Push the Limit of Highly Accurate Ranging on Commercial UWB Devices

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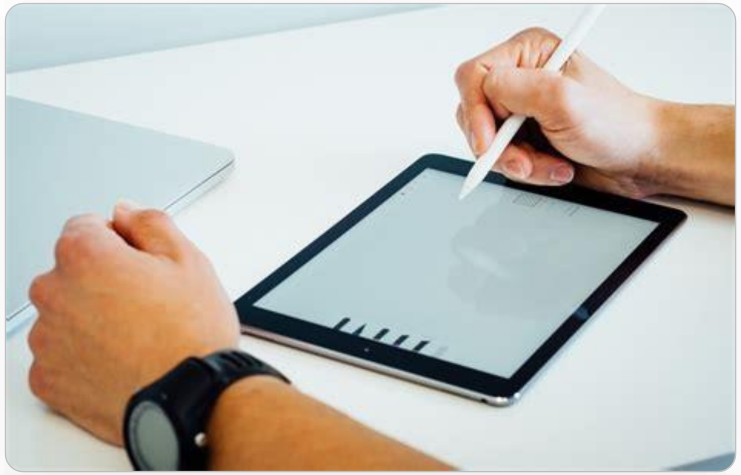
Background

Ranging plays a crucial role in many sensing applications

- Indoor localization
- In-air handwriting recognition
- Device tracking in virtual reality (VR)

Indoor localization



In-air handwriting

Device tracking in VR

Limitations of existing techniques

Existing methods cannot achieve robust and fine-grained ranging

Wi-Fi

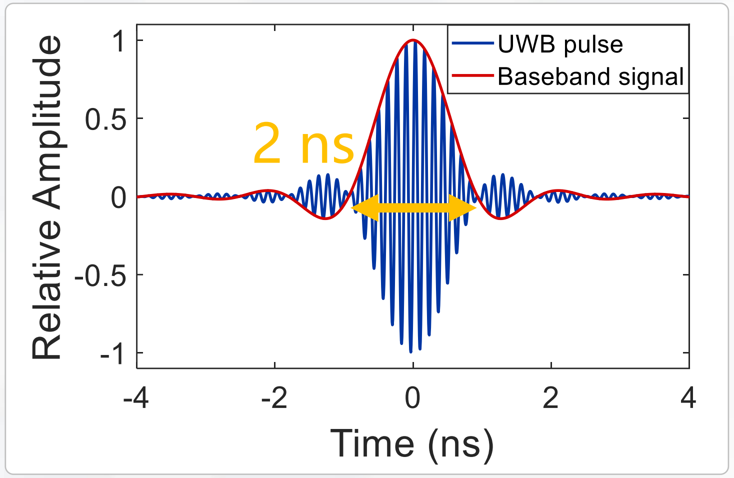
- **Limited bandwidth, low multipath resolution**
- **Decimeter-level accuracy**

Acoustic signals

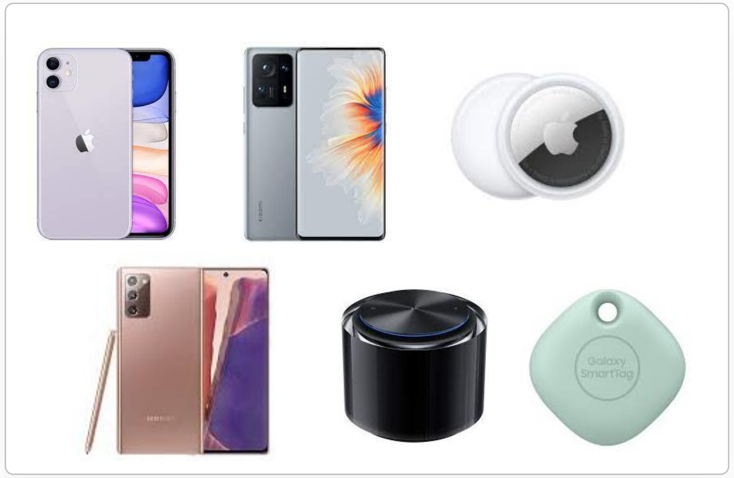
- **Rapid attenuation (i.e. < 1 m)**
- **Sensitive to environmental factors (e.g. temperature, occlusion)**

Ultra-Wideband (UWB): A new opportunity

- UWB offers **cm-level ranging accuracy**, owing to its large bandwidth
- UWB modules are widely adopted on consumer-level electronics
- The ecosystem of UWB is well established



Baseband waveform of UWB signal



Widely adopted on consumer-level electronics

Well-established standards

Limitations of existing UWB ranging solutions

- Existing solutions are mainly based on **Time of Arrival (ToA)** estimation
- The ranging accuracy is constrained to cm-level due to the limited timestamp resolution of commercial UWB devices

Single-Side Two-way Ranging — ***≥ 20 cm*** — ***Before 2016***

Double-Side Two-way Ranging — ***5-10 cm*** — ***WPNC’16***

★ **IEEE 802.15.4z standard**

UWB Concurrent Ranging — ***5-10 cm*** — ***IPSN’19***

UWB Virtual Two-way Ranging — ***5-10 cm*** — ***UbiComp’22***

Now

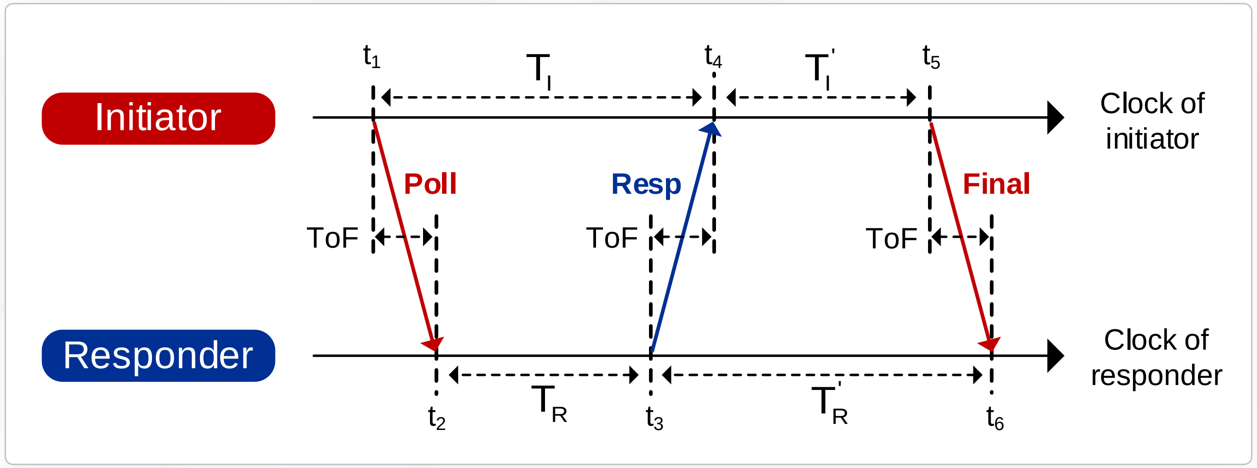
- Modern sensing applications typically require sub-cm-level accuracy
  - In-air handwriting
  - Trajectory tracking for VR

How to further push the limit of UWB ranging accuracy ?

UWB Primer

Principle of traditional UWB ranging (DS-TWR)

- IEEE 802.15.4z standard employs DS-TWR scheme to remove clock skew in UWB ranging
- The ranging devices sequentially exchange 3 UWB messages, and extract 6 timestamps for ToF calculation
- Consider a bandwidth of 500 MHz and SNR of 10 dB, the CRLB for TWR is about **2 cm**



DS-TWR scheme[1]

$$var(ToF) \geq \frac{1}{8\pi^2 c\eta B^2}$$

c: Speed of light $\quad$ η: SNR

B: Signal bandwidth

CRLB for DS-TWR accuracy[2]

[1] Dries Neirynck, Eric Luk, and Michael McLaughlin. "An alternative double-sided two-way ranging method." IEEE *WPNC*, 2016.

[2] WC Chung, and Dong Ha. "An accurate ultra wideband (UWB) ranging for precision asset location." *IEEE Conference on Ultra Wideband Systems and Technologies, 2003*. IEEE, 2003.

Ranging with UWB phase

- **Opportunity:** Commercial UWB devices can report fine-grained phase estimates, which is related to the distance between ranging devices

$$\Phi = arctan\frac{imag(h_{los})}{real(h_{los})} = \left(-2\pi\frac{d}{\lambda}\right) mod\ 2\pi$$

- We can thus obtain the distance using UWB phase estimates

$$d = \left(\frac{\Phi}{2\pi} + N\right)\lambda$$

Integer ambiguity number **Wavelength**

- The phase estimates on commercial devices has a precision of **0.003 rad**, corresponding to a distance resolution of **0.03 mm** at 4.5 GHz

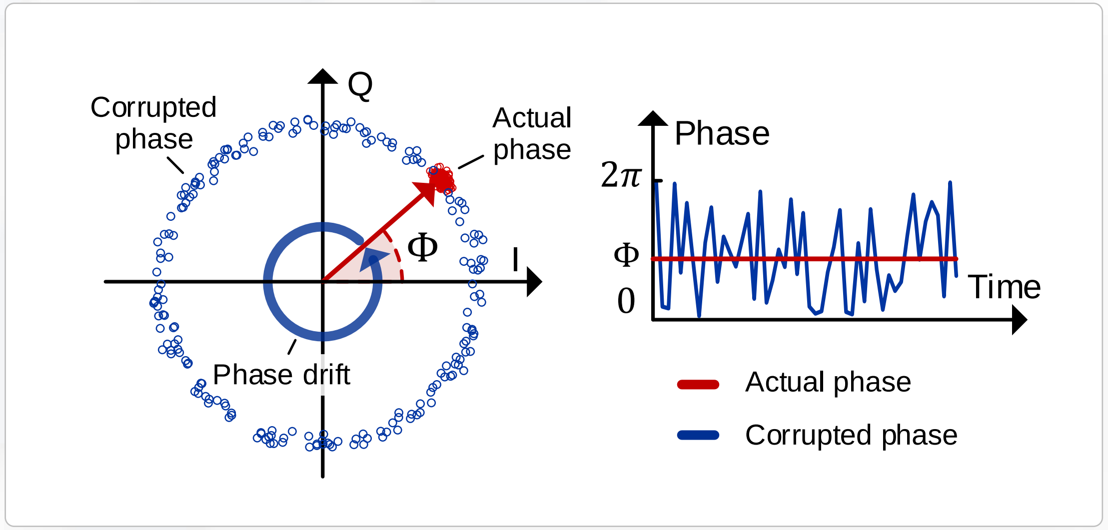
Challenges of ranging with UWB phase

Challenge1：How to remove time-varying phase offset?

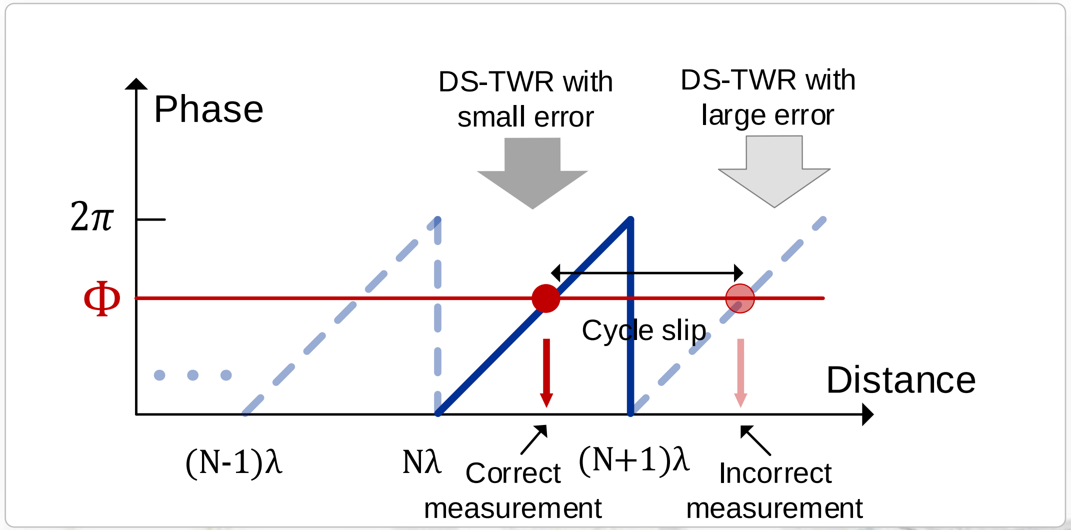
- Due to the lack of synchronization, the raw extracted UWB phase is corrupted by CFO, PLL initial phase, which change rapidly overtime

Challenge2：How to robustly resolve integer ambiguity?

- Due to the phase wrapping issue, the distance measured from UWB phase includes an unknown number of whole wavelengths, which should be correctly resolved



Time-varying phase offset

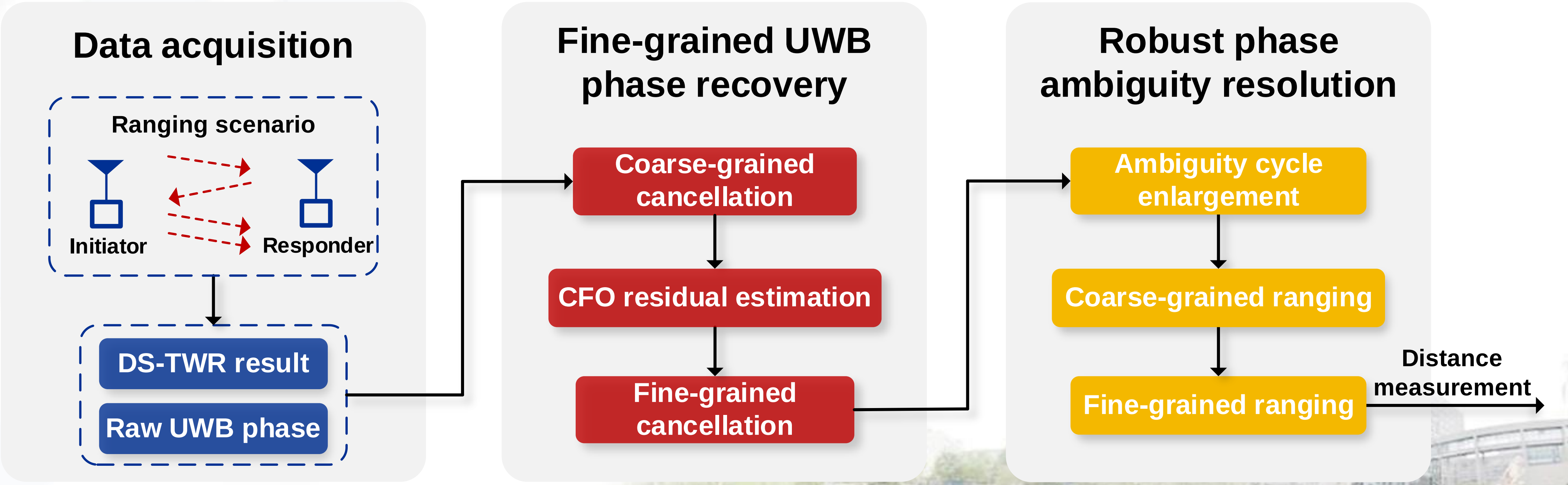


Unknown integer ambiguity

System Design

System overview

- **Data acquisition：** Obtaining raw UWB estimates (DS-TWR result & phase)
- **Phase recovery：** Removing time-varying offsets in raw phase estimates
- **Integer ambiguity resolution：** Resolving ambiguity number and obtain the absolute distance between devices



System overview

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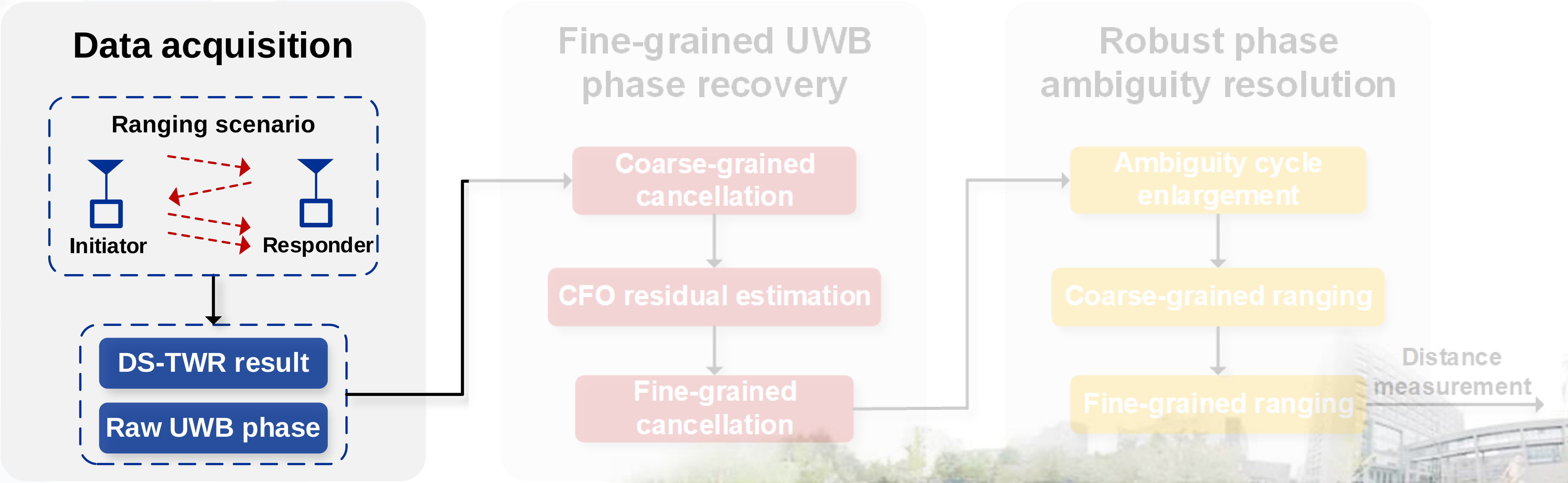

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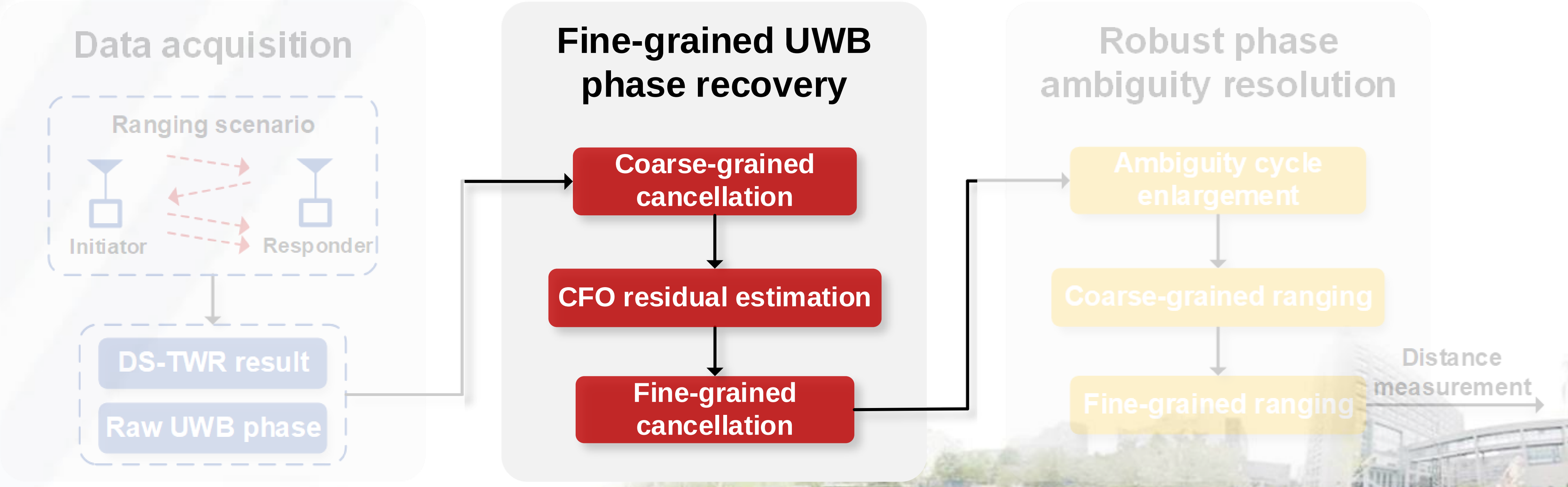


Coarse-grained phase recovery

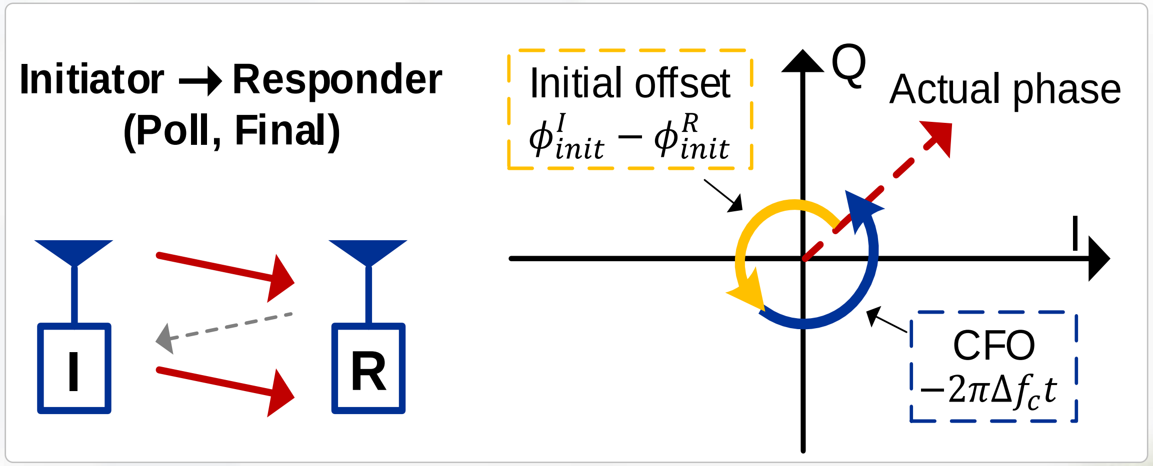
- The **bi-directional UWB signals** in DS-TWR propagate through the same path and **share identical actual phase**, but exhibit **converse time-varying offsets**

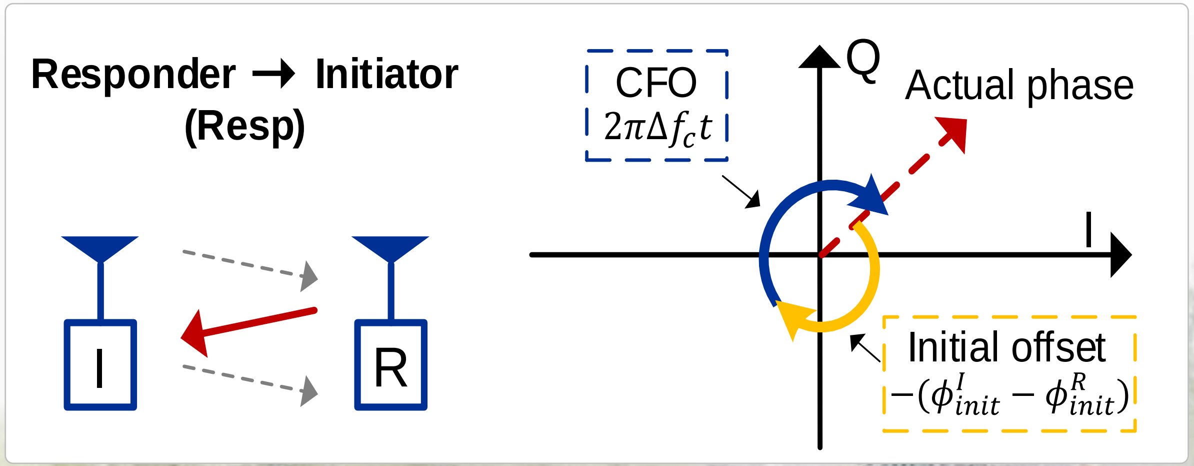
$$\Phi_{Poll}(t) = [\underbrace{-2\pi f_c \tau_{los}}_{Actual\ Phase} \underbrace{-\,2\pi\Delta f_c t}_{CFO} + \underbrace{(\phi^I_{init} - \phi^R_{init})}_{Initial\ Offset}]\ mod\ 2\pi$$

Identical **Converse**

$$\Phi_{Resp}(t) = [-2\pi(f_c + \Delta f_c)\tau_{los} + 2\pi\Delta f_c t + (\phi^R_{init} - \phi^I_{init})]\ mod\ 2\pi$$

$$\approx [\underbrace{-2\pi f_c \tau_{los}}_{Actual\ Phase} + \underbrace{2\pi\Delta f_c t}_{CFO} - \underbrace{(\phi^I_{init} - \phi^R_{init})}_{Initial\ Offset}]\ mod\ 2\pi,$$



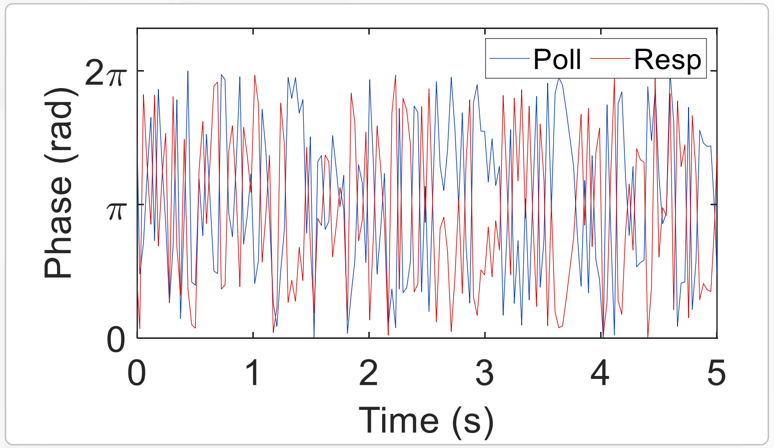


Coarse-grained phase recovery

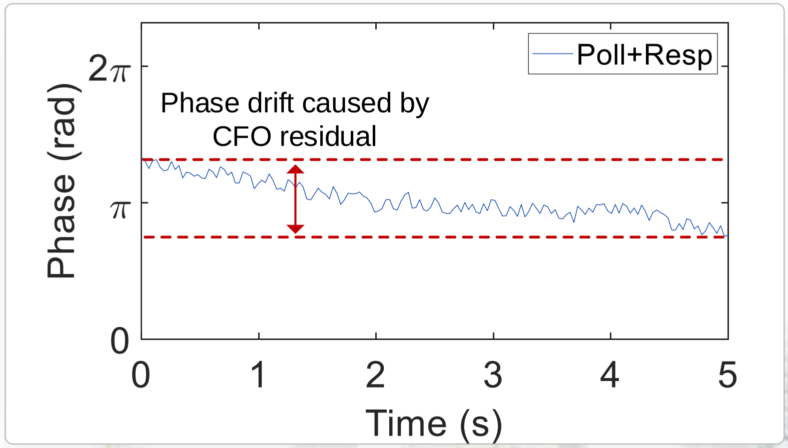
- We can thus remove these offsets by **adding the phase of bi-directional signals** (e.g. *Poll* and *Resp*)

$$\begin{aligned}\Phi_{Poll}(t_2)+\Phi_{Resp}(t_4) &= [-2\pi f_c\tau_{los}-2\pi f_c\tau_{los}-2\pi\Delta f_c t_2+2\pi\Delta f_c t_4+(\phi^I_{init}-\phi^R_{init})-(\phi^I_{init}-\phi^R_{init})]\ mod\ 2\pi\\ &= [-4\pi f_c\tau_{los}+2\pi\Delta f_c(t_4-t_2)]\ mod\ 2\pi\\ &= [-4\pi f_c\tau_{los}+2\pi\Delta f_c(t_3-t_2)+2\pi\Delta f_c(t_4-t_3)]\ mod\ 2\pi\\ &\approx [-4\pi f_c\tau_{los}\underbrace{+2\pi\Delta f_c(t_3-t_2)}_{CFO\ Residual}]\ mod\ 2\pi,\end{aligned}$$

- However, due to the interval between these signals, **a small residual term** still exists



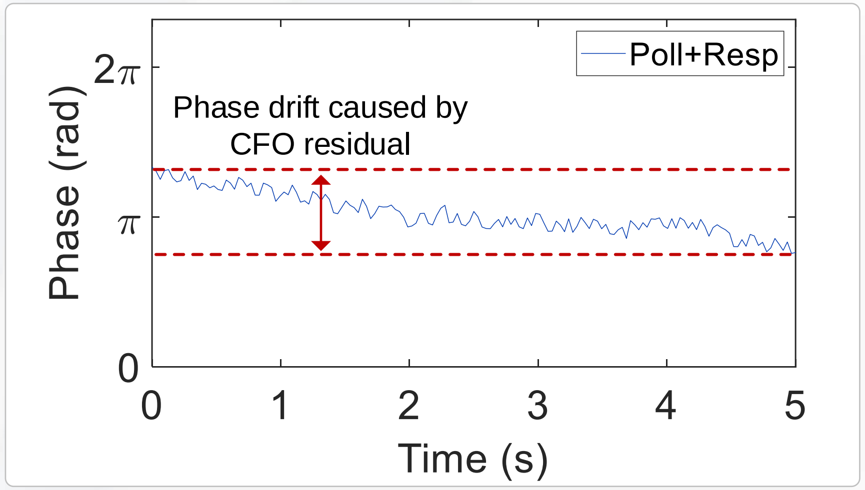
Raw UWB phase estimates



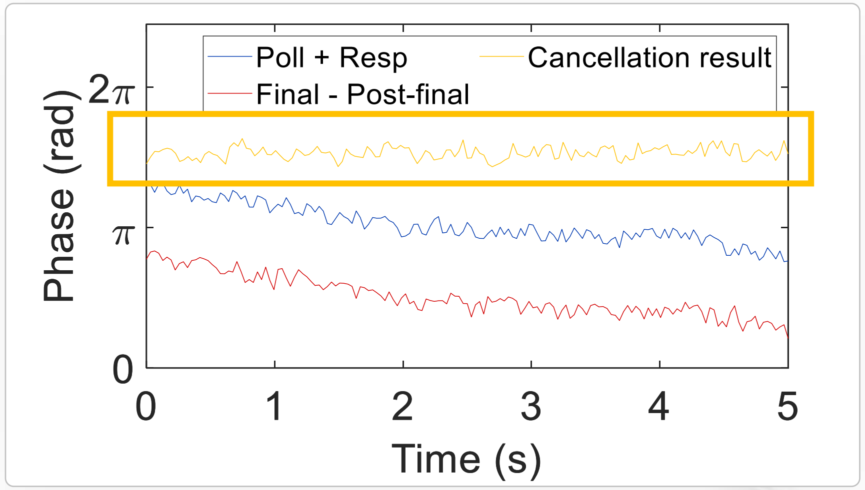
Result of coarse-grained recovery

Fine-grained phase recovery

- **Observation:** UWB signals with **the same propagation direction** also share **the same actual phase** but have **different CFO**
- We can thus estimate the residual CFO **by subtracting the phase of these signals** and remove it from coarse-grained result



Result of coarse-grained recovery (exhibit long-term drift)



Result of fine-grained recovery (exhibit no long-term drift)

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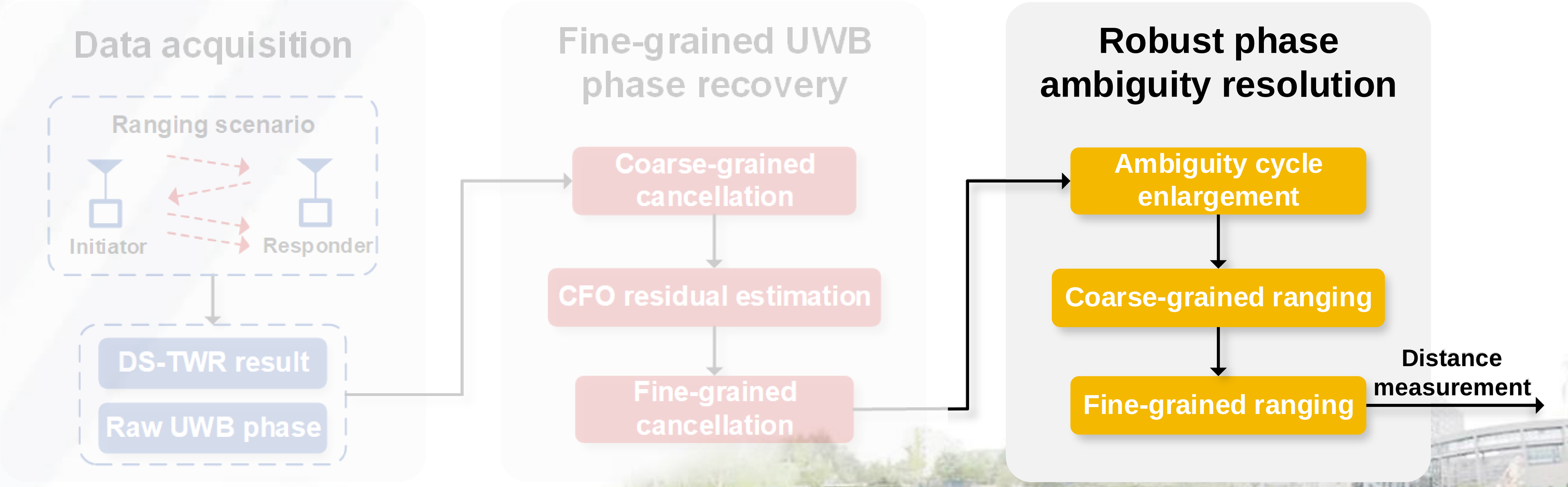
- **Integer ambiguity resolution**：Resolving ambiguity number and obtain the absolute distance between devices



Enlarging ambiguity cycle with two UWB frequencies

- **Observation:** IEEE 802.15.4 standard divides the UWB band (3-10 GHz) into 15 sub-channels with different center frequencies
- Commercial devices typically support more than two sub-channels (e.g. Ch.1-5 are supported by DW1000)
- **Our idea:** We find that the phase difference also has a relationship to the distance d, We can thus ranging with the phase difference

$$\Delta\Phi = \Phi_{rec}^{1} - \Phi_{rec}^{2} = [-2\pi(f_{eq}^{1} - f_{eq}^{2})\frac{d}{c}] \ mod\ 2\pi$$

$$\boxed{d_{diff} = (\frac{\Delta\Phi}{2\pi} + N_{diff})\frac{c}{f_{eq}^{1} - f_{eq}^{2}} = (\frac{\Delta\Phi}{2\pi} + N_{diff})\lambda_{diff}}$$

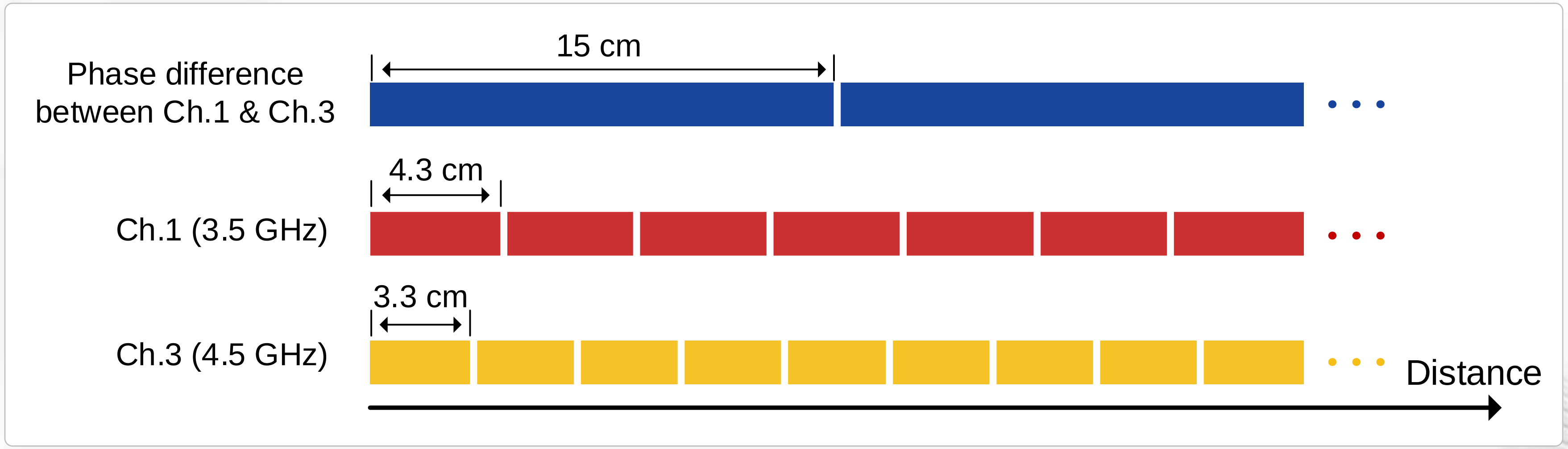
Formular of ranging with phase difference

$$\boxed{\lambda_{diff} = \frac{c}{f_{eq}^{1} - f_{eq}^{2}}}$$

New ambiguity cycle

Enlarging ambiguity cycle with two UWB frequencies

- We perform frequency hooping between UWB Ch.1 and 3 (3.5 and 4.5 GHz)
- The new ambiguity cycle of ranging result with phase difference is **15 cm**, which is much larger than the result of using a single frequency
- Note that DS-TWR typically has a ranging error of less than **10 cm**, we can thus safely determine the ambiguity cycle with DS-TWR result



Enlarged ambiguity cycle with phase difference

Demonstration

Push the Limit of Highly-accurate Ranging on Commercial UWB Devices

Conclusion

- We propose a novel approach to cancel phase drift and **retrieve UWB phase with high accuracy**
- We propose a method to **enlarge the ambiguity cycle with phase differences** and greatly improving the robustness in phase ambiguity resolution
- We design three real-life applications to demonstrate that the performance of our system significantly **outperforms the state-of-the-art in UWB ranging**

Thank you!

Q & A

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