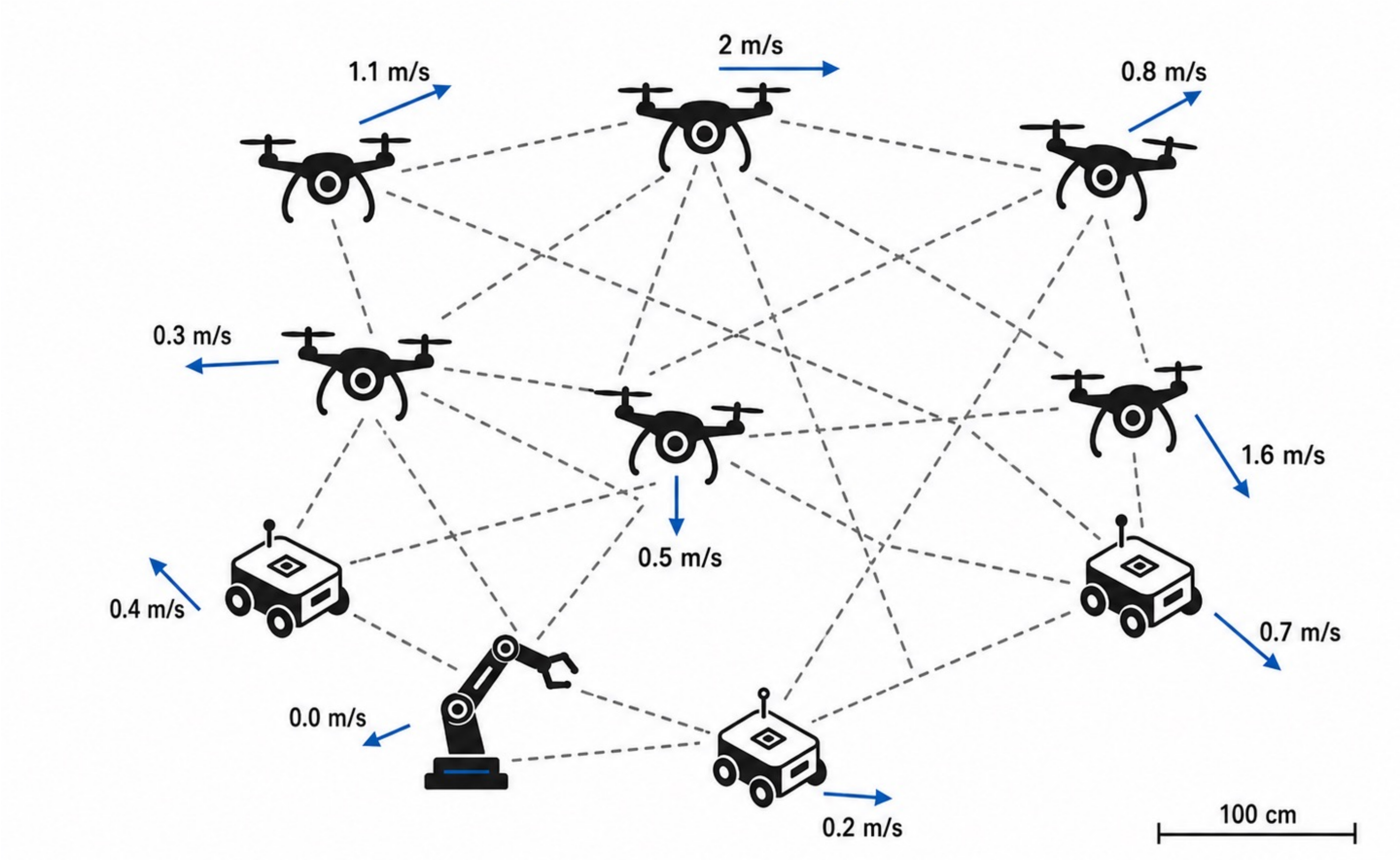
Southeast University, China

Optimal Swarm Ranging Protocol for Dynamic and Dense Ultra-Wideband Networks

Yunxi Hou, Feng Shan, Wangxiao Mao, Jiangpeng Liu, Ye Liu, Wenjia Wu, Runqun Xiong, Junzhou Luo

Central problem



Distance Sensing in high-dense and high-dynamic robot swarms

Outline

1 Research Background

2 Motivation and Core Idea

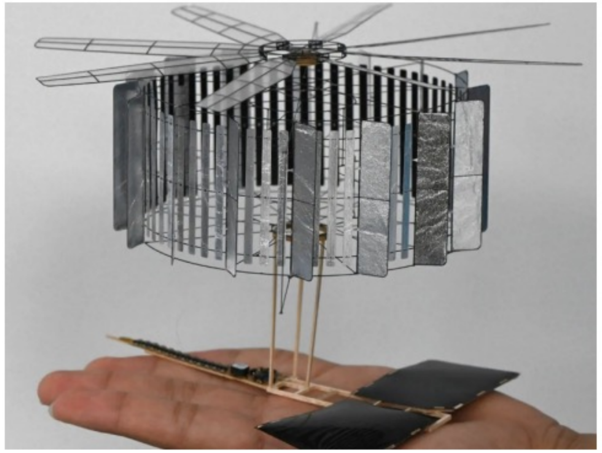
3 Optimal Swarm Ranging Protocol Design

4 Experimental Results and Evaluation

Outline

1. Research Background： Micro robots and devices

Crazyflie 2.1 Micro UAV
(27g,2019)



CoulombFly Micro UAV
（5g, 2024）

Aerial-Ground Robot
（27g, 2025）

Advantage

- Compact size: suitable for narrow, complex spaces
- Low cost: easy for large-scale deployment
- High extensibility: supports various types of sensors

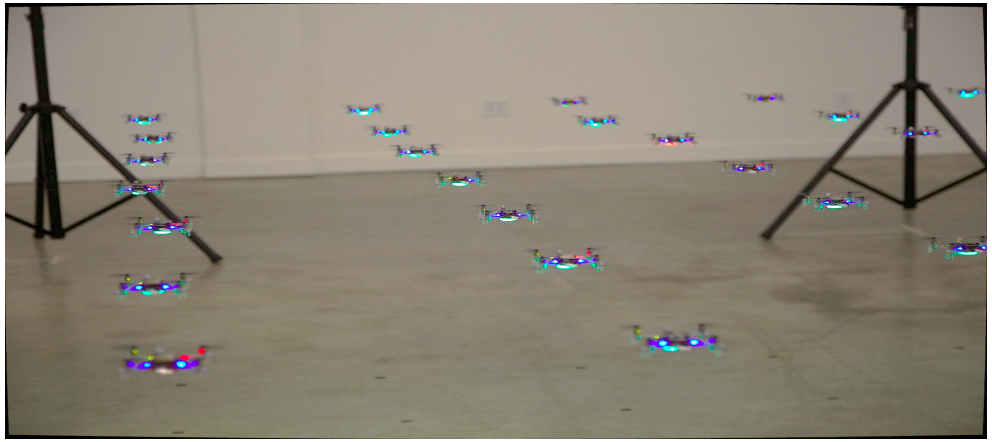
Disadvantage

- Limited computing power and memory capacity
- Low battery capacity; restricted operational range

1. Research Background: Micro robots and devices Swarm

How to resolve:

Forming swarms of micro robots or devices to work collaboratively is key to overcoming these limitations.



Advantages

- **High operational efficiency:** enable swarm to execute multiple concurrent tasks.
- **High fault tolerance:** single-node failures do not disrupt overall operation

Difficulties

- The high node density and close proximity demand **real-time ranging**
- **High precision** and L**ow latency**.

Real-time, high-precision ranging sensing is essential for enabling effective swarm collaboration.

1. Research Challenge: Perception of Relative Distances within Swarm

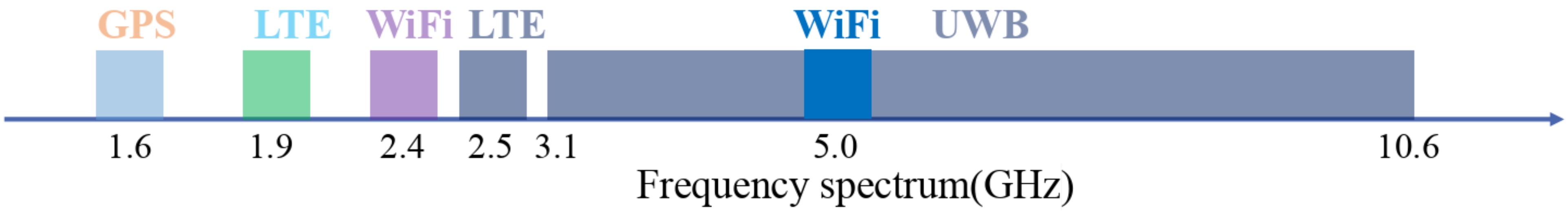
Challenges in relative distance perception

High-density	large number of robots relatively close	require	➢ **High efficiency,** Ranging sensing must make full use of limited channel resources. ➢ **High Robustness**, Range sensing must ... enarios.
High-dynamic	rotots are maneuverable locations change rapidly	require	... st be sufficiently accurate to prevent collisions ➢ **Low latency,** distance sensing must respond promptly to changes in the topology

Challenge: How can we design an efficient and robust swarm ranging protocol that achieves high-precision, low-latency ranging in dense and dynamic robot swarms?

Ultra-Wide Band (UWB) technology

- UWB propagates data at high bit rates over a wide frequency spectrum(3.1~10.6GHz)
- So time sensitive that an accurate distance can be calculated using transmit and receive timestamps
- Ranging accuracy around **10 cm**

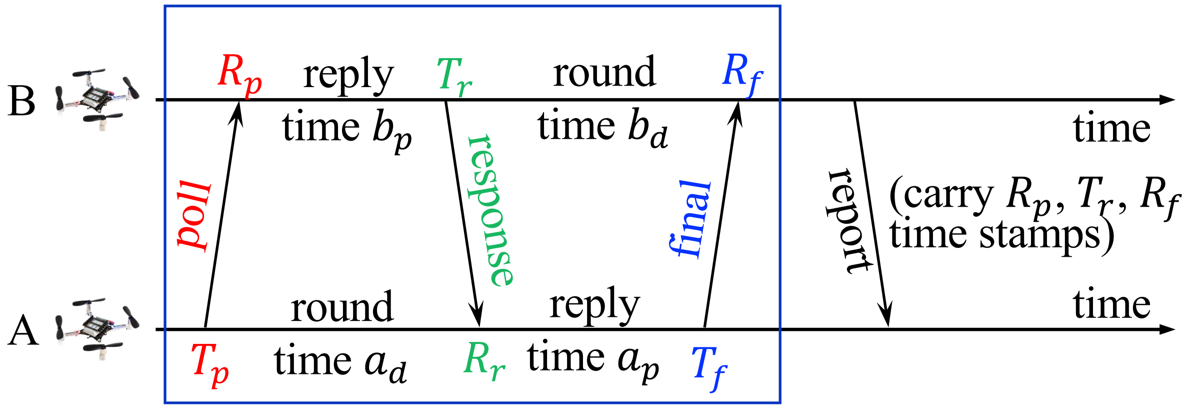


Related Work: Principle of DS-TWR protocol

- The UWB ranging protocol in IEEE 802.15.4z-2020 standard:

  Double-Sided Two-Way Ranging (DS-TWR)

  - exchanging a total of ***4*** messages
  - **Four message type: *poll*, *response*, *final*, *report***



In high-density **many-to-many** scenarios, **this approach is inefficient**, suffers from **performance limitations**, and cannot be easily scaled

Six Timestamps for the Send-Receive-Send Sequence

$$a_d = R_r - T_p, \quad b_p = T_r - R_p$$
$$b_d = R_f - T_r, \quad a_p = T_f - R_r$$

TOF equation

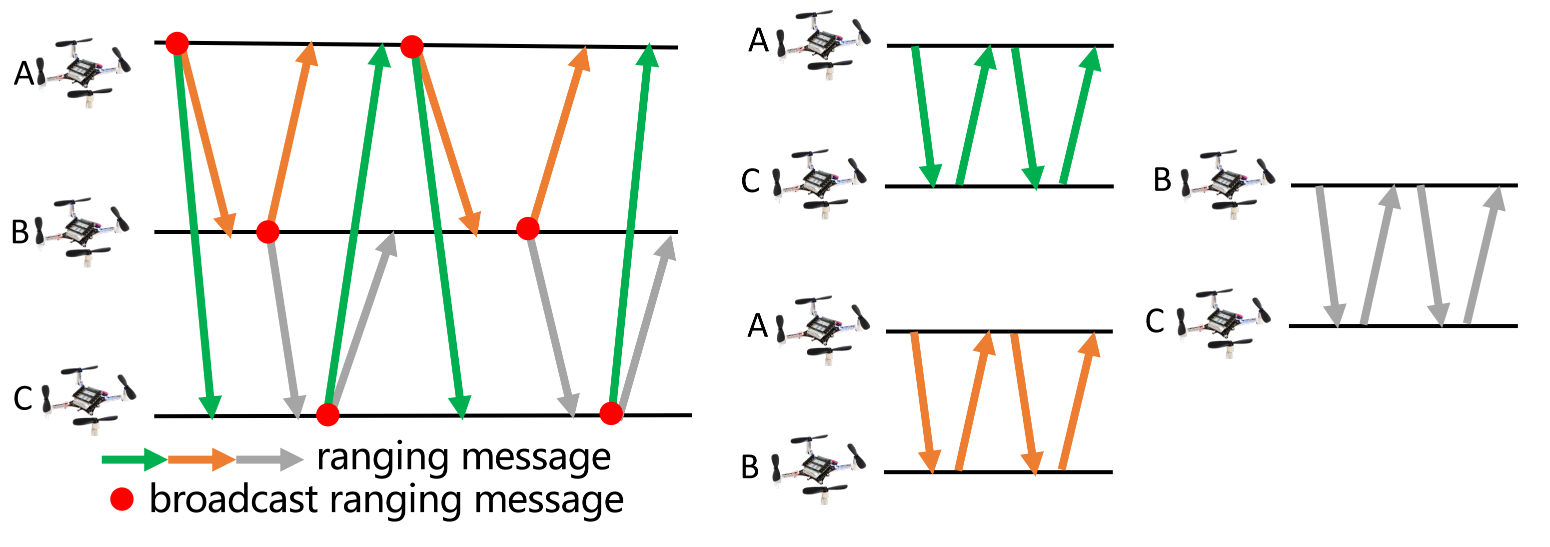
$$t_p = \frac{a_d b_d - a_p b_p}{a_d + b_d + a_p + b_p}.$$

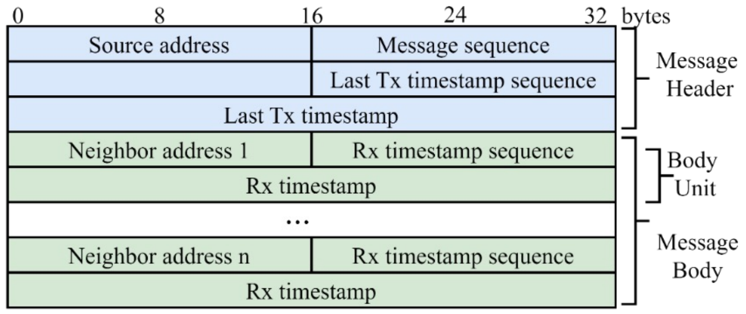
distance calculation

distance $= t_p c$, (c speed of light)

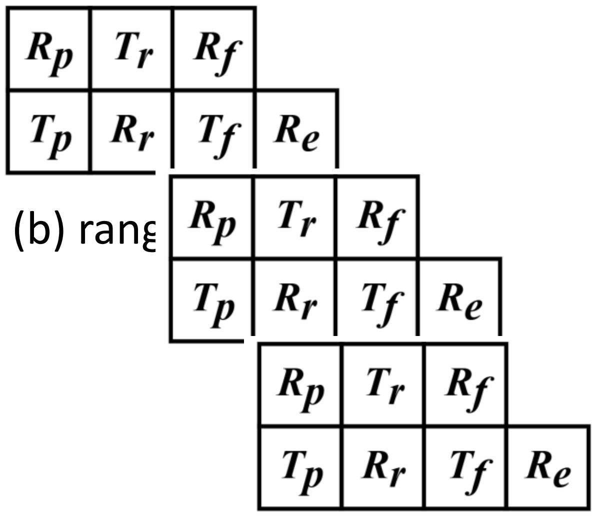
Related Work: Principle of Swarm Ranging 1.0（SRv1） protocol

- Only **one type of message** implement **Streaming Ranging**
- Each device broadcasts **ranging messages** at specific intervals





(a) ranging message format



(b) rang

Under the conditions of consistent ranging period and zero packet loss, **each received message enables a new ranging**. By fully utilizing every message timestamp, we achieve a pipelined ranging mechanism.

Content

2. Motivation and Core Idea

motivation 1

UAV numbers	packet receive rate	ranging rate
25	77.7%	49.6%

gap is so large
(*28% ranging opportunities is loss*)

- What factors lead to ranging performance degradation ?
- How can we design to reduce the loss of ranging opportunities ?

motivation 2

design
case by case

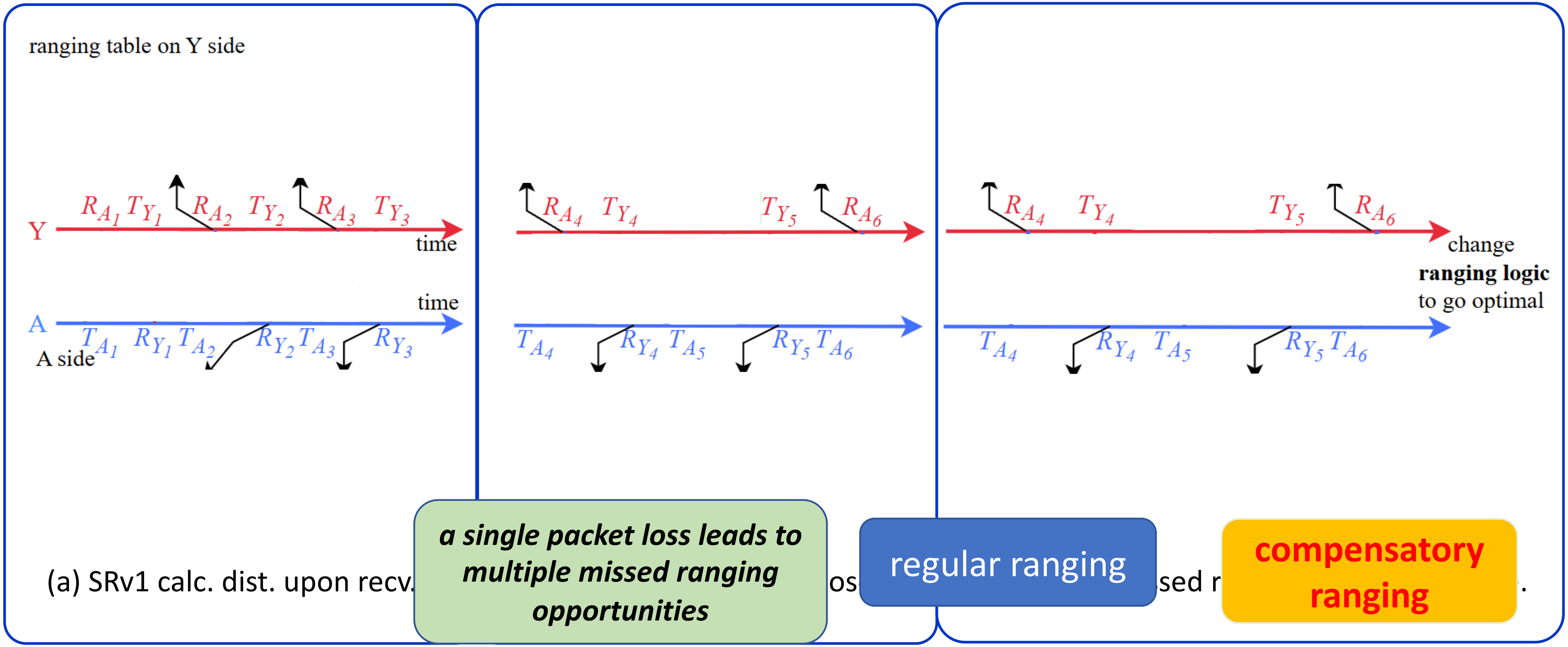
complex, hard to scale, and difficult to analyze.

- What is the theoretical upper bound of ranging performance ?
- How can we approach this theoretical limit to achieve optimal swarm ranging ?

Analysis and redesign this protocol to achieve an ***optimal*** swarm ranging （2.0 version）

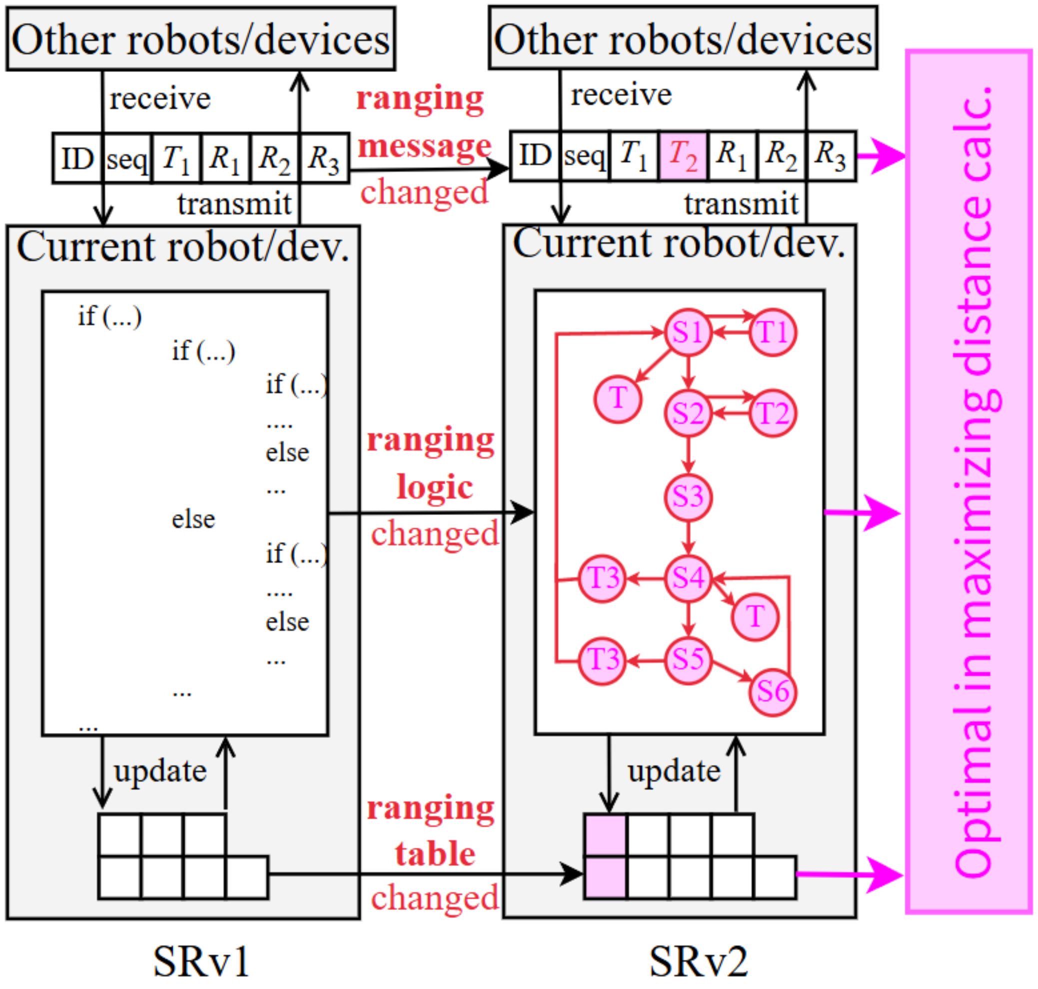
2. Core Idea: maximize the number of ranging

1. Ranging Message and Ranging Table Redesign



2. Core Idea: maximize the number of ranging

2. State machine design for modeling and analysis

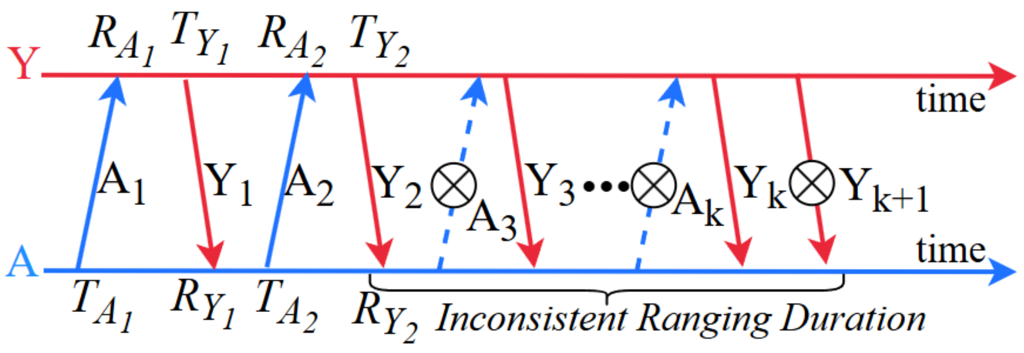


- By regular and compensatory ranging
- By redesigned ranging message and ranging table
- By state machine

We prove SRv2 is theoretically **optimal** and **pushes the classical DS-TWR method to its limits**

Outline

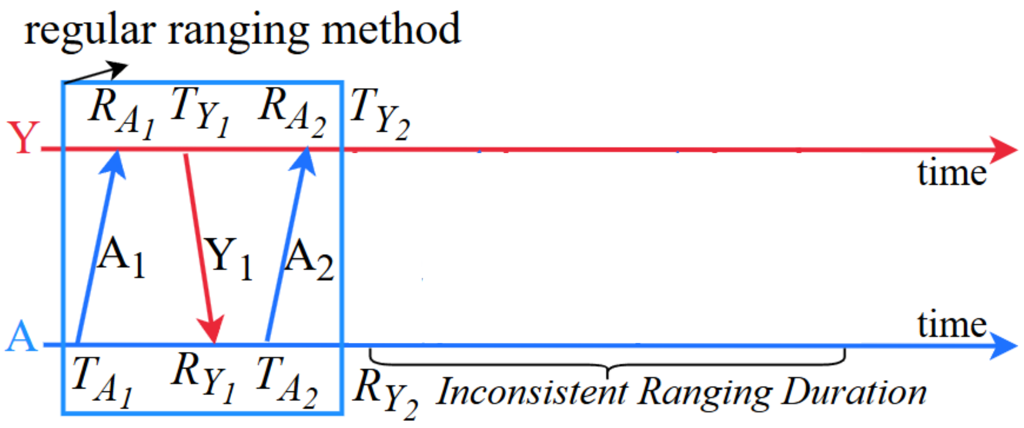
(1) Compensatory Ranging and Ranging Table Design



Inconsistent Ranging Duration: refers to a sub-duration during which a robot/device A receives k packets ($k > 1$)from neighbor Y, while Y receives none from A, either due to packet loss or unsent packets.

3. Design of Swarm Ranging 2.0 Protocol

(1) Compensatory Ranging and Ranging Table Design

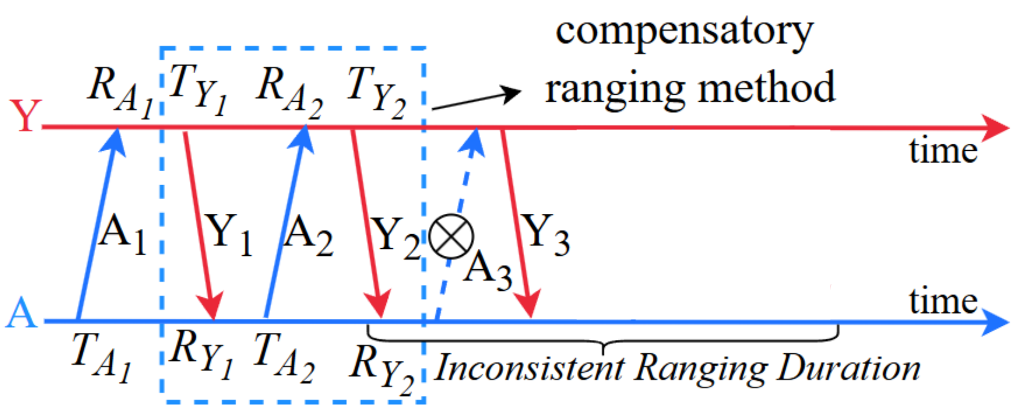


Inconsistent Ranging Duration: refers to a sub-duration during which a robot/device A receives k packets $(k > 1)$from neighbor Y, while Y receives none from A, either due to packet loss or unsent packets.

STEP	Ranging Table		
A Receive Y_3 & Compute Distance	$R_p = R_{A_1}$		
Regular Ranging Method	$R_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$

3. Design of Swarm Ranging 2.0 Protocol

(1) Compensatory Ranging and Ranging Table Design



Inconsistent Ranging Duration: refers to a sub-duration during which a robot/device A receives k packets $(k > 1)$from neighbor Y, while Y receives none from A, either due to packet loss or unsent packets.

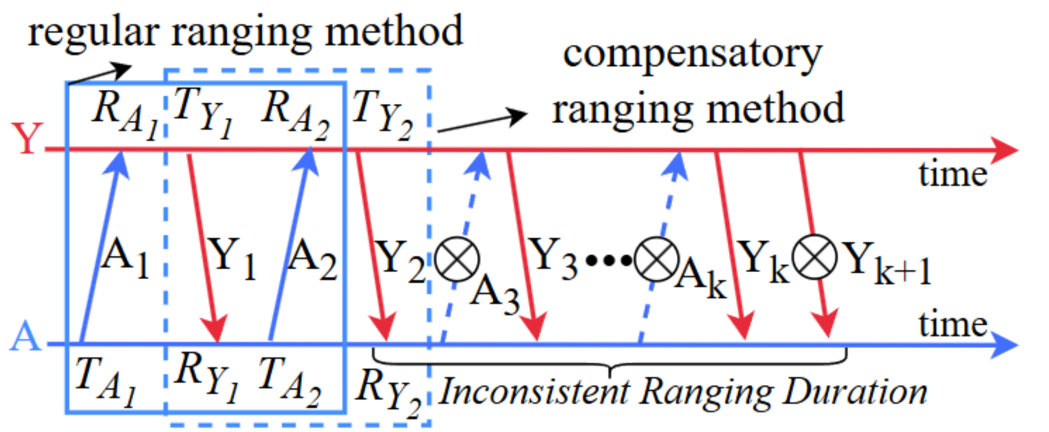
regular ranging method: using six timestamps generated from three messages: the most recent **send-receive-send** sequence.

STEP	Ranging Table				
A Receive Y_3 & Compute Distance		$R_p = R_{A_1}$	$T_r = T_{Y_1}$	$R_f = R_{A_2}$	
Regular Ranging Method		$R_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$	$R_e = R_{Y_2}$
Rearrange tht Table		$R_p = R_{A_2}$	$T_r =$	$R_f =$	
		$R_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f =$	$R_e =$
Cannot ranging		$R_p = R_{A_2}$	$T_r = T_{Y_2}$	$R_f =$	
		$R_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f =$	$R_e = R_{Y_3}$

Only 4 timestamp(need 6 for ranging)

3. Design of Swarm Ranging 2.0 Protocol

(1) Compensatory Ranging and Ranging Table Design



regular ranging method: using six timestamps generated from three messages: the most recent **send-receive-send** sequence.

compensatory ranging method: using six timestamps generated from three messages: the most recent **receive-send-receive** sequence.

R_p	T_r	R_f	
T_p	R_r	T_f	R_e

→

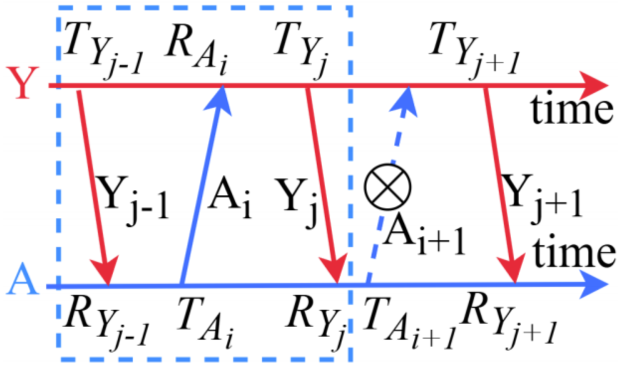
T_b	R_p	T_r	R_f	
R_b	T_p	R_r	T_f	R_e

STEP	New Ranging Table				
A Receive Y3 & Compute Distance *Regular Ranging Method*	$T_b =$	$R_p = R_{A_1}$	$T_r = T_{Y_1}$	$R_f = R_{A_2}$	
	$R_b =$	$R_p = T_{A_1}$	$R_r = R_{Y_1}$	$T_f = T_{A_2}$	$R_e = R_{Y_2}$
Rearrange tht Table	$T_b = T_{Y_1}$	$R_p = R_{A_2}$	$T_r =$	$R_f =$	
	$R_b = R_{Y_1}$	$R_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f =$	$R_e =$
A Receive Y3 & Compute Distance *Compensatory Ranging Method*	$T_b = T_{Y_1}$	$R_p = R_{A_2}$	$T_r = T_{Y_2}$	$R_f =$	
	$R_b = R_{Y_1}$	$R_p = T_{A_2}$	$R_r = R_{Y_2}$	$T_f =$	$R_e = R_{Y_3}$

Every incoming packet triggers a new ranging calculation！！！

(2) Design of Ranging Message for Packet Loss

(a) Packet loss on our side： This is equivalent to Inconsistent Ranging Duration



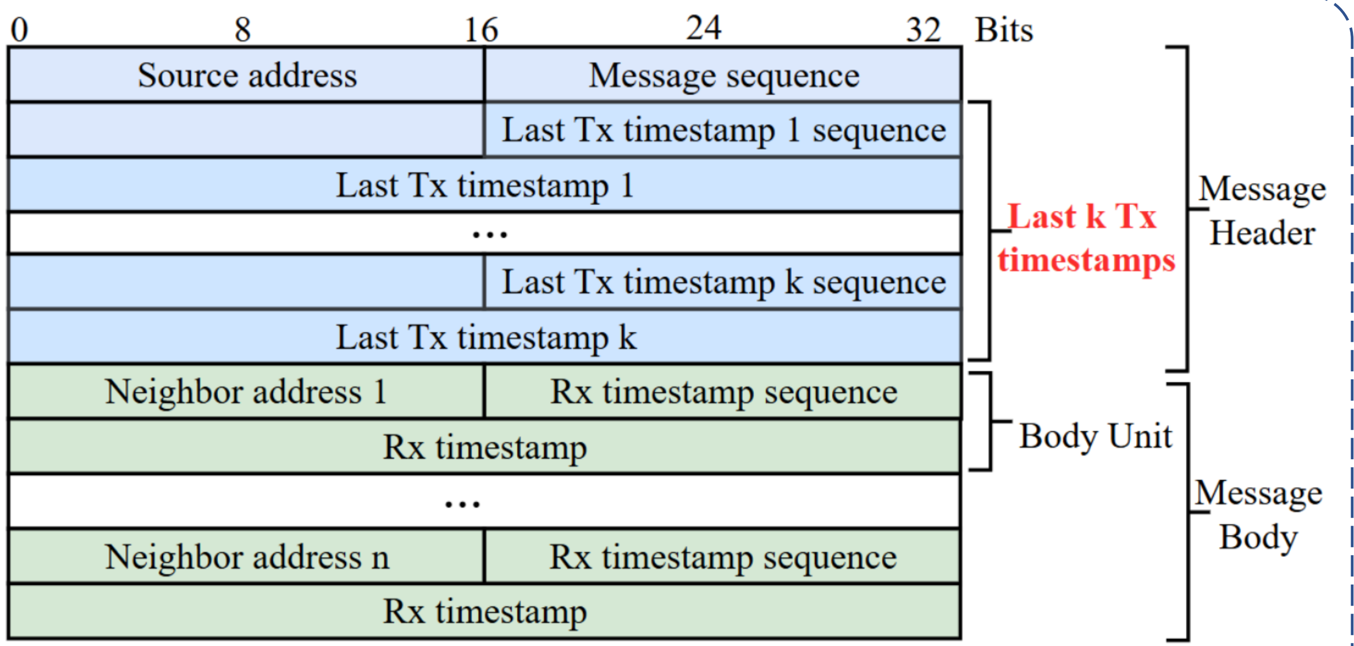
(a) Packet loss on our side

3. Design of Swarm Ranging 2.0 Protocol

(2) Design of Ranging Message for Packet Loss

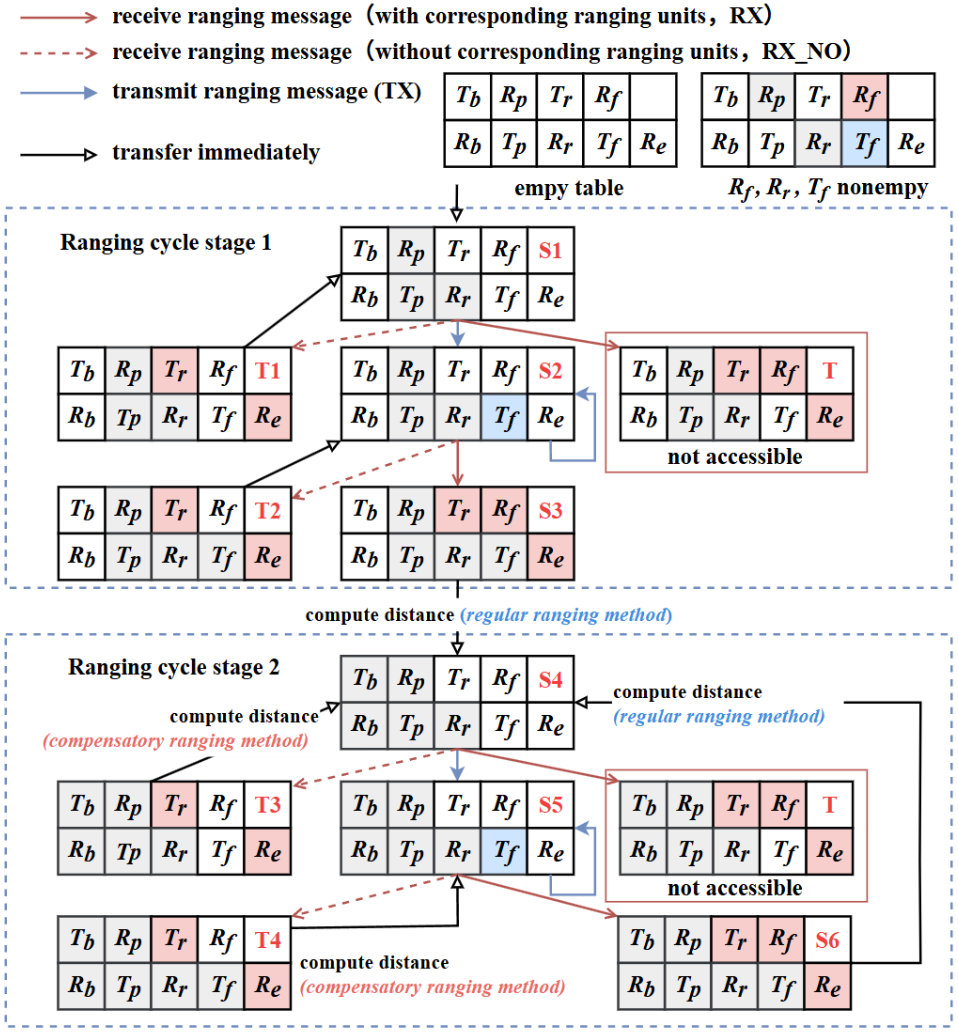
Rule1: The SRv2 protocol incorporates multiple last transmission timestamps in the ranging message.

Rule2: The SRv2 protocol always carries the latest reception timestamp for each neighbor in the ranging message.



The newly designed ranging message ensures that even in cases of **k−1 consecutive packet losses**, the most recent available timestamps **can still be** effectively utilized for **ranging**.

(3) Basic State Machine Model for Efficient Swarm Ranging



- **Cycle Stage 1**: initialize state machine
- **Cycle Stage 2**: complete ranging with latest unused timestamps using ranging table

In Cycle stage2,Every incoming packet triggers a new ranging calculation using the latest and unused timestamp.
That is so cool ! ! !

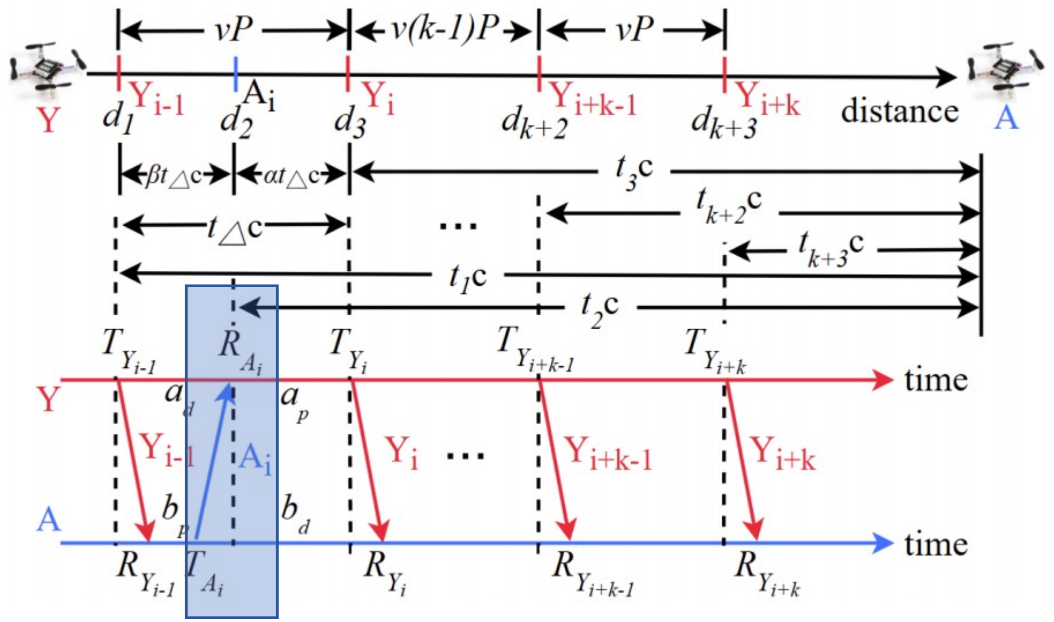
does every calculation actually correspond to a physically updated distance?

What is the theoretical limitation of swarm ranging?

3. Design of Swarm Ranging 2.0 Protocol

(3) Analysis of DS-TWR method ranging limitation

High Dynamic Scenario



A receives consecutive messages from Y,
while Y receives no valid new message from A.

conclusion

$t_{k+3}^{computed} \approx t_2$

independent of k;

it doesnot update to the latest distance d_{k+3}

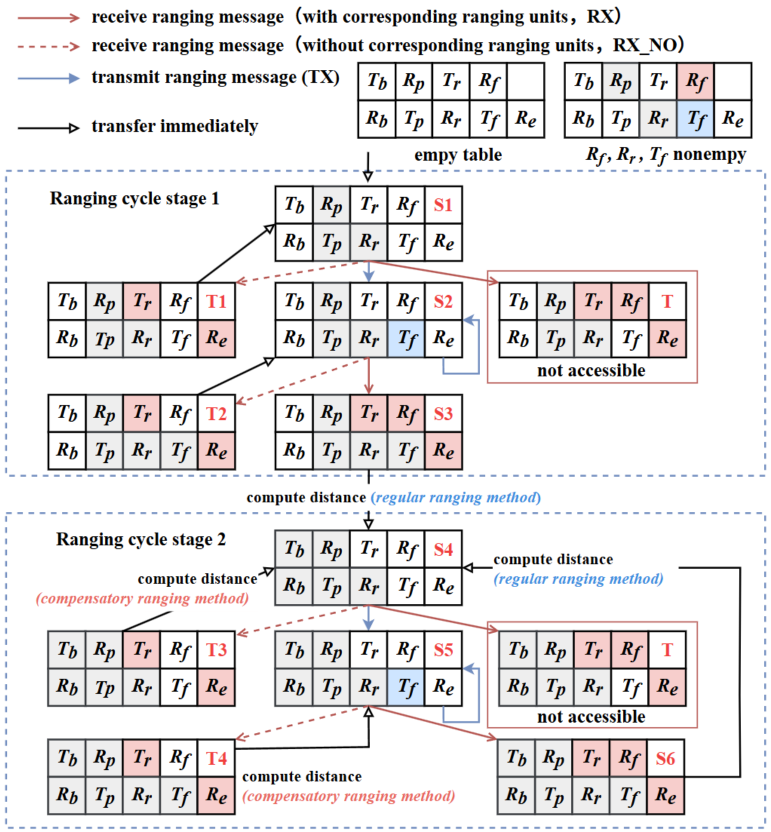
$$t_{k+3}^{computed} = \frac{a_{d_k} \times b_{d_k} - a_{p_k} \times b_{p_k}}{a_{d_k} + b_{d_k} + a_{p_k} + b_{p_k}}$$

$$= t_2 + \frac{t_2 t_\Delta(\beta - \alpha) + (\beta a_p - \alpha b_p)t_\Delta - \alpha\beta t_\Delta^2 + (k-1)t_\Delta(-t_2 + \beta P - b_p - \beta t_\Delta)}{4t_2 + 2a_p + 2b_p + t_\Delta(\beta - \alpha) + (k-1)(2P - t_\Delta)}$$

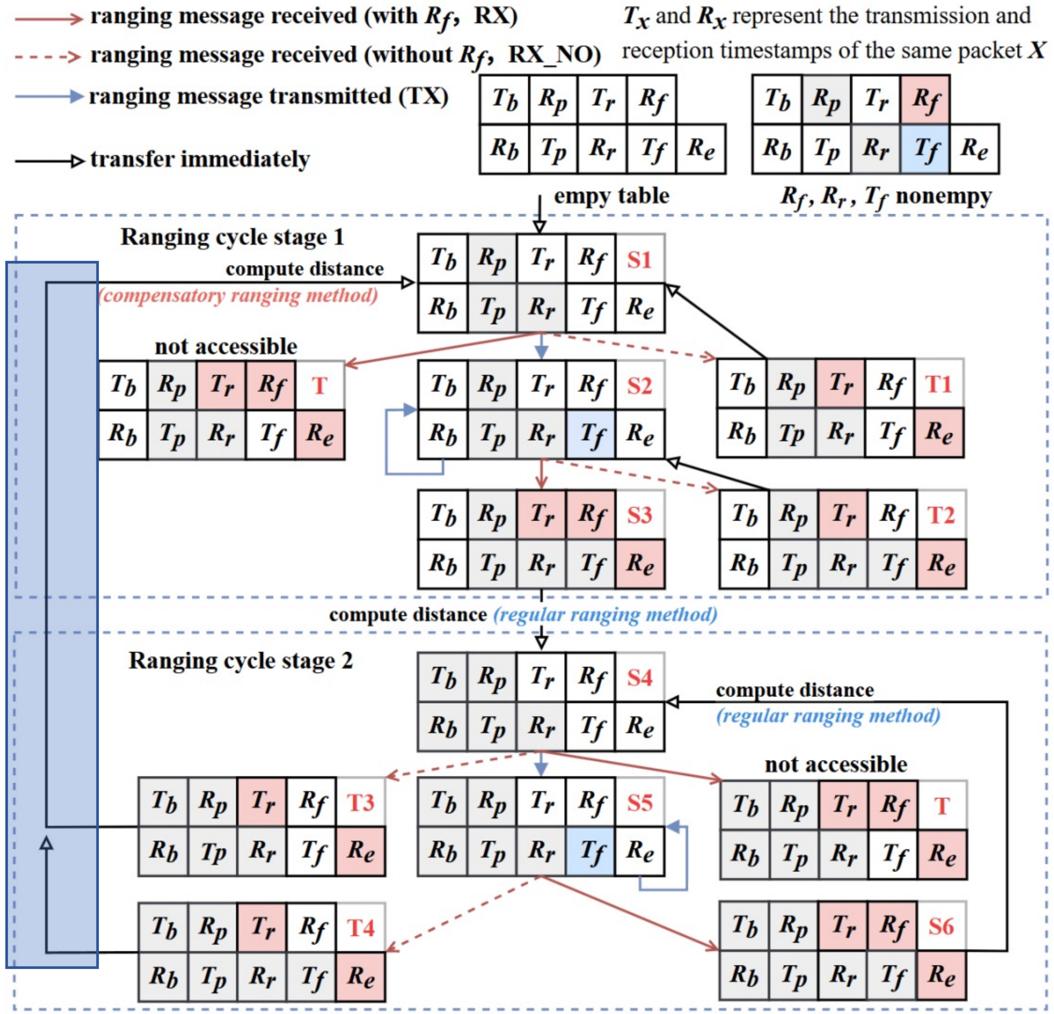
$$= t_2 + \frac{t_2 t_\Delta(\beta - \alpha) + (\beta a_p - \alpha b_p)t_\Delta - \alpha\beta t_\Delta^2 + (k-1)t_\Delta t_2}{4t_2 + 2a_p + 2b_p + t_\Delta(\beta - \alpha) + (k-1)(2P - t_\Delta)} \approx t_2$$

Lemma 1. For an inconsistent ranging duration in which messages are received ($k > 1$), ***only the initial compensatory ranging calculation yields the most recent distance***. Alternatively, any DS-TWR-based method benefits only from the first compensatory ranging calculation.

3. Final State Machine Model for Efficient Swarm Ranging



Return to stage 1

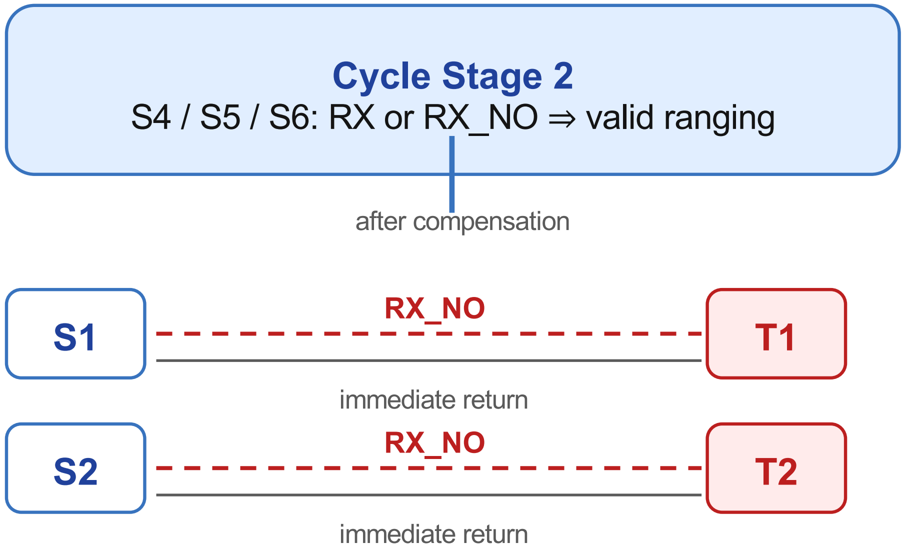


4. SRv2 Protocol Optimality Analysis

Theorem 1: SRv2 maximizes the number of valid distance calculations.

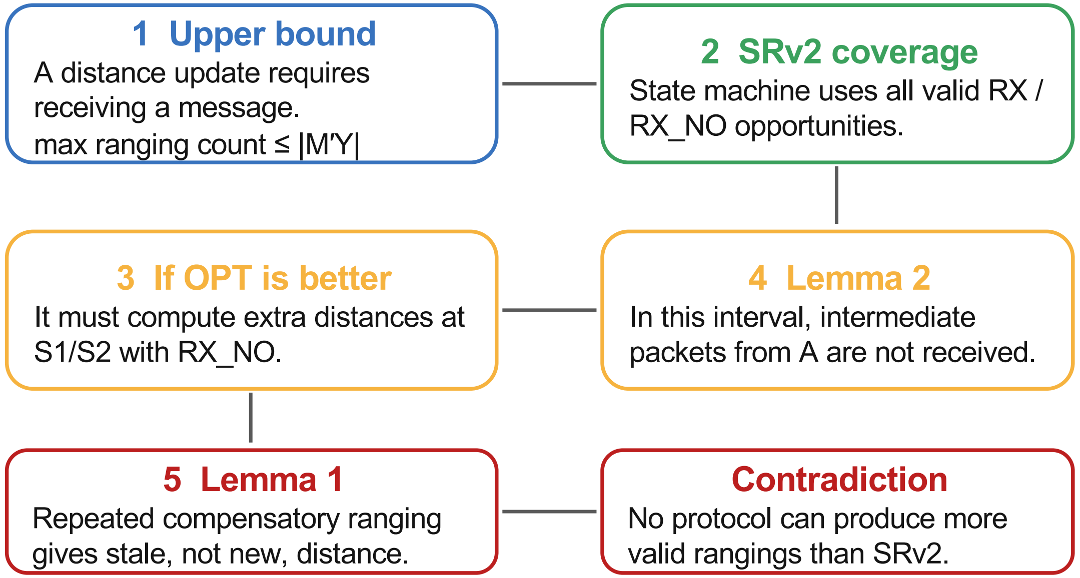
State-machine view

Only possible gap



Meaning: extra ranging can only be claimed at S1/S2 with RX_NO.

Proof chain



SRv2 pushes ths DS-TWR method to its theoretical limit.

Content

Hardware devices

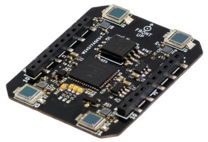
DW3000

HTC Lighthouse

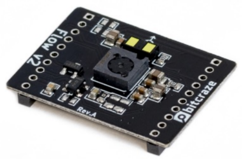
Crazyflie 2.1

Crazyradio PA

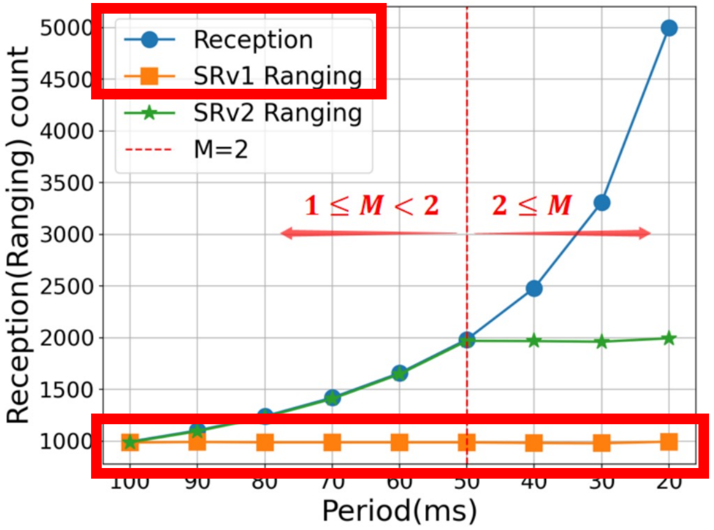
Lighthouse deck



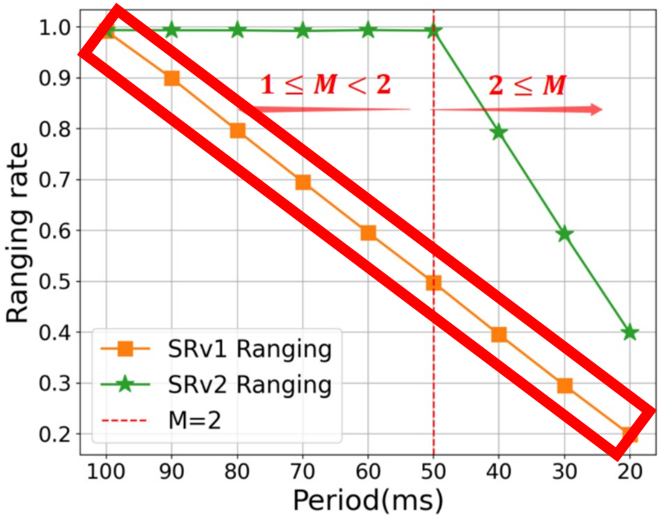
Flow deck



1. Performance for Inconsistent Ranging Duration



(a) Comparison of ranging count



(b) Comparison of ranging rate

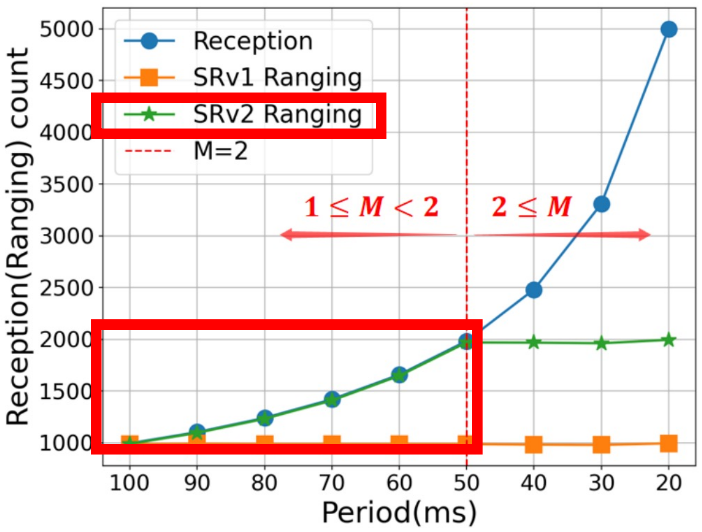
We defined **Inconsistent Frequency Degree M** as

$$M = \frac{P_l}{P_s}$$

where P_l and P_s denote the periods of the long- and short-period messages, respectively.

Clearly, $M \geq 1$.

1. Performance for Inconsistent Ranging Duration



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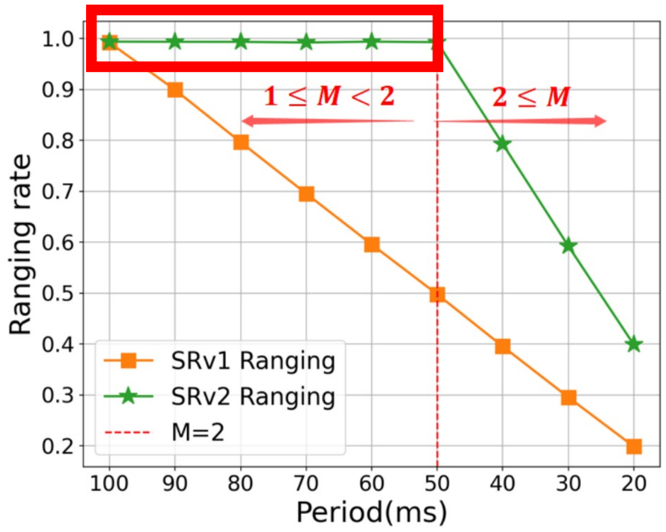

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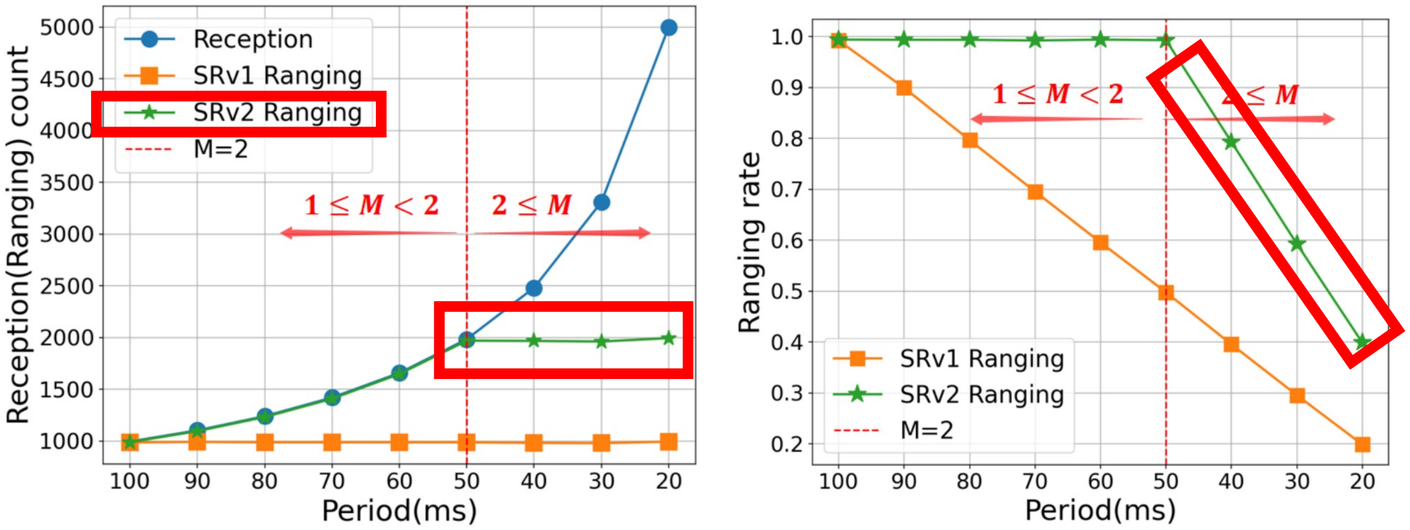
Conclusion:

- when $M \leq 2$, high-frequency ranging messages can be fully utilized, maximizing the number of ranging and ***reaching the theoretical limit of DS-TWR method***.
- When M > 2 , further increasing transmission frequency no longer improves ranging count.(due to lemma1)

1. Performance for Inconsistent Ranging Duration



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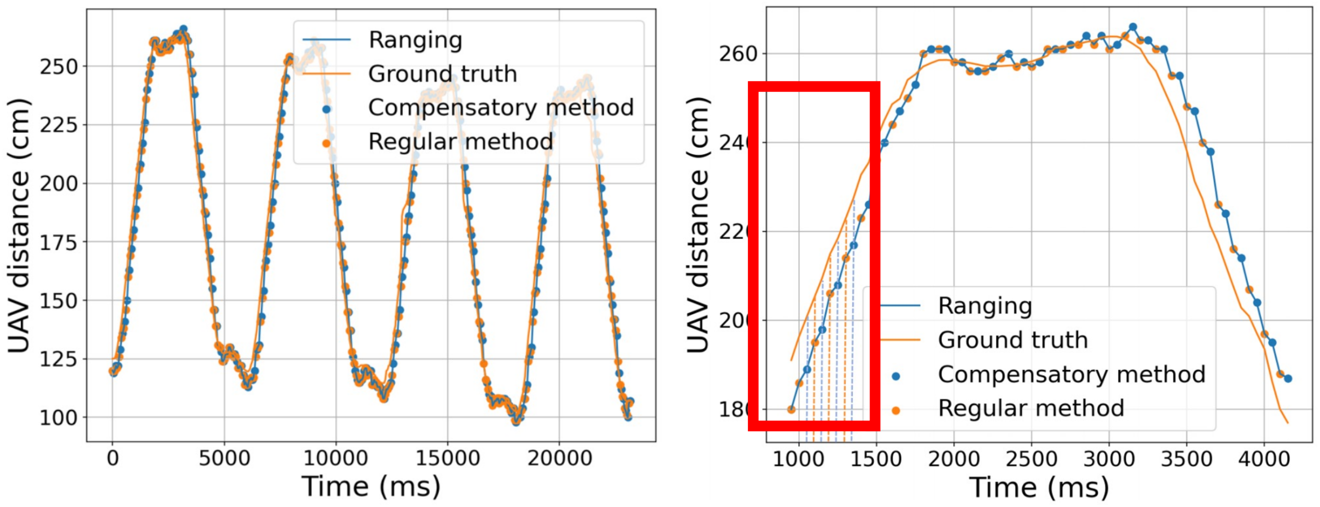
5. Experimental Results and Evaluation

2. Accuracy of Ranging in Dynamic Scenarios



(a) Four cycles of move-away and move-close motion

(b) Zoomed-in view of a segment from (a).

	Regular Method		Compensatory Method	
	Mean(cm)	Standard Deviation	Mean(cm)	Standard Deviation
Move away	8.34	2.57	9.23	3.15
Move close	-6.72	3.07	-9.25	3.41

Experiment Settings

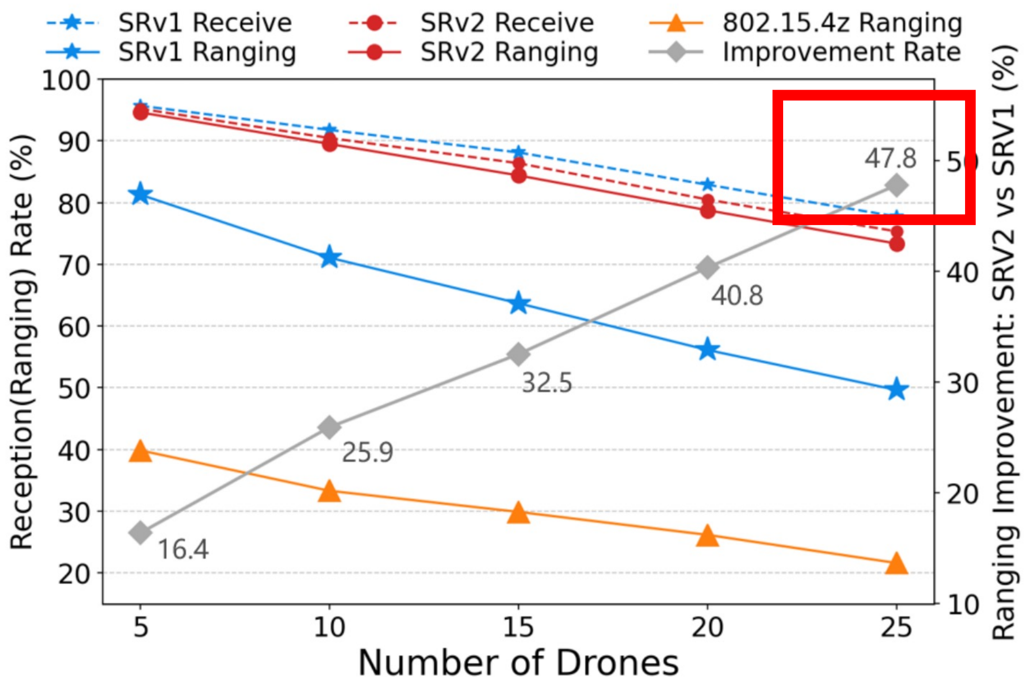
- Drone A hovers steadily, while drone B flies at a speed of 1 m/s, repeatedly moving close and away over multiple cycles.
- Transmission period was 100 ms for A and 50 ms for B, resulting in ***one compensatory ranging performed between every two regular ranging.***

- ***Conclusion: the proposed protocol can increase the overall ranging frequency by combining regular and compensatory ranging methods.***

3. Comparison with SRv1 and IEEE 802.15.4z in dense swarms

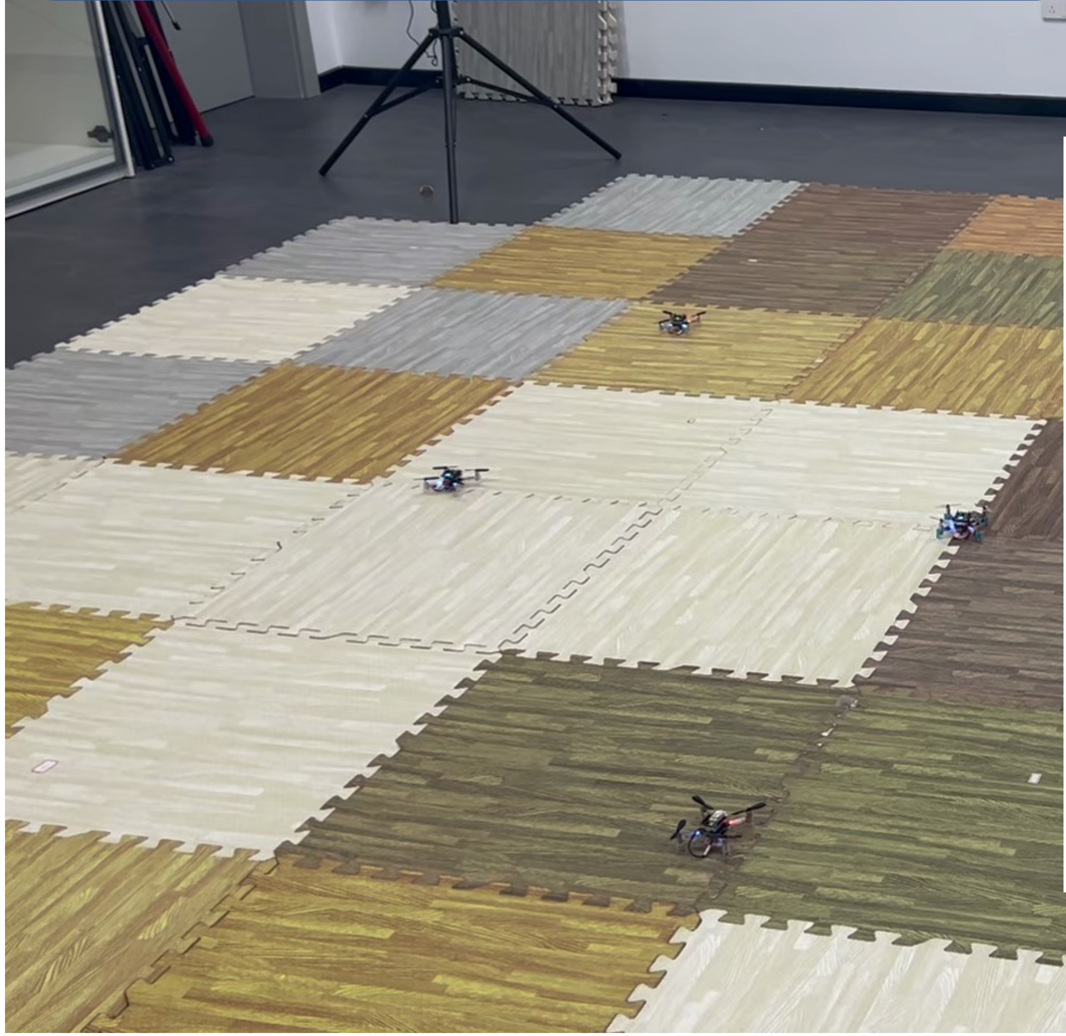
Experiment settings
- **ranging periods**: 40+rand()%40
- **k**: each message carries 4 last transmission timestamps.

- **SRv2 exhibits a slightly lower reception rate** than SRv1 as the number of drones increases. This is primarily due to the additional processing overhead introduced by the extra k timestamp information carried in SRv2 ranging message.
- **SRv2's *ranging rate* improves significantly, with *the gain becoming more pronounced as the swarm size grows.***



with 25 drones, SRv2 achieves a ***47.8% increase*** in ranging rate over SRv1, and ***300%+ improvement*** over standard protocol

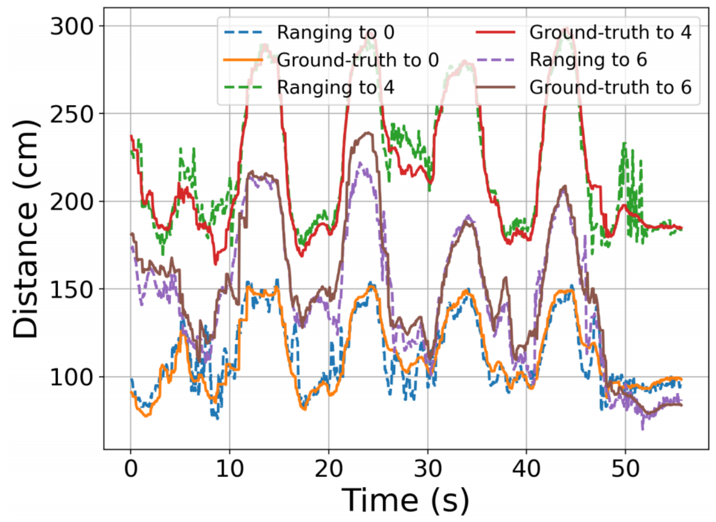
4. Demonstration experiment



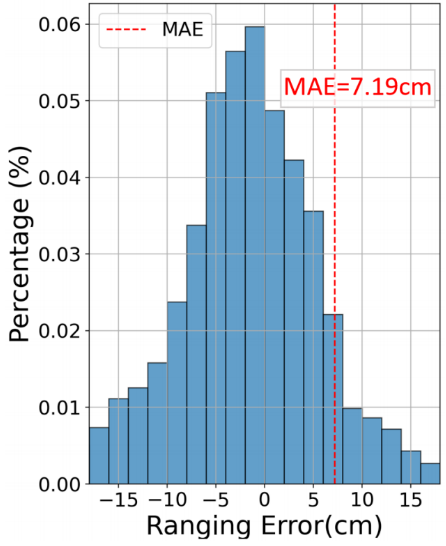
Real-world validation

- 8 drones, 2 m × 2 m area
- Random periods: 40–80 ms
- Drone 1 → three neighbors

MAE = 7.19 cm （Qofficial Qorvo 10cm）



(a) Ranging vs. Ground Truth over Time: drones random flight for the first 10s, formation flight from 10s to 50s, and landing afterward



(b) Frequency distribution of ranging error relative to ground truth, along with the mean absolute error (MAE).

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Thank you for your attention!

Q&A session