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Trans-Barrier Communication Device Characterization Using Frequency Fitting Methods

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***Abstract*—The extraction of the electrical model of a piezoelectric device used for transferring energy across a metallic barrier is described. The model is based on a linear time-invariant (LTI) representation of the channel obtained from frequency fitting methods of the device's S-parameter data. To ensure the model is passive and causal, we resort frequency fitting methods supported in Matlab. We show that Matlab's rational object function produces similar results to those from vector fitting but with lower order (complexity) for the device types treated here. Impulse response results from the model were used to set the parameters for an off-the-shelf powerline communication (PLC) system to obtain high data rate communication using mechanical transduction across a metallic barrier.**
[1]

***Index Terms*—channel characterization, vector fitting, impulse response, mechanical transduction, wireline communication**

I. Introduction

The idea of providing power or communicating across a metal barrier without feedthroughs, holes, or other apertures has gained considerable interest recently. Some applications include down-bore hole sensors for drilling and fracking [1] as well as nuclear waste monitoring [2] using enclosed sensors. This has led to the exploration of high data rate communications through a metallic barrier using piezoelectric devices as highlighted in [3] [4] [5].

Sandia National Laboratories has developed a series of novel piezoelectric device structures that have a sufficiently high mechanical frequency while also being agnostic to barrier material. The devices are suitable for trans-barrier communication and the goal becomes characterizing the channel response to maximize data rate transfer through the barrier. We seek to apply a frequency fitting method on the S-parameter measured data and extract the time-domain channel impulse response (CIR) and therefore apply those parameters in a communication application.

One approach to fitting a rational function in the complex domain to a complex vector of frequency response data is vector fitting (VF) [6]. Vector fitting employs a sequential solution to a frequency function represented as a sum of partial fraction terms in the complex frequency domain. The vector fitting method has been shown to be robust, accurate, and fairly efficient when compared to other techniques for approximating a frequency response [7]. To that end, vector fitting was used to characterize piezoelectric devices in [8].

In this paper, we use Matlab's `rational object` introduced in Matlab R2020a [9]. This method is described as an interpolation algorithm to create a rational fit to frequency-dependent data using partial fractions in the complex frequency domain. The fit is performed by specifying the number of poles and provides the error to the fit so the response can be tailored to improve accuracy. Another advantage of using Matlab's `rational object` is that there is the companion function `zpk` that extracts the poles and zeros from the object [10]. This can be used to understand additional properties of the frequency fit and the resulting impulse response.

Our paper is therefore organized as follows. First, we consider device characterization using S-parameters and review various methods to understand the characteristics of the response. Next, Matlab's `rational object` approach is used to obtain a mathematical representation of the spectral response. The impulse response is generated and the channel delay estimated to obtain the cyclic prefix length for an orthogonal frequency division multiplex (OFDM) communication system. Test results through a metallic barrier using an off-the-shelf powerline communication (PLC) system using OFDM confirms high data rate performance as predicted by the model. It is shown that the proposed method can be used to characterize frequency and temporal behavior of piezoelectric trans-barrier devices for communication applications.

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II. Device Characterization

A pair of devices based on lead zirconate titanate (PZT) are aligned on opposite sides of a 1mm-thick copper barrier enclosed in electromagnetically isolated 6"×6" aluminum boxes as shown in Figure 1. Shielded RF cables feed the signal to the devices inside the metallic boxes to make the frequency measurements. A calibrated vector network analyzer (VNA) measured the 2-port S-parameters of the test configuration.

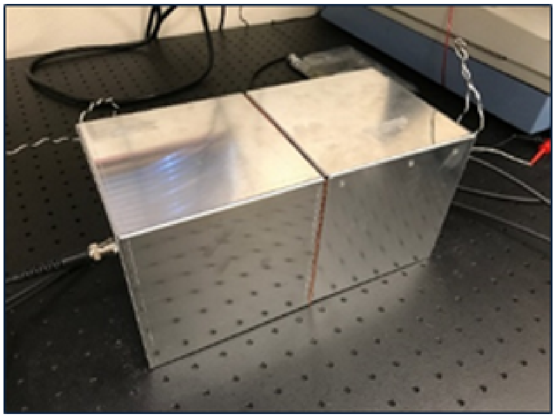

Fig. 1. Device frequency measurement setup showing aluminum Faraday cages butted together and corresponding signal ports. Each transducer is inside the respective cage connected to the barrier that is common to the enclosures.

The physical channel consists of a two-port transducer converting mechanical motion into electrical energy and vice versa. The device is passive and we assume it is electrically well-defined by a linear time-invariant (LTI) filter channel model as discussed in [11]. The frequency response is measured using S-parameters that describe device electrical performance in terms of incident and reflected electrical waves. The voltage transfer function is related to the two-port S-parameters via the relation [12]

$$A_V = \frac{S_{21}(1+\Gamma_L)}{(1-S_{22}\Gamma_L)+S_{11}(1-S_{22}\Gamma_L)+S_{12}S_{21}\Gamma_L} \quad (1)$$

where Γ_L is the load reflection coefficient. In a properly terminated system $\Gamma_L = 0$ and the transfer voltage becomes

$$A_V = \frac{S_{21}}{1+S_{11}} \quad (2)$$

There are several properties we can determine from the S-parameters in relation to device characteristics. One property is *Reciprocity* given by the relation

$$S = S^T \quad \text{or} \quad S_{ji} = S_{ij} \quad \text{for } i \neq j \quad (3)$$

If a network is reciprocal it can imply that linear reciprocal materials are used in the device. Another property is *Symmetry* given by

$$S_{ii} = S_{jj}, \quad \text{for } i \neq j \quad (4)$$

Symmetrical networks are often physically symmetrical, but this need not be the case in general. Both of these properties are checked as part of the characterization of the piezoelectric devices.

Another important property is *Passivity*. Passivity has been shown to be the most stringent requirement of an electrical network as it implies both causality and stability [13]. Passivity can be confirmed directly from the S-parameters by checking the condition

$$\text{eig}[I - S^*S] \geq 0 \Rightarrow \text{eig}[S^*S] \leq 1 \quad (5)$$

where eig$[M]$ refers to the eigenvalues of the matrix M. Any frequencies that violate this condition must be further analyzed in relation to the measured data to understand the nature of the passivity violation. Passivity of the measured data is a crucial component for performing the frequency fit of the data.

III. Frequency Fitting Methods

The measured S-parameters of the piezoelectric device from 0.1 to 50 MHz are plotted in Figure 2. The S_{21} frequency response exhibits multiple resonant lobes starting at 5 MHz and spaced roughly 10 MHz apart. The peak of each lobe is approximately 15 dB below the previous lobe peak as the frequency increases. The phase responses are approximately linear with slight bumps coinciding with the nulls of the magnitude response. The input and output return loss are highly reflective throughout most of the band. Over the entire frequency range the piezoelectric device is passive and reciprocal but not necessarily symmetric. This lack of symmetry means the device may not achieve identical data rates depending on the port being stimulated.

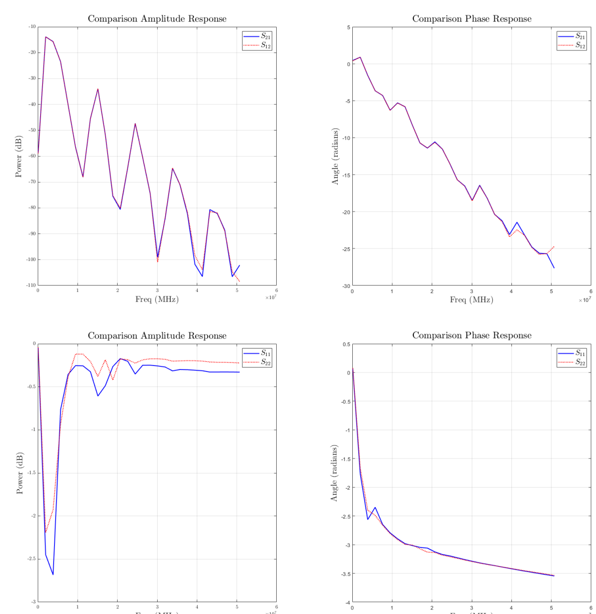

Fig. 2. S-parameter measurements of sample piezoelectric device in frequency range $0 \leq f \leq 50$ MHz over all ports of interest.

The `rational object` fit to the magnitude and phase given (2) are plotted in Figure 3. The method results in a good fit over the first three lobes of the frequency response. Beyond the fourth lobe, the amplitude response climbs slightly. This effect is due to using $N = 16$ poles in the approximation to make the response less sensitive. The error between the original and fitted magnitude response is -29.9 dB. The fitted phase responses deviate substantially beyond 30 MHz with the phase becoming constant, but the energy contribution beyond the 30 MHz frequency does not play a significant role in the response.

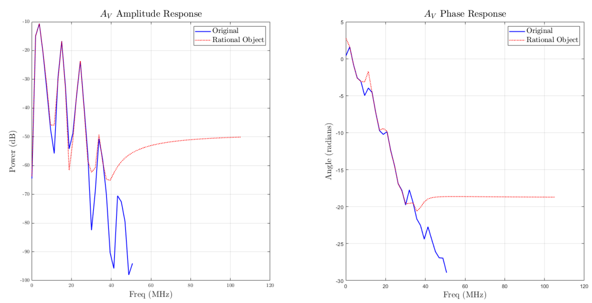

Fig. 3. Plot of rational object fit to measured S_{21} frequency response of the device spectrum in dB and unwrapped phase in radians.

A plot of the pole-zero diagram of the fitted response using the `zpk` function is given in Figure 4. All poles and zeros are complex conjugate pairs. There are two zeros near the origin. The presence of zeros in the right-half plane indicate the fitted function is non-minimum phase. This has the following implications. First, the resulting group delay is not minimum. Second, a minimum phase system has its energy concentrated near the start of the impulse response [14]. A non-minimum phase response may add some delay to the resulting impulse response, providing a conservative estimate of the impulse response of the actual device.

IV. Time-Domain Response Characterization

In Figure 5 we plot the time-domain responses from the `rational object` fit as well as the vector fitting (VF) method. It is evident that the results of the VF and rational object methods are very close despite the fact that the `rational object` used a lower order $N = 16$. The impulse response of the `rational object` method introduces an impulse at $t = 0$ which is evident in the plot. The peak of the impulse response occurs at 0.17 μsec and the response decays to 10% of that peak at $t = 0.8$ μsec. Note that because the methods are based on the summation of simple poles resulting in passive and stable complex conjugate poles, the time-domain response is causal.

To understand the effects of the impulse response on a signal, it is of interest to evaluate the impulse response duration. A LTI system results from the convolution of the impulse response with the input signal. Convolution inverts the impulse response about the time axis and slides it across the signal generating a result that corresponds to the area under of the curve of the overlap between the two. A longer impulse response has more overlap that extends the response at the tail of the signal producing inter-symbol interference (ISI). Higher levels of ISI means communication systems must either

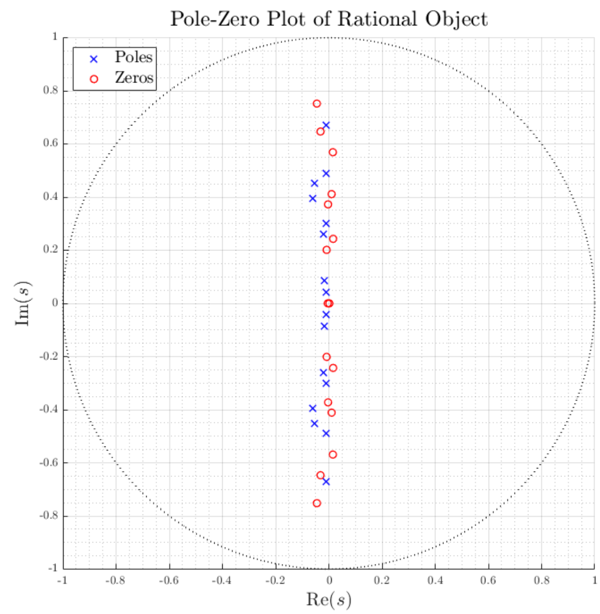

Fig. 4. Pole-zero plot from rational object fit to S-parameter data of device frequency response.

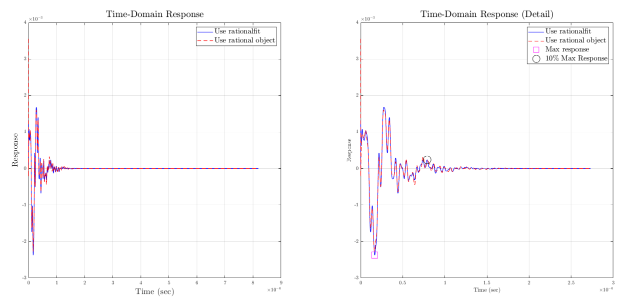

Fig. 5. Plot of channel impulse response from the rational object approach compared to a similar extraction using vector fitting (VF) method. Left plot shows response and right plot shows response detail including maximum of time response and time when response is down 10% from the maximum for VF result.

implement longer symbols or provide more separation between symbols resulting in reduced data rates.

A way to estimate the impulse response duration is to determine the amount of time required for the impulse response to decay to some specific value. If the maximum value of the impulse response is A, then we seek to find the time $t_\gamma > 0$ where the impulse response has decayed $A \rightarrow \gamma A$ with $0 < \gamma < 1$. This value can be determined by using Matlab's `timeresp` function to obtain the impulse response at a proper sampling rate relative to the frequency range of the frequency response. Sorting the samples in descending order we find the maximum value $|A|$ and then the value closest to $\gamma|A|$. The index of this value corresponds to the time t_γ. This approach was used to find the levels highlighted in the time-domain plots of the impulse responses provided here.

V. Device Communication Performance

The usable bandwidth of the piezoelectric device is generally below 50 MHz, so powerline communication (PLC) technology is suitable. Powerline ethernet devices provide plug & play capabilities using a home's powerline as a virtual cable to connect devices. They can handle complex loads and can deliver good data rates under adverse conditions. The estimated channel response indicated that the impulse response decays to 10% of the highest value in under 1 μsec, so a cyclic prefix beyond this value is suitable. Using the subcarrier spacing and cyclic prefix parameters from the HomePlug AV standard [15] from 2 to 30 MHz we estimated the trans-barrier data rate would exceed 70 Mbps with bit loading.

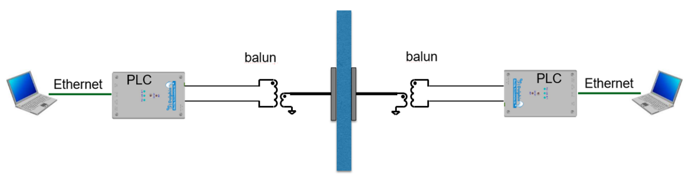

Fig. 6. Drawing showing laptops connected to BlueChip PLC units for throughput tests through a metallic barrier.

Sandia acquired a BlueChip Dolphin evaluation kit [16] that uses a combination of IEEE 1901 and ITU-G.9905 standards using OFDM physical layer. Pulse amplitude modulation (PAM) and low density parity check (LDPC) coding are used in the BlueChip implementation. The frequency response ranges between 2 and 28 MHz and up to 240 Mbps data rate is possible with bit loading.

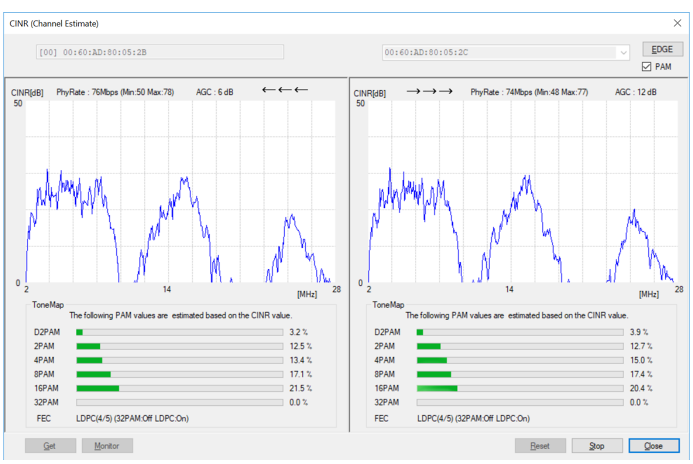

Fig. 7. Capture from BlueChip's tool showing CINR over 2 to 28 MHz spectrum with corresponding bit loading and data rates.

Two laptops were set up and the eval kit units were used to drive the piezoelectric devices through baluns for signal transmission as shown in Figure 6. Bluechip's integrated iPerf [17] network testing tool was used to evaluate the data rate performance through the barrier. Modulation ranged from differential 2-PAM to 16-PAM; 32-PAM was disabled. LDPC code rate $4/5$ was implemented. BlueChip's internal tool for plotting the carrier to interference plus noise ratio (CINR) was used to plot the spectrum in Figure 7. The raw data rate was about 76 Mbps with lossless packet data rate of 43 Mbps. This agrees quite well with the estimated data rate based on the HomePlug parameters.

VI. Conclusion

An electrical model of piezoelectric devices for transferring energy across a metallic barrier was obtained using frequency fitting methods. The piezoelectric devices were shown to be passive and exhibited reciprocity but not symmetry. By assuming a LTI channel we applied Matlab's `rational object` method to the measured S-parameter data to enforce causality in the temporal response of the system. The impulse response was extracted from the frequency fit and a simple method used to find the time when the impulse response decayed to some desired level and estimate the required cyclic prefix for an OFDM system. The data rate performance was estimated with these parameters and subsequently verified using an off-the-shelf BlueChip PLC evaluation kit with up to 76 Mbps raw data rate achieved.

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