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Elganimi, Taissir Y, Elmajdub, Retaj I, Nauryzbayev, Galymzhan and Rabie, Khaled (2023) IRS-assisted beamspace millimeter-wave massive MIMO with interference-aware beam selection. In: IEEE 96th Vehicular Technology Conference (VTC2022-Fall), 26 September 2022 - 29 September 2022, London/Beijing.

DOI: https://doi.org/10.1109/VTC2022-Fall57202.2022.10012839

Publisher: IEEE

Version: Accepted Version

IRS-Assisted Beamspace Millimeter-wave Massive MIMO with Interference-Aware Beam Selection

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***Abstract*—Intelligent reflecting surface (IRS)-assisted beamspace millimeter-wave (mmWave) multiuser massive multiple input multiple output (MIMO) with interference-aware (IA) beam selection scheme is proposed in this paper. This proposed scheme is capable of intelligently reconfiguring the radio environment and utilizing the beam selection for the sake of reducing the number of required radio frequency (RF) chains without any noticeable performance degradation. To ensure a fair comparison, the achievable sum-rate and energy efficiency (EE) performance metrics of the proposed scheme are evaluated and compared to that of IRS-assisted fully-digital systems with zero-forcing (ZF) precoding and the conventional systems without the IRS technology. Simulation results demonstrate that the proposed IRS-assisted beamspace mmWave massive MIMO system with IA beam selection algorithm outperforms the conventional system without IRS. It is also shown that the performance improves when the number of reflecting elements is more than the total number of mobile users. Moreover, the proposed scheme can potentially offer higher EE than the conventional schemes. Therefore, this shows that the proposed system can be considered as an alternative solution for the future generation of wireless systems.**

***Index Terms*—Beamspace, beam selection, IRS, massive MIMO, millimeter-wave.**

I. INTRODUCTION

Future wireless systems are aiming at searching for a breakthrough communication technology that can provide a tremendous high data rates. One option is the intelligent reflecting surface (IRS) technology which was first proposed in [1], using metasurface materials that are real-time software-controllable. However, the main purpose of IRS is to achieve smart and reconfigurable wireless channels as well as reflected signals with controllable amplitude and/or phase using a large number of low-cost passive elements [2], [3]. Correspondingly, IRS is called *reconfigurable intelligent surfaces (RIS)* [4], [5] depending on its type of implementation, i.e., where transmission occurs in a reflective or a transmissive manner or, alternatively, *large intelligent surfaces (LIS)* [6], *smart reflect arrays* [1] and *software controlled metasurfaces* [7].

Recently, IRS-assisted wireless communications has caught significant attention because of its low hardware and energy cost, and its reconfigurability in improving the wireless propagation condition of channels [5]. More specifically, in the past year, integrating the IRS technology into beamspace millimeter-wave (mmWave)-based massive multiple input multiple output (MIMO) systems with beam selection schemes has been considered in some recent studies and showed significant performance improvements achieved over the conventional systems [8]–[11]. In [8], a downlink IRS-assisted non-orthogonal multiple access (NOMA) system for beamspace mmWave massive MIMO was proposed with employing a lens antenna array, where the base station (BS) is connected to the single-antenna users but without direct links and grouped as a single NOMA group with the aid of IRS. The reported results in [8] showed that the proposed system outperforms the conventional single-beam system. In another work [9], an IRS-aided wireless communication with environment-aware beam selection algorithm was proposed. It is demonstrated in [9] that significant rate improvements are achieved by the proposed scheme over various benchmark schemes. Later, the design of single-user wideband mmWave communication system employing lens antenna array assisted by multiple IRSs was presented in [10] in order to realize low complexity and cost-effective mmWave communication system with high robustness, where IRS is used to overcome the blockage issues and further enhance the performance of mmWave massive MIMO systems. The reported results in [10] showed that a gain of about 5 dB can be achieved in the proposed scheme compared with existing algorithms. More recently, the authors in [11] proposed a model for the IRS-enabled beamspace channel, where IRS is considered just a part of the wireless channel. In this system model, IRS is emphasized as a controlled scattering cluster that responsible of a group of multipath components that are reflected to the receiver instead of dealing with IRS as a node in the center between the source and the destination. It is demonstrated in [11] that a significant improvement for large IRSs can be achieved at close distances even with low number of transmit antenna elements.

In the light of the foregoing introduction and recent work, an IRS-assisted beamspace mmWave multiuser massive MIMO system with interference-aware (IA) beam selection is proposed in this paper. More specifically, this system considers the potential multiuser interferences where all mobile users are classified into two groups, namely, the interference-users (IUs) and non-interference-users (NIUs). In this corresponding, the optimal beams are selected in the former group by a low-complexity incremental algorithm with the sake

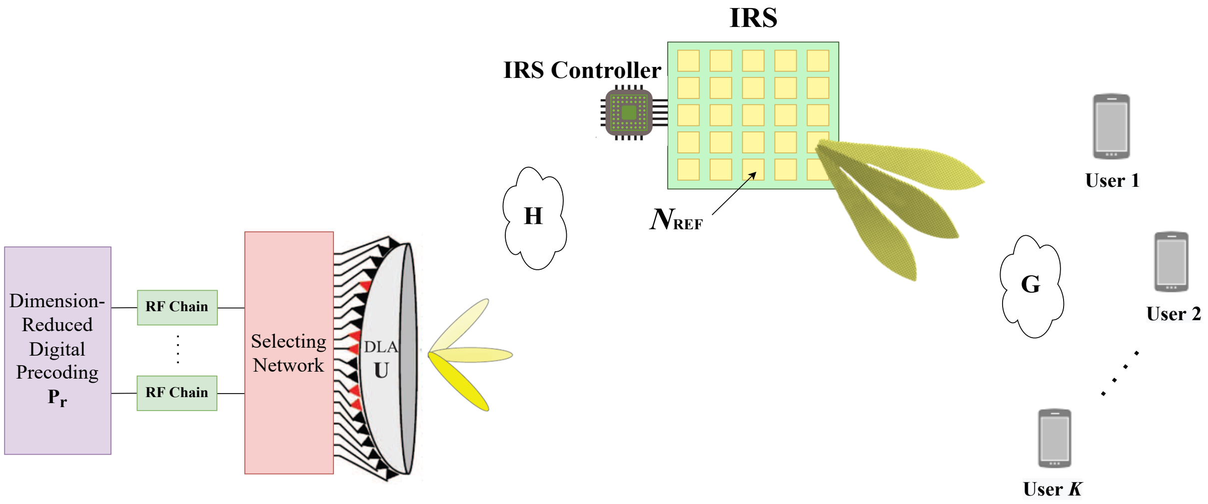

Fig. 1. System model of IRS-assisted beamspace mmWave massive MIMO with IA beam selection scheme.

of maximizing the achievable sum-rate, while for the latter, the beams with largest power are directly selected. In this system, however, beam selection is utilized to reduce the number of the power-hungry radio-frequency (RF) chains without any noticeable performance drop. In particular, the main aim of this proposed system is to solve the problem of selecting the same beam for different devices in IRS-assisted beamspace mmWave multiuser massive MIMO systems which may occur with conventional beam selection schemes such as magnitude maximization (MM) beam selection scheme [12], and hence avoid the problem of wasting some RF chains [13]. Simulation results demonstrated that the proposed system is capable of achieving a considerable performance gain over the conventional system without IRS in terms of both the achievable sum-rate and EE.

The rest of the present paper is divided into three sections as follows. Section II presents the system model of the proposed IRS-assisted beamspace mmWave massive MIMO system. In Section III, the numerical results and comparisons are discussed. Finally, Section IV gives the conclusions of this paper and possible future work.

II. SYSTEM MODEL

As depicted in Fig. 1, the block diagram of the proposed IRS-assisted beamspace mmWave massive MIMO system with IA beam selection scheme is shown. The BS is equipped with a discrete lens array (DLA) antenna composed of N antenna array elements and N_{RF} RF chains to support K single-antenna users simultaneously. It is assumed in this paper that the transmission occurs through an IRS composed of N_{REF} reflecting units, where it is properly deployed and effectively used as a reflector to assist the downlink communications. In this proposed system model, a smart controller is attached with IRS for the sake of controlling and coordinating the reflecting modes of the IRS reflecting elements. The following diagonal phase-shifting matrix represents the properties of these low-cost reflecting elements [14]

$$\mathbf{\Phi} = \alpha \ \mathrm{diag}(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_{\text{REF}}}}), \tag{1}$$

where $\alpha \in (0; 1]$ is the fixed amplitude coefficient, diag(.) is the diagonal matrix whose a diagonal contains the entries of vector $(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_{\text{REF}}}})$, $j \triangleq \sqrt{-1}$ is the imaginary unit, while $\theta_1, \ldots, \theta_{N_{\text{REF}}}$ are the IRS phase-shifts for each passive reflecting element.

As shown in Fig. 1, a carefully designed DLA is employed in order to realize the spatial discrete Fourier transformation using the transform matrix $\mathbf{U}$ with size of $N \times N$. For the predefined spatial directions, $\overline{\psi}_n = \frac{1}{N}\left(n - \frac{N+1}{2}\right)$, where $n = 1, 2, \ldots, N$, the array steering vectors of these N orthogonal directions are contained in this transform matrix to cover the entire space as follows [13]

$$\mathbf{U} = [\mathbf{a}(\overline{\psi}_1), \mathbf{a}(\overline{\psi}_2), \ldots, \mathbf{a}(\overline{\psi}_N)]^H, \tag{2}$$

where $(.)^H$ denotes the Hermitian (conjugate transpose) of a matrix.

The received signal vector $\tilde{\mathbf{y}}$ for all users in the proposed IRS-assisted beamspace mmWave massive MIMO system with IA beam selection, where $k \in (1, 2, \ldots, K)$, can be presented by

$$\tilde{\mathbf{y}} = \underbrace{\left[\sum_{i=1}^{N_{\text{REF}}} \mathbf{G}(k,i) \mathbf{\Phi} \mathbf{H}^H(i,k) \right]}_{\mathbf{H}_{\text{eff}}^H} \mathbf{U}^H \mathbf{P} \mathbf{s} + \mathbf{n}, \tag{3}$$

where $\mathbf{G} \in \mathbb{C}^{K \times N_{\text{REF}}}$ is the channel matrix between the IRS and the K mobile users, which is modeled in this paper as a Rayleigh fading channel with zero mean and unit variance, $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{N_{\text{REF}}}]$ is the channel matrix between the BS and IRS, $\mathbf{h}_i \in \mathbb{C}^{N \times 1}$ is the channel vector between the BS and the i-th passive element, and $\mathbf{H}_{\text{eff}} = [\mathbf{h}_{\text{eff}1}, \mathbf{h}_{\text{eff}2}, \ldots, \mathbf{h}_{\text{eff}K}]$ is the effective channel matrix. In addition, $\mathbf{s} \in \mathbb{C}^{K \times 1}$ is the original signal vector for all users satisfying the following normalized power constraint, $\mathbb{E}\left(\mathbf{s}\mathbf{s}^H\right) = \mathbf{I}_K$, and $\mathbf{P} \in \mathbb{C}^{N \times K}$ is the digital precoding matrix satisfying the total transmit power constraint as tr($\mathbf{P}\mathbf{P}^H$) $\leq \rho$, where tr(.) denotes the trace of a matrix, and ρ is the total transmit power. Finally, $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2\mathbf{I}_K)$ is the additive white Gaussian noise (AWGN) vector of size $K \times 1$ with zero mean and noise power of σ^2.

In this paper, Saleh-Valenzuela model for mmWave communications is assumed for the channel vector $\mathbf{h}_i$ of each i-th reflecting element as [12]

$$\mathbf{h}_i = \beta_i^{(0)}\mathbf{a}(\psi_i^{(0)}) + \sum_{l=1}^{L} \beta_i^{(l)}\mathbf{a}(\psi_i^l), \tag{4}$$

where $\beta_i^{(0)}$ $\mathbf{a}(\psi_i^{(0)})$ denotes the line-of-sight (LoS) component of the i-th reflecting element with $\beta_i^{(0)}$ being the complex gain, while $\psi_i^{(0)}$ is the spatial direction. In addition, $\beta_i^{(l)}$ $\mathbf{a}(\psi_i^l)$ is the l-th non-line-of-sight (NLoS) component of the i-th reflecting element, where $1 \leqslant l \leqslant L$, and L is the number of NLoS components. Finally, $\mathbf{a}(\psi) \in \mathbb{C}^{N \times 1}$ is the corresponding steering vector.

The steering vector for the typical uniform linear array (ULA) antenna with N elements can be presented by [13]

$$\mathbf{a}(\psi) = \frac{1}{\sqrt{N}}[e^{-j2\pi\psi m}]_{m \in \mathcal{J}(N)}, \tag{5}$$

where $\mathcal{J}(N) = \{q - (N-1)/2,\, q = 0, 1, \ldots, N-1\}$ is a set of symmetric indices centered at zero [13]. If θ denotes the physical direction, d is the spacing between the array elements satisfying the constraint of $d \leq \lambda/2$ at mmWave frequencies, and λ denotes the corresponding signal wavelength, the spatial direction can be found as $\psi \triangleq \frac{d}{\lambda}\sin(\theta)$ [14], [15].

The received signal vector in the beamspace can be written as

$$\tilde{\mathbf{y}} = \tilde{\mathbf{H}}_{\text{eff}}^H\mathbf{P}\mathbf{s} + \mathbf{n}, \tag{6}$$

where $\tilde{\mathbf{H}}_{\text{eff}}$ is the effective beamspace channel matrix that can be written as

$$\begin{aligned}\tilde{\mathbf{H}}_{\text{eff}} &= [\tilde{\mathbf{h}}_{\text{eff}1}, \tilde{\mathbf{h}}_{\text{eff}2}, \ldots, \tilde{\mathbf{h}}_{\text{eff}K}] \\ &= \mathbf{U}\mathbf{H}_{\text{eff}} = [\mathbf{U}\mathbf{h}_{\text{eff}1}, \mathbf{U}\mathbf{h}_{\text{eff}2}, \ldots, \mathbf{U}\mathbf{h}_{\text{eff}K}].\end{aligned} \tag{7}$$

The dimension of the proposed system model can be reduced without obvious performance loss by selecting a few number of beams based on the sparse beamspace channel which is assumed to be known by the BS. Therefore, the received signal vector can be expressed as

$$\tilde{\mathbf{y}} \approx \tilde{\mathbf{H}}_{\text{effr}}^H\mathbf{P}_{\text{r}}\mathbf{s} + \mathbf{n}, \tag{8}$$

where $\tilde{\mathbf{H}}_{\text{effr}}^H = \tilde{\mathbf{H}}_{\text{eff}}^H(s,:)_{s \in \mathfrak{B}}$ is the effective dimension-reduced beamspace channel, and $\mathfrak{B}$ contains the indices of the selected appropriate beams. Additionally, $\mathbf{P}_{\text{r}}$ denotes the dimension-reduced baseband digital precoding matrix, which is found based on zero-forcing (ZF) precoding as follows [16]

$$\mathbf{P}_{\text{r}} = \beta\Big(\tilde{\mathbf{H}}_{\text{effr}}\big[\tilde{\mathbf{H}}_{\text{effr}}^H\tilde{\mathbf{H}}_{\text{effr}}\big]^{-1}\Big), \tag{9}$$

where $\beta = \sqrt{\frac{K}{\text{tr}(\mathbf{P}_{\text{r}}\mathbf{P}_{\text{r}}^H)}}$ is the power normalization factor, and $(.)^{-1}$ denotes the inverse of a matrix.

It is worth mentioning that the proposed IRS-assisted beamspace mmWave massive MIMO system is capable of reducing the number of required power-hungry RF chains. This is mainly because the dimension of $\mathbf{P}_{\text{r}}$ matrix is much smaller than the dimension of the digital baseband precoding matrix $\mathbf{P}$ in (6). It is also worth mentioning that the smallest number of RF chains at the BS should be equal to the number of users, i.e., $N_{\text{RF}} = K$, for the sake of fully achieving the multiplexing gains, as well as utilizing the near-optimal sum-rate performance. Without loss of generality, it is assumed in this paper that $N_{\text{RF}} = K$.

It is found in the literature that in hybrid beamforming technique, both the power consumption and hardware implementation complexity can be significantly reduced. However, it is impossible to transmit all beams simultaneously due to the limited number of required RF chains in the transmitter of such systems. Therefore, a certain criterion is used to select the transmitting beams, and before the transmission, the selected beams are digitally precoded. Thus, the system performance is significantly influenced by the beam selection method [17]–[20].

In the proposed system, the IA beam selection is utilized as an efficient scheme to address the multiuser interference problem that arises in the conventional MM algorithm. The main idea behind this scheme is to divide all mobile users into two groups based on the potential multiuser interferences. In particular, for users with severe interference, the optimal beams are found and selected by an incremental algorithm with the sake of maximizing the achievable sum-rate, while for users with low interference, the beams with large power are directly selected. To be more precise, the proposed IA beam selection consists of two stages in order to choose the best K unshared beams out of N beams and, as a result, maximize the sum-rate [13].

The signal-to-interference-plus-noise ratio (SINR) of user k in the proposed system can be presented by

$$\gamma_k = \frac{|\tilde{\mathbf{H}}_{\text{effr}k}^H\mathbf{P}_{\text{r}_k}^{BB}|^2}{\sum_{k' \neq k}^{K}|\tilde{\mathbf{H}}_{\text{effr}k}^H\mathbf{P}_{\text{r}_{k'}}^{BB}|^2 + \sigma^2}, \tag{10}$$

where $\mathbf{P}_{\text{r}_k}^{BB}$ is the k-th column of $\mathbf{P}_{\text{r}}$, and $|.|$ denotes the absolute value of a matrix.

The achievable sum-rate of the proposed system can be formulated as

$$R = \sum_{k=1}^{K}\log_2(1 + \gamma_k) \quad \text{(bps/Hz)}. \tag{11}$$

In this paper, the EE of the proposed IRS-assisted beamspace mmWave massive MIMO system with IA beam selection scheme is found as

$$\zeta = \frac{R}{\rho + N_{\text{RF}}P_{\text{RF}} + N_{\text{REF}}P_{\text{E}}} \quad \text{(bps/Hz/W)}, \tag{12}$$

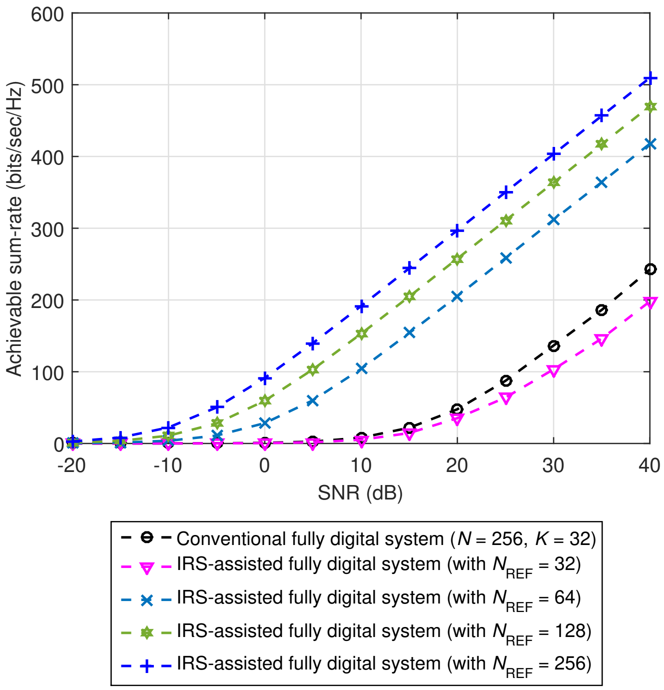

Fig. 2. Achievable sum-rate performance of IRS-assisted fully digital systems with ZF precoding scheme employing $N = 256$ antenna elements and supporting $K = 32$ users.

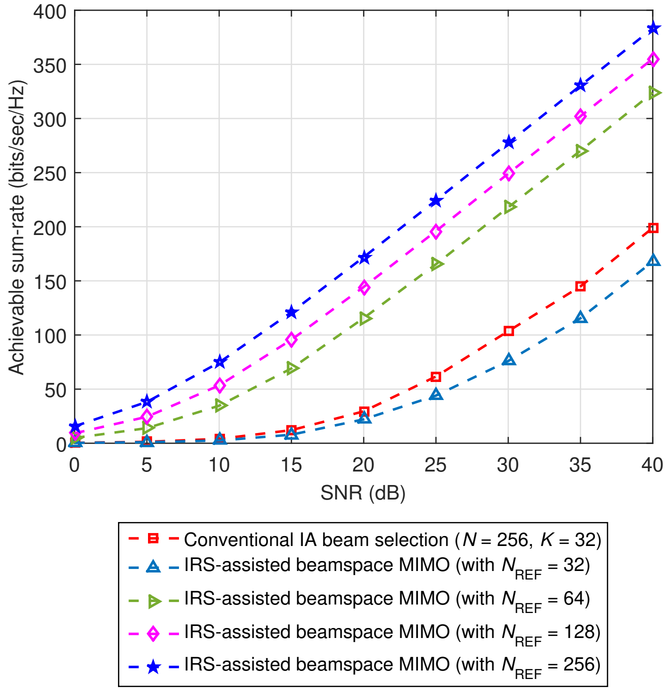

Fig. 3. Achievable sum-rate performance of IRS-assisted mmWave massive MIMO with IA beam selection scheme employing $N = 256$ antenna elements and supporting $K = 32$ users.

where P_{RF} and P_{E} are the power consumed by each RF chain and each reflecting element, respectively.

For the sake of fair comparison, IRS-assisted fully digital system with ZF precoding is also proposed in this paper, where the number of RF chains, N_{RF}, is equal to the total number of antenna elements, N, since each RF chain is directly connected to one BS antenna in fully digital systems. Therefore, the EE of IRS-assisted fully digital system with ZF precoding is modeled as

$$\zeta = \frac{R}{\rho + NP_{\text{RF}} + N_{\text{REF}}P_{\text{E}}} \quad (\text{bps/Hz/W}). \tag{13}$$

III. NUMERICAL RESULTS

In this section, the simulation results of the proposed IRS-assisted beamspace mmWave massive MIMO systems with IA beam selection scheme and fully digital systems with ZF precoding are presented. The performance of the proposed systems is also compared to the performance of the conventional systems without the IRS technology. Throughout the simulation, it is assumed that the signal wavelength λ = 1 mm, and the spacing between the antenna elements $d = \frac{\lambda}{2}$. For the spatial channel of the k-th user, it is assumed that there is one LoS component and L = 2 NLoS components. It is also assumed that $\beta_i^{(0)} \sim \mathcal{CN}(0,1)$ and $\beta_i^{(l)} \sim \mathcal{CN}(0,10^{-1})$ for l = 1, 2. In addition, $\psi_i^{(0)}$ and $\psi_i^{(l)}$ follow the uniform independent and identically distribution within [-$\frac{1}{2}$, $\frac{1}{2}$]. Finally, it is assumed in this paper that $\alpha = 1$.

Fig. 2 depicts the achievable sum-rate performance versus the signal-to-noise ratio (SNR) of IRS-assisted fully digital systems with ZF precoding. It is assumed in this figure that N = 256 antenna elements are employed to serve K = 32 users, and IRS is equipped with N_{REF} = 32, 64, 128 and 256 reflecting elements. This comparison shows that the proposed IRS-assisted fully digital systems with ZF precoding scheme outperform the conventional fully digital system by an SNR gain of approximately 17 dB, 21 dB and 24 dB when N_{REF} = 64, 128 and 256 reflecting elements, respectively. It can be also noticed from this figure that the performance improvement is achieved only when N_{REF} is larger than K. This is mainly because the low number of passive elements cannot support the reflection.

The achievable sum-rate performance of the proposed IRS-assisted beamspace mmWave massive MIMO systems with IA beam selection scheme is shown in Fig. 3 with N = 256 antenna elements are employed to serve K = 32 users, and various numbers of reflecting elements are considered. It is found in this figure that an SNR gain of about 12 dB, 15 dB, and 18 dB is achieved when N_{REF} = 64, 128 and 256 passive elements, respectively, over the conventional scheme employing N = 256 antenna elements and supporting K = 32 mobile users.

In Figs. 4 and 5, the EE performance of IRS-aided fully digital systems with ZF precoding against the number of users is evaluated and compared to the conventional fully digital systems with ZF precoding employing N = 128 and 256 antenna elements, respectively. The SNR is set in these two figures as 30 dB, and different values of N_{REF} are considered, while K varies from 1 to 64. In these comparisons, P_{RF} =

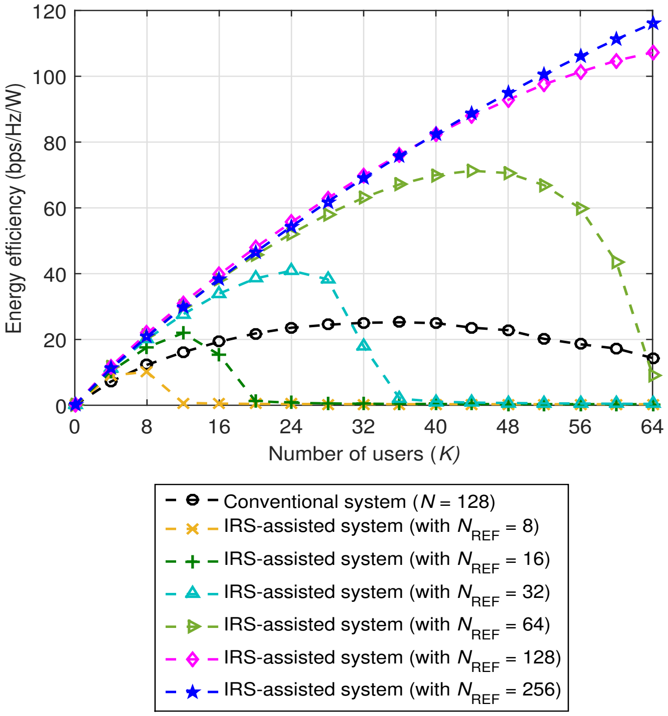

Fig. 4. EE performance of IRS-assisted fully digital systems with ZF precoding scheme employing $N = 128$ antenna elements at SNR = 30 dB.

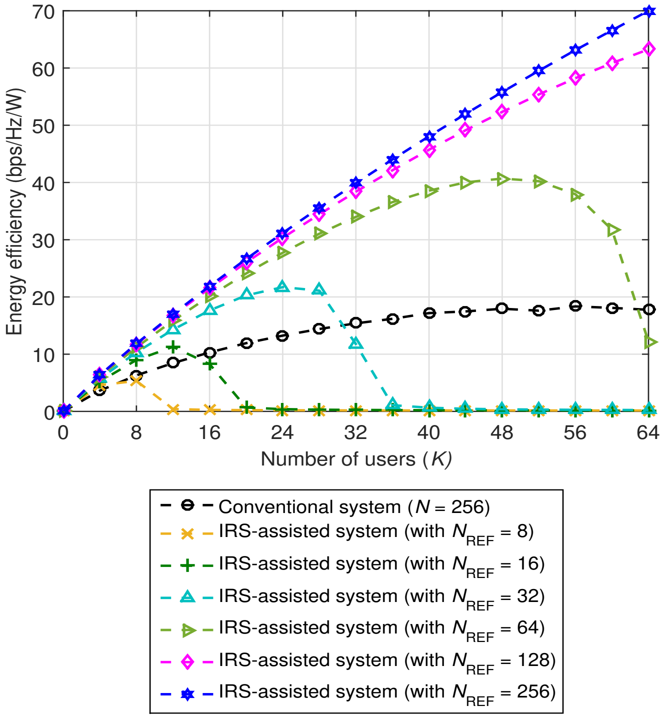

Fig. 5. EE performance of IRS-assisted fully digital systems with ZF precoding scheme employing $N = 256$ antenna elements at SNR = 30 dB.

34.4 mW and ρ = 32 mW (15 dBm) are assumed as practical values of the power consumption [20]. In addition, P_{E} = 5 mW is also assumed as considered in [16] and [21]. It can be clearly noticed from these figures that the larger the number of users, K, the more EE improvements are achieved. It can be also noticed from these figures that increasing the number of antenna elements, N, affected the EE performance. For example, the amount of EE improvement is about 55.6 bps/Hz/W when N = 128 antenna elements and N_{REF} = 128 at K = 40 users, and approximately 31.33 bps/Hz/W when N = N_{REF} = 256, and K = 40 users.

Moreover, the EE of the proposed IRS-assisted beamspace mmWave massive MIMO with IA beam selection scheme employing N = 128 and 256 antenna elements is depicted in Figs. 6 and 7, respectively. The EE is evaluated in these two figures with varying the number of passive elements, and SNR is set as 30 dB. These two figures show that the EE improves as the number of passive elements increases, and the proposed IRS-assisted beamspace mmWave massive MIMO system with IA beam selection scheme outperforms the conventional system with IA beam selection scheme when the number of reflecting elements is higher than the number of users. In other words, the EE performance of the proposed system is worse than the EE of the conventional system when the number of reflecting elements is lower than the number of users. Additionally, it is noticeable that almost the same EE performance is achieved in the proposed IRS-assisted systems with IA beam selection scheme regardless the number of antenna elements.

In contrast, the previous results reveal that IRS-assisted beamspace mmWave massive MIMO systems with IA beam selection scheme provide lower achievable sum-rate performance than the fully digital ZF systems for the same configuration. On the other hand, the proposed IRS-assisted systems with IA beam selection scheme always provide higher EE than the fully digital ZF systems.

IV. CONCLUSIONS

In this paper, IRS-assisted beamspace mmWave massive MIMO system with IA beam selection scheme is proposed by taking the potential multiuser interferences into account. It has been shown from the simulation results that this proposed scheme can achieve a considerable performance gain over the conventional schemes. Additionally, it is found that this gain increases when the number of low-cost passive elements exceeds the number of users. Moreover, the proposed systems can potentially offer high EE as compared to the conventional systems. Our future studies will focus on the performance of multiple distributed IRS-assisted beamspace massive MIMO systems with beam selection schemes and deep learning-based channel estimation.

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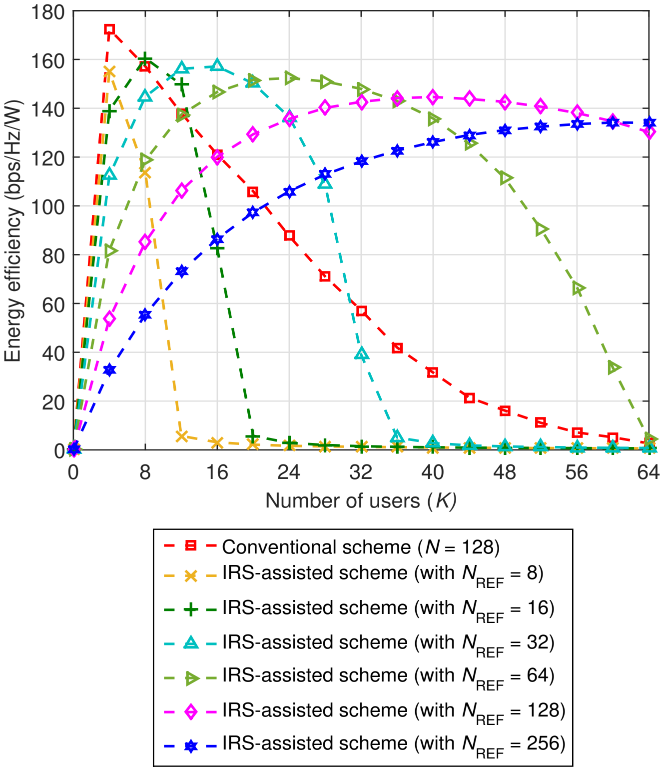

Fig. 6. EE performance of IRS-assisted beamspace mmWave massive MIMO with IA beam selection scheme employing $N = 128$ antenna elements at SNR = 30 dB.

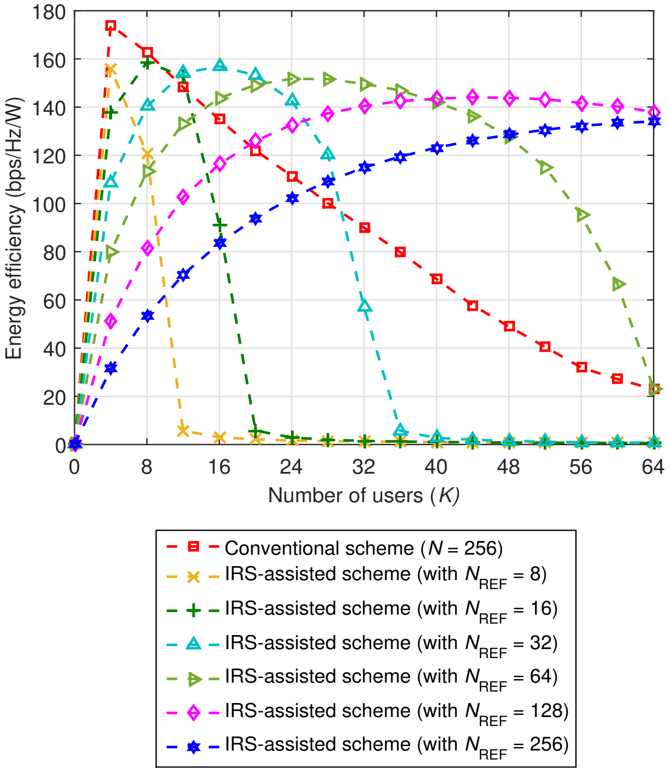

Fig. 7. EE performance of IRS-assisted beamspace mmWave massive MIMO with IA beam selection scheme employing $N = 256$ antenna elements at SNR = 30 dB.

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