Transmission Pattern Optimization for Sonar Antennas that suffer under Mutual Transducer Interactions

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Introduction

For sonar transmitters it is often desirable to provide a constant source level over a wide angular width while transmitting no power elsewhere [1]. The realization is only possible approximately due to limited antenna lengths and a limited amount of transmitters. Similar to electronic filters this results in degradations like passband ripples, a transition band with limited steepness and a stopband with finite attenuation.
To achieve a desired steering direction or beam widths transmit antennas in sonar applications usually apply an optimized amplitude and time-delay or phase shading to the individual transducers [2]. With possibly non-equidistant transmitter spacing and inherent characteristics the transmission pattern can often only be calculated numerically and hence makes numerical optimization methods necessary to obtain the shading coefficients.

In the calculation of the shading parameters the different transducers are usually assumed as independent. Nevertheless in certain applications, especially if neighboring transducers are spatially close together, the increased interaction results in undesired performance degradations. Hence the aim is to include the interaction of the neighbors into the modelling of the transducer output.

In this paper the electrical and acoustical behavior of a transducer is described by an N-gate. Here the acoustical output of a single transducer is not only depending on its electrical input but also on the acoustical impacts caused by the adjacent transducers in the antenna. These are modelled by mutual interaction admittances, which are identified by measurements using a test setup and are incorporated into the determination of the antenna beam pattern. For different example patterns the optimal shading parameters are then calculated by exploiting numerical optimization techniques. To evaluate the influence of the mutual interaction effect, finally, different setups containing the mutual interaction admittance are compared by assessing the performance degradation of the transmit patterns.

Active Sonar Processing Systems

Aim of this work is to find the optimum array shading parameter for an active sonar processing chain. An example setup is displayed in Figure 1.

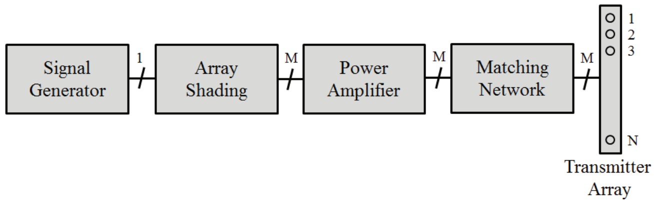

Figure 1: Example setup of a sonar transmitter signal processing chain with M shaded channels and N transducers.

Here we assume M seperatly shaded channels for the N transmitters where $N \geq M$ and for symmetric transmission pattern requirements usually $N = 2M$. Nevertheless in certain applications, especially if neighboring transducers are spatially close together an increased interaction between the transducers occurs and results in undesired performance degradations. Hence the aim is to model and include the interaction between the transmitters and include this into the optimization procedure.

Beampattern Optimization

To estimate the transmit behavior of the antenna we model each transducer as a single sound source. The far field superposition of the signals from each source depending on azimuth angle ϕ and elevation angle θ is given by the complex beampattern

$$bp(\varphi,\theta) = \frac{1}{\hat{Q}} \sum_{n=1}^{N} Q_n c_n(\varphi,\theta) \cdot e^{jkd_n(\varphi,\theta)} \qquad (1)$$

where $\hat{Q}$ is a normalization constant, Q_n are the complex shading parameters, $c_n(\varphi,\theta)$ is the inherent characteristic of the n-th transmitter and

$$\begin{aligned} d_n(\varphi,\theta) &= \cos(\varphi)\cos(\theta)\,x_n \\ &\quad + \sin(\varphi)\cos(\theta)\,y_n \qquad [\text{m}] \qquad (2) \\ &\quad + \sin(\theta)\,z_n \end{aligned}$$

is the relative transmitter distance in the far field approximation. The logarithm of the squared magnitude of the complex beampattern given by

$$BP(\phi,\theta) = 20\lg(|bp(\phi,\theta)|). \qquad [\text{dB}] \qquad (3)$$

is denoted as beampattern.

Mutual Interaction Modelling

The interaction between the transmitters is modelled by coupled impedances. The nearest neighbor coupling is shown exemplarily with the acoustic equivalent circuit network displayed in Figure 2.

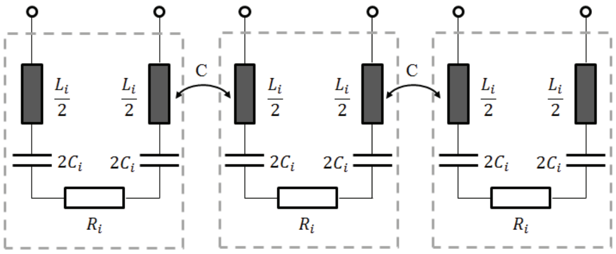

Figure 2: Modelling of the acoustic properties of the sonar transducers by equivalent series resonant circuit in symmetric representation with inductance L_i, capacitance C_i, resistance R_i and coupled inductivities with coupling factor C.

The calculation of the coupling factor C for the next neighbor interaction might be possible but cumbersome for simple transmitter setups. However if the coupling to the next transducers and further is of interest, combined with the complexity of modern transmitter layouts, FEM models are required for its determination.

Measurement of the Mutual Admittance

Nevertheless, if a test setup is available the coupling factor or mutual admittance can be derived from measurements. It is performed by selective signal supply and successive short circuiting of the staves. Given a transmitter a on which voltage and current are measured and a transmitter b on which a sinusoidal test signal is supplied we can calculate the couple admittance Y_{ab} from the measurements requiring that all transmitters except a and b are short circuited. Hence we can perform L^2 measurements where L is the number of available test staves resulting in

$$\tilde{\boldsymbol{Y}} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1L} \\ Y_{21} & Y_{22} & & \vdots \\ \vdots & & \ddots & \\ Y_{L1} & \cdots & & Y_{LL} \end{bmatrix}. \qquad [\mathrm{S}] \qquad (4)$$

We can generally assume a reciprocal channel between two staves such that $\tilde{\boldsymbol{Y}}$ becomes a symmetric matrix. Given an equidistant setup with similar staves we obtain from the $a = b$ measurements the own admittance Y_0 of the transmitters. The measurements with $a \neq b$ provide the m-th order mutual admittance Y_m with $m = |a - b|$. Hypothetically a perfect test setup and the absence of measurement errors would result in the symmetric Toeplitz matrix

$$\tilde{\tilde{\boldsymbol{Y}}} = \begin{bmatrix} Y_0 & Y_1 & \dots & Y_L \\ Y_1 & Y_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & Y_1 \\ Y_L & \cdots & Y_1 & Y_0 \end{bmatrix}. \qquad [\mathrm{S}] \qquad (5)$$

Nevertheless multiple measurements available for the same admittance will differ and hence these are averaged to obtain a single value.

The current test setup consists of three transmitters. Hence we can only determine the next neighbour (1st order) mutual admittance and the next but one (2nd order) mutual admittance. Due to the normalization in the beampattern calculation we can also apply normalized admittances in the calculation. The mutual admittances relative to the own admittance of the transmitter are given in Table 1.

Table 1: Measurement result of the mutual impedance in multiples of the own impedance of the transducer

	Measured Admittance $[\cdot Y_0]$	
	Magnitude	Phase [deg]
Mutual 1st Order	0.095	83.87
Mutual 2nd Order	0.084	-116.65

Modelling of the Mutual Admittance

In the processing chain the network is virtually inserted between the matching network and the transmitter array and connects the M input channels from the power amplifiers to the N transmitters which is outlined in Figure 3. The input to the network is a voltage provided by the power amplifier. The output of the network is the current flowing through the ceramic which is proportional to the physical displacement of the piezoelectric material.

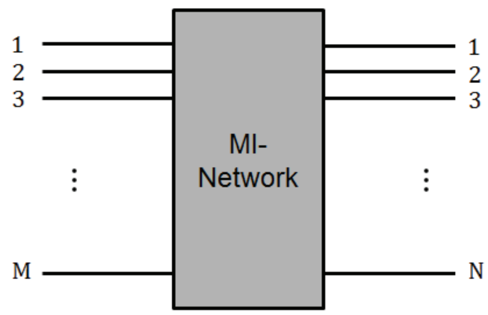

Figure 3: Mutual Interaction Network modeled as a P-gate with M inputs and N outputs.

The mutual interaction is modelled by a P-gate with $P = M + N$. Hence the P-gate can be characterized by an $P \times P$ admittance matrix [3]. Since output to output as well as input to input relations are not of special interest in our case we can reduce the matrix to an $N \times M$ admittance matrix which connects the voltage input from the power amplifier $\boldsymbol{U} = (U_1, U_2, \dots, U_M)^{\mathrm{T}}$ to output current at the transducer $\boldsymbol{I} = (I_1, I_2, \dots, I_N)^{\mathrm{T}}$ by

$$\boldsymbol{I} = \boldsymbol{Y} \cdot \boldsymbol{U} \qquad [\mathrm{A}] \qquad (6)$$

In general we have no access to the complete admittance matrix $\boldsymbol{Y}$. Hence we use an estimate which is constructed using the measured mutual admittances. The actual setup depends on the interconnection between the M shaded channels and the N transmitters. In the simplest case e.g. $M = N$ we obtain the symmetric Toeplitz matrix

$$\hat{\boldsymbol{Y}} = \begin{bmatrix} Y_0 & Y_1 & \cdots & Y_N \\ Y_1 & Y_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & Y_1 \\ Y_N & \cdots & Y_1 & Y_0 \end{bmatrix}. \qquad [\mathrm{S}] \qquad (7)$$

Due to the increasing spatial distance between the staves higher order mutual admittances should asymptotically converge to zero. Hence non-available mutual admittances are replaced by zeros. By replacing all mutual admittances by zeros it is also possible to 'switch off' the mutual interaction network model.

Finally we obtain the N shading parameters for the beampattern calculation

$$\boldsymbol{Q} = (Q_1, \dots, Q_N)^{\mathrm{T}} = \hat{\boldsymbol{I}} = \hat{\boldsymbol{Y}} \cdot \boldsymbol{U} \qquad [\mathrm{A}] \qquad (8)$$

by optimizing the M inputs $\boldsymbol{U}$ by numerical optimization methods. Hereby it is also desirable to realize the optimization by applying mainly phase shadings to avoid a loss of transmission power. Hence for the optimization we require the constraint

$$\frac{1}{M}\sum_{m=1}^{M} |U_m| \geq \frac{1}{\sqrt{2}} \qquad (9)$$

assuming normalized amplitudes with $\max(|U_m|) = 1$.

Exemplary Investigations

The shading coefficients U_m for $m = 1, \dots, M$ are optimized using the '*fmincon*' function from the MATLAB '*Optimization Toolbox*'. Here gradient based methods are applied also allowing the definition of linear and nonlinear constraints and boundaries [see 4 for further information].

In two scenarios the effect of the mutual impedance on the antenna performance is evaluated. Aim for both is to achieve minimum ripple over a passband of 60° centered around 0 °, a transition band of 10° and a stop band attenuation of at least 20 dB. Due to the symmetric pattern requirement we choose a symmetric setup with $M = N/2 = 18$ complex shading parameters to be estimated.

In the first example scenario we consider a linear antenna of 36 rectangular transmitters with an edge length $a = 0.3\lambda$ and an equidistant spacing of 0.4λ.

In the second example scenario we consider an equivalent setup besides we assume that the antenna is made from four decoupled segments with separated backings and molding. Hence we assume a larger gap of 0.6λ as well as no mutual impedance between the separated segments.

In Figure 4 and 7 the result for an optimization without mutual impedance is displayed. Using the estimated shading parameters we now include mutual impedance into the beampattern calculation. The results are given in Figure 5 and Figure 8. By including the mutual impedance into the optimization procedure we obtain the beampattern in Figure 6 and Figure 9.

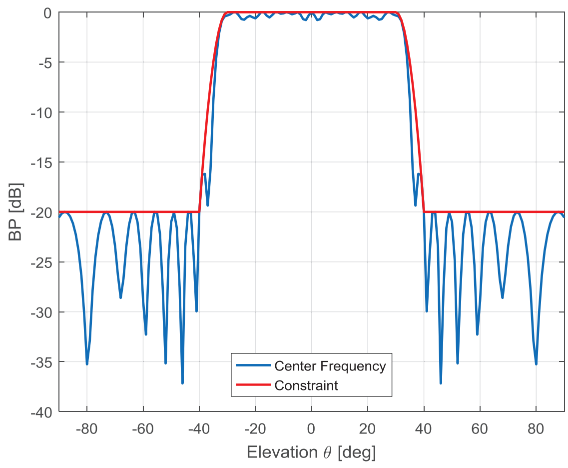

Figure 4: Transmit characteristic of a linear antenna with optimized shading parameters without including mutual interaction effects.

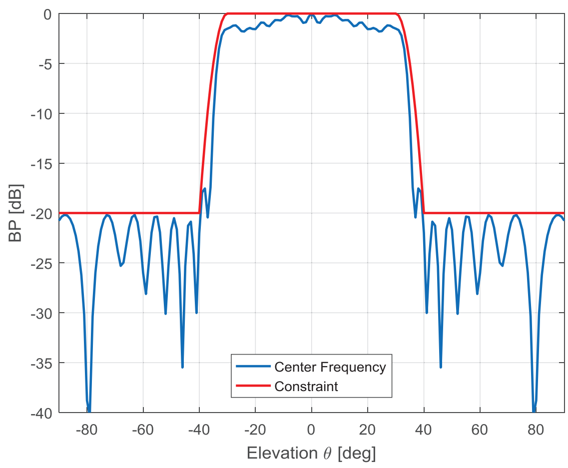

Figure 5: Transmit characteristic of a linear antenna with optimized shading parameters without including mutual interaction effects although the mutual interaction is present.

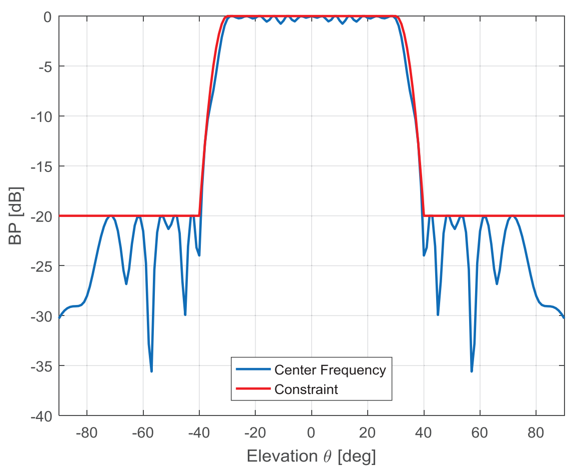

Figure 6: Transmit characteristic of a linear antenna with optimized shading parameters including mutual interaction.

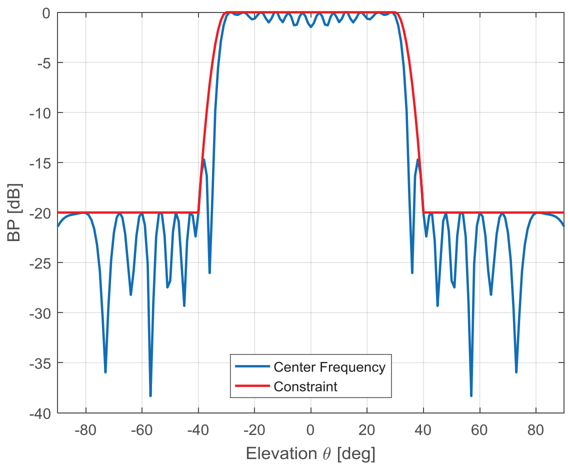

Figure 7: Transmit characteristic of a segmented linear antenna with optimized shading parameters without including mutual interaction effects.

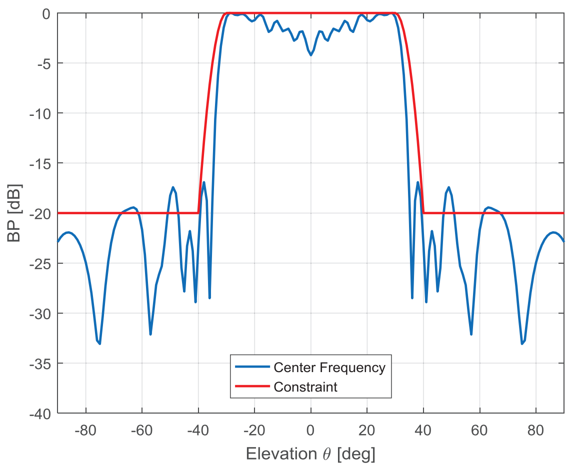

Figure 8: Transmit characteristic of a segmented linear antenna with optimized shading parameters without including mutual impedance effects although the mutual interaction is present.

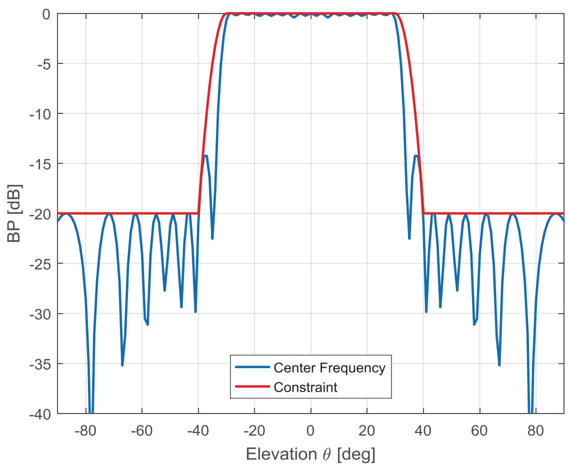

Figure 9: Transmit characteristic of a segmented linear antenna with optimized shading parameters including mutual interaction.

From both experiments we conclude that mutual impedance results in a significant impact on the transmit behavior mainly resulting in a degradation in the angular transmission band. For the first antenna the transmission band ripple increases from 0.6 dB to 2.4 dB while it increases for the second antenna from 1.6 dB to 4 dB. The higher ripple in the second setup can be explained by the violation of the spatial sampling theorem due to the segmentation. Nevertheless in both cases the inclusion of the mutual interaction into the optimization routine allows a compensation of the effect. In case of the second antenna the optimization including mutual interaction gives a better result compared to the standard optimization which shows that the correlation of the shading channels aids the optimization routine to avoid local optima.

The stronger degradation of the transmit characteristic of the second experiment results from the stronger influence of the mutual impedance on edge transducers. Transducers located closer to the center of the antenna possess a similar surrounding to both sides and hence are influenced similarly. Edge transmitters however with an asymmetric surrounding are affected differently. Due to the segmentation the second antenna setup contains four times the edge transmitters and hence is stronger degraded by not including the interaction.

Conclusion

In the paper we examined a method to include the acoustical interaction between the transmitters by mutual admittances. These were determined by a measurement performed with a test setup and inserted into the antenna model. The model is then used to estimate the shading parameters. Thereby the relevance of the mutual interaction is evaluated.

The simulation shows a significant increase of the ripple in the angular transmission band if the mutual interaction effect is present but not considered in the optimization. The degradation can be compensated by including the effect into the optimization. Additionally we conclude that the mutual interaction mainly influences the end staves of the setup.

In further investigations a two-dimensional mutual interaction as well as an adaption for the receiving case should be considered. To improve the optimization results methods like genetic algorithms or stimulated annealing also combined with traditional gradient based methods are possible. Also the effect of mutual impedance on broadband applications and hence optimizations for multiple frequencies are a possible future research topic.

Literature

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