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Millimetre Wave MIMO-OFDM with Index Modulation: A Pareto Paradigm on Spectral-Energy Efficiency Trade-off

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ABSTRACT

Multiple-input multiple-output orthogonal frequency division multiplexing with index modulation (MIMO-OFDM-IM) has recently received increased attention, due to the potential advantage to balance the trade-off between spectral efficiency (SE) and energy efficiency (EE). In this paper, we investigate the application of MIMO-OFDM-IM to millimetre wave (mm Wave) communication systems, where a hybrid analogy digital (HAD) beamforming architecture is employed. Taking advantage of the Pareto-optimal beam design, we propose a feasible solution to approximately achieve a globally Pareto-optimal trade-off between SE and EE, and the collision constraints of the multi-objective optimization problem (MOP) can be solved efficiently. Correspondingly, the MOP of SE-EE trade-off can be converted into a feasible solution for energy-efficient resource usage, by finding the Pareto-optimal set (POS) towards the Pareto front. This combinatorial-oriented resource allocation approach on the SE-EE relation considers the optimal beam design and power control strategies for downlink multi-user mm Wave transmission. To ease the system performance evaluation, we adopt the Poisson point process (PPP) to model the mobile data traffic, and the evolutionary algorithm is applied to speed up the search efficiency of the Pareto front. Compared with benchmarks, the experimental results collected from extensive simulations demonstrate that the proposed optimization approach is vastly superior to existing algorithms.

Index Terms—MIMO-OFDM, index modulation, spectral efficiency, energy efficiency, Pareto-optimal set, mm Wave communication.

1. INTRODUCTION

In recent years, large-scale wireless networks such as the Internet of things (IoT) and wireless drawback, especially for non-chargeable devices. In addition to a large amount of power consumption for transmission, RF chains also contain some of the most energy hungry components in a transmission system, e.g., digital-to-analog converters (DACs), amplifiers, and frequency synthesizers. These components substantially increase the circuit power dissipation of the BS. In this context, many studies discussed circuits design challenges in implementing energy efficient multi-antenna architectures [10]–[15]. Meanwhile, it has been demonstrated that the energy costs represent a significant portion of the total energy consumption of a network. Seriously, the radio network itself could be the most energy-consuming part, occupying ca. 80% of an operator’s entire energy consumption. This results in major economic and technical challenges [16], [17]. Due to these facts, wireless operators resort to green wireless networks, where energy efficiency (EE) and SE are the main performance metrics for reducing the prohibitive cost and energy consumption. Unfortunately, according to the Shannon-Hartley theorem, conflicts of objects are usually difficult to balance while optimizing both SE and EE simultaneously. For mm Wave MIMO systems with HAD beamforming, spectral- and energy-efficient system-level design is still an imminent challenge. It is mainly because the power consumption is very high owing to a large number of radiating elements, ultra-dense BS sites, and heavy data traffic load, etc [18]. It should be emphasized that a large number of the existing investigations on the general SE-EE relation have been comprehensively conducted. They provided good insights into the joint SE-EE trade-off for different scenarios, e.g., single/multiple cell deployment etc [18]–[22]. To jointly solve the multi-objective optimization problem (MOP) in the wideband regime, there have been some works focusing on energy efficient resource allocation/scheduling with guaranteed quality of service (QoS) [19], [23], and optimal resource allocation policy [19], [24], [25]. For example, a complete analysis of the SE and EE of two hybrid structures was provided in [13], [26]. The relationship between SE and EE with partially-connected HAD architecture was examined for optimal trade-off in [26]– [28]. The work in [27] proposed a successive interference cancelation (SIC)-based HAD beamforming for mm Wave MIMO systems. The authors of [29] formulated a decoupled two stage HAD design to maximize the SE and EE in a mm Wave massive MIMO system. In [30], Ribeiro et al. investigated the EE of quantized hybrid transmitters and proved that the topology of phase-shifting components can offer a better SEEE trade-off. Similarly, the authors of [31] studied the trade-off between SE and EE in consideration of the impact of nonlinear power amplifiers. Furthermore, the extensive investigations in [32]–[34] showed that the configurable hybrid precoding and energy-efficient beam designs are capable of effectively improving the SE and EE, respectively. In an effort to relax the paradox in the SE-EE trade-off, an alternative way is to decompose the MOP into a number of subproblems and optimize them simultaneously. The prospective study on multi-objective signal processing, revealed some facts, such as the respective scalarized problems, the resource optimization and allocation, as well as algorithmic tools in related fields. The authors of highlighted the fact that the multi-component Pareto-optimization will gradually become the norm. It differs from simply minimizing a single metric of the system, such as the bit error rate (BER), the power consumption or the complexity. In Di Renzo et al. derived an explicit analytical formulation of the SE-EE Pareto front to solve a bi-objective optimization problem, and proved that the Pareto front is constituted by a subset of the SEEE trade-off. In brief, the use of Pareto property has recently emerged as an attractive solution, showing a connection of an allocation state of resources with Pareto-optimal transmission design . As a novel digital modulation scheme with high SE and EE, index modulation uses the indices of the building blocks of the communication system to implicitly convey additional information bits. These approaches thereby create completely new dimensions for data transmission. Inspired by the concept of subcarrier index modulation (SIM) in OFDM with index modulation (OFDM-IM) has been regarded as a possible candidate for next-generation wireless networks. More specifically, the extensions of OFDM-IM in various formats have been regarded as appealing modulation candidates for mm Wave communications and MIMO-OFDM systems. Among different IM schemes, MIMO-OFDM with index modulation (MIMO-OFDM-IM) provides a beneficial transmission paradigm. The study demonstrated that MIMO-OFDM-IM can offer significantly improved transmission rates for practical systems, as well as a better error performance than conventional

MIMO-OFDM. In the MIMO-OFDM-IM scheme, each parallel stream of information is modulated by both subcarrier indices and M-ary constellation symbols. Therefore, it has the potential to provide a flexible trade-off between SE and EE. For a typical MIMO-OFDM mm Wave system, it is worth noting that with the extremely increasing of bandwidth and frequency at mm Wave frequencies, the escalating energy consumption necessitates a high EE as well as a desirable SE. In this context, MIMO-OFDM-IM has the potential to satisfy the above requirements. Motivated by these facts, we propose an SE-EE maximization IM scheme for multi-user mm Wave MIMO-OFDM systems. Pareto-optimal beam design is taken into account with respect to the energy-efficient resource allocation in beam space. Because the total energy consumption of cellular system is dominated by the BS, we focus on the SE-EE trade off in downlink. The main contributions of this paper can be summarized as follows:

- We propose a MIMO-OFDM-IM scheme for HAD beamforming mm Wave systems, and a maximum likelihood (ML) detector is employed to decode the information bits from each subblock of MIMO-OFDM-IM. To the best of our knowledge, this is the first work that integrates the concept of IM into mm Wave MIMO-OFDM communication systems. Meanwhile, we investigate the energy efficient aspects on designing the HAD precoder and combiner. Interestingly, the proposed scheme integrating MIMO-OFDM-IM can improve the SE-EE and transmission reliability with low complexity. It has the potential to extend the coverage without capacity penalty. This, collaborating with the HAD beamforming architecture, allows more degrees of freedom to achieve realistic SE-EE maximization in mm Wave cellular networks.
- From the perspective of Pareto principle, we propose a Pareto-optimal beam design scheme for energy-efficient resource usage for downlink mm Wave transmissions. By the construction of the Pareto-optimal set (POS), we propose a feasible combinatorial-oriented power control strategy, i.e., resource reallocation scheme, to approximately achieve a Pareto-optimal trade-off between SE and EE. We give a fundamental guideline to tackle the MOP, where Pareto front is constituted by a subset of the SE-EE trade-off.
- In this new paradigm, our approach for solving the SE-EE trade-off is to convert the MOP into an evolutionary search process of POS. We show that there exists a globally optimal solution that maximizes EE, while still maintaining an increased SE. Moreover, we show that the combinational-oriented transmit power control strategy is effective to balance the total transmit power, and the globally optimal solution to the SE-EE maximization can be achieved.

To systematically evaluate the performance of multiuser networks, we introduce a Poisson point process (PPP) to model the spatial distribution of users, and the evolutionary algorithm is applied to speed up the search process for approaching the Pareto front asymptotically. The solving process of POSs associated with all users is abstracted as an evolutionary population-based MOP, which is potentially capable of applying to other multiuser communication systems.

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2. LITERATURE SURVEY

Mobile communication has been one of the most successful technology innovations in modern history. The combination of technology breakthroughs and attractive value proposition has made mobile communication an indispensable part of life for 5 billion people. Due to the increasing popularity of smart phones and other mobile data devices such as netbooks and eBook readers, mobile data traffic is experiencing unprecedented growth. Some predictions indicate that mobile data will grow at 108 percent compound annual growth rate (CAGR) [1] with over a thousandfold increase over the next 10 years. In order to meet this exponential growth, improvements in air interface capacity and allocation of new spectrum are of paramount importance. The current fourth-generation (4G) systems including LTE and Mobile WiMAX already use advanced technologies such as orthogonal frequency-division multiplexing (OFDM), multiple input multiple-output (MIMO), multi-user diversity, link adaptation, turbo code, and hybrid automatic repeat request (HARQ) in order to achieve spectral efficiencies close to theoretical limits in terms of bits per second per Hertz per cell [2]. With limited room for further spectral efficiency improvement, another possibility to increase capacity per geographic area is to deploy many smaller cells such as femtocells and heterogeneous networks. However, because capacity can only scale linearly with the number of cells, small cells alone will not be able to meet the capacity required to accommodate orders of magnitude increases in mobile data traffic. As the mobile data demand grows, the sub-3 GHz spectrum is becoming increasingly crowded. On the other hand, a vast amount of spectrum in the 3–300 GHz range remains underutilized. The 3–30 GHz spectrum is generally referred to as the super high frequency (SHF) band, while 30–300 GHz is referred to as the extremely high frequency (EHF) or millimetre-wave band. Since radio waves in the SHF and EHF bands share similar propagation characteristics, we refer to 3–300 GHz spectrum collectively as millimetre-wave bands with wavelengths ranging from 1 to 100 mm. Millimetre-wave communication systems that can achieve multigigabit data rates at a distance of up to a few kilometres already exist for point-to-point communication. However, the component electronics used in these systems, including power amplifiers, low noise amplifiers, mixers, and antennas, are too big in size and consume too much power to be applicable in mobile communication. The availability of the 60 GHz band as unlicensed spectrum has spurred interest in gigabit-per-second short-range wireless communication. Several industrial standards have been developed, such as Wireless HD technology, ECMA-387, IEEE 802.15.3c, and IEEE 802.11ad. Integrated circuit (IC)-based transceivers are also available for some of these technologies. Much of the engineering efforts have been invested in developing more power efficient 60 GHz RFICs [3]. Many of these technologies can be transferred to RFIC design for other millimetre-wave bands. In this article, we explore the 3–300 GHz spectrum and describe a millimetre-wave mobile broadband (MMB) system that utilizes this vast spectrum for mobile communication. We describe the millimetre-wave spectrum and its propagation characteristics. We then discuss the network architecture, followed by the air interface design of the MMB system. After that, we conclude the article with a summary and brief discussion of future work. Millimeter wave (mm Wave) technology is one of the promising candidates for future generation wireless cellular communication systems to address the current challenge of bandwidth shortage [1]– [3]. The mm Wave signals experience severe path loss, penetration loss and rain fading as compared to signals in current cellular band (3G or LTE) [4]. However, the shorter wavelength at mm Wave frequencies also enables more antennas to be packed in the same physical dimension, which allows for large-scale spatial multiplexing and highly directional beamforming. This leads to the advent of large-scale or massive multiple-input multiple-output (MIMO) concept for mm Wave communications. Although the principles of the beamforming are the same regardless of carrier frequency, it is not practical to use conventional fully digital beamforming schemes [5]–[9] for large-scale antenna arrays. This is because the implementation of fully digital beamforming requires one dedicated radio frequency (RF) chain per antenna element, which is prohibitive from both cost and power consumption perspectives at mm Wave frequencies [10].

To address the difficulty of limited number of RF chains, this paper considers a two-stage hybrid beamforming architecture in which the beamformer is constructed by concatenation of a low-dimensional digital (baseband) beamformer and an RF (analog) beamformer implemented using phase shifters. In the first part of this paper, we show that the number of RF chains in the hybrid beamforming architecture only needs to scale as twice the total number of data streams for it to achieve the exact same performance as that of any fully digital beamforming scheme regardless of the number of antenna elements in the system. The second part of this paper considers the hybrid beamforming design problem when the number of RF chains is less than twice the number of data streams for two specific scenarios:

- The point-to-point multiple-input multiple-output (MIMO) communication scenario with large-scale antenna arrays at both ends;
- The downlink multi-user multiple-input single-output (MU-MISO) communication scenario with large-scale antenna array at the base station (BS), but single antenna at each user. For both scenarios, we propose heuristic algorithms to design the hybrid beamformers for the problem of overall spectral efficiency maximization under total power constraint at the transmitter, assuming perfect and instantaneous channel state information (CSI) at the BS and all user terminals.

The numerical results suggest that hybrid beamforming can achieve spectral efficiency close to that of the fully digital solution with the number of RF chains approximately equal to the number of data streams. Finally, we present a modification of the proposed algorithms for the more practical scenario in which only finite resolution phase shifters are available to construct the RF beamformers. It should be emphasized that the availability of perfect CSI is an idealistic assumption which rarely occurs in practice, especially for systems implementing large-scale antenna arrays. However, the algorithms proposed in the paper are still useful as a reference point for studying the performance of hybrid beamforming architecture in comparison with fully digital beamforming. Moreover, for imperfect CSI scenario, one way to design the hybrid beamformers is to first design the RF beamformers assuming perfect CSI, and then to design the digital beamformers employing robust beamforming techniques [11]– [15] to deal with imperfect CSI. It is therefore still of interest to study the RF beamformer design problem in perfect CSI. To address the challenge of limited number of RF chains, different architectures are studied extensively in the literature. Analog or RF beamforming schemes implemented using analog circuitry are introduced in [16]–[19]. They typically use analog phase shifters, which impose a constant modulus constraint on the elements of the beamformer.

3. PROPOSED SYSTEM

The transceiver block diagram of MIMO-OFDM-IM for the multi-user mm Wave system is illustrated in Fig. 1, where the conventional configuration of HAD beamforming architecture is adopted. In this paper, we focus on the downlink multiuser transmission and consider a single cell MIMO-OFDM network. A BS with Nt transmit antennas and Mt RF chains serves K active users, each of them using Nr, k receives antennas and Mr, k RF chains, where k ∈ {1, . . ., K}. For any user k, we assume that the BS transmits Jk ≤ Nr, k data streams with Mt, k RF chains and Nt, k transmit antennas (ÍK k=1 Jk ≤ Mt ≤ Nt). The HAD beamforming architecture of BS is constructed by the concatenation of a digital precoder associated with the nth subcarrier.

For such a system incorporating the OFDM-IM transceiver, a total of Tk, Jk incoming bits from the input alphabet are first split into Jk parallel streams. Each Tk -bit stream to the digital precoder Un, k is pre-processed in each branch of the transmitter by the OFDM-IM modulator. Afterwards, the BS applies the baseband digital precoder Uk to modify the obtained OFDM-IM data blocks. Typically, the inverse fast Fourier transform (IFFT) is applied to derive a time-domain signal, and the cyclic prefix (CP) is appended to prevent the OFDM symbol from inter-symbol interference. At the receiver, the mobile station (MS) performs an FFT of the time-domain received signal and removes the CP. At the end, MS applies the digital combiner Vn, k, and the received signal can be separated and demodulated by the ML or minimum mean square error (MMSE) detector. In our work, the effect of CP on SE and EE could be regarded as a stable impact factor, since the length of CP is conservatively chosen and fixed in most current standards. Within the OFDM-IM modulator, the incoming Tk -bit stream is equally divided into G groups, in which p = Tk /G bits for each group are split into two subgroups, i.e., the index selection and M-ary modulation subgroups. For a feasible frequency bandwidth BT with total OFDM subcarriers, we assume that N consecutive OFDM subcarriers are assigned for each given subblock g.

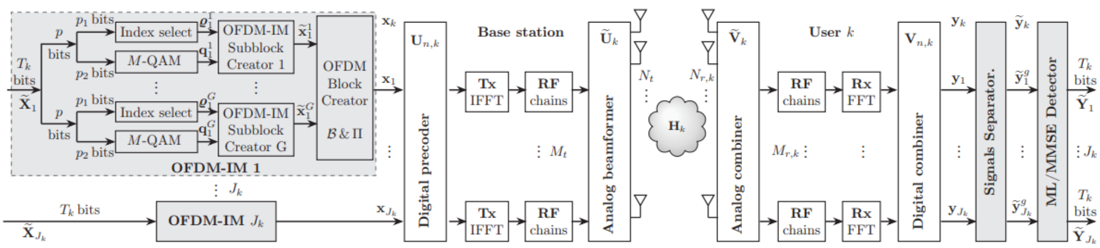

Fig 3.1: Block diagram of the mm Wave MIMO-OFDM-IM

For each subblock g, considering the number of active subcarriers NA, k , the corresponding index selection subgroup contains p1 = blog2 C(N, Na, k)c bits for determining the indices of the active subcarriers, where g ∈ {1, . . ., G}; The M-ary modulation subgroup contains the remaining p2 = NA, k log2 M bits, which are mapped onto a predefined M-array quadrature amplitude modulation (M-QAM) signal constellation S to obtain the first-stage modulation subblock from the OFDM-IM subblock creator. For simplicity, we denote Nk as the index pattern of user k.

In practice, the total energy consumption of a cellular system, consisting of both circuit power consumption and transmit power consumption, is dominated by the BS. Generally, the power consumption model at the BS consists of static and dynamic power consumption. The static power consumption model is constructed by the power consumption of all power amplifiers. The transmit power (dynamic) contains all the other circuit power. In this paper, we adopt a linear power consumption model proposed by:

$$P_{\mathrm{sys},k} = P_{t,k} + J_k P_{\mathrm{RF},k} + P_{c,k} + N_{t,k} P_{\mathrm{shift}},$$

It is worth to note that an exact computation of the dissipated power is a very difficult task [28]. Therefore, our work focuses on a generalized power consumption model, whose energy consumption can have a direct impact on energy-efficient optimal beam design.

$$\mathrm{SINR}_{\mathrm{sys}} = \sum\nolimits_{k=1}^{K} \omega_k \mathrm{SINR}_k .$$

To guarantee the fairness among users in the multiuser network, the max-min SINR problem is considered, which deals with the sum-rate maximization problem and guarantees the best performance of receivers. It is worth highlighting that the theoretical and algorithmic connection between maximizing the weighted sum rate and the max-min SINR problem was revealed in. Leveraging on this fact, the joint optimization of SE-EE maximization is equivalent to the max-min SINR power control. This transformed problem has already been constructed and the interested readers can refer to a detailed proof in the aforementioned literature. Typically, the max-min SINR problem satisfying the overall transmit power constraint can be formulated as

$$\text{s.t.} \quad P_{t,k} \leq P_{t,k}^{\max}, \ \forall\, k, \ K \leq \sum\nolimits_{k=1}^{K} J_k \leq M_t,$$

where P max t, k is the maximum downlink transmission power of user k. It should be noted that only considers a single-user case, which represents a locally optimal solution, only with respect to feasible solutions close to that point. To find the globally optimal solution, a global coordination is naturally required for every feasible solution of whole users. Equivalently, since each global maximum is also

$$\zeta_k = J_k \left[\mathbb{E}\left(\frac{N_{A,k}}{N}\right) \log_2 \det(\mathbf{I}_{J_k} + \mathbf{W}_{n,k} \mathbf{\Lambda}_{n,k}^{-1} \mathbf{W}_{n,k}^{H} \mathbf{H}_k \mathbf{F}_{n,k}^{H} \mathbf{F}_{n,k} \mathbf{H}_k^{H}) + \frac{1}{N} \log_2 C(N, N_{A,k}) \right],$$

A local maximum, we can determine the overall optimization problem by maximizing the minimum weighted sum of SINR. The objective function in terms of EE is defined as the system capacity (bits/s) divided by the total power consumption. The EE (bits/J) of user k is then defined as

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$$\begin{aligned} \max_{\{\mathbf{F}_k,\mathbf{W}_k\}_{k=1}^{K}} \quad & \eta_k = \frac{B_{T_k} \cdot \zeta_k}{\sum_{n=1}^{N} \left\|\mathbf{F}_{n,k}\right\|^2 + J_k P_{\mathrm{RF},k} + P_{c,k} + N_{t,k} P_{\mathrm{shift}}} \\ \text{s.t.} \quad & \sum_{n=1}^{N} \left\|\mathbf{F}_{n,k}\right\|^2 \leq P_{t,k}^{\max}. \end{aligned}$$

In the following, our goal is to concurrently optimize the SE and EE under the individual SINR constraints. It inevitably brings about conflicts of interest among objective functions and needs a trade-off. According to the classical SE-EE trade-off paradigm, the objective function can be rewritten a

$$\eta_{\mathrm{total}} = \frac{B_T \cdot \zeta_{\mathrm{total}}}{\log_2\left(\sum_{k=1}^{K} P_{\mathrm{sys},k}\right)}.$$

4. NUMERICAL RESULTS

Simulation settings:

In the considered simulation scenario, a cellular mm Wave network with the HAD architecture is considered. The azimuth angles are assumed to be uniformly distributed over [0; π], and the AoA/AoD elevation angles are uniformly distributed over [−π/2; π/2]. As shown in Section IV-A, the users are independent and uniformly distributed abiding a spatial PPP.

Parameters	Value	Parameters	Value
Carrier frequency	28 GHz	K	8
Bandwidth	200 MHz	Maximum $\mathbf{J}_k$ at BS/MS	16/4
Number of subcarriers	32	N_t	256
Symbol duration	3.7 µs	$N_{r,k}$ with per-user	16
Cell radius	200 m	$P_{k,t}^{max}$	38 dBm
Modulation	QPSK	$P_{RF,k}$	250 mW [6]
Number of channel paths	4	$P_{c,k}$	200 mW
Receiver Noise	-174 dBm/Hz	P_{shift}	88 mW [28]

TABLE I: System configuration and simulation setting parameters

The population then evolves toward nearby globally optimal SE-EE trade-off, i.e., sorting the best non-dominated solution {XPOSk }kK=1, through subsequent iterations, called generations. Finding the optimal solution to toward the Pareto front involves three key steps for the decision-making process. Correspondingly, the user own expected throughput is independently characterized by the PPP intensity λ. To simulate strong users and weak users, the desirable users are chosen from 100 user samples, which are all generated by an independent two-dimensional homogeneous PPP. The performance evaluation is carried out through Monte Carlo simulations, and each result is the average of 100 independent realizations. Finally, the convergence behaviour of the proposed POS searching algorithm is investigated. Table 1 summarizes the simulation parameters and the experimental setup

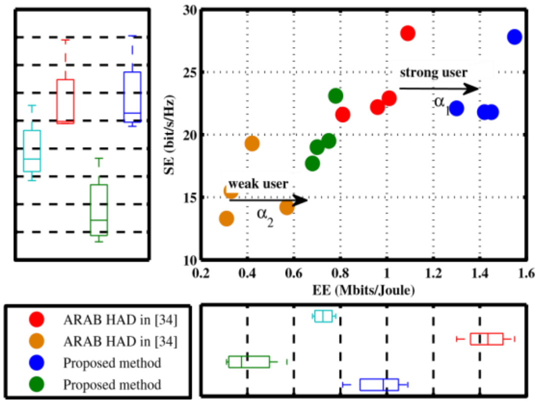
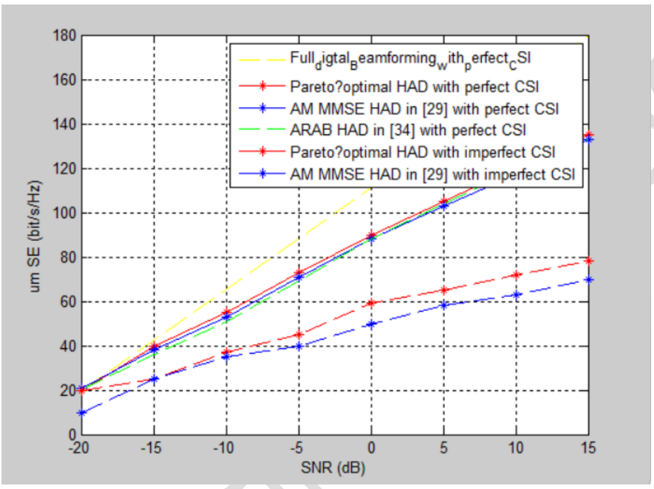
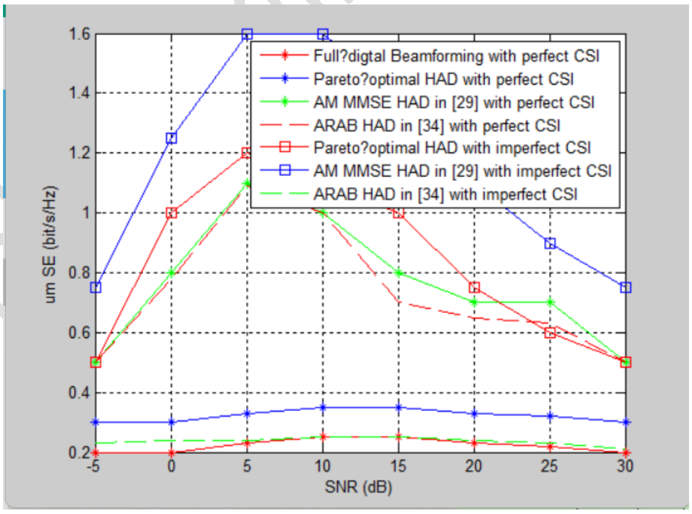


Fig 1: Globally Optimal Trade Off





5. CONCLUSION

An energy-efficient mm Wave MIMO-OFDM-IM system with the HAD beamforming architecture was proposed and investigated. We provided the optimal solution that allows a higher degree of freedom to achieve realistic SE-EE maximization in mm Wave cellular networks. We have given a baseline design to solve the SE-EE trade-off for mm Wave MIMO-OFDM-IM systems. The key finding of this study is that the use of Pareto-optimal beam design can achieve a globally optimal trade-off between SE and EE, and the collision constraints of

MOP can be efficiently released. Also, the flexible power reallocation scheme can significantly extend the coverage for the cell-edge users. It is expected that the density of the BS may have a more significant impact on the network SE and/or spatial SE, as well as EE scales with the user density. In future work, we will consider a wide range of conditions as well as the equivalent form of the SE-EE trade-off, such as combining some fundamental results from random matrix theory

REFERENCES

[1] Y. Yang, S. Dang, M. Wen, and M. Guizani. Mmwave MIMO-OFDM with index modulation: A Pareto-optimal trade-off on spectral-energy efficiency. In Proc. IEEE Global Common. Conf., pages 1–6, Taipei, Taiwan, December 2020.

[2] Z. Pi and F. Khan. An introduction to millimetre-wave mobile broadband systems. IEEE Common. Mag., 49(6):101–107, June 2011.

[3] T. S. Rappaport et al. Millimetre wave mobile communications for 5G cellular: It will work! IEEE Access, 1:335–349, May 2013.

[4] F. Sohrabi and W. Yu. Hybrid digital and analog beamforming design for large-scale antenna arrays. IEEE J. Sel. Topics Signal Process., 10(3):501–513, April 2016.

[5] A. Alkhateeb, J. Mo, N. Gonzalez-Prelcic, and Jr. R. W. Heath. MIMO precoding and combining solutions for millimetre-wave systems. IEEE Commun. Mag., 52(12):122–131, December 2014.

[6] Jr. R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed. An overview of signal processing techniques for millimetre wave MIMO systems. IEEE J. Sel. Topics Signal Process., 10(3):436– 453, April 2016.

[7] M. Xiao et al. Millimetre wave communications for future mobile networks. IEEE J. Sel. Areas Commun., 35(9):1909–1935, June 2017.

[8] X. Yu, J. C. Shen, J. Zhang, and K. B. Letaief. Alternating minimization algorithms for hybrid precoding in millimetre-wave MIMO systems. IEEE J. Sel. Topics Signal Process., 10(3):485–500, April 2016.

[9] A. Alkhateeb, J. Palacios, and Jr. R. W. Heath. Frequency selective hybrid precoding for limited feedback millimetre wave systems. IEEE Trans. Commun., 64(5):1801–1818, May 2016.

[10] Y. Li, B. Bakkaloglu, and C. Chakrabarti. A comprehensive energy model and energy-quality evaluation of wireless transceiver front-ends. In Proc. IEEE Workshop Signal Process. Syst. Des. Implementation, pages 262–267, Athens, Greece, November 2007.

[11] Z. Hasan, H. Boostanimehr, and V. K. Bhargava. Green cellular networks: A survey, some research issues and challenges. IEEE Commun. Surv. Tut., 13(4):524–540, November 2011.
[12] Recommendation ITU-T L.1350 (2016), energy efficiency metrics of a base station site, October 2016.

[13] A. Puglielli et al. Design of energy- and cost-efficient massive MIMO arrays. Proc. IEEE, 104(3):586–606, March 2016.

[14] E. Bjornson, M. Matthaiou, and M. Debbah. Massive MIMO with non- Ü ideal arbitrary arrays: hardware scaling laws and circuit-aware designs. IEEE Trans. Wireless Commun., 14(8):4353–4368, August 2015.

[15] H. Yan, S. Ramesh, T. Gallagher, C. Ling, and D. Cabric. Performance, power, and area design trade-offs in millimetre-wave transmitter beamforming architectures. IEEE Circuit. & Syst. Mag., 19(2):33–58, May 2019.

[16] M. Wen, B. Zheng, K. J. Kim, M. Di Renzo, T. A. Tsiftsis, K.-C. Chen, and N. Al-Dhahir. A survey on spatial modulation in emerging wireless systems: Research progresses and applications. IEEE J. Sel. Areas Commun., 37(9):1949–19972, September 2019.

[17] A. Zappone and E. Jorswieck. Energy Efficiency in Wireless Networks via Fractional Programming Theory. Now Foundations and Trends, Boston, MA, USA, 2015.

[18] L. Sboui, Z. Rezki, A. Sultan, and M. Alouini. A new relation between energy efficiency and spectral efficiency in wireless communications systems. IEEE Wireless Commun., 26(2):168–174, June 2019.

[19] C. Xiang, G. Li, S. Zhang, Y. Chen, and S. Xu. Energy- and spectral efficiency trade off in downlink OFDMA networks. IEEE Trans. Wireless Commun., 10(11):3874–3886, November 2011.

[20] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta. Energy and spectral efficiency of very large multiuser MIMO systems. IEEE Trans. Commun., 61(4):1436–1449, April 2013.