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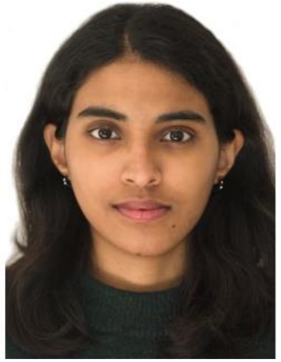

A Generalized Signal Quality Estimation Method for IoT Sensors

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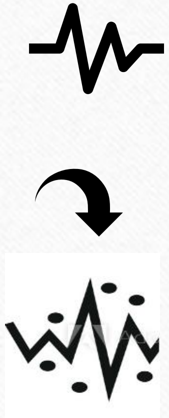
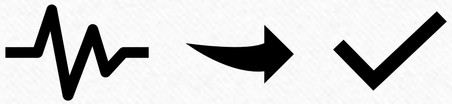
Context

- Current healthcare scenarios- shift of care/ monitoring from hospitals to homes.
- Ambulatory healthcare monitoring- IoT sensors.
- Corrupted by noise.

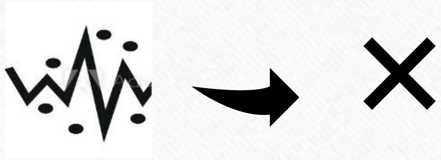


Context

- Signal quality analysis.



- Quality assessment at the edge.



- Confidence metric.

Research Gap

- No general definition of signal quality.
- Designed for a specific signal or noise scenario.
- Instantaneous signal quality assessment method not discussed.

a. Any stage of signal acquisition and processing.
b. Applicable to a number of signals and noise scenarios.
c. Instantaneous signal quality.

Curve SQI (cSQI)

- A generalized signal quality indicator - any periodic or quasi-periodic signals.
- Amount of noise contained in the signal.
- A monotonically increasing function of SNR.
- Based on the waveform morphology - curve SQI (cSQI).
- Performance on ECG signals.

Methodology - Template Generation

Generation of a single cycle template.

Template generation use N cycles of clean data .

Example: ECG signals

Methodology - Template Generation

Table 1: Algorithm for Template Generation

Setup:

A. Signal sequence of interest $\mathbf{x}$

B. Signal vector $\mathbf{X_n}$ of length $2M+1 \triangleq [\mathbf{x}[n-M],\ldots\mathbf{x}[n],\ldots\mathbf{x}[n+M]]$ where M has been decided based on the time period.

C. Let $\mathbf{X}_{\mathbf{n}\,(c)}$ be the correlation Toeplitz matrix of $\mathbf{X_n}$ of dimensions (2M+1, 4M+1) where $\mathbf{X}_{\mathbf{n}\,(c)}=$

$$\begin{bmatrix} \mathbf{x}[n+M] & \ldots\mathbf{x}[n] & \ldots\mathbf{x}[n-M] & \ldots 0 & 0 \\ 0 & \mathbf{x}[n+M] & \ldots\mathbf{x}[n] & \mathbf{x}[n-M] & 0 \\ . & . & . & . & . \\ . & . & . & . & . \\ 0 & 0 & ..\mathbf{x}[n+M] & \ldots\mathbf{x}[n] & \ldots\mathbf{x}[n-M] \end{bmatrix}$$

, where the k^{th} column of $\mathbf{X}_{\mathbf{n}\,(c)}$ is indicated by $\mathbf{X}_{\mathbf{n}}{}^{(k)}{}_{(c)}$ where $k \in [0, 4M]$

D. Let $\mathbf{X_n}^{(t)}$ be t^{th} circular shifted version of $\mathbf{X_n}$ ie., $\mathbf{X_n}^{(t)} = [\mathbf{x}[n-M+t]\ \mathbf{x}[n-M+t+1]\ldots\mathbf{x}[n+M]\ \mathbf{x}[n-M]\ldots\mathbf{x}[n-M+t-1]]$

Template Generation:

1. Identify a signal segment containing N consecutive fiducial features of interest (From the time period or otherwise).
2. Let $\mathbf{n_0}$ be the center of the first segment of length $2M+1$, $\mathbf{Xn_0}$.
3. Initialize $\mathbf{T}=\mathbf{Xn_0}$.
4. For $\mathbf{i}=(M+1)$ to $(\mathbf{N}(2M+1)\text{-}M)$ in steps of $2M+1$
   a. Let $\mathbf{X}_{\mathbf{n_0+i}\,(c)}$ be the correlation Toeplitz matrix of $\mathbf{X}_{\mathbf{n_0+i}}$
   b. Let $\mathbf{k} = \text{argmax}_j\ [\left|\mathbf{T}.\mathbf{X}^{(j)}_{\mathbf{n_0+i}\,(c)}\right|]$
   c. If $\mathbf{k} \approx \mathbf{n_0}$

      $$\mathbf{T}=\mathbf{T}+\mathbf{X}^{(\mathbf{k})}_{\mathbf{n_0+i}}$$

      End

   End
5. Normalize $\mathbf{T}$ based on number of times condition 4.c was satisfied.

Methodology - Template Generation

x[1]	x[2]	x[3]	x[4]	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		.

- Window of length 2M+1
- Centered at say n_0

$x[n_0-M]$	$x[n_0-M+1]$	.	.	$x[n_0]$	.	.	$x[n_0+M-1]$	$x[n_0+M]$

x[1]	x[2]	x[3]	x[4]	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		.

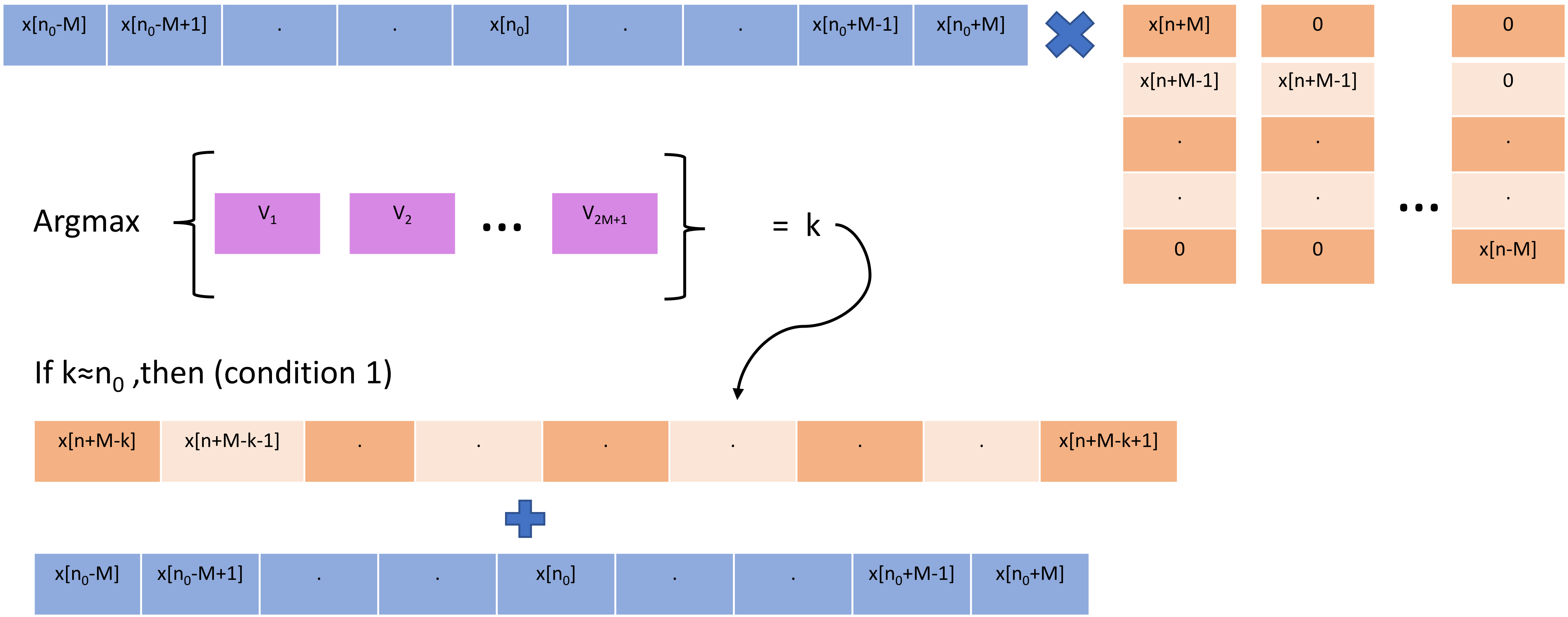
x[n-M]	x[n-M+1]	.	.	x[n]	.	.	x[n+M-1]	x[n+M]

Methodology - Template Generation

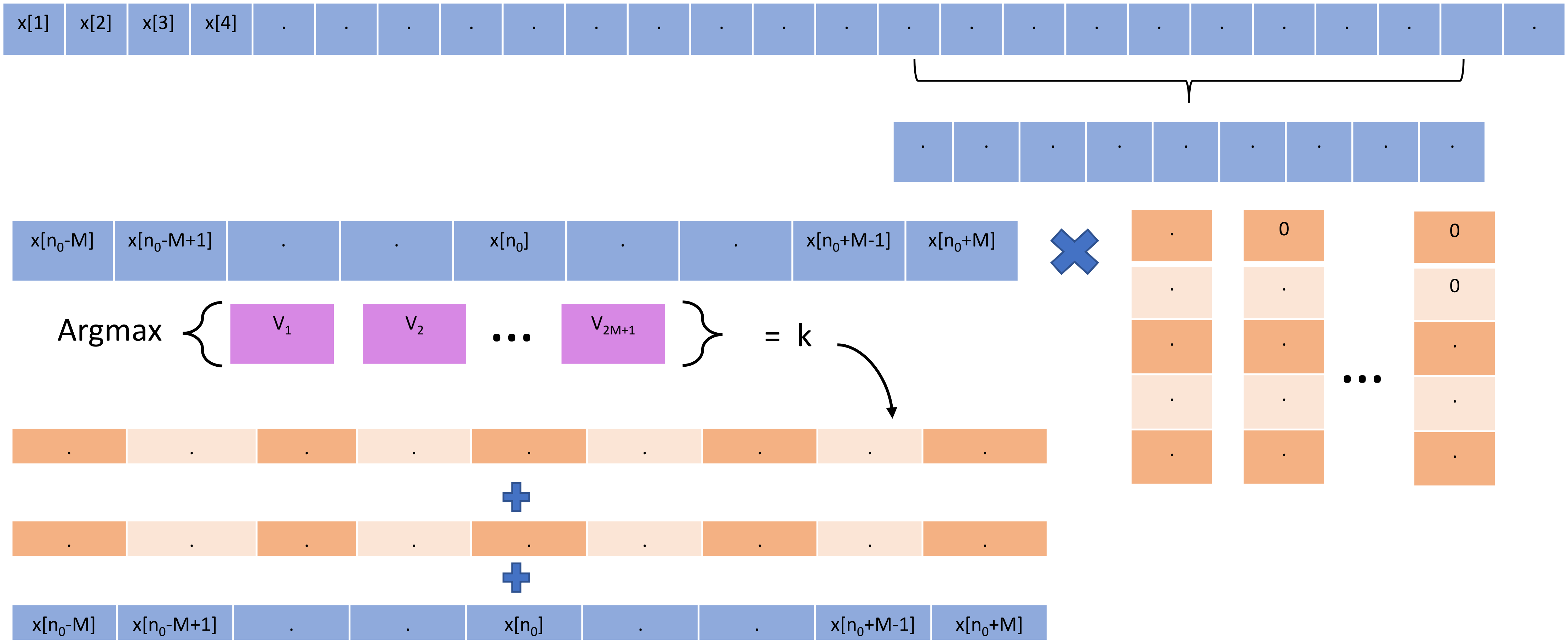
x[n-M]	x[n-M+1]	.	.	x[n]	.	.	x[n+M-1]	x[n+M]

x[n+M]	x[n+M-1]	.	.	X[n]	x[n-1]	.	.	x[n-M+1]	x[n-M]	0	.	.	0
0	x[n+M]	x[n+M-1]	.	.	x[n]	x[n-1]	.	.	x[n-M+1]	x[n-M]	0	.	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
0	0	.	0	0	.	.	.	0	0	x[n+M]	.	x[n-M+1]	x[n-M]

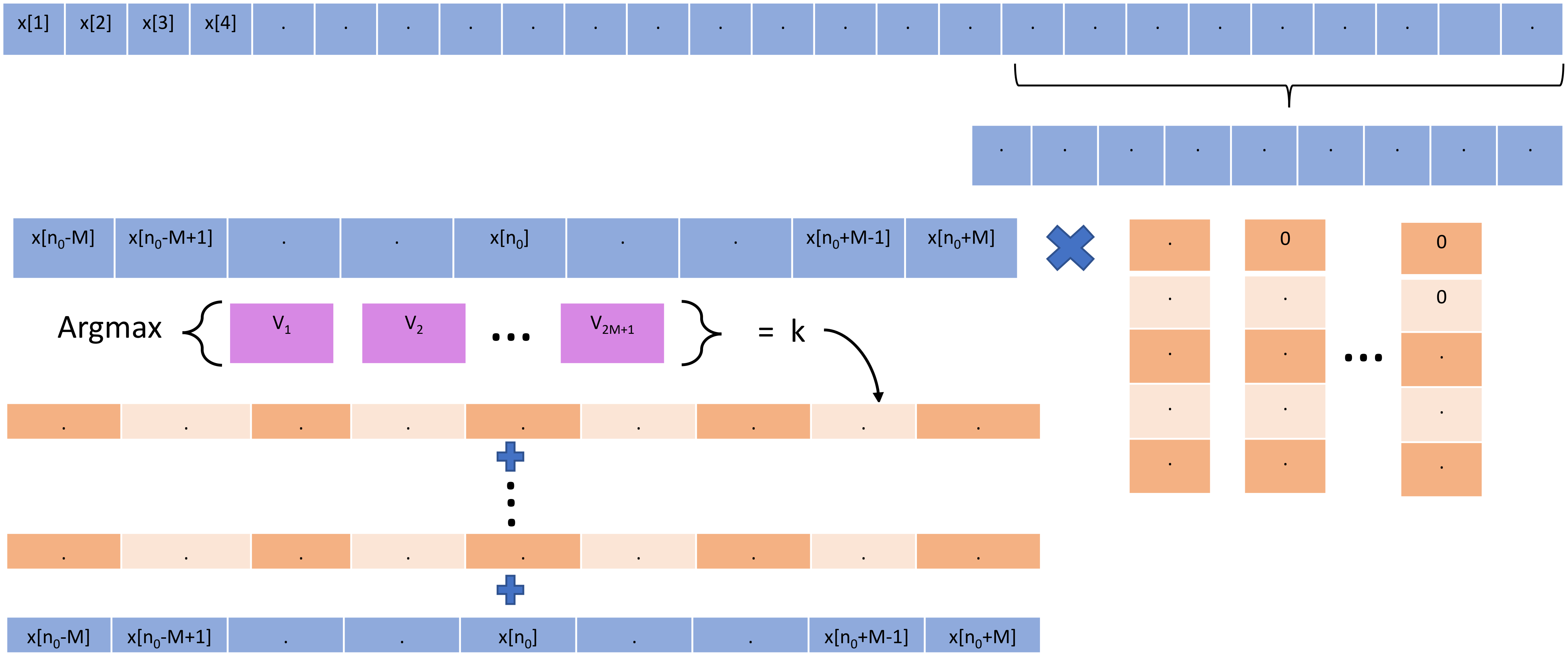
Methodology - Template Generation



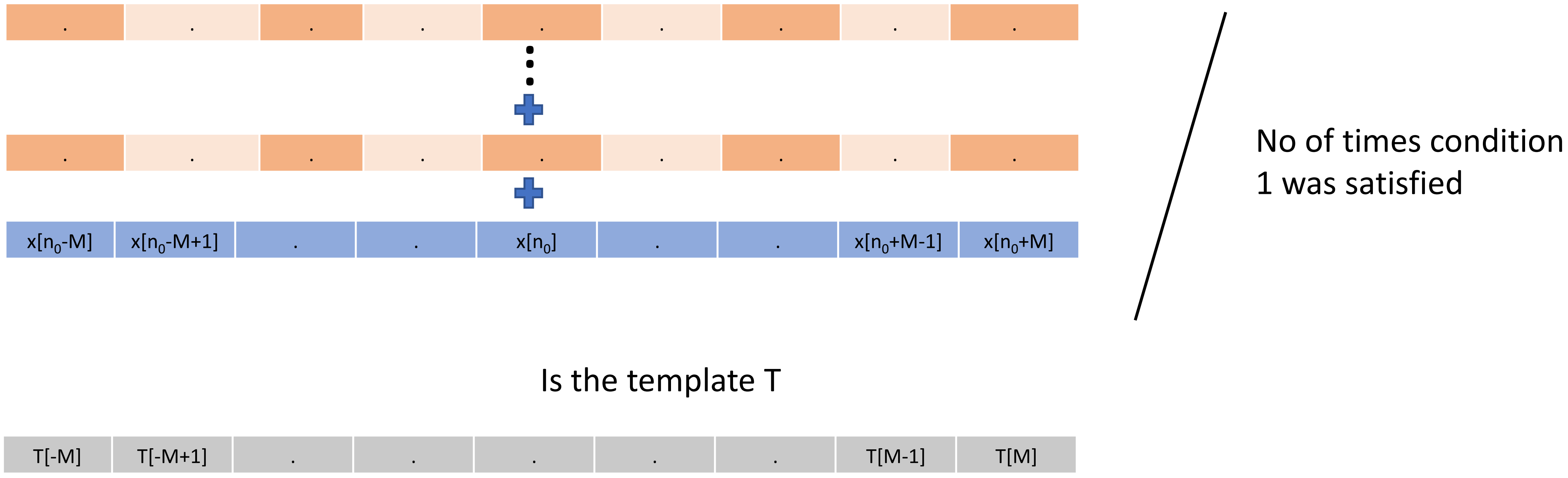
Methodology - Template Generation



Methodology - Template Generation



Methodology - Template Generation



Methodology - Template Generation

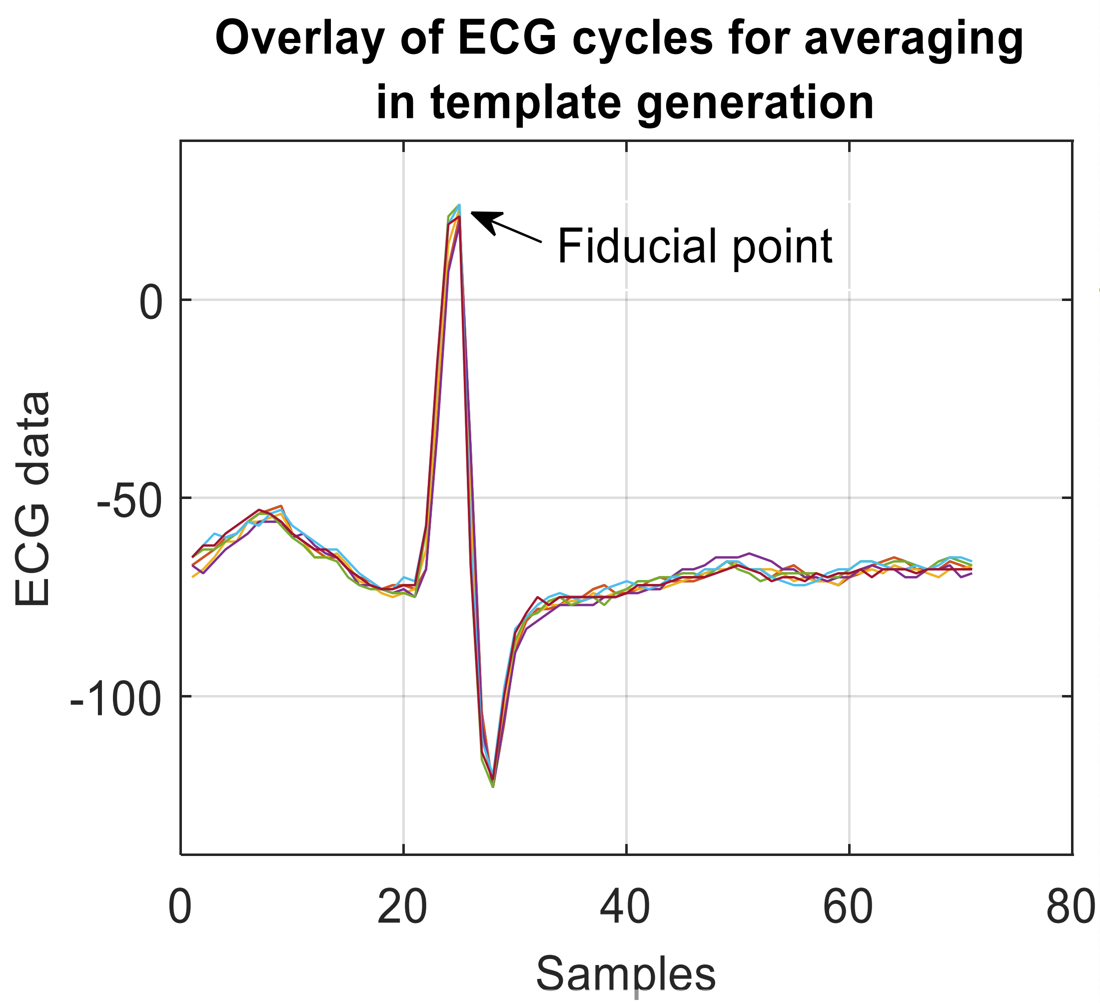


Fig. 1

- 10 cycles.
- template length- 70% of the average time period.
- missed fiducial point- segment discarded (condition 1).
- ECG- Q wave

Methodology- cSQI calculation

- Assigns quality value for each signal sample.
- Signal window centered at that sampled.
- cSQI [t_0] -> inverse of the variance of the difference between the template and signal window centered at t_0 at the point of maximum correlation with the template.
- cSQI [t_1] -> shifting the window.

Methodology- cSQI calculation

Table 2: Algorithm for cSQI calculation

Initialize and calculate c[0]:

A. Let $\mathbf{T}_{(c)}$ be the Toeplitz correlation matrix of the template **T.** $\mathbf{T}_{(c)}$ [u] indicates u^{th} row of the matrix with $u \in [0, 2M]$

B. Signal vector $\mathbf{S_0}$ of length $2M+1 \triangleq$ [**s**[-M],… **s**[0],…**s**[M]] where M has been decided based on the time period, centered at **s**[0].

C. Lag sequence **L=**[-M -M+1 …0…M-1 M]

D. Calculate **A'= S₀** X **T** where **A'** is the L-R flipped result of the correlation sequence

E. Lag t=**L**[argmax(**A**)]

F. **c** [0]= $(\mathrm{var}(\mathbf{S_0}-\mathbf{T}^{(t)}))^{-1}$ and **b=s**[-M]

Loop till no signal is read:

For **i**=1 to **Z** in steps of 1

a. Window centered at **s**[i], $\mathbf{S_i}$ of length 2M+1.

b. **NR**=s[i+M]**.** $\mathbf{T}_{(c)}$ [2M] and **FR**=**b.** $\mathbf{T}_{(c)}$ [0]

c. Calculate L-R flipped correlation sequence $\mathbf{A'}=(\mathbf{A'}-\mathbf{FR})^{(1)}+\mathbf{NR}$

d. Lag t=**L**[argmax(**A**)]

e. **c** [i] = $(\mathrm{var}(\mathbf{S_k}-\mathbf{T}^{(t)}))^{-1}$ and **b**=s[i-M]

End

cSQI= LPF(c), where the low pass filter could be a moving average filter to avoid rapid variations that can be attributed to edge effects of windowing. The block diagram of the algorithm for a circuit implementation is shown in Fig 1.

cSQI calculation

T[-M]	T[-M+1]	.	.	.	.	.	T[M-1]	T[M]

T[n+M]	T[n+M-1]	.	.	T[n]	T[n-1]	.	.	T[n-M+1]	T[n-M]	0	.	.	0
0	T[n+M]	T[n+M-1]	.	.	T[n]	T[n-1]	.	.	T[n-M+1]	T[n-M]	0	.	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
0	0	.	0	0	.	.	.	0	0	T[n+M]	.	T[n-M+1]	T[n-M]

.	.	.	s[3]	s[2]	s[1]	s[0]	s[1]	s[2]	s[3]	.	.	.	.	.	.	.	.	.	.	.	.

s[-M]	s[-M+1]	.	.	s[0]	.	.	s[M]

cSQI calculation

s[-M]	s[-M+1]	.	.	s[0]	.	.	s[M]

×

T[n+M]	T[n+M-1]	.	.	T[n]	T[n-1]	.	.	T[n-M+1]	T[n-M]	0	.	.	0
0	T[n+M]	T[n+M-1]	.	.	T[n]	T[n-1]	.	.	T[n-M+1]	T[n-M]	0	.	0
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
0	0	.	0	0	.	.	.	0	0	T[n+M]	.	T[n-M+1]	T[n-M]

= A_0' =

A[M]	A[M-1]	.	.	A[0]	.	.	A[-M+1]	A[-M]

=> A_0 =

A[-M]	A[-M+1]	.	.	A[0]	.	.	A[M-1]	A[M]

cSQI calculation

Lag Matrix, L=

-M	-M+1	.	.	0	.	.	M-1	M

Argmax

A[-M]	A[-M+1]	.	.	A[0]	.	.	A[M-1]	A[M]

= arg

1	2	3	.	.	arg	.	.	2M+1
-M	-M+1	.	.	0	.	.	M-1	M

Lag t

c[0] = 1 / Var

A[-M]	A[-M+1]	.	.	A[0]	.	.	A[M-1]	A[M]

$T^{(t)}$ =

T[-M+t]	T[-M+1+t]	.	.	.	.	.	T[-M+t-2]	T[-M+t-1]

cSQI calculation

For every subsequent c[i]:

To calculate, c[1] =

.	.	.	s[3]	s[2]	s[1]	s[0]	s[1]	s[2]	s[3]	.	.	.	.	.	.	.	.	.	.	.	.

s[-M+1]	s[-M+2]	.	.	s[1]	.	.	s[M+1]

s[M+i]

s[M+1] ✖ Last row of Template Toeplitz matrix

0	0	.	0	0	.	.	.	0	0	T[n+M]	.	T[n-M+1]	T[n-M]

=

NR[0]	NR[1]	.	.	.	.	.	.	.	.	.	.	NR[M-1]	NR[M]

cSQI calculation

s[-M] ✖ First row of Template Toeplitz matrix

s[-M-(i-1)]

T[n+M]	T[n+M-1]	.	.	T[n]	T[n-1]	.	.	T[n-M+1]	T[n-M]	0	.	.	0

=

FR[-M]	FR[-M+1]	.	.	.	FR[0]	.	.	.	.	.	.	FR[M-1]	FR[M]

A_{i-1}'- FR=

A[M]-FR[-M]	A[M-1]-FR[-M+1]	.	.	A[0]-FR[0]	.	.	A[-M+1]-FR[M-1]	A[-M]-FR[M]

$(A_0' - FR)^{(1)}$ =

A[M-1]-FR[-M+1]	.	.	A[0]-FR[0]	.	.	A[-M+1]-FR[M-1]	A[-M]-FR[M]	A[M]-FR[-M]

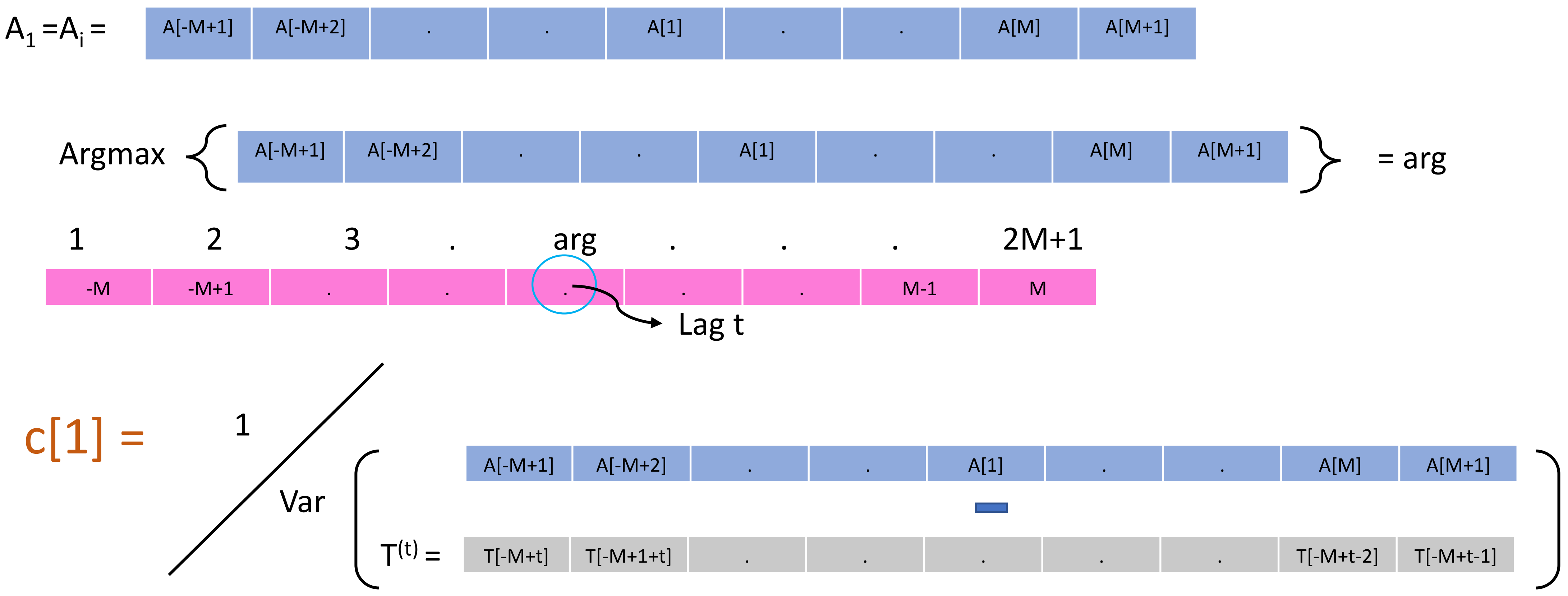
$A_i'=A_1'$=

A[M-1]-FR[-M+1]	.	.	A[0]-FR[0]	.	.	A[-M+1]-FR[M-1]	A[-M]-FR[M]	A[M]-FR[-M]

+

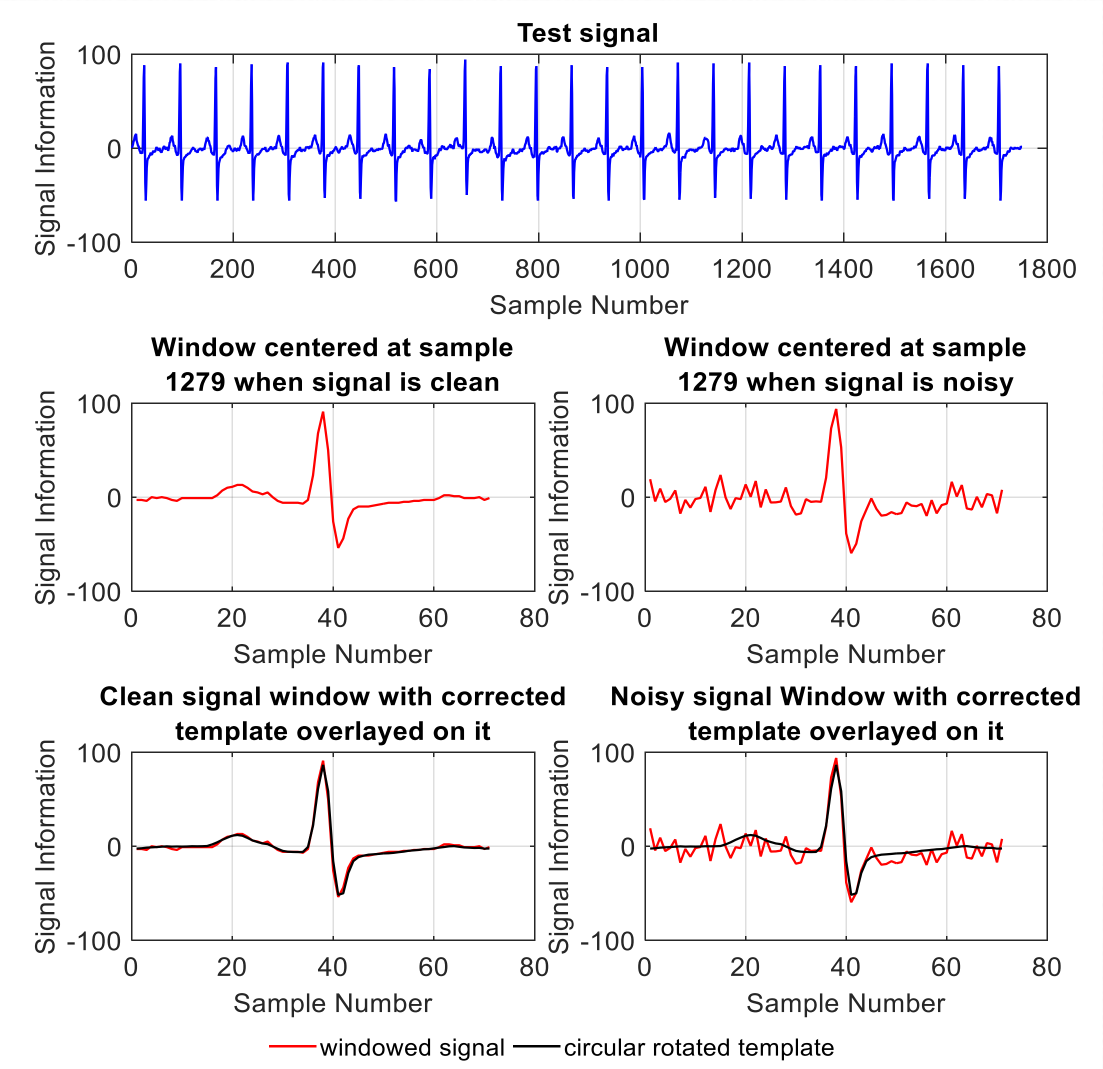
NR[0]	NR[1]	.	.	.	.	.	NR[M-1]	NR[M]

cSQI calculation



Methodology- cSQI calculation

- cSQI - corrupted by 5 dB Gaussian noise and when clean.
- The template generated (Fig. 1) is circularly rotated – align with fiducial feature.
- Difference - would correspond to noise.



Performance Evaluation

- cSQI
  - 50 Hz power line interference,
  - Baseline Wander,
  - Muscle Artifacts, and
  - Electrode Motion at -10 dB.

- For all noisy samples- cSQI lower than clean samples

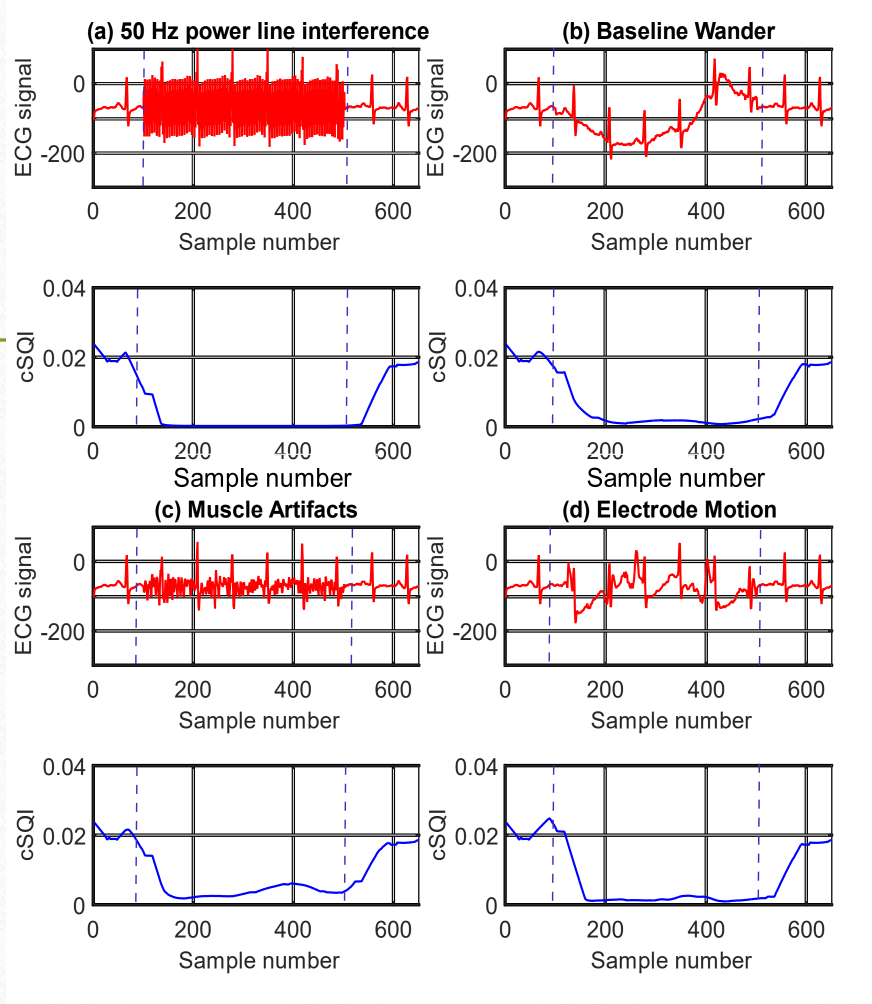


Fig. 3.

Performance Evaluation

- The cSQI vs SNR plot
- SQI averaged over the entire signal
- cSQI- almost linear behavior in the medium SNR ranges

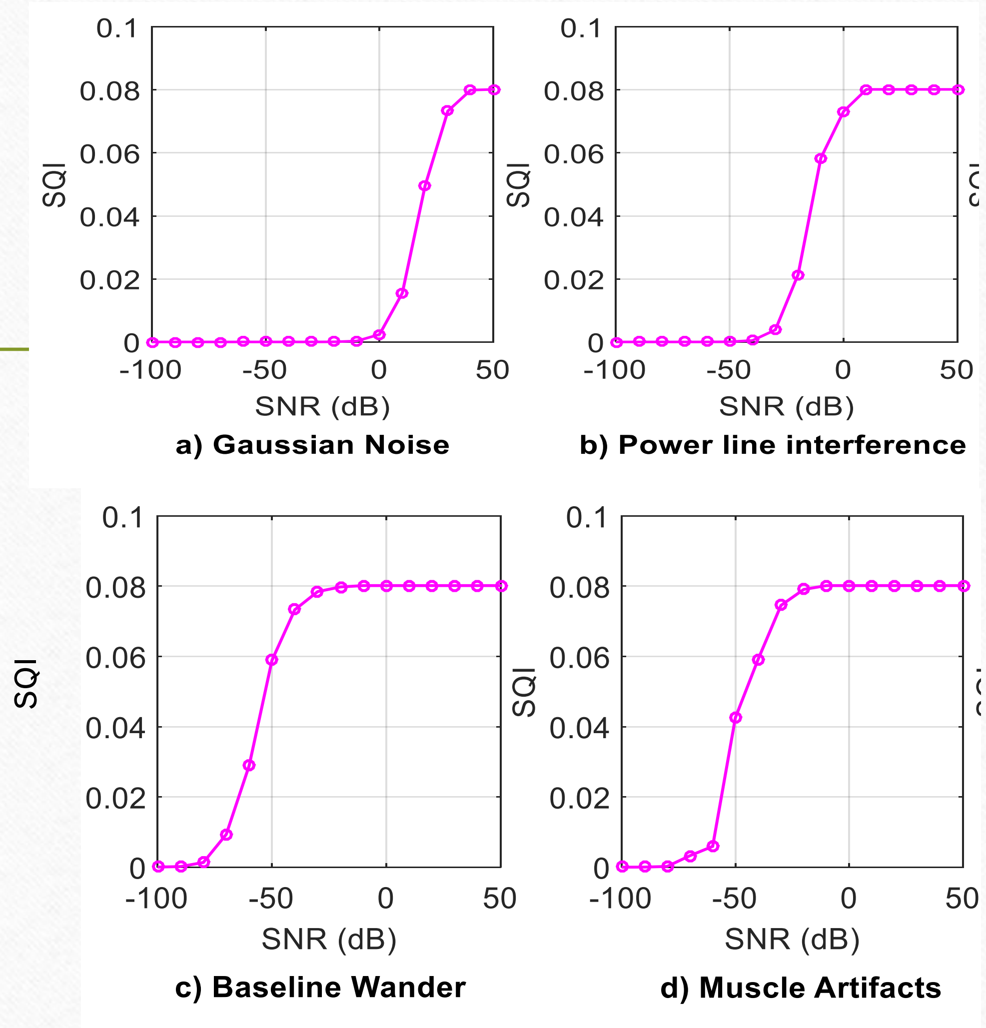


Fig. 4.

Performance Evaluation

cSQI performance- records of CinC 2011 challenge.

Validation set score - 0.938.

Test set score - 0.904 (Event 1)

Circuit Diagram

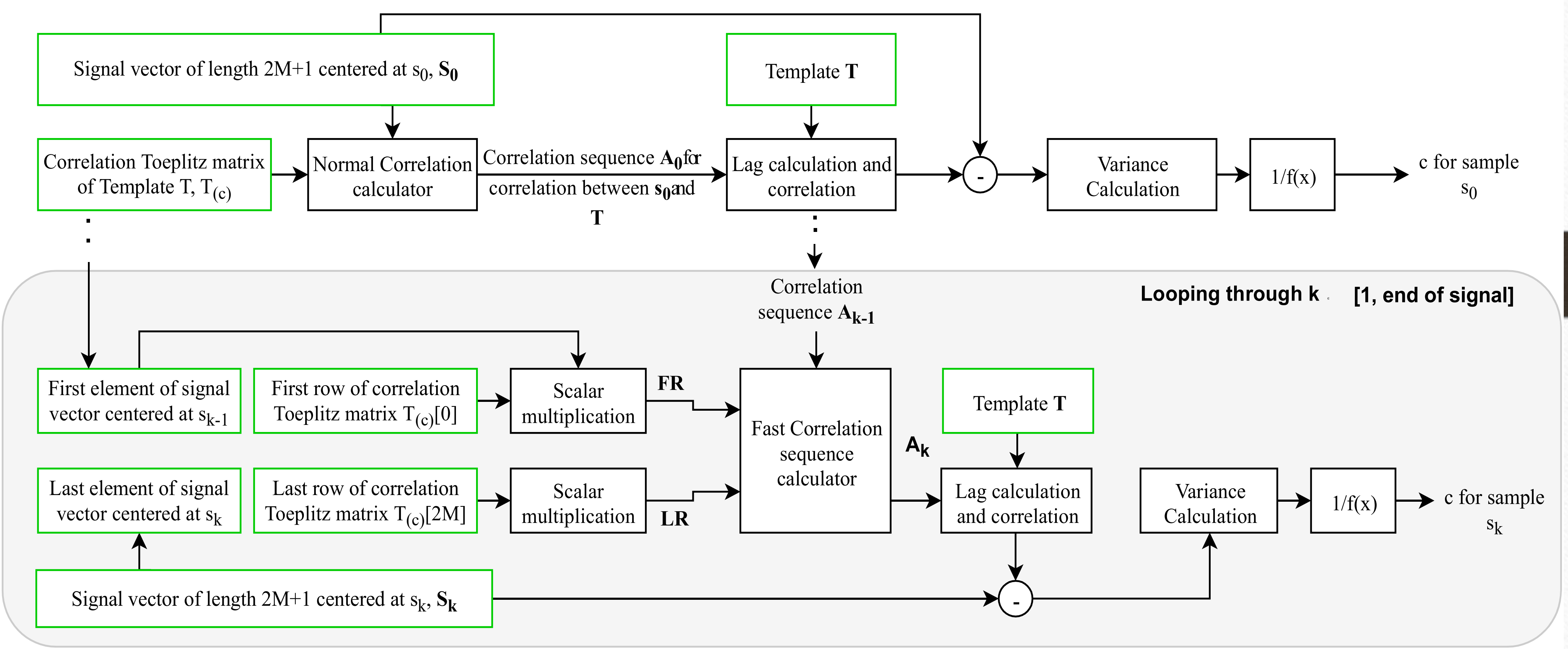


Fig. 4.

Complexity Evaluation

Operation	Count	Count for N=10, M=35 for F_s=125
Multiplication	N ($8M^2+6M+1$)	100110
Addition	N ($8M^2+4M+1$)	99410

TABLE 3. Complexity of template generation

Operation	Count	Count for M=35 for F_s=125
Multiplication	$8M^2+8M+3$	10083
Addition	$8M^2+6M+1$	10011

TABLE 4. Complexity of cSQI calculation for the first c[0]

- Low computational complexity.
- Smart Algorithm design.

Operation	Count	Count for M=35 for F_s=125
Multiplication	10M+3	353
Addition	12M+3	423

TABLE 5. Complexity of cSQI calculation for every subsequent sample after initialization

Conclusions

Novel generalized signal quality indicator

Any periodic or quasi-periodic signal- identifiable fiducial point.

A monotonically increasing function of SNR.

Low complexity- attractive option for edge IoT devices.

THANK YOU