Multi-Cluster Coordination Industrial IoT: The Era of Non–Orthogonal Transmission

Haiyong Zeng, *Student Member, IEEE*, Jingjing Wang, *Senior Member, IEEE*, Zhongxiang Wei, *Member, IEEE*,
Xu Zhu, *Senior Member, IEEE*, Yufei Jiang, *Member, IEEE*, Yuanchen Wang, *Student Member, IEEE*,
and Christos Masouros, *Senior Member, IEEE*

Abstract—**The imminent industrial Internet of Things (IIoT) aims to provide massive device connectivity and support ever increasing data demands, making today's production environment on the edge of a new era of innovations and changes. In multi-cluster IIoT, the devices may suffer severe inter-cluster interference due to the intensive frequency reuse among adjacent access points, thus deteriorating their quality of service. To address this issue, conventional multi-cluster coordination in IIoT provides orthogonal code-, frequency-, time- or spatial-domain multiple access for interference management, which yet results in a waste of resources, especially in the context of explosively increased number of devices. In this article, we review the recent advances in energy-efficient solutions for multi-cluster coordination relying on non-orthogonal multiple access and constructive interference exploitation techniques. Moreover, their applications for handling interference management are elaborated at different levels of multi-cluster coordination. Departing from traditional orthogonal multiple access, this line of research provides a new dimension for inter- and intra-cluster multi-device interference management in IIoT. This family of exciting solutions enables disruptive visions for multi-cluster coordination with an eye on massive devices' access and high energy-efficient design tailored for IIoT systems.**

Index Terms—**Industrial Internet of Things, multi-cluster coordination, interference management, non-orthogonal multiple access, constructive interference.**

I. INTRODUCTION

Industrial Internet of Things (IIoT), capable of supporting massive access, sensing and interacting with everyone and everything, has been envisioned as a potential support for the imminent industry 4.0 [1]. The ubiquitous connectivity, which includes a variety of industrial devices, such as robots, sensors, co-robots and other facilities, enables data collection, exchange and analysis. This potentially facilitates improvements in efficiency, productivity and other economic benefits. IIoT networks aim to provide heterogeneous services for the massive devices, where the use cases can be roughly classified into massive machine-type communications (MMTC), and ultra-reliable and low latency communications (URLLC). Specifically, MMTC, which is the focus of our paper, is featured by massive connectivity, low power consumption and high energy efficiency, while URLLC is mainly designed to provide high reliability and low latency for serving mission critical applications, such as industrial real-time automation. Evidently, wireless communications in IIoT cause severe access congestion due to insufficient frequency, time, power, antennas, and other resources. One of the efficient techniques is to cluster massive devices into a number of small groups [2], with a part of resources being shared and reused in different clusters, referred to as multi-cluster IIoT. A typical cluster-based IIoT is depicted in Fig. 1. Each cluster is equipped with one or more access points (AP)s to provide high-quality wireless transmissions. A number of APs are connected by a high-speed optical fiber to data collection module and application server for resource coordination, authentication and interference management.

The wireless interface management between APs and devices is essential in IIoT, from the perspectives of radio spectrum allocation and interference management. The conventional radio resource management techniques have been extensively investigated in cellular networks, where frequency reuse is adopted among base stations. Nevertheless, the number of connections in IIoT overwhelms that in cellular networks, typically requiring a dense AP deployment. The frequency reuse design leads to a low level of resource utilization and incurs stronger inter-cluster interference [3] [4], which is even severer for the devices at the edge of the clusters, and significantly deteriorates their quality of service (QoS). Considering the infrastructure of multi-cluster IIoT where the deployed APs are connected to a centralized cloud manager for storage, computing, and signal processing, the coordination techniques are naturally suitable for the wireless interface management in IIoT. Hence, the APs can coordinate with each other to share channel state information (CSI) and/or the intended transmission data for joint signal processing and interference control [1] [2]. More specifically, in [1], a coordination scheme was adopted in IIoT to assist data offloading and assure load balance, while an energy-efficient coordination IIoT framework was presented for balancing the traffic load, alongside an associated switching-on/off scheme for prolonging the lifetime of the system in [2]. Nevertheless,

---

H. Zeng, X. Zhu, and Y. Jiang are with the School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen, China. X. Zhu is also with the Department of Electronics and Electrical Engineering at the University of Liverpool, Liverpool, UK. Email: zenghaiyong@stu.hit.edu.cn; xuzhu@liverpool.ac.uk; jiangyufei@hit.edu.cn.

J. Wang is with the School of Cyber Science and Technology, Beihang University, Beijing 100191, China. Email: drwangjj@buaa.edu.cn.

Z. Wei (corresponding author) is with the College of Electronic and Information Engineering, Tongji University, Shanghai 200092, China. Email: z_wei@tongji.edu.cn.

Y. Wang is with the Department of Electronics and Electrical Engineering at the University of Liverpool, Liverpool, UK. Email: yuanchen.wang@liverpool.ac.uk.

C. Masouros is with the Department of Electronics and Electrical Engineering at the University College London, London, UK. Email: c.masouros@ucl.ac.uk.

both the coordination designs in [1] [2] are based on the orthogonal multi-device access, and thus extra resources, *i.e.*, time, frequency and antennas, are required for multi-device access.

According to the coordination level among APs, the multi-cluster coordination techniques in IIoT can be mainly categorized into two modes: partially-coordinated beamforming (PBF) [5] [6] and fully-coordinated joint transmission (FJT) [1] [2] [7]. For the PBF mode, CSI is shared by a number of APs to design cooperative beamforming for suppressing inter-cluster interference. For the FJT mode, in addition to CSI, the intended transmission data are shared [7]. Since both CSI and the corresponding transmission data are available at all the coordinated APs, the FJT mode allows the coordinated APs to transmit the same data to the corresponding devices. Therefore, the FJT mode provides an improved degree-of-freedom (DoF) in terms of spatial diversity gain and achieves superior system performance than the PBF mode.

The research of the multi-cluster coordination IIoT has been conducted ranging from information-theoretic studies to protocol designs, as briefly summarized in TABLE I. In [5] and [6], the PBF schemes were considered where each AP only encodes and transmits signals to its local devices, and the inter-cluster interference is jointly suppressed by the APs as undesired noise. Generally, since only CSI is shared among APs, the beamforming design of the PBF system makes a trade-off between inter-cluster interference suppression and maximizing the devices' signal-to-interference-plus-noise ratio (SINR) within the cluster of interest, with a moderate level of coordination overhead. On the other hand, the FJT scheme can be regarded as a virtual multiple input and multiple output (MIMO) system where all AP-device links are utilized to convey data, at the expense of higher coordination overhead due to the CSI and data sharing mechanism among the APs [1] [2] [7].

These multi-cluster coordination techniques have distinct advantages and disadvantages, whereas their implementation in IIoT is still restrictive. It is because:

- Due to the massive connections of devices, intra-cluster (multi-device) interference within each cluster becomes a critical limitation for ensuring QoS target of devices. In terms of multi-device interference management, by the existing coordination systems, wireless resources such as time and frequency can only be exclusively assigned to one device on the basis of orthogonal multiple access (OMA). Nevertheless, the limitations of the orthogonality based methods are increasingly extrusive. Since IIoT is typically loaded with massive equipments, the conventional orthogonal approaches inevitably require extra time and frequency resources for providing strict orthogonality, otherwise only part of devices can be served at the cost of high latency and poor fairness.
- Apart from the orthogonal time/frequency access, another approach is based on the interference alignment (IA) technique, which provides spatial orthogonality for multi-device access. Nevertheless, it requires large-scale antennas to achieve strict spatial orthogonality by carefully designing the beamforming vector to cancel multi-device interference, which is cost/power consuming and thus may not be suitable for the small-sized APs.
- In IIoT communications, there is an urgent demand for providing high system throughput while limiting energy consumption. Hence, energy-efficiency (EE), defined as the ratio of throughput to total power consumption, has attracted much attention from vendors and researchers, where the conventional throughput maximization-oriented designs in cellular networks become incongruous.

In recent years, there has been increasing interest in collaborating non-orthogonal multiple access (NOMA) in IIoT and providing multi-device multiplexing. Since NOMA is able to multiplex a large number of devices onto the same frequency resource, it is particularly suitable for the MMTC application due to its enhanced multi-device access capability [3] [4]. Its applications in IIoT have been researched in terms of the NOMA-based parallel spaceborne antenna arrays calibrations [3] and impulsive noise mitigation [4]. Nevertheless, they merely applied NOMA for non-coordination IIoT, where the system performance may be significantly impaired by the intra-cluster interference. Furthermore, note that the intrinsic intra-cluster multi-device interference, also deemed as an underlying resource, has not been fully exploited when designing non-orthogonal transmission techniques. Considering the high device density in IIoT, if the rich multi-device interference can be utilized rather than being mitigated, the system performance can be significantly enhanced. This inspires the interest in treating the ubiquitous interference in IIoT as a green source with the aid of the spatially non-orthogonal design, namely constructive interference (CI).

Motivated by the above open issues, in this overview, we review the recent advancement of multi-cluster coordinated schemes in IIoT. Departing from the OMA-based coordination IIoT design [1] [2] or NOMA based non-coordination IIoT [3] [4], we analyze the fundamentals of accommodating non-orthogonal multi-device access, and even exploiting interference as a green source for multi-cluster coordinated IIoT. The rest of this paper is organized as follows. We first review the potential application of NOMA for multi-cluster coordinated IIoT in Section II. Afterwards, the fundamentals of CI and its application in the multi-cluster coordination schemes are introduced in Section III. Open challenges are investigated in Section IV, and a conclusion is drawn in Section V.

II. MULTI-CLUSTER COORDINATION WITH NON-ORTHOGONAL MULTIPLE ACCESS

As mentioned above, the conventional multi-cluster coordination methods (such as the PBF and FJT) provide orthogonal code-, time-, frequency- or spatial-domain multi-device access for interference management, which strictly limit the number of devices being served. To alleviate this, it is imperative to collaborate NOMA with multi-cluster coordination to provide flexible multi-device access, which also enables an improved level of DoFs in resource allocation and interference management. Together with the low power and high EE demands of IIoT communications, green multi-cluster coordinated NOMA

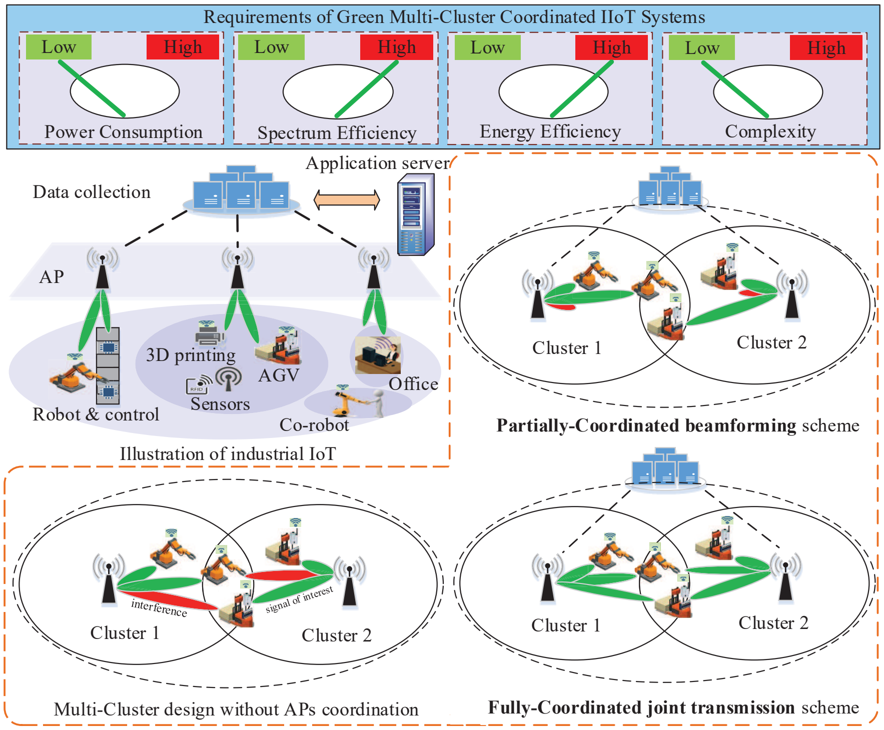


Fig. 1. Low energy consumption, high energy efficiency and low complexity techniques are preferable to enable an energy-efficient multi-cluster coordinated IIoT system.

TABLE I
BRIEF SUMMARY OF VARIOUS MULTI-CLUSTER COORDINATION TECHNIQUES

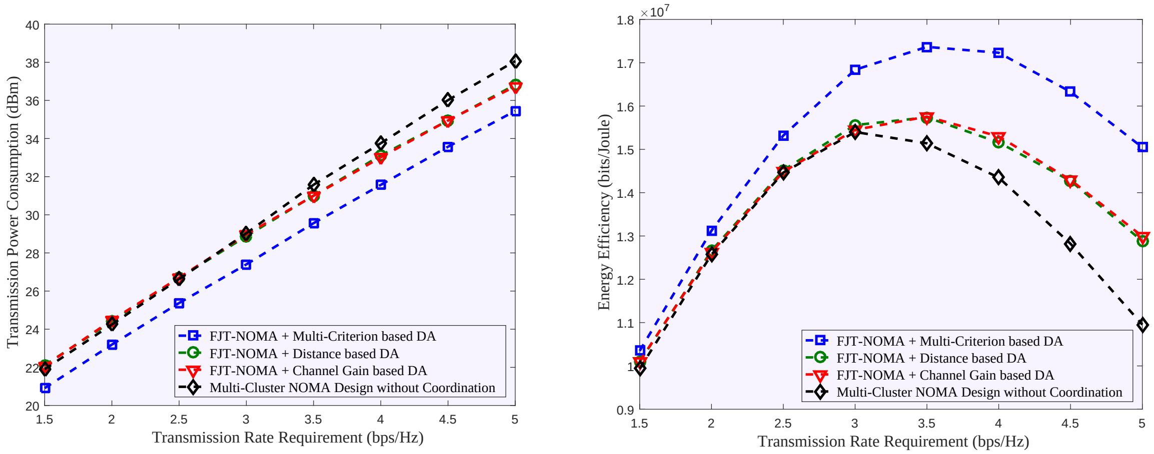
	PBF [5][6]	PBF-NOMA [8][9]	FJT [1][2][7]	FJT-NOMA [10][11]
Coordination Level	Low	Low	High	High
Shared Content among APs	CSI	CSI	CSI and intended transmission data	CSI and intended transmission data
Coordination Overhead	Moderate	Moderate	High	High
User Access Mode	OMA	NOMA	OMA	NOMA
Data Transmission	Cooperative beamforming	Cooperative NOMA beamforming	Joint transmission among APs	Joint transmission via a virtual MIMO and globe-manner NOMA
Number of Serving Devices	Limited multi-device access capacity	High multi-device access capacity	Limited multi-device access capacity	High multi-device access capacity
Interference Management	Suppressing inter-cluster interference		Utilizing the inter-cluster interference channel for data transmission	
	1. The intra-cluster interference is considered as a harmful element. 2. The effect of the intra-cluster interference needs to be suppressed as much as possible.			

IIoT system has become an essential and practical issue, as shown in Fig. 1. In this section, we first outline the design principles of NOMA in PBF and FJT. Then the device association (DA), successive interference cancellation (SIC) design, device grouping and power control policies tailored for IIoT are detailed.

A. Multi-Cluster Coordination NOMA Design

Based on the shared information among the coordinated APs, the multi-cluster coordinated NOMA techniques can be classified into partially-coordinated beamforming NOMA (PBF-NOMA) and fully-coordinated joint transmission NOMA (FJT-NOMA).

1) PBF-NOMA: In the PBF-NOMA, the devices are served by their associated local APs, and the devices within each cluster are scheduled into NOMA groups [8] [9]. Based on the shared devices' CSI among the APs, inter-cluster interference is suppressed by the partially-coordinated beamforming, while intra-cluster interference is handled by SIC design, as will be detailed in Subsection II-B. Compared to the conventional PBF-OMA designs [5] [6], the PBF-NOMA scheme can simultaneously support more device connections and provide a high level of DoFs in multi-device interference management.



(a)

(b)

Fig. 2. Transmission power consumption and EE performance, where 9 devices are randomly located into 2 coordinated clusters. The system bandwidth is 5 MHz. It is observed that 1) The FJT-NOMA scheme consumes less power and hence higher EE over the multi-cluster NOMA method without coordination; 2) With the multi-criterion based DA scheme, a greener multi-cluster coordinated NOMA IIoT system can be achieved over the conventional single-criterion based DA scheme.

2) FJT-NOMA: In the FJT-NOMA, the devices can be jointly served by the coordinated APs, where a global manner NOMA is achieved among all the coordinated clusters. Hence, this higher level of coordination system is more device-centric, as the devices can be scheduled into the same groups even they locate into different APs' coverage [10] [11]. In addition, compared to the PBF-NOMA scheme where inter-cluster interference is extensively suppressed, the FJT-NOMA takes advantage of the inter-cluster interference channel for data transmission and benefits from the spatial diversity gain from the distributed APs [10] [11].

For the FJT mode, each AP shares CSI and the transmitted data to other coordinated APs. With K devices in each AP's coverage and N coordinated APs, the total overhead of sharing CSI and data is given $O\left(N\left(N-1\right)K\left(\chi_C+\chi_S\right)\right)$, where χ_C denotes the required bits for describing one device's CSI while χ_S denotes the required bits for exchanging each device's data symbols. Generally, only a few bits are enough to describe a MISO channel for each user [12]. For the overhead on sharing data symbols, it is decided by the downlink frame structure of communication protocol. Hence, the overhead on sharing data symbols is reasonable, considering the fact that the APs have been connected to a centralized cloud-manager through high-speed optical fibers [1].

B. Multi-Cluster Coordinated NOMA Resource Allocation

1) Device Association: DA plays a significant role in load balancing and performance enhancement. The existing DA designs can be generally classified into distance based and channel gain based methods. In particular, the distance based method is sensitive to channel fading and shadowing, while the performance of the channel gain based method may be significantly impaired by the inter-cluster interference. As a result, multiple criteria, such as distance, channel gain and inter-cluster interference *etc.*, should be jointly considered to make a comprehensive decision for DA. Recently, artificial intelligence (AI) techniques have been proposed to strike an attractive balance among different criteria, enhancing the robustness against the effects of channel fading, shadowing and inter-cluster interference [13].

2) SIC Design: SIC is employed at the receive side for superposed signal decoding and demodulating. There are two fundamental rules, namely rule 1) the optimal SIC decoding order of devices is based on the increasing order of their channel gains from the APs [9], and rule 2) the rate of the device with a higher decoding order (*e.g.*, the device i) to detect the signal of the device j should be no lower than the targeted rate of the device j, so that the signal of the device j can be successfully decoded and removed at the device i. For the single-cluster NOMA IIoT, rule 1 is equivalent to rule 2. Nevertheless, in the multi-cluster NOMA, due to the incurred inter-cluster interference, the rate of the device i to decode the device j may be lower than the targeted rate of the device j, which results in the failure of SIC process. Therefore, to successfully perform SIC, dedicated SIC design considering the effect of the inter-cluster interference should be developed to guarantee the validity of rule 2 [10] [11].

3) Device Grouping and Power Control: For the PBF-NOMA, the devices within each cluster can be scheduled into a number of NOMA groups, and power allocation policies are carefully designed by the coordinated APs to suppress the intra-cluster inter-group interference. On the other hand, for the FJT-NOMA scheme, both the CSI and transmission data are available at coordinated APs. As a result, the devices located in the different clusters could be scheduled into the same NOMA group, thereby enabling a higher DoF in device grouping. In addition, since the inter-cluster interference channels from the coordinated APs to devices can be utilized to carry useful information, only the intra-cluster inter-group interference needs to be suppressed, which results in lower power consumption and higher EE performance.

By applying the multi-criterion based DA, device grouping and power allocation schemes, the multi-cluster coordinated IIoT can provide an energy-efficient transmission [13]. Fig. 2 shows the power consumption and EE with different coordination designs. It can be observed that, with stringent transmission rate requirements, the multi-cluster FJT-NOMA scheme consumes lower transmission power and achieves higher EE performance over the non-coordinated multi-cluster NOMA design, *i.e.*, EE enhancement of more than 27.4% and transmission power reduction of around 34.6 dBm. In addition, the multi-criterion based DA scheme provides 16.8% EE enhancement and 31.1 dBm transmission power reduction than the single-criterion based methods, enabling a greener multi-cluster coordinated NOMA IIoT system. Note that though SIC incurs additional power at the receiver sides, typically ranging from -3 dBm to 20 dBm, this only contributes a tiny proportion to the total power consumption. Hence, the amount of power saving achieved by the NOMA-based multi-cluster design overwhelms the additional power consumption incurred by the SIC operation.

III. CI AIDED MULTI-CLUSTER COORDINATION WITH INTERFERENCE MANAGEMENT

In the aforementioned section, we have reviewed the superiority of applying NOMA into multi-cluster coordinated IIoT systems. Relying on the interference-mitigation based design, it is able to multiplex a massive number of devices onto the same frequency resource while ensuring a reasonable reception quality. Due to the non-orthogonal access of devices, the incurred intra-cluster multi-device interference needs to be strictly suppressed by SIC, regardless of the multi-cluster coordination levels. Nevertheless, there is scope to exploit the multi-device interference as a beneficial element based on the concept of CI precoding. It transmits spatially non-orthogonal signals, and makes the intrinsic spatial leakage (*i.e.*, multi-device interference) constructive [12] [14] [15] for further enhancing system performance. In this section, we first review the CI technique, and then elaborate on it with the cluster coordination techniques.

A. CI Signal Design

CI exploitation involves judiciously characterising interference by considering the signal constellation size. Departing from the conventional interference suppressing techniques which constrain the received signals within a proximity area around the modulated signal constellation point, the CI scheme can exploit, rather than suppressing, the correlation between the transmission signal to make the multi-device interference constructive [14] [15]. Specifically, to clarify the fundamental concept mentioned above, an elementary example of the CI exploitation with two devices is given in Fig. 3 (a), whose signals belong to a binary phase shift keying (BPSK) constellation. Assume that the device 1's desired signal x_1 equals to 1 and interfering signal x_2 equals to -1, respectively. Without loss of generality, a lossless channel is assumed from the transmitter to the device 1, and the interfering channel is denoted as ρ. Ignoring noise, it is easy to verify that when the interfering channel equals to 0.5, the interfering signal x_2 is destructive to the device 1 as it pushes the received signal closer to the BPSK decision threshold, thereby reducing the SINR performance. On the contrary, when the interfering channel equals to -0.5, the interfering signal x_2 becomes constructive to the desired signal x_1, as the interfering signal is moved further away from the decision threshold, effectively raising the received SINR.

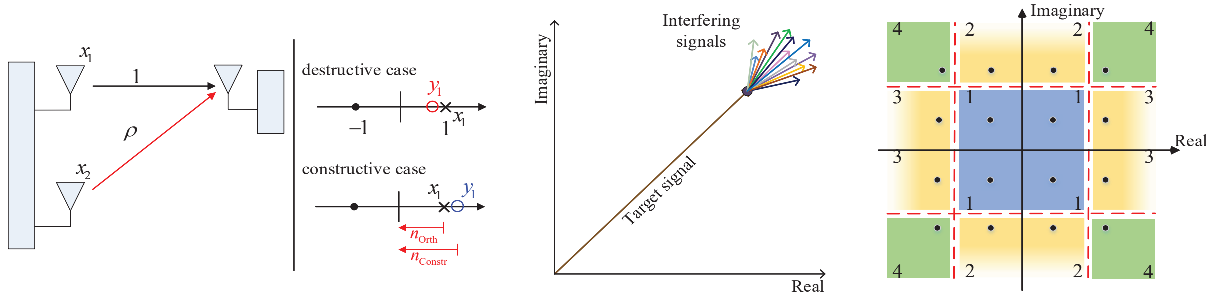
On the basis of the CI characterization, CI precoding can be performed to make interference constructive for devices, where the ubiquitous interference is judiciously transformed into a green signal source for improving the devices' reception performance. In other words, by employing CI, lower transmission power is required at the devices to achieve a targeted performance since interference contributes constructively rather than being suppressed. The above fundamental example can be extended to general M-order of PSK (as shown in Fig. 3 (b)) and quadrature amplitude modulation (QAM) (as shown in Fig. 3 (c)) [15]. Take 16-QAM for illustration, it can be seen that for the inner constellation points (the group of constellation points in the box labelled 1), interference that shifts the received inner constellation point away from one decision threshold pushes it closer to another decision threshold. Hence, the concept of CI does not hold. However, for the outer constellation points (the group of constellation points in the boxes labelled 2, 3, and 4), the CI can push the received signals fall in the detection region away from the decision boundaries to enhance the signal reception performance.

Moreover, as for the existing zero forcing (ZF) or other optimization-based precoders, the number of the served devices should not be larger than that of the transmit-antennas. By contrast, the CI locates the desired signals into constructive regions (where the received signals have increased the distance to the detection threshold of demodulation), rather than strictly locating the signals in the proximity region around the constellation point. With a higher design DoF at the transmitter-side, the number of the served devices can be larger than that of the transmit-antennas [12] [14], while achieving an enhanced reception performance. Hence, the CI is particularly suitable for massive downlink-connectivity in MMTC scenario.

B. CI Design for Multi-Cluster Coordination

The key challenge of integrating CI and multi-cluster coordination lies in the inter-cluster interference presented from the adjacent APs and the multi-device interference within each cluster, which need to be separately managed.

1) Partially-Coordinated Beamforming CI (PBF-CI): In the PBF-CI scheme, since CSI is available at the coordinated APs, the intra-cluster multi-device interference can be predicted and characterized before transmission, which then can be treated as a beneficial element at the receiver side enabled by the CI precoding. However, the intended data is merely transmitted by the local APs, which makes it difficult to exploit inter-cluster interference as a constructive element. To this end, the philosophy of the PBF-CI is to exploit intra-cluster multi-device interference while carefully mitigating inter-cluster interference [12].



(a) (b) (c)

Fig. 3. (a) An elementary example of CI exploitation with BPSK constellation; (b) QPSK constellation example: CI precoding exploits interference as a beneficial element to enhance the reception performance, where the desired signal is pushed away from the decision threshold in demodulation; (c) Schematic representation of 16-QAM constellation points.

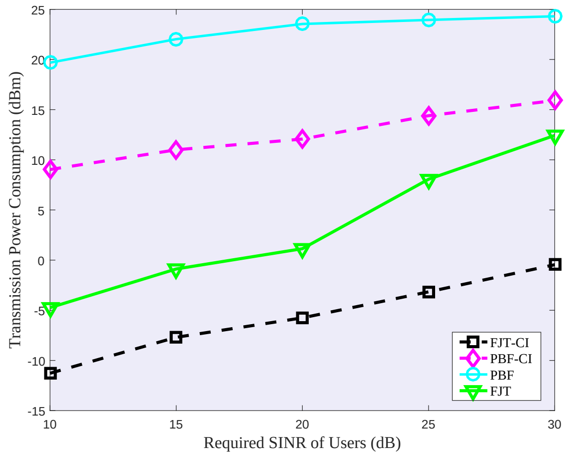


Fig. 4. Performance gain of the FJT-CI and PBF-CI designs over the conventional coordination techniques. A 3-cluster scenario is considered. Each AP is equipped with 4 antennas, while each downlink device is equipped with single antenna.

2) Fully-Coordinated Joint Transmission CI (FJT-CI): In the FJT-CI, both CSI and the intended transmission data of the devices are shared among the coordinated APs. As a result, not only the inherent intra-cluster multi-device interference but also the inter-cluster interference can be exploited as constructive elements, which achieves a higher level of DoFs in interference management and significantly enhances performance, at the cost of higher coordination overhead over the PBF-CI scheme.

The impact of the devices' SINR requirements on the total transmission power is shown in Fig. 4. As can be seen, the FJT-CI scheme consumes the lowest power, providing 12.2 dBm power saving over the FJT, 15.8 dBm over the PBF-CI, and 24.2 dBm over the PBF scheme, respectively. The reason lies in that the FJT-CI scheme utilizes both inter-cluster and intra-cluster multi-device interference as constructive elements, which leads to much lower transmission power for achieving a targeted SINR. In addition, the FJT-CI can also benefit from the spatial diversity gain by taking advantage of the inter-cluster interference channel, thanks to the distributed coordinated APs. For the PBF-CI scheme, as the intended transmission data is not shared among the APs to reduce coordination overhead, only intra-cluster multi-device interference can be made constructive while inter-cluster interference should be carefully mitigated by joint precoding design. It is clear from the above results that the employment of the CI exploitation in IIoT has the potential of orders-of-magnitude reduction in the power consumption.

The CI design also has a high potential in the URLLC scenario. The symbol error rate and execution time performance are demonstrated in Fig. 5. It can be concluded that the CI endorses the lowest symbol error rate (SER) at moderate/high SINR regimes, and thus outperforms the ZF, minimum mean square error (MMSE), SINR balancing precoders in terms of the reliability performance. In addition, the CI design requires the same execution time to the ZF and MMSE precoders, which are known as the most practical precoders due to their low complexities. As a result, the CI design imposes no additional latency on the signal transmission, and is readily compatible to existing URLLC-dedicated techniques.

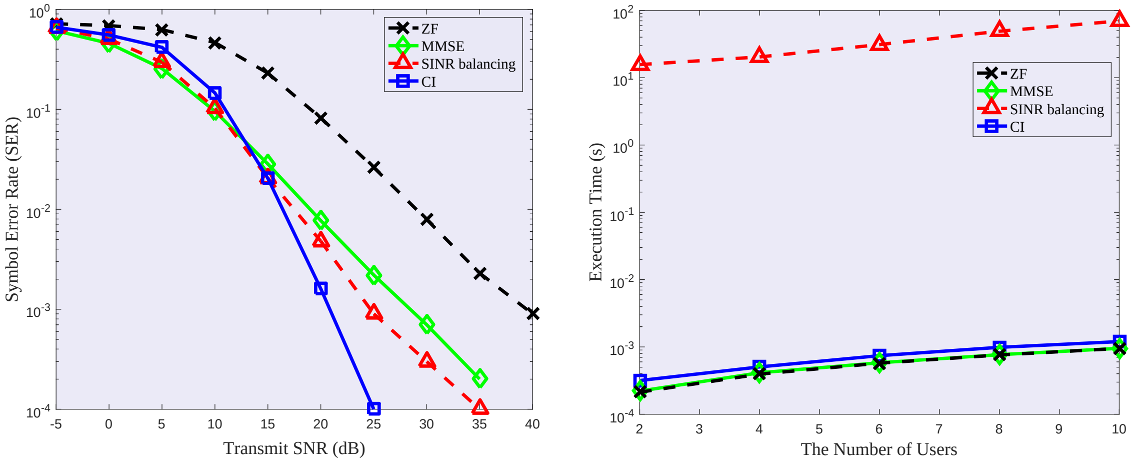
IV. OPEN CHALLENGES AND FUTURE WORKS

A. Hybrid NOMA and CI Transmission for Multi-Cluster Coordination IIoT

NOMA is able to provide massive device access with limited number of antennas, while its performance may be significantly reduced if the devices are with high channel correlation. To this end, hybrid NOMA and CI transmission can be exploited for multi-cluster coordination, according to the devices' distinct traffic demands and channel conditions. For example, the devices with instant access request and high channel disparity can be served by NOMA, while the devices having channel correlations and requiring high throughput can be served by CI. Hence, how to adaptively provide the synthetic NOMA and CI transmission while guaranteeing devices' QoS requirements is still open issues.

B. Multi-Cluster Coordination IIoT with Fog-Networks Computing

Fog computing is envisioned as a crucial technology in IIoT to provide low latency and local processing, by offloading the computing and functionalities storing from the centralized cloud center to the edge-fog devices. Nevertheless, how to



(a) (b)

Fig. 5. Symbol error rate and execution time of different precoders in the FJT scenario, where the coordinated APs act as 10 distributed antennas for serving 10 single-antenna devices. It is observed that in (a), the CI endorses the lowest SER at moderate/high SINR regimes, and outperforms the ZF, MMSE, SINR balancing precoders in terms of the reliability. On the other hand in (b), the CI design requires the same execution time (at 10^{-4}s level) to the ZF and MMSE precoders, demonstrating its practicality on the low latency application.

cooperate fog computing-based radio access networks (F-RAN) with multi-cluster coordination is still challenging. It requires new topology design such as the design and allocation of fog nodes across multiple clusters. Since the fog devices in F-RAN are supplemented with additional computation capacity, how to jointly leverage the computation capacity of fog nodes with low overhead is yet to be explored.

C. Multi-Cluster Coordination Design with Limited, Statistical or Unavailable CSI Devices

The existing coordination techniques generally rely on the availability of CSI at the transmitter (CSIT). In some typical applications of IIoT, such as ambient or back-scatter communications, obtaining accurate CSIT of devices may be difficult. In this case, limited, statistical or unavailable CSIT of devices are more prone to present. How can we exploit the advantage of the CI with limited, statistical or unavailable CSIT of the devices? The energy-efficient multi-cluster coordination in this case is not yet well understood.

D. Joint Device Detection and Channel Estimation in Grant-Free Multi-Cluster Coordination

Low latency is an important metric for some IIoT applications, such as early warning of malfunctioned equipments. However, the complicated handshake mechanism, that has been extensively used for grant access in cellular networks, leading to high access delay and outdated CSI. Considering the sporadic transmission at uplink, joint active devices detection and channel estimation would benefit system performance in terms of low access delay and accurate CSI acquiring. Since in practice the number of the active devices may be much lower than the total number of devices, it is reasonable to apply compressed sensing theory for the device detection based on the transmission sparsity. The integration of NOMA and grant-free has been extensively researched, however, how to further improve the detection performance with the multi-cluster coordination needs more fundamental analysis.

E. Artificial Intelligence Aided Non-Orthogonal Transmission in Multi-Cluster Coordination IIoT

In IIoT scenario, the actions and operations of the devices may be programmed, and thus their positions, motions, and the associated channel quality could be observable, predictable, and learnable. Especially, periodic transmission is incurred by the devices at uplink, such as the periodic monitoring and reporting of sensors, as well as the control feedback of robotic arms. These regularities lay a strong foundation for the AI aided non-orthogonal transmission designs, in terms of cluster association, device grouping, massive device access, coordination level selection, and resource allocation, etc. However, the burst transmission of the devices harms the regularities in IIoT, complicates the learning process, and impairs the testing performance. This again requires fundamental analysis and designs for the learning-aided non-orthogonal transmission in the multi-cluster coordination IIoT.

V. CONCLUSION

This paper has introduced disruptive approaches for inter-cluster and intra-cluster interference management for multi-cluster coordinated IIoT. Focusing on the typical MMTC scenarios in multi-cluster coordination, we have discussed the potential of accommodating non-orthogonal multi-device access, and even exploiting the ubiquitous interference as a green source by CI for enhancing reception performance. These novel solutions enable an energy-efficient transmission, and offer a new design philosophy of interference management for the emerging multi-cluster coordinated IIoT. The challenges relating to emerging multi-cluster applications are also envisaged, and these give promise of exciting and insightful research over the following years to come.

VI. ACKNOWLEDGEMENT

Z. Wei would like to acknowledge the financial support of the NSFC under Grant 62101384, as well as of the Chongqing Key Laboratory of Mobile Communication Technology under Grant cqupt-mct-202101. X. Zhu would like to acknowledge the financial support of the National Natural Science Foundation of China under Grants 62171161 and 61901138, the Natural Science Foundation of Guangdong Province under Grant 2021A1515011832, as well as the Shenzhen Science and Technology Program under Grants ZDSYS20210623091808025, JCYJ20210324133009027, JCYJ20210324131010028 and KQTD20190929172545139. J. Wang would like to acknowledge the financial support of the Young Elite Scientist Sponsorship Program by CAST under Grant No. 2020QNRC001.

REFERENCES

[1] T. Qiu *et al.* "Edge computing in industrial internet of things: architecture, advances and challenges," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2462–2488, Jul. 2020.

[2] K. Wang *et al.*, "Green industrial internet of things architecture: an energy-efficient perspective," *IEEE Communications Magazine*, vol. 54, no. 12, pp. 48–54, Dec. 2016.

[3] J. An *et al.*, "Antenna array calibration for IIoT oriented satellites: from orthogonal CDMA to NOMA," *IEEE Wireless Communications*, vol. 27, no. 6, pp. 28–36, Dec. 2020.

[4] B. Selim *et al.*, "NOMA-Based IoT networks: impulsive noise effects and mitigation," *IEEE Communications Magazine*, vol. 58, no. 11, pp. 69–75, Nov. 2020.

[5] Q. Chen, K. Yang, H. Jiang and M. Qiu, "Joint beamforming coordination and user selection for CoMP enabled NR-U networks," *IEEE Internet of Things Journal*, 2021. (Early Access)

[6] P. Jia *et al.*, "Distributed clock synchronization based on intelligent clustering in local area industrial IoT systems," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 6, pp. 3697–3707, June 2020.

[7] B. Cheng *et al.*, "Situation-Aware dynamic service coordination in an IoT environment," *IEEE/ACM Transactions on Networking*, vol. 25, no. 4, pp. 2082–2095, Aug. 2017.

[8] X. Liu and X. Zhang, "NOMA-Based resource allocation for cluster-based cognitive industrial internet of things," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 8, pp. 5379–5388, Aug. 2020.

[9] Y. Cao *et al.*, "Secure transmission via beamforming optimization for NOMA networks," *IEEE Wireless Communications*, vol. 27, no. 1, pp. 193–199, Feb. 2020.

[10] M. S. Ali, E. Hossain, and D. I. Kim, "Coordinated multipoint transmission in downlink multi-cell NOMA systems: models and spectral efficiency performance," *IEEE Wireless Communications*, vol. 25, no. 2, pp. 24–31, Apr. 2018.

[11] S. Khairy *et al.*, "Constrained deep reinforcement learning for energy sustainable multi-UAV based random access IoT networks with NOMA," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 4, pp. 1101–1115, Apr. 2021.

[12] Z. Wei, *et al.*, "Multi-Cell interference exploitation: enhancing the power efficiency in cell coordination," *IEEE Transactions on Wireless Communications*, vol. 19, no. 1, pp. 547–562, Jan. 2020.

[13] H. Zeng *et al.*, "A green coordinated multi-cell NOMA system with fuzzy logic based multi-criterion user mode selection and resource allocation," *IEEE Journal of Selected Topic on Signal Processing*, vol. 13, no. 3, pp. 480–495, Apr. 2019.

[14] Z. Wei *et al.*, "Energy- and cost-efficient physical layer Security in the Era of IoT: The Role of Interference," *IEEE Communications Magazine*, vol. 58, no. 4, pp. 81–87, Apr. 2020.

[15] T. Xu, C. Masouros and I. Darwazeh, "Waveform and space precoding for next generation downlink narrowband IoT," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5097–5107, June 2019.

Haiyong Zeng is currently pursuing the Ph.D. degree with the School of Electrical and information Engineering, Harbin Institute of Technology, Shenzhen, China. His research interests include interference management, communication algorithm and resource allocation.

JingJing Wang received his B.S. degree in Electronic Information Engineering from Dalian University of Technology, Liaoning, China in 2014 and the Ph.D. degree in Information and Communication Engineering from Tsinghua University, Beijing, China in 2019, both with the highest honors. From 2017 to 2018, he visited the Next Generation Wireless Group chaired by Prof. Lajos Hanzo, University of Southampton, UK. Dr. Wang is currently an associate professor at School of Cyber Science and Technology, Beihang University. His research interests include AI enhanced next-generation wireless networks, swarm intelligence and confrontation. He has published over 100 IEEE Journal/Conference papers. Dr. Wang was a recipient of the Best Journal Paper Award of IEEE ComSoc Technical Committee on Green Communications & Computing in 2018, the Best Paper Award of IEEE ICC and IWCMC in 2019.

Zhongxiang Wei is an associate professor of Electronic and Information Engineering at Tongji University. He received his Ph.D. from the University of Liverpool (2017). He was a postdoc researcher at University College London (UCL) (2018-2021), United Kingdom, and was a research assistant at A*STAR Singapore (2016-2017). He has served as a TPC Chair/member of various international flagship conferences. He was a recipient of an Exemplary Reviewer of IEEE Transactions on Wireless Communications, an Outstanding Self-Financed Students Abroad award in 2018, and the A*STAR Research Attachment Programme in 2016. His interests include MIMO systems, PHY security, and anonymous communication designs.

Xu Zhu received the Ph.D. degree in electrical and electronic engineering from the Hong Kong University of Science and Technology in 2003. She is a reader at the University of Liverpool and also at the Harbin Institute of Technology. She has more than 200 peer-reviewed publications. Her research interests include MIMO, channel estimation and equalization, green communication. She has served as an Editor for *IEEE TWC* and Symposium Co-Chair of IEEE ICC and GLOBECOM.

Yufei Jiang received the Ph.D. degree in electrical engineering and electronics from the University of Liverpool in 2014. From 2014 to 2015, he was a Post-Doctoral Researcher with the University of Liverpool. From 2015 to 2017, he was a Research Associate with the Institutes for Digital Communications, University of Edinburgh. He is currently an Assistant Professor with the Harbin Institute of Technology, Shenzhen. His research interests include Li-Fi, synchronization, full-duplex, and blind source separation.

Yuanchen Wang is currently pursuing the Ph.D. degree with the Department of Electrical Engineering and Electronics, University of Liverpool. His research interests include sparse signal processing, NOMA and the Internet of Things.

Christos Masouros is a full professor at the University College London. He received his Ph.D. from the University of Manchester in 2009. His research interests include wireless communications and signal processing. He was the recipient of Best Paper Awards at IEEE GLOBECOM 2015 and IEEE WCNC 2019. He is an Editor for *IEEE TCOM* and *IEEE TWC*. He has been an Associate Editor for *IEEE COML* and a Guest Editor for *IEEE JSTSP*.