Compressive Initial Cell Discovery and Beamforming
Training in Millimeter-Wave Cellular Networks
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1. Introduction

Beam management in mmW network
• In 5G-NR, BS and UE need to reach initial discovery, synchronization, and beam training
• Challenge: sounding beam design and signal processing with low latency and overhead

Mature and emerging beam management
• Directional vs pseudorandom sounding beams
• Universal vs sparsity oriented processing

Key research questions answered in this work
• How to use pseudorandom beam for initial access?
• How to exploit sparsity to reduce access latency?
• How to handle timing offset (TO) & carrier frequency offset (CFO)?

2. Preliminary: 5G-NR Frame & Directional Sounding

• How does direction beam enable cell discovery?
  Thresholding with peak power of M bursts.

• How does direction beam enable beam training?
  Only coarse beam training due to wide sounding beams. Hierarchy refinement is used in dedicated CSI-RS slots

• What is its limitation?
  Latency due to CSI-RS scheduling

3. System Model & Problem Formulations

Post sounding beam measurement model
• mmW UE commonly uses simple phased array; only post-preceding w_n & post-combining w_M measurement is available

Initial synchronization error
• Carrier frequency offset ε_c and timing offset ε_t between BS and an UE

Discrete time sparse mmW channel model
• Features sparse scattering with L (≤ 3) multipaths

Problem 1: initial discovery and timing acquisition
• Discovery: binary detection problem with unknown parameters.
• Timing acquisition: estimate ε_c from y[n]

Problem 2: beam training robust to CFO
• Estimate AoA/AoD of path with significant power θ*, φ* from y[n]
• Report beam pair \( n^* = (θ^*, φ^*) \)

4. Cell Discovery with Quasi- Omni Sounding

• PSS correlation (process gain w. pilots signals)

• Multi-burst energy detector for cell discovery initiation
  Pseudorandom beams do not give "pencil" peaks; but the total energy over M burst still enable detection

• Integer timing offset estimator

5. Initial Beam Training w. Received IA Signals

CP removal from est. timing offset
• Time domain signal rearrangement

The rearranged observation model
\[ y[n] = \sum_{k=0}^{N-1} Q(f_{\text{est}} f[k] \xi[n]) + e[n] + \eta[n] \]
where \( f_{\text{est}} \) is the freq. basis, \( Q(x) \) is phase rotation within symbol, \( y[n] \) is post sounding beam gain

We proposed the algorithm that addresses above challenges via
• Post sounding beamformer channel gain estimation
• Joint AoA/AoD estimation robust to CFO
• Off grid refinement
More details are provided in our recently paper [1]

6. Overhead and Latency Model

• Overhead: Freq/time resource of IA & CSI-RS w. various CSI-RS density

Average CSI-RS scheduling time \( T_{\text{avg}} \) depends on UEs in network and CSI-RS density

Fig. Beam sweeping based initial access in 5G-NR mmW system

7. Simulation Results

Fig. Simulated (Sim.) and theoretical (Theo.) results of the miss detection. Directional sounding with two codebook are used as benchmark. The BS and UE have \( N_h = 128 \) and \( N_x = 12 \) ULA and channel has \( L = 2 \) paths.

Fig. Simulation results for the proposed algorithm, w/ and w/o refinement steps, and theoretical bound of MMSE of AoA/AoD estimation in 5G. Both array geometry settings, \( [N_y, N_x] = (64, 12) \) ULA and \( [N_y, N_x] = (128, 64) \) are evaluated. System has 5ppm CFO

8. Conclusions

• We propose novel algorithm that uses pseudorandom beamformed SS burst for initial discovery, synchronization and AoA/AoD estimation
• Proposed approach has equally good discovery performance as directional IA
• Proposed algorithm exploits sparsity to reach perfect alignment in IA
• By avoiding CSI-RS scheduling, our approach has two more of magnitude latency improvement
• Simulations in realistic 28GHz 3D urban pico cell show advantages holds true for various link distances for LOS/NLOS environment

9. Reference and Acknowledgement

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10. Conclusion

• In summary, the proposed algorithm addresses the challenges of initial discovery, synchronization, and beam training in mmW cellular networks.

Fig. Diagram showing the proposed algorithm for initial access and beamtraining.

(a) Network illustration where a UE is randomly distributed in the horizontal plane with height of UE within 20 meters.

(b) The CDF of SNR using reported beam pair, \( w^* \) and \( v^* \), in the data phase.

Fig. Initial access and beam training performance of proposed and benchmark approaches in 28GHz mmMAGIC 3D UMa LOS/NLOS environment. The discovery rate, post-training SNR, required overhead, and access latency are evaluated.