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Experimental demonstration of the angular resolution enhancement of a monostatic MIMO sonar

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In this contribution we show by experimental tests the improvement of the angular resolution of an active monostatic Sonar system when using the Multiple-Input-Multiple-Output (MIMO) principle. This principle allows the design of a high-resolution sonar with a lower number of transducers required compared to a conventional Sonar, thus allowing the costs of the Sonar to be significantly reduced. For this purpose, a MIMO Sonar demonstrator was built and experiments were performed in a harbor basin. It is shown that the travel time information can be extended in a manner that allows a factoring of the angular resolution of the system by the number of transmitters. The key to this principle is that the respective transmission pulses of the transmitter modules can be separated from each other during signal processing on the receiver side. This can be achieved through different techniques. In this paper novel transmitter signals are presented, which are coded in a way that they can be transmitted in the same frequency and time window and afterwards be sufficiently separated by correlation filters. To evaluate and model the experiment, also a simulation was developed, which uses a simplified model of the acoustic channel to generate the received signals.

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1. INTRODUCTION

An active sonar emits acoustic waves to detect and locate objects and structures under water. Usually it consists of a transmitter or transmitter array (transmitter unit) and a receiver array. These systems will be referenced as convential system in this paper. The transmitter unit can be considered as a point source with a certain directional characteristic, which emits acoustic energy in a certain area by using a transmitter pulse, e.g. a Continuous Wave (CW) or Frequency Modulated (FM) pulse [1]. It can be considered as a single input to the acoustic channel. In the acoustic channel the signal passes through the medium, is backscattered by objects, the seafloor and surface and by the medium itself and is received by the elements of the receiver array. The receiver elements can be interpreted as multiple outputs of the acoustic channel. Therefore the conventional active sonar system is called Single-Input-Multiple-Output (SIMO) Sonar. Using the travel time information of the transmitted pulse the localization of objects can be estimated by beamforming techniques. Therefore the range resolution depends on the characteristics of the transmitted pulse. The angular resolution depends on the geometry of the receiver array and the number of receiver elements, which often leads to limitations in the angular resolution.

An approach to increase the angular resolution of a sonar system is the principle of a Multiple-Input-Multiple-Output (MIMO) system, which uses more than one transmitter unit. This technique is already widely investigated by the Radar community [2]. Also in the Sonar community this topic is of increasing interest, e.g. the authors of [3] use the MIMO principle as a key element in a congnitive Sonar system. In [4] MIMO is applied on target tracking in a simulated harbor environment, whereas [5] shows the capabilities of spatially distributed MIMO Sonar systems.

Experimental demostrations of MIMO systems in the field of Sonar are however rare, which motivates the following experiment. For this work, a monostatic MIMO Sonar is considered, whereby multiple colocated transmitter units emit different transmitter signals within the same area. The receiver elements receive a superposition of all backscattered transmitter signals. Therefore the transmitter signals are designed to be nearly uncorrelated. This allows for signals to be separated in the receiver signal processing, which enables a link between each transmitter unit and receiver element. If the transmitter units and receiver array are arranged carefully in a monostatic setup, the travel time information is multiplied by the number of transmitter units [6]. This technique allows a significant improvement of the angular resolution.

To demonstrate the improvement of the angular resolution when using MIMO systems, a simulation and experiments using airbourne sound are done [7]. In the experiments two transmitters and a receiver array of 37 microfones are used to gain the travel time information of a virtual array with 74 elements. There has been shown that the ability to seperate two targets can be increased by this technique. However, the transmitting pulses that are used in the experiment (linear frequency modulated up- and down-sweep), are not sufficient for more than two transmitters. That motivates the design of novel pulseforms for use of a large number of transmitters.

2. MIMO CHANNEL DESCRIPTION

The monostatic Sonar system considered within this work has M transmitters and N receivers, which are located at the positions $\mathbf{q}_{T,m} \in \mathbb{R}^3$ with $m = 0, ..., M-1$, and $\mathbf{q}_{R,n} \in \mathbb{R}^3$ with $n = 0, ..., N-1$. In a general static scenario the relationship between the mth transmitter and the nth receiver can be described by the impulse response $h_{mn}(t)$. The nth receiver signal resulting from the superposition of all transmitter signals $s_m(t)$ after passing through the acoustic channel can be expressed by

$$s_n(t) = \sum_{m=0}^{M-1} s_m(t) * h_{mn}(t) . \tag{1}$$

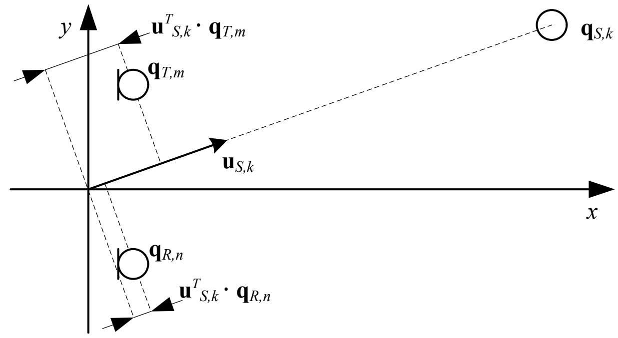

Figure 1: Approximation of the travel path in a far field scenario

In an ideal channel with K point scatterers at the locations $\mathbf{q}_{S,k} \in \mathbb{R}^3$ with $k = 0, ..., K-1$, (1) can be described in detail by

$$s_n(t) = \sum_{m=0}^{M-1} \sum_{k=0}^{K-1} a_{mnk} \cdot s_m(t - \tau_{mnk}) \tag{2}$$

with the propagation losses a_{mnk} and the travel time

$$\tau_{mnk} = \frac{|\mathbf{q}_{T,m} - \mathbf{q}_{S,k}| + |\mathbf{q}_{R,n} - \mathbf{q}_{S,k}|}{c} \tag{3}$$

between transmitter, scatterer and receiver, where c is the speed of sound. For a scatterer located in the far field, (3) can be approximated to

$$\tilde{\tau}_{mnk} = \frac{2|\mathbf{q}_{S,k}| - \mathbf{u}^T_{S,k}(\mathbf{q}_{T,m} + \mathbf{q}_{R,n})}{c} \tag{4}$$

where $\mathbf{u}_{S,k}$ is a unit position vector, which points in the direction of the scatterer (cf. Fig. 1). Here it becomes clear, that the same travel time information can be obtained by a virtual array with NM elements at the positions

$$\mathbf{q}_{V,mn} = \{\mathbf{q}_{T,m} + \mathbf{q}_{R,n} | m = 0, ..., M-1; n = 0, ..., N-1\} \tag{5}$$

Thus, by careful arrangement a linear virtual array with MN elements can be created by only using $M + N$ physical transducers. This allows a higher angular resolution in a setup with comparatively less transducers.

3. TRANSMITTER SIGNALS

A. METHODS OF MULTIPLE-ACCESS

A key element of MIMO systems is the design of transmitter signals, since the separation of the transmitter signals in the receiver signal processing is essential for the functionality of the system. From literature, methods for signal separation are often divided into Time-Division-Multiple-Access (TDMA), Frequency-Division-Multiple-Access (FDMA) and Code-Division-Multiple-Access (CDMA) [8].

Using the TDMA method, all transmitter signals use the same frequency band, but different time slots. The time slots are carefully arranged to ensure that the signals are distinguishable at the receiver, therefore a previous knowledge of the acoustic channel is necessary. The sequential emitting of the transmitted signals leads then to a perfect signal separation, but since time passes between the single measurements the channel can change, e.g. by movement of the target. In addition, the duration of the emitting sequence and therefore the ping period increases with the number of transmitters.

In the FDMA method, signal separation is achieved by dividing the transmit band into sub-bands, in which the transmit signals are distributed. This allows simultaneous transmission and in theory a perfect signal separation. However, the bandwidth of electroacoustic transducers is usually very limited, thus dividing the available frequency band by the number of transmitters further limits the bandwidth of the transmitted pulses.

With the CDMA method all transmitters use the same time slot and frequency band, whereby signal separation is accomplished using coding techniques. The advantage of the CDMA method is that it allows a large number of transmitters without having to restrict the transmission duration or bandwidth of the respective transmission pulses, as would be the case with TDMA and FDMA. However, this also has the consequence that many transmitters radiate their energy at the same time in the same frequency spectrum and the separation of the signals is only possible to a limited extent. The signal separation is realized by using matched filter banks in the receiver signal processing, which provide a correlation between the received signal and the transmitted signals. Therefore, the properties of the cross correlations between the transmitter signals determine the property of the signal separation [9].

B. MIMO PULSEFORM DESIGN

In this demonstration the CDMA method is used to separate transmitter signals. A frequency modulation based approach, which is often found in the literature, was adopted and improved. It is based on dividing a transmitter signal and its frequency band into discrete time and frequency cells, which are filled with micro-chirp signals (LFM up- and down-sweeps). The improvement of this method is to avoid the discretization of the frequency cells and to match the start and stop frequencies and phases of two adjacent micro chirps (cf. Fig. 2). Therefore, the time signal is continuously differentiable and is ideal for transmission by electroacoustic transducers, since there are no jumps in the phase. The coding is done by assigning a sequence $\mathbf{f}$ of $N_t + 1$ frequency values f_i for $i = 0, ..., N_t$. The complete transmitter signal is then a chain of N_t LFM subpulses $s_i(t)$ and is given by

$$s(t) = \sum_{i=0}^{N_t-1} 1_{[iT,(i+1)T]}(t) \cdot s_i(t - iT), \tag{6}$$

where

$$1_{\mathbf{M}}(t) = \begin{cases} 1, & t \in \mathbf{M} \\ 0, & t \notin \mathbf{M} \end{cases} \tag{7}$$

is a indicator function. A single subpulse is defined by

$$s_i(t) = e^{j\left(2\pi f_i t + \pi \frac{f_{i+1}-f_i}{T} t^2\right)} \prod_{m=0}^{i-1} e^{j\pi T(f_m + f_{m+1})}. \tag{8}$$

A set of four transmitter pulses was designed. Fig. 3 shows the auto- and cross-correlation functions of all transmitter signals.

4. DEMONSTRATION

A MIMO Sonar demonstartor manufactured by ATLAS ELEKTRONIK GmbH was built to validate the improvement in angular resolution by forming a virtual aperture. It consists of a receiver module and $M = 4$ transmitter modules. The receiver module is a uniform linear array with $N = 8$ channels, which

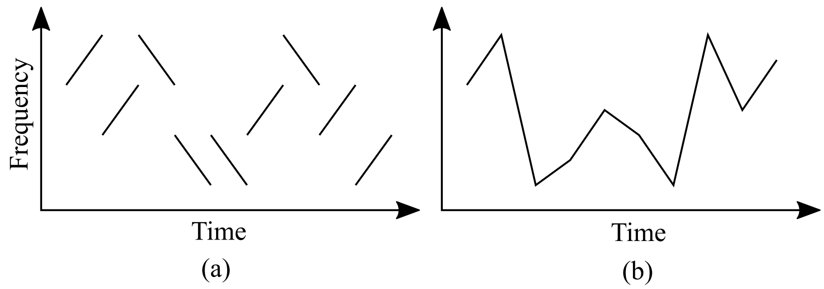

Figure 2: (a) LFM sequence with discrete time and frequency cells (b) Improved LFM sequence (LFM-Chain)

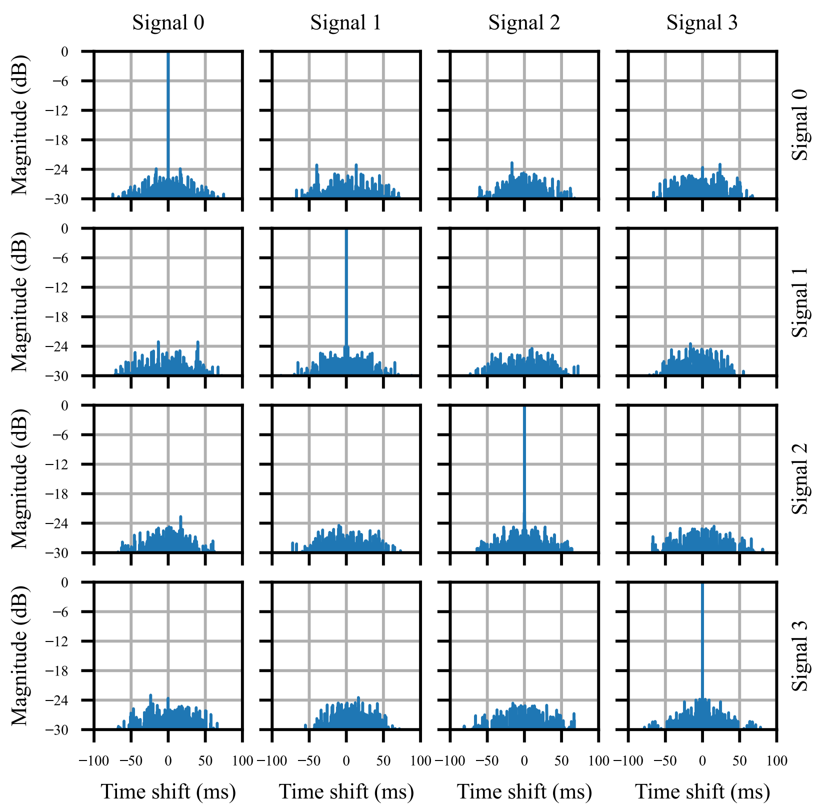

Figure 3: Auto- and cross-correlation of all transmitter signals

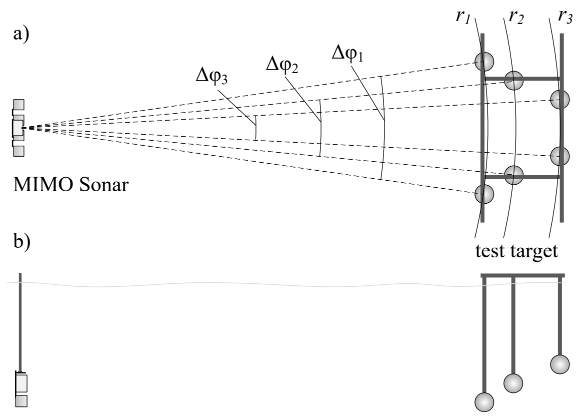

Figure 4: Test setup with resolution target. $\Delta\phi_l$ represents the angle between a pair of targets, whereas r_l is the distance to the Sonar system. (a) top view (b) side view

have a spacing of $d_r = \lambda/2$ with respect to the center frequency f_c. They have a bandwidth of 20 kHz at a center frequency of 50 kHz. The four modules are mounted in a row below the receiver module with a spacing of $d_t = N \cdot d_r$, forming together with the receiver module a virtual linear array with $N \cdot M = 32$ elements. The receiver signals are converted into digital signals, synchronized and passed to the signal processing unit. In the signal processing the receiver signals are mixed in the baseband and seperated by a matched filter bank to enable a link between every transmitter module and receiver channel. These $M \cdot N$ signals are processed in a coherent time domain back projection beamformer, to deduce the direction and range information of the targets.

The experiment takes place in a harbor basin. The water depth is ~6 m, whereby the Sonar system is mounted at a depth of 1.2 m. The speed of sound is estimated to be 1480 m/s. A resolution target is used as test target (cf. Fig. 4). It consists of 6 air-filled plastic spheres, which are arranged in three rows. This results in 3 different angles $\Delta\phi_1$, $\Delta\phi_2$ and $\Delta\phi_3$ between a pair of targets within the same range, which can be tested within one ping period.

In order to get an understanding of the theoretical model behind MIMO and to be able to predict experimental results, a simulation has been developed, which simulates the acoustic channel described in Section II. Fig. 5 shows the results from a simulation of the experimental setup. In the SIMO case only one transmitter unit of the demonstrator is active and emits an LFM up-sweep, whereas in the MIMO case all transmitter units are using the designed LFM-Chain signals. The test target has a distance of $r_1 = 2.6$ m to the Sonar system. This leads to the azimuth angles $\Delta\phi_1 = 20°$, $\Delta\phi_2 = 15°$ and $\Delta\phi_3 = 10°$ between the point targets. In the beamformer output of the SIMO Sonar (cf. Fig. 5(a)) only targets with a 20° angle are distinguishable, whereas the other pairs of targets can not be separated. In the MIMO case all targets can be clearly separated (cf. Fig. 5(b)). The results from experiment are shown in Fig. 6. Good agreement between experiment and simulation can be observed, which confirms the model of the acoustic channel. In both simulation and experiment it is clear that angular resolution is improved with the use of the MIMO system since all target pairs can be resolved. This can be compared with the SIMO system, where it is only possible to resolve the target pairs with the largest angular separation of 20°. In the experimental data, the targets seem to be more blurry in range compared with simulation. This can be explained by reflections from the frame, where the test targets are mounted. In general, the results of the MIMO system also show more clutter in the beamformer output. This has its origin in the coherent processing of all transmitted signals that do not decorrelate perfectly.

In addition, a further simulation is carried out in which two targets are located at the same distance r, whereas the angle $\Delta\phi$ between them is varied in a range from 0° to 90° in 1° steps. As an example

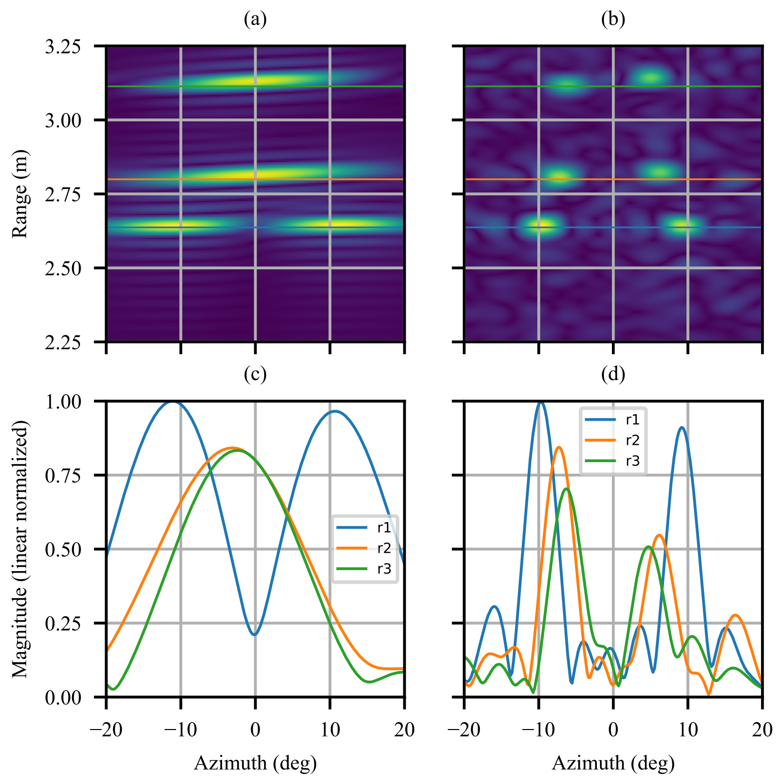

Figure 5: Results of a simulation of the experimental setup with $r_1 = 2.6$ m. (a) SIMO beamformer output (b) MIMO beamformer output (c) SIMO beamformer output for 3 different ranges (d) MIMO beamformer output for 3 different ranges

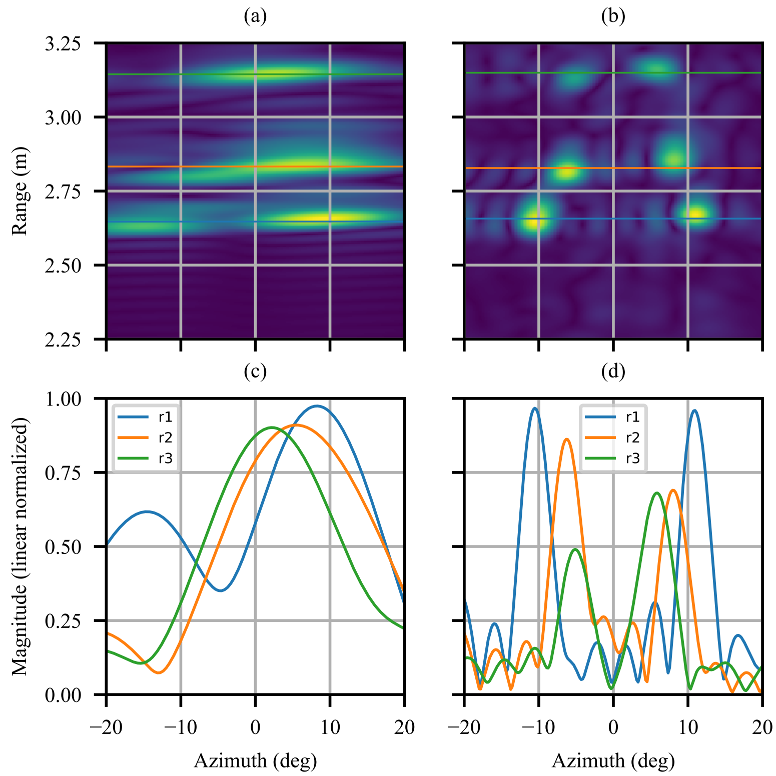

Figure 6: Results of the experiment with $r_1 = 2.6$ m. (a) SIMO beamformer output (b) MIMO beamformer output (c) SIMO beamformer output for 3 different ranges (d) MIMO beamformer output for 3 different ranges

Fig. 7(a) provides the beamformer output at the range r for a single step in which the angle between both targets is $\Delta\phi = 28°$. In this case both targets can be resolved and are represented by local maxima. A target separation level is now defined, which corresponds to the minimum level between both local maxima as long as the targets can be seperated. When separation is not achieved, the target separation level is 0 dB. Fig. 7(b) shows the target separation level for each simulated $\Delta\phi$. With SIMO Sonar a separability of approx. $20°$ is achieved, whereas with MIMO two targets can be resolved at approx. $5°$. Thus, as expected, a four times higher angular resolution is achieved by using $M = 4$ transmitters.

5. SUMMARY AND OUTLOOK

In this paper a complete MIMO sonar system was presented. New CDMA transmitter signals were shown, which have a continuously differentiable time signal, with a constant amplitude and are suitable for systems with a large number of transmitters. A simulation tool and a MIMO demonstrator were built to demonstrate the ability to acheive an improved angular resolution, which is explained by the concept of a virtual array. It was shown that the MIMO Sonar has a significant gain in resolution over SIMO Sonar, allowing the resolution test target to be resolved. The developed simulation, based on a simple model of the acoustic channel, was found to show excellent agreement with the experimental results. Further simulations show the capability of target separation for SIMO and MIMO depending on the azimuth angle between two targets. It confirms that the travel time information and therefore the angular resolution is multiplied by the number of transmitters. Future work could involve the study of methods to surpress clutter

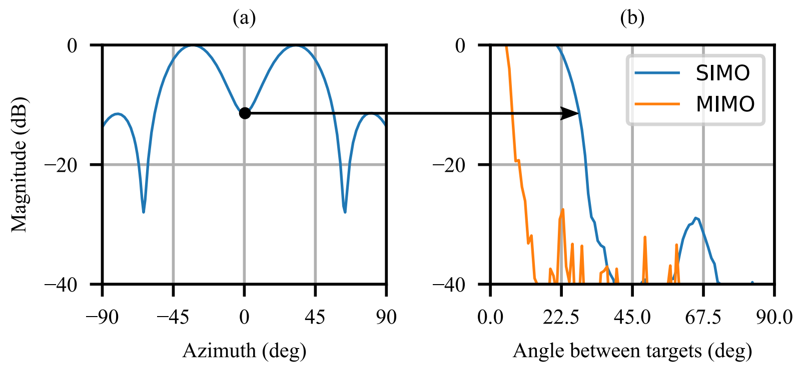

Figure 7: Target separation level for different angles between two targets (simulated). (a) Example: SIMO, 28° angle between targets (b) Target separation level

through image processing or further improved transmitter pulses. In the next steps the flexibility of a MIMO system will also be further investigated. This includes the use of different transmitter signals with different characteristics, which are sent simultaneously within a ping period, for example to improve the detection of moving objects.

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