Accepted for presentation in: IEEE INFOCOM Workshops, Tokyo, Japan, May 2026.

Hybrid Active-Passive Network Design Enabled by Physics-Informed ML-based Propagation Modeling

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***Abstract*—Industrial applications of future 6G networks require extremely high data rates, which can be achieved using the large bandwidths available for millimeter wave frequencies (mmWave), but which exhibit complex and sensitive propagation behavior. Careful planning of these networks is hence essential. In this paper, we present a first-of-its-kind end-to-end software framework for mmWave network planning combining accurate Machine Learning (ML)-enabled channel modeling with active base stations and passive reflectors to enable sustainable deployments.**

I. Towards Sustainable Private 6G mmWave

The ongoing digitalization of industrial environments imposes stringent requirements on wireless communication systems, i.e., in terms of data rate and latency. The mmWave frequency bands offer large bandwidths to meet these demands. However, the electromagnetic (EM) propagation at these frequencies is highly challenging due to severe path loss, i.e., strong blockage and weak diffraction, and pronounced angular dependence from directional beamforming [1, 2]. Consequently, Base Stations (BSs) must be carefully positioned to ensure sufficient coverage and performance. Cost- and power-effective network planning of future 6G networks requires the consideration of passive Intelligent Reflecting Surfaces (IRSs), which offer an efficient solution for coverage extension and signal enhancement [2, 3]. This emphasizes the need for an integrated network planning concept that jointly considers FR2 propagation characteristics, optimal deployment of BSs, and the strategic placement and design of passive IRSs, enabling a sustainable balance between active and passive infrastructure.

In this work, we present a design concept for 5G and beyond networks operating in FR2 to form the basis for resolving the 6G problem of a yet missing hybrid network design routine with intelligent balancing between additional active and passive elements. A systematic overview is provided in Fig. 1: To accurately predict FR2 path loss, we use a Physics-Informed Neural Network (PINN)-based radio propagation model (see Sec. II). Based thereon, network planning identifies the optimal poses of BSs and custom-tailored IRSs (see Sec. III). [1]

II. End-to-End 6G mmWave Propagation Modeling

Since traditional propagation models are either too inaccurate (e.g., empirical models), computationally intensive (e.g., ray-tracing), or lack Beyond Line-of-Sight (BLOS) modeling, we adopt ML-driven path loss estimation to close this gap. We introduced the so-called IndoorDRaGon for predicting the path loss in industrial indoor environments at FR1 in [4]: Given a 3D environmental model, two synthetic gray-scale images of the BS and User Equipment (UE) direct path are generated to describe the propagation environment. Overall, 28 numerical features derived from these images, the BS and UE poses, the direct path, and the radio channel are used to train a Machine Learning (ML) model to predict a correction to the 3GPP Indoor Factory (InF)-SL (*sparse* clutter, *low* BS) model [5].

[1]The contents from Secs. II-III are presented in more detail in the poster.

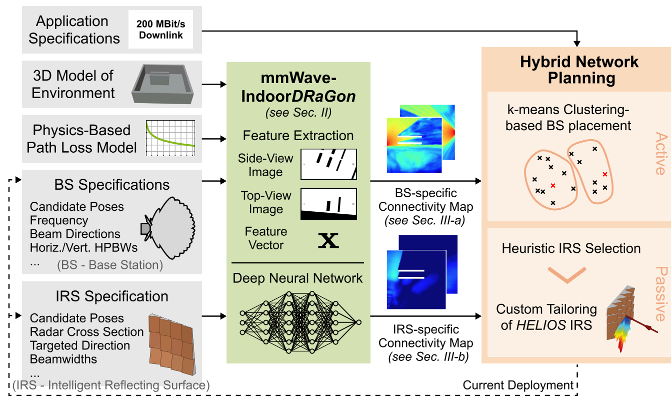

Fig. 1: Physics-informed ML-based network design with precise propagation modeling and intelligent BS&IRS placement

Adaptation to FR2: The former model was trained on data points measured for FR1, where beam directivity did not factor in as much as for FR2 systems. We thus extended the feature set with six additional features: elevation and azimuth to mechanical beam direction and electronical steering, horizontal and vertical Half-Power Beam Width (HPBW). We trained the model on approximately 1.5 billion samples originating from a synthetic dataset generated using *Wireless InSite*. The dataset covers over 450 scenarios with divcerse obstacle distribution inspired by logistics and production environments. Various BS poses (position, orientation) and 1,000 beam pattern variations are included in the simulations. The center frequency was set to 27.1 GHz. The PINN, which combines empirical path loss modeling with ML-based corrections, was trained using 80% and tested on 20% of the data. The resulting test Root Mean Square Error (RMSE) measures 4.3 dB. For comparison, the 3GPP InF-SL model yields 37.4 dB RMSE.

Modeling IRS-based Paths: Similar to the approach in [6], the reflected path is modeled based on radar equation by estimating the Line-of-Sight (LOS) link between BS and IRS, the link between IRS and UE, and a compensation factor. To consider their directional patterns, both channels are estimated utilizing the just presented *mmWave-IndoorDRaGon*.

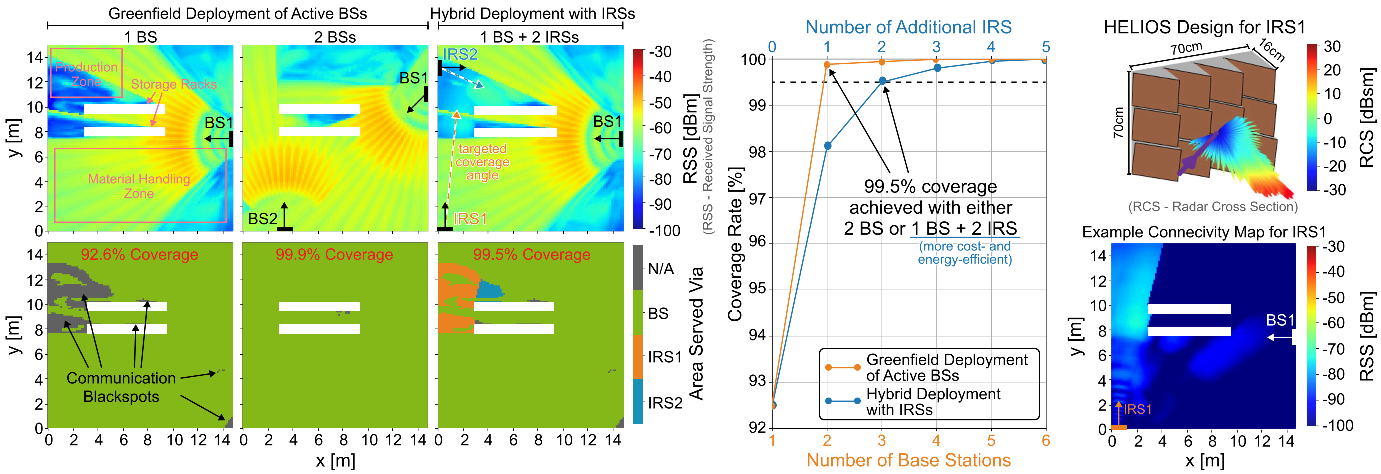

Fig. 2: Illustration of the planning process: *(left)* connectivity and coverage maps for greenfield BS deployment and brownfield IRS integration, *(middle)* coverage evolution with added infrastructure, and *(right)* IRS-specific connectivity and reflector design

III. ML-based Network Planning with BSs & IRSs

Based on a 3D model of the environment, given specifications for both the BSs and application, the network planning routine can be initiated (see Fig. 1). Below, we show the BSs and IRSs placement for a simplified logistics scenario (cf. Figs. 1, 2). The considered data rate requirement is 200 Mbps in downlink direction for the whole area at 1.5 m UE height.

a) Greenfield Planning of Active BSs: We consider twelve BS positions around the walls with three different mechanical orientations each. The beambook configuration is fixed and the EIRP equals 20 dBm. For each BS candidate, we utilize the mmWave-IndoorDRaGon (cf. Sec. II) to retrieve pose-specific BS-UE connectivity maps. The k-means clustering method for outdoor BS placement [7] has been expanded to indoor environments for this work: For each of the BS-UE connectivity maps, it is determined where the service requirement is met to produce a coverage polygon. Their respective centroids are entered into the k-means clustering process. For the first cluster, the utility rate maximizing BS pose is selected. For the remaining clusters, the BS is chosen that maximizes the utility rate given the already selected BSs. Fig. 2 shows the connectivity maps of the first two iterations.

b) Brownfield Planning of passive IRSs: Instead of active BSs, the FR2 deployment can also be extended by passive IRSs. Given a BS set, under-connected areas, which can be potentially served with a HELIOS IRSs [6], and possible reflector positions along the walls are identified. The latter must be in LOS with both the BS and the to serving area. For each IRS candidate, the required reflection pattern and reflection gain are automatically derived for a potential custom-tailored HELIOS reflector [8]. The IRSs can be evaluated in terms of their coverage potential, required beamwidth, and geometric alignment. For this work, we have derived a (45%, 45%, 10% weighting) heuristic that combines these metrics and thus identifies the most suitable IRS candidate. Fig. 2 shows the connectivity map after adding two IRSs to the single-BS deployment. Comparing the coverage rates, 99.5% can be achieved either with two active BSs or with a single active BS combined with two passive IRSs, thus constituting a more energy-efficient solution. Also, the derived reflector geometry and IRS-specific connectivity map are illustrated for IRS 1.

IV. Ongoing Research

In this work, we presented an end-to-end software framework for efficient 6G network planning with IRS assistance. We not only showed the evolution of [4] into an ML-based directional FR2 EM propagation model and the adaptation of the BS placement from [7] to indoor environments, but also the combination of these approaches with the IRS planning approach [8] as an efficient network design concept for FR2 networks. In future work, we aim to consolidate the individual components and, in particular, enable effective hybrid network planning through the development of a smart decision agent. Therefore, we aim to develop an energy- and costs-based model to quantitatively evaluate the efficiency of deploying passive IRSs as an alternative to additional active BSs.

Acknowledgment

This work was funded by the German Federal Ministry of Research, Technology and Space (BMFTR) in the course of the *6GEM+* transfer hub under grant no. 16KIS2412 and the *PANGOLIN Networks* project under grant no. 16KIS2357.

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