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

Ozlem Yildiz, Abbas Khalili, Elza Erkip

Asilomar Conference on Signals, Systems, and Computers 2022

Nov 19, 2023

NYU TANDON SCHOOL OF ENGINEERING

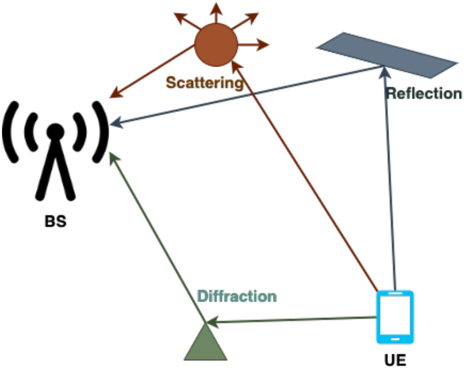
NYU WIRELESS

Introduction

MmWave and THz frequencies:

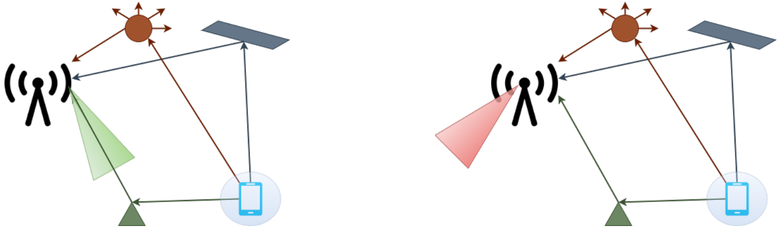
- Larger bandwidth
- High data rates
- Obstacles
  - High path loss
  - Shadowing
  - Sparse channel

- MmWave and THz channels are sparse and consist of a few spatial clusters



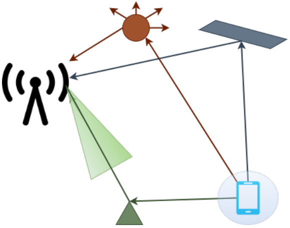
Beam Alignment

- One needs to find directional beams to localize the direction of the channel clusters
  → Beam Alignment (BA)

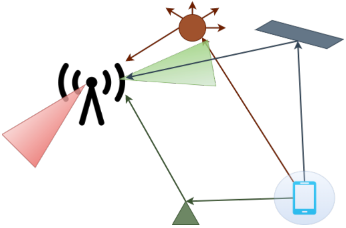


Beam Alignment

BA schemes can be classified as *analog*, *hybrid*, and *digital* according to the number of Radio-Frequency (RF) Chains, N_{RF}, used.



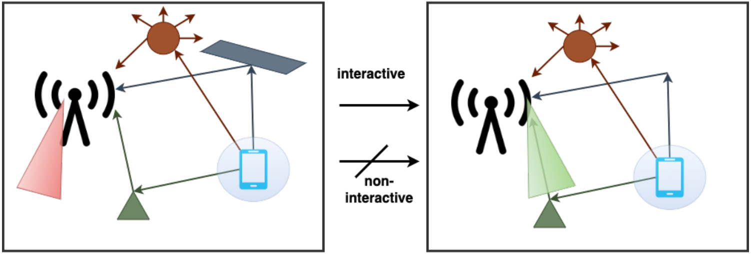
$N_{\mathrm{RF}} = 1$



$N_{\mathrm{RF}} = 2$

Beam Alignment

BA can be classified as *interactive* and *non-interactive* according to when the feedback is received.



This paper

Goal

Identify multiple paths by using hybrid, interactive BA

- Experimental studies demonstrate that there are up to four channel clusters.

Approach

We develop algorithms using the theory of Group Testing (GT)

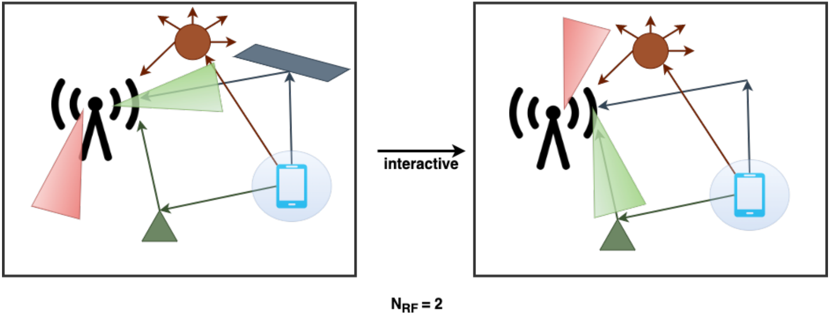
Group Testing Overview:

- 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

.

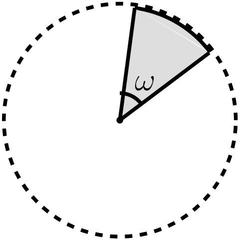
Network Model

- Base Station $\rightarrow$ BA
- User $\rightarrow$ Omnidirectional transmission
- Hybrid BA with N_{RF} RF Chains
- Interactive BA
- Uplink, single user
- M channel clusters
- Noiseless



Beam Alignment

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



Problem Formulation

Problem

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

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

Related Work

- Multi-lobe beam search (MLBS) [Aykin *et al.*, 2019, IEEE INFOCOM]
  - *Analog*, interactive BA for downlink to find multiple spatial clusters
- Beam alignment and group testing [Suresh *et al.*, 2019, IEEE JSTSP]
  - *Analog*, non-interactive BA for downlink to find multiple spatial clusters
- Generalized binary splitting algorithm (GBS) [Hwang, 1972, J Am Stat Assoc] .
  - Noiseless and interactive GT

Proposed Methods

- Establish duality between interactive hybrid BA for multiple paths and interactive GT.
- Analog BA method based on Hwang's Generalized Binary Splitting
- Extension to novel GT-based hybrid BA for $N_{\mathrm{RF}} = 2$

Group Testing and Beam Alignment

- Fixed beamwidth $\omega \rightarrow N = \frac{2\pi}{\omega}$ angular intervals

Duality

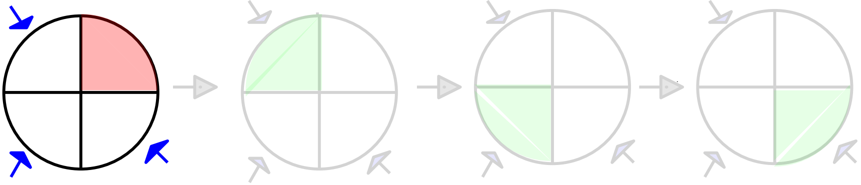
- GT $\leftrightarrow$ BA
- N items $\leftrightarrow$ N Angular intervals
- M defectives $\leftrightarrow$ M Angular intervals that include the AoAs
- Tests $\leftrightarrow$ Scanning beams
- Binary test results $\leftrightarrow$ ACK/NACK at the BS

Analog Beam Alignment

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

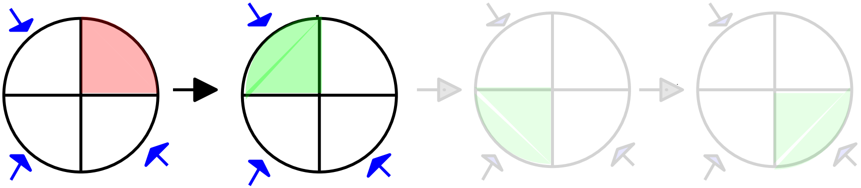
Exhaustive Search

$N = 4, \ M = 3$



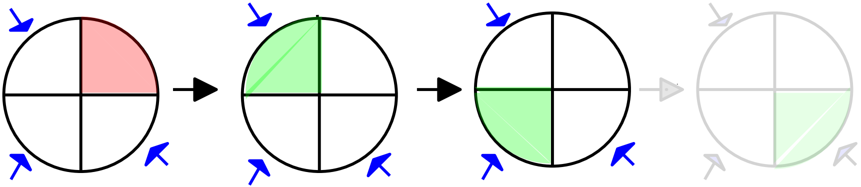
Exhaustive Search

$N = 4,\ M = 3$



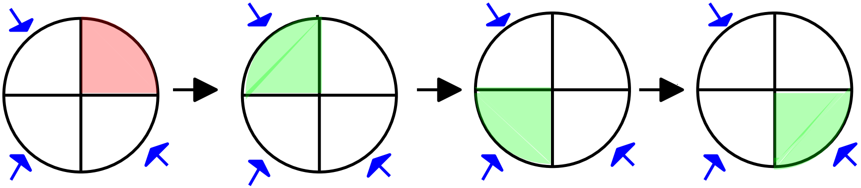
Exhaustive Search

$N = 4, \ M = 3$



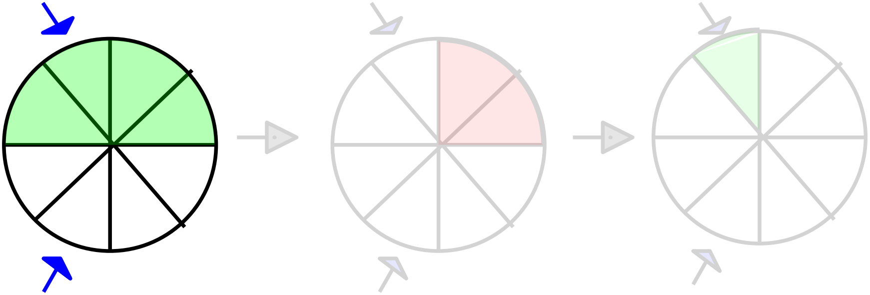
Exhaustive Search

$N = 4, \; M = 3$



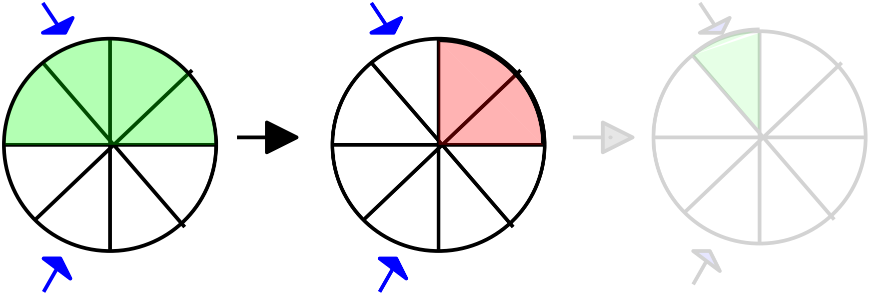
Bisection Search

$N = 8, \ M = 2$



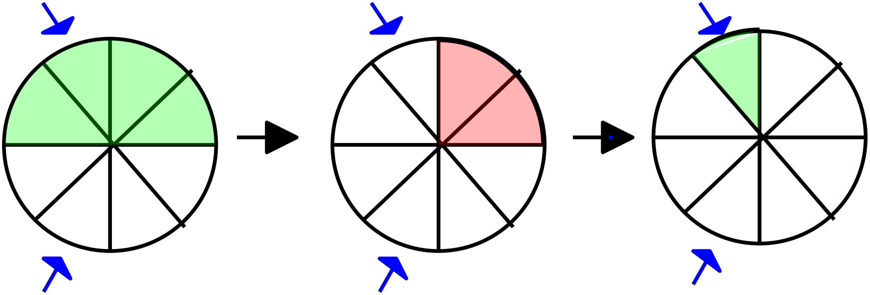
Bisection Search

$N = 8,\ M = 2$

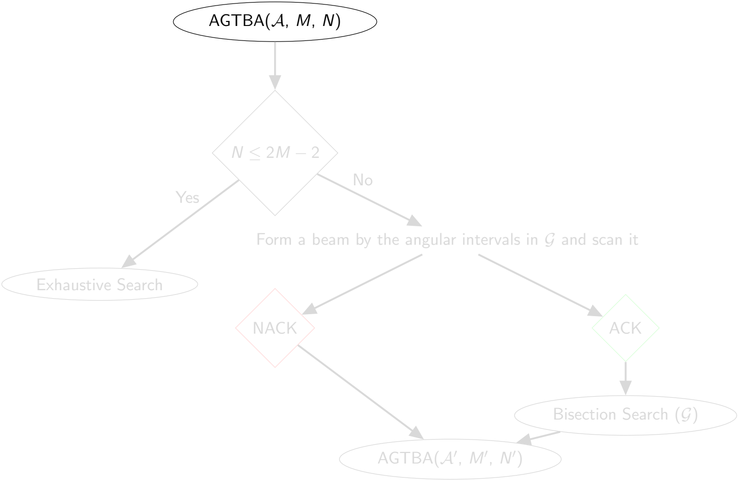


Bisection Search

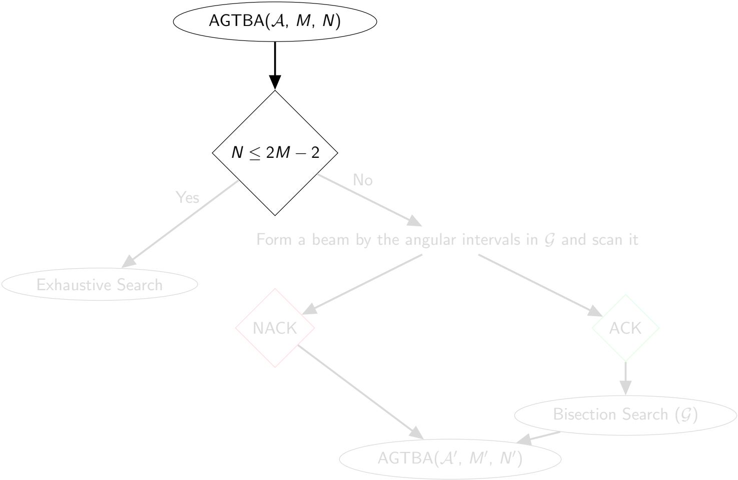
$N = 8, \ M = 2$



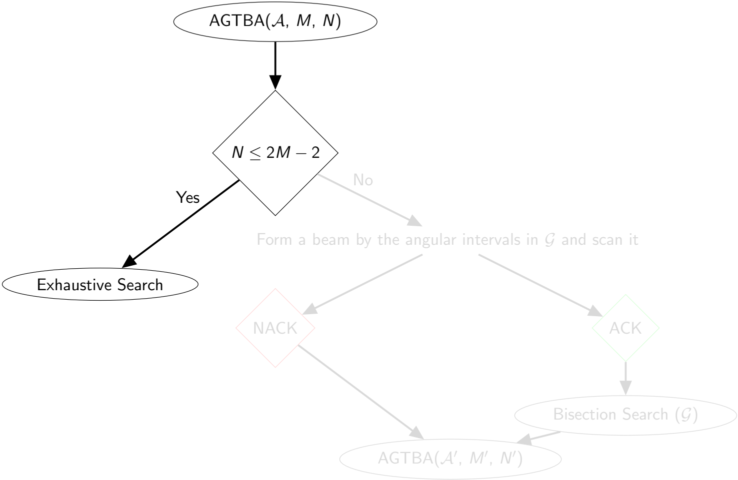
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
Exhaustive Search
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

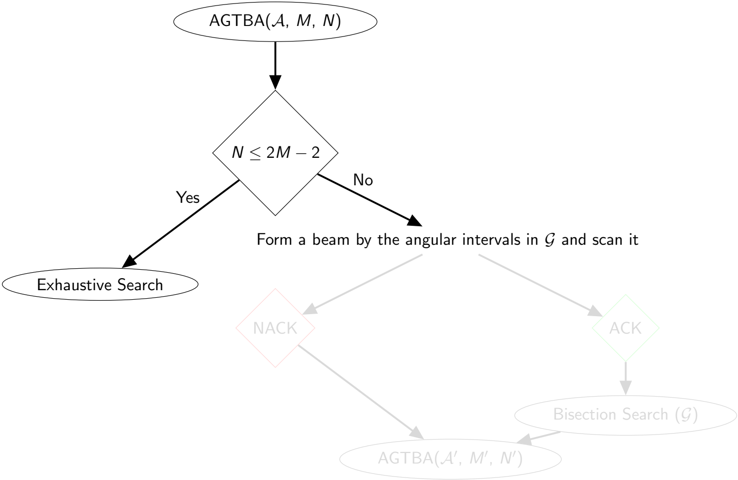
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
Exhaustive Search
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

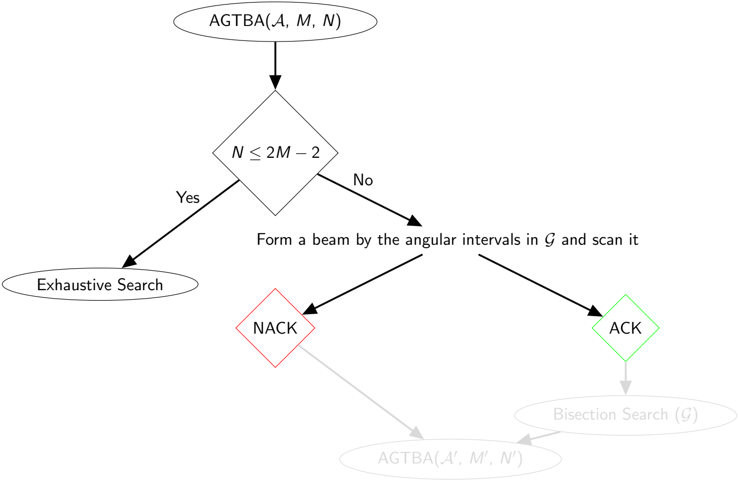
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Exhaustive Search
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

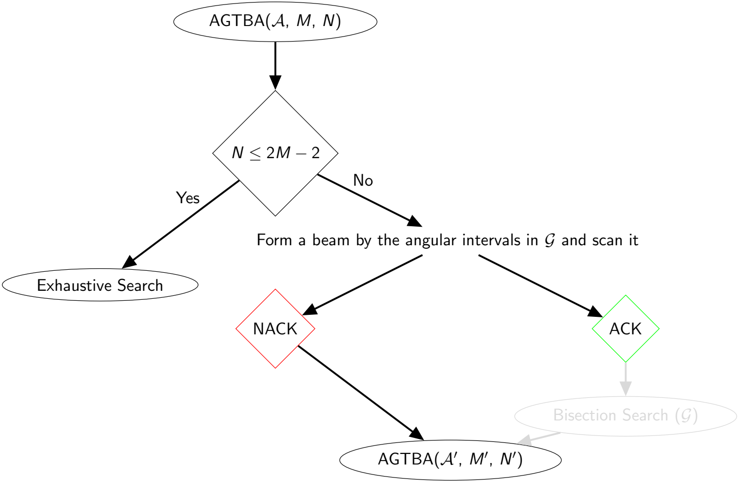
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Exhaustive Search
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

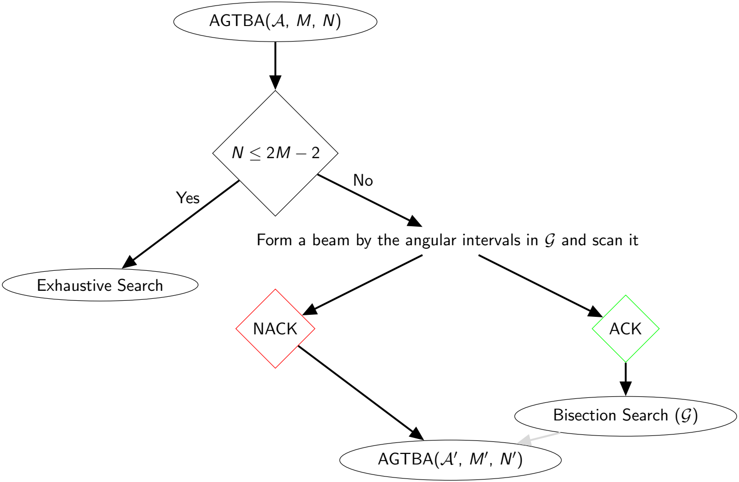
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Exhaustive Search
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

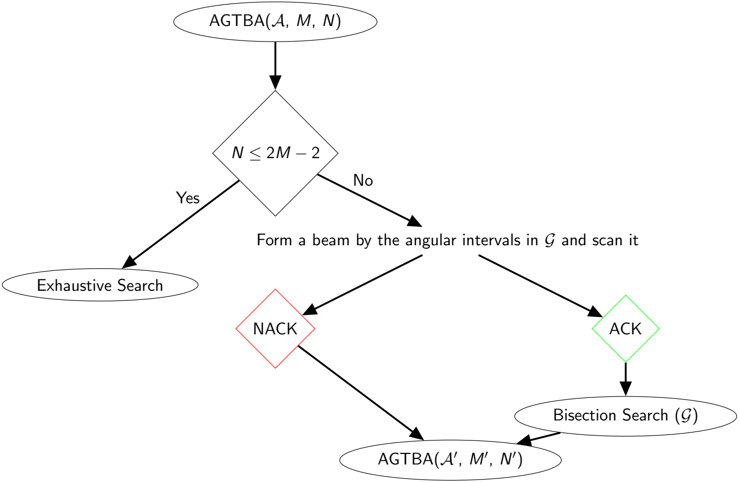
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Exhaustive Search
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
Exhaustive Search
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

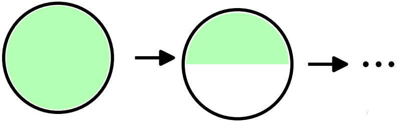
AGTBA


AGTBA($\mathcal{A}$, M, N)
$N \leq 2M - 2$
Yes
No
Form a beam by the angular intervals in $\mathcal{G}$ and scan it
Exhaustive Search
NACK
ACK
Bisection Search ($\mathcal{G}$)
AGTBA($\mathcal{A}'$, M', N')

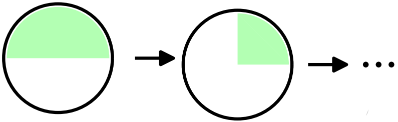
Differences between GBS and AGTBA

For $M = 1$,

- Generalized Binary Splitting:

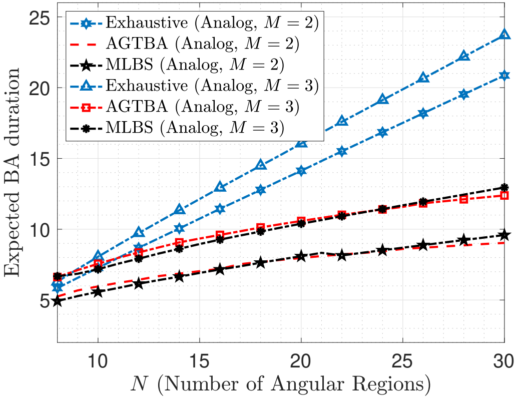


- AGTBA:



Simulations

Comparison of AGTBA, MLBS and Exhaustive search.
($N_{\mathrm{RF}} = 1$ RF-chain and M angular of arrivals)



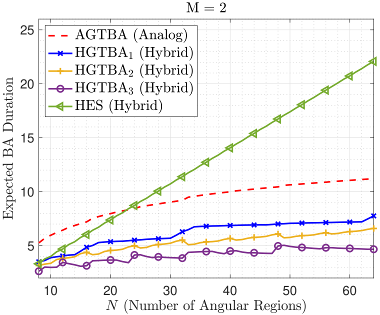
- Similar performance with the state of the art (MLBS)
- Lower computational complexity
- Contiguous beams

Hybrid Algorithms

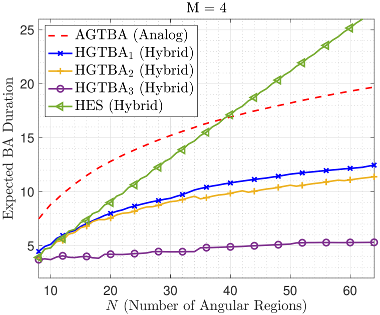
$N_{\mathrm{RF}} = 2$

- HGTBA_1
  - Divide the problem into two sub-problems and solve them in parallel
- HGTBA_2
  - Jointly design the scanning beams of the two sub-problems in HGTBA_1
- HGTBA_3
  - Take advantage of every ACK response used by HGTBA_2

Simulations



(a) $M = 2$

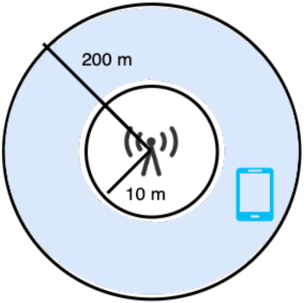


(b) $M = 4$

- HGTBA_3 requires the least BA duration
- HGTBA_3 reduces $E[T_{\mathrm{BA}}]$ by a factor of two and three compared to AGTBA when $M = 2$ and $M = 4$, respectively.

5G Network Simulations

Parameter	Value
Carrier frequency	28 GHz
Bandwidth	57.6 MHz
OFDM symbol duration	8.93 μ s
BS antenna height	10 m
UE antenna height	2 m
Subcarrier spacing	120 kHz
Transmission power	20 dBm
Number of RX antennas	64



Beam Scanning Result

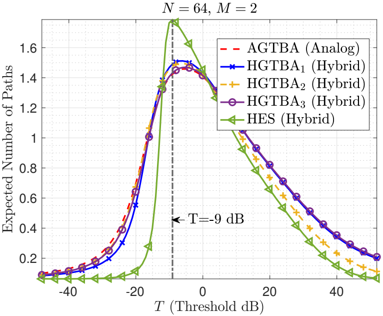
Energy detection approach:

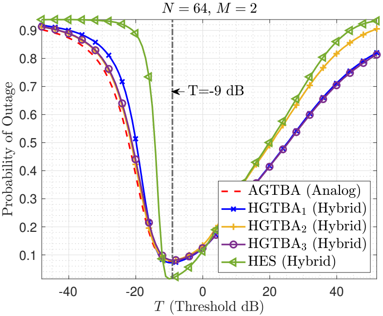
- If $P_{\mathrm{RX}}/N_a \geq T$, we consider it acknowledgement (ACK), else negative ACK (NACK)
  - P_{RX} : the energy of the measured signal
  - N_a : number of active antennas
  - T : threshold

Therefore,

- Low threshold $\rightarrow$ High false alarm probability
- High threshold $\rightarrow$ High missdetection probability

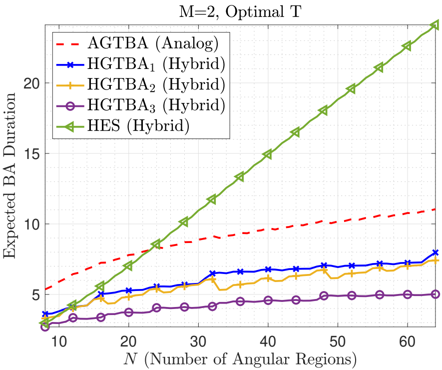
Expected Number of Paths and Probability of Outage





- Proposed BA methods are more sensitive to false alarm than missdetection probability
- Hybrid exhaustive search(HES) is less robust (sharper transitions) to variations of the threshold

Expected BA Duration



- $HGTBA_3$ has the best performance in terms of expected BA duration

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 beam alignment, generalization to $N_{\mathrm{RF}} > 2$
- Optimization for noisy channels
- Multi-level scanning beam results instead of binary (a.k.a. ACK and NACK)

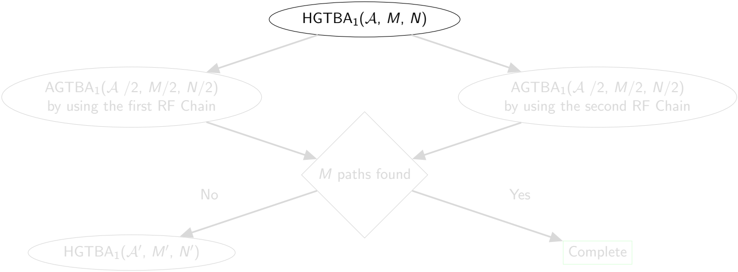
References

- M. Aldridge, O. Johnson, J. Scarlett *et al.*, "Group testing: An information theory perspective," *Foundations and Trends® in Communications and Information Theory*, vol. 15, no. 3-4, pp. 196–392, 2019.
- 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.
- V. Suresh and D. J. Love, "Single-bit millimeter wave beam alignment using error control sounding strategies," *IEEE JSTSP*, vol. 13, no. 5, pp. 1032–1045, 2019.
- 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.

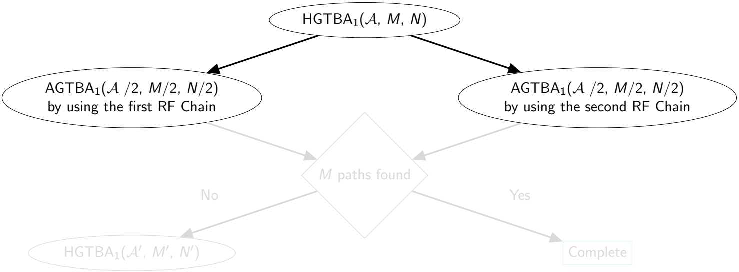
Hybrid Algorithm-1

- Dividing the problem into two sub-problems and solving them in parallel

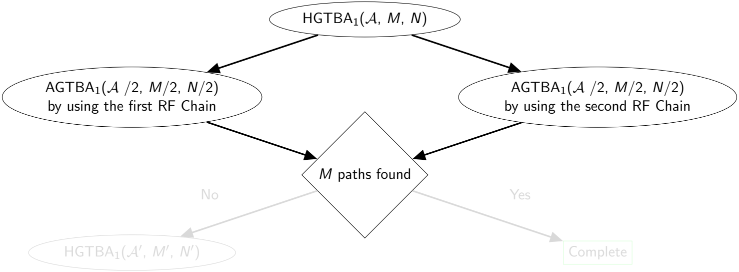
Hybrid Algorithm-1



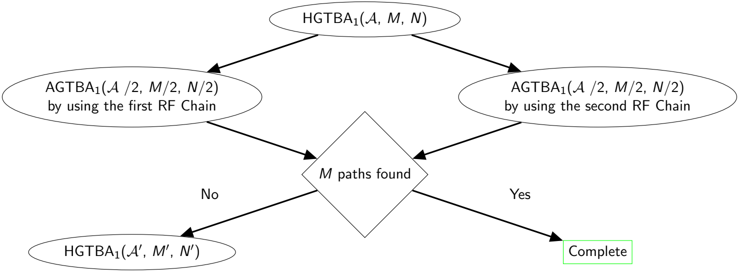
Hybrid Algorithm-1



Hybrid Algorithm-1



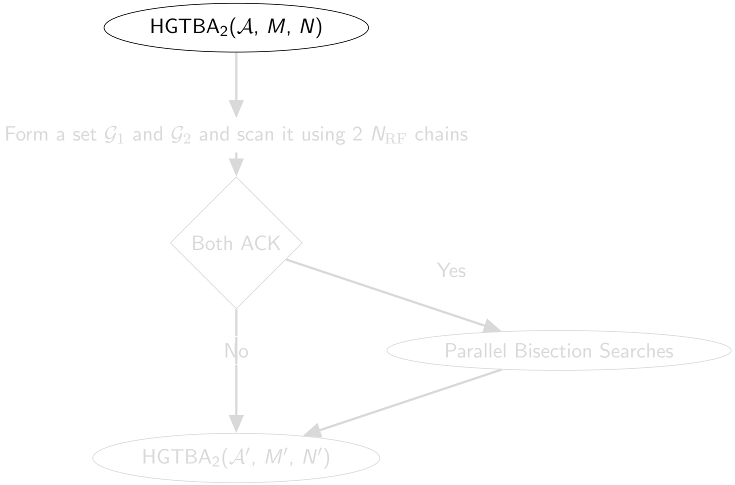
Hybrid Algorithm-1



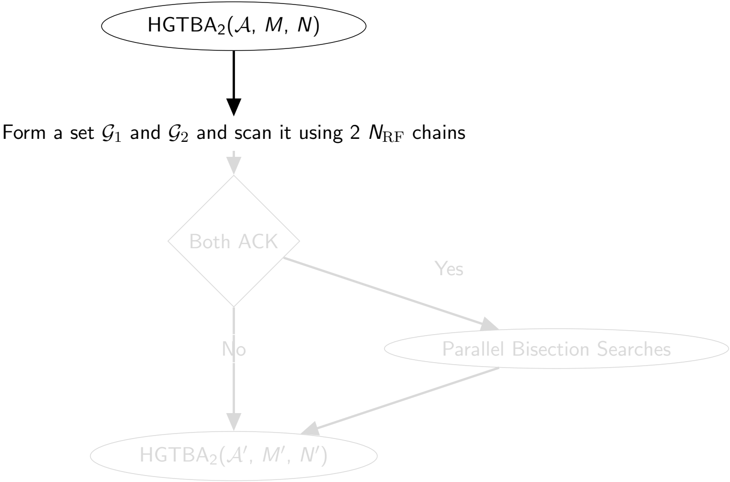
Hybrid Algorithm-2

- Modification: Jointly design the scanning beams of the sub-problems posed in HGTBA_1

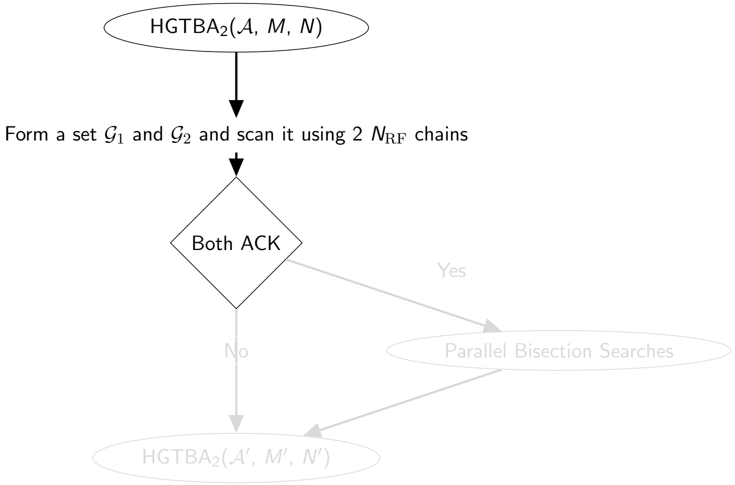
Hybrid Algorithm-2



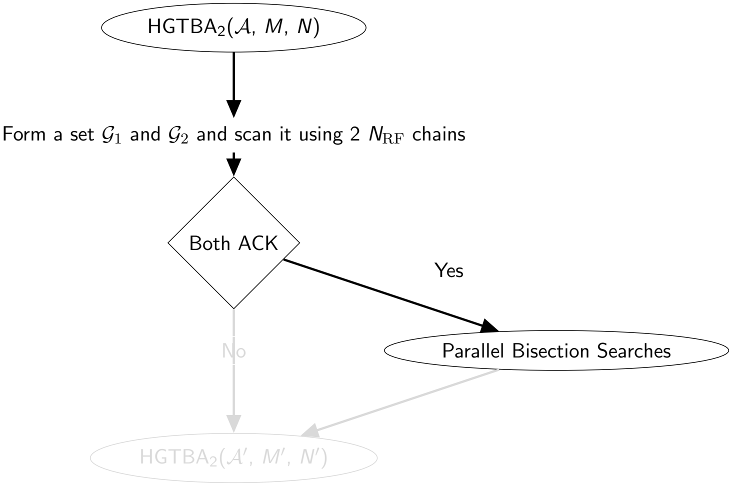
Hybrid Algorithm-2



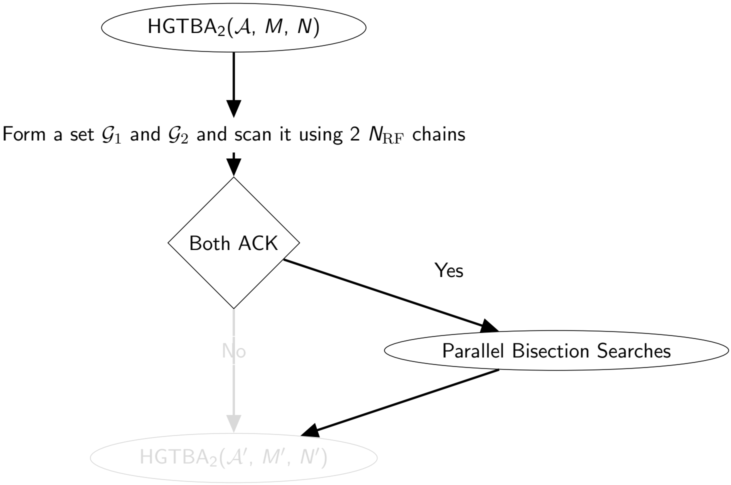
Hybrid Algorithm-2



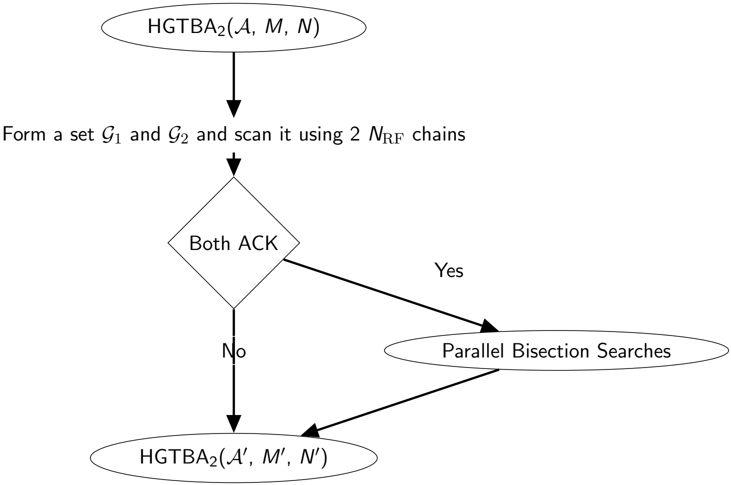
Hybrid Algorithm-2



Hybrid Algorithm-2



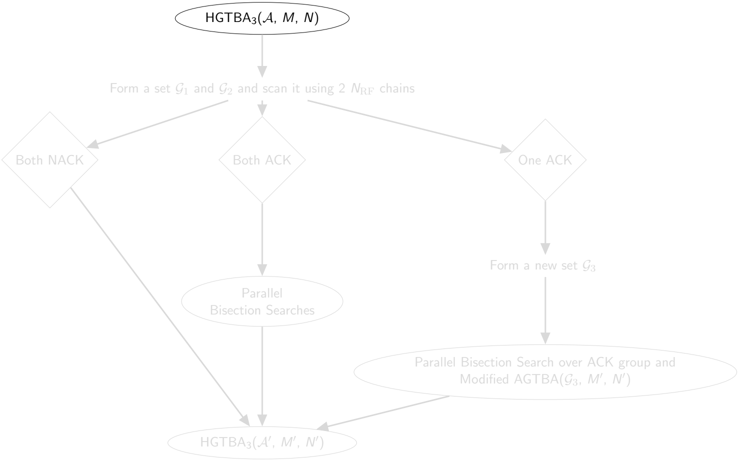
Hybrid Algorithm-2



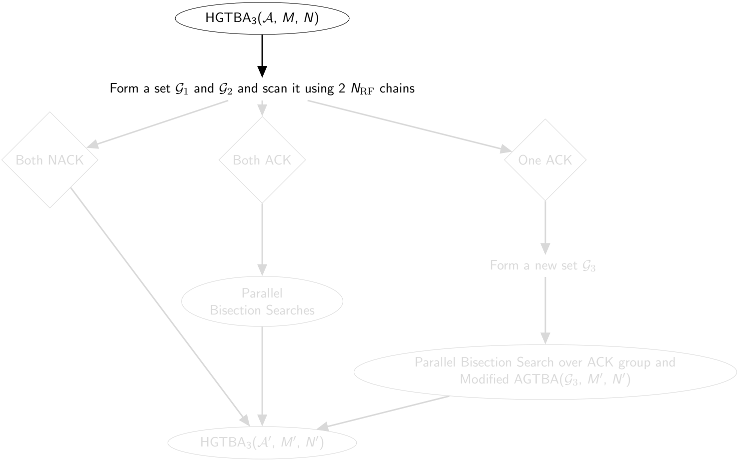
Hybrid Algorithm-3

- Modification: Utilizing the every ACK information while $HGTBA_2$ only utilizes when both sub-problems results as ACK.

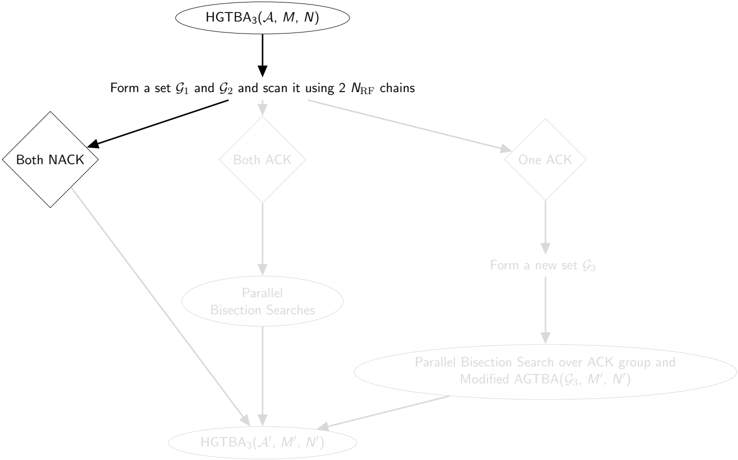
Hybrid Algorithm-3



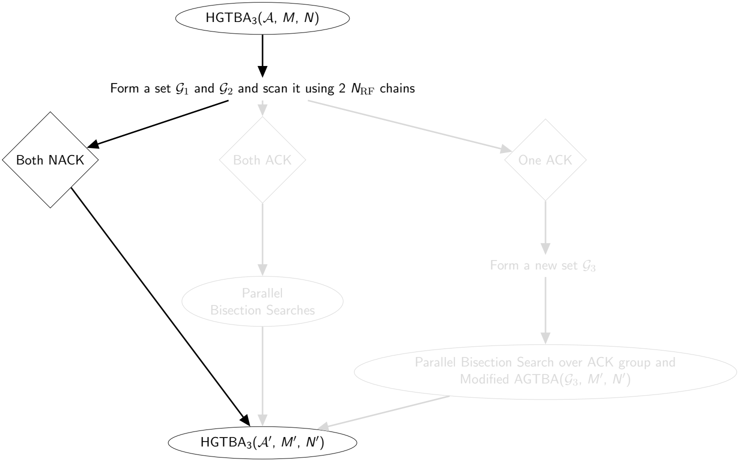
Hybrid Algorithm-3



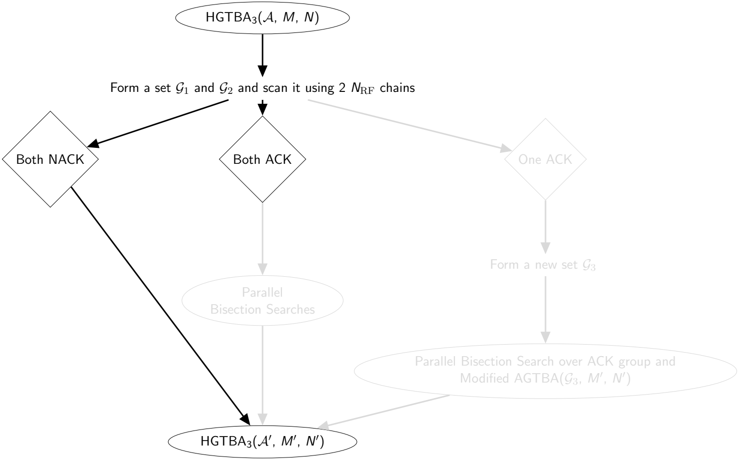
Hybrid Algorithm-3



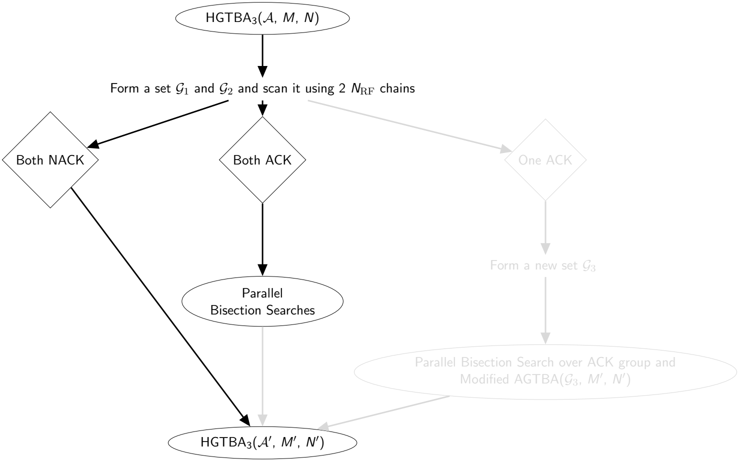
Hybrid Algorithm-3



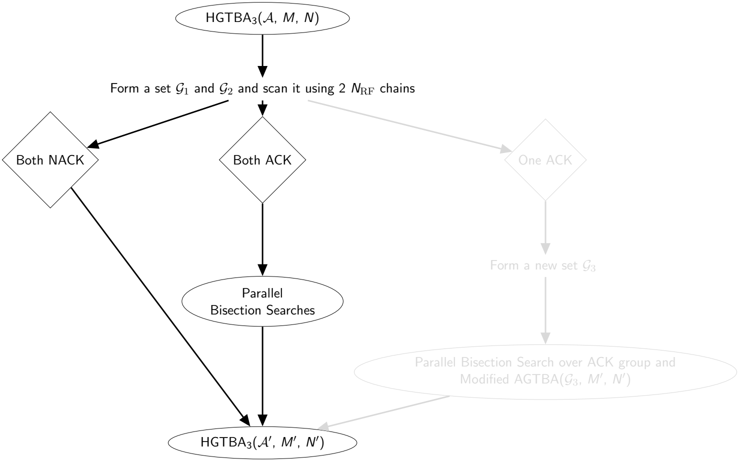
Hybrid Algorithm-3



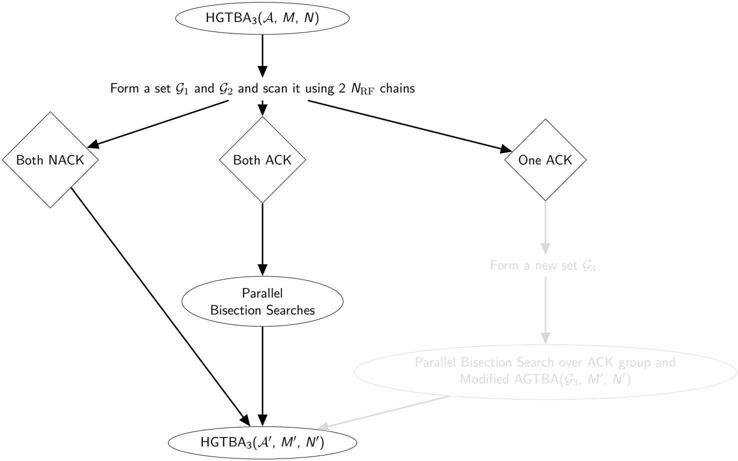
Hybrid Algorithm-3



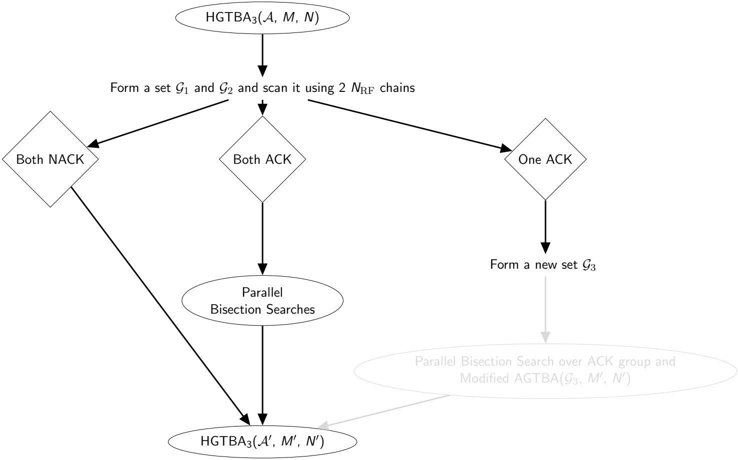
Hybrid Algorithm-3



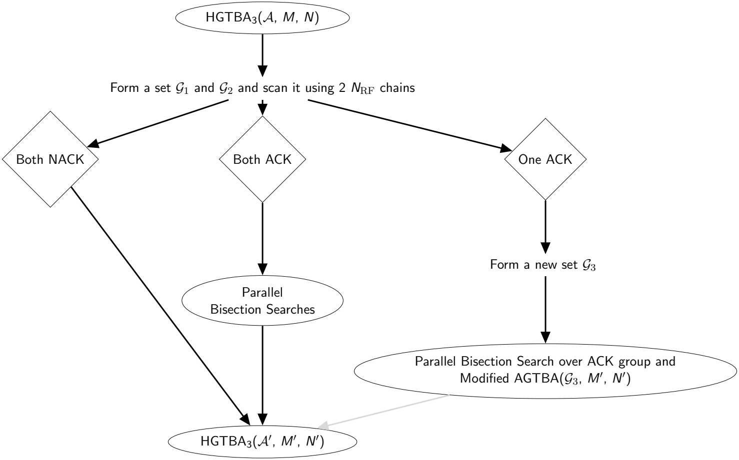
Hybrid Algorithm-3



Hybrid Algorithm-3



Hybrid Algorithm-3



Hybrid Algorithm-3