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DISAC Architecture: Functions, Semantics, Protocols, Orchestration, and Demonstrator

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***Abstract*—The concept of Integrated Sensing and Communication (ISAC) is a cornerstone of the upcoming Sixth-Generation (6G) wireless networks. However, current centralized architectures struggle to meet the demands of scalable, multi-modal perception in complex environments. This paper focuses on the recently proposed Distributed Intelligent Sensing and Communication (DISAC) framework, including the final architecture of the project that pushes intelligence to the network edge. Key novel components of this architecture include: (i) a novel semantic plane that enables goal-oriented, context-aware data fusion across heterogeneous sensing modalities; and (ii) distributed orchestration protocols that seamlessly coordinate diverse network elements, including User Equipments (UEs), base stations, and, potentially multi-functional, Reconfigurable Intelligent Surfaces (RISs). Preliminary experimental results are proposed in the orchestration framework for distributed devices: a RIS-aided distributed sensing methodology for dynamic network resource balancing; and a link-level experiment demonstrating over-the-air distributed computation capabilities. Finally, the plan to validate the 6G-DISAC framework through a proof-of-concept demonstrator is discussed: a system-level assisted parking scenario that intelligently fuses radar, LiDAR, and camera datasets for autonomous navigation.**

***Index Terms*—ISAC, 6G, distributed sensing, network architecture, dynamic orchestration, distributed protocols, semantics, over-the-air computation.**

I. Introduction

The transition toward Sixth-Generation (6G) wireless systems marks a fundamental paradigm shift, moving beyond traditional connectivity-focused networks to intelligent, integrated platforms that natively combine communication with environmental sensing capabilities [1]. Integrated Sensing and Communication (ISAC) is now recognized as a key enabler for 6G, allowing the radio interface to perform high-resolution localization, object tracking, and environmental mapping concurrently with data transmission [2]–[4]. Although initial standardization efforts within 3GPP Releases 19 and 20 have begun to explore these capabilities, they predominantly focus on monostatic or loosely coupled bistatic configurations that rely on centralized processing [5]. However, the ambitious use cases envisioned for 6G, such as autonomous mobility in mixed indoor-outdoor environments or immersive digital twins, expose the limitations of these centralized, monostatic architectures, especially considering how single-perspective sensing is vulnerable to blockage and lacks the spatial diversity. Furthermore, the integration of non-Radio-Frequency (RF) sensing modalities (e.g., LiDAR and cameras) alongside radio sensing generates vast volumes of heterogeneous data that centralized controllers cannot efficiently process or transport [3]. To address these challenges, building on previous preliminary designs [6], this paper presents the final *Distributed Intelligent Sensing and Communication* (DISAC) architecture of the 6G-DISAC project. DISAC follows a hierarchical design in which local sensing and preprocessing are distributed, while service-level orchestration and global fusion remain logically coordinated. This design choice enables scalability and reduced backhaul load without assuming that all nodes share a common global view or run consensus-based control. The proposed distributed architecture advances beyond traditional centralized ISAC by embedding intelligence and processing at the network edge. This contribution incorporates a novel *distributed orchestration protocol* for seamless coordination of heterogeneous nodes and a novel *semantic plane* for goal-oriented, context-aware multi-modal data fusion, enabling scalable, multi-perspective environmental perception tailored to demanding 6G use cases. The specific contributions of this paper are summarized as follows: (i) *DISAC architecture*: We present the functions of the proposed architecture as well as their interactions. A key component of the DISAC architecture is a novel semantic plane that interfaces with the Network-Centric Application Layer (NCAL) to enable semantic and goal-oriented multi-modal fusion. (ii) *Distributed processing and control mechanisms*: We detail protocols and orchestration strategies for distributed processing of the sensing data, as well as control and orchestration strategies for distributed nodes with heterogeneous sensing capabilities, reinforced by experimental results. (iii) *6G-DISAC planned demonstration and Proofs-Of-Concept (PoC)*: The design of the final demonstrator of the 6G-DISAC project [4], capitalizing on the proposed DISAC architecture, is discussed. Specifically, the key components of a system-level assisted parking scenario that intelligently fuses radar, LiDAR, and camera datasets for autonomous navigation in environments denying the Global Navigation Satellite System (GNSS) are presented.

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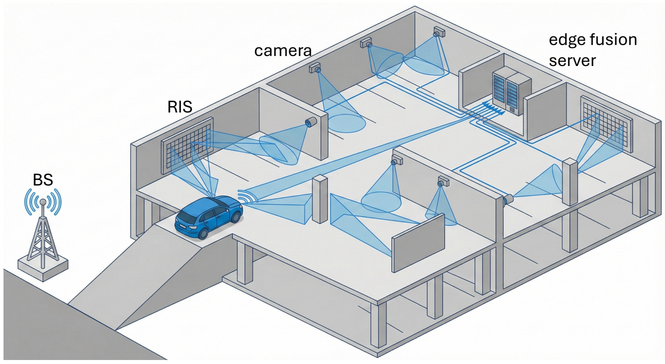

Fig. 1. The DISAC-assisted parking scenario in GNSS-denied environments.

II. The DISAC Architecture

The DISAC architecture is designed to support complex, distributed sensing scenarios where multiple heterogeneous nodes need to cooperate to build a coherent view of the environment. To motivate the architectural choices presented in the following sections, we consider a mixed indoor-outdoor assisted parking scenario, which is a key validation case for 6G sensing [7], as shown in Fig. 1. In this use case, the objective is to assist a human driver in identifying a suitable parking space and safely navigating toward it. The infrastructure supports detection and selection of available slots, including those not directly visible, and assists navigation by monitoring the environment and detecting hazards. The scenario also anticipates future evolution toward fully autonomous operation, where the same infrastructure-supported perception and communication capabilities enable automated parking manoeuvres. A vehicle transitions from an outdoor environment (GNSS-available) to an indoor parking facility (GNSS-denied), requiring a seamless handover of localization services. This scenario demands: (i) *Multi-modal fusion:* The infrastructure must fuse data from disparate sources (e.g., radar for range/velocity estimation, RISs for localization/mapping [8], cameras for semantic object classification (e.g., pedestrians vs. cars), and LiDAR for precision mapping) to create a unified environmental model; (ii) *Distributed processing:* Due to the high bandwidth of raw sensor data transfer (especially video and LiDAR), processing must occur at the edge (Local Sensing Processing Function (SePF)) rather than streaming everything to a central core; (iii) *Goal-oriented semantics:* A driver searching for a parking spot needs specific semantic information (e.g., "Slot 4B is free") rather than raw point clouds. Hence, based on this specific goal, the network must filter and interpret data. To support this and relevant use cases, the DISAC architecture adopts a layered approach comprising the *Network Functions Layer* (NFL) and NCAL for semantic intelligence [3], as illustrated in Fig. 2. This architecture introduces a novel *semantic plane* (center) comprising three key functions: Semantic Sensing Orchestration (SSO) for goal management, Semantic Sensing Goals (SSG) for task refinement, and Semantic Sensing Fusion and Representation (SSFR) for unifying multi-modal data.

A. Distributed Sensing Functions

The distributed sensing functions constitute the core operational components within NFL, providing the essential capabilities for coordinating, processing, and managing sensing operations across the distributed network infrastructure. This layer hosts the following functions, responsible for the configuration and execution of sensing tasks.

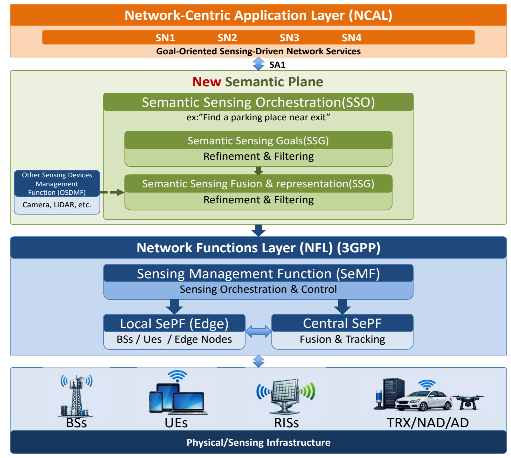

Fig. 2. The final DISAC architecture of the 6G-DISAC project.

Sensing Management Function (SeMF): Located in the core network, the SeMF serves as the central orchestration entity for DISAC operations. It processes sensing service requests from applications, performs dynamic discovery and selection of available sensing nodes (including Transmission Reception Points, User Equipments (UE), and RIS devices), and negotiates critical sensing parameters, such as waveform characteristics, measurement periodicity, data representation formats, and resource allocation. The SeMF also manages the lifecycle of sensing services, including activation, reconfiguration, and deactivation, based on changing network conditions and application requirements.

Sensing Processing Function (SePF): DISAC employs a hierarchical processing architecture that distributes computational load across network tiers to optimize latency, bandwidth utilization, and processing efficiency:

Local SePF (LSePF): Deployed at edge locations (BSs, sensing-capable UEs, or edge computing nodes), LSePF performs real-time, low-latency processing of raw sensing measurements. This includes signal preprocessing, feature extraction, clutter suppression, and initial target detection. The LSePF adapts its processing complexity based on local computational capabilities and network conditions, supporting flexible data representation formats (from raw IQ samples to processed target lists) as negotiated with the SeMF.

Central SePF (CSePF): Located in the core network, CSePF aggregates and fuses processed sensing data from multiple LSePFs across the sensing service area. It performs high-level analytics, including multi-target tracking, environmental mapping, and cross-correlation analysis. It also handles data fusion from heterogeneous sensing modalities and maintains global situational awareness for complex sensing scenarios spanning over large geographical areas.

B. The Semantic Plane

Intelligent distributed processing can be extended to include multi-modal sensing, by integrating different devices to combine multiple sensing modalities, such as point cloud, imagery, radar, and acoustic data. A major challenge for

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multi-modal ISAC is the heterogeneous nature of multi-modal data: diversity of data formats, temporal resolution, continuous stream or discrete packets, and so on. To overcome this challenge, the incorporation of Artificial Intelligence (AI) is essential [9]. Semantic-based approaches can enhance the entire data processing pipeline by enabling precise data fusion, comprehensive understanding, and optimized multi-task processing. Large Language Models (LLMs) further improve semantic comprehension, providing contextual learning and efficient reasoning over high-dimensional multi-modal datasets [10]. AI-driven multi-modal ISAC can achieve robust feature alignment, dynamic environment modelling, and intelligent beam management, while enabling adaptive resource allocation between sensing and communication which can promote distributed knowledge across the network [11]. To address the multi-modal fusion requirements in scenarios of interest like the reference cooperative assisted parking use case from the architecture perspective, the 6G-DISAC project introduced a *semantic plane* [3] to make use of semantics in the NCAL, instead of the NFL as proposed in [12]. For this purpose, we proposed the following three novel functions (Fig. 2):

Semantic Sensing Orchestration (SSO) This function acts as the intelligent controller. It receives high-level service requirements (e.g., "Find parking near the exit") from the Application Layer (interface SA1) and translates them into specific sensing goals. It interacts with the SeMF (interface SN2) to trigger the necessary physical resources.

Semantic Sensing Goals (SSG) This function refines the broad directives from the SSO. For example, in the parking scenario, it would query the fusion engine specifically for "available slots in Sector B," filtering out irrelevant data about distant traffic, thereby minimizing overhead.

Semantic Sensing Fusion and Representation (SSFR) This function serves as the central semantic engine. In particular, it receives processed data from the CSePF and non-3GPP sensors (via the *Other Sensing Devices Management Function* (OSDMF)). Then it unifies these diverse data streams into a coherent semantic representation (e.g., a dynamic knowledge graph of the parking garage).

III. Protocols and Orchestration

Implementing the proposed distributed architecture described in Section II requires a new suite of control plane, protocols, and orchestration algorithms. In contrast to centralized systems where a single node controls all parameters, DISAC relies on distributed coordination to effectively manage heterogeneous capabilities and dynamic network topologies.

A. Distributed Sensing Protocols

To enable scalable sensing across multiple transmission (STx) and reception (SRx) points, we define a *Distributed Sensing Protocol* that coordinates distributed nodes for target detection [13]. The protocol is depicted in the message flow of Fig. 3, where optional steps are illustrated as dashed lines and boxes, and proceeds in the following four logical phases:

Setup Phase (Steps 1 to 4): The SeMF initiates a sensing request based on the sensing client's Field of View (FoV), and selects the appropriate STx and SRx nodes based on their geographical location and current capabilities (e.g., computational resources and power constraints. If energy-saving modes are employed within the network, an optional wake-up signal can be transmitted to activate these sleepy or standby STx and SRx nodes only when their participation is required for the sensing task (step 3.a.1). Crucially, individual nodes including non-sensing transceiver (TRX), such as UEs, Network-Assisted Devices (NAD), such as RISs, or Autonomous Devices (AD), such as autonomous RISs, could retain the autonomy to accept or reject these requests, enabling semi-autonomous operation. The SSO can optionally interact with the SeMF to select and configure sensing devices, following a semantic sensing request from sensing applications to collect descriptive information about the task. These descriptions simplify data collection and reduce resource usage, while including important details.

Sensing Phase (Steps 5 to 6): Selected STx nodes transmit orthogonal probing signals, ensuring minimal inter-node interference and enabling coherent signal separation at the receivers. Simultaneously, SRx nodes capture the reflected echoes scattered by sensing targets (STs), as well as signals originating from TRX/NAD/AD nodes within the sensing field. To minimize control-plane latency, synchronization is embedded directly into the native 6G radio frame structure rather than relying on explicit, handshake-based procedures. A common time and frequency reference is maintained through frame, slot, and symbol-level alignment, supported by flexible numerologies and deterministic frame timing. The periodicity and predictability of radio frames, together with predefined reference and pilot signals, enable implicit coordination across functional entities at well-defined transmission occasions. This tight coupling to the radio frame allows control actions and sensing/communication functions to be triggered at specific symbols or slots, significantly reducing signaling overhead and enabling fast, deterministic reaction times required for low-latency DISAC operation.

Processing Phase (Steps 7 to 10): Instead of forwarding raw IQ samples to the core, SRx nodes act as LSePFs. They perform initial feature extraction (e.g., range-Doppler map generation) and transmit only the compressed semantic features to the CSePF for fusion. This distributed processing significantly reduces the backhaul load compared to the available centralized baselines. Optionally, the LSePF can report the processed sensing result directly to the SeMF, enabling lower latency and core offloading for simple or standalone tasks (as shown in step 9.b.). The SSFR can optionally process the text descriptions (e.g., using LLMs) to extract data useful for the goal and send the final information through the SSG and SSO back to the SeMF. The SSFR can also integrate and correlate heterogeneous data received from the SePR (eventually involving the OSDMF) performing multi-modal fusion to create a better representation of the environment and fulfil the pre-defined task.

Report Phase (Step 11 and 12): Once the CSePF has compiled the unified sensing or localization report, it forwards this result to the SeMF in Step 11 for final service alignment and goal verification. Then, in Step 12, the SeMF delivers the finalized outcome to the Sensing Client, enabling real-time application decisions with reduced overhead.

Overall, the proposed protocol supports both static anchor nodes (BSs) and mobile opportunistic nodes (UEs), with

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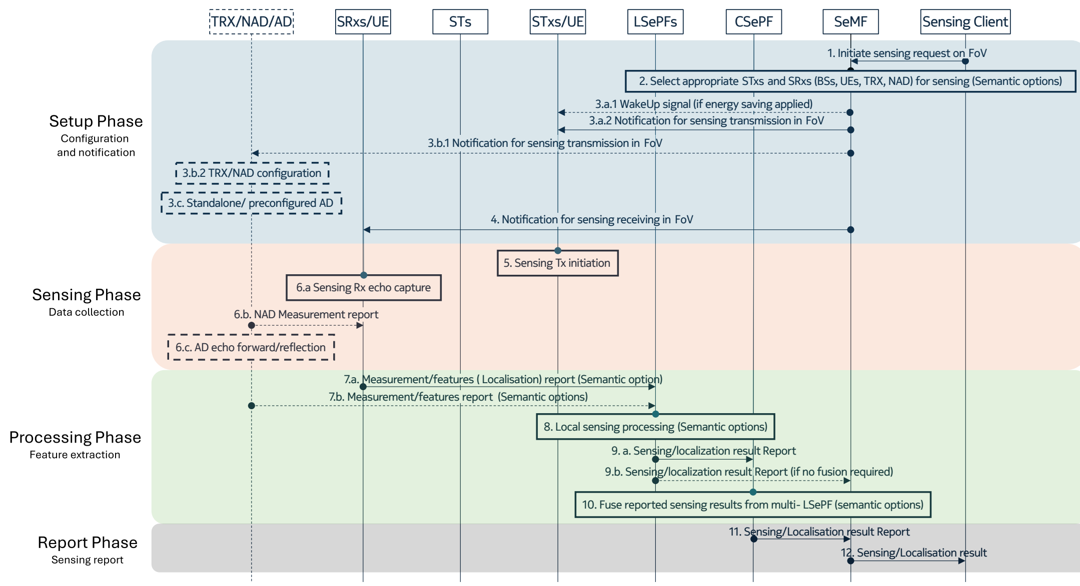

Fig. 3. The proposed distributed sensing protocol with scalable sensing across multiple transmission (STx) and reception (SRx) points.

specific extensions defined for controlling RISs via a dedicated RIS-Controller interface.

B. Orchestration of Distributed Devices

Effective ISAC requires dynamic orchestration to balance the conflicting resource demands of sensing accuracy and communication throughput. In distributed scenarios, this becomes a multi-objective optimization problem.

1) RIS-aided Distributed Sensing

The integration in a communication network of sensing capabilities relying on spatially distributed reflective RISs arises with specific challenges in terms of resource allocation and operating trade-offs. In this context, we propose an opportunistic shadowing-based sensing method, aiming to mutualise the deployed network resources (i.e. avoiding the use of active nodes uniquely dedicated to sensing), where the UEs or BSs involved as SRx nodes can also be engaged in parallel communication links with the other nodes belonging to the same network [14].

Proposed methodology: For illustration, we first consider a link-level RIS-aided scenario with a single dual-beam RIS, exhaustively scanning the radio environment by sweeping (in azimuth) its "input" beam during the sensing period, while pointing its "output" beam towards a sensing node (SRx). The latter being also involved in a reference communication link. Multiple other UEs and BSs are active in the environment, acting as STxs and providing beneficial ambient non-coherent signals for shadowing-based or backscattering-based sensing. Without loss of generality, the sensing node is assumed to be a UE communicating in Downlink (DL) with its serving BS. The data communication operations can be scheduled by the orchestrator together with the sensing operations, according to sequential/time-sharing or concurrent/simultaneous schemes (Fig. 4a and Fig. 4b respectively). In the former case, given an imposed resource budget, sensing and communication occur in orthogonal time slots, thereby maximizing sensing accuracy by eliminating interference (e.g., refining spatial resolution) at the cost of a reduced effective communication duty cycle. In the latter case, the spectral efficiency is globally improved, at the cost of potential harmful interferences caused by RIS-reflected signals. Adequate resource allocation schemes must thus be designed in both cases, to achieve relevant operating trade-offs between communication and sensing performances, either at link and network levels. More concretely, depending on the application requirements and operating conditions (e.g., on the radio environment), an orchestration algorithm should dynamically select the operating mode and optimize the RIS phase profiles to maximize the *sensing signal-to-interference-plus-noise ratio*, or spatial resolution, subject to a minimum *communication quality of service* constraint.

Results: The numerical evaluation of the orchestration approach in Fig. 4c shows how the average capacity of the reference DL communication link over a typical service frame increases monotonically with the sector width of the RIS beamforming within both sequential and concurrent modes [13]. Given the two different y-axis ranges, we note that this effect is much more pronounced in the former case. The reason is that finer scanning resolutions (i.e. narrower sectors) imply longer scanning periods and therefore shorter periods left for DL communications, while in the latter case narrower RIS "Input" beams come with higher power gains and hence stronger interfering power from ambient sources (reflected by the RIS to the UE) that negatively impacts the communication link. In addition, other complementary results suggest that the concurrent orchestration of RIS-assisted shadowing-based blocker detection [14] and DL data communication (both with respect to the same receiver node) produces higher aggregate system utility in relatively sparse radio environments. However, it can temporarily lead to degraded capacity in denser, interference-limited scenarios.

2) Over-the-Air Distributed Computing

The orchestration and resource allocation in the DISAC workflow may potentially entail excessive data rate demands

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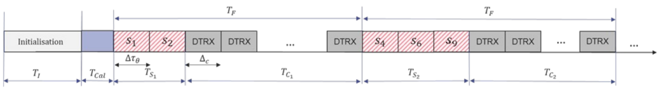
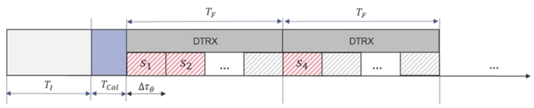
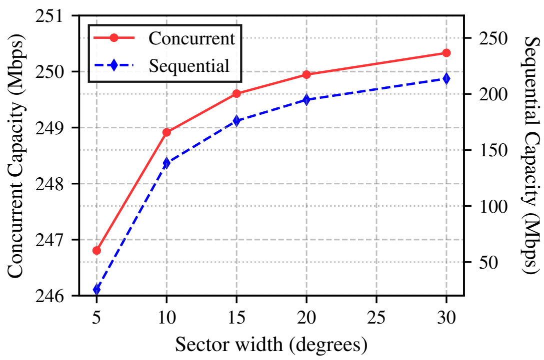


(a) Sequential ISAC mode.



(b) Concurrent ISAC mode.



(c) Achievable spectral efficiency of both ISAC modes vs. the sensing spatial resolution.

Fig. 4. Performance evaluation of sequential and concurrent sensing in conjunction with data communication.

on control and feedback channels when multiple SRx's operate under the "transmit-then-compute" mode, sending sensing observations to a centralized SePF to be processed. In contrast, a "compute-then-transmit" approach, where each SRx processes data at its LSePF before transmitting the information to the SeMF, may exceed the capabilities of low-power devices. A third paradigm, "compute-while-transmitting", uses over-the-air computation to shift part of the processing onto the channel and RF front-ends. To validate this methodology, we evaluate a goal-oriented orchestration scheme on sensing data.

Setup: We implement a multi-static RF sensing setup in which an STx broadcasts sensing beacons that are absorbed, diffracted, and reflected by a target within the sensing area, while the reflected signals are captured by several single-antenna SRx nodes distributed around the scene. The goal is to determine, at the SeMF, the type of object present in the environment. To this end, the system leverages a machine learning (ML) approach trained on historical data consisting of pairs of sensing signals collected at the SRx nodes (model inputs) and the corresponding object-type labels (target outputs). A centralized approach would require each SRx to transmit its sensing signals to the CePF/SeMF using separate resource blocks across time, frequency, or spatial domains. The CePF/SeMF would then decode the signals and feed them to an ML model executed on suitable hardware (e.g., a graphics processing unit (GPU)). Conversely, following the "compute-while-transmitting" paradigm, we employ a two-layer neural network in which all SRx nodes simultaneously transmit their sensed complex values over the same time-frequency resources without additional modulation. The first-layer computations are effectively carried out by the multiplicative random channel fading coefficients. We further assume a large metasurface-based antenna at the CePF, with each receiving

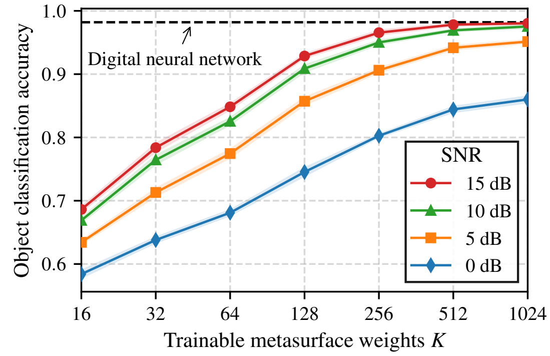


Fig. 5. Performance of the over-the-air ML model for classification of sensed object type based on distributed SRx measurements across different receive SNR regimes and increasing number of trainable metasurface elements.

element exhibiting a nonlinear response. These responses are then combined in analog with controllable weights, forming the second neural network layer. Following the methodology of [15], the optimal weights minimizing the model output over the dataset can be obtained in closed form, enabling fast training and inference. Further details can be found in [3].

Results: For the RF sensing synthetic dataset, we have collected images of handwritten digits from the MNIST dataset. The non-background pixels of each image correspond to the individual scattering points onto a 2D sensing area, and we employed the RF modeling of [16] to compute the received signals at the SRxs. Numerical results presented in Fig. 5 demonstrate that as the number of elements (i.e., trainable parameters) at the CePF's metasurface increases, the overall system achieves near-optimal classification of the sensed object's types. Higher receive Signal-to-Noise Ratio (SNR) values may further reduce the need for large metasurfaces. Notice that, in this scenario, the computations taking place are exclusively implemented over-the-air and through analog RF circuitry, offering important benefits in terms of energy consumption and computational latency compared to the fully digital computation process described earlier.

IV. DISAC Demonstrator: Assisted Parking

To illustrate the application of the proposed DISAC architecture, orchestration methods, and protocols, we describe the planned design of a comprehensive PoC platform that addresses different layers of the protocol stack [4].

Scenario and Environment: Assisted parking in real-world facilities represents a particularly demanding mobility scenario due to the combination of mixed indoor-outdoor operation, limited maneuvering space, and high environmental complexity. Vehicles typically transition from outdoor areas with GNSS availability to indoor structures where GNSS signals are degraded or unavailable. These environments are characterized by strong multipath propagation and frequent occlusions caused by pillars, ramps, and parked vehicles. The DISAC assisted-parking demonstrator targets this setting by leveraging a sensor-rich infrastructure. Rather than relying solely on onboard vehicle sensors, the infrastructure provides a cooperative perception layer that supports safe navigation and localization throughout the full outdoor-to-indoor transition. It is worth noting a key characteristic of this scenario: vehicles in parking facilities move at very low

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speeds (typically below 10 km/h), which relaxes latency and Doppler-resolution requirements compared to higher-mobility cases such as urban intersections or highway platooning. This makes assisted parking a suitable starting point for validating the DISAC architecture and demonstrating multi-modal fusion under controlled conditions, though it does not fully test the framework's real-time performance. In particular, the slow motion leads to gradual scene dynamics and a relatively generous time budget for orchestration, fusion, and feedback. Future work will consider more demanding mobility scenarios to evaluate the proposed protocols under stricter latency and real-time constraints.

Actors and Sensing Infrastructure: The main actors are the vehicle, which can be autonomous or operated by a human driver, and the parking infrastructure. The infrastructure integrates multiple sensing modalities (radar, RIS elements, LiDAR, and cameras) deployed at fixed locations to ensure spatial coverage. RISs are installed at strategic positions to enhance observability in occluded regions. All sensing elements are connected to an edge fusion server, which acts as the aggregation point for perception data.

Operational Flow and Mapping to Architecture: The operational flow of the demonstrator aligns directly with the DISAC functional architecture presented in Section II.

Phase 1 – Service Initiation: When a vehicle enters the facility, an initial identification step establishes a logical association between the vehicle and the infrastructure. This triggers the SeMF, which determines that the assisted-parking service is required and prepares the system for orchestration.

Phase 2 – Orchestration and Resource Selection: The SeMF coordinates the activation of relevant sensing resources based on the vehicle's trajectory and the environmental context. It selects appropriate sensing entities (e.g., specific cameras or RIS elements) dynamically. This exemplifies the DISAC principle of context-aware orchestration, where resources are engaged only when needed. Decisions are communicated to distributed sensing nodes, which operate as LSePFs.

Phase 3 – Local Processing and Reporting: Active sensing nodes perform local perception tasks (detection, classification). Instead of transmitting raw sensor data, the LSePFs generate standardized, object-level representations (e.g., ISO 23150-compliant object lists) containing semantic attributes and confidence indicators [17]. This reflects the key architectural concept of distributed processing, significantly reducing the backhaul load compared to centralized raw data streaming.

Phase 4 – Centralized Fusion: Object-level reports are forwarded to the CSePF, which is instantiated on the edge server. This function performs time alignment and multi-modal fusion to generate a coherent environmental model. This model integrates observations from multiple viewpoints, allowing the system to maintain consistent object tracks and detect occluded areas that individual sensors cannot see.

Phase 5 – Feedback and Guidance: Based on fused perception, CSePF derives application-level outputs (e.g., parking slot recommendations), which are communicated back to the vehicle via Collective Perception Messages (CPM), enabling infrastructure-assisted awareness. SeMF continuously adapts sensing configurations as the vehicle moves, demonstrating the closed-loop adaptive nature of the DISAC architecture.

V. Conclusion

This paper presents the final architecture and planned PoC demonstrator of the 6G-DISAC project, outlining a promising path toward distributed, intelligent sensing in 6G wireless networks. By decoupling sensing control from processing and introducing a semantic plane, the DISAC framework supports multi-modal data fusion while reducing backhaul demands through goal-oriented, semantics-native mechanisms. Our contributions address three pillars of distributed ISAC: (i) Architecture: a hierarchical framework integrating heterogeneous nodes (from BSs to low-power RISs) under goal-oriented semantic protocols; (ii) Orchestration: protocols for distributed sensing coordination, including dynamic trade-offs between communication and sensing, and distributed over-the-air computation at the physical layer; (iii) Demonstrator design: the planned PoC for an assisted parking scenario with system-level multi-modal fusion in GNSS-denied autonomous navigation environments. Future work will scale these orchestration mechanisms to large deployments and refine semantic interfaces for fully autonomous cross-layer optimization.

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