Evaluation of Tracking Regimes for, and Security of PLI Systems

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer Engineering

by

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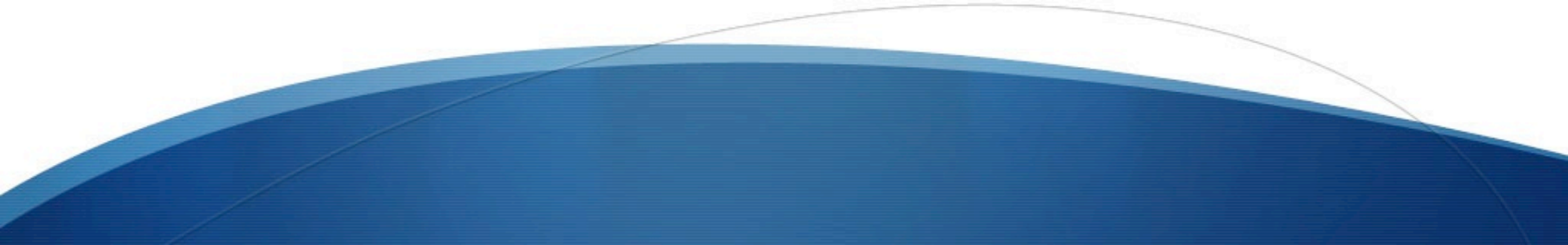
Overview

1. Introduction
2. Physical Layer Identification System
3. Tracking System Models
4. PLI System Security Evaluation
5. Conclusion
6. Acknowledgement
7. Questions



Introduction

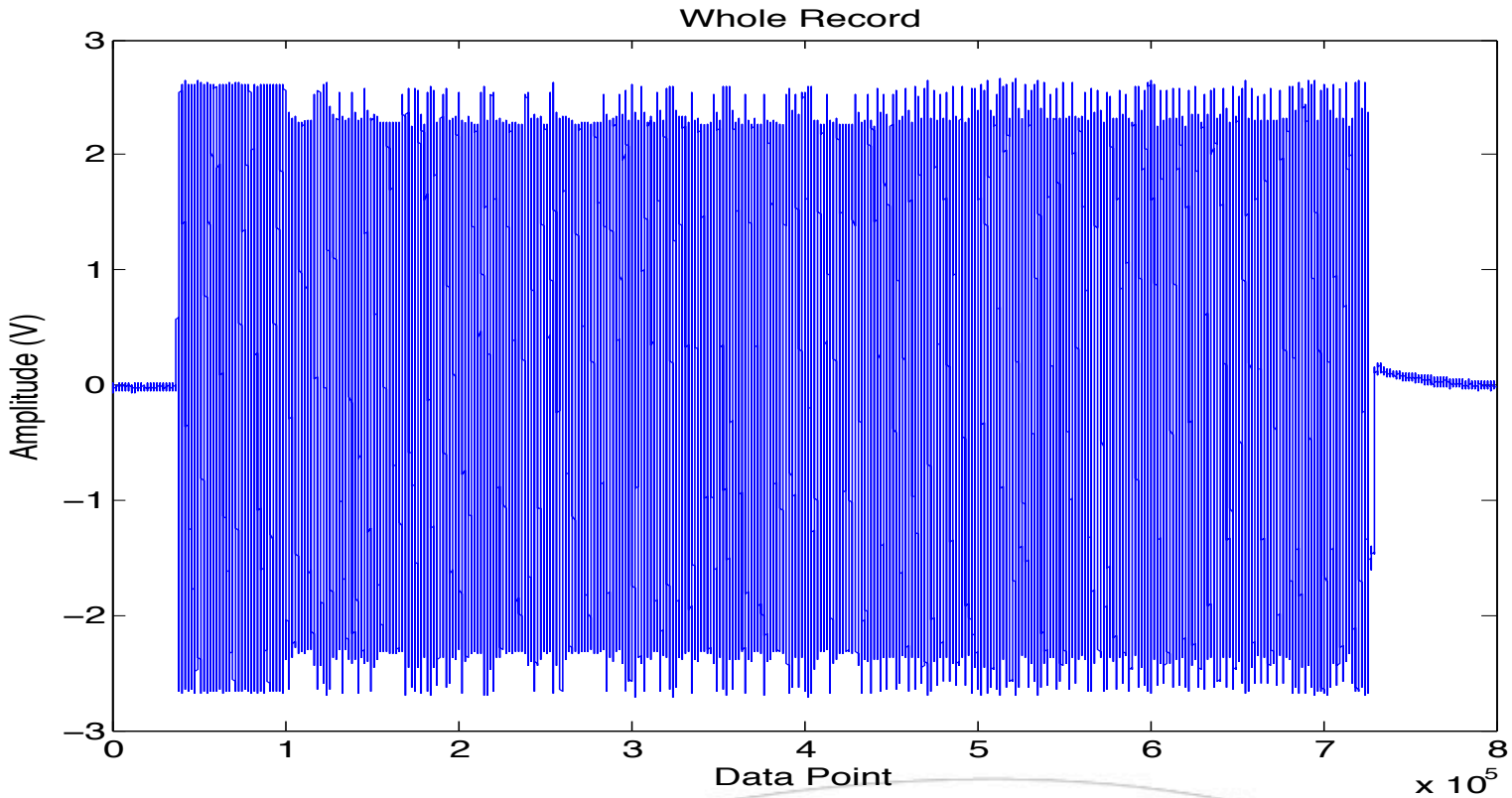
- Methods in the area of computer and network security:
  - Digital Domain
    - Flexible and controllable in design
    - **Problem**: Vulnerable in front of recent cyber attacks
    - Example: Leakage of identifiers (username and password)
    - **Solution**: Analog signaling behaviors
  - Physical Domain
    - Designing methods based on the analog representation of data
    - Unique variations for identification and monitoring purposes

Introduction …

- Physical Layer Identification (PLI)
  - Using the first layer of the OSI model for identification of the devices
- PLI Methodology
  - Identify and acquire a certain signal (i.e. Fingerprint)
  - Extract a set of meaningful features from the signal
  - Compare the test feature set with the reference feature set
  - Determination of the device identity

Introduction …

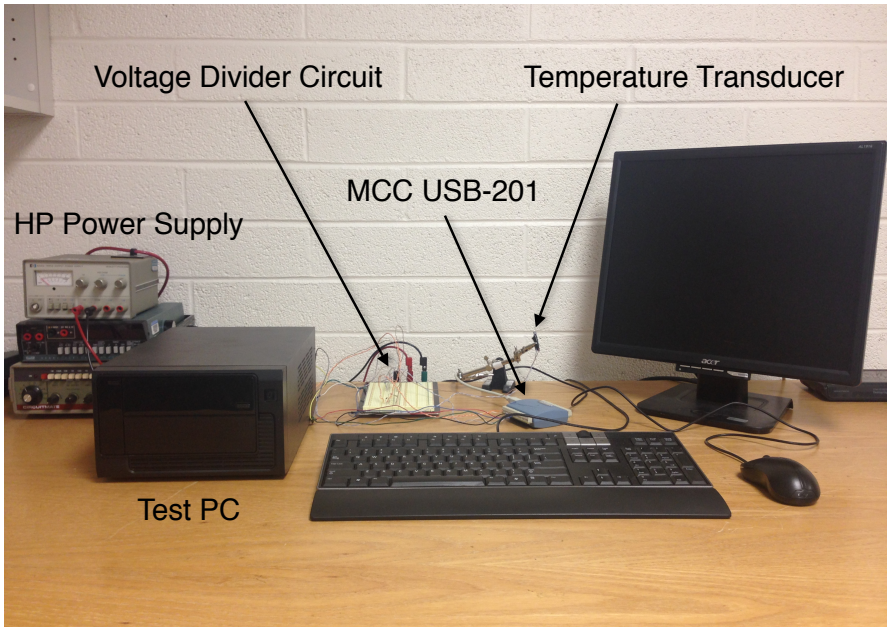
- Ethernet card record – Example for fingerprint:

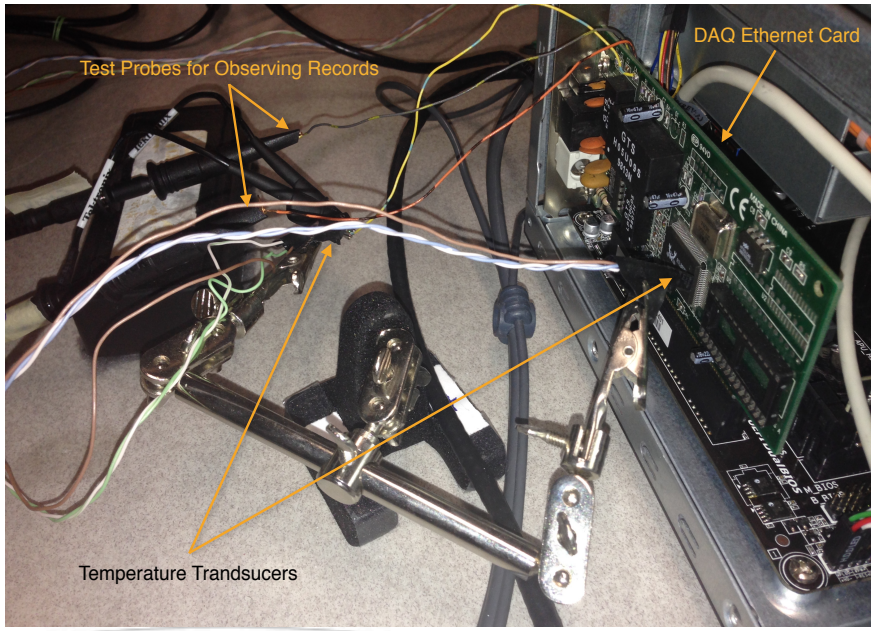


m5c1 card – Experiment 4 , Dataset 8

Introduction …

- PLI System
  - Any systematic approach for accomplishment of the PLI operation
  - Including: Equipment, Algorithm, …

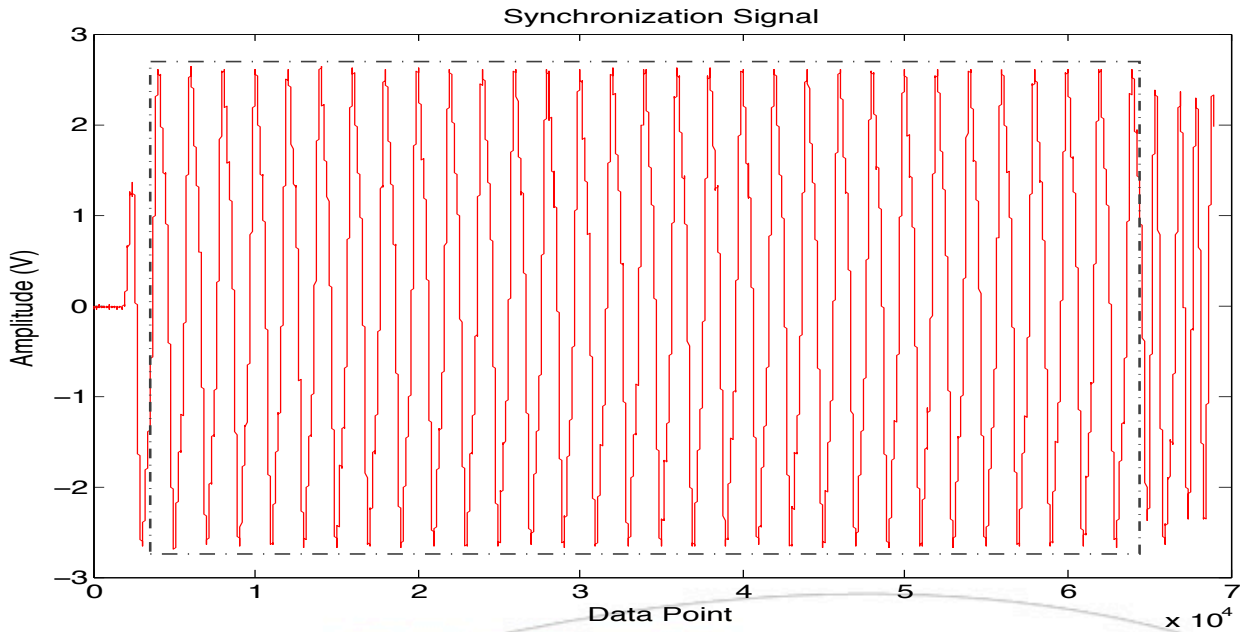




Experimental Setup for Test PC and DAQ PC

Introduction …

- Employing a PLI system, used for wired Ethernet cards:
  - Information profiles for identification of the devices
  - Using profiles for understanding the device behavior over time
  - Using the steady-state portion of the device's record for identification



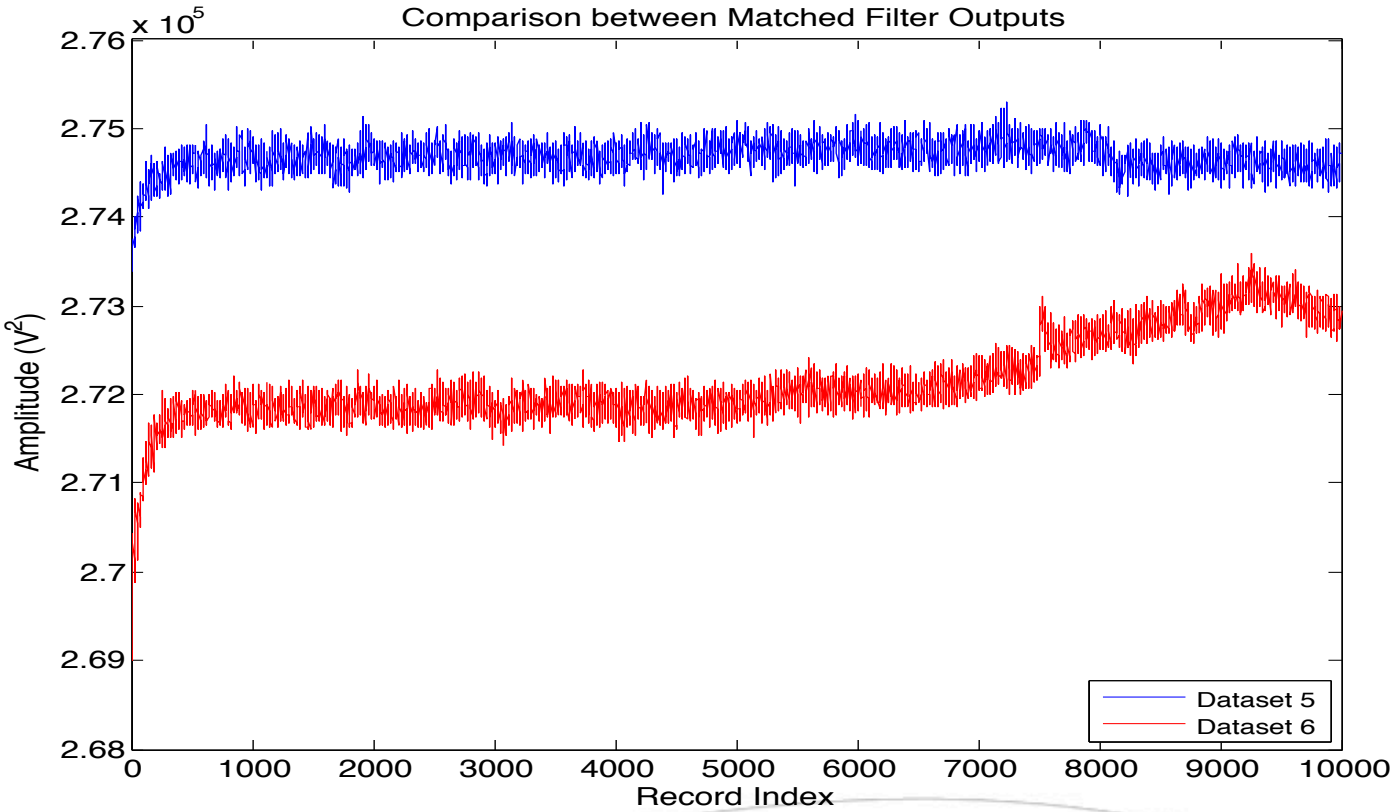
m5c1 card – Experiment 4 , Dataset 8

Introduction …

- Three main components in each information profile:
  - Matched Filter
  - Matched filter outputs for all of the collected records
  - All of the calculated threshold ranges for acceptance of the upcoming data
- The PLI system problem:
  - Lack of identification of the devices in different conditions
  - Significant changes in the features of the device's signal
  - **Solution**: Tracking these changes

Introduction …

- An example of the significant change in the device's signal



m5c3 card – Experiment 3 , Datasets 5 and 6

Introduction …

- Developing a Tracking System (a.k.a. tracking regime)
  - Capable of explaining the amount of variations of a device's signal
  - A Transductive Transfer Learning problem
  - **System performance**: Similarity between the predicted and actual data
- Security Evaluation of the PLI System
  - Exposing the system to different types of attack
  - **Attack Type**: Generating the forged version of a device's signal using an arbitrary waveform generator (AWG)

Physical Layer Identification System

1. Matched Filter
2. Adaptive Thresholding Strategy
3. APRS Metrics
4. Experimental Approach
5. Results

PLI System – Matched Filter

- Maximizing the signal-to-noise ratio of an input signal
- Transfer function of the filter:

$$H(\omega) = k.\frac{A^*(\omega)}{P(\omega)}.\exp(-j\omega t_0) \qquad h(t) = \begin{cases} \alpha(t_0 - t) & 0 \le t \le T \text{ (Period)} \\ 0 & \text{Otherwise} \end{cases}$$

- Matched Filter Output: A value that is a measurement of the closeness of the input signal to the reference signal

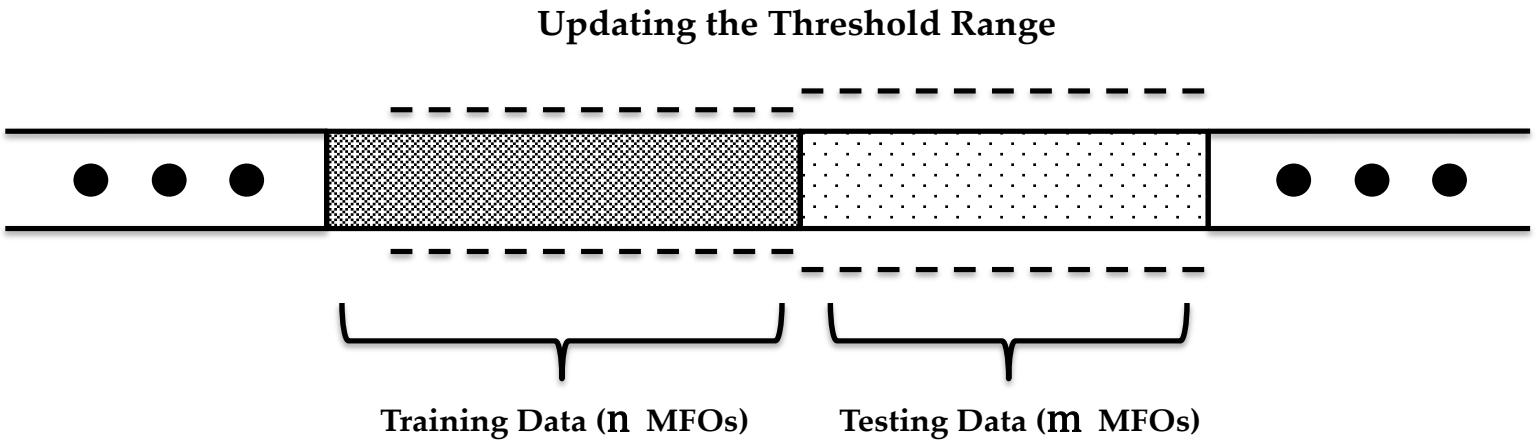
$$MFO : \lambda(t_0) = h(t_0) * \beta(t_0) = \int_{t_0-T}^{t_0} \alpha(\tau).\beta(\tau).d\tau$$

$\alpha(t)$: Reference Signal , P(ω): Power Spectral Density

$\beta(t)$: Input Signal , t_0 = Sampling Time

PLI System – Adaptive Thresholding Strategy

- Determining the threshold range for acceptance of the future signals
- Updating the threshold range periodically



$$threshold_{+/-}(MFO^{j},\ldots,MFO^{j+m-1}) =$$

$$\mu(MFO^{j-n},\ldots,MFO^{j-1}) \pm r_{(1-\gamma;m,n)} \times \sigma(MFO^{j-n},\ldots,MFO^{j-1}) \quad , \quad n < j$$

j = Record Index , r = Range Parameter

PLI System – APRS Metrics

- Metrics for evaluation of the system performance in device identification
- The result parameters for calculation of the system performance metrics:
  - **True Positive (TP)**: Correctly rejection of a record
  - **False Positive (FP)**: Wrongly rejection of a record
  - **True Negative (TN)**: Correctly acceptance of a record
  - **False Negative (FN)**: Wrongly acceptance of a record

PLI System – APRS Metrics …

- Accuracy (A), Precision (P), Recall (R), and Specificity (S):

$$A = \frac{TP + TN}{TP + TN + FP + FN}$$

$$P = \frac{TP}{TP + FP}$$

$$R = \frac{TP}{TP + FN}$$

$$S = \frac{TN}{TN + FP}$$

PLI System – Experimental Approach

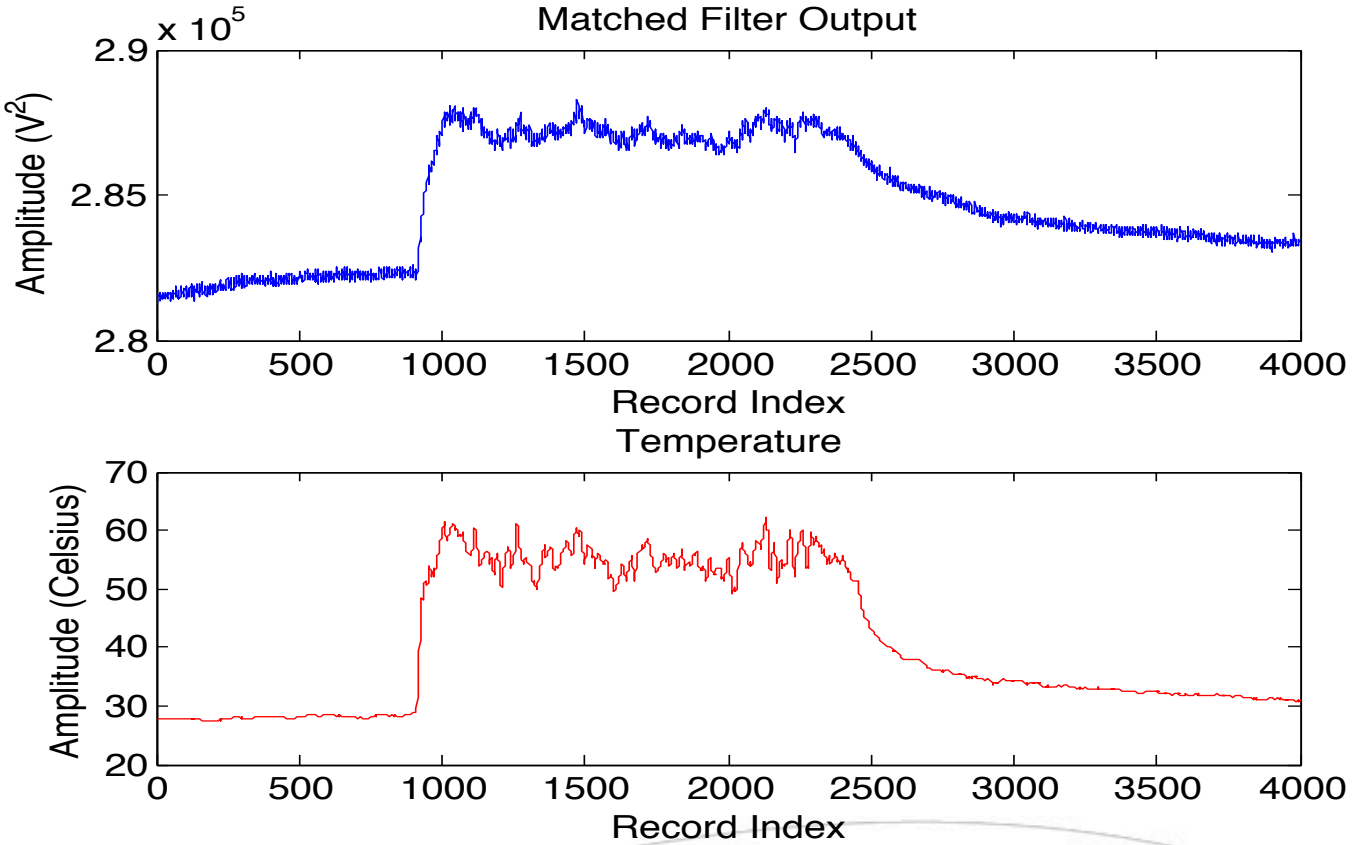
- The desired objectives for behavioral analysis of the devices:
  - **Experiment 1**: Analyzing the device behavior with respect to the **small** variations of its surrounding temperature
  - **Experiment 2**: Analyzing the device behavior with respect to the **large** variations of its surrounding temperature
  - **Experiment 3**: Analyzing the similarities and differences between the device's signal and the supplied voltages to the circuit's general bus and the mounted IC
  - **Experiment 4**: Analyzing the device behavior with respect to the **factual** variations of its surrounding temperature

PLI System – Experimental Approach …

- Data collection for five Ethernet cards
- Having two test runs for each experiment
- Acquiring the related auxiliary data along with the devices records
- Collecting 10,000 numbers of records for each device in each test run

PLI System – Results

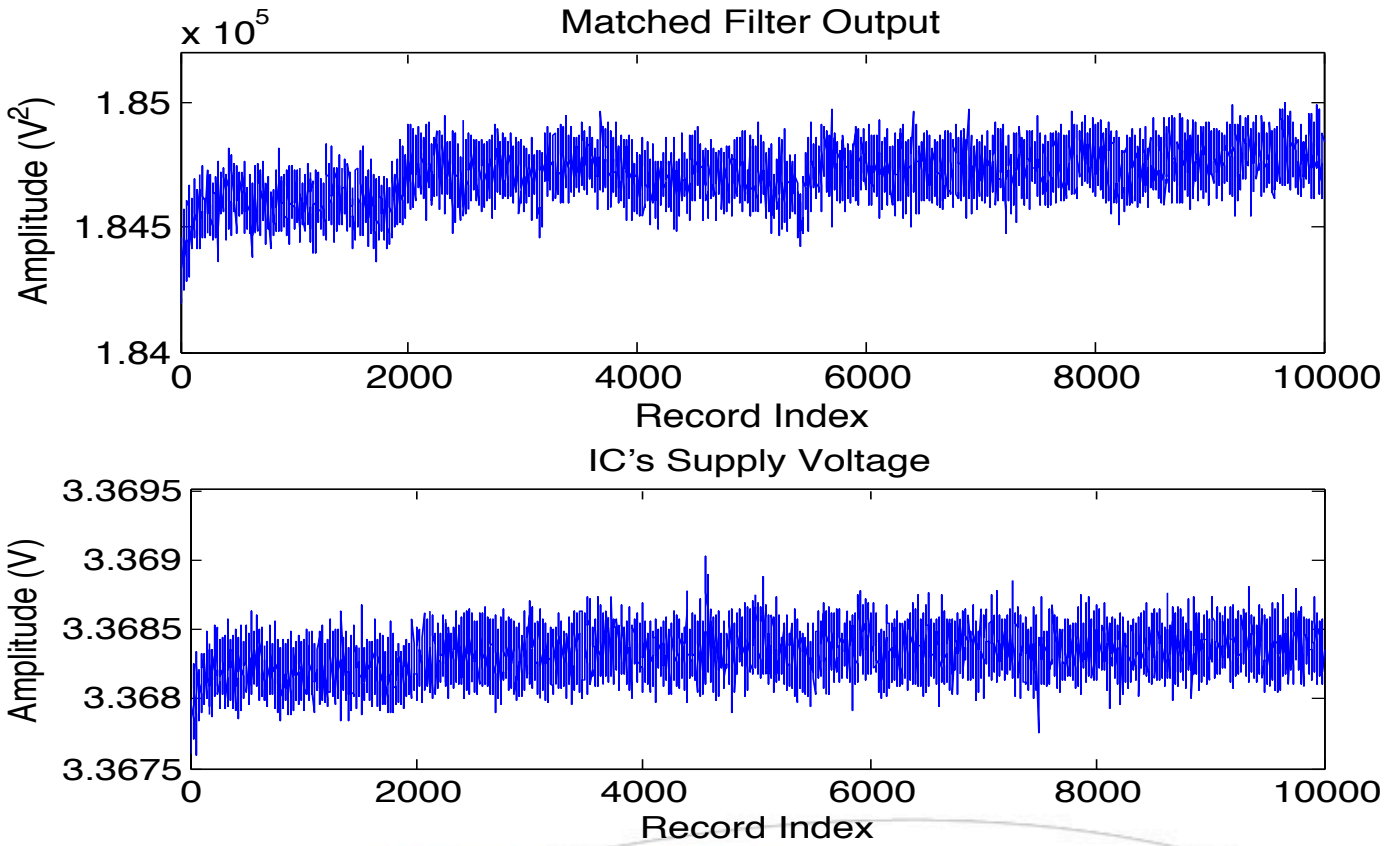
- Similarity between the matched filter output and the surrounding temperature



m5c7 card – Experiment 2 , Dataset 4

PLI System – Results …

- Similarity between the matched filter output and the IC's supply voltage



m5c1 card – Experiment 4 , Dataset 8

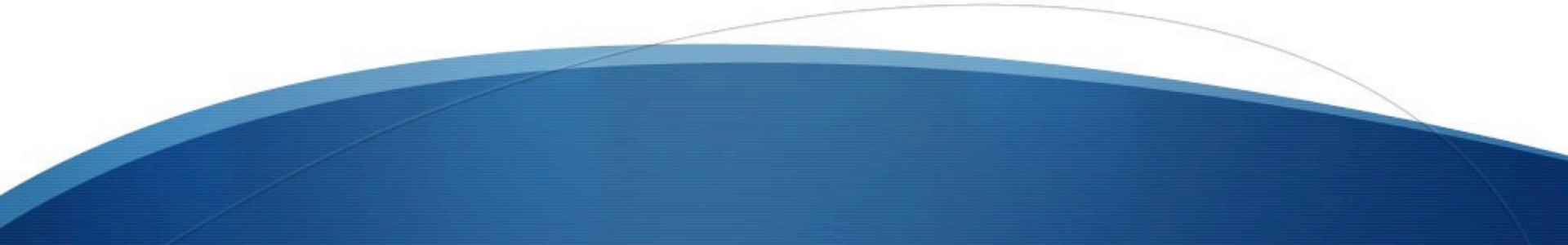
PLI System – Results …

- In Datasets 3-4: Effect of large temperature variations
- Getting a large number of false positives and low specificity values

Experiment	Dataset	A	P	R	S
1	1	0.941	1.000	0.926	1.000
	2	0.927	1.000	0.909	0.999
2	3	0.838	0.853	0.964	0.331
	4	0.832	0.870	0.932	0.431
3	5	0.938	1.000	0.923	0.999
	6	0.933	1.000	0.916	0.999
4	7	0.924	1.000	0.906	0.998
	8	0.924	0.999	0.906	0.998

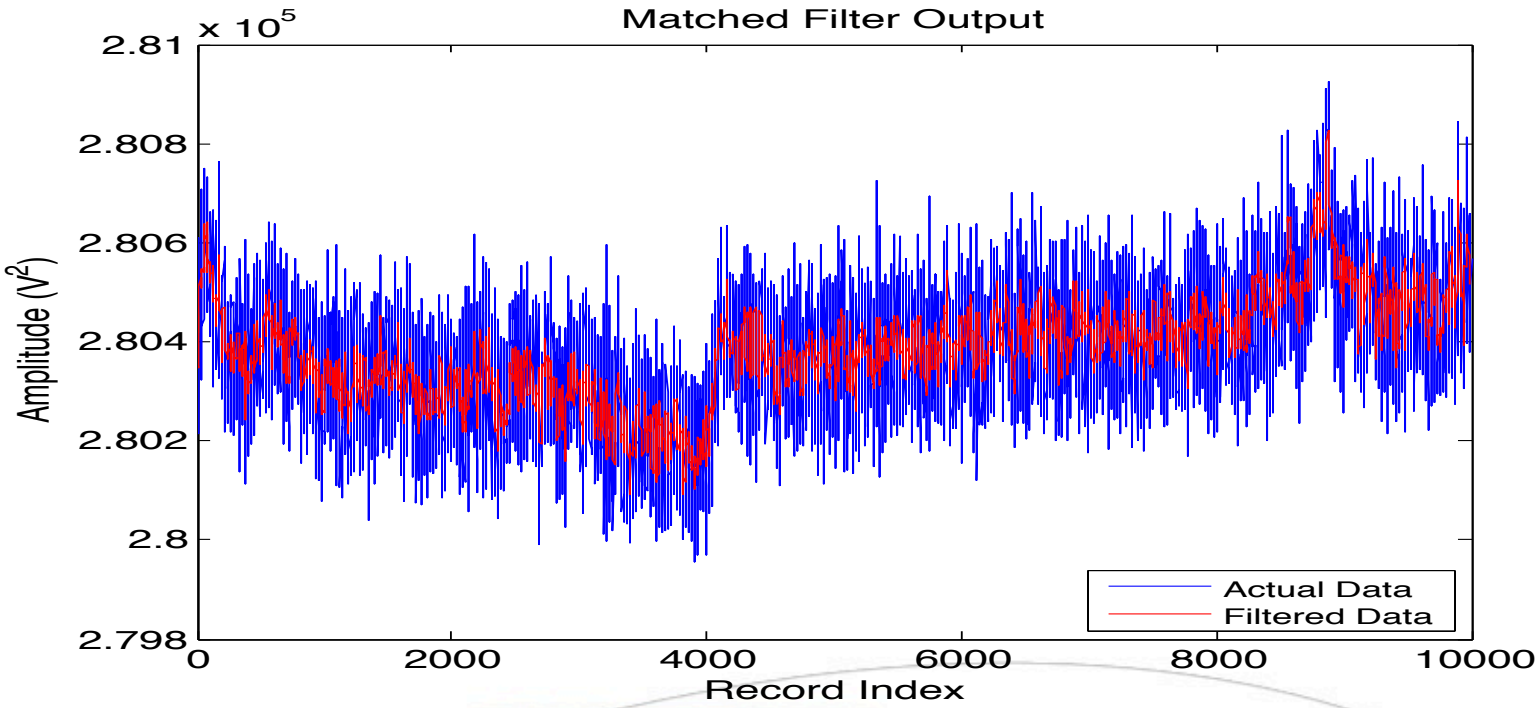
Tracking System Models

1. Data Preparation Concepts
2. Data Modeling Techniques
3. Results



Tracking System Models – Data Preparation Concepts

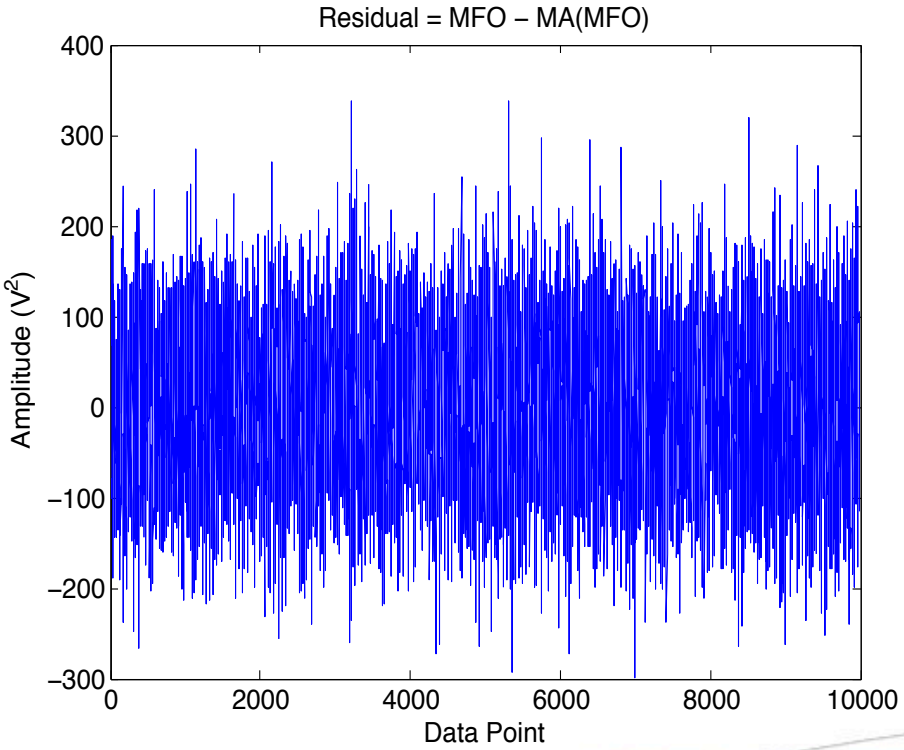
- Moving Average
  - A filter for smoothing out short-term fluctuations of a signal
  - **Filtering process**: Averaging the signal data points in equal length subsets

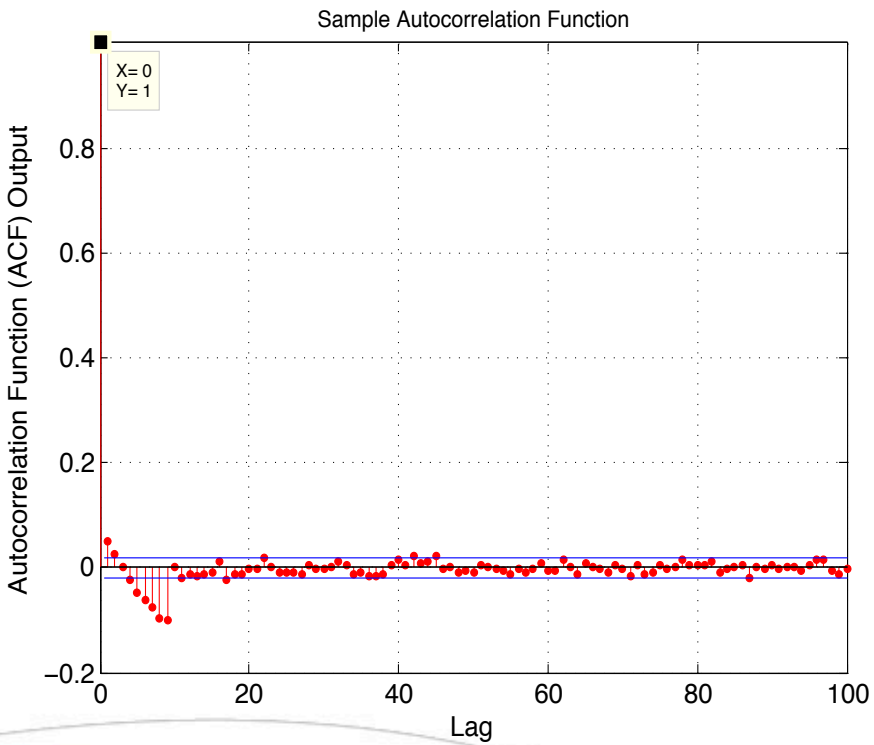


m5c2 card – Experiment 1 , Dataset 1

Tracking System Models – Data Preparation Concepts

- Moving Average
  - Eliminated noise from the signal





m5c2 card – Experiment 1 , Dataset 1

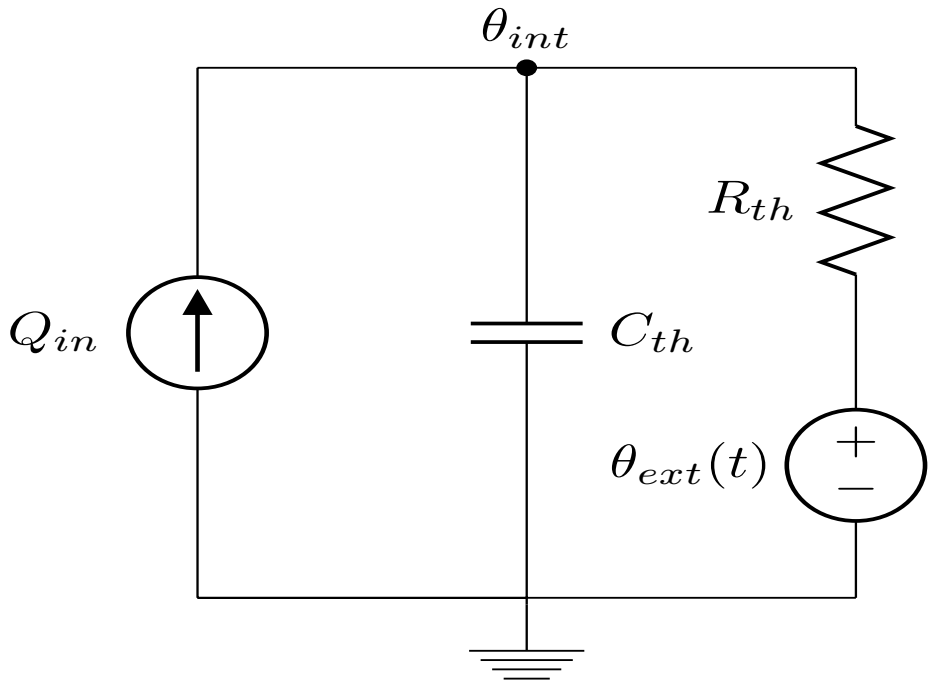
Tracking System Models – Data Preparation Concepts …

- Charging/Discharging Trend
  - MFO signal shows charging/discharging trend in the device behavior
  - **Simple Modeling**: Using the formulations of series RC circuit
  - **Advanced Modeling**: Using Thermal System Modeling
- Thermal System Modeling
  - Thermal system operation: Storing and/or transferring the heat flux
  - Three mechanisms for heat flow: **Conduction**, Convection, Radiation
  - **Energy Balance Theory**: Entered Heat = Emitted Heat + Stored Heat
  - Similar to electrical circuit modeling

Tracking System Models – Data Preparation Concepts …

Q_{in} = Heat Source , R_{th} = Thermal Resistance , C_{th} = Thermal Capacitance

θ_{int} = Internal Temperature , $\theta_{ext}(t)$ = External Temperature



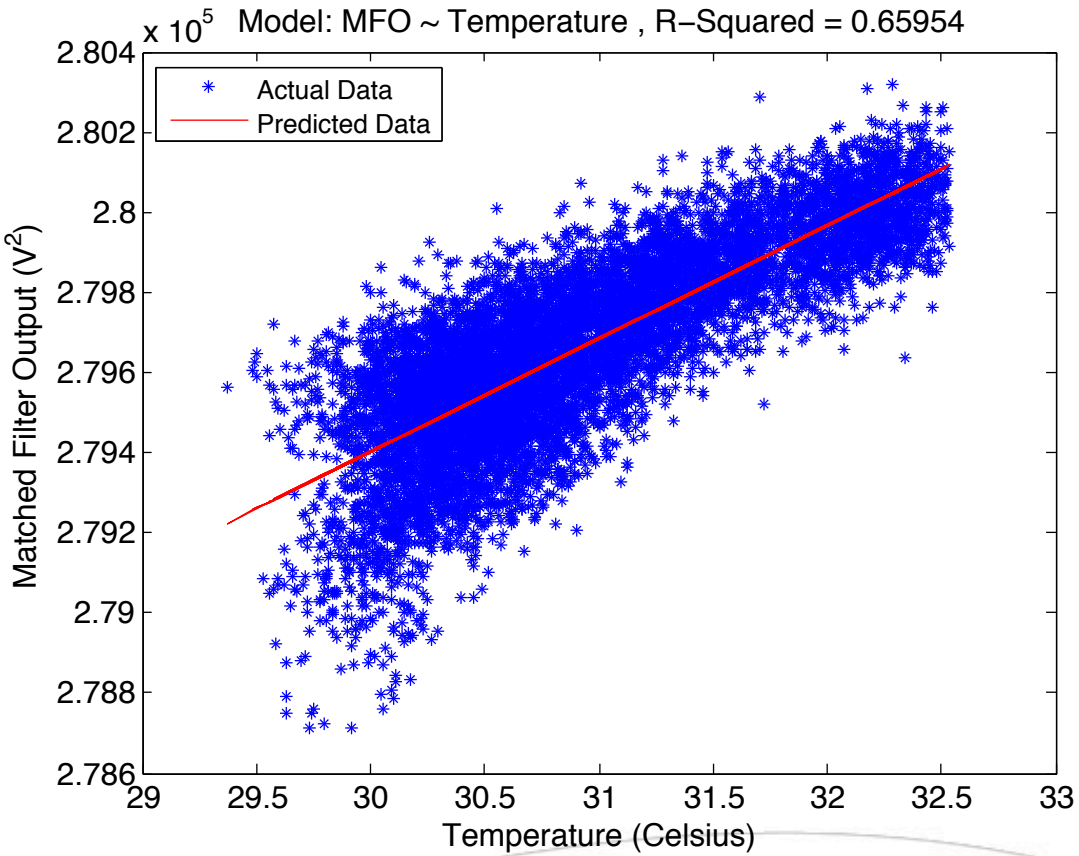
Employed Thermal System Model

Tracking System Models – Data Modeling Techniques

- Linear Regression
  - To find a linear relationship between a response variable and one or more explanatory variable(s)
  - Predicting future response data using the constructed model
  - **Residuals**: Actual Data – Predicted Data
  - **R-Squared**: To show the model accuracy in predicting data
- Smoothing Spline
  - Using as a low-pass filter for the system's output signal

Tracking System Models – Data Modeling Techniques …

- An example for scatter plot of linear regression:



m5c2 card – Experiment 1 , Dataset 1

Tracking System Models – Data Modeling Techniques …

- Robust Regression
  - Common data modeling technique
    - ✓ Having certain underlying assumptions
    - ✓ Example: Normal distribution for error data in linear regression
  - Dissatisfaction of these assumptions → Insensibility to the outliers
  - Robust Regression → Reduce the influence of outliers
  - A common method for this purpose: **Least Absolute Residuals**
    - ✓ Finding a line or curve that minimizes the absolute difference of the residuals

Tracking System Models – Results

- 50 models were tried to find the most efficient data predictive model

- Device's Surrounding Temperature

  - The best option for predicting the device behavior
  - An intruder into the device's signal
  - Trend of MFO signal ~ Trend of temperature signal
  - Larger variations of the temperature signal → Higher R-Squared value

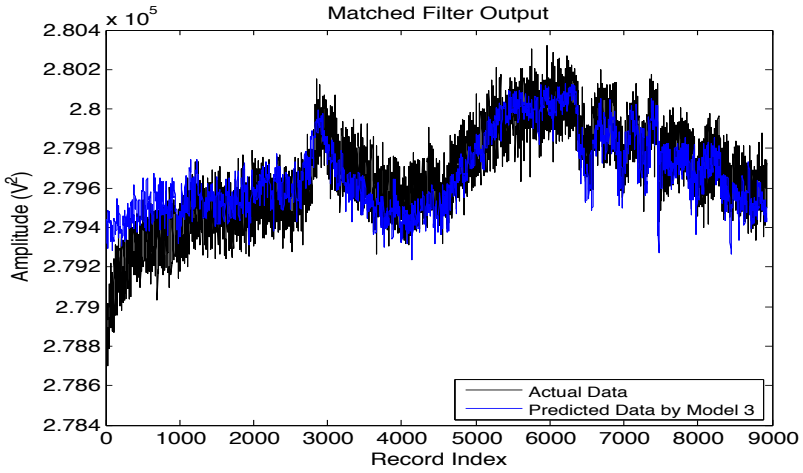
- Strengthening the data prediction process, using:

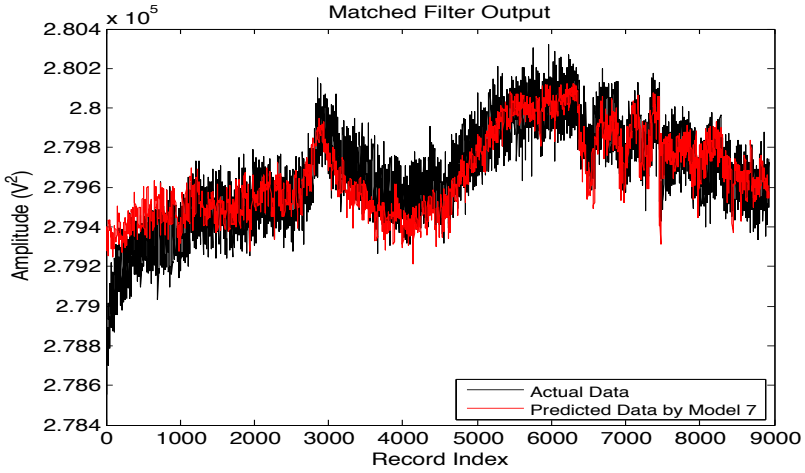
  - IC's supply voltage signal
  - Charging/discharging trend data

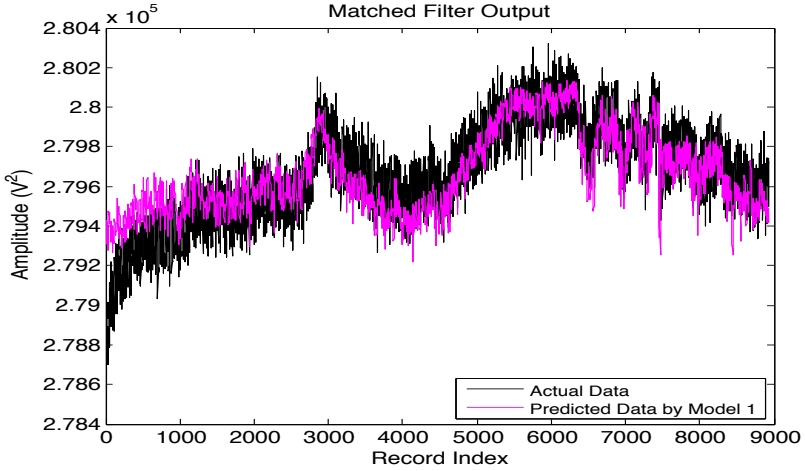
Tracking System Models – Results …

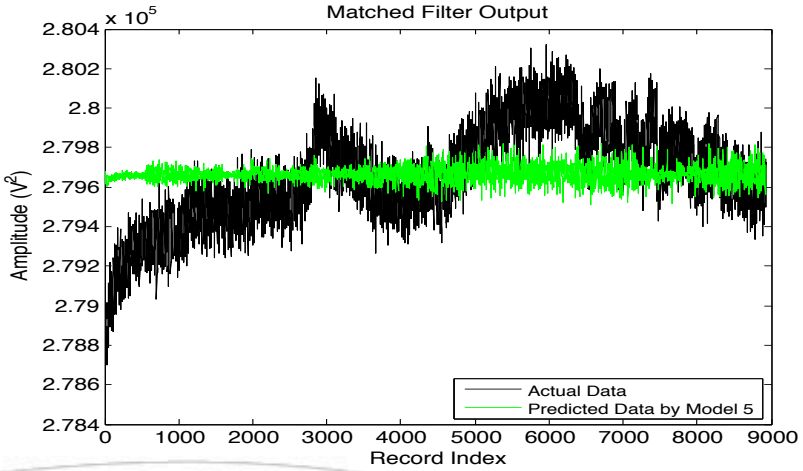
Number	Model	Experiment	R-Squared Values (%)			
			Minimum	Mean	Median	Maximum
1	MFO ~ Temperature	1	2.2955	11.0092	7.8574	24.7855
		2	88.9905	92.0434	92.518	94.4505
		3	0.0406	16.9359	6.7058	42.0475
		4	6.6724	21.3197	13.3645	38.9905
2	Moving Average(MFO) ~ Moving Average(Temperature)	1	11.251	41.7109	39.622	69.4915
3	Spline(MFO) ~ Temperature Robust Mode = Least Absolute Residuals	1	81.4355	92.5322	94.6145	97.8655
		3	44.2801	79.7687	84.657	98.6255
4	MFO ~ Device's Internal Temperature	4	6.7102	21.3772	16.6935	39.139
5	MFO ~ IC's Supply Voltage	3	0.0699	1.7399	0.5696	5.0276
		4	1.3272	6.6198	5.0743	13.7611
6	MFO ~ Bus's Supply Voltage	3	0.2070	3.0754	2.2827	8.4348
		4	0.7487	4.5355	3.9416	9.1063
7	MFO ~ Temperature + IC's Supply Voltage + Charging Trend Data	3	29.071	47.8629	44.3565	68.227
8	MFO ~ Temperature + IC's Supply Voltage + Discharging Trend Data	3	39.8315	53.1384	54.346	65.412

Tracking System Models – Results …









m5c2 card – Experiment 3 , Dataset 6

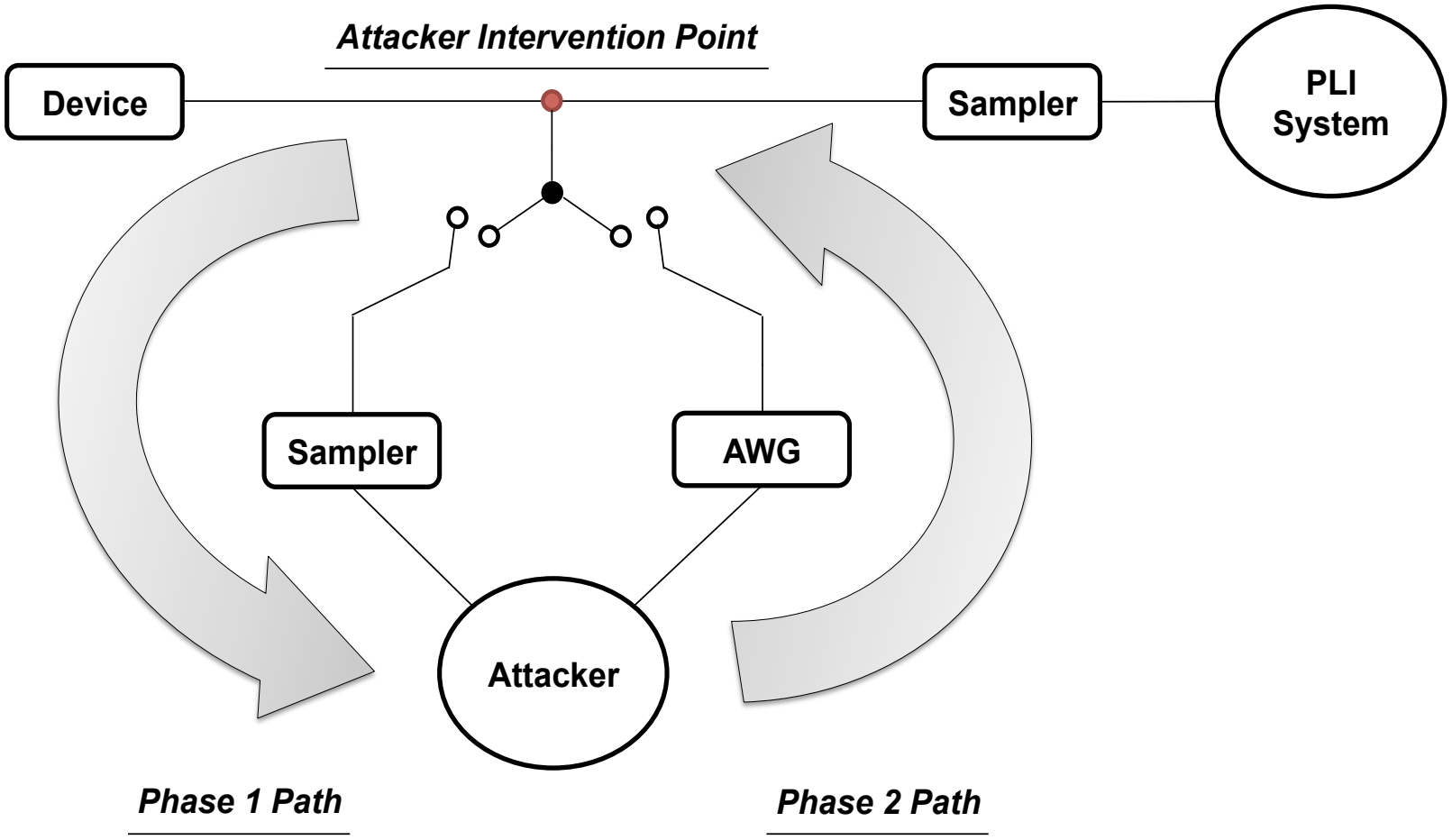
PLI Systems Security Evaluation

1. Architecture of Attack
2. AWG Configuration
3. Results

PLI System Security Evaluation – Architecture of Attack

- Attacking the PLI system by:
  - **Signal Replay**: Generating the forged version of a device's signal using an arbitrary waveform generator (AWG)
- The attacking process consists of two phases:
  - **Phase 1**: Delivering the sampled version of the device's signal to the attacker and PLI system
  - **Phase 2**:
    - ✓ Generation of a forged version of the acquired signal by the attacker
    - ✓ Sending the forged signal to the PLI system.

PLI System Security Evaluation – Architecture of Attack …



PLI System Security Evaluation – AWG Configuration

- Three main components in an AWG structure:
  - **Source Memory**: Location of the sampled version of the device's signal
  - **Digital-to-Analog Converter**: For generation of a stepped analog waveform with certain characteristics
  - **Low-Pass Filter**: For smoothing the generated signal
- Evaluating the AWG's output quality based on the DAC performance
- The most important parameters for the DAC performance analysis:
  - Settling Time
  - Resolution
  - Total Harmonic Distortion
  - Signal-to-Noise Ratio

PLI System Security Evaluation – AWG Configuration …

- Settling Time
  - The required time for the steady-state of a system's output (approximately)
  - Having inverse relationship with the sampling rate
  - Considering a very low value for this parameter

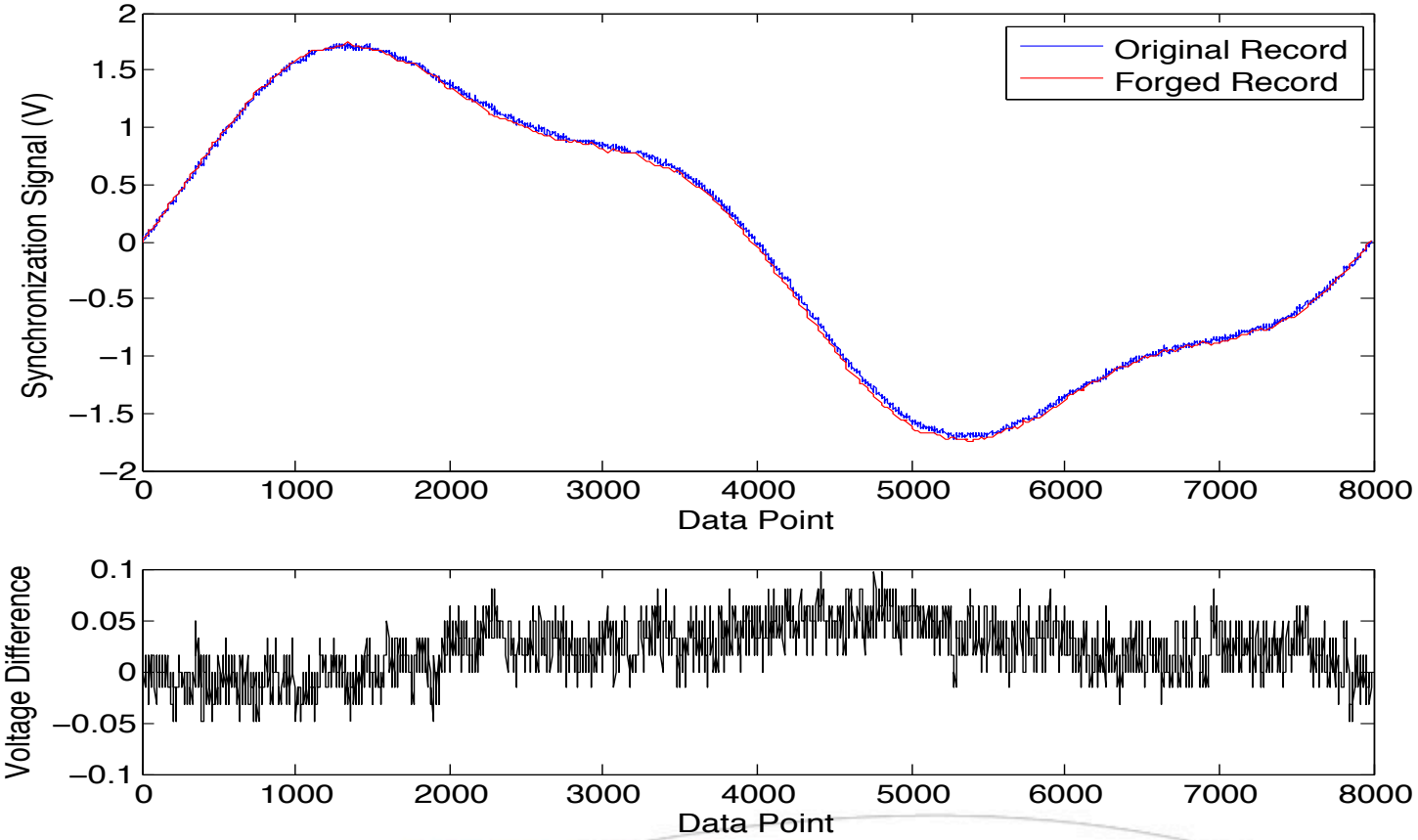
- Resolution
  - The number of discrete values for the range of values of an analog signal
  - **Discretizer**: For matching between the voltage levels of the signals

PLI System Security Evaluation – Experimental Approach

- Forged Record Generation:
  - Having 10,000 collected records for each of the 26 tested Ethernet cards
  - Selecting 25 records (i.e. 1001-1025) to be forged
- Using two different sampling rates:
  - 2.0 GS/s (the highest possible value)
  - 1.0 GS/s
- The discretizer outcome – close to the actual record voltages:
  - Maximum Voltage = 1.982 (V)
  - Minimum Voltage = -1.968 (V)
- Aligning the original and forged records before applying the matched filter

PLI System Security Evaluation – Results

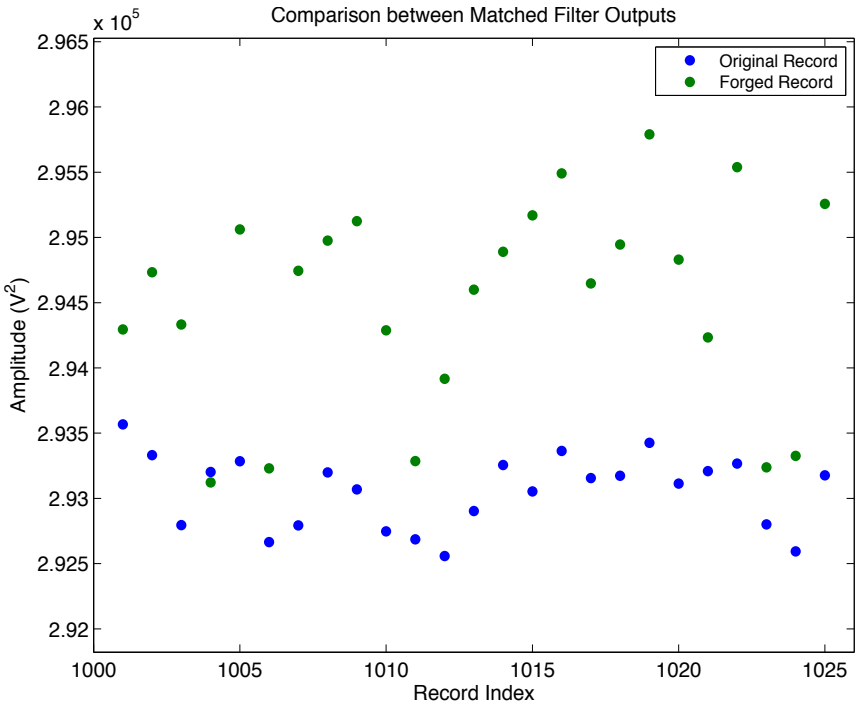
- Small difference between the original and forged records → Mean = 0.021 (V)

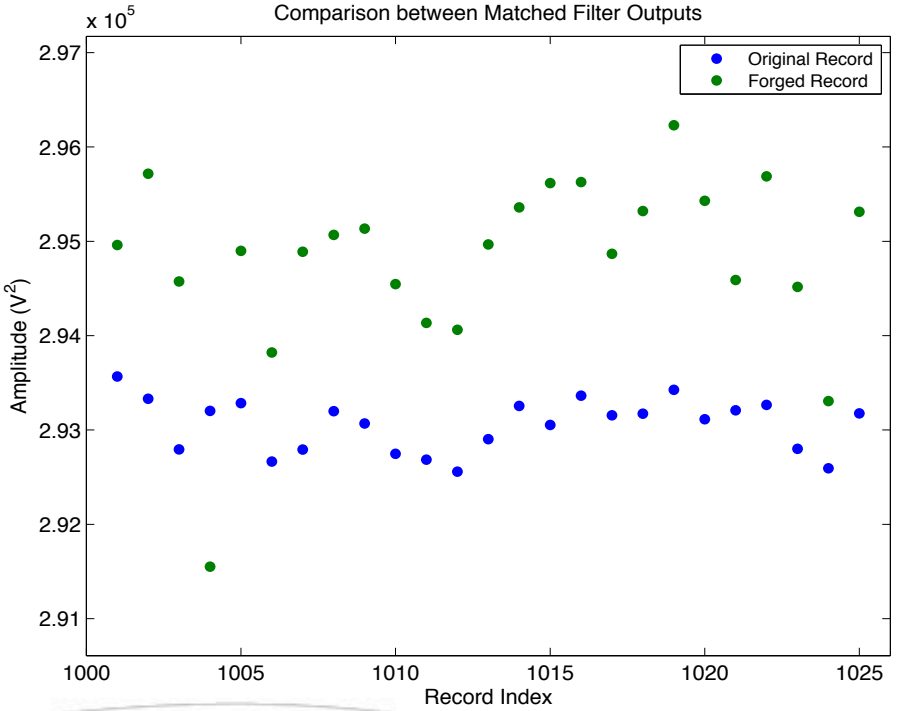


1023th record of the m5c8 card - Sampling Rate: 1.0 GS/s rate

PLI System Security Evaluation – Results …

- Forged Records → Larger expected value and dispersion of data → Defended !
- Sampling Rate Effect → Not deterministic in getting larger or smaller dispersion





m5c8 card
The generated forged records at 1.0 GS/s (left) and 2.0 GS/s (right) rates

Conclusion

- PLI System and Tracking System Models
  - Device's surrounding temperature
    - Its trend is similar to the matched filter output
    - Having large variations → Disruption in identification of the devices
    - The best option for prediction of the MFO signal
    - **Role**: Intruder into the circuit activities

Conclusion …

- PLI System Security Evaluation
  - MFO signals of forged records
    - Having larger expected value and dispersion of data
  - The PLI system isn't consistently defeatable

Acknowledgment

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Questions