3DVidar: A Contact-free 3D Vibration Sensing System Based on a Single mmWave Radar

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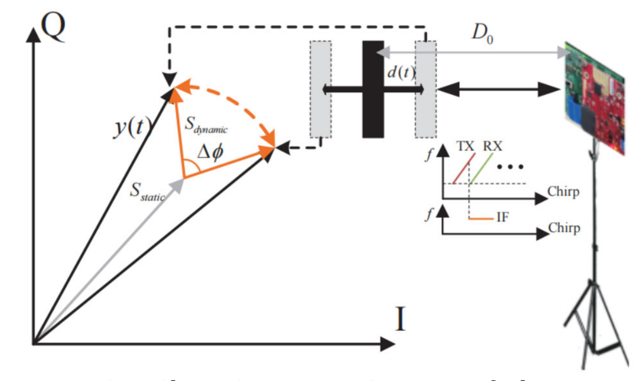
Background

- **Industry 5.0**
  - Higher requirements are placed on the efficiency and reliability of industrial systems.
  - Industrial equipment running for long periods is prone to failure.
- **Vibration Sensing**
  - Abnormal vibrations in machinery can often be an early sign of potential safety incidents.
  - Vibration sensing allows for real-time tracking of equipment status.
- **Existing Vibration Sensing Technologies**
  - Contact-based Method: Attaching vibration sensors directly.→ Potential Deployment Issues.
  - Contact-free Solutions: Laser systems and high-speed cameras.→ High Cost.
- **Wireless Vibration Sensing Solutions**
  - RFID and UWB radar: Low-frequency vibrations with relatively large amplitudes.
  - **mmWave Radar**: High-frequency, weak vibrations of industrial equipments.

mmWave Based Vibration Sensing

Technical Principles

Current mmWave radar-based vibration sensing methods primarily focus on 1D radial vibration or 2D vibration trajectories.



Basic vibration sensing model.

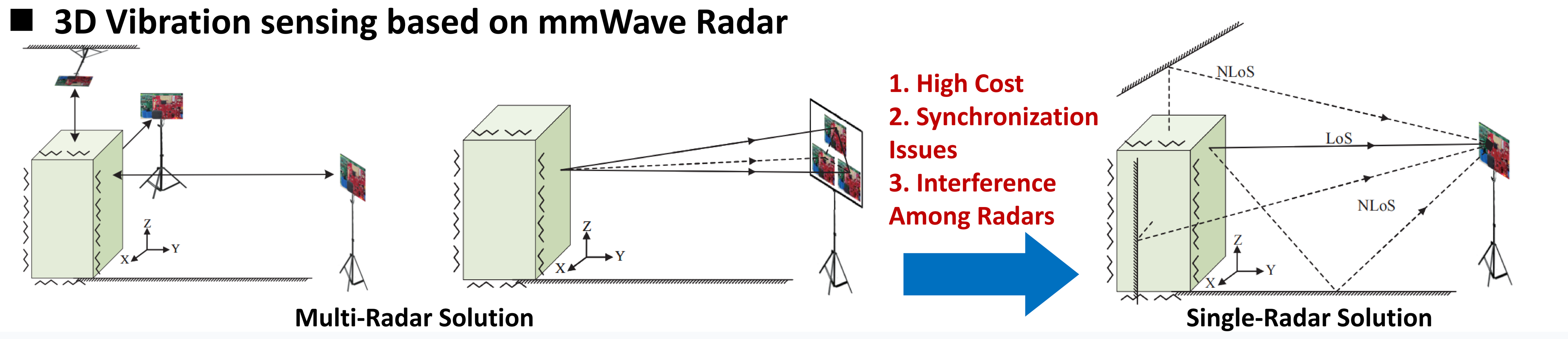
$$s_{TX}(t) = \exp\left[j(2\pi f_c t + \pi K t^2)\right],$$
$$s_{RX}(t) = \alpha s_{TX}\left[t - \frac{2D(t)}{c}\right],$$
$$s_{IF}(t) = s_{TX}(t) \cdot s_{RX}^{*}(t) \approx \alpha \exp\left[j2\pi\left(\frac{2f_c D(t)}{c} + \frac{2KD(t)}{c} \cdot t\right)\right].$$

The transmitted and received signal.

$$\phi(t) = \frac{4\pi f_c D(t)}{c} = 4\pi f_c \frac{D_0}{c} + 4\pi f_c \frac{d(t)}{c} \stackrel{\text{def}}{=} \phi_0 + \Delta\phi(t),$$
$$\boxed{d(t) = \frac{c}{4\pi f_c}\left(\Delta\phi(t)\right),}$$

Relationship between phase change and vibration

3D Vibration sensing based on mmWave Radar

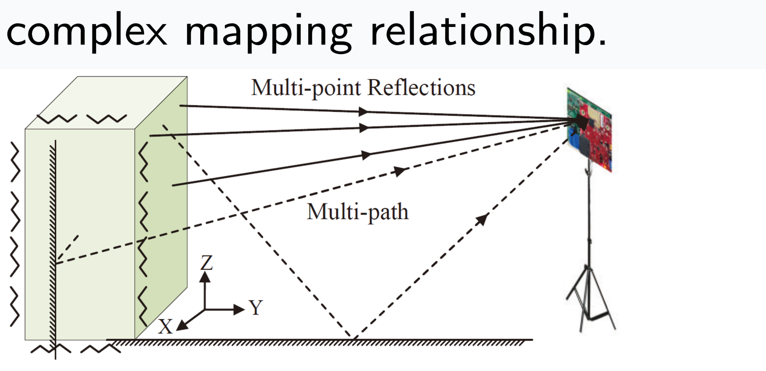


Multi-Radar Solution **Single-Radar Solution**

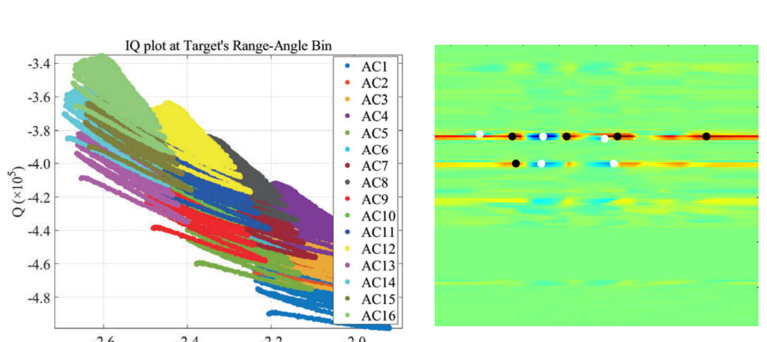
- Objective: Use a single radar to recover the 3D vibration trajectory of the target.
- Challenge1: Radar lacks tangential sensitivity, limiting 3D vibration recovery.
- Challenge2: Radar echoes complicate 3D vibration mapping due to complex superpositions.

Motivations and Solutions

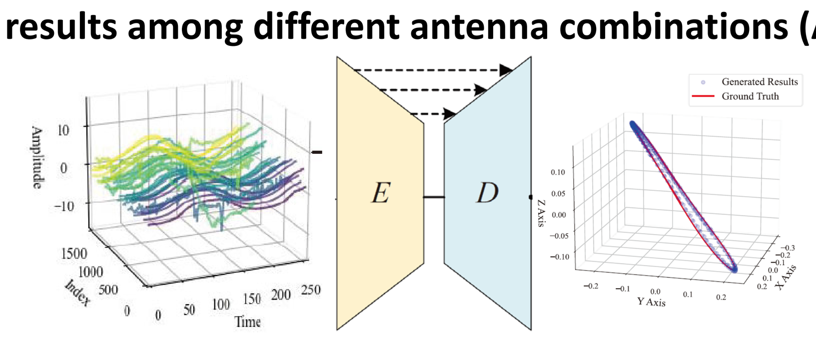
- **Motivations**
  - Multipath signals can help enrich vibration information.
  - Multiple antennas combinations can offer multi-view of the target vibration.
  - AI based approaches have strong capacity to learn complex mapping relationship.



Target Multipath and Multi-Point Signal Reflections.



Differences in IQ plane and Range-Angle Map results among different antenna combinations (ACs)

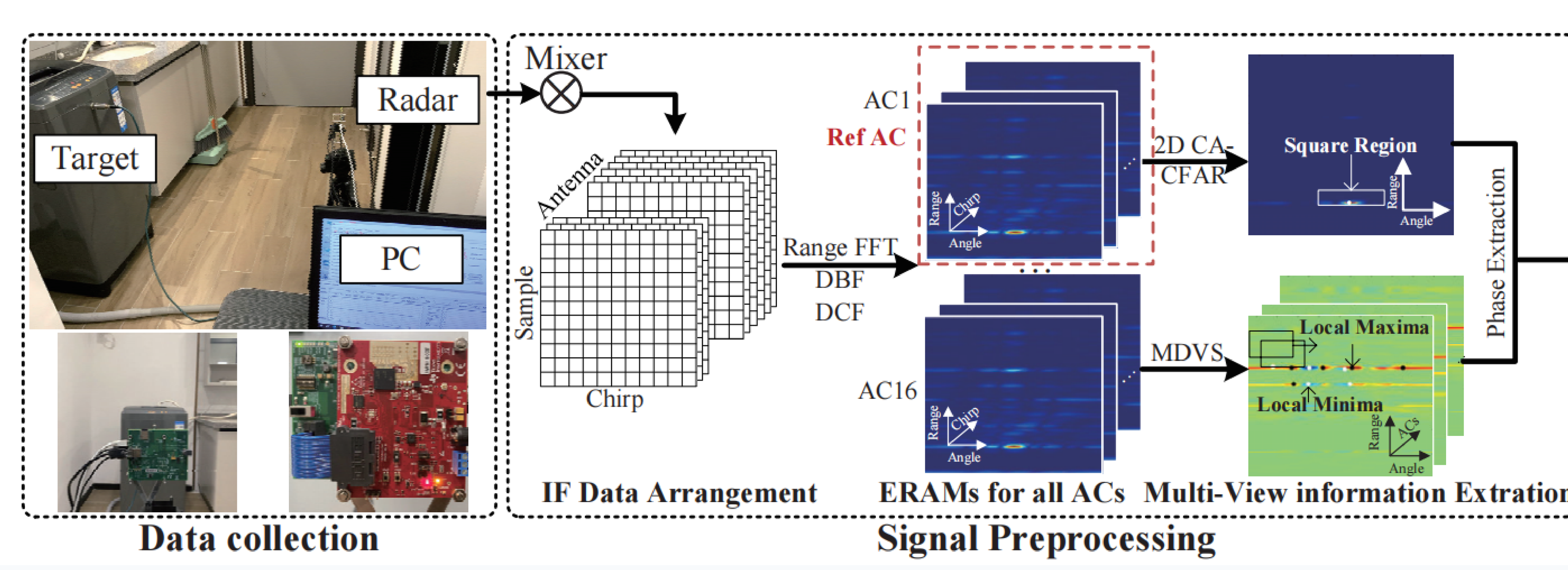


AI based approaches to learn the mapping relationship

- **Solutions**
  - Utilize multiple paths-points-antennas to expand information dimensions.
  - Use AI based approaches to learn the 3D vibration mapping relationship.

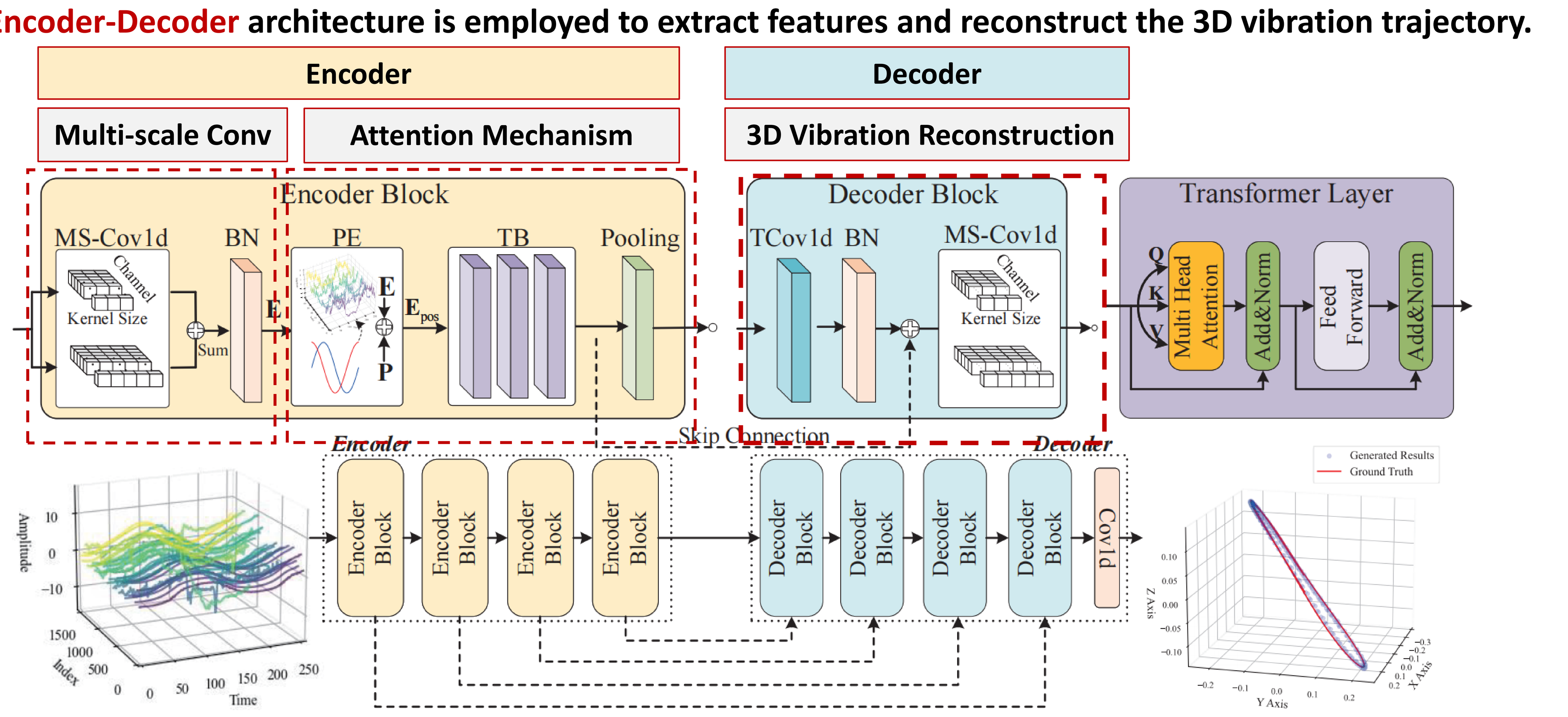
System Design

Solution



Data-Driven Approach

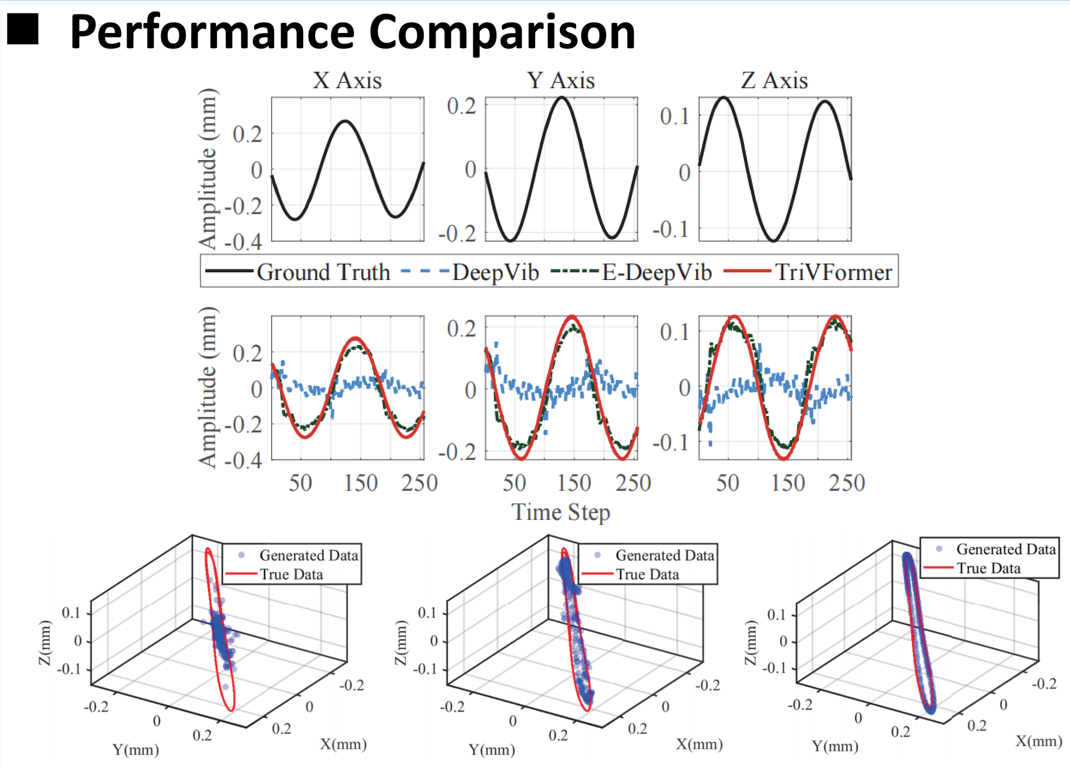
An Encoder-Decoder architecture is employed to extract features and reconstruct the 3D vibration trajectory.



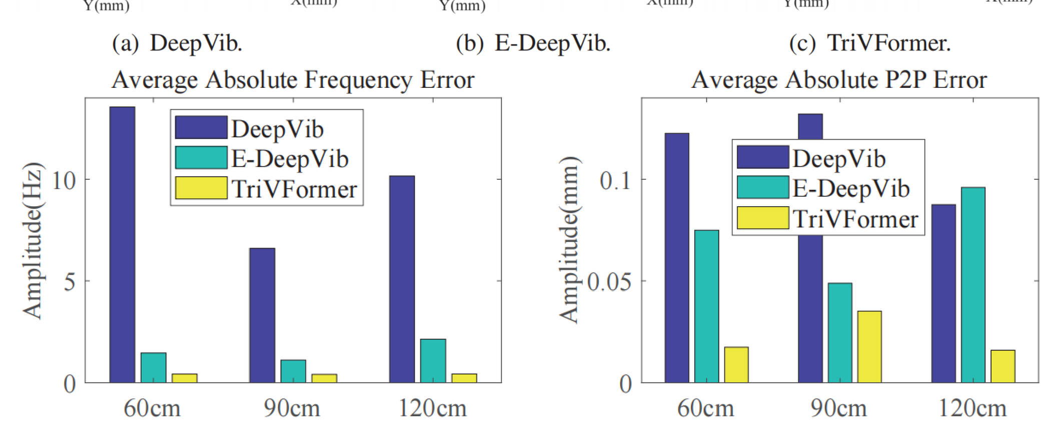
Input : Multi-view Radar Phase Data **Network Architecture: TriVFormer** **Output : 3D Vibration Trajectory**

Experiment

Performance Comparison



(a) DeepVib. (b) E-DeepVib. (c) TriVFormer.

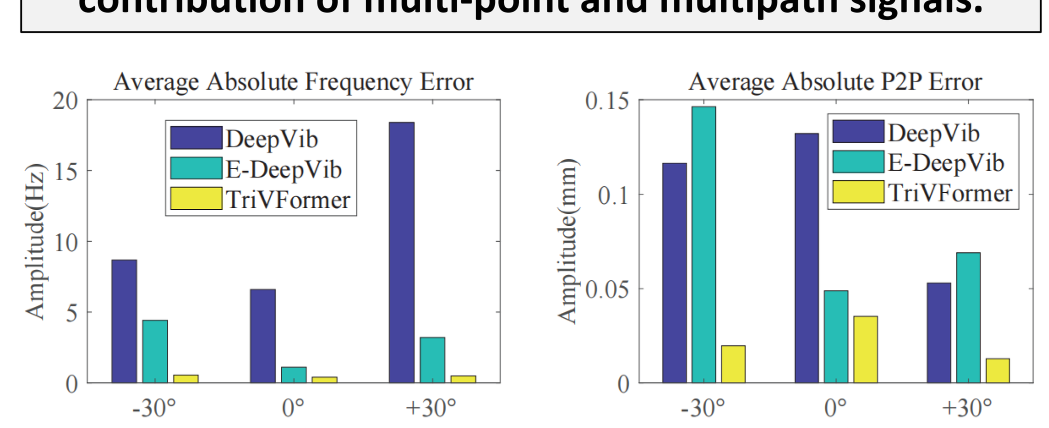


(a) AAFE. (b) AAPPE.

TABLE III
ABLATION STUDY. ↑: THE HIGHER THE BETTER, ↓: THE LOWER THE BETTER.

Formulation	AAFE(Hz)↓	AAPPE(mm)↓
3DVidar (w/o TB)	1.7223	0.0449
3DVidar (w/o MP^2SE&VAC)	1.1931	0.0570
3DVidar (w/o VAC)	0.6560	0.0265
3DVidar (**Ours**)	**0.4526**	**0.0202**

Network ablation studies demonstrate the effectiveness of the self-attention mechanism, while architectural ablation experiments validate the contribution of multi-point and multipath signals.



(a) AAFE. (b) AAPPE.

Conclusion

- In this paper, we propose 3DVidar, a contact-free 3D vibration sensing system using a single mmWave radar. We develop multi-point multi-path signal enhancement and virtual antenna combination methods to fully expand the radar information from different views.
- Then, we propose a data-driven approach called TriVFormer to learn the complex relationship between the radar information and the 3D vibration trajectory. We implement 3DVidar on a commercial mmWave radar. The results demonstrate that it can effectively reconstruct 3D vibration trajectories under various conditions, achieving low mean errors in both frequency and amplitude.
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