Multiple-Input-Multiple-Output (MIMO-) High-Resolution Monostatic Sonar for Target Detection

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Abstract — The detection of small targets like divers or mines in a reverberation-dominated environment found in harbors or in shallow waters is a challenging task for an active sonar system. Increasing the spatial resolution of a sonar system is an effective way to reduce the reverberation and to enhance the detection performance in the particular direction. Traditionally, this can be achieved by increasing the array aperture size. In this paper we propose a monostatic MIMO sonar method that combines transmit- and receive beamforming, after the pulse is transmitted. Thereby it is possible to massively increase the spatial resolution by virtually enlarging the aperture and without increasing the number of physical hydrophones on the system.

1 Introduction

One of the key performance criteria of an active sonar system is its resolution. For different types of sonar systems, a higher resolution can lead to various positive effects, e.g.: a higher accuracy for seafloor mapping sonars, an earlier detection of obstacles or mines for a forward-looking sonar (FLS) -especially in a reverberation-limited environment- or a higher detection range for anti-submarine-warfare sonars (ASW).

This paper describes a method that increases the resolution of an active sonar system significantly while no additional receive- and transmit elements are used. This is achieved by utilizing certain features of the transmitted signals in combination with a particular placement of the location of receive- and transmit elements.

2 Beamforming

The beamforming technique is a spatial filter that is used for directional transmission or reception of signals. To achieve a controllable directivity, it is necessary to utilize multiple receive and/or transmitting elements (arrays).

2.1 Delay-and-sum beamforming

The simplest form of beamforming is the “delay-and-sum” beamforming. This method can be used on the receiving (RX) part or on the transmitting (TX) part of an array. **RX**: The signals, received on each channel of the array, are delayed in a certain amount, corresponding to the “steering direction” of the beamformer. After the delay is applied, the signals are summed up. As a result, coherent signals, coming from the steering direction, are amplified.

TX: The transmit signal is emitted on every channel of the TX-array. To steer a beam, the signal on each channel gets delayed, corresponding to the desired steering direction of the TX-beamformer. The summation of the signals is then carried out “physically” within the medium (water). This leads to the downside of TX-Beamfoming: In contrast to the RX-beamforming the TX-beamforming cannot be steered afterwards. The direction of the TX-beamformer is irrevocable imposed in the RX signals. With the MIMO technique, this paradigm can be changed.

2.2 Beampattern

An important measure for the resolution of the beamformer is the beampattern. It shows the performance for a certain beamforming configuration in one particular steering direction. An example beampattern is shown in figure 1.

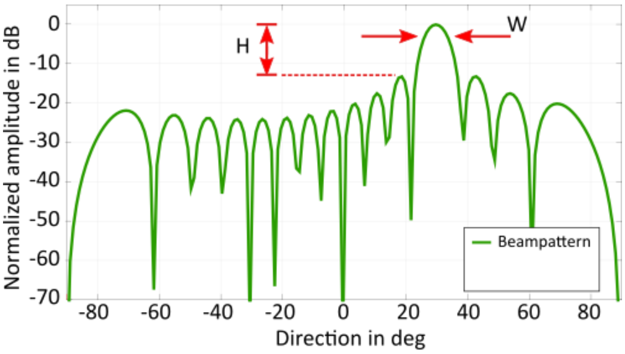

Fig. 1. Beampattern for a beamformer with 16 RX channels and 30° steering direction.

It visualizes the performance of a beamformer array with 16 RX channels and a steering direction of 30°. Two important measures should be taken into account: The width of the main lobe (W) and the height of the side lobes (H). Generally speaking: When W is decreased and H is increased, the beamformer performs better and thereby the resolution of the sonar system increases.

2.3 Performance modification

There are two basic physical possibilities to modify the beampattern:

- Adding more channels to the beamformer to enlarge the aperture. Under optimal frame conditions: The more, the better. H increases and W decreases.

- Spacing between the elements: Normally the optimal spacing is linked to the frequency of interest. Increasing the spacing leads to a decrease of W (which is good) but on the downside, it adds uncertainties (grating lobes) in the beampattern.

3 The MIMO principle

The typical modern sonar system is a single-input-multiple-output (SIMO) sonar. This means that during one detection process one coherent transmit signal (e.g. CW or FM) is used. If the transmitter is an array, the system transmits a beamformed version of the signal, that steers the transmit energy in a particular direction.

The MIMO principle transmits on every transmitter channel a different signal. The signals are orthogonal to each other. This means that the signals do not influence each other coherently. For this reason, there is no physical TX-beamforming inside the medium (see section 2.1). Hence, transmission becomes omnidirectional.

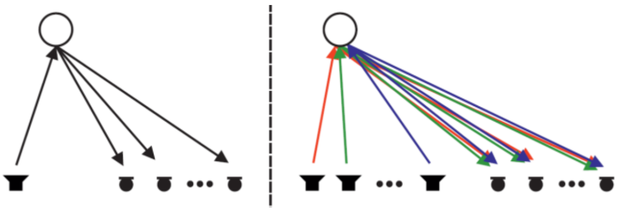

Fig. 2. SIMO principle (left), MIMO principle (right) while illuminating a target (circle).

In figure 2, the basic principle of SIMO and MIMO is depicted.

3.1 Subsequent TX-beamforming

Because of the missing beam steering, the MIMO sonar lacks of physical transmit energy in the steering direction compared to the SIMO sonar. This is positive because it lowers the risk interception during operations. On the other hand, it seems to be a disadvantage in terms of the detection range.

With the MIMO technique, it is possible to do a subsequent TX-beam steering. After the signals on each RX-channel are received, the original TX-signals are divided using a matched filter. The “re-cohering” of the signals follows this. re-cohering means: With the prior knowledge on how the signal orthogonality was established, the orthogonality can be revoked. Not only does this method compensate the lack of physical TX-beam steering, it enables additional features.

3.2 Combining beampatterns

Because the TX-beamforming can be done subsequently, the direction of the TX-beamformer is <u>not</u> irrevocable imposed in the RX signals. This enables the possibility of an optimal combination of the TX- and RX-beampattern (in the dB domain this operation is an addition). This allows a modification of the physical geometry of the TX-array in a non-optimal way (see section 2.3). The resulting uncertainties (grating lobes), due to violation of the optimal spacing, can be compensated with the RX-beampattern.

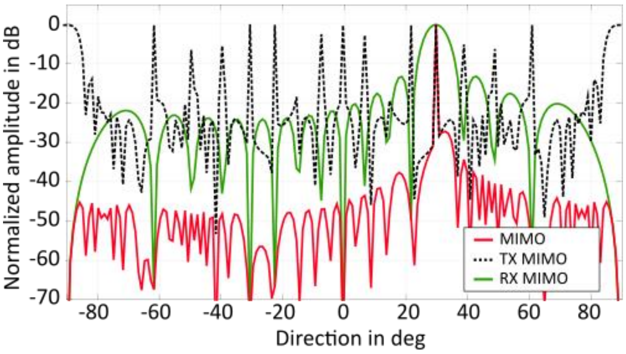

Fig. 3. MIMO Beampattern with 16 RX and 16 TX channels and 30° steering direction.

This is visible in figure 3. The number of used elements in figure 1 and figure 3 is the same. Due to the larger spacing of the TX channels, in figure 3 the grating lobes in the black dashed line (spikes) are visible. The spacing is chosen in a way, where the spikes of the grating lobes matching exactly on the zero points of the RX-beampattern (green line). The red line indicates the resulting beampattern of the MIMO system, realized with co-located uniform linear RX and TX arrays.

The aperture is increased virtually and corresponds to an array consisting of $N_{TX} \cdot N_{RX}$ elements[1].The resolution of the sonar system in the shown case is 16 times higher than a SIMO sonar.

4 Conclusion

With the MIMO technique, it is possible to do to a subsequent TX-beamforming. This provides the sonar designer a new degree of freedom. One possible advantage is the virtual enlargement of the aperture. In this paper it is shown, that this can increase the resolution of a sonar system drastically.

Author/Speaker Biographies

Dr. Tim Claussen — received his diploma degree in industrial engineering in the year 2012. Afterwards he worked as a researcher and doctorate student at the technical department of the University of Kiel. The research was carried out in the field of underwater signal processing for target detection and communications. In 2015, Tim Claussen started working as a system engineer at Wärtsilä ELAC Nautik in Kiel. Since 2018, he is head of the system-engineering department.

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[1] N_{TX} : Number of TX elements
N_{RX}: Number of RX elemnts