In-network Angle Approximation for Supporting Adaptive Beamforming

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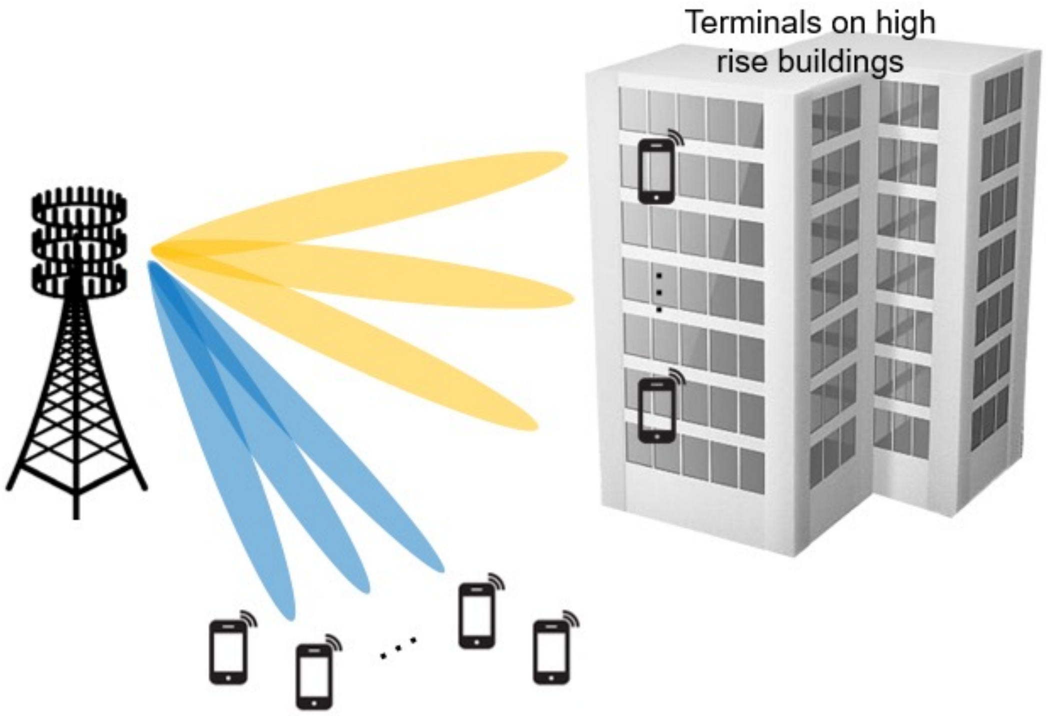
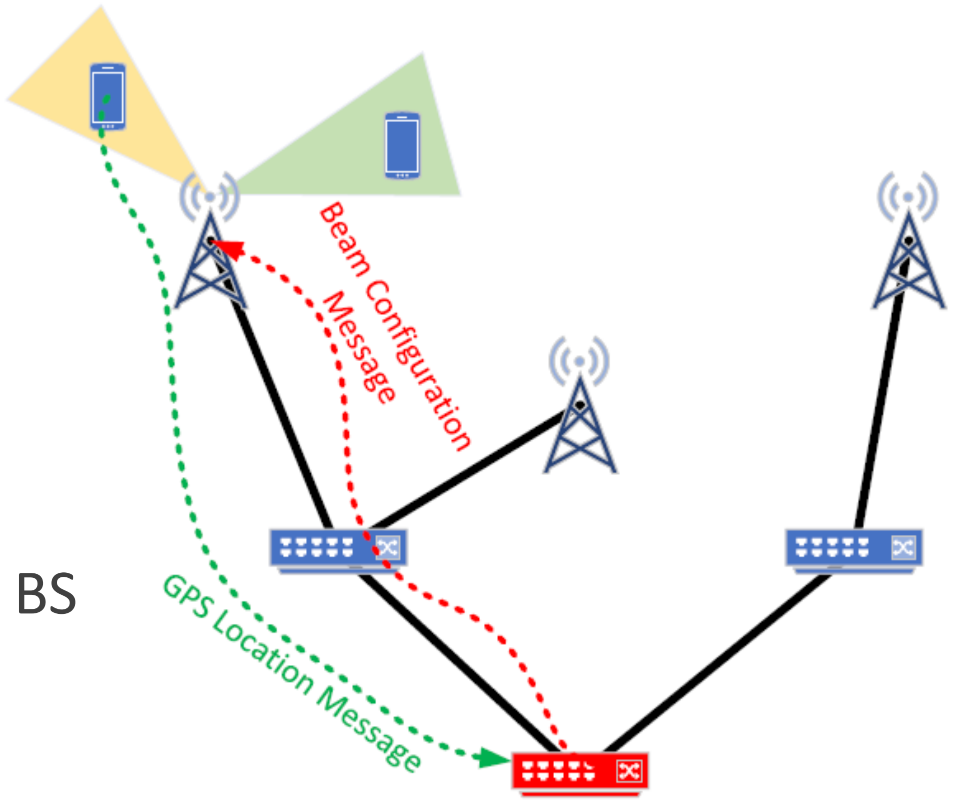
Beamforming

- mmWave transmission in 5G
  - High propagation loss, signal blockage
  - Reduced distance
- Beamforming
  - Extended communication range
  - Enhanced signal quality
  - Many advantages…
- Beamforming direction is challenging
  - BS needs to determine the DOA of its users
  - Scanning-like approaches has high energy consumption
  - Other techniques has high computational complexities



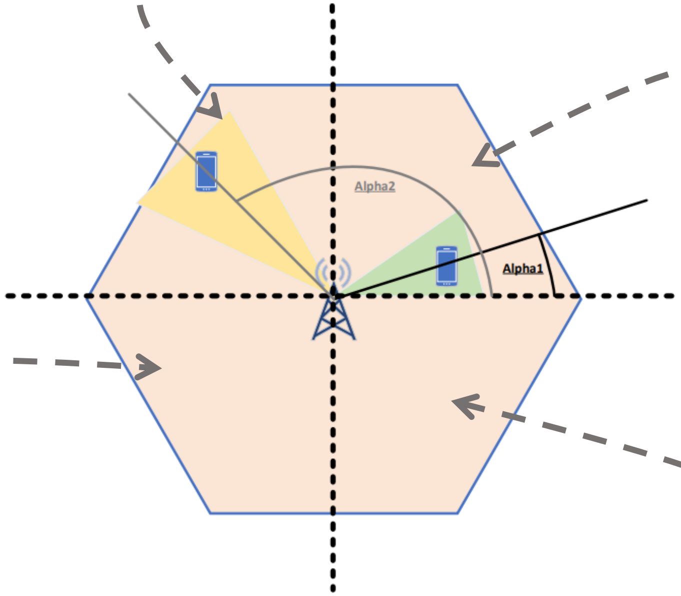
An User-Assisted Approach

- UE reports it's location
  - based on GPS or other sources
- Processing inside the AAN
  - Messages handled as control packets
- P4 switch assumption
  - Angle computation (or distance, etc.)
  - Generate configuration message to be sent to the BS
- BS reconfigures the beam
  - According to new angle (and other) information



Angle computation is simple

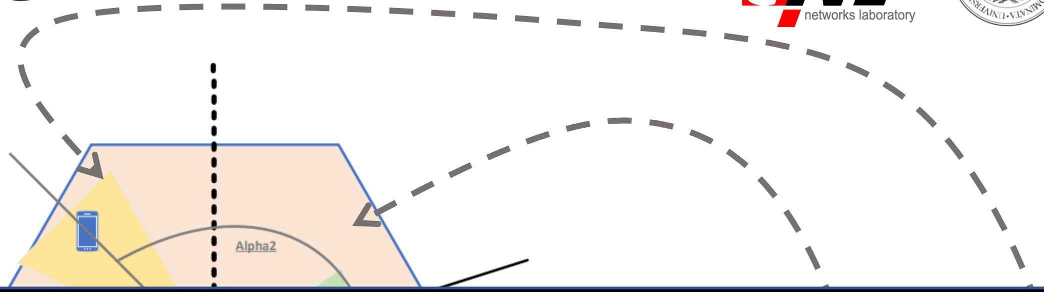
- UE coordinates: *loc.x, loc.y*
- BS coordinates: *bs.x, bs.y*



$$\alpha = \begin{cases} \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y > bs.y \; and \; loc.x > bs.x \\ \pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y > bs.y \; and \; loc.x < bs.x \\ \pi + \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \; and \; loc.x < bs.x \\ 2\pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \; and \; loc.x > bs.x \end{cases}$$

Angle computation is simple

- UE coordinates: *loc.x, loc.y*

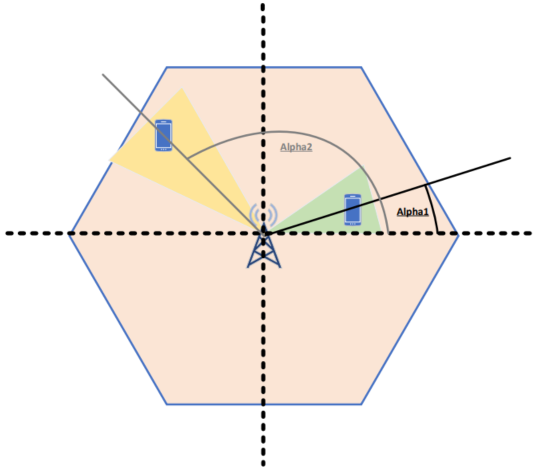


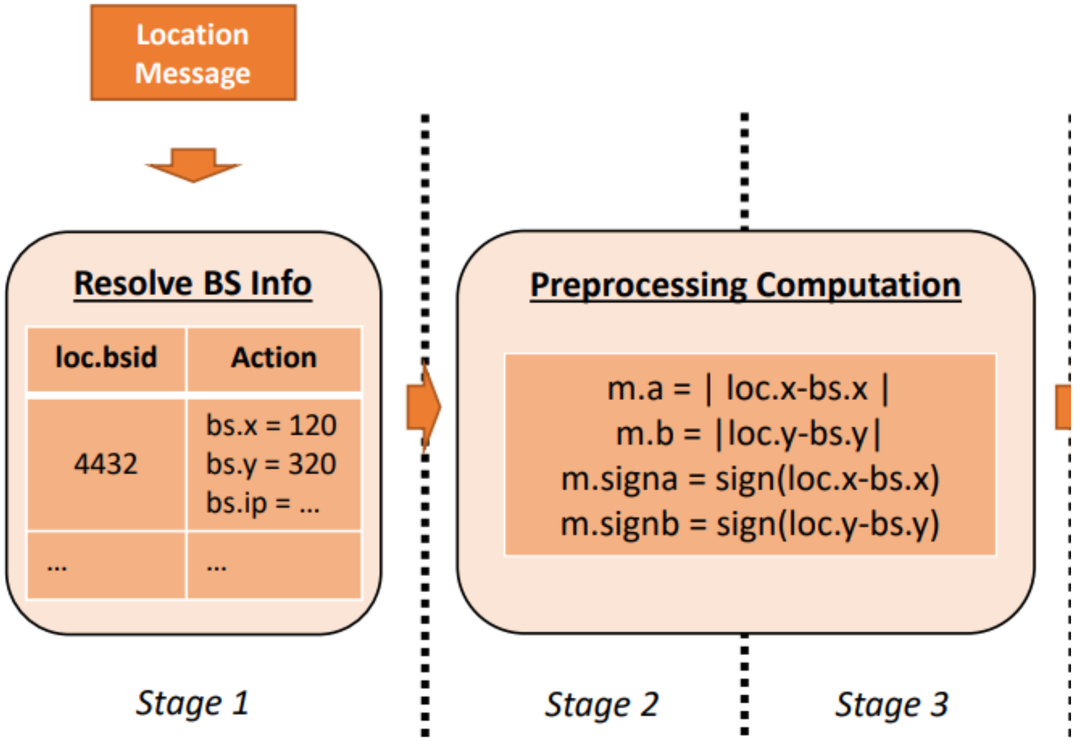
...but, in P4?

$$\alpha = \begin{cases} \pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y > bs.y \text{ and } loc.x < bs.x \\ \pi + \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \text{ and } loc.x < bs.x \\ 2\pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \text{ and } loc.x > bs.x \end{cases}$$

In P4?
Preparation

- Assuming Tofino-like capabilities
  - Constrained hardware
  - Pipeline packet processing with lookup tables
- Location message from a UE
  - Special header format, coordinates and BS id
- BS locations stored in a lookup table
  - Mapping BS id to coordinates
- Absolute value of location difference and the sign of the difference
  - The signs determines the quarter around the BS

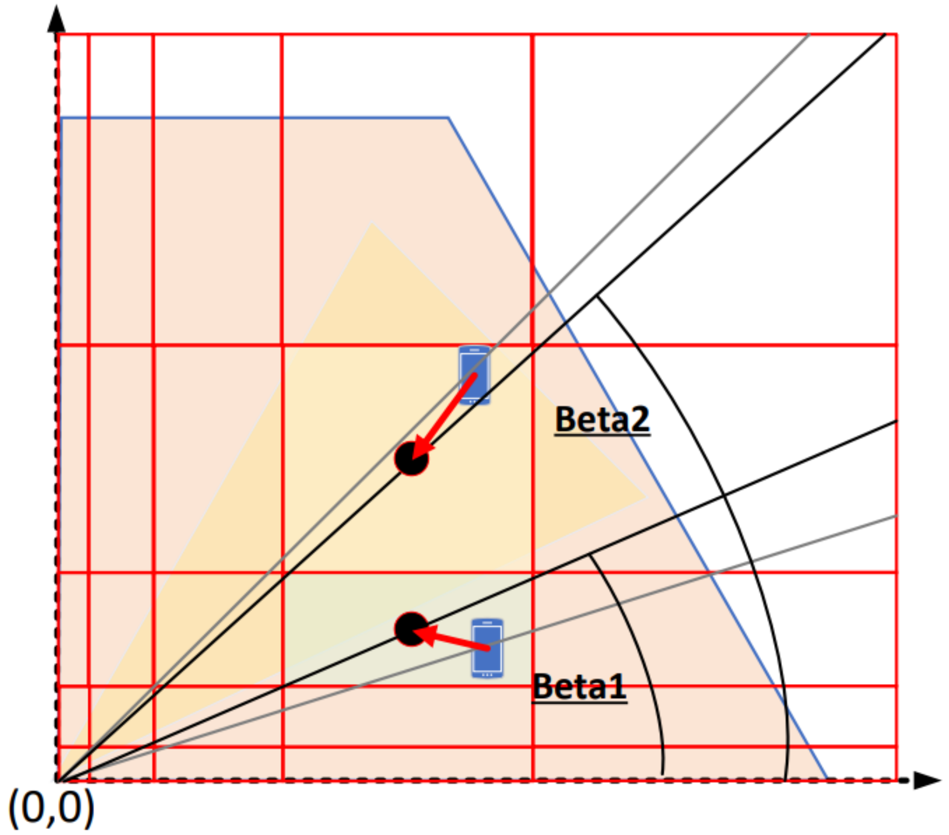




In P4?
Computing arctan

- Goal: $arctan\left(\frac{m.b}{m.a}\right)$

- Grid-based approximation with exponential binning
- The grid points on both axes are the same:
  $0, B^1, B^2, \ldots, B^N = D,$
  - where B is the base number,
  - N is the granularity factor (the number of bins on the axes)
  - while D is the cell diameter (the maximum range)
  - **Approx. based on the centroid point of the containing grid-cell**



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<u>Few properties</u>

- Desired accuracy determines the required TCAM space
- Other parameters like power, signal strength can similarly be added in the future...
- Customization of the table is also possible

<u>Table Angle Approximation</u>

m.a:range, m.b:range	Action
(0 .. 136, 0 .. 136)	m.beta = 45
(0 .. 136, 136 .. 186)	m.beta = 67
...	...
($C*B^{j-1}$ .. $C*B^{j}$, $C*B^{k-1}$ .. $C*B^{k}$)	m.beta = $\frac{180}{\pi}\arctan\left(\frac{B^k+B^{k-1}}{B^i+B^{i-1}}\right)$
...	...

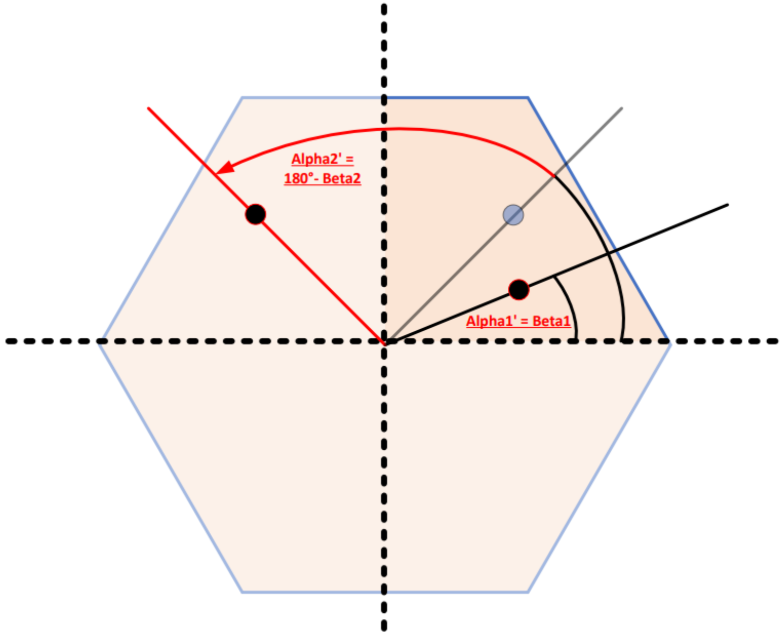
Stage 4

... ...

In P4?
Final angle transformation

- Signs determine the quadrant

$$\alpha = \begin{cases} \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y > bs.y \text{ and } loc.x > bs.x \\ \pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y > bs.y \text{ and } loc.x < bs.x \\ \pi + \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \text{ and } loc.x < bs.x \\ 2\pi - \arctan\left(\frac{|loc.y - bs.y|}{|loc.x - bs.x|}\right) : loc.y < bs.y \text{ and } loc.x > bs.x \end{cases}$$



Configuration Message

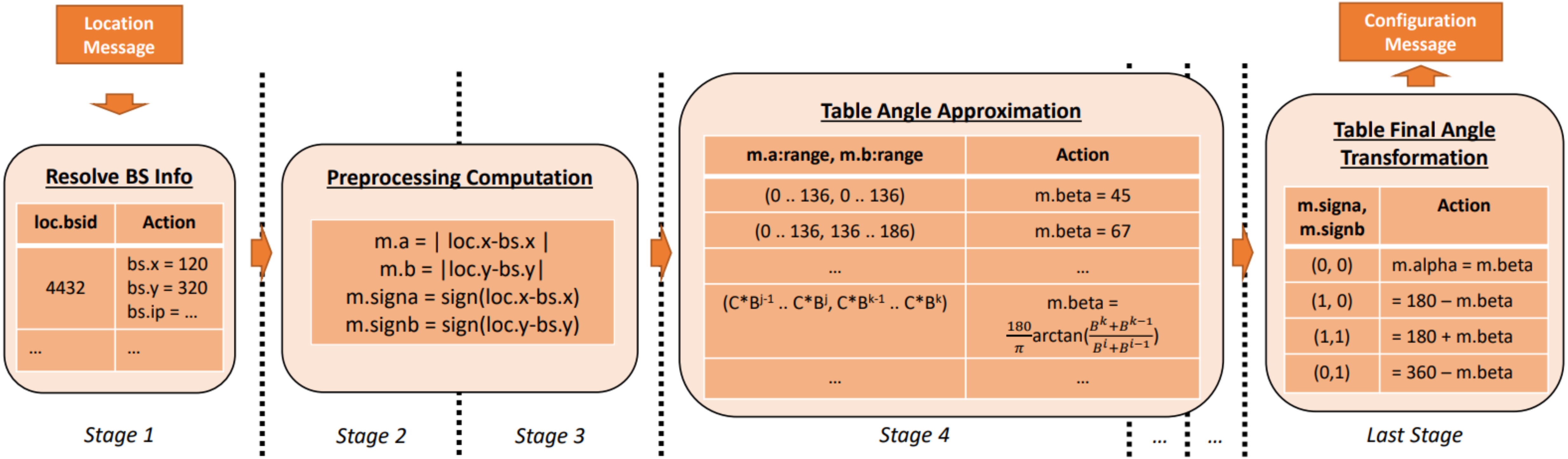
Table Final Angle Transformation

m.signa, m.signb	Action
(0, 0)	m.alpha = m.beta
(1, 0)	= 180 – m.beta
(1,1)	= 180 + m.beta
(0,1)	= 360 – m.beta

Last Stage

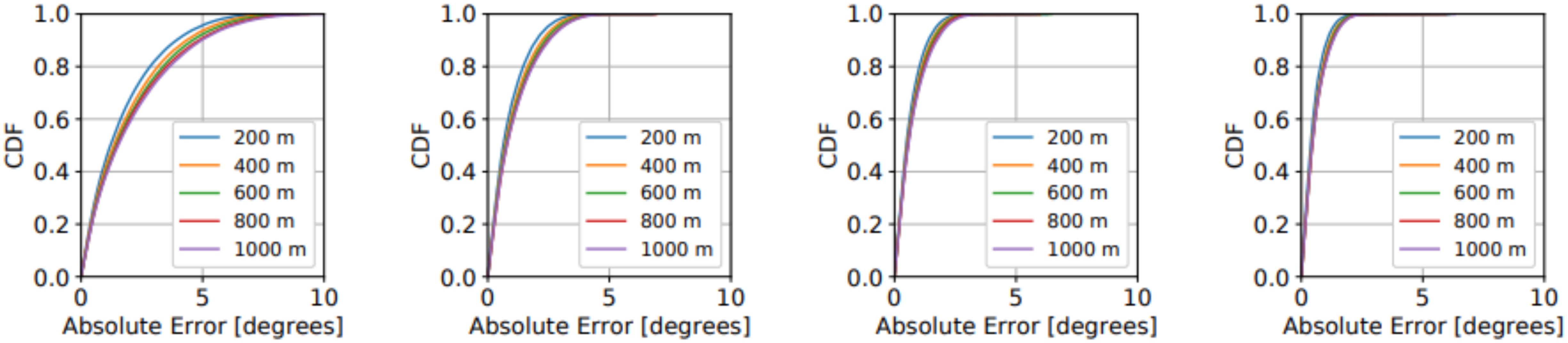
In P4?
The whole pipeline

- Implemented on Tofino-1 ASIC
- Theoretical bound on the angle approximation accuracy
- Accuracy vs TCAM space



Evaluation
Approximation Error in static scenarios

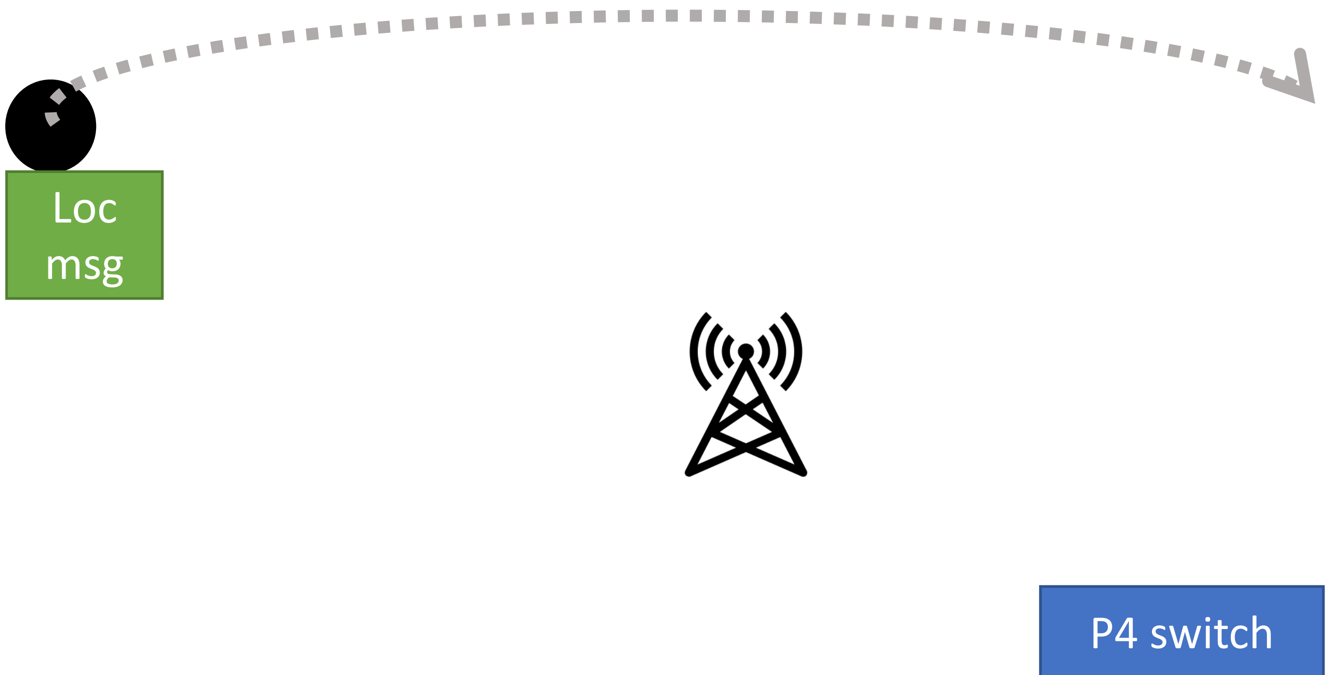
- Various cell diameters (D): 200-1000 meters
- Various numbers of bins (N): 20-80



(a) N=20 (b) N=40 (c) N=60 (d) N=80

Evaluation
Moving UE and control latency

- UE moving at a constant speed
- Control cycle
  - time from sending a location message to the reconfiguration of the beam at the BS



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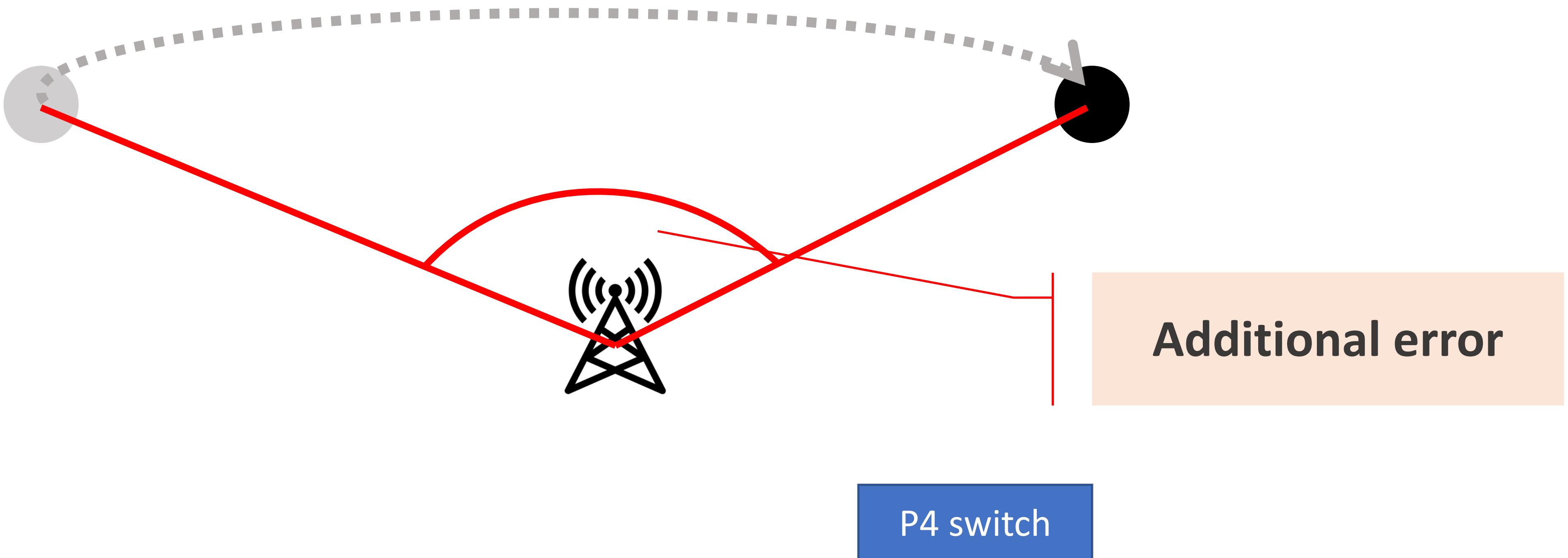
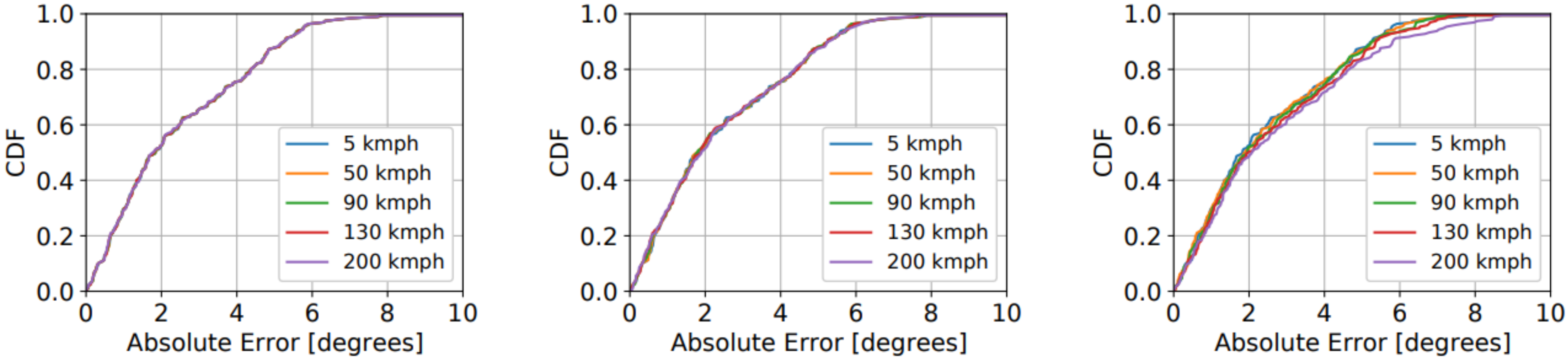


Evaluation
Moving UE and control latency

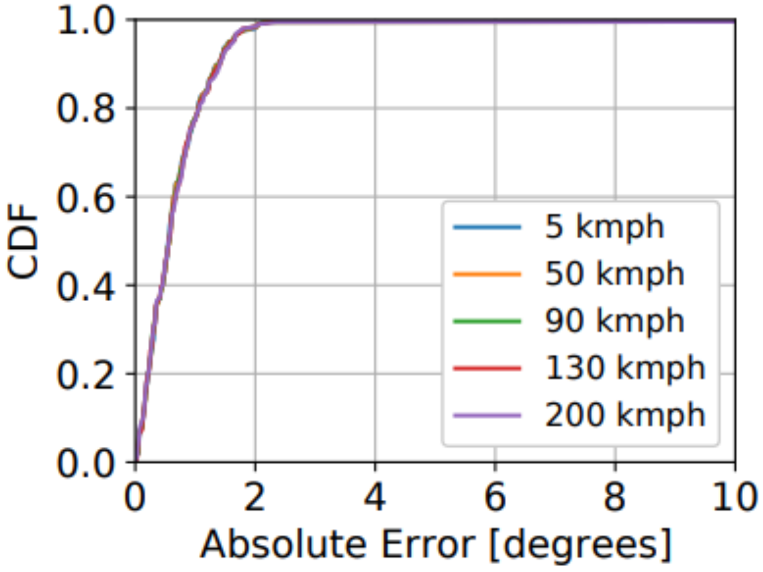
- UE's speed: 5-200 kmph
- Control cycle: 5-100ms
- Simulation
- Number of bins (N): 20
- Diameter fixed: 800m



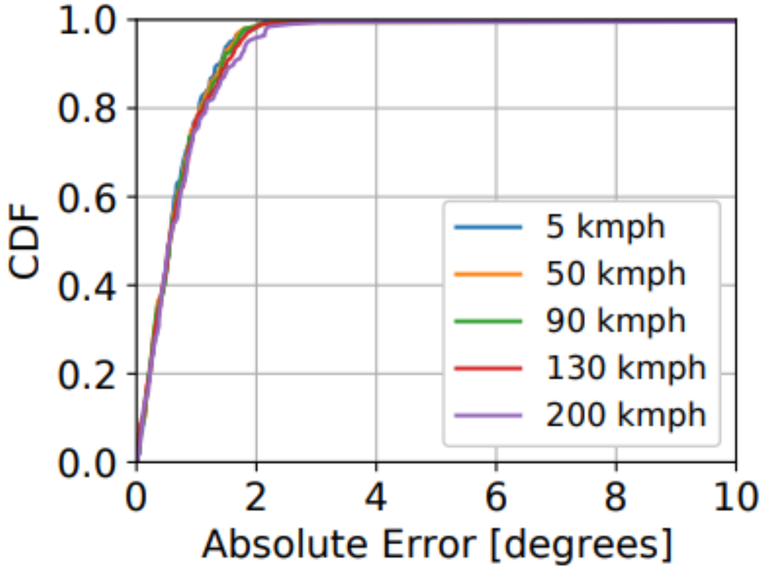
(a) Control Cycle=5ms (b) Control Cycle=20ms (c) Control Cycle=100ms

Evaluation
Moving UE and control latency

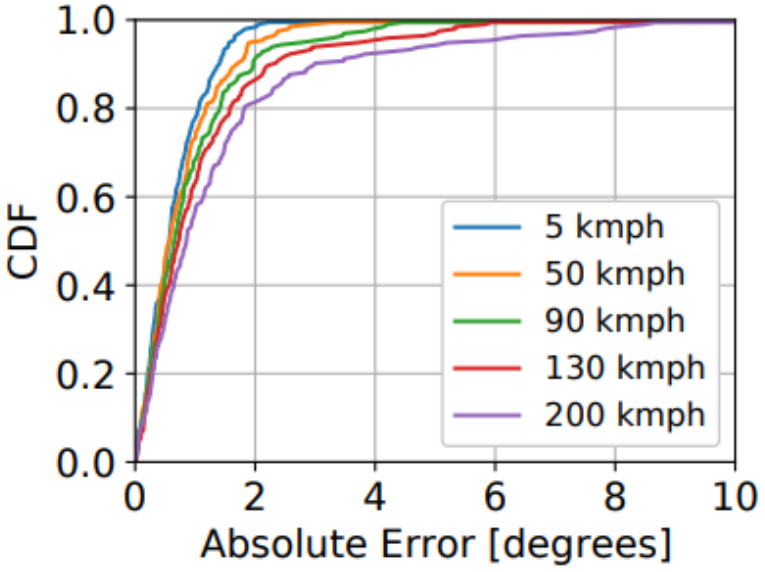
- UE's speed: 5-200 kmph
- Control cycle: 5-100ms
- Simulation
- <u>Number of bins (N): 80</u>
- Diameter fixed: 800m



(a) Control Cycle=5ms



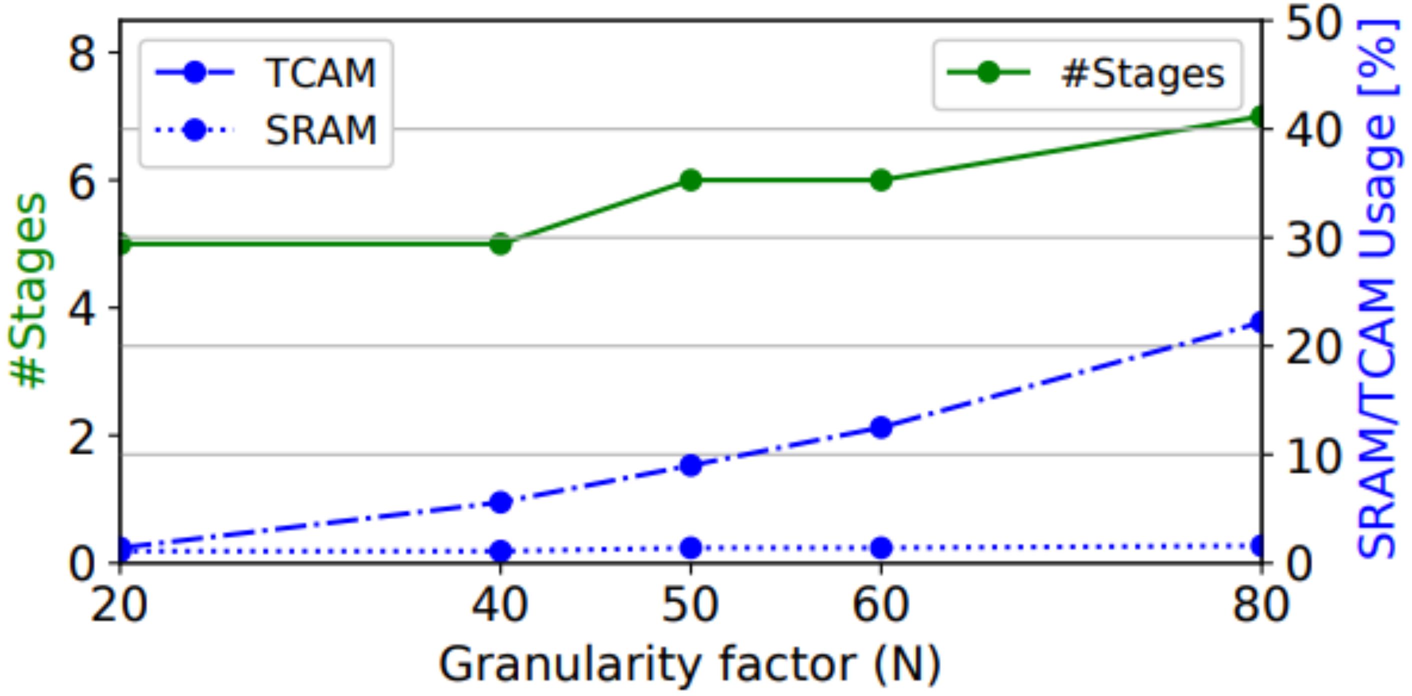
(b) Control Cycle=20ms



(c) Control Cycle=100ms

Evaluation
Cost of accuracy

- Predictable TCAM size
  - And stage number
- Low SRAM usage



Conclusion & *Future plans*

- In-network solutions results in low latency replies
- Angle computation is complex but can be approximated
  - Bound on the accuracy
- Requires moderate per-stage resources
  - Possibility to co-locate with other pipelines like 5G-UPF

- *Integration with a realistic radio propagation simulator*
  - *to quantify the effect of our method on channel quality*
- *Efficient customization of angle prediction table*
  - *E.g., considering BS profiles*

communication networks laboratory

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