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UniChirp: Unwrapping In-Chirp Phase Misalignment for Weak LoRa Signal Demodulation

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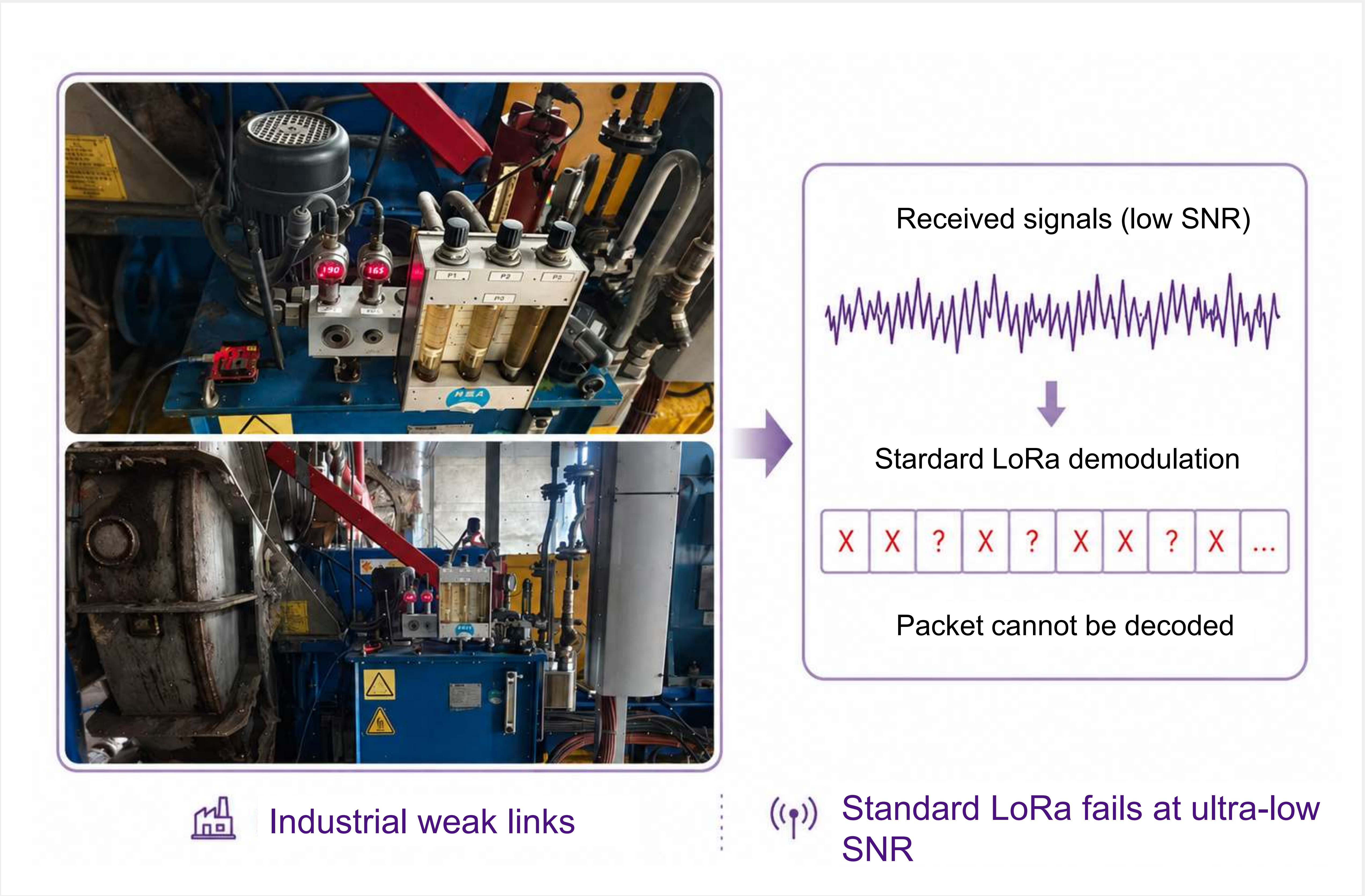
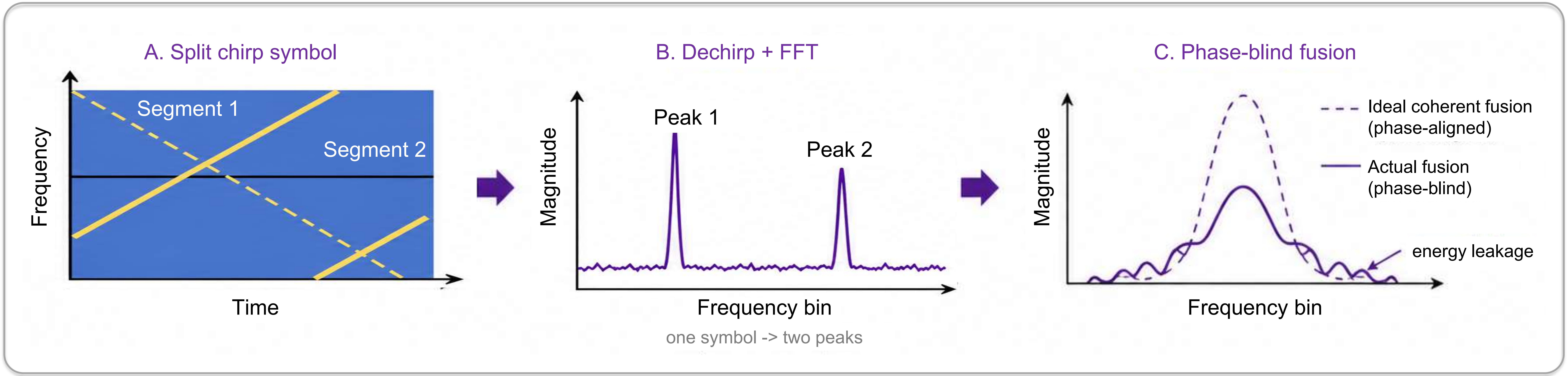
Motivation: LoRa Fails in Industrial Weak Links

1. Sensors are deployed inside pipelines,tanks,and dense machinery.
2. Occlusion, metal structures, multipath, and interference severely attenuate chirps.
3. The received SNR can fall below the decoding threshold of standard LoRa.
4. The receiver should improve robustness without changing end devices or protocol stacks.



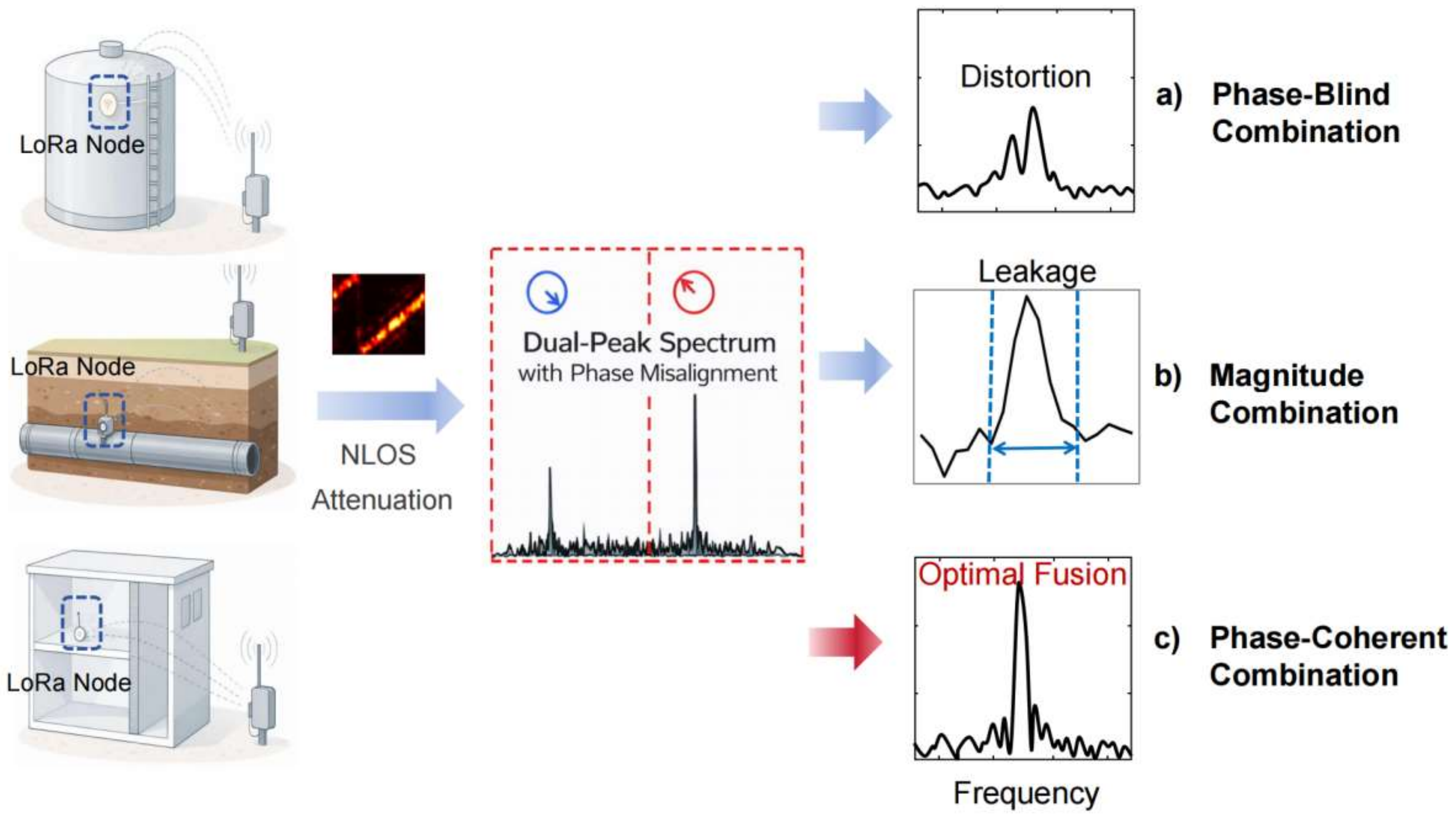
Problem focus: weak-signal demodulation under ultra-low SNR

Why Conventional LoRa Demodulation Breaks



> Can we recover weak LoRa packets by restoring phase-coherent energy aggregation?

Core Contribution: Phase-Coherent Weak-Signal Demodulation



Phase discontinuity is predictable

$$\varphi_{mis}[n] = -2\pi BW\left(\frac{SFO}{Fs}\right)n - 2\pi BWTO + \varphi_0$$

1. CFO: continuous rotation
   does not break the in-chirp phase jump
2. TO: constant offset
3. SFO: linear trend
   makes the jump drift across chirps

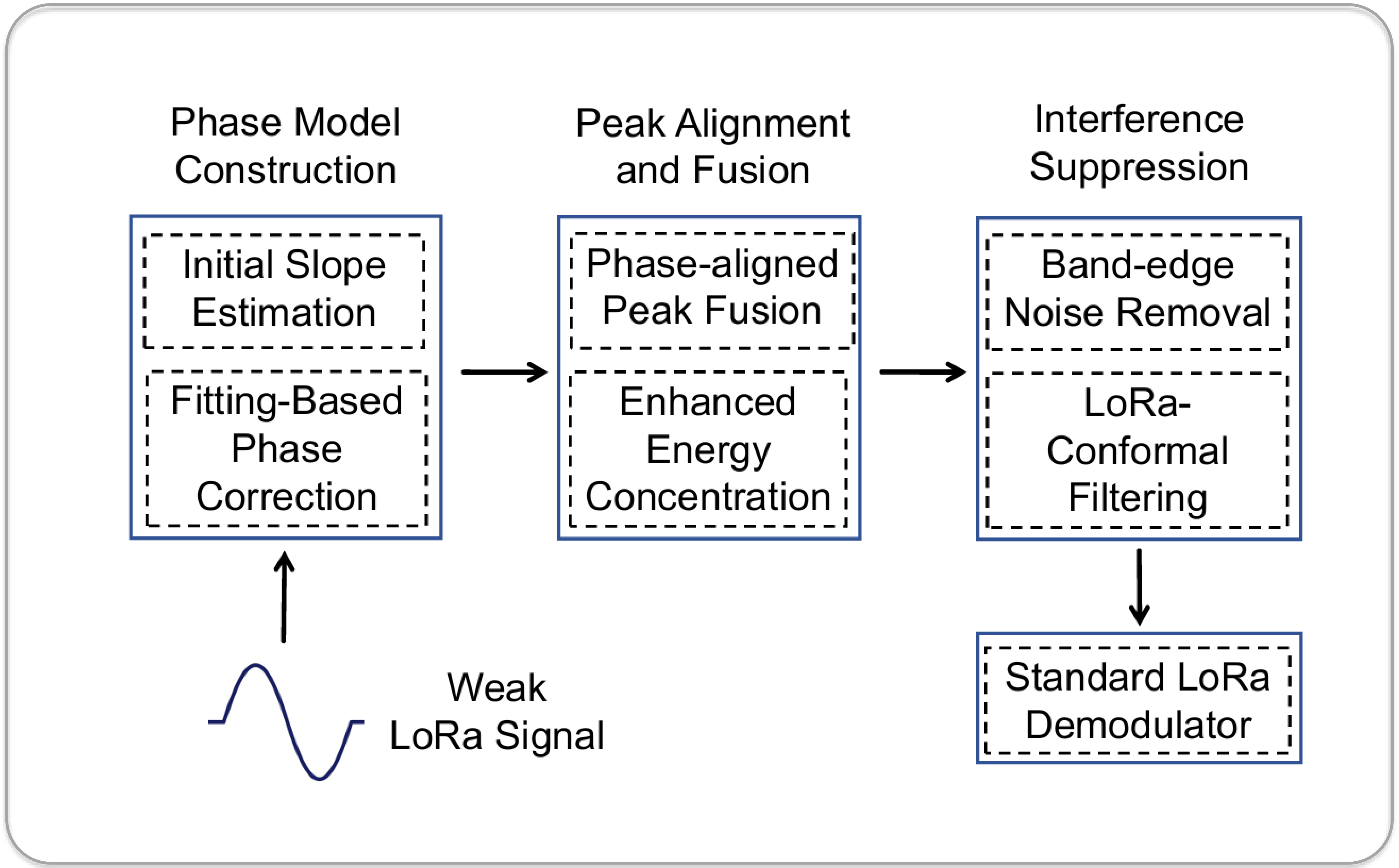
Model — closed-form phase trajectory → **Predict** — packet-level phase prior → **Fuse** — phase-aligned peak aggregation

Overview: UniChirp Decoding Pipeline

Phase Model Construction
packet-level phase prior

Peak Alignment and Fusion
phase-coherent dual-peak aggregation

Interference Suppression
Interference Suppression



Software-only receiver — no change to LoRa end devices or protocol stacks

MODULE 1

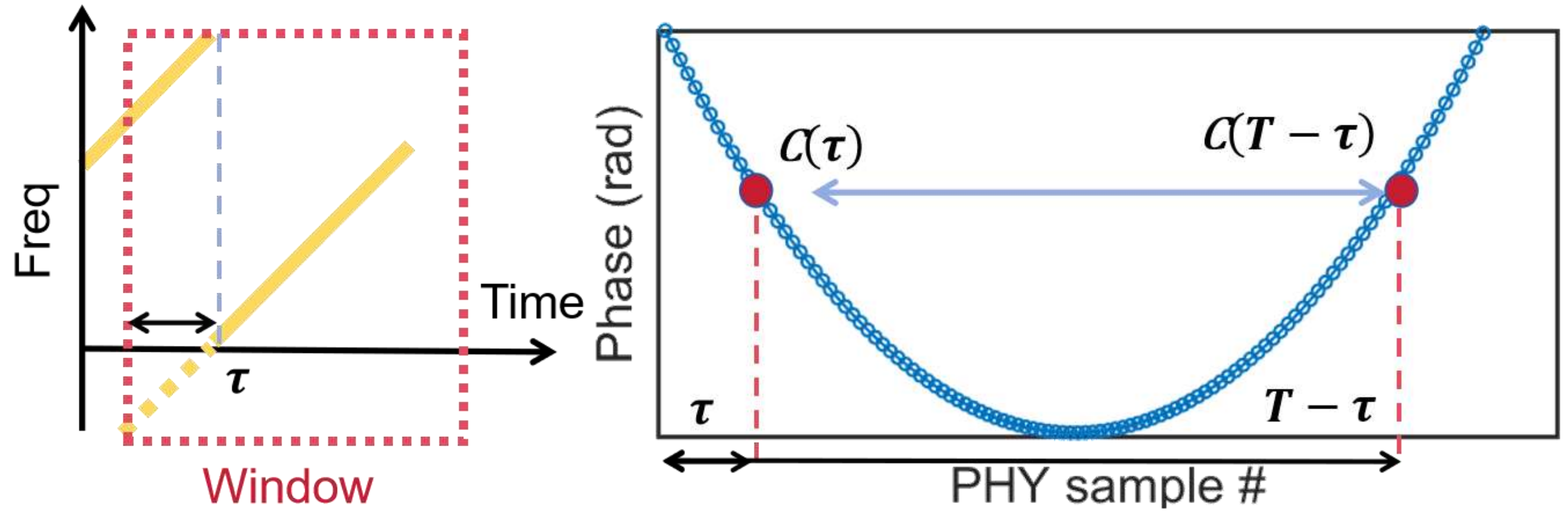
Preamble-Guided Phase Prior

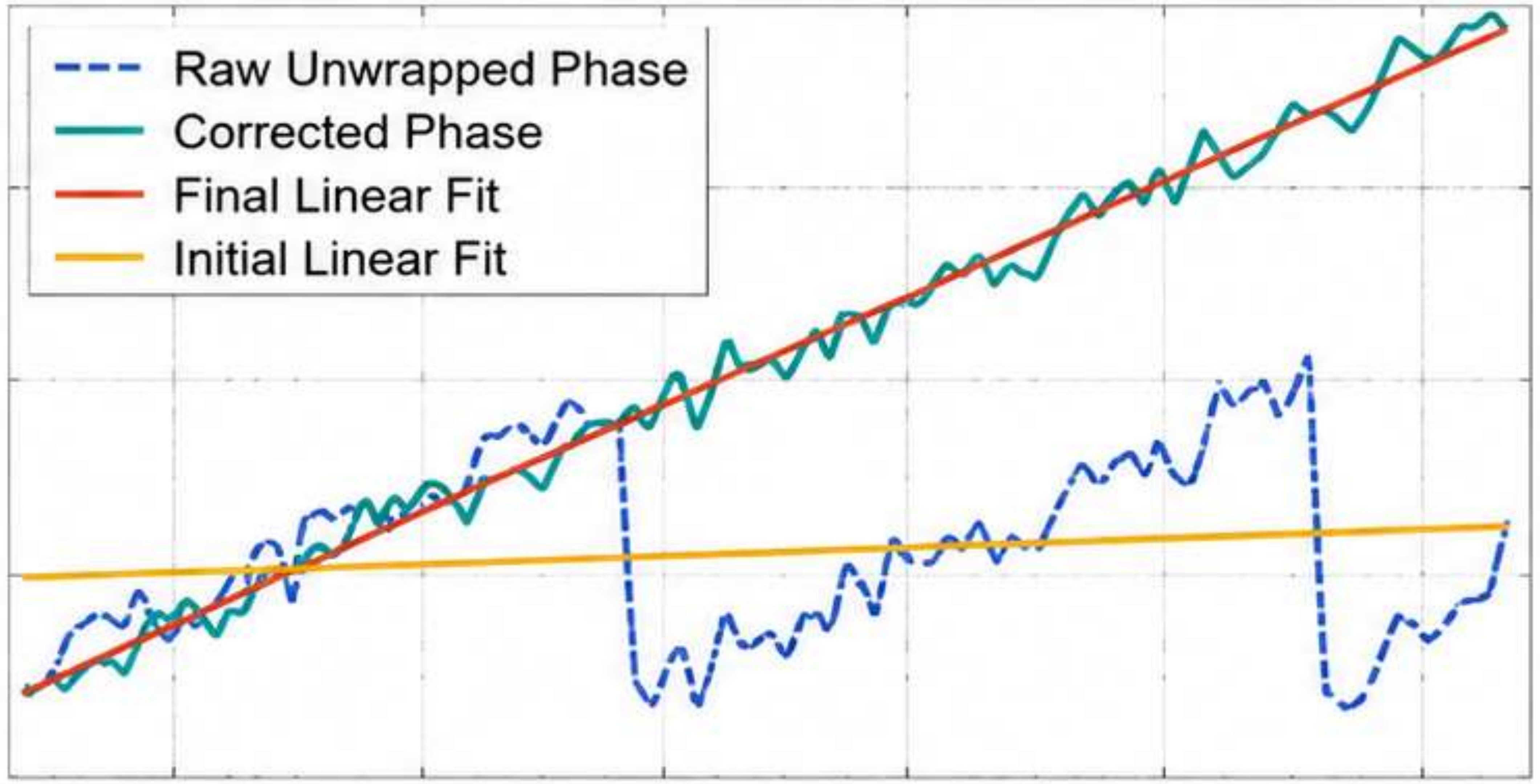
Core idea

- Estimate packet-level phase trajectory from preamble symbols.
- Fit slope and intercept to construct a phase prior.
- Extrapolate the fitted trend to payload symbols.

Practical role

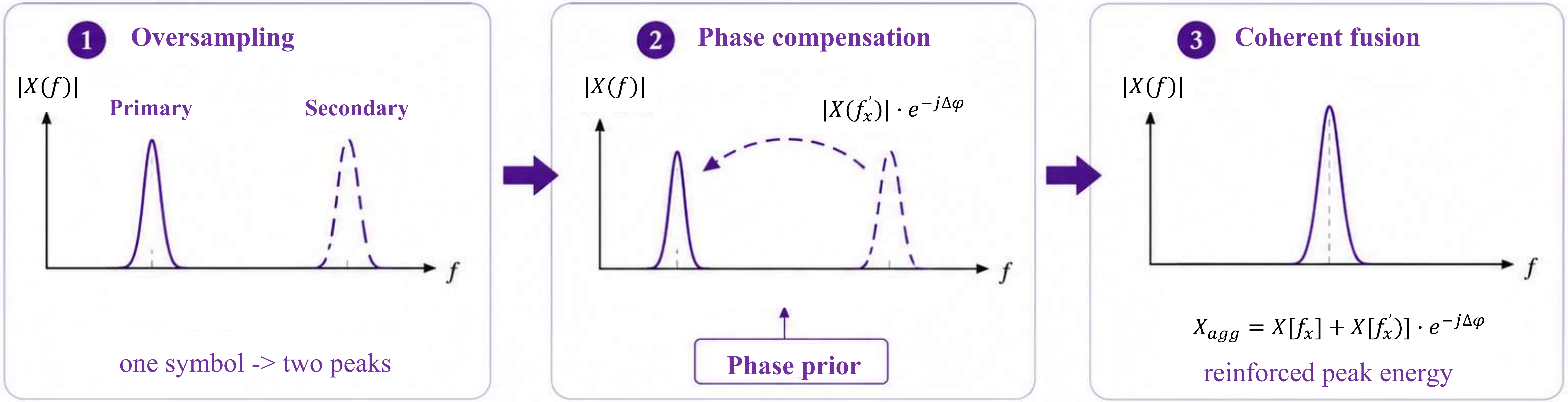
Provides a packet-level phase prior that guides coherent fusion during payload decoding.





MODULE 2

Phase-Coherent Dual-Peak Fusion



Separate
oversampling reveals dual peaks.

Compensate
phase prior aligns the secondary peak.

Fuse
coherent addition boosts weak-signal decoding.

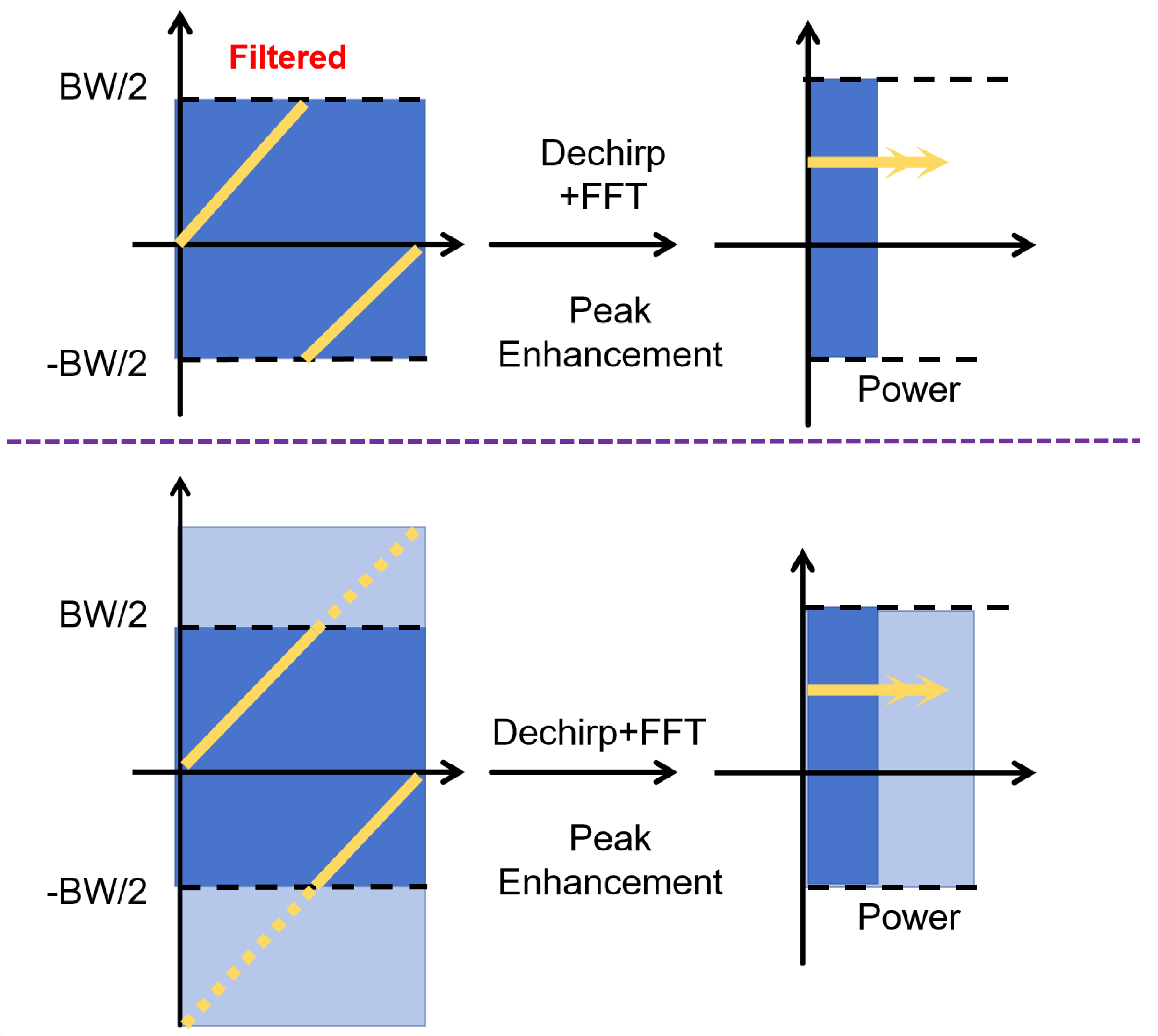
Structure-Aware Spectral Filtering

Core idea

- LoRa chirps occupy a narrow valid band around baseband.
- Apply low-pass filtering before dechirp+FFT to suppress out-of-band noise.
- Preserve in-band signal energy and improve peak detectability under low SNR.

Practical role

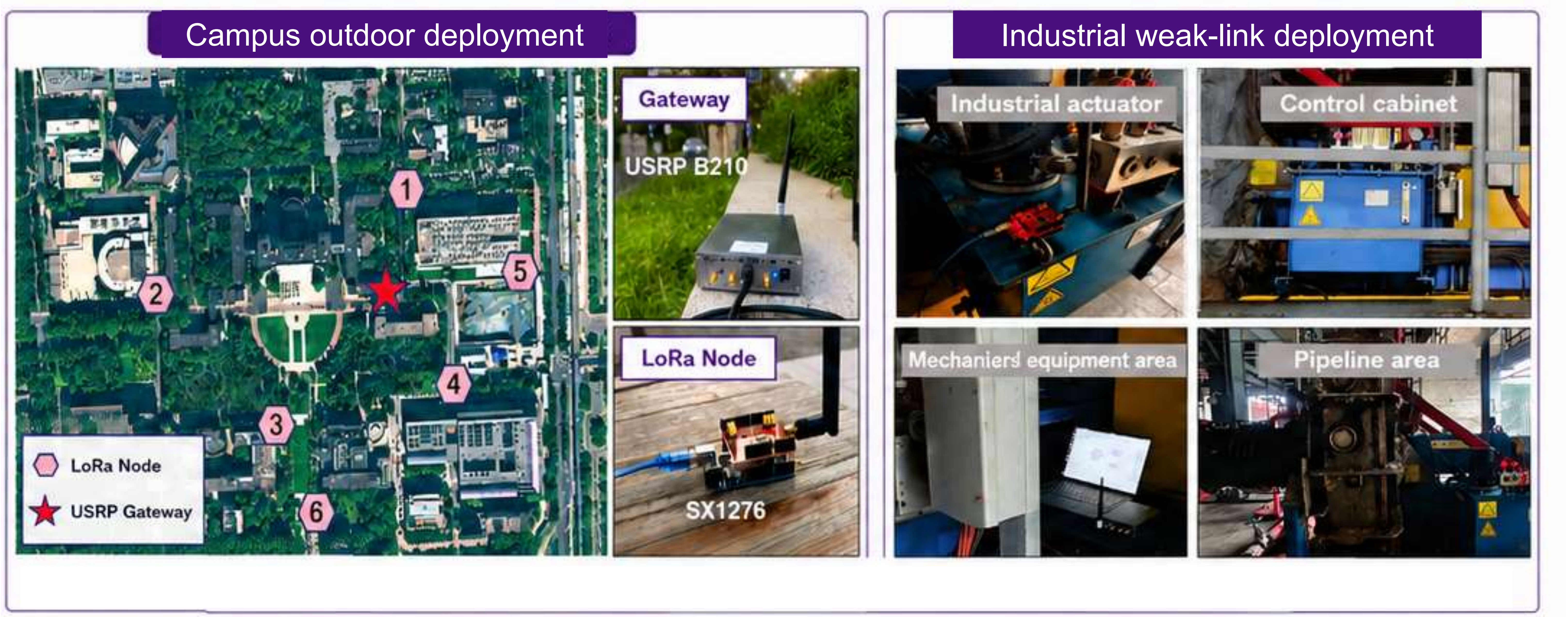
Reduces noise power before FFT demodulation, making weak peaks easier to detect.



Implementation and Evaluation Setup

Experimental settings

- SDR testbed: USRP N210 / B210 with SBX daughterboards
- Baseband processing: GNU Radio + MATLAB
- Field nodes: off-the-shelf SX1276-based LoRa nodes
- Outdoor scenario: campus-scale deployment around buildings and vegetation



Baselines and metrics

LoRaWAN

standard LoRa demodulation

Ostinato

repeated-symbol accumulation

Choir

magnitude-domain dual-part summation

LoRaTrimmer

phase compensation with candidate search

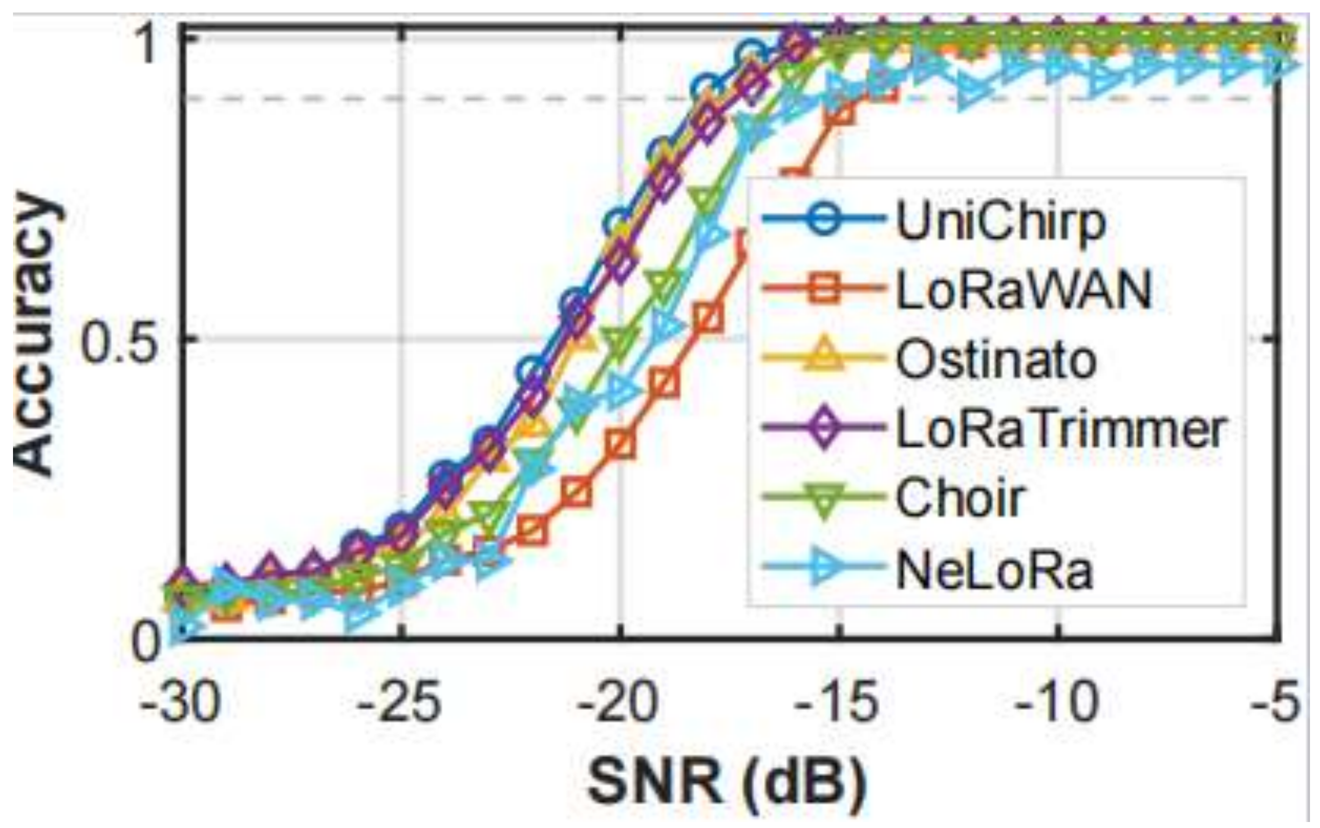
NELoRa

learning-based weak-signal demodulation

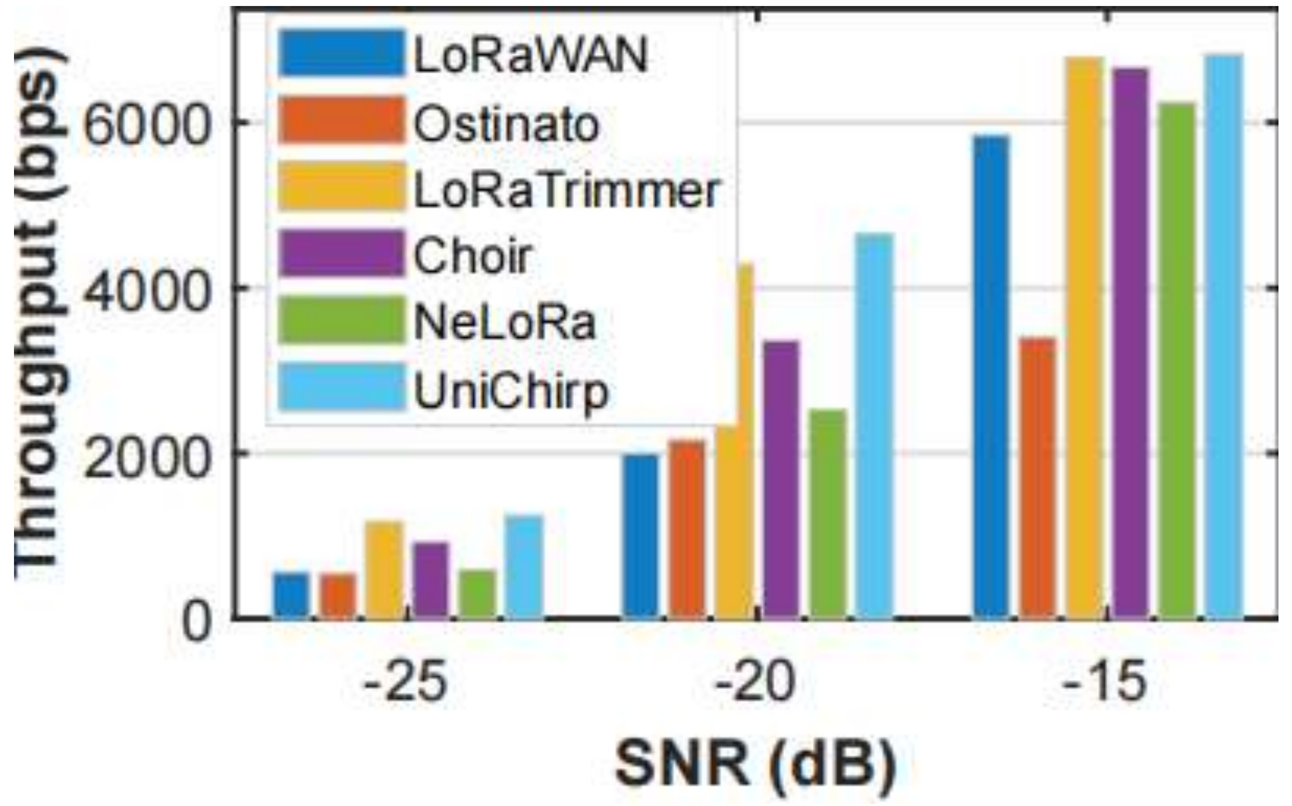
Metrics

symbol accuracy, SER, BER, throughput, runtime

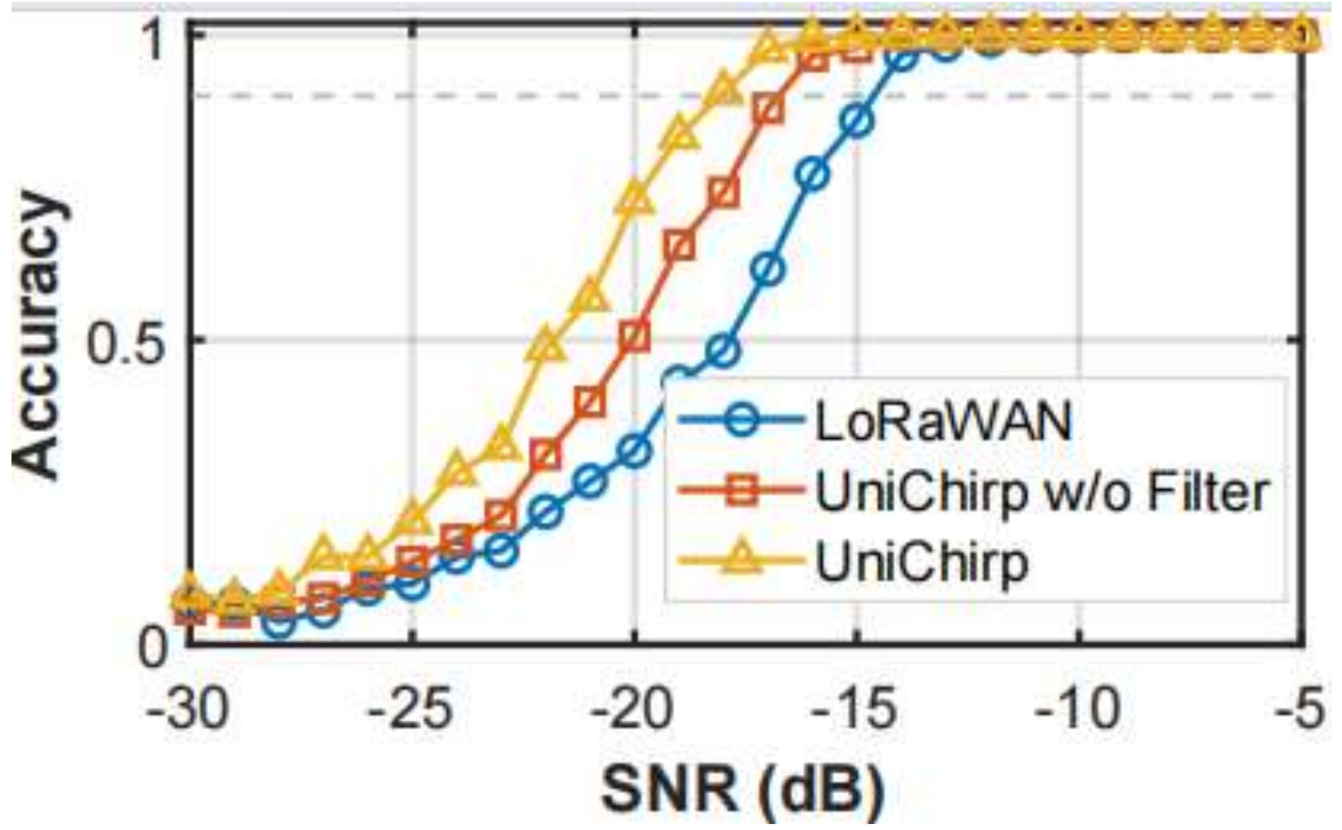
Main Results: Better Robustness under Low SNR



- 90% accuracy down to -18 dB
- At -20 dB: +3.5% to +35.2% vs. baselines



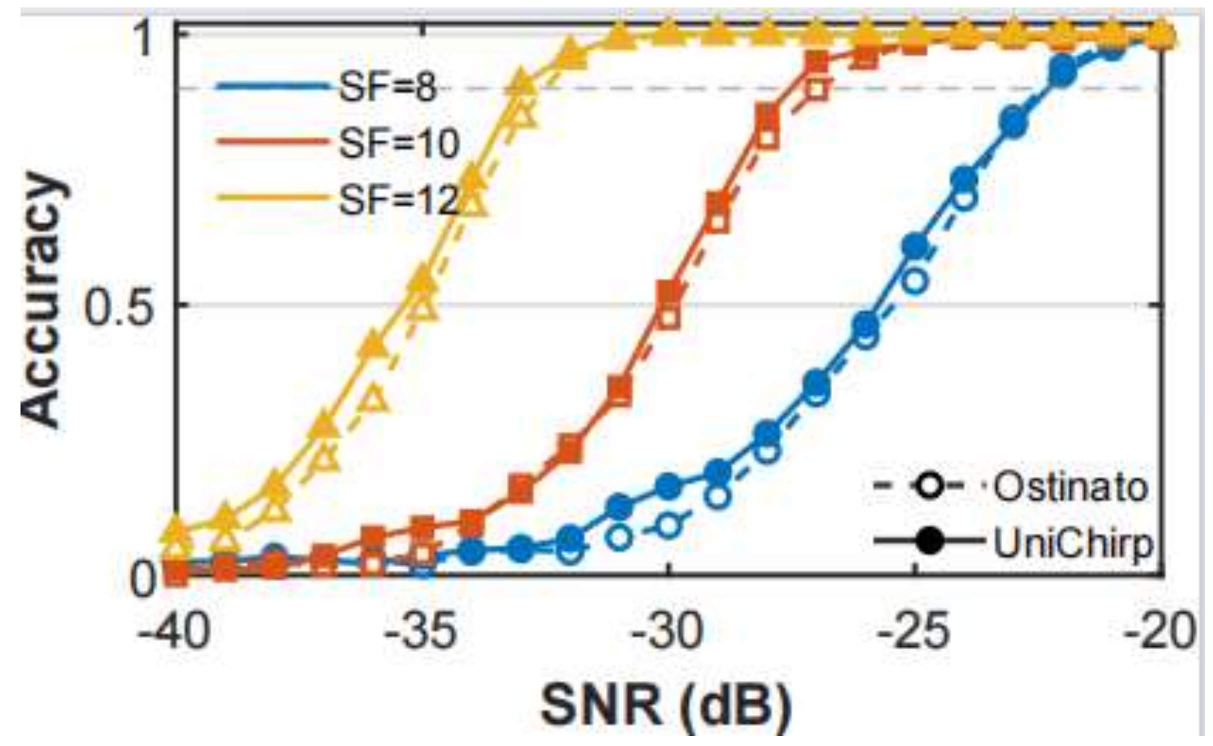
- Highest throughput across tested SNRs
- Up to +3421.4 bps gain; up to 35.3% in low SNR



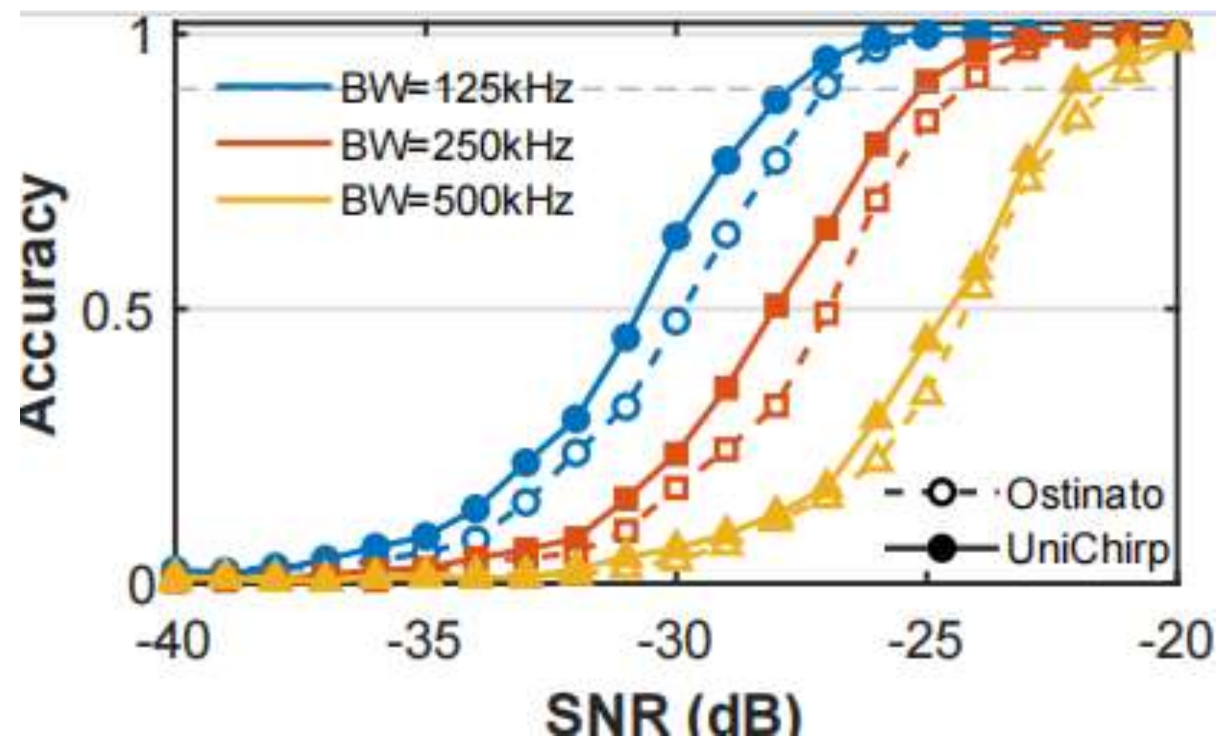
- Phase prior already brings clear gains
- w/o Filter: up to +18.8% at -20 dB
- Filtering adds another +22.2%

☆ Takeaway: UniChirp improves both reliability and effective throughput under low SNR, and both phase prior and filtering are essential.

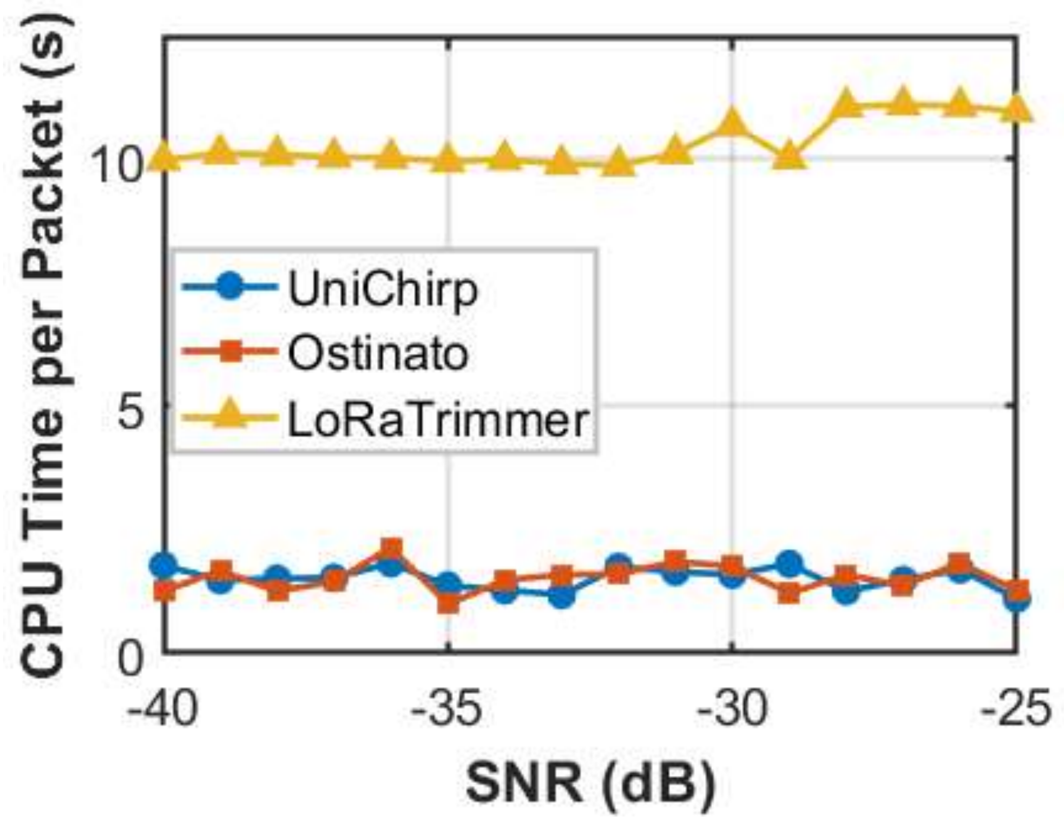
Efficiency, Generality, and Takeaways



- At -30 dB, gains reach 6.0% at SF=8 and 5.2% at SF=10.



- At -30 dB, gains are 11.2%, 4.0%, and 2.8% at 125/250/500 kHz.



- At SF=12: 1675 ms for UniChirp vs. 10931 ms for LoRaTrimmer.
- LoRaTrimmer reaches 12156 ms, about 6.5× UniChirp.

☆ Generalizes across LoRa parameter settings while maintaining practical receiver-side efficiency.

Conclusion

Problem

- Weak industrial links fall below standard LoRa decoding thresholds.
- Phase misalignment prevents coherent chirp energy aggregation.

Method

- Predict packet-level phase trajectory from preamble symbols.
- Compensate and fuse dual peaks without exhaustive search.

Result

- 90% accuracy down to −18 dB.
- Robust across LoRa settings with practical receiver-side runtime.

Thanks