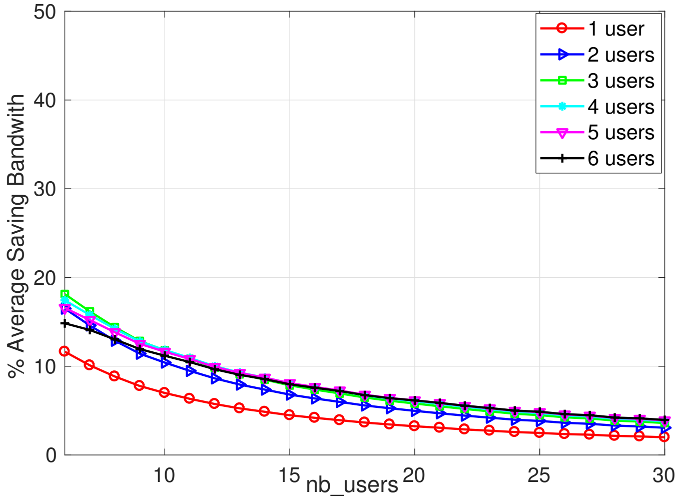

Fig. 3. Percentage of bandwidth savings with respect to number of served users for variable number of assisted users by the IRS (d_{SR}=200m, Algorithm: exhaustive search).

IRS is positioned near the BS. We can see that up to 47% of bandwidth saving can be achieved when the number of served users is small and when the number of assisted users by IRS is the same as n_b. The figure also shows that increasing the number of assisted users increases the bandwidth savings. This means that distributing the IRS blocks over the largest number of users to assist will enhance the overall spectral efficiency of the BS. In addition, the bandwidth saving decreases when the number of served user increases. This is due to the decrease of the percentage of users that can be assisted with respect to the number of users served by the BS.

When the IRS is positioned at an edge of the cell (d_{SR}=200m), the saved bandwidth is presented in Figure 3. Similarly, the saved bandwidth decreases with the number of users served by the BS. However, in contrast to the case where IRS is positioned near the BS, smaller bandwidth saving is achieved when the IRS is at the edge of the cell. This due to the uniform distribution of users and the position of IRS. When the IRS is near the BS, the average distance between the IRS and the users is smaller than the case where the IRS is at the edge. In the latter case, edge users that are near the IRS witness more enhancements but the overall bandwidth savings is better when the IRS is near the base station.

Figure 4 shows the percentage of saving bandwidth for different bit rates when the IRS is positioned near the BS and exhaustive search is applied. The figure shows that increasing the bit rate reduces the bandwidth savings. This is due to higher bandwidth requirement to fulfill the users' demand. Note that similar pattern is observed when the IRS is at an edge of the cell.

The effect of cell radius on the saved bandwidth is presented in Figure 5. When the radius is small, very small bandwidth saving is achieved. This is due to the fact that the power transmitted by the BS is sufficient to have good users' condition. When the radius of the cell increases, more bandwidth saving

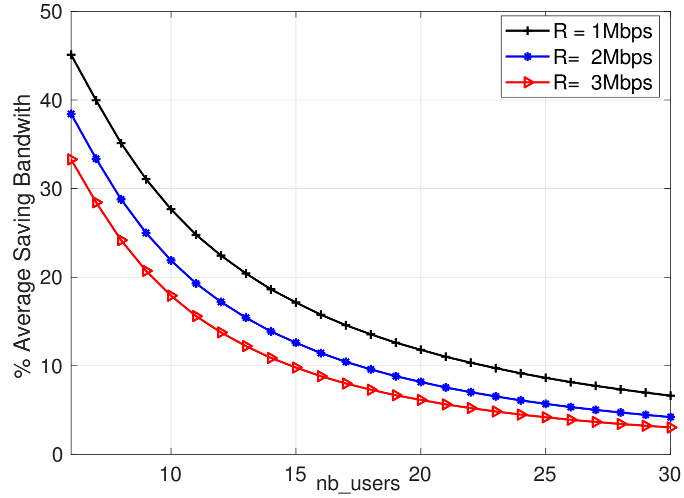

Fig. 4. Percentage of bandwidth savings with respect to the number of served users for different bit rates (d_{SR}=50m, Algorithm: exhaustive search).

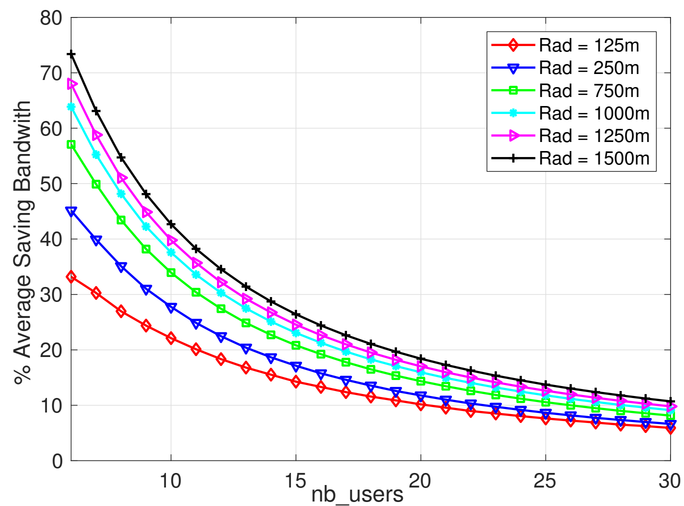

Fig. 5. Percentage of bandwidth savings with respect to the number of served users for different cell radii (d_{SR}=50m, Algorithm: exhaustive search).

is achieved since the distance between the users and the BS increases.

In the following, we compare the performance of proposed heuristic algorithms with the exhaustive search in terms of bandwidth and power savings. Figure 6 shows the average bandwidth savings for the simulated algorithms (exhaustive search, MAX-BS, MIN-IRS) with respect to the number of served users. The figure shows that the performance of MAX-BS is almost the same as the exhaustive search algorithm, while MIN-IRS achieves lower savings. This means that assisting users with low SNR-conditions from the BS is more beneficial than assisting those that have good conditions with respect to IRS, which also have good conditions with respect to the BS as the IRS is placed near the BS. Figure 7 shows the power savings for the simulated algorithms (exhaustive search, MAX-BS, MIN-IRS) with respect to the number of served users. The power of the BS for different cases (without IRS,

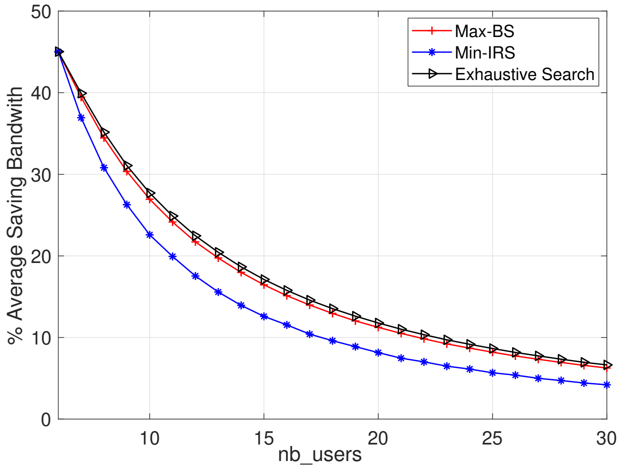

Fig. 6. Percentage of bandwidth savings with respect to the number of served users for the simulated algorithms (d_{SR}=50m, R=1Mbps).

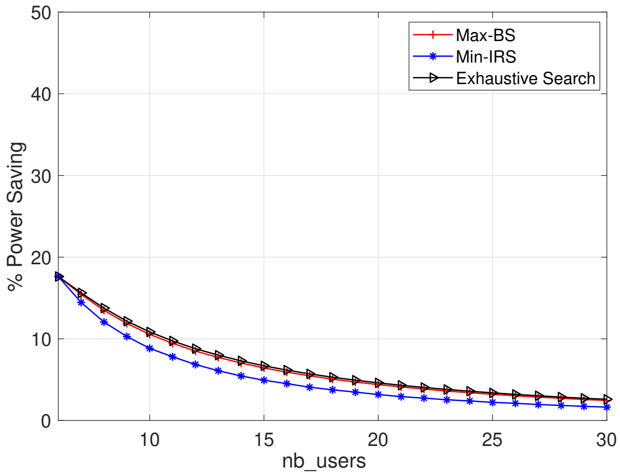

Fig. 7. Percentage of power savings with respect to the number of served users for the simulated algorithms (d_{SR}=50m, R=1Mbps).

and with IRS for different algorithms) is calculated based on the power model presented in [21]. The figure shows that the power savings follows the same trend as MAX-BS achieves higher power savings than MIN-IRS. However, lower power savings are achieved compared to the bandwidth savings, which is due to the static power of the BS.

V. Conclusion

With the increase in traffic demand, reducing the bandwidth required for users and decreasing the energy footprint of networks have became critical objectives to be achieved in future cellular networks. In this paper, we study the effect of using IRS to assists users in a cellular network. We consider that the IRS consists of blocks that can be used to assist several users. The problem is formulated as nonlinear integer problem. We solve the optimization problem using exhaustive search, and propose two low complexity heuristic algorithms. Results show that significant bandwidth and power savings can be achieved when the IRS is located near the base station and the IRS resources are well managed. In future work, we aim at jointly optimizing the BS and IRS resources when considering MIMO system.

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