ICASSP 2023
Paper ID: 6849

Sub-Nyquist TEM-Based Hardware for Heart Rate Monitoring of ECG Signals

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Motivation and Contributions

- Critical ADC tasks: Sampling and quantization play vital roles in an ADC
- Inefficient conventional ADCs: Conventional ADCs waste power and bandwidth due to underutilization of signal information
- TEM for signal encoding: Time encoding machines (TEM) encode input signals into time sequences, effectively utilizing signal information
- Enhanced noise robustness: Moving the quantization process from the signal amplitude domain to the time domain improves amplitude noise robustness
- Power-efficient sub-Nyquist sampling: Our presented TEM hardware enables efficient sub-Nyquist sampling and recovery of ECG signals, facilitating heart rate monitoring applications

ECG Sampling and Reconstruction

- Variable width pulses: $x(t) = \sum_{k=0}^{L-1} x_k(t), where, x_k(t) = x_k^s(t) + x_k^a(t)$

$$x_k^s(t) = c_k \sum_{p\in\mathbb{Z}} \frac{r_k}{\pi(r_k^2 + (t - t_k - pT)^2)}$$

$$x_k^a(t) = d_k \sum_{p\in\mathbb{Z}} \frac{t - t_k - pT}{\pi(r_k^2 + (t - t_k - pT)^2)}$$

- The signal components $x_k^s(t)$, $x_k^a(t)$ are the symmetric and antisymmetric parts of the pulse
- $4L+1$ Fourier samples of $x(t)$ uniquely determine the parameters $\{t_k, r_k, c_k, d_k\}_{k=0}^{L-1}$
- If the signal is defined on the interval $[0, T]$ the local the rate of innovation is $\frac{4L+1}{T}$
- Sub-Nyquist sampling scheme enables computation of the Fourier samples from low rate samples

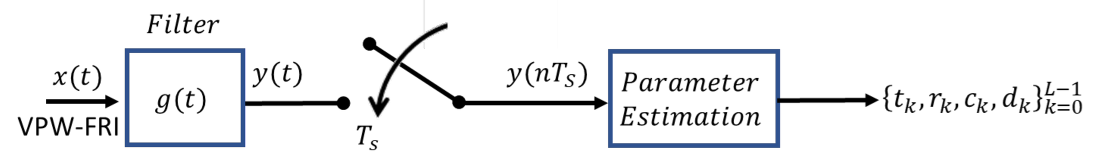


Fig: Sampling and reconstruction of VPW-FRI signal by using a sampling kernel $g(t)$

Baechler, G., Scholefield, A., Baboulaz, L., & Vetterli, M., 2017

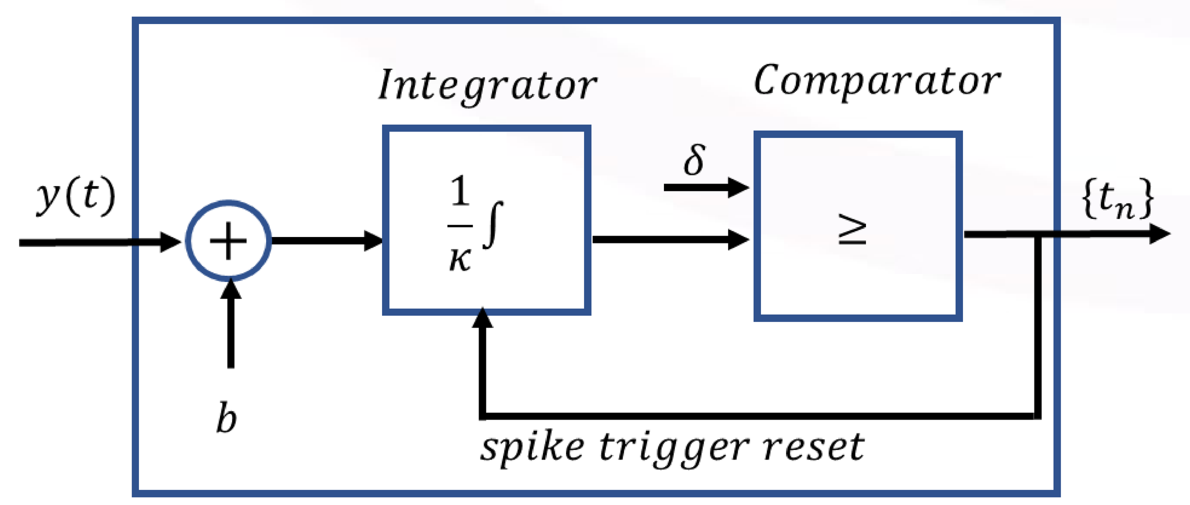
IF-TEM

- An integrate-and-fire time-encoding machine is paramerised by:

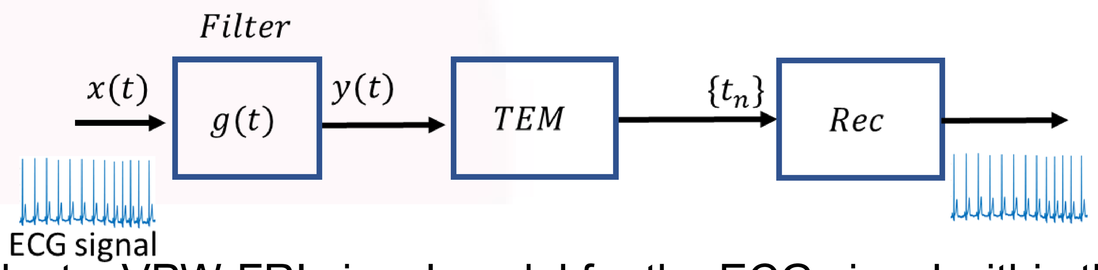
b: The bias

δ: The threshold

κ: The integrator constant

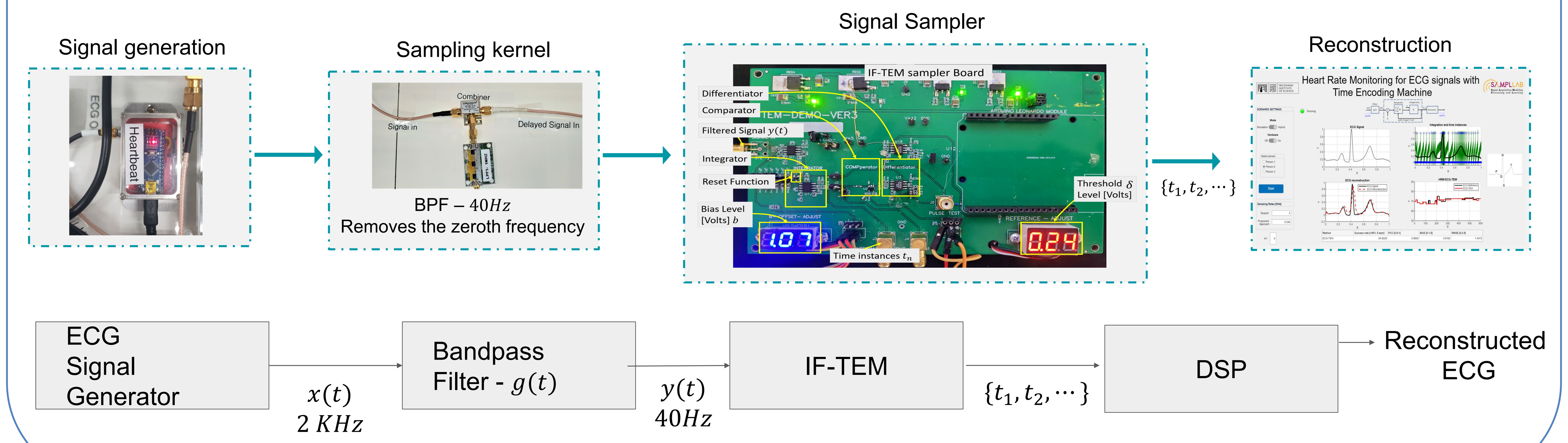


ECG-TEM Sampling

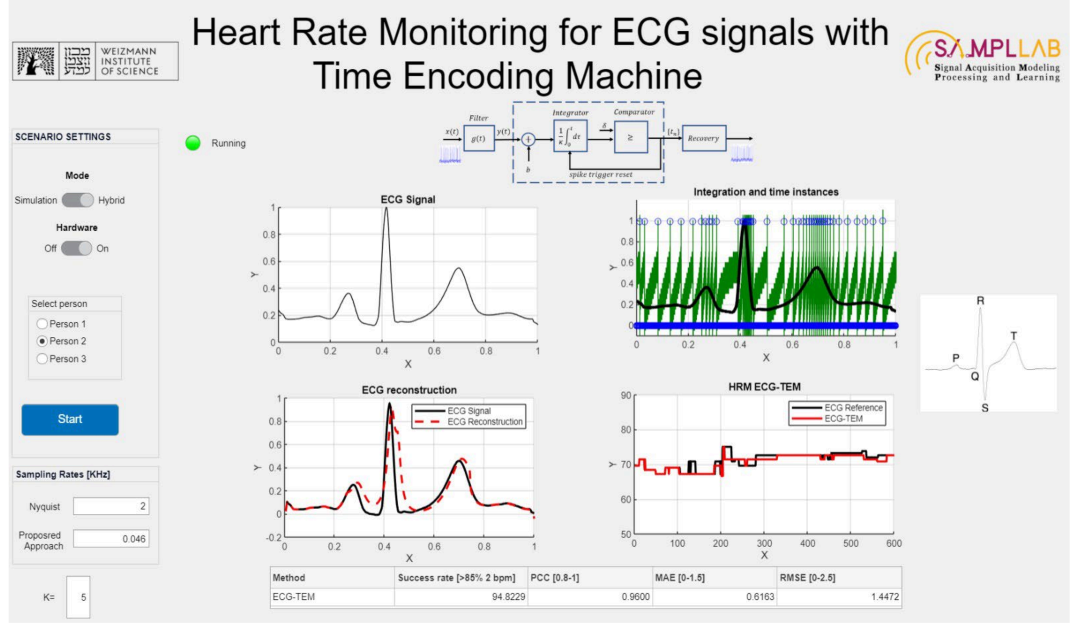


- ECG signal modeling: We adopt a VPW-FRI signal model for the ECG signal within the interval $[0, T]$
- IF-TEM input and output: The IF-TEM takes in a filtered ECG signal and produces time instants as outputs
- Selection of IF-TEM parameters: We choose IF-TEM parameters to ensure there are $8L+2$ time instants within the time interval T
- Definition of IF-TEM firing rate: The firing rate of the IF-TEM is determined by the number of time instants in the interval $[0, T]$
- Computation of Fourier coefficients and estimation: By utilizing TEM time instants, we compute the Fourier coefficients of $x(t)$ and estimate VPW-FRI parameters from them

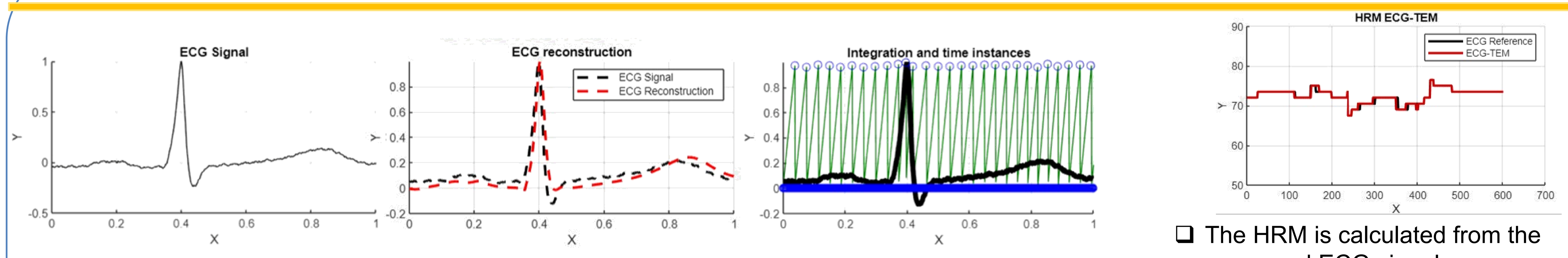
Hardware



User Interface



Results – ECG reconstruction and HRM



Sampling rates: Nyquist 2KHz, IF-TEM firing rate: 42-80Hz

Method	Success rate [>85% 2 bpm]	PCC [0.8-1]	MAE [0-1.5]	RMSE [0-2.5]
ECG-TEM	91.7038	0.9108	0.1519	0.7429

- The HRM is calculated from the recovered ECG signal
- Specifically, we examined the resting scenario, and compared the statistical metrics of the HR estimate with the reference output

Conclusions

- Power-efficient sub-Nyquist sampling: Our TEM hardware enables efficient sub-Nyquist sampling and recovery of ECG signals, benefiting heart rate monitoring
- Enhanced noise robustness: The ECG signal is filtered to remove its zeroth frequency to improve noise resilience
- The processed filtered signal, y(t), is sampled using an IF-TEM sampler, resulting in a firing rate of 42-80Hz, equivalent to approximately 1/20-1/40 of the Nyquist rate

Naaman et. al, 22 Naaman et. al, 23