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DASformer: real-time simultaneous demodulation and denoising network for distributed acoustic sensing

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Distributed acoustic sensing (DAS) technology enables intensive and continuous environmental monitoring by extracting Rayleigh backscattering (RBS) signals from optical fiber sensors. Leveraging its distributed detection capability and wide measurement bandwidth, this technology generates massive datasets that have significantly advanced geophysical research [1]. Furthermore, it provides sensing and measurement solutions for emerging applications such as intelligent urban traffic monitoring scenarios [2]. Coherent detection-based phase demodulation schemes enable quantitative measurement of phase variations in RBS signals, thereby achieving proportional recovery of relative changes induced by external disturbances. However, conventional methods suffer from three major limitations: (i) manual band segmentation for interference fading mitigation increases computational overhead and degrades spatial resolution; (ii) phase unwrapping errors under high strain violate the Itoh criterion, causing progressive signal distortion [3]; and (iii) inability to support real-time processing of massive DAS data streams.

To overcome these limitations while enhancing the processing efficiency of massive DAS data, we experimentally demonstrate a Transformer-based network (DASformer) for simultaneous phase demodulation and denoising through campus fiber field trial. Unlike convolutional neural network (CNN)-based approaches, the Transformer's self-attention mechanism and parallel architecture inherently accelerate demodulation speed while capturing global context to restore local perturbation details. Trained on synthetic datasets via supervised learning, the network directly outputs differential phase, eliminating phase-unwrapping errors and synchronously suppressing random noise, laser-induced phase drift, and interference fading. Custom shifted patch dual attention (Shifted-PDA) blocks and locally enhanced feed-forward (LeFF) layers enhance spatial resolution to sub-meter scales, enabling discrimination of adjacent disturbances. DASformer thus enables real-time demodulation-denoising processing, streaming high-quality phase signals to downstream decision modules for intelligent sensing applications.

Network framework. In Figure 1(a), DASformer adopts an encoder-only Transformer architecture with stacked Shifted-PDA blocks and PDA blocks. The network tokenizes raw RBS traces into continuous embeddings, enabling parallel processing of fixed-length sequences corresponding to 20-meter fiber spans. Shifted-PDA alternates patch cyclic shifts to capture multi-scale local-global dependencies, while LeFF employs depthwise separable convolution along the temporal axis for enhanced local feature extraction ability, shown in Figure 1(b). Trained on 50000 synthetically generated fiber channels with physics-based data augmentation (see Appendix B), DASformer suppresses noise and fading without requiring manual band segmentation or reference traces. The supervised learning paradigm incorporates accumulated phase noise modeling to ensure robustness against laser frequency drift. Detailed self-attention mechanisms, loss function design, and ablation experiments are provided in Appendix C.

Experimental setup. Field trials were conducted using ground-armed fiber loosely laid along a 200-meter campus road section in Figure 1(c), with sections crossing asphalt, marble slabs, and soil to emulate heterogeneous urban environments. A heterodyne-detection DAS system injected 1 μs chirped pulses (100–1100 MHz bandwidth) at a 2000 μs repetition rate, acquiring RBS traces at 3.2 GSps. The experimental campaign included buried-fiber active-source localization using an iron ball striker, and traffic monitoring of pedestrians and vehicles. Detailed optical configurations, acquisition parameters, and the full schematic of the experimental apparatus are described in Appendix D.

Demodulation performance. Evaluation metrics including spatial resolution, SNR improvement, computational latency, and floating-point operations per second (FLOPs) are systematically defined in Appendix E. Figure 1(d) compares DASformer with the sub-chirped-pulse extraction algorithm (SPEA) [4] for resolving vehicle front/rear wheel signals. DASformer achieves sub-meter spatial resolution and clearly distinguishes adjacent wheels, whereas SPEA suffers from degraded spatial resolution and fails to separate the two wheel signatures. SNR improvements of DASformer over SPEA are demonstrated across multiple fiber tests, located directly beneath the ground-armed fiber shown in Figure 1(c), including active-source localization, pedestrian running detection and vehicle signal detection. Figure 1(e) quantifies real-

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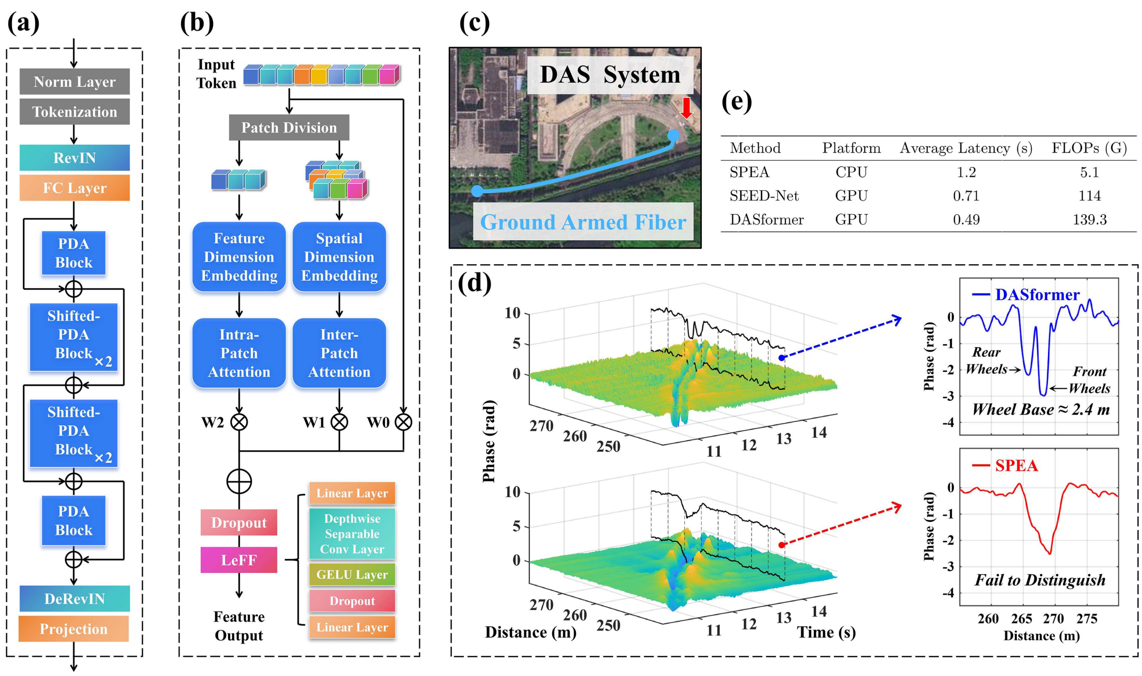

Method	Platform	Average Latency (s)	FLOPs (G)
SPEA	CPU	1.2	5.1
SEED-Net	GPU	0.71	114
DASformer	GPU	0.49	139.3

Figure 1 (Color online) (a) Overall structure of DASformer; (b) shifted-PDA block and LeFF layer; (c) campus fiber layout for field trials; (d) three-dimensional zoom-in and the results of 6750th time-channel by DASformer (blue) and SPEA (red); (e) computational efficiency comparison.

time performance: average computational latency and FLOPs are evaluated for DASformer, SPEA and SEED-Net [5]. Detailed demodulation-performance benchmarks and comparisons are provided in Appendix F.

Discussion. DASformer's ability to stream demodulated data to downstream decision modules enables integrated demodulation-denoising-decision (3D-Processing) for intelligent DAS applications. In a 30-minute field trial, DASformer's outputs processed by a Swin-Transformer decision module achieved 94% overall detection accuracy (170/180 windows correctly identified). Detailed per-class precision, recall, and F1-scores are provided in Table F1 of Appendix F.2. This validates DASformer's capability to provide stable, high-quality data for real-time AI-driven analysis. The parallel architecture delivers substantial speed advantages over both conventional SPEA and CNN-based SEED-Net, particularly as data size scales. While fiber coupling conditions affect all demodulation methods equally, DASformer's superior noise suppression and spatial resolution enable sub-meter feature extraction, such as distinguishing vehicle wheelbases. This establishes a practical foundation for DAS deployment in smart-city infrastructure, facilitating broader adoption of fiber-optic sensing technologies beyond geophysical research.

Conclusion. We demonstrate DASformer as a real-time Transformer-based solution overcoming conventional DAS phase demodulation limitations. With enhanced spatial resolution, significant SNR improvement, and faster processing than conventional methods, it enables intelligent 3D-Processing for traffic monitoring. This work establishes a foundation for AI-driven DAS systems in smart-city applications, providing stable, high-quality data streams for downstream intelligent modules.

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Supporting information Appendixes A–F. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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