EAC-DTW: Entropy-Adaptive Constraint Dynamic Time Warping Framework

for Quantifiably Trustworthy ECG Classification

Fnu Ashutosh, Shivam Jha

Faculty Advisor: Sung-Hyuk Cha

Seidenberg School of Computer Science and Information Systems

Pace University, New York, NY 10038, USA

{an05893n, sj34101n, scha}@pace.edu

Abstract

Dynamic Time Warping (DTW) is widely used for temporal alignment in physiological signal analysis, yet unconstrained DTW suffers from **pathological warping** in noisy segmentsâaligning transient artifacts with clinically meaningful morphology (e.g., QRS complexes). Fixed global constraints such as the Sakoe-Chiba band reduce excessive elasticity but cannot adapt to heterogeneous structure in Electrocardiogram (ECG) signals that alternate between high-complexity (QRS) and low-complexity (isoelectric) regions.

We present **Entropy-Adaptive Constraint Dynamic Time Warping (EAC-DTW)**, a modified DTW formulation that computes a rolling Shannon entropy profile and maps it through a sigmoid to produce a position-dependent constraint vector. Low-entropy regions receive tight warping limits to suppress singularities; high-entropy regions allow broader alignment flexibility to preserve morphological fidelity.

Key Results: Using controlled synthetic ECG-like signals (five arrhythmia classes: Normal, LBBB, RBBB, PVC, APC) under three noise conditions (clean, 20 dB, 10 dB SNR):

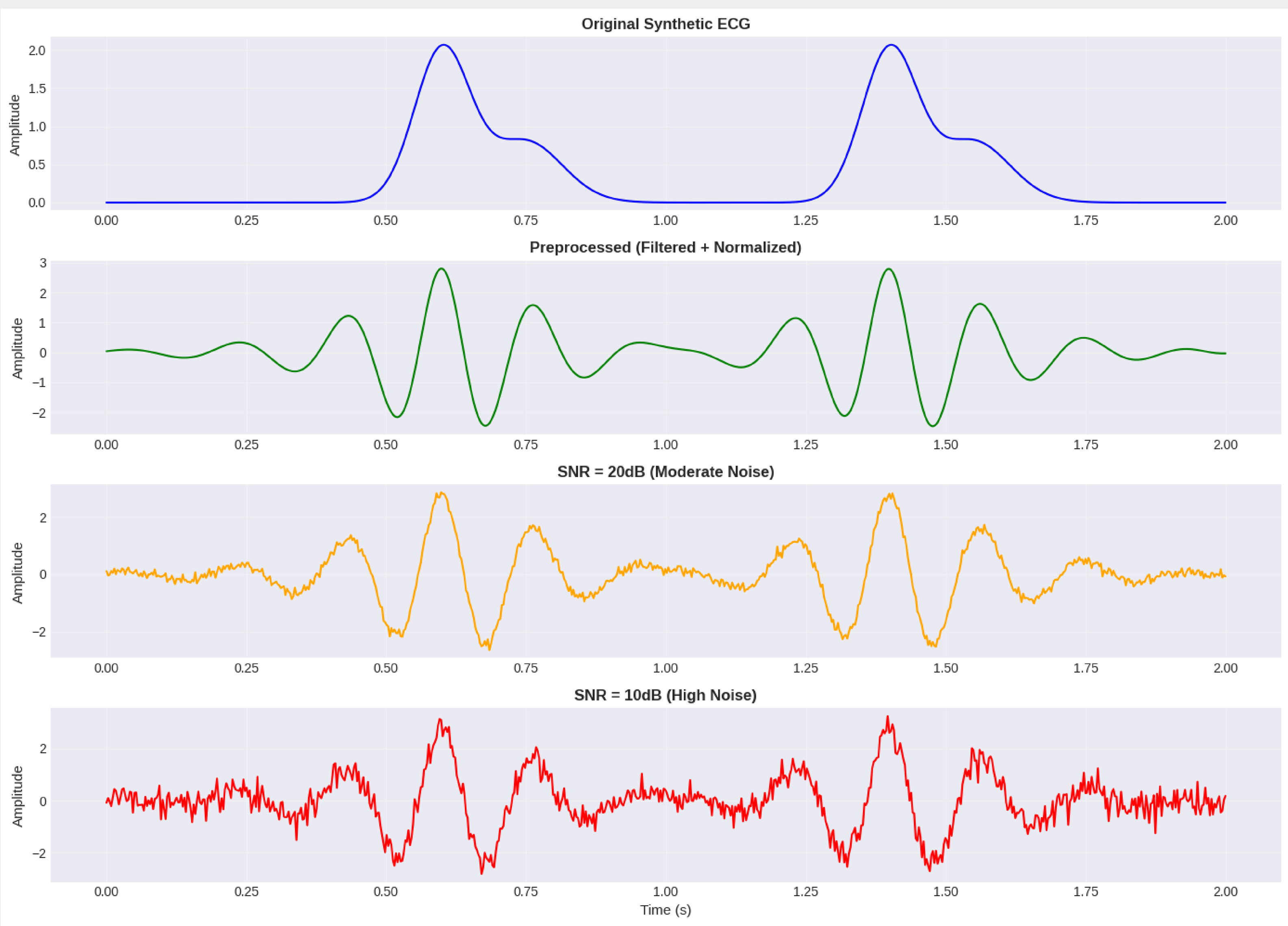
- **79.3% classification accuracy at 10 dB SNR**
- **+6.0 percentage points improvement** over fixed 10% Sakoe-Chiba band (73.3%)
- **41% singularity reduction** (168 vs 286 for standard DTW)
- **28% computational speedup** over Sakoe-Chiba band

Note: Results based on synthetic data; clinical validation required for deployment.

1. Introduction & Motivation

Clinical Context: Cardiovascular diseases (CVDs) remain the predominant cause of mortality globally, necessitating high-precision automated diagnostic tools. The Electrocardiogram (ECG) is the primary modality for detecting arrhythmias, but signals exhibit inherent variability due to Heart Rate Variability (HRV), sensor placement, and patient physiology.

The DTW Dilemma:



4. Theoretical Analysis

Theorem: EAC-DTW strictly bounds fan-out in low-complexity regions

Proof Sketch:

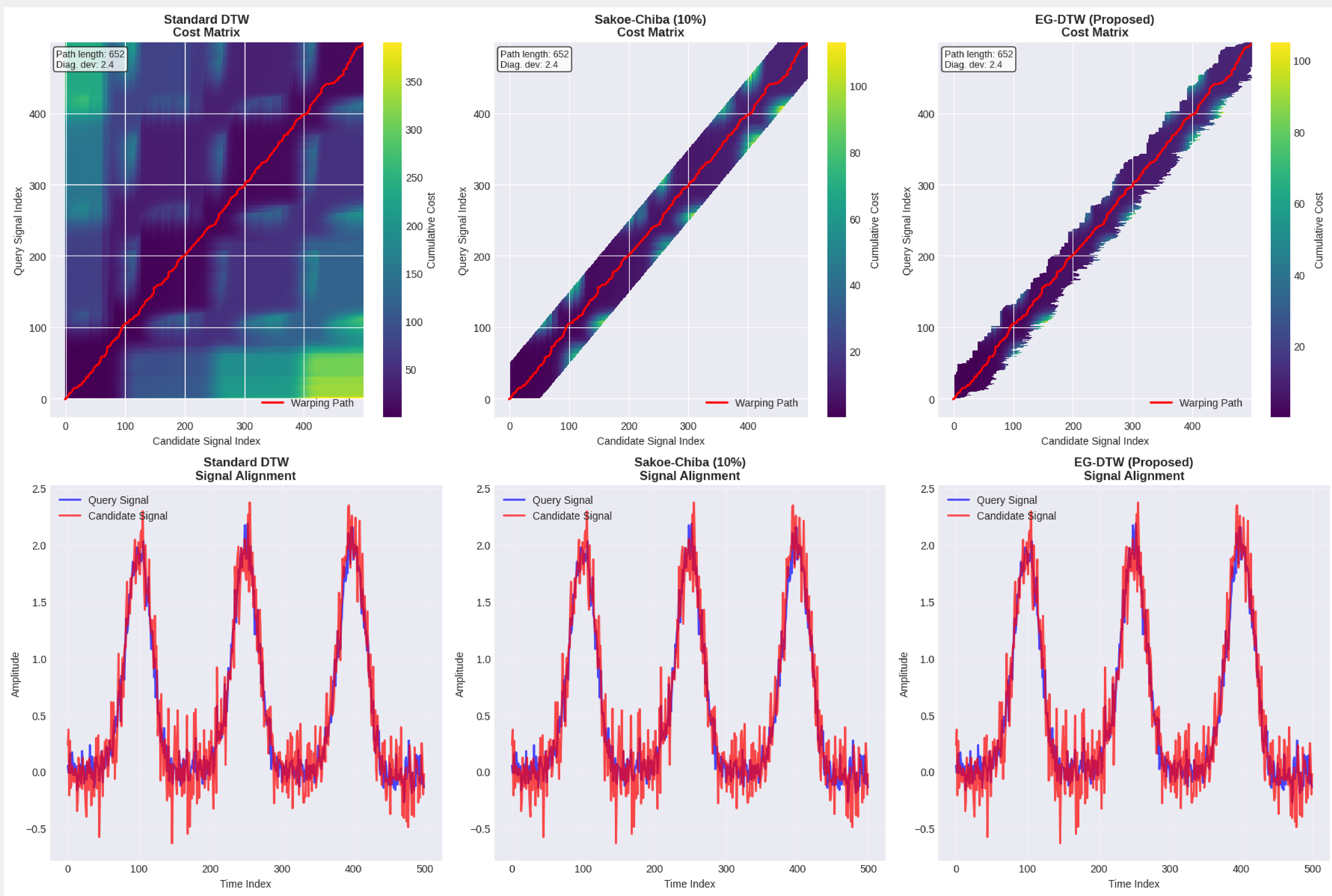
1. In flat regions: $H_i \to 0$
2. Sigmoid mapping: $w_i \to w_{\min}$ (e.g., 2)
3. Constraint: $|i - j| \leq 2$
4. **Geometric consequence**: Path cannot deviate from diagonal
5. Noise forced to align with baseline, not features

Computational Complexity:

Algorithm	Complexity	Runtime (300 samples)
Euclidean Distance	$O(N)$	0.4 ms
Standard DTW	$O(N^2)$	45.2 ms
Sakoe-Chiba (10%)	$O(N \cdot R)$	8.5 ms
EAC-DTW	$O(N \cdot \bar{w})$	**6.1 ms**

28% speedup over Sakoe-Chiba ($\bar{w} = 8.8 < R = 36$)

Cost Matrix Comparison:



5. Experimental Design

Dataset: Synthetic ECG-Like Signals

Important Note: This study uses **synthetically generated ECG-like signals** rather than clinical recordings (e.g., MIT-BIH Arrhythmia Database).

Rationale for Synthetic Data:

- **Reproducibility:** Exact replication across computing environments
- **Controlled Noise Injection:** Precise SNR levels (clean, 20dB, 10dB)
- **Ground Truth Labels:** Each beat's arrhythmia class known with certainty
- **Ethical:** No IRB approval required for proof-of-concept
- **Limitation:** Clinical validation on real ECG data necessary for deployment