Beyond Blind Zones: Physical Limits and Algorithmic Gaps in 5G NR Passive Sensing

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Urban intersections present high safety risks due to sensor blind spots. Passive sensing via 5G infrastructure offers a cost-effective solution, yet its capability is spatially non-uniform, depending on scene geometry and multipath coupling. For safety-critical deployment, the central challenge is not average performance, but whether the system fails at specific high-risk locations. This motivates a critical pre-deployment question: given a physical scene, which locations are inherently detectable and why?

Existing approaches fail to characterize this spatial non-uniformity in cluttered environments. ISAC parameter estimation focuses on localization accuracy assuming observability, while stochastic geometry yields network-wide averages that mask local failures [1]. Prior geometric models for indoor sensing are insufficient for complex outdoor multipath scenarios [2]. Crucially, none of these methods provides a tool to decouple the information physically carried by the channel from the efficiency of the algorithm exploiting it.

We establish an algorithm-independent upper bound grounded in the physics of the sensing task, modeled after a real-world 5G intersection at the University of Edinburgh [3]. The scenario employs a base station ($N_r = 4$) monitoring vehicles ($N_t = 4$) across 88 discretized 5m cells. Using the Sionna ray-tracing platform [4], we generate channel matrices $\mathbf{H} \in \mathbb{C}^{16\times 2048}$ that incorporate realistic RF impairments, resulting in an observation dimensionality of $D = 32,768$.

At each cell n, detection is framed as a binary hypothesis test on the perturbation $\Delta\mathbf{H} = \mathbf{H}_{\text{obs}} - \mathbf{H}_{\text{ref}}$, where $\mathbf{H}_{\text{ref}}$ is the estimated background. Modeling target-absent fluctuations as complex Gaussian noise $\mathcal{CN}(0, \sigma_N^2\mathbf{I})$, the presence of a target introduces a deterministic mean shift $\boldsymbol{\mu}_n = \mathbb{E}[\Delta\mathbf{H}(n)]$:

$$\mathcal{H}_0 : \Delta\mathbf{H} \sim \mathcal{CN}(\mathbf{0}, \sigma_N^2\mathbf{I}), \quad \mathcal{H}_1 : \Delta\mathbf{H} \sim \mathcal{CN}(\boldsymbol{\mu}_n, \sigma_N^2\mathbf{I}). \tag{1}$$

Under the Neyman-Pearson framework, the optimal likelihood-ratio test reduces to a matched filter that projects $\Delta\mathbf{H}$ onto the signature $\boldsymbol{\mu}_n$. The resulting output Signal-to-Noise Ratio (SNR) is equivalent to twice the Kullback-Leibler divergence between the hypotheses, which we define as the physical detectability metric $\Omega(n)$:

$$\Omega(n) = \frac{\|\boldsymbol{\mu}_n\|_F^2}{\sigma_N^2} = 2D_{\text{KL}}(p_1 \| p_0), \tag{2}$$

where p_1 and p_0 represent the distributions under $\mathcal{H}_1$ and $\mathcal{H}_0$, respectively.

Figure 1 reveals a critical decoupling between physical information availability and algorithmic performance. At the physical level (Fig. 1, Left), the NP-optimal metric $\Omega(n)$ exceeds 15 dB globally, proving that absolute physical blind zones do not exist in the 5G channel. Conversely, a vanilla CNN suffers catastrophic failure with a mean recall of only 0.135 (Fig. 1, Right) because it lacks the structural prior to perform coherent integration. This results in a 45 dB processing gain penalty, forcing the model to track the raw per-element SNR (Fig. 1, Centre) which drops as low as -30 dB. These results confirm that the observed failures are not physical limitations, but rather *algorithmic blind zones* where high-quality signal information remains unexploited.

The contrast between $\Omega(n)$ and algorithmic recall establishes a new pre-deployment audit paradigm for passive sensing. By utilizing $\Omega(n)$ as an algorithm-independent tool, designers can quantify the inherent sensing headroom of BS configurations via simulation without hardware costs. This framework identifies spatial regions where physical information is wasted, directly motivating a transition toward *physics-informed* architectures. Future models incorporating channel priors, such as low-rank structures, are essential to recover the 45 dB coherent gain lost by black-box approaches. Ultimately, decoupling physical from algorithmic undetectability provides the principled foundation for the systematic advancement of 5G sensing systems.

References

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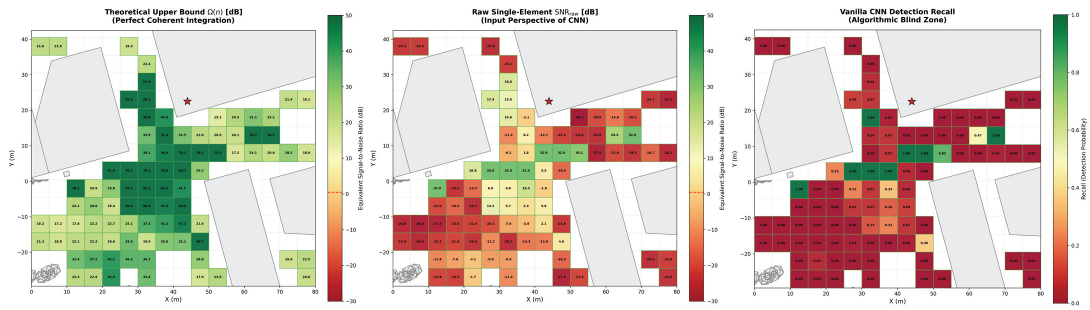

Figure 1: Spatial maps of (Left) physical detectability $\Omega(n)$, (Centre) raw input SNR, and (Right) vanilla CNN recall.