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Anchor-free Ranging-Likelihood-based Cooperative Localization

ARLCL

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Outline

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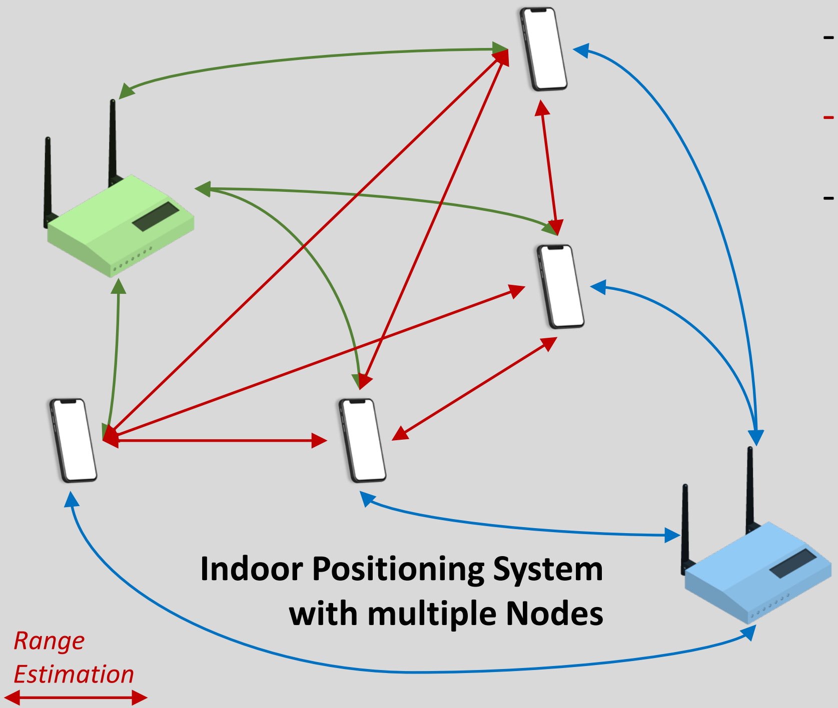
- **Introduction** *(Recap since last year)*
  - *Background, Motivation & Current Solution*
- **Proposed Methodology**
  - *Creating the required Ranging-Likelihood model*
  - *How to perform positioning using ARLCL*
- **Assessing ARLCL**
- **Results**

Introduction
Motivation



- The more signals, the better
- Yet, no effective node cooperation
- Recent advances and opportunities

(Samsung Ad for Galaxy S21 Ultra)

Introduction
Various applications

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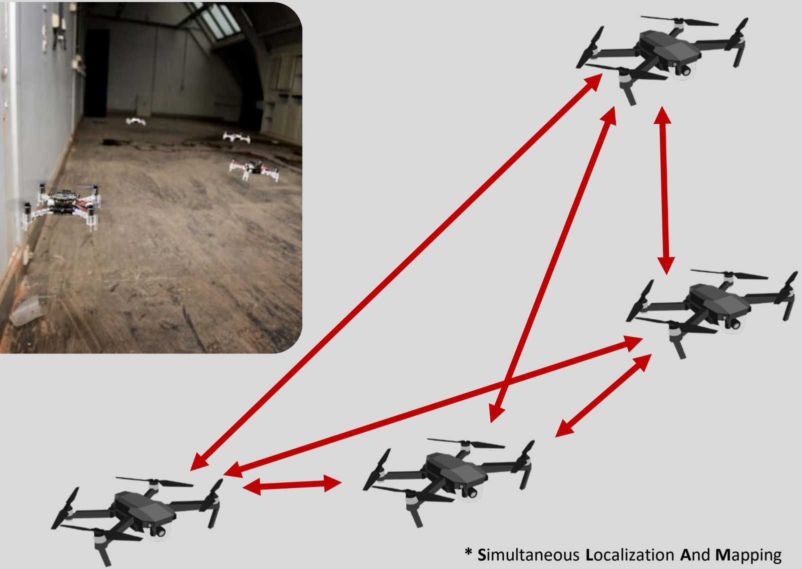

Range Estimation

* **S**imultaneous **L**ocalization **A**nd **M**apping

Cooperative SLAM* using UAV's

- More information available
  → Higher positioning accuracy
- Facilitates limited to **No**-Infrastructure positioning
  → **Anchor Free localization**
  (where position estimations have arbitrary origin)
- Covid Tracking

Introduction

Anchor-free Ranging-based Cooperative Localization (ARLCL) today

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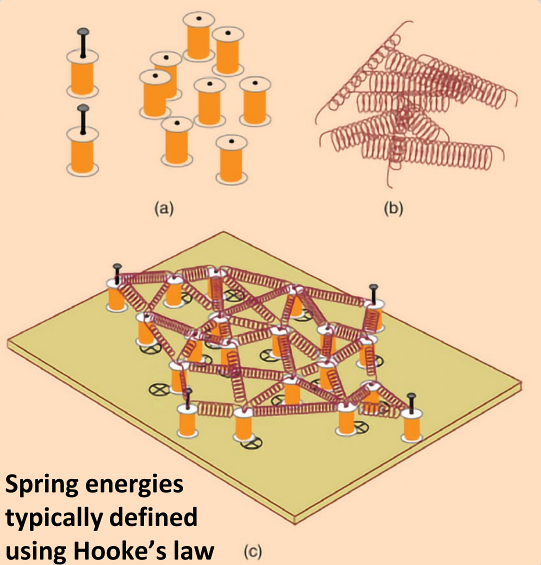
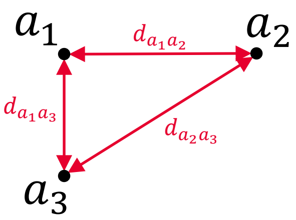
Mass-Spring Localization



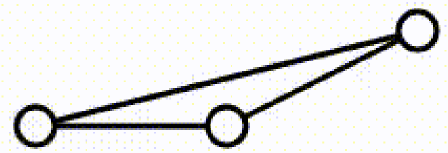
Spring energies typically defined using Hooke's law



- *Unknown position of agent* $\boldsymbol{a_i}$ at **Pos(**$\boldsymbol{x_i, y_i}$**)**
- *Distance estimation* $\boldsymbol{d_{a_ia_j}}$ *based on noisy measurements*

→ **Non-Linear Optimization problem**

Minimize the energy to reach equilibrium



But.. are all measurements equally important?

Estimations of far distances → more uncertainty

- We need to model this uncertainty.

Ranging likelihood as a requirement for ARLCL

A function to describe P(Distance; Measurement)

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- **ARLCL utilizes iteratively the Density Function $P_{Measurement}$(distance) to assign proper importance**

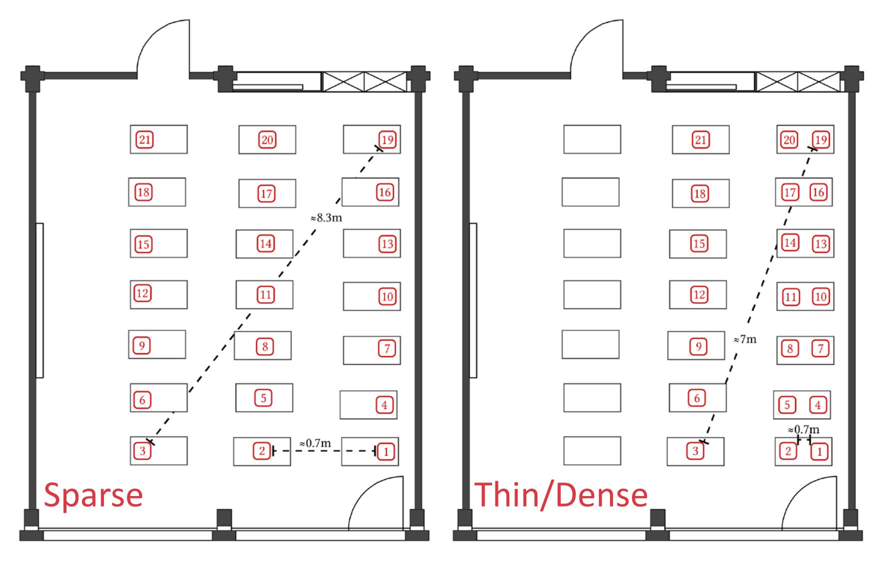
- **Method is technology-agnostic**
  (WiFi ranging, Ultrasonic ranging, BLE ranging, etc..)

.. Given that Node-A received from Node-B this measurement,
how likely is that Node-B is 5m far?

Modelling the ranging likelihood

Sampling process

Collect **Received Signal Strength (RSS)** measurements between *all pairs of 21* ***BLE-Enabled*** *Raspberries (RPi's)*



- **True Positions recorded with LiDAR Scanner** *(Leica BLK360)*
- **x2 deployment shapes** (Sparse & Thin/Dense)
- **x10 times** (@random RPi's orientations)
- **x 5mins**

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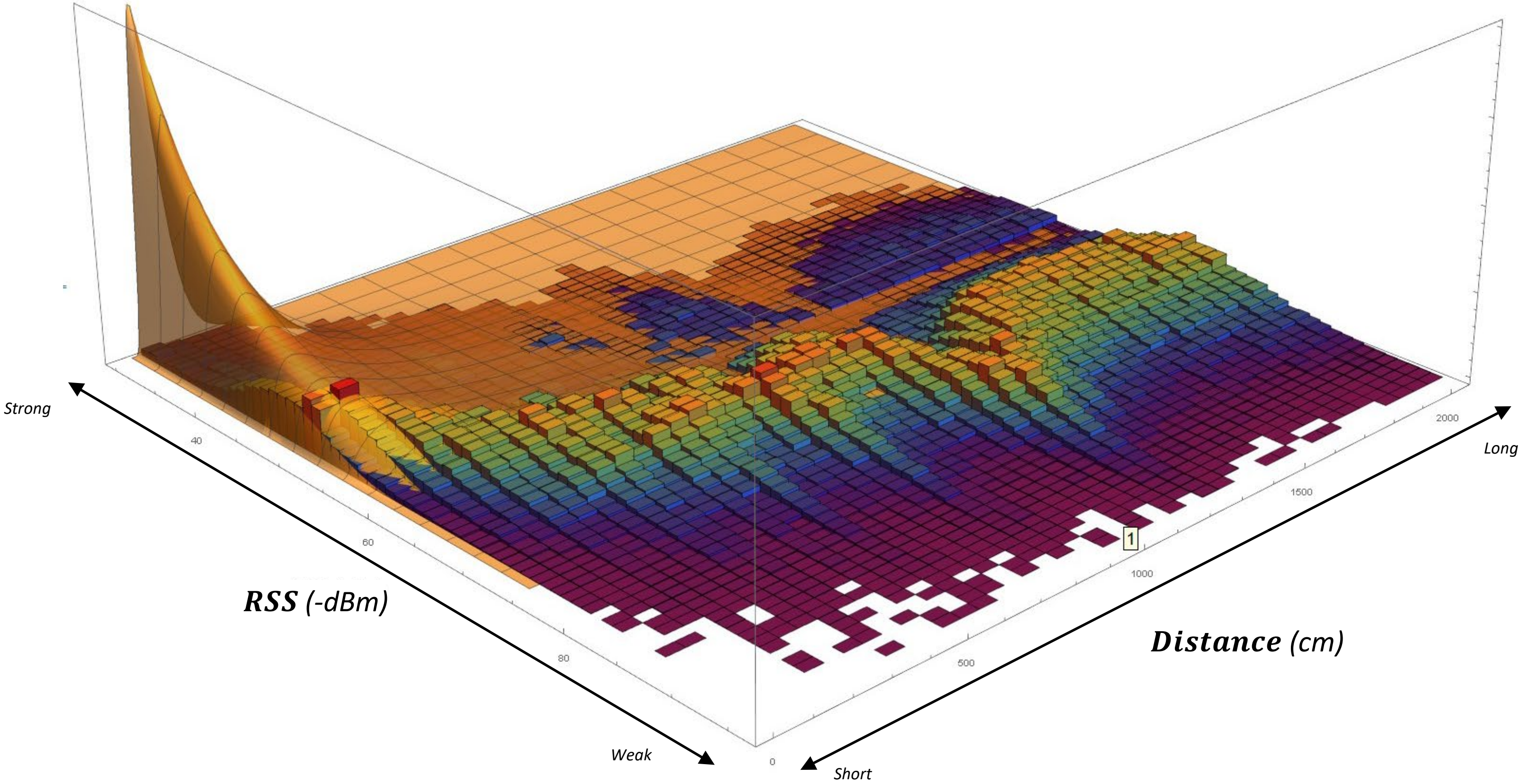
Modelling the ranging likelihood

From Frequency Histogram to Final Model



Performing swarm positioning with ARLCL

The methodology outline

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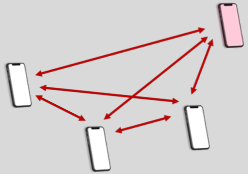
Init

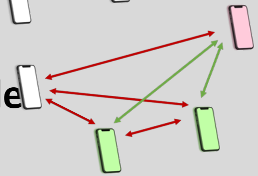
- **Place the Nodes** *(i.e. the Swarm)* **randomly on space**

Cycle

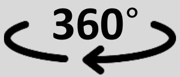
- **Select the 1st Node** (according to some selection order) **to correct his position**



- **Select all Neighbor Nodes that have effective measurements towards that Node**



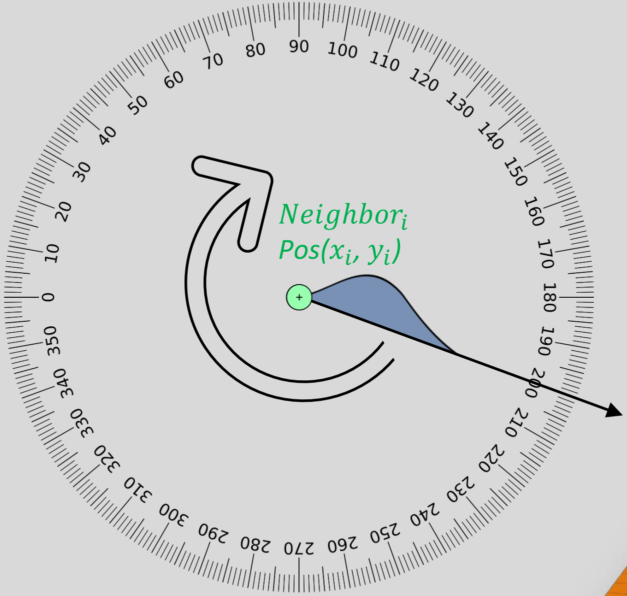
- **Get each measurement's PDF and rotate it** *(according to the modelled DoF)*



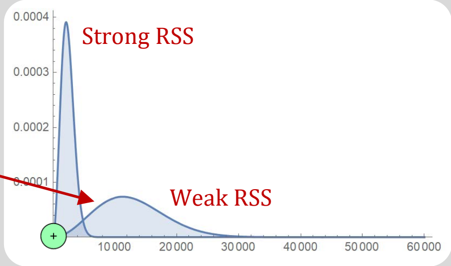
- **Find the global max of the product of these PDFs and move the 1st Node to that position**
- **Proceed with the 2nd Node and continue until the last one.** *>> Repeat cycle until we converge..*

Performing swarm positioning with ARLCL

Rotating the Position's PDF



- Get the $\mathbf{P}(\boldsymbol{x_c}\,;\boldsymbol{RSS})$ that corresponds to some measurement



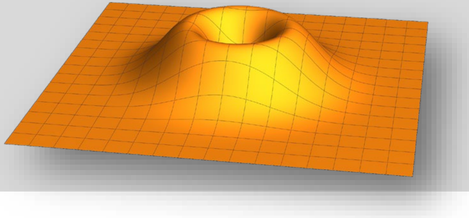
Current Node $Pos(x_c)$ lies on this axis

$Neighbor_i\ Pos(x_i)$

- *We expand considering 2-Dimensions → i.e. go from $Pos(x_c)$ to $Pos(x_c, y_c)$*

- *Replace $\boldsymbol{x}$ in $\mathbf{P}(\boldsymbol{x_c}\,;\boldsymbol{RSS})$ with the eq.* $\sqrt{(x_i - \boldsymbol{x_c})^2 + (y_i - \boldsymbol{y_c})^2}$

$Neighbor_i$ $Cur.Node$



Assessing ARLCL

Compare against Mass Spring Method

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- Using our developed **Ranging Model** and **True positions** of the 21 RPi's..
- Get a noisy **RSS measurement** between each pair

Evaluated variables

- **Swarm shape**	x2	$(Sparse, Thin/Dense)$
- **Swarm size**	x19	$(3..21)$
- **Noise level**	x20	$(1..20)$ *(PDF resamplings to get an average RSS)*

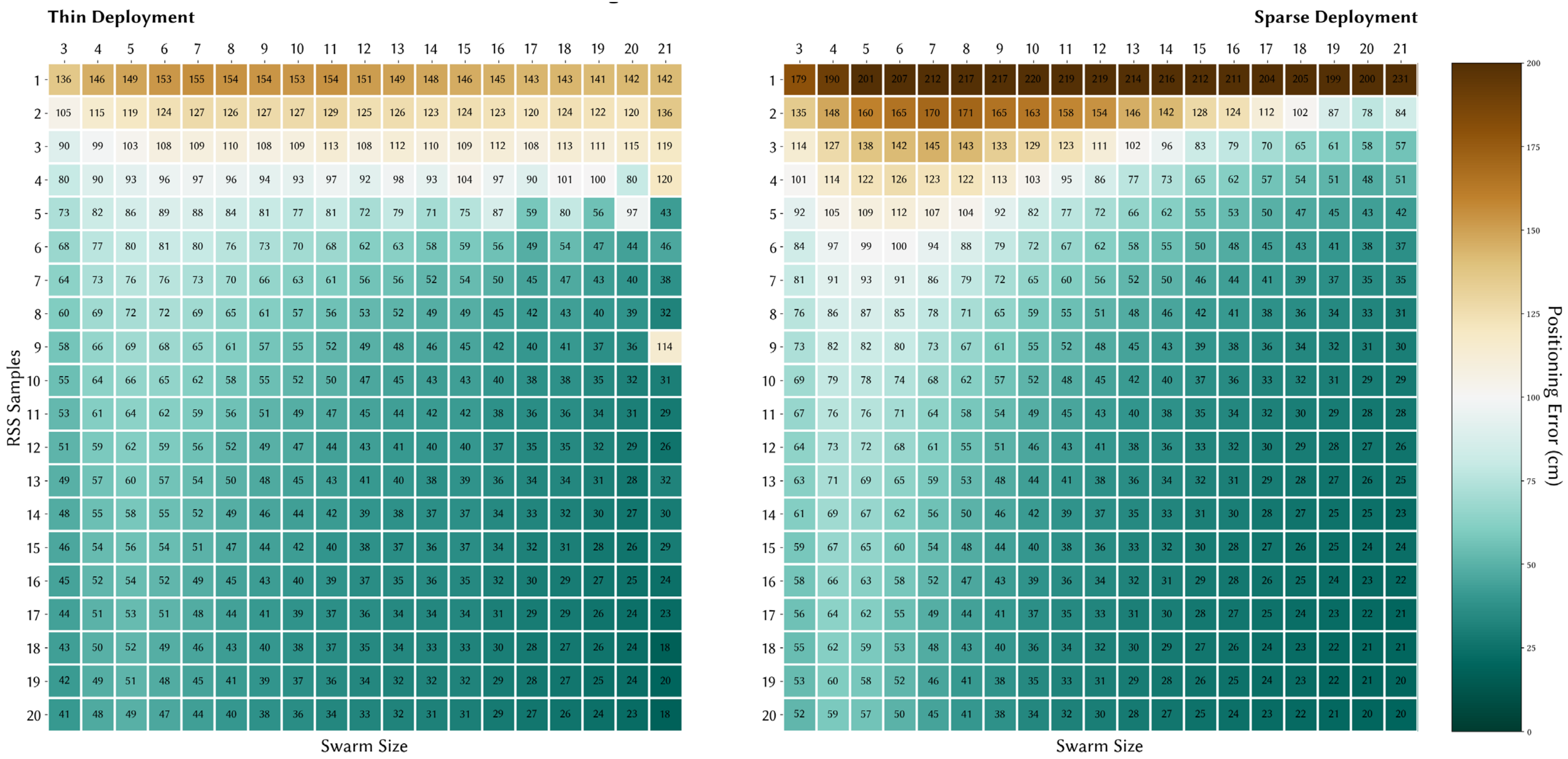
Repetition parameters

- **Position initialization**	x100	$(1..100)$ *(Random initial node placement)*
- **Node Combinations**	x200	

= ~14m Evaluated cases

Results

Positioning Error of ARLCL at 75th Percentile



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Results

% Reduction of Error at 75th Percentile

$(E_{MS} - E_{ARLCL})/E_{MS} \quad x100$

Thin Deployment

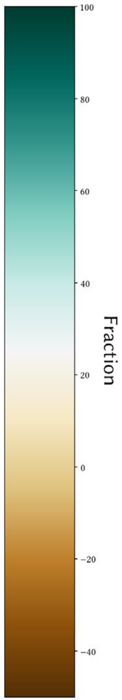
RSS Samples	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	7	8	9	10	11	12	12	12	12	13	13	13	13	14	13	13	13	11	12
2	7	7	9	9	9	9	11	10	10	11	10	10	8	8	9	5	5	5	1
3	5	8	8	9	10	12	14	12	11	12	9	10	9	5	6	1	1	-3	-7
4	5	6	8	9	11	14	18	19	17	19	14	17	6	11	16	3	3	21	-22
5	4	6	8	10	14	17	21	29	26	33	27	33	28	15	42	18	42	3	57
6	3	6	8	11	14	20	24	32	35	38	40	43	41	44	50	42	49	52	57
7	3	5	8	11	16	21	27	34	39	42	45	47	45	48	52	47	52	55	64
8	3	5	8	11	17	21	27	36	42	44	47	50	49	52	54	51	54	54	63
9	3	5	7	11	16	22	28	38	46	46	50	52	51	54	56	52	57	59	-10
10	3	5	8	11	17	22	28	39	46	47	52	54	53	56	58	55	58	62	55
11	3	5	7	12	17	24	29	39	47	47	53	54	55	57	58	56	60	61	72
12	3	6	7	12	18	24	28	39	51	48	55	56	55	58	60	58	61	63	62
13	3	5	7	13	18	24	27	37	48	50	56	59	56	58	60	58	62	64	60
14	3	6	7	13	18	23	26	40	52	51	58	59	57	60	61	61	63	67	70
15	2	6	8	13	18	24	28	41	52	51	58	59	58	60	63	61	64	67	72
16	2	6	8	14	19	25	30	40	51	51	60	59	60	63	64	63	66	66	59
17	3	6	8	13	19	25	29	40	52	53	60	62	60	64	65	64	66	67	77
18	2	6	8	14	19	25	27	38	52	51	61	62	62	65	66	65	67	68	80
19	2	6	8	13	19	24	27	36	53	57	62	63	62	65	67	66	68	70	75
20	2	5	8	14	19	26	29	41	55	56	62	64	63	66	67	66	69	67	81

Swarm Size

Sparse Deployment

RSS Samples	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	-1	0	2	4	5	6	7	7	8	8	8	7	7	6	6	2	0	-7	-12
2	2	3	4	5	5	7	8	9	10	8	8	5	1	-4	-3	-2	8	13	3
3	3	4	5	6	7	9	11	12	9	9	6	5	8	7	12	14	16	17	18
4	3	4	5	8	10	11	12	14	10	10	12	10	13	13	15	16	17	19	17
5	3	5	7	10	13	16	17	19	15	11	12	12	15	14	16	17	18	19	19
6	3	5	8	12	15	19	18	18	16	13	13	12	15	15	17	18	19	20	19
7	3	5	8	13	17	21	18	18	15	13	14	13	15	16	17	18	19	20	17
8	3	5	9	13	17	22	18	17	16	14	13	14	15	15	18	18	19	20	22
9	2	4	8	14	17	20	17	17	15	14	14	14	15	15	17	18	19	20	18
10	2	4	9	14	17	20	17	18	16	14	15	14	16	16	18	18	19	19	19
11	2	5	8	14	16	19	16	17	16	15	16	15	17	16	17	18	20	20	17
12	2	4	8	14	16	18	17	17	16	15	15	15	16	16	18	18	19	20	19
13	2	4	8	14	16	20	17	17	16	15	15	15	17	16	18	19	19	20	20
14	2	5	8	15	16	20	17	18	17	15	16	15	17	16	18	19	20	20	24
15	2	5	8	14	17	19	17	18	17	15	16	16	17	17	18	19	20	19	21
16	2	5	9	14	17	19	18	18	17	15	16	16	17	16	18	19	20	21	21
17	2	4	9	15	17	20	18	18	17	16	16	16	17	16	18	19	20	20	20
18	2	5	10	16	17	20	18	19	17	16	16	16	17	16	18	19	19	20	21
19	1	5	9	15	18	20	18	18	17	16	16	16	17	16	18	19	20	20	22
20	2	6	10	17	18	20	17	19	18	15	16	16	17	17	18	19	20	20	22

Swarm Size



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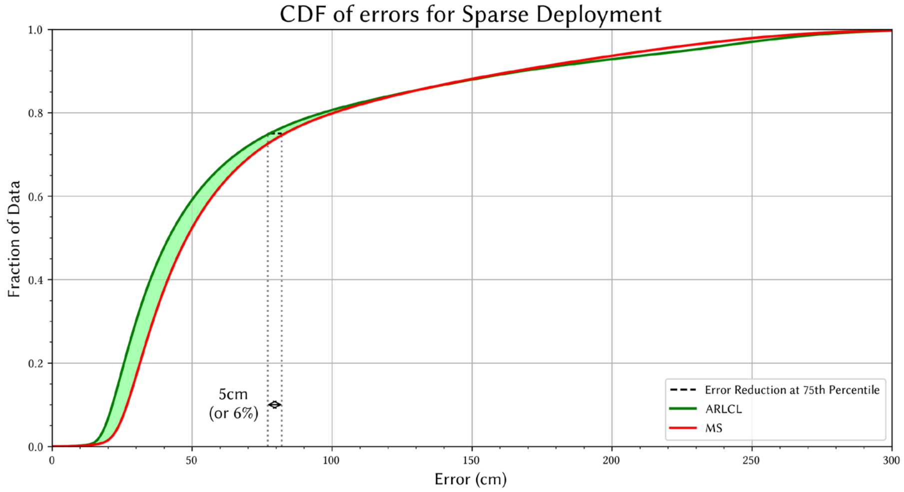
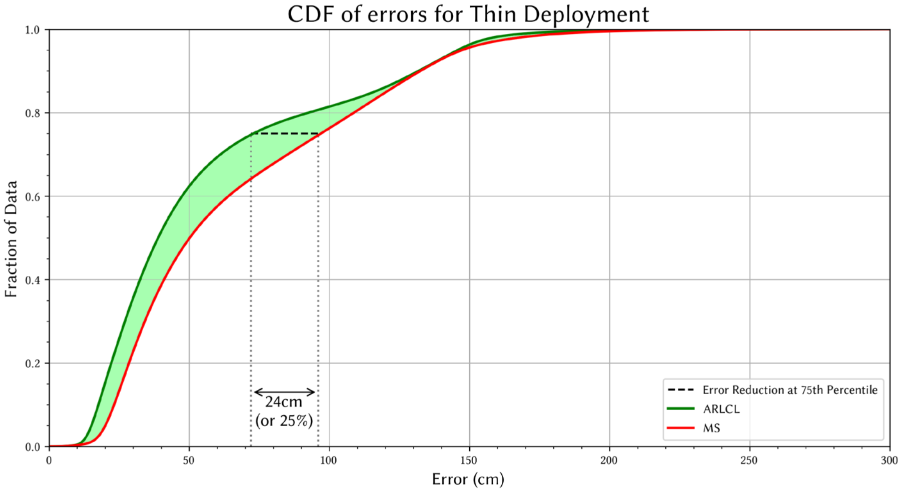
Results

Cumulative distribution function of the positioning errors





Results

Fraction of improved cases

Thin Deployment

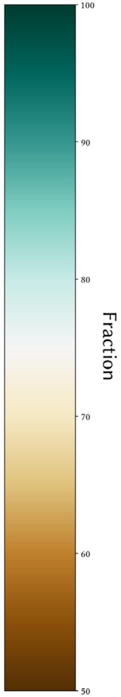
RSS Samples \ Swarm Size	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	62	71	76	79	80	81	81	81	79	79	79	78	78	78	78	77	77	74	79
2	63	71	74	76	76	76	76	75	75	75	75	75	74	73	75	74	74	73	69
3	62	70	73	74	73	74	75	75	74	74	73	74	74	73	74	73	74	73	75
4	61	68	71	72	72	73	74	73	73	73	73	73	72	73	74	73	73	74	69
5	60	67	70	70	71	72	72	74	72	74	72	73	72	72	73	72	73	73	81
6	60	66	69	70	71	72	72	73	72	73	73	73	72	73	74	71	73	73	73
7	59	65	68	70	70	72	73	73	72	73	73	73	71	72	73	72	73	75	79
8	59	65	68	69	71	71	73	74	73	73	72	73	72	72	73	71	73	72	77
9	58	65	67	69	70	72	73	73	73	73	72	72	71	72	73	71	73	73	66
10	58	64	67	69	71	71	73	73	72	73	72	72	71	72	73	72	73	75	70
11	58	64	66	69	70	72	73	73	72	73	72	72	71	72	73	71	73	73	76
12	57	63	67	68	71	72	72	72	73	72	72	72	71	72	73	72	73	75	71
13	57	63	66	69	71	72	73	73	72	73	72	73	71	71	73	71	73	74	67
14	58	63	66	68	71	72	73	73	72	73	72	72	71	72	73	72	73	75	72
15	57	63	66	68	70	72	73	73	73	74	73	72	71	72	73	72	74	74	71
16	57	62	66	69	70	72	72	73	73	73	73	72	71	72	74	73	74	75	75
17	57	62	65	68	70	72	73	74	73	73	73	73	72	73	73	73	74	75	78
18	56	63	66	68	70	72	73	74	73	73	73	73	72	73	74	73	74	76	83
19	57	63	66	68	70	72	73	73	73	74	73	73	72	73	74	74	75	76	79
20	57	63	65	68	71	73	74	74	74	74	73	73	72	73	74	74	75	77	83

Swarm Size

Sparse Deployment

RSS Samples \ Swarm Size	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	56	61	66	68	69	67	67	66	66	66	66	65	65	65	65	65	66	67	63
2	59	66	68	68	68	66	67	67	68	67	70	69	71	71	73	74	76	79	77
3	59	66	67	68	67	67	69	69	70	71	72	73	75	75	78	79	81	82	83
4	59	66	67	67	68	67	69	71	72	73	75	75	78	78	80	81	82	84	82
5	59	65	67	67	68	69	71	73	74	74	76	76	80	79	81	82	84	83	91
6	58	65	66	67	68	70	72	74	75	75	77	77	80	80	82	83	84	86	87
7	58	64	66	67	68	70	73	75	76	76	78	78	80	80	82	84	85	85	83
8	58	64	66	67	69	72	74	75	77	77	78	79	81	80	83	84	85	86	91
9	58	63	65	67	69	71	73	76	76	77	79	79	81	81	83	84	85	85	87
10	57	63	65	68	70	72	74	76	77	78	79	79	82	82	84	84	86	85	86
11	57	63	66	68	70	72	74	77	78	78	80	80	82	81	83	84	86	87	85
12	56	63	65	68	70	73	75	77	78	79	80	80	82	82	84	84	86	86	85
13	57	62	65	68	71	73	75	78	78	79	80	80	83	82	84	85	86	86	89
14	56	61	65	68	71	74	75	78	79	79	80	80	83	82	84	85	86	86	93
15	56	62	65	68	72	74	76	78	79	79	80	81	83	83	85	85	86	87	86
16	56	62	65	68	71	74	76	78	79	80	81	81	83	83	85	85	86	89	90
17	55	61	65	68	72	75	76	78	79	80	81	81	83	83	85	85	87	88	85
18	56	61	66	69	72	75	77	79	79	80	81	81	84	83	85	86	86	86	88
19	56	61	65	69	72	75	77	79	80	80	81	81	83	83	85	85	87	88	91
20	55	62	65	69	72	75	76	80	80	80	81	81	84	83	85	86	87	87	87

Swarm Size



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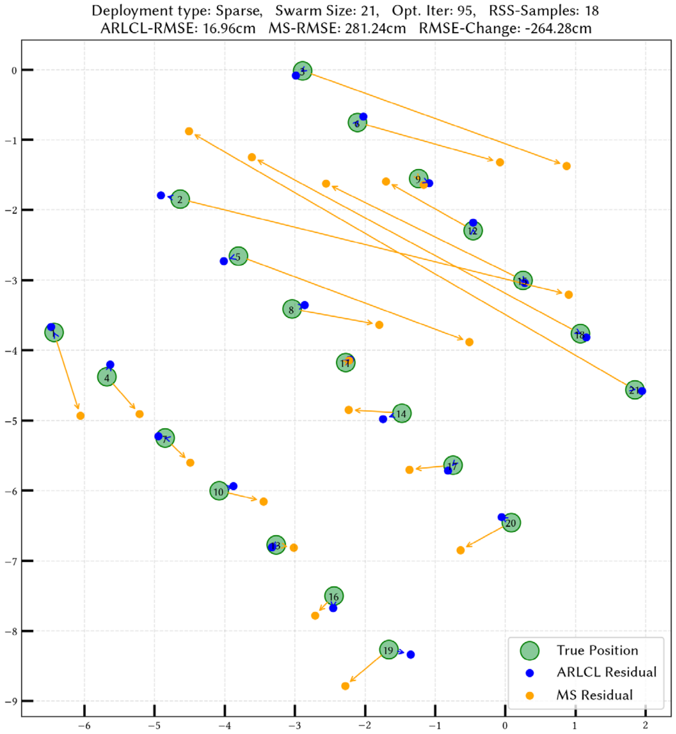
Results

Estimation residuals and trajectories (best ARLCL win for Size:21)



Results

Conclusions

- Positioning error for both **ARLCL** and **MS** is correlated to both **Swarm Size** and **Sample Size**
- **Sparse** deployments are more **prone to signal noise**
- Bellow **85^{th} percentile**, **ARLCL** introduces an overall **improvement** (same performance above that)
- **ARLCL's** gain is also correlated to both **Swarm Size** and **Sample Size**
- **ARLCL's** gain depends also on the Swarm Shape (more gain at **Thin/Dense** scenarios)

Results

Future work

- Assess more swarm deployment scenarios
  (of different densities/shapes/with in-between obstacles/etc.)
- Assess common ranging models under different environments
- Assess other ranging technologies (UWB/WiFi)
- Fuse other types of signals into the localization process (Inertial data)
- Take it from offline to online positioning

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Thank you for your time!

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