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SOUTHEAST UNIVERSITY

Ultra-Wideband Swarm Ranging

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Outline

- Introduction
- Preliminary
- Swarm Ranging Protocol
- Experiment
- Conclusion

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- **Introduction**
- Preliminary
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Swarm of robots and devices

- Aerial/ground robots, wearable/portable devices are becoming smaller, lighter, cheaper, and popular.

Crazyflie 2.1

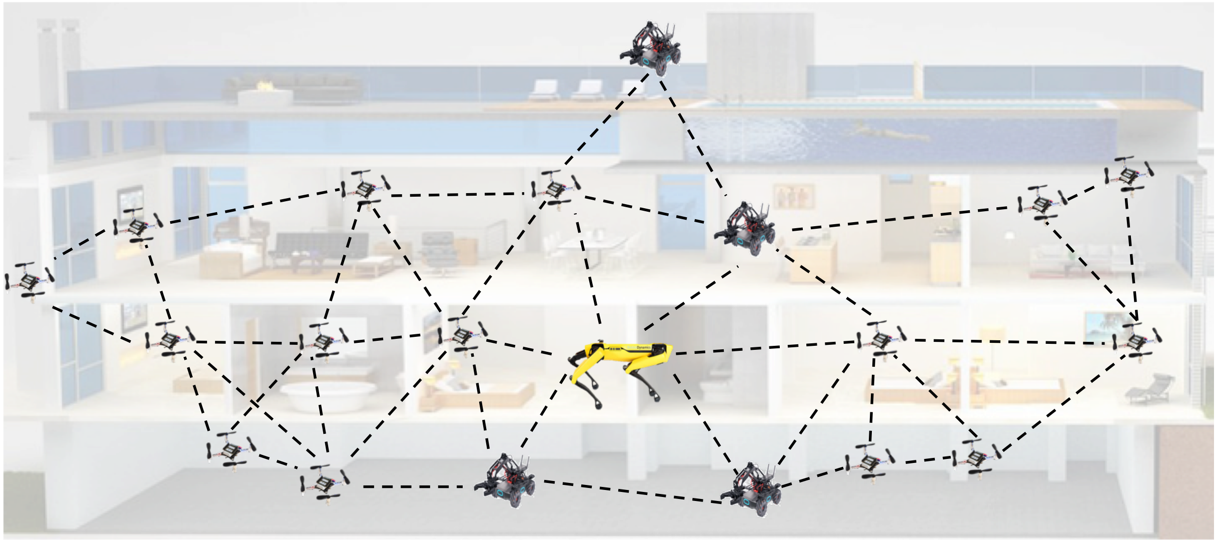
RoboMaster EP

SPOT

- Tens and thousands of them are to form a swarm to complete complicated cooperative tasks.
  - A team of indoor drones search for given targets
  - A swarm of small robots explore and map unknown indoor environments
  - An army of legged robot dogs battle in a deep forest

Dynamic and dense swarm features

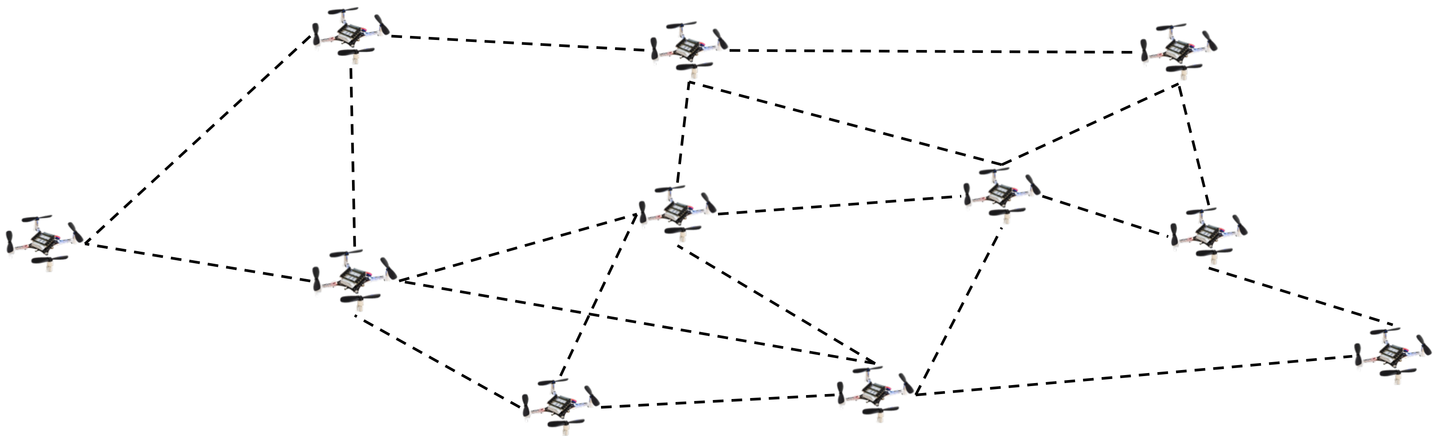
- Dynamic and dense swarm
  - *large number*
  - *high mobility*
  - *short distance.*



- When no outside supportive infrastructures, critical to
  - Real-time internal distance ranging for localization
  - Low latency ad hoc networking and communication

Ultra-wideband swarm ranging protocol

- Ultra-wideband (UWB) wireless technology support simultaneously ranging and communication.
- **Our target** is to design a UWB ranging protocol for a **dynamic and dense** swarm of robots and devices.



Challenges to design such a ranging protocol

- Design a ***simple yet efficient*** protocol
  - A large number share the same UWB channel.
  - Inappropriate cause conflicting and high computation cost.
- Design a ***adaptive and robust*** protocol
  - High mobility requires high frequency ranging.
  - Ranging frequency should be reduced whenever necessary.
  - Also cause wireless channel unstable and packet lose.
- Design a ***scalable and compatible*** protocol
  - Message has limitation space for dense neighbor.
  - Support existing networking and localization protocols.

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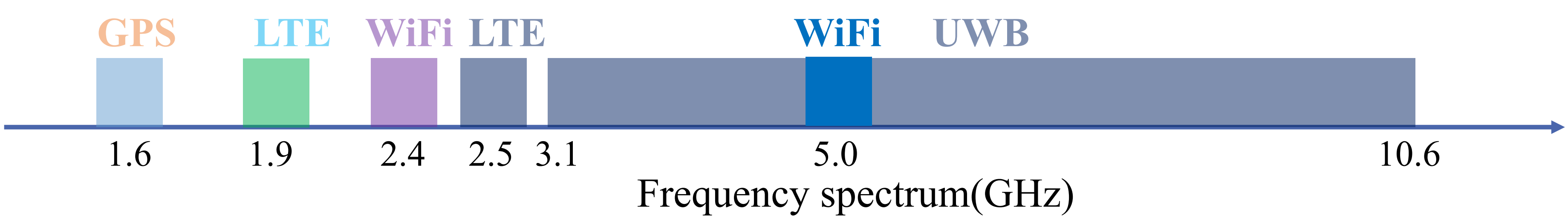
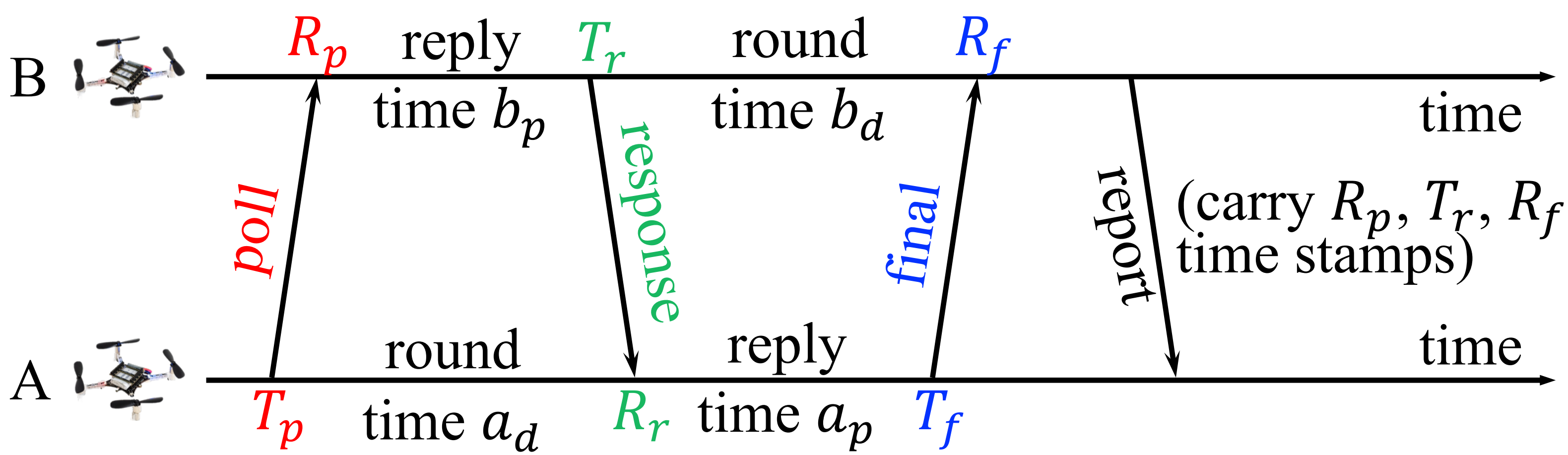
Ultra-Wide Band (UWB) technology

- 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



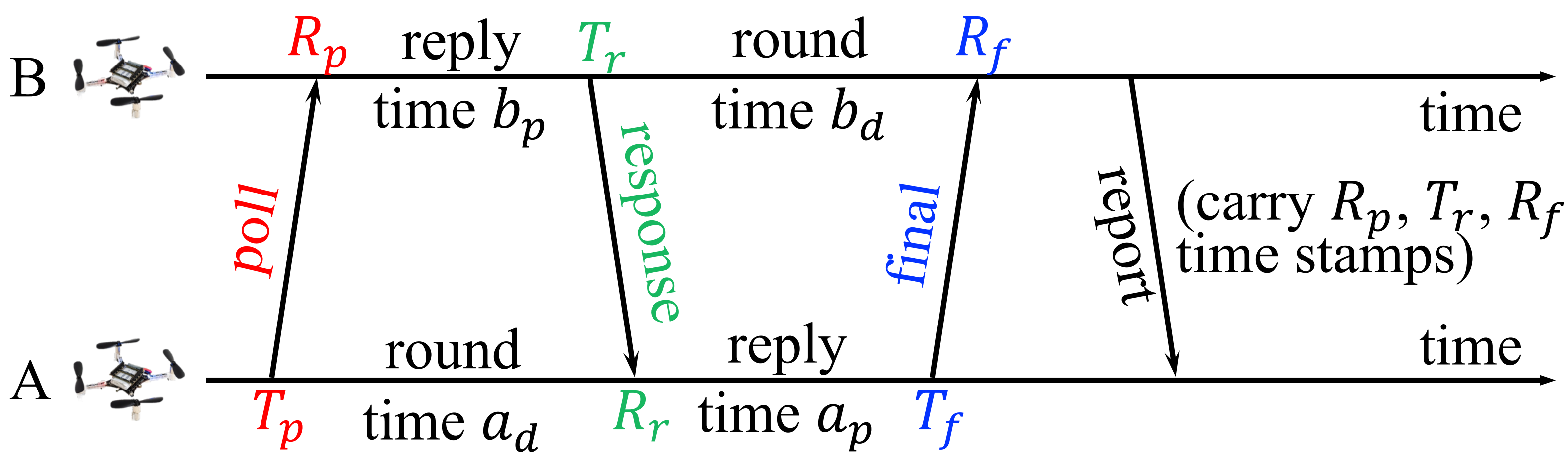
Double-sided two-way ranging (DS-TWR)

- Double-sided two-way ranging (DS-TWR)
  - An existing ranging protocol from IEEE Standard 802.15.4-2011 is later improved by industry giant Decawave.
- Distance calculated after exchanging four messages
  - ***poll*, *response*, *final*, and *report* messages.**



Double-sided two-way ranging (DS-TWR)

- Recorded timestamps : $T_p,\ R_p,\ T_r,\ R_r,\ T_f,\ R_f$
- Calculate the round and reply time:
  $a_d = R_r - T_p, b_p = T_r - R_p, b_d = R_f - T_r, a_p = T_f - R_r$
- Time of flight: $t_p = \frac{a_d b_d - a_p b_p}{a_d + b_d + a_p + b_p}$

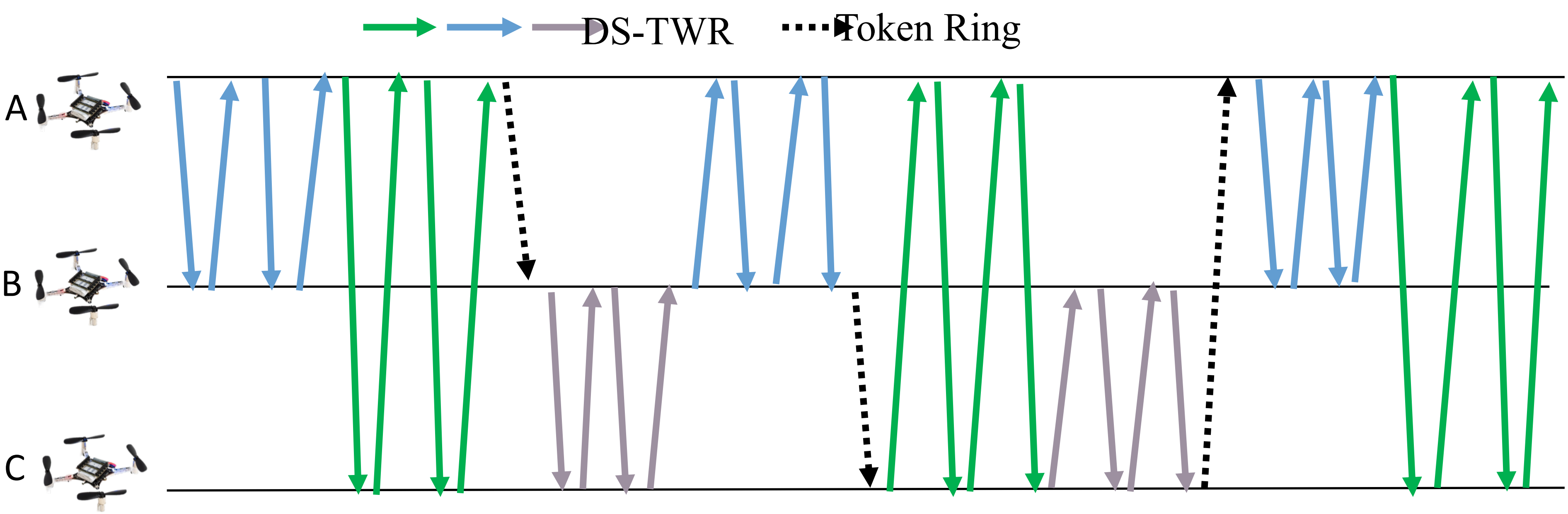


- Conclusion: ranging if has

B side	R_p	T_r	R_f	
A side	T_p	R_r	T_f	R_e

Simple extension of standard protocol

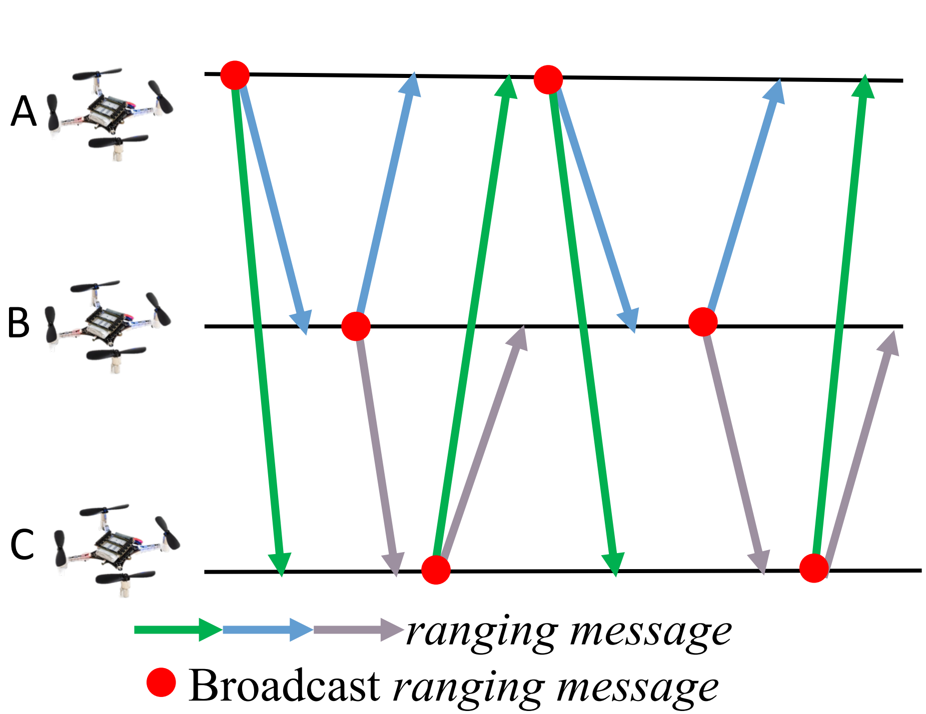
- Use the token ring method to control the ranging process.
- Token owner initializes ranging process with all its neighbors, one by one. Then, pass the token to the next in the ring.

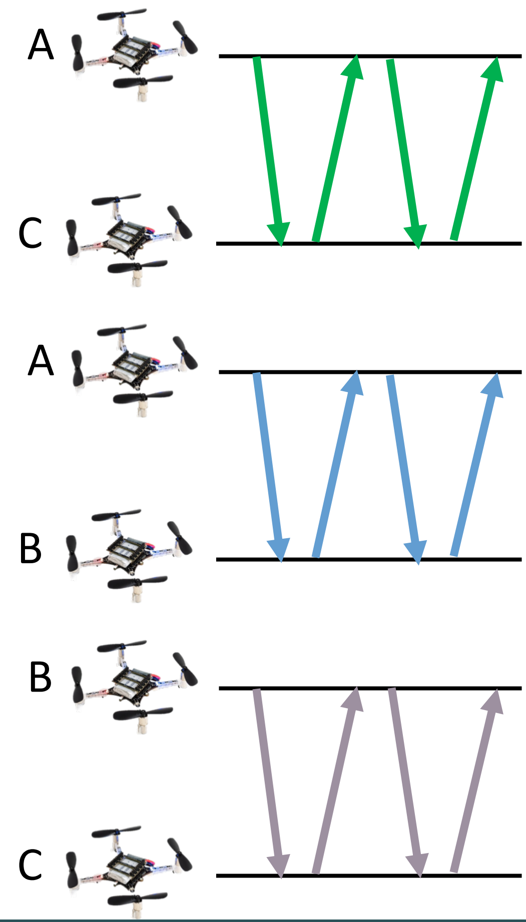


- Inefficient: messages heard by all neighbors, but are mostly ignored.

The basic idea of swarm ranging

- Define one single message named *ranging message*
- Each side periodically broadcasts the *ranging message*





The basic idea of swarm ranging

- To deal with the challenges of the **dynamic and dense** swarm, the following questions must be answered.
  - **Q1**: How to **design the ranging message** so that sufficient timestamps are carried?
  - **Q2**: Does the enlarged transmit period affect accuracy?
  - **Q3**: How does **high mobility** affect the ranging accuracy?
  - **Q4**: **How often** should the ranging message be broadcasted?
  - **Q5**: What if **message lost or ranging frequency mismatched**?
  - **Q6**: How to handle **dense neighbors**?
  - **Q7**: Does the swarm ranging protocol supports or compatible with other **higher level protocols**?

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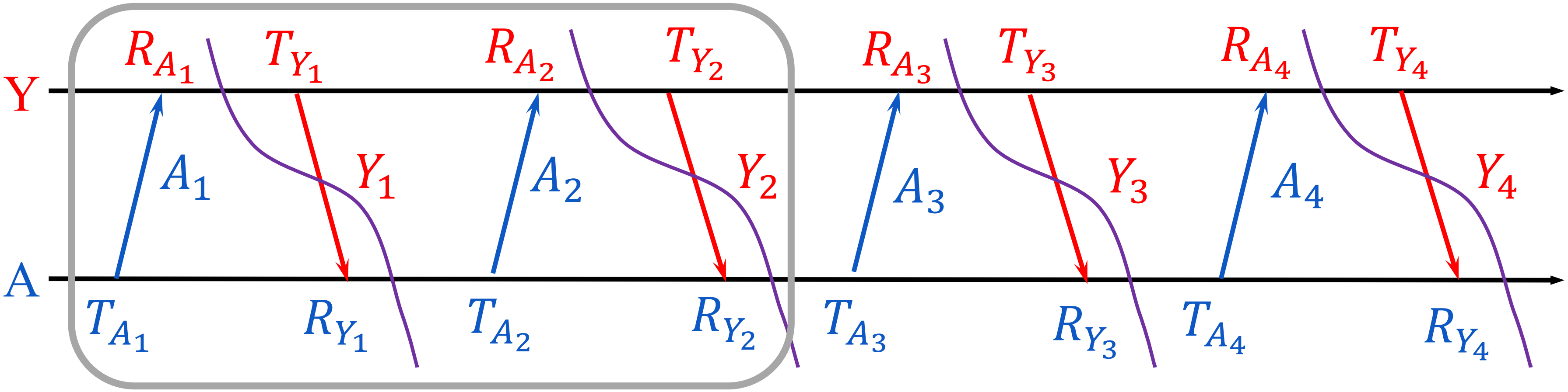
Ranging message and ranging table

- Each ranging message includes
  - The last transmit timestamp
  - All receive timestamps since last transmit



- Ranging table keeps only few timestamps

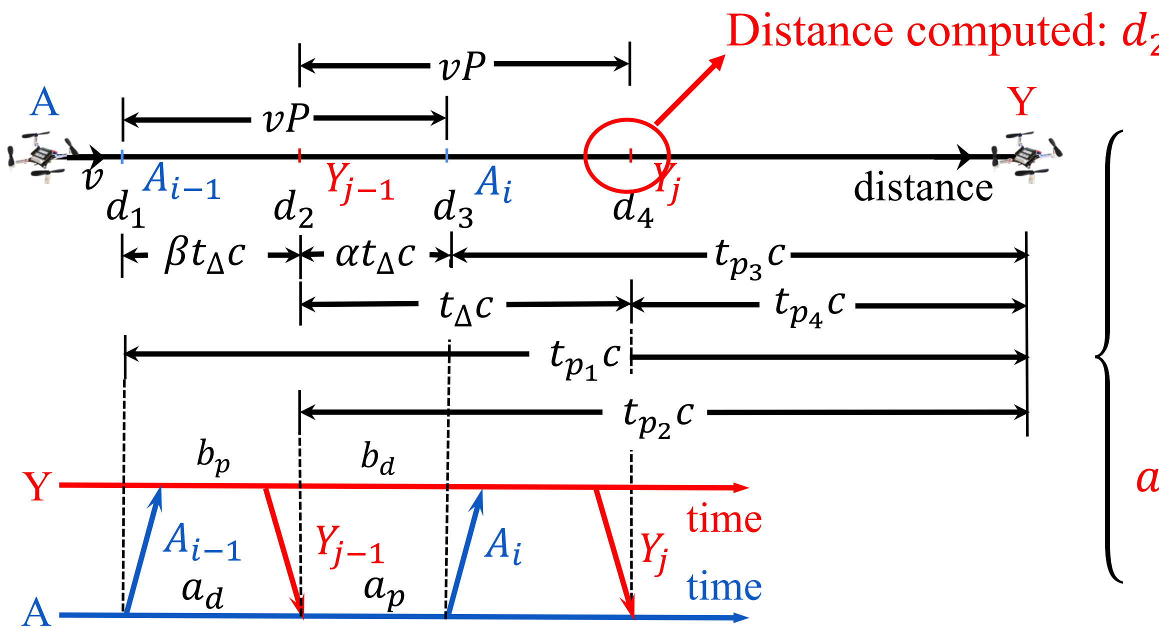
Y side	$\boldsymbol{R_p} = R_{A_{i-1}}$	$\boldsymbol{T_r} = T_{Y_{j-1}}$	$\boldsymbol{R_f} = R_{A_i}$	
A side	$\boldsymbol{T_p} = T_{A_{i-1}}$	$\boldsymbol{R_r} = R_{Y_{j-1}}$	$\boldsymbol{T_f} = T_{A_i}$	$\boldsymbol{R_e} = R_{Y_j}$

Ranging message and ranging table

- Each ranging message includes
  - The last transmit timestamp
  - All receive timestamps since last transmit
- Ranging table keeps only few timestamps

Q1 (*ranging message* design) is answered

How mobility affect ranging accuracy



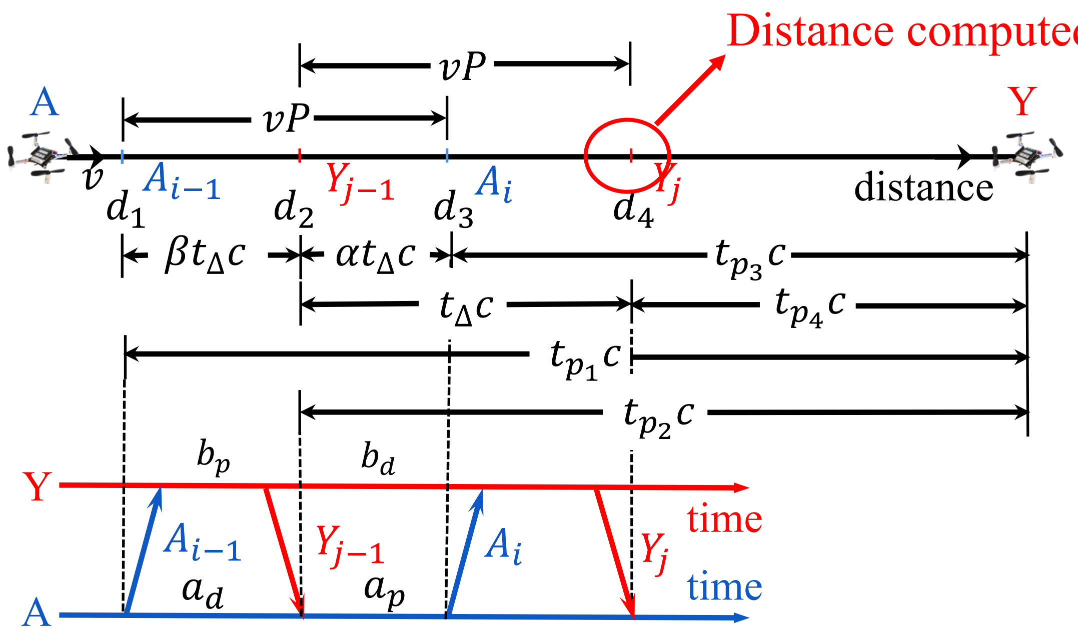
$$
\begin{cases}
t_{p_1} = t_{p_2} + \beta t_\Delta \\
t_{p_3} = t_{p_2} - \alpha t_\Delta \\
t_{p_4} = t_{p_2} - t_\Delta \\
a_d = b_p + 2t_{p_2} + \beta t_\Delta \\
b_d = a_p + 2t_{p_2} - \alpha t_\Delta \\
a_d \approx b_p, \because t_\Delta, t_{p_2} \ll a_d, b_p \\
b_p : a_p \approx \beta : \alpha
\end{cases}
$$

$$
ToF = t_p^{computed} = \frac{a_d b_d - a_p b_p}{a_d + b_d + a_p + b_p} = t_{p_2} + \frac{t_{p_2} t_\Delta(\beta - \alpha) - \alpha\beta t_\Delta^2}{4t_{p_2} + 2a_p + 2b_p + t_\Delta(\beta - \alpha)} \approx t_{p_2}
$$

$$
\begin{aligned}
&\boldsymbol{a_d b_d - a_p b_p} \\
&= 4t_{p_2}^2 + 2a_p t_{p_2} + 2b_p t_{p_2} + 2t_{p_2} t_\Delta(\beta - \alpha) - \alpha\beta t_\Delta^2 - \beta a_p t_\Delta + \alpha\, b_p t_\Delta \\
&\approx 4t_{p_2}^2 + 2a_p t_{p_2} + 2b_p t_{p_2} - \alpha\beta t_\Delta^2
\end{aligned}
$$

$$
\boldsymbol{a_d + b_d + a_p + b_p} = 4t_{p_2} + 2a_p + 2b_p + t_\Delta(\beta - \alpha)
$$

How mobility affect ranging accuracy



$$
\begin{cases}
t_{p_1} = t_{p_2} + \beta t_\Delta \\
t_{p_3} = t_{p_2} - \alpha t_\Delta \\
t_{p_4} = t_{p_2} - t_\Delta \\
a_d = b_p + 2t_{p_2} + \beta t_\Delta \\
b_d = a_p + 2t_{p_2} - \alpha t_\Delta \\
a_d \approx b_p, \because t_\Delta, t_{p_2} \ll a_d, b_p \\
b_p : a_p \approx \beta : \alpha
\end{cases}
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$$
ToF = t_p^{computed} = \frac{a_d b_d - a_p b_p}{a_d + b_d + a_p + b_p} = t_{p_2} + \frac{t_{p_2} t_\Delta (\beta - \alpha) - \alpha\beta t_\Delta^2}{4t_{p_2} + 2a_p + 2b_p + t_\Delta(\beta - \alpha)} \approx t_{p_2}
$$

Q3 (mobility affects accuracy) is answered

Design of adaptive ranging protocol

- $t_p^{computed} = \frac{a_d b_d - a_p b_p}{a_d + b_d + a_p + b_p} \approx t_{p_2}$
- Calculation occurs at receiving Y_j, the actual ToF:

$$t_p^{actual} = t_{p_4} = t_{p_2} - t_\Delta = t_p^{computed} - \frac{vP}{c}$$

- Bound the error:

$$\frac{\left|t_p^{actual} - t_p^{computed}\right|}{t_p^{actual}} \le e_0$$

- Then:

$$\frac{t_\Delta}{t_{p_2}} \le \frac{e_0}{1 - e_0}$$

- Consider $t_\Delta c = vP$, Finally:

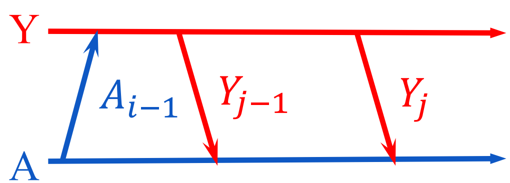
$$\boldsymbol{P \le \frac{e_0}{1 - e_0} \frac{d_2}{v}}$$

- As a conclusion
  - When two sides are close, use short ranging period;
  - When two sides move fast, use short ranging period.

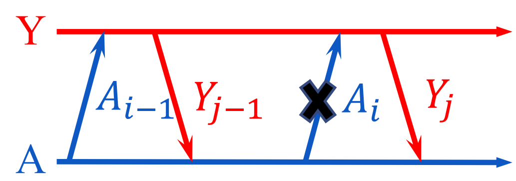
Q4 (broadcast frequency) is answered

Packet loss and ranging period mismatch

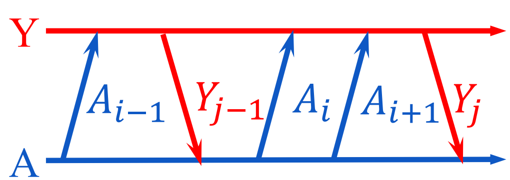
- We summary four cases.
  - Case 1, A side receives more than it transmits.
  - Case 2, one message from A side is lost.
  - Case 3, A side transmits more than it receives.
  - Case 4, one message from Y side is lost.



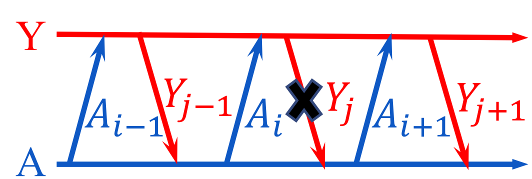
Case 1



Case 2



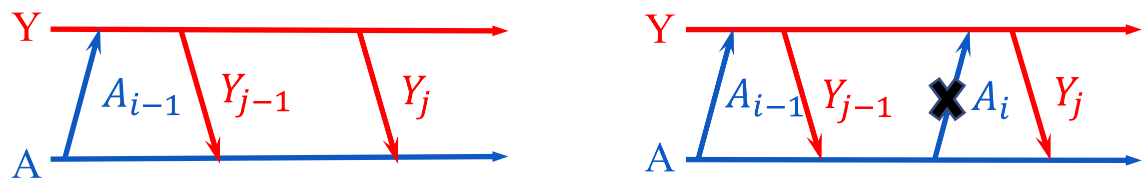
Case 3



Case 4

Handle mismatch and loss

- Handle Case 1 and Case 2



Case 1

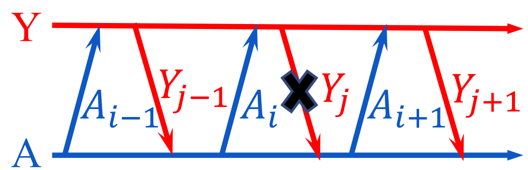
Case 2

Y side	$R_p = R_{A_{i-1}}$	$T_r = T_{Y_{j-1}}$	$R_f =$	
A side	$T_p = T_{A_{i-1}}$	$R_r = R_{Y_{j-1}}$	$T_f = T_{A_i}$ or $T_f =$	$R_e = R_{Y_j}$

Y side	$R_p = R_{A_{i-1}}$	$T_r =$	$R_f =$	
A side	$T_p = T_{A_{i-1}}$	$R_r = R_{Y_j}$	$T_f =$	$R_e =$

Handle mismatch and loss

- Handle Case 4



Case 4

Y side	$R_p = R_{A_{i-1}}$	$T_r = T_{Y_j}$	$R_f = R_{A_{i+1}}$	
A side	$T_p = T_{A_{i-1}}$	$R_r = R_{Y_{j-1}}$	$T_f = T_{A_{i+1}}$	$R_e = R_{Y_{j+1}}$

Y side	$R_p = R_{A_{i+1}}$	$T_r =$	$R_f =$	
A side	$T_p = T_{A_{i+1}}$	$R_r = R_{Y_{j+1}}$	$T_f =$	$R_e =$

Q5 (packet loss and mismatched frequency) is answered

Handle dense neighbors

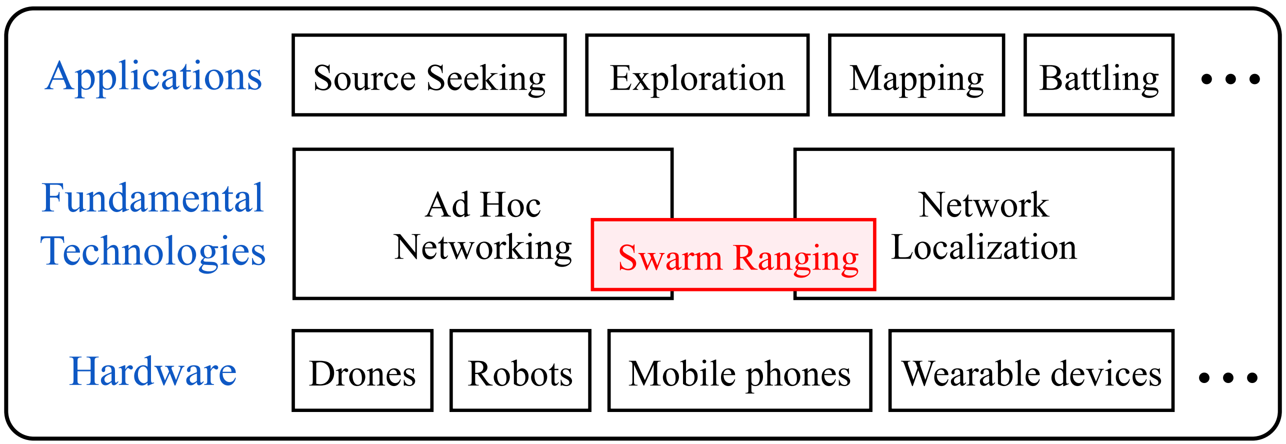
- When the neighbors are dense, ranging message capacity will not be enough to carry all timestamps for every neighbor.
- Our solution:
  - **Allow** neighbors to have different ranging periods.
  - **Carry** neighbors' information only when necessary.
  - **Expire** neighbors' information after a certain time.
- Upgrade the ranging table by adding new elements
  - $\boldsymbol{P}$: the newest ranging period for A and Y
  - $\boldsymbol{t_n}$: the next (expected) delivery time for neighbor Y
  - $\boldsymbol{t_s}$: the expiration time for neighbor Y

Y side	$\boldsymbol{R_p}$	$\boldsymbol{T_r}$	$\boldsymbol{R_f}$	$\boldsymbol{P}$	$\boldsymbol{t_n}$
A side	$\boldsymbol{T_p}$	$\boldsymbol{R_r}$	$\boldsymbol{T_f}$	$\boldsymbol{R_e}$	$\boldsymbol{t_s}$

Q6 (dense neighbor) is answered

Support higher level protocols/algorithms

- **Maintains neighbor list** for higher level protocol, e. g., OLSR.
- Support for localization by **providing the fundamental distance information**



Q7 (support higher level protocols) is answered

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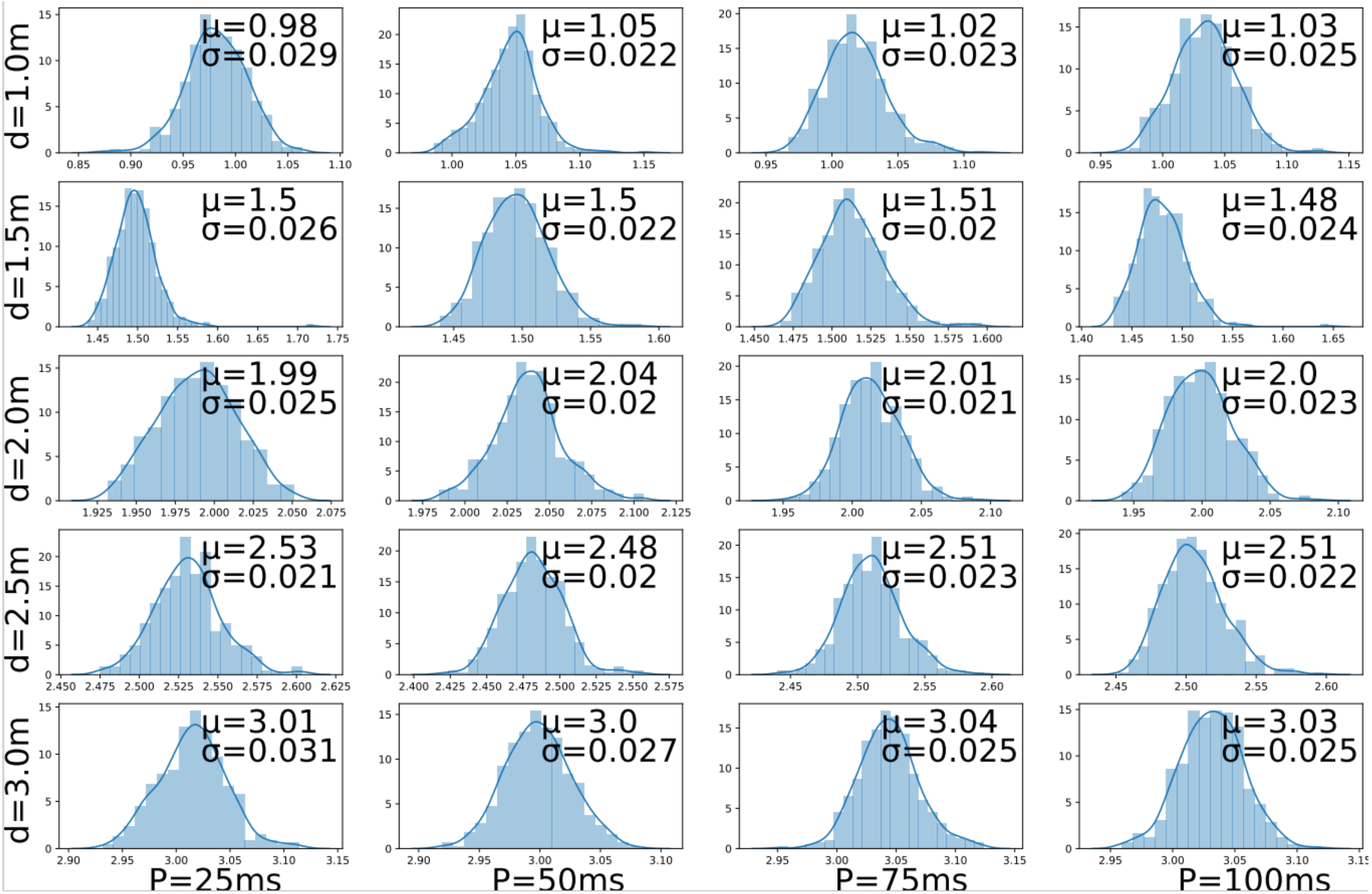
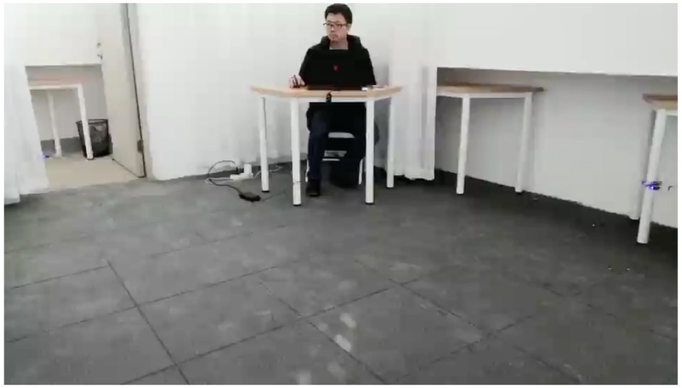
Ranging period and accuracy

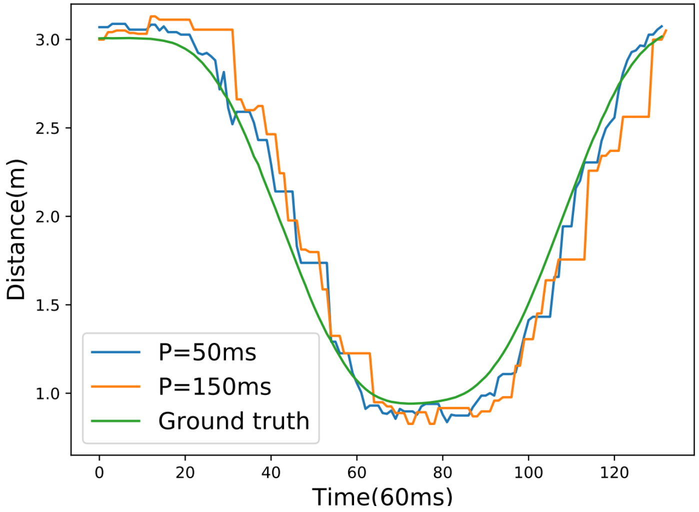
- The impact of ranging period on ranging accuracy



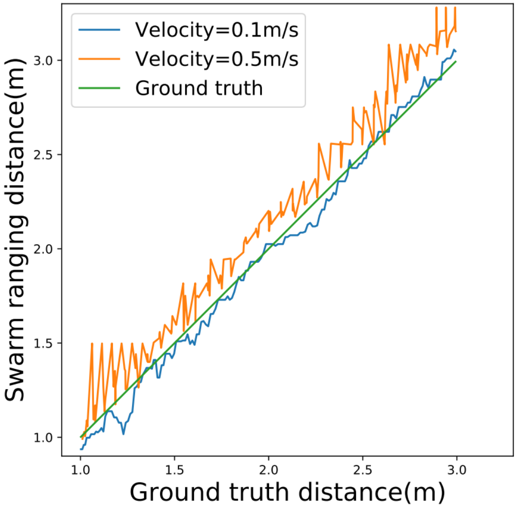
Velocity, ranging period and accuracy

- The ranging results are delayed compare to the ground truth.
- The larger P, the bigger delay.
- Velocity also affects the delay .

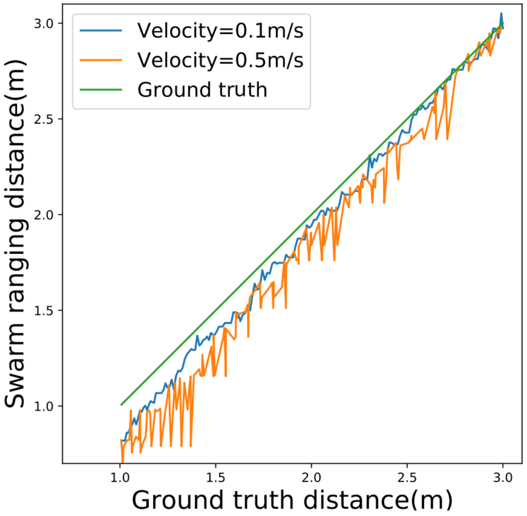




Impact of ranging period



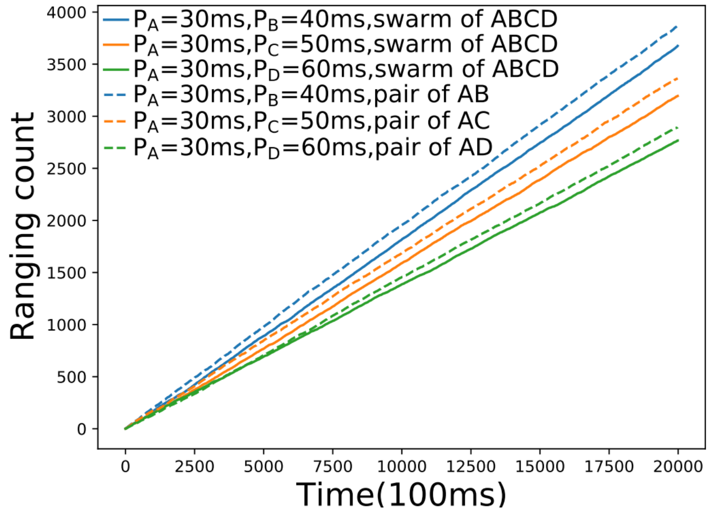
moving towards

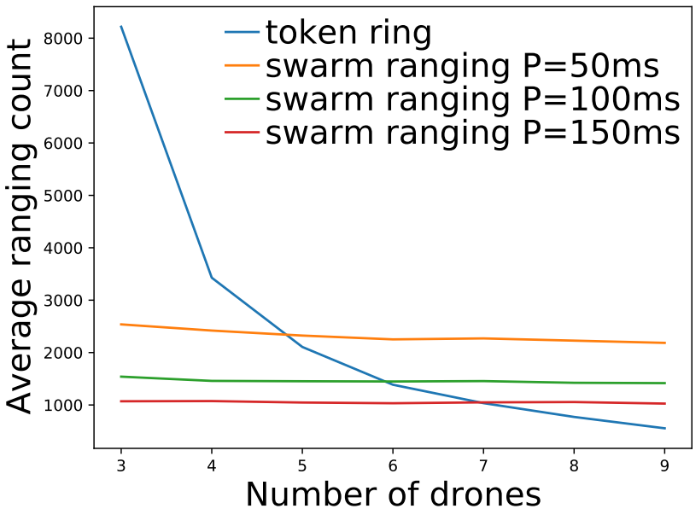


moving away

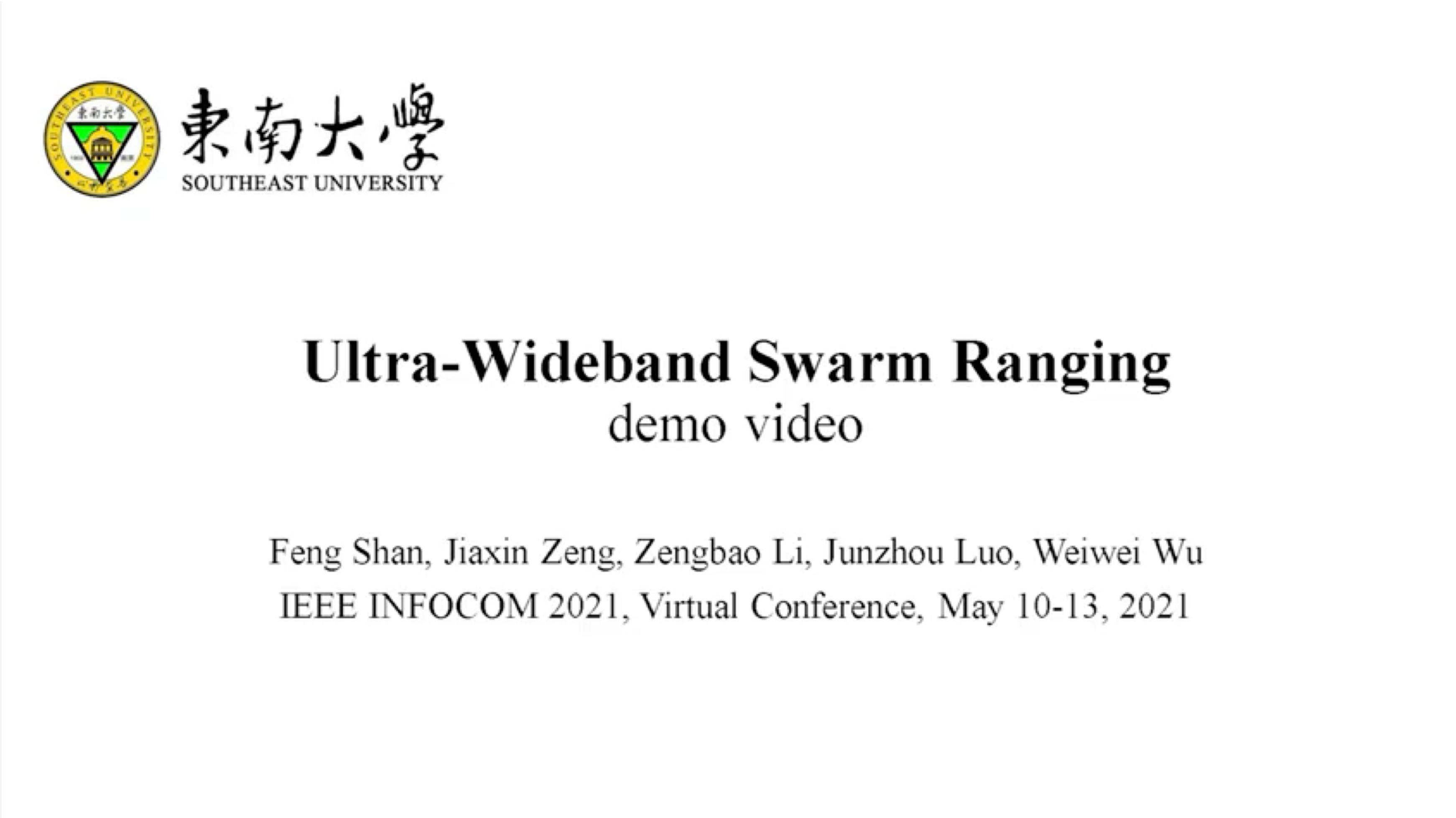
Protocol performance

- Performance for mismatched ranging period
- Comparison with ranging based on token ring.





Demo Video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Ultra-Wideband Swarm Ranging
demo video
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Conclusion

1. This paper proposes a UWB swarm ranging protocol, designed specially for **dynamic and dense** swarm.
2. It is ***simple yet efficient***. All messages are unified in one, i.e., *ranging message,* which is broadcasted periodically.
3. It is ***adaptive and robust***. The ranging period adapts to the ranging pair's speed and distance. Packet loss is handled appropriately.
4. It is ***scalable and compatible***. A rotation scheme is designed to handle dense neighbors. Higher level networking and localization protocols and algorithms are supported.
5. Physical experiment is conducted. The protocol is implemented on Crazyflie drones, that are powered by STM32 microcontrollers and have only 192KB memory.

Thank You!

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