Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks

Citation for the original published paper (version of record):
Guo, H., Wymeersch, H., Makki, B. et al (2024). Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks. IEEE Wireless Communications

Integrated Communication, Localization, and Sensing in 6G D-MIMO Networks

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***Abstract*—Future generations of mobile networks call for concurrent sensing and communication functionalities in the same hardware and/or spectrum. Compared to communication, sensing services often suffer from limited coverage, due to the high path loss of the reflected signal and the increased infrastructure requirements. To provide a more uniform quality of service, distributed multiple input multiple output (D-MIMO) systems deploy a large number of distributed nodes and efficiently control them, making distributed integrated sensing and communications (ISAC) possible. In this paper, we investigate ISAC in D-MIMO through the lens of different design architectures and deployments, revealing both conflicts and synergies. In addition, simulation and demonstration results reveal both opportunities and challenges towards the implementation of ISAC in D-MIMO.**

***Index Terms*—6G, Integrated sensing and communication (ISAC), D-MIMO, testbed, sensing, MIMO, localization.**

I. INTRODUCTION

With the success of multiple-input multiple-output (MIMO), it is expected that multi-antenna technologies will evolve in beyond-5G systems, either in a centralized or a distributed way. In the centralized case, the access points (APs) or user equipments (UEs) will be equipped with an even larger number of antennas. In the distributed case, also referred to as distributed MIMO (D-MIMO), multiple multi-antenna APs with potentially different capabilities will cooperate to serve the UEs [1]. Unlike conventional MIMO, where multiple antennas are concentrated at a single location, the distributed architecture of D-MIMO facilitates a new level of spatial diversity and cooperative communication with a degree of freedom that enables, e.g., blockage avoidance and increased link margin despite per node output power limitations, leading to high reliability and availability as well as uniform service over the coverage area [2], [3].

With these promising features, D-MIMO can be an attractive solution for so-called integrated sensing and communication (ISAC), where the same hardware and/or frequency bands are used to perform these functionalities in a distributed and cooperative way [4]. In general, sensing involves detecting physical or environmental conditions using radio frequency (RF) signals, with localization being a specific service of sensing. In this paper, we define sensing in a narrower sense, focusing on radar-like sensing, i.e., detecting the presence of passive objects and estimating their state(s), whereas localization specifically refers to determining the position of an active device, such as a transmitter or receiver, in space.

Traditionally, radar sensing and communication have operated in separate frequency bands using dedicated hardware. However, with 5G and beyond, the wireless communication bands are merging with radar bands, such as millimeter-wave (mmWave) and the sub-THz bands foreseen for 6G. This merging has fueled the research on integrating communication, localization, and sensing functionalities within the same system, which can offer several benefits. One major advantage of ISAC is centralized resource allocation and interference management for all functionalities, leading to cost-efficient operations. Compared to existing cellular networks, D-MIMO yields a diversity gain thanks to multiple uncorrelated sensing observations with bi- or multi-static sensing, and the probability of finding line-of-sight (LOS) links is improved [5]. Also, in [6], the achievable communication-sensing region is derived for the ISAC D-MIMO system, and the scalability with the number of APs is evaluated. The implementation of ISAC also brings benefits to D-MIMO networks compared to communication-focused systems. Specifically, localization and sensing (L&S) enhance the network's radio environment comprehension, such as efficient channel estimation and blockage detections [3]. This knowledge simplifies backhaul/fronthaul designs and reduces coordination overheads, as only APs with strong links to UEs/objects need to collaborate.

Despite a large body of research on D-MIMO communication and also on distributed radar, few studies on ISAC D-MIMO have been conducted. For instance, with proper optimization, ISAC beamforming can reach similar performance as sensing-prioritized or communication-prioritized systems [4]. It is also shown that one can deploy a cloud radio access network architecture to facilitate centralized ISAC processing of all APs [7]. In [8], a downlink D-MIMO system is studied from a positioning perspective. Moreover, there are inevitable challenges for implementing ISAC D-MIMO systems. For example, [5] points out that phase-coherent centralized joint processing is desired in ISAC D-MIMO systems, which results in a synchronization challenge. Also, the issue of finite resources and channel estimation error should be properly addressed [6]. To the best of our knowledge, limited studies are providing a comprehensive vision of ISAC in D-MIMO systems and an analysis of the key challenges and opportunities of ISAC in D-MIMO.

In this paper, we investigate the potentials and challenges of D-MIMO networks providing ISAC operations, referred to as ISAC D-MIMO. As illustrated in Fig. 1, we assume that a set of cooperative multi-antenna APs with different

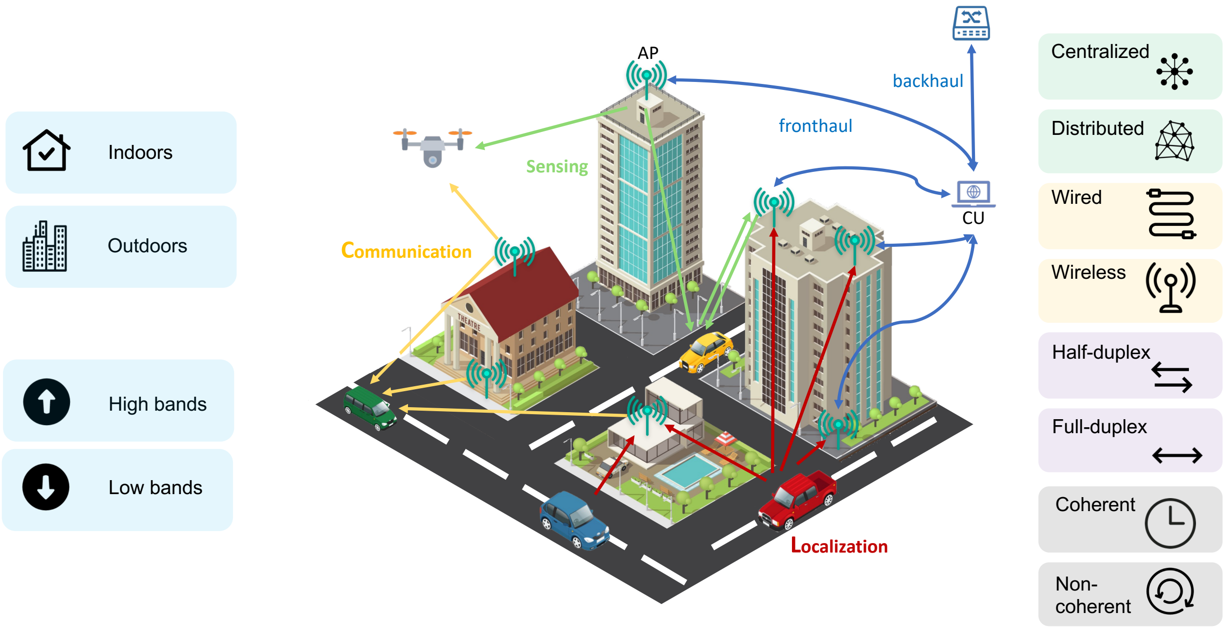

Fig. 1. Illustration of the ISAC functionalities in D-MIMO systems with key network components as well as different architectural options and characteristics of deployment scenarios. Acronyms: user equipment (UE), access point (AP), central unit (CU). Icons designed by Freepik.

capabilities perform communication, localization, and sensing jointly, possibly within the same spectrum resources. We introduce the architecture requirements of ISAC D-MIMO networks and present the key open problems to be addressed in such distributed multi-functional networks. Also, simulation results, as well as initial testbed evaluations, are presented. As demonstrated, the distributed and cooperative characteristics of D-MIMO networks enable efficient joint communication, localization, and sensing, with reduced coordination requirements. We reveal that there are multiple open problems to be addressed before such systems can be implemented in practice.

II. DEPLOYMENTS AND ARCHITECTURES OF D-MIMO NETWORKS

In this section, we present the deployment and architecture options for D-MIMO networks. This also provides the basis for the architecture options of ISAC D-MIMO to be discussed in Section III.

Figure 1 illustrates ISAC functionalities in D-MIMO systems along the different architectural options and characteristics of deployment scenarios. A desirable D-MIMO architecture is scalable, adaptive, and compatible with the current network standards allowing for seamless addition/removal of APs[1] with minimal network impact. A further exploration into each deployment and architectural option follows.

First of all, D-MIMO is of interest in both indoor and outdoor deployments, with different use cases, objectives, and different kinds of connection options between the APs. A possible use case is critical communications for indoor scenarios, e.g., in factories, warehouses, and offices, with support for dense machine-type communication or extended reality applications. In dense urban area scenarios, e.g., in airports, stadiums, public squares, outdoor D-MIMO could still boost the capacity, where necessary, and provide coverage regardless of the site location and/or UE mobility.

Second, taking different deployment options into account, D-MIMO is expected to support the spectrum ranging from sub-6 GHz to high bands. At low bands, e.g., frequency range (FR)1, D-MIMO can improve the spectral efficiency (SE) via, e.g., coherent joint transmission (CJT), which can also improve the sensing performance with phase-coherent operation. At higher bands, e.g., FR2 and beyond, D-MIMO can be used to improve the reliability of the access links to the UEs, thanks to macro-diversity against blockers and the large available bandwidth resulting in high data rates even with low SE.

Third, for both centralized and distributed processing, the fronthaul (between the central unit (CU) and AP) and the backhaul (between CU and network) requirements depend on the number of UEs, the deployment of CUs/APs, their processing capabilities, and the supported operation modes of the D-MIMO network. The goal is to reduce the required processing at the nodes close to the UEs, reducing their cost, complexity, and simplifying deployment, which in turn increases the fronthaul/backhaul traffic.

Fourth, the fronthaul/backhaul transport medium is expected to be based on a combination of fiber and wireless for both communication and L&S. Fiber is preferred, when feasible, while wireless fronthaul/backhaul provides increased flexibility and short time-to-market.

Fifth, full-duplex operations may improve communication performance, compared to half-duplex systems using, e.g., dynamic time division duplex (TDD). With the flexibility of adjusting uplink (UL) and downlink (DL) durations, dynamic TDD provides more degree of freedom in resource allocation and enhances the interference coordination among

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[1] The terminology AP in this paper may represent different levels of capability in the network implementation. For a more comprehensive terminology, please refer to [1]

distributed APs. The improved performance of half-duplex with dynamic TDD, however, is affected by implementation challenges such as signaling overhead, AP synchronization, and interference. From communication perspectives, dynamic TDD is in general not preferred for outdoor, due to extra interferences. With ISAC more opportunities arise but proper interference cancellation schemes are desired. Also, full-duplex enables mono-static sensing, like some conventional radars. To integrate sensing, localization, and communication, full-duplex or short DL/UL switching delays could be beneficial. However, canceling self-interference in practice is challenging and often requires more than $100\,\mathrm{dB}$ isolation and stringent hardware capabilities. Proper deployment of antenna panels or beamforming can reduce self-interference, and dense D-MIMO APs deployment will lower the power difference of transmitted/received signals.

The sixth and final architectural option relates to phase synchronization in D-MIMO, which enables the alignment of signal phases across multiple distributed antennas, i.e., establishing *phase coherence*. This ensures that signals combine constructively at the APs and UEs to achieve the desired array gain. Phase synchronization is essential for CJT and it is easier to achieve at low frequencies. It is likely that, at least in the early roll-outs of D-MIMO, non-coherent transmission will be considered at high frequencies for both communication and L&S. On the other hand, at low frequencies, over-the-air calibration methods can be applied to enable phase-aligned reciprocity-based beamforming across APs.

III. A MULTI-FUNCTIONAL VIEW OF D-MIMO

Based on the D-MIMO architectures and deployments described in Section II, in this section, we discuss how communication, localization, and sensing tasks can be accomplished and how these services can benefit from D-MIMO.

A. D-MIMO from a Communication Perspective

Some of the opportunities and challenges of D-MIMO for communications are as follows:

- *Indoor and outdoor considerations:* Indoor D-MIMO benefits from a more controlled environment with lower mobility of users and objects, making it easier to deploy fibers for connecting APs. However, the denser multipath environment indoors requires higher resolution measurements. In contrast, outdoor D-MIMO deals with less challenging multipath due to the greater distances between objects, although proximity to large buildings or UEs can diminish this advantage. Outdoor deployments also face challenges such as the need for larger coverage areas, which may necessitate fibers to all APs, and the higher mobility of users, which shortens the duration of pilots and affects signal-to-noise ratio (SNR). Both indoor and outdoor D-MIMO must address the availability of LOS to APs. In this context, ISAC could enhance D-MIMO performance by leveraging sensing and context information to aid communications [3]. Simulation examples are presented in Fig. 3.
- *Operational bands:* One opportunity for D-MIMO is multi-band operations where, for instance, depending on the traffic model, service requirement, and number of cooperative nodes/antennas per node, some APs may operate at low or high bands. For instance, assume a highway scenario with a large number of vehicles at low speeds in the morning, and few vehicles at high speeds during the night. In this situation, the network experiences diverse quality-of-service requirements and sensing/communication priorities during the day. Here, the presence of multiple nodes gives flexibility for multi-band operation.
- *Centralized and distributed processing:* Distributed or centralized processing is based on the APs capabilities. For instance, depending on the operational frequency, their associated processing can be in the CUs or APs. Distributed antenna deployment provides broader resource trade-off options based on local data traffic and nodes' deployment. Moreover, the existence of multiple nodes opens opportunities for preventing service outages and reducing self-interference, through optimized deployment and coordinated beamforming techniques.
- *Fronthaul and backhaul:* Wireless fronthaul/backhaul is preferred outdoors with low cost and fast deployment, whereas wired fronthaul/backhaul could be more beneficial indoors with improved reliability and capacity. Also, at higher operation bands, wireless deployment is preferred with less restricted synchronization requirements. Moreover, some benefits provided by the architecture of fronthaul/backhaul in D-MIMO networks include:
  - Cooperative communications. Here, the presence of fronthaul/backhaul helps the nodes to have multiple views on the UE/object which improves the channel state information (CSI) quality significantly; see Fig. 3 as an example with a set of cooperative APs jointly performing ISAC to improve the system performance.
  - Multi-band operation. Here, the nodes can operate in different bands, obtain information, and then share them via fronthaul/backhaul. This is advantageous in terms of interference mitigation and resource allocation.
  - Scalability. Different protocol layers should support the scalability requirements. While some long-term management may be handled by the CU(s), a large part of each UE can be handled by its serving AP(s).
- *Half- and Full-duplex:* Theoretically, full-duplex is preferred for communication because it almost doubles the SE; however, the existing problem with self-interference at the AP, i.e., the interference between the transmit and receive antenna arrays, could reduce the expected SE gains significantly. In D-MIMO systems, full-duplex could provide more flexibility in terms of, e.g., channel estimation and interference coordination.
- *Coherent and non-coherent processing:* Coherent-phase synchronization refers to the process of aligning the phase of the signals transmitted or received by different APs. This alignment is crucial in coherent D-MIMO systems because it ensures that the signals from different APs interfere constructively, maximizing the signal strength at the receiver. Recent findings in over-the-air massive synchrony are presented in [9] and synchronization solutions are clas-

sified into reciprocity calibration and full calibration. One important conclusion from [9] is that using the so-obtained phase corrections everywhere in the system is optimal for any D-MIMO network size. Non-coherent processing has a lower cost and might be sufficient for narrow beams and spatial multiflow, while coherent processing could improve the reliability at the cost of increased complexity.

B. D-MIMO from a Localization and Sensing Perspective

In the D-MIMO context, sensing can rely on DL or UL pilots. UL pilots are more compatible with standard D-MIMO processing, as they are used for channel estimation and reciprocity-based DL precoding. On the other hand, orthogonal DL pilots are preferred since they can allow the same pilots to be reused efficiently for all UEs. APs can receive and process DL transmissions from other APs, (providing opportunities for bi- and multi-static sensing) or from themselves (for mono-static sensing). As for localization, both UEs and APs may need to be localized. APs localization can be seen as a form of calibration.

With this background, we can now consider the architectural dimensions.

- *Indoor and outdoor considerations:* Indoor scenarios are challenging as they have more clutter, which causes more multipath that affects localization accuracy and missed detection of the wanted target in sensing, while the high path-loss and high mobility may limit outdoor performance. To remove or suppress the interference of clutter, either more bandwidth or novel signal processing is needed, while novel waveforms and/or processing are needed to support high mobility. For outdoor, it is challenging to find good LOS links between the sensing transceivers and the object, especially in dense areas. The height of objects and UE mobility cause more issues for synchronization and processing overhead. The indoor and outdoor deployments are likely to differ. For instance, from a localization perspective, it is desirable to have APs distributed at different heights to estimate the elevation of the UE, which could be seen as more important for outdoor use cases.
- *Operational bands:* The low-frequency ranges, i.e., in FR1, have a rich multipath profile, which makes it harder to perform L&S due to multipath interference. On the other hand, the possibility of phase-coherent processing provides a means to resolve multipath and attain high accuracy. A promising alternative is the use of machine learning at lower frequencies in the form of fingerprinting. Fingerprinting L&S at lower frequencies improves the use of a database of signal characteristics for position estimation, which is matched to real-time measurements. Lower frequencies improve this method by providing better obstacle penetration and longer range, enhancing accuracy in indoor environments. Higher frequency ranges have a more sparse multipath profile and larger available bandwidth, providing a direct way to reject multipath interference. However, at FR2 and above, phase synchronization may not be attainable, so we revert to classical L&S methods. To some extent in FR1, but especially in FR2, LOS blockage detection will play an important role, as each receiver may be associated with a large number of transmitters but only a subset of which will have a LOS condition.
- *Centralized and distributed processing:* Three important scalability aspects should be considered when it comes to network structures:
  - L&S are low-rate services, requiring periodic activation at a low rate of 10 or 100 Hz, depending on the application and mobility. This means that they allow flexible scaling with the number of users or objects to be tracked.
  - The transmitters should ideally apply orthogonal waveforms, which require coordination in time and frequency. Consequently, L&S pilot transmissions scale with the number of transmitters, e.g., UL localization scales with the number of UEs/objects, and multi-static sensing scales with the number of transmitting APs.
  - DL localization can be performed in a decentralized way at each UE, while data fusion from each receiver is needed for sensing and UL localization, causing processing delays. Under non-coherent processing, it is sufficient to perform fusion based on the locally processed information. Under phase-coherent processing, fusion is based on the raw in-phase and quadrature (IQ) data and benefits for centralized processing.
- *Fronthaul and backhaul:* Precise time synchronization and/or phase synchronization between the APs place additional demands on the fronthaul or backhaul, as wired links to a master clock must be installed or continuous operation over an over-the-air synchronization protocol must be provided. Similarly, sensing also requires time or phase synchronization for improved performance.
- *Half- and full-duplex:* Full-duplex is needed to enable mono-static sensing, but is not needed for other types of sensing, for localization, or for communication. Nevertheless, full-duplex may improve these services (e.g., enhance sensing capabilities without any dedicated radio resources).
- *Coherent and non-coherent processing:* For delay-based positioning, precise time synchronization (sub ns-level) between the APs is needed to relate the delay measurements to/from different APs. If such synchronization is not possible, round-trip-time protocols can be used for positioning, while for sensing, LOS paths can provide a timing reference. For CJT in both L&S tasks, precise phase synchronization between the APs must be attained, so that the signal phase at one AP can be related to the UE/object location and the signal phase at another AP, creating effectively a very large-aperture array. The phases should not only be fixed but also be perfectly known. The reason is that in L&S, phase measurements are exploited to extract geometric information (distances relate to phase rotations of the signals at each AP). Hence, the phase center of each AP must be determined and phase offsets, e.g., due to cables, must be calibrated.

As an example, Fig. 2 shows the impact of the number of APs on position error bound (PEB) and positioning root-mean-square error (RMSE), comparing conventional time-coherent positioning with phase-coherent D-MIMO positioning. This shows the theoretical benefits of a D-MIMO solution for

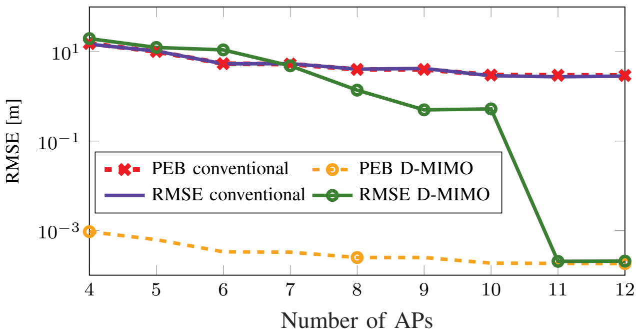

Fig. 2. Impact of the number of APs on PEB and positioning RMSE, comparing conventional time-coherent positioning with phase-coherent D-MIMO positioning. The system operates at 28 GHz with 6 MHz of bandwidth, under pure LOS conditions. The APs are randomly distributed in 3D around the user, with a standard deviation of 100 m. The channel is modeled as free-space path loss. The transmit power is 0 dBm. Here, PEB represents a fundamental lower bound on the RMSE of unbiased estimators, and it is derived from Fisher information. We obtain the RMSE by Monte Carlo simulation using a maximum likelihood estimator based on the delay and phase measurements at each AP. The overlap of RMSE and PEB indicates that the estimator is efficient and attains the optimal performance of the considered algorithm, while the gap between RMSE and PEB can be ascribed to noise peaks in the likelihood function or ambiguities, both of which cause estimates to diverge from the true value.

accurate positioning. In terms of PEB, D-MIMO performance outperforms the corresponding conventional PEB by several orders of magnitude. In terms of RMSE, the gap would disappear when a sufficient number of connected APs are present. Otherwise, the ambiguities due to the use of carrier phase limit the performance. Note that the results were generated under the condition of resolved LOS. In practice, non-line-of-sight (NLOS) performance degradation can be mitigated by observing the user over an extended period of time where the user moves, especially when the user has access to internal sensors, such as inertial measurement units.

IV. Toward ISAC in D-MIMO: Potentials and Implementations

In this section, we consider a converged ISAC D-MIMO system, from four perspectives: i) the architecture and deployment; ii) standardization; iii) quantitative benefits of ISAC D-MIMO; and iv) implementation challenges.

A. *ISAC D-MIMO Architectures*

Based on the discussions from Sections II and III, and with specific focus on the indoor vs. outdoor and higher vs. lower bandwidth options, we summarize in Table I the main implications of the different architectural options. Green blocks indicate that both scenarios are possible/feasible, while blue blocks show that there is a preferred deployment. Each block assesses the suitability for communication and L&S. Note that because of the similarities between L&S, we do not treat them separately in Table I. It is evident that for D-MIMO communication, the favored architecture encompasses phase-coherent distributed processing, half-duplex, and wired fronthaul and backhaul, particularly for outdoor environments in the FR1. For L&S, while half-duplex and wired connections are favored, interest also extends to both distributed non-coherent FR2 and centralized coherent FR1 operations across indoor and outdoor settings. Hence, a preferred ISAC D-MIMO architecture mirrors the preferred communication architecture but incorporates centralized processing, such as phase-coherent IQ samples sharing for L&S.

B. *ISAC D-MIMO Standardization*

Communication networks primarily rely on standardized operations, while sensing signal processing methods are based on proprietary, i.e., non-standardized solutions. On the other hand, with ISAC, the transmitted signals for ISAC, supporting both communication and sensing functions require standardization, as well as the associated control signaling. In some sense, these considerations are general for all 6G ISAC technologies. What sets D-MIMO apart is the multi-static sensing perspective, considering several concurrent AP transmitters and/or receivers. Again, processing will be proprietary, but signal design and coordination will rely on standardized solutions. This necessitates extensive standardization efforts to incorporate sensing into D-MIMO. For instance, the current 3GPP standardization on multi-APs concentrates mainly on the case of ideal backhaul/synchronization, but work on enhancements for non-ideal operation has started in 3GPP Rel-19. 3GPP started preliminary discussions on ISAC from Rel-19 in early 2024.

C. *ISAC D-MIMO Quantitative Benefits—A Case Study*

Communication, localization, and sensing can operate harmoniously in ISAC D-MIMO. As an example, we consider a scalable D-MIMO simulation scenario, assuming perfect time and phase synchronization between UEs and APs. We also compare it with a Cellular MIMO scenario. Fig. 3 shows the UL SEs per UE as a function of transmit SNR averaged over different UE locations and shadow fading realizations. With the setups shown in the caption, maximum ratio combining is used to leverage channel estimations in various scenarios where sensing is used to detect blockage status, while localization is used for CSI estimation (assuming a prior radio map exists): *(i) with ISAC:* Having both blockage status information and CSI, the UEs are assigned to APs without AP-UE blockage with perfect CSI; *(ii) with localization:* The UEs have perfect CSI but without the information of blockage from sensing, they are still served by the default APs; *(iii) with sensing:* The UEs are assigned to the back-up APs but with no CSI from localization; *(iv) without ISAC:* The UEs are served by default APs without CSI. As shown in Fig. 3, L&S significantly enhances the UL SE. For example, with an SNR of 15 dB, the UL SE improves by 3× with localization (providing CSI), 4× with sensing (providing knowledge about blockage), and 6× with both L&S. Additionally, the comparison with a cellular massive MIMO network indicates that D-MIMO is more effective than cellular MIMO in leveraging sensing and localization knowledge.

D. *ISAC D-MIMO Waveform Design*

Two main aspects should be considered for ISAC D-MIMO waveform designs: 1) The actual waveform type (e.g., orthogonal frequency-division multiplexing (OFDM), orthogonal

TABLE I

SUITABILITY MATRIX OF ARCHITECTURAL OPTIONS COMBINATIONS WITH IMPLEMENTATION COMMENTS: EVALUATING COMMUNICATION AND LOCALIZATION & SENSING.

🟩 : Both options are feasible/possible 🟪 : One of the options is preferable

	Indoor vs. Outdoor	**Higher bands vs. Lower bands**
Centralized	**Both options** are *feasible* **Com.**: improves spectral efficiency/dynamic blocking mitigation **L&S**: suitable for time- and phase-coherent processing, only lower mobility	**Higher bands** *preferred* (dense APs and low cost) **Com.**: fast control of narrow beams, but high requirements on backhaul/fronthaul **L&S**: phase-coherent capability
Distributed	**Both options** are *possible* **Com.**: improves scalability (less reliability for indoor) **L&S**: suitable for time-coherent processing	**Lower bands** *preferred* (less dense APs/high resolution converters) **Com.**: Lower data rates allow for more advanced APs, resulting in low backhaul requirements, but interference might limit spectral efficiency **L&S**: suitable for time-coherent processing
Wireless front- and backhaul	**Outdoor** *preferred* (*less blockers*) **Com.**: low cost and fast deployment, but less reliability **L&S**: time-coherent processing	**Higher bands** *preferred*, (less restricted sync requirements) **Com.**: low cost and fast deployment, but less reliability **L&S**: time-coherent processing
Wired front- and backhaul	**Indoor** *preferred* (might be costly for outdoors) **Com.**: improves reliability and backhaul fronthaul capacity **L&S**: supports tight sync requirements for phase-coherent processing	**Both options** are *feasible* **Com.**: improves reliability and backhaul fronthaul capacity, important especially in higher bands **L&S**: not needed for higher bands, except for certain challenging cases or use of artificial intelligence (AI)
Half-Duplex	**Both options** are *possible* **Com.**: lower cost, but increased delays **L&S**: suitable for time- and phase-coherent processing	**Both options** are *possible* **Com.**: lower cost, but increased delays **L&S**: suitable for time-coherent processing (higher bands) phase-coherent processing (lower bands)
Full-Duplex	**Indoor** *preferred* (due to low transceiver signal strength difference) **Com.**: lower latency **L&S**: enables monostatic sensing, severe leakage challenges	**Higher bands** *preferred* (due to beam-based spatial transceiver isolation and short hops) **Com.**: flexible TDD deployment **L&S**: enables monostatic sensing, severe leakage challenges
Non-coherent	**Both options** are *possible* **Com.**: lower cost but might result in insufficient reliability **L&S**: suitable for time-coherent processing	**Higher bands** *preferred* (low spectral efficiency and resolution in Lower bands) **Com.**: lower cost and might be sufficient for narrow beams and spatial multiflow **L&S**: suitable for time-coherent processing
Coherent	**Indoor** *preferred* (due to short inter-AP distances) **Com.**: improves reliability **L&S**: suitable for time- and phase-coherent processing	**Lower bands** *preferred* (due to lower carrier frequency) **Com.**: improves reliability **L&S**: suitable for time- and phase-coherent processing

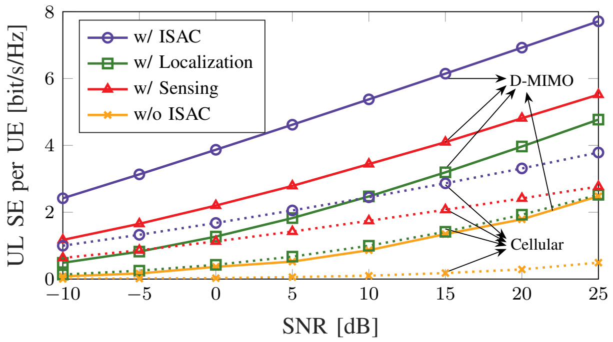

Fig. 3. Impact of L&S on the UL SEs in a simulated phase-coherent D-MIMO system. The dotted lines represent the results from a cellular MIMO system. The D-MIMO setup is based on [2], featuring 5 UEs served by nearby APs (200 in total) within the dynamic cooperation clustering framework. Both APs and UEs are uniformly distributed over a 1x1 km area. Initially, UEs are served by default APs where the links are blocked. A Rician fading channel model is used, with the same parameters as in [10].

time-frequency-space (OTFS), and single carrier) to support ISAC use cases (e.g., high mobility may need OTFS, and coverage might need single carrier). 2) The allocation of power across the available dimensions of that waveform (e.g., power allocation across time, frequency and beams in MIMO-OFDM) to optimize ISAC performance.

Here, the main challenges are managing the increased complexity that comes with dual-function waveforms, achieving low latency for real-time applications and high sensing resolution, and maintaining synchronization across distributed APs. Additionally, the waveform must adapt to dynamic environments where ISAC requirements can change rapidly. A particular challenge in D-MIMO is that in DL the power allocation must provide a trade-off between scanning (using orthogonal signals at each transmit AP) and tracking performance (using phase adjustments for beamforming). Potential solutions to these challenges involve hybrid waveforms that combine elements of both communication and radar waveforms, advanced modulation schemes that cater to dual-purpose use, and various resource allocation strategies [6]. These strategies include adaptive power control, bandwidth allocation, and time-sharing mechanisms. By addressing these challenges and implementing these solutions, ISAC systems can efficiently operate within distributed antenna setups, enhancing overall system performance and enabling more effective integration of communication and sensing capabilities.

E. ISAC D-MIMO—Implementation Opportunities and Challenges

Only limited testbed activities exist involving D-MIMO in general [11], ISAC in general [12], and ISAC in D-MIMO, in particular, [13]–[15]. There is currently an urgent need to validate D-MIMO, especially in conjunction with ISAC.

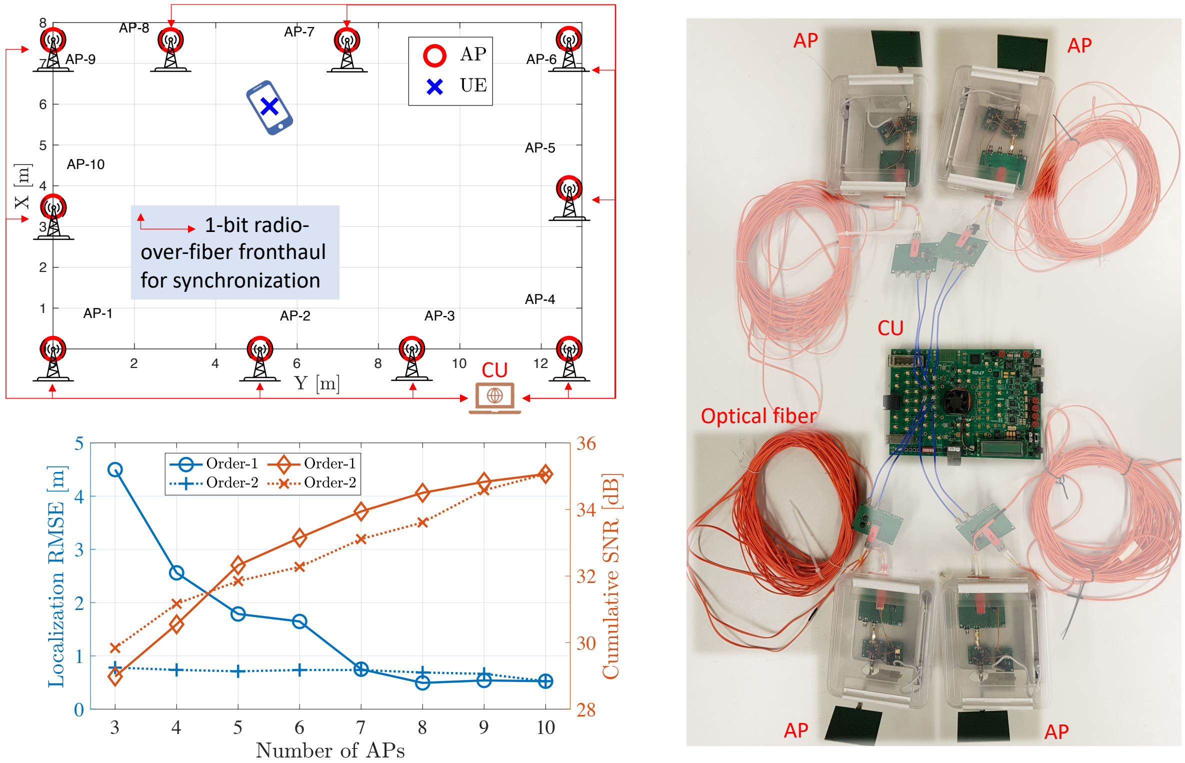

Fig. 4. A D-MIMO testbed used for ISAC demonstrations (right) with 1-bit radio-over-fiber fronthaul, the geometric configuration of the APs and the UE (upper left), and the experimental results for localization and communications (lower left). Localization RMSE and communication SNR performances are shown for different orders of deployment of APs (Order-1: 1 2 3 10 9 8 7 6 5 4, Order-2: 1 7 4 10 5 2 8 3 9 6).

Two of the main technical challenges are *scalability* and *synchronization* [14]. Moreover, in D-MIMO demonstrators, synchronization is typically achieved over the Ethernet or via dedicated cables. Both solutions, however, result typically in non-scalable architectures [14]. A natural alternative is to perform synchronization over the air [9], which may result in significant overhead for certain deployment scenarios. A completely different approach for solving the synchronization problem is put forward in our testbed described in [15] (see Fig. 4), where phase synchronization issues are avoided by letting the APs transfer to the CU a 1-bit quantized version of the analog RF signal via an optical cable. The advantage of this approach, which we refer to as 1-bit radio-over-fiber fronthaul, is that no local oscillators (which need to be synchronized for coherent transmission and reception) are present at the APs. Furthermore, such a D-MIMO architecture involves low cost APs that can be built out of off-the-shelf components. The disadvantage of this architecture is its limited scalability.

Fig. 4 demonstrates a setup and the results of ISAC experiments with the D-MIMO 1-bit radio-over-fiber testbed [8]. The goal is to localize the UE in DL using known pilot signals from the fully synchronized APs. We investigate the impact of AP deployments on the performance of localization and communication, quantified by RMSE and SNR, respectively. Fig. 4 shows the RMSEs and cumulative SNRs as the number of APs increases sequentially, considering two different orders for adding APs to the D-MIMO network, as stated in the figure caption. As expected, the geometric arrangement of the APs (and the resulting geometric dilution of precision (GDOP)) plays a key role in localization accuracy, while it has a negligible impact on communication performance. Specifically, decreasing the number of APs increases the sensitivity to the AP locations for localization purposes, whereas its effect on location sensitivity in communication remains minimal. Thus, network planning can be simplified and flexible deployment can reduce the costs in D-MIMO networks.

V. DISCUSSIONS AND OUTLOOK

D-MIMO and ISAC are set to be among the key enablers for 6G. This paper analyzed how the integration of ISAC in D-MIMO affects the underlying architecture. This analysis revealed both synergies and conflicts, while pointing towards D-MIMO architectures that can support all ISAC functionalities. We highlight preferred embodiments for communication and L&S. Specifically, for communication, i) indoor, lower bands: coherent, wired backhaul, distributed processing, half duplex, and ii) higher bands: noncoherent, centralized processing, half duplex (no wired/wireless backhaul preference, no indoor/outdoor preference) are preferred. For L&S, i) lower bands: coherent, wired backhaul, centralized processing, full duplex (no indoor/outdoor preference), and ii) higher bands: noncoherent, distributed processing, full duplex (no wired/wireless backhaul preference, no indoor/outdoor preference) are desired.

The paper also delved deeper into the quantitative performance benefits of ISAC in D-MIMO, from L&S and communication perspectives. These studies reveal significant synergies between communication and L&S. Finally, the practical challenges of ISAC in D-MIMO implementation were considered, in particular, related to synchronization and scalability, highlighting the need for continued development in this area.

Overall, ISAC in D-MIMO has great potential to create synergies between sensing and communication by communication-aided sensing (e.g., D-MIMO infrastructure design and reuse of data signals for sensing), sensing-aided communications (e.g., blockage detection and location information utilization), and more generally context-aided communications. However, there are still several open questions in D-MIMO that become further enriched by ISAC, especially related to scalability, suitability to outdoor dynamic environments, and efficient support of fast-moving users.

ACKNOWLEDGMENTS

This work was supported, in part, by the Gigahertz-ChaseOn Bridge Center at Chalmers in a project financed by Chalmers, Ericsson, and Qamcom. This work was also supported by the Swedish Foundation for Strategic Research (SSF), grants no. ID19-0021, ID19-0036, and FUS21-0004, the Swedish Research Council (VR grant 2022-03007, 2023-00272), the Chalmers Area of Advance Transport 6G-Cities project, and the MSCA-IF grant 101065422 (6G-ISLAC). We would like to thank Dr. Yigeng Zhang for his help with the illustrations.

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