Convolutional Filtering for Accurate Signal Timing from Noisy Streaming Data

Jonathan Wang*†, Kesheng Wu (Advisor)*, Alex Sim (Advisor)*
*Lawrence Berkeley National Laboratory
†Rice University
Emails: *{jonathanwang, kwu, asim}@lbl.gov,

I. Introduction

Our society depends heavily on the electric power infrastructure, so key power grid components such as transformers are extensively monitored for signs of failure [1]. This work concentrates on analyzing massive high-frequency streaming sensor data to locate the source of partial discharges (PD), which are the symptoms of insulation weakness, the most common cause of transformer failures [2].

Our localization method consists of two steps: determine the signal arrival times from signal samples and then locate the PD position based on arrival time differences. To determine the arrival time, we develop a convolutional filtering method based on the Savitzky-Golay filter [3]. To provide accurate locations, we simulate electromagnetic wave propagation using finite-difference time-domain (FDTD) [4] to generate a reference table of travel times from each FDTD mesh point to the sensors.

We exercise our method using two sets of ultra-high frequency (UHF) sensor data streams with different signal-to-noise ratios. In both cases, our method provides more accurate locations than other methods. The difference is particularly prominent when the signal is weak, where existing methods are only able to predict the PD location within 300 mm of the known sources in 13% of the test cases, while our method is correct in 48% of the test cases.

II. Methods

UHF sensors collect signals at frequencies ranging from 300 MHz to 1 GHz with a resolution of 0.4 nanoseconds per record, resulting in a data streaming rate of 12 GB per second. We apply a voltage threshold to the streaming data and collect 500 points (200 ns) before and after threshold hits to create 1000 point (400 ns) PD signal samples as shown in Figure 1.

The primary challenge of signal timing is the low signal-to-noise ratios (SNR) present in certain sensors. To improve the SNR, we use the Savitzky-Golay filter (SG filter), which smooths data through convolution, by fitting windows of the signal to a low degree polynomial using least squares. This filter preserves features better than other methods, making it easier to find the signal arrival with threshold methods. We use the SG filter with a threshold, determined by the mean and standard deviation of the noise data, to define a window for the arrival time. Once we identify this initial window, we use a moving average to further eliminate noise and refine our initial estimate with another threshold to find the signal arrival time.

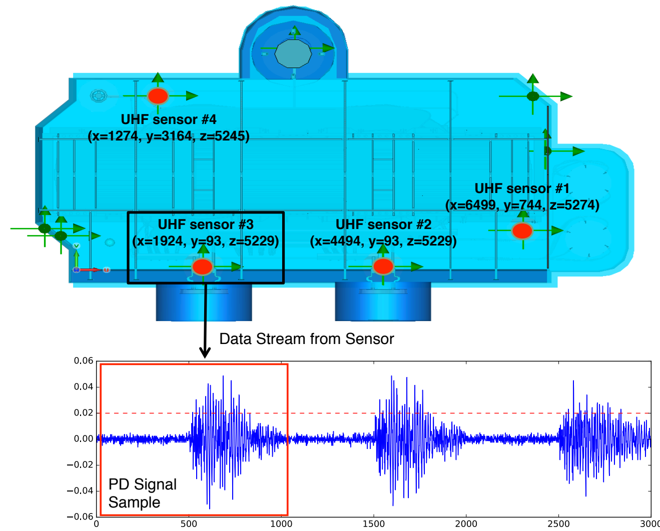

Fig. 1. Streaming Data from UHF Sensors with Voltage Threshold

For PD localization, solving systems of equations by multilateration fails, since PD signals do not travel in straight lines due to the internal structure of the transformer. To account for the path of the signals, we use FDTD simulation. The transformer is divided into 300 mm mesh points, and a PD signal is simulated from each point. The time that it takes to travel from each mesh point to each of the four sensors is recorded, and used to calculate three time differences. We select the FDTD mesh point whose time differences have the lowest root mean squared error (RMSE) from the time differences of the signal timings as the PD source. The entirety of our localization method is summarized in Figure 2.

Since we have a large number of signal samples in the streaming data, we cluster the localized PDs using DBSCAN. Any PD not in the main cluster is deemed an outlier and removed from consideration. This step is outlined in Figure 3.

III. Experimental Results

We have two PD locations each with 26 possible coordinates. To quantify our methods, we measure the number of those coordinates encompassed within the error range of the localized PD. FDTD lookup has much higher accuracy that

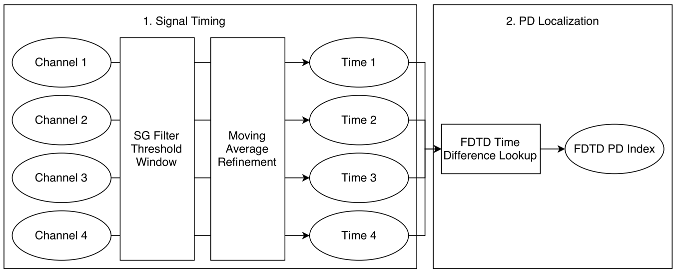

Fig. 2. Overview of PD Localization Method

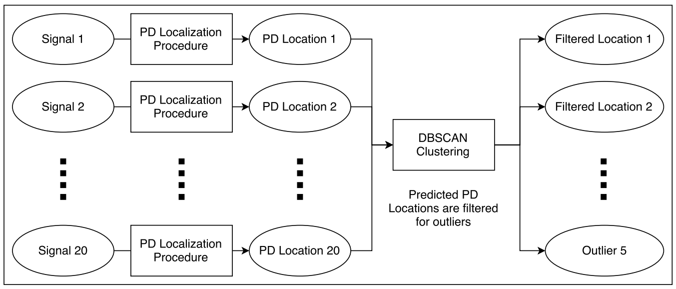

Fig. 3. Overview of DBSCAN Outlier Detection Method

multilateration, at 100% accuracy for both locations compared to 40% and 79% for multilateration. This result is visualized in Figures 4 and 5 for one PD location.

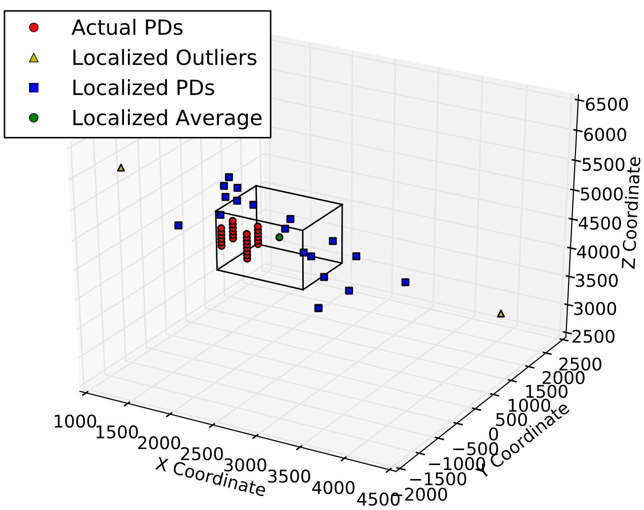

Fig. 4. Localization Results of Multilateration

Our SG filter timing method performs better than existing methods. At a 300 mm error range, PD localization with the SG filter method has 95% and 48% accuracy compared to 91% and 13% for existing methods. This is further illustrated in the signal arrival comparison in Figure 6.

IV. Conclusion

In tests with FDTD simulation data, our SG filter method produces the best timing results among all the methods we tested. By looking up the PD location using FDTD, we are able

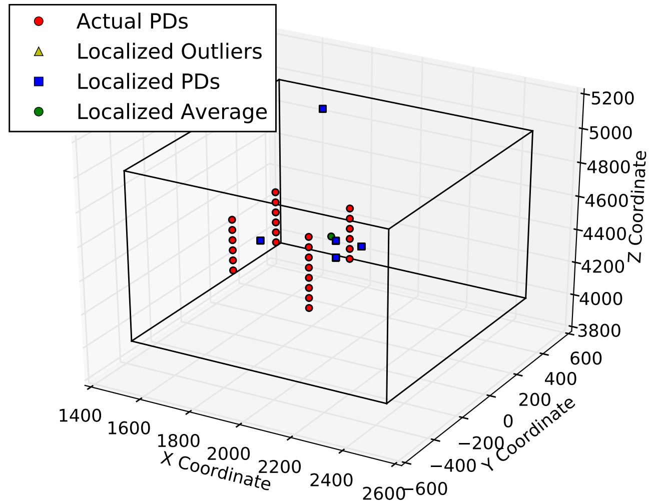

Fig. 5. Localization Results of FDTD

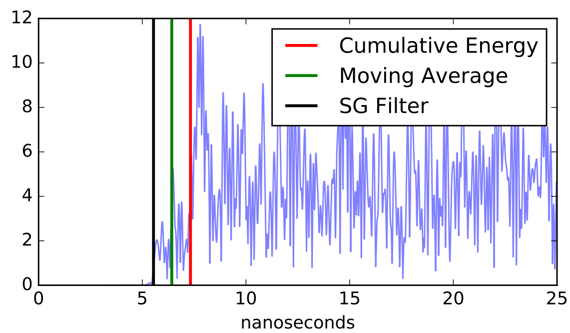

Fig. 6. Comparison of Signal Arrival Times

to locate the PD to within 500 mm and 300 mm much more frequently than with multilateration. With 300 mm tolerance, in the high SNR dataset, the accuracy with the best existing method is 91% and our method is 95%. Moreover, in the low SNR data, we had a more drastic improvement from 13% accuracy to 48% with our method. As a result of our work, we present a streaming data PD localization procedure based on the Savitzky-Golay filter and FDTD lookup that outperforms existing localization methods.

References

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