Hybrid Beam Alignment for Multi-Path Channels: A Group Testing Viewpoint

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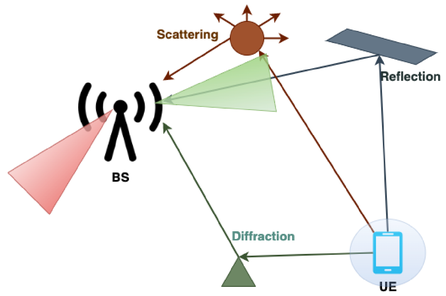
I. Introduction

- MmWave and THz frequencies:
  - Larger bandwidth
  - High data rates
  - Obstacles
    - High path loss
    - Shadowing
    - Sparse channel
- Need directional beams that align with the direction of the channel clusters → Beam Alignment (BA).



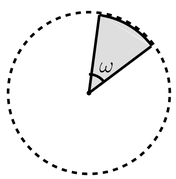
- BA can be classified as:
  - *analog*, *hybrid*, and *digital* according to the number of Radio-Frequency (RF) Chains, N_{RF}, that allows to scan N_{RF} beams simultaneously.
  - *interactive* and *non-interactive* according to when the feedback is received.

II. Network Model

- Base Station → BA
- User(UE) → Omnidirectional transmission
- Hybrid BA with N_{RF} RF Chains
- Interactive BA
- Uplink, single UE
- M channel clusters

III. Beam Alignment

- Fixed beamwidth ω
- **Goal:** to locate angle of arrivals (AoAs) using the fewest number of BA time slots



IV. Problem Formulation

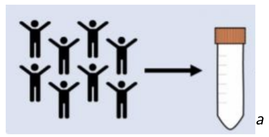
$$S^*(\omega, M, N_{\mathrm{RF}}) = \underset{S(\omega,M,N_{\mathrm{RF}})}{\arg\min}\ \mathbb{E}[T_{\mathrm{BA},S}(\Psi)]$$

- $S(\omega, M, N_{\mathrm{RF}})$: Hybrid interactive BA procedure
- $\Psi = (\psi_1, \psi_2, \ldots, \psi_M)$: AoAs realizations, $\psi_m \overset{i.i.d.}{\sim} Unif([0, 2\pi])$
- $T_{\mathrm{BA,S}}$: BA duration for the procedure S
- ω: Angular width of the data beams
- M: Number of AoAs
- N_{RF}: Number of RF Chains

V. The Group Testing and BA

We provide the connection between group testing and hybrid interactive BA whose goal is to identify multiple paths and propose algorithms for the defined BA problem.

Group testing overview



[a]"Testing logistics." [Online]. Available:here

- Total N items, M are defective
- Tests with binary results
- **Goal:** to have small number of tests
- Pool the items and test them together
- *Interactive* or *non-interactive* GT

Duality:

- N items ↔ N angular intervals
- M defectives ↔ M Angular intervals that include the AoAs
- Tests ↔ scanning beams
- Binary test results ↔ ACK/NACK at the BS

For interactive GT based BA, we consider Hwang's Generalized Binary Splitting, which is an interactive GT scheme that is proven to be asymptotically optimal in terms of the number of tests when an upper bound on the number of defectives is given [2].

VI. Proposed Methods

Analog Beam Alignment

- Analog GT-based BA (AGTBA)
- Based on Generalized Binary Splitting with some modifications [2]

Hybrid Beam Alignment

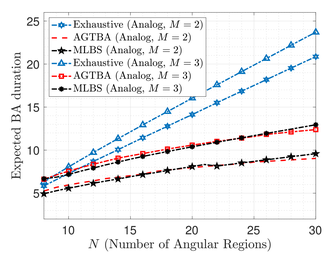
- Hybrid GT-based BA (HGTBA) for $N_{\mathrm{RF}} = 2$
- Three modifications of AGTBA:
  1. Divide the problem into two sub-problems and solve them in parallel
  2. Jointly design the scanning beams of the sub-problems HGTBA_1.
  3. Take advantage of every ACK response used by HGTBA_2

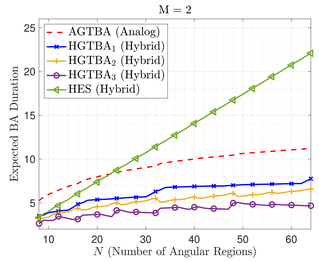
VII. Results

Comparison with MLBS [3], Exhaustive Search, Hybrid Exhaustive Search (HES)

- Realistic 5G mmWave network model, sectored antenna model
- Energy detection approach: If $P_{\mathrm{RX}}/N_a \leq T$, we consider it ACK, else NACK
  - P_{RX} : the energy of the measured signal, N_a : number of active antennas, T : threshold
- Low (High) threshold → High false-alarm (missdetection) probability

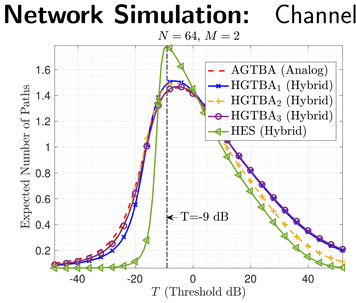
Noiseless Simulation: No channel noise

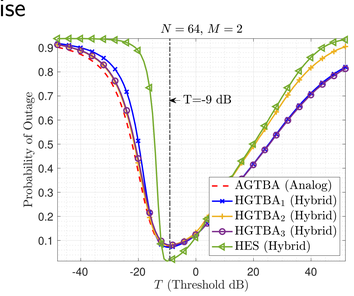


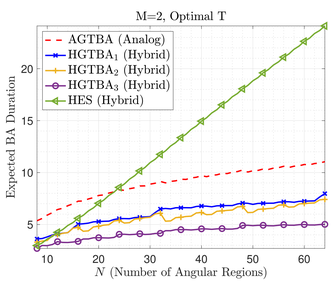


- Similar performance with the state-of-the-art (MLBS)
- Lower computational complexity
- Contiguous beams
- HGTBA_3 reduces $\mathbb{E}[T_{\mathrm{BA}}]$ by a factor of two compared to AGTBA

5G Network Simulation: Channel noise







- Proposed BA methods are more sensitive to a false alarm than missdetection probability
- HES is less robust (sharper transitions) to variations of the threshold
- HGTBA_3 has the best performance in terms of expected BA duration

VIII. Conclusion

- Interactive hybrid BA in uplink single user, where the channel between UE and BS consists of multiple paths
- Developed novel GT-based analog and hybrid BA strategies
- Proposed BA strategies outperform state-of-the-art methods both in performance and complexity
- **Future work**: Hybrid BA for $N_{\mathrm{RF}} > 2$, optimization for noisy channels, multi-level scanning beam results

X. References

[1] O. Yildiz, A. Khalili, and E. Erkip, "Hybrid beam alignment for multi-path channels: A group testing viewpoint," *arXiv preprint arXiv:2111.08159*, 2021.

[2] F. K. Hwang, "A method for detecting all defective members in a population by group testing," *J Am Stat Assoc*, vol. 67, no. 339, pp. 605–608, 1972.

[3] I. Aykin, B. Akgun, and M. Krunz, "Multi-beam transmissions for blockage resilience and reliability in millimeter-wave systems," *IEEE JSAC*, vol. 37, no. 12, pp. 2772–2785, 2019.