Comparisons Between Code- and Time-Division-Multiplexing for MIMO Sonar Signal Processing

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Abstract: *Multiple-input multiple-output (MIMO) sonar systems enhance angular resolution by using travel-time information from all transmitter–receiver pairs compared to conventional single-input multiple-output (SIMO) systems. When dealing with multiple transmitters in a MIMO system it is crucial to separate pulses properly at the receiver side, which is possible by using multiplexing methods such as code division multiplexing (CDM), time division multiplexing (TDM), or frequency division multiplexing (FDM). The latter is not suitable for MIMO systems due to spatial ambiguities and image artifacts it introduces and is therefore not considered within this study. CDM enables simultaneous pulse transmission, however, it suffers from crosstalk caused by a non-zero cross-correlation of the pulses, which limits its performance. On the other hand, TDM allows for perfect pulse separation and thus a reduction of the crosstalk. However, during a prolonged overall ping period changes in the acoustic channel may occur which lead to artifacts after coherent processing. This work investigates the performance of MIMO sonar systems which implement CDM, TDM, and their combination with a focus on the reduction of crosstalk in a short range application. The pulse separation methods are studied through simulations and experimental validation in a harbour environment using various pulse types and number of transmitters. The results show that the generalised integrated sidelobe level (GISL) as a measure for the crosstalk can be reduced by the integration of TDM.*

Keywords: *multiple-input multiple-output sonar, MIMO, pulse separation, code division multiplexing, time division multiplexing*

1. INTRODUCTION

Multiple-input multiple-output (MIMO) systems are widely investigated in modern radar [1] and recently more often in sonar systems [2, 3, 4]. Among other configurations such as single-input single-output (SISO), single-input multiple-output (SIMO), and multiple-input single-output (MISO), MIMO stands out by improving angular resolution through the use of a virtual array that exceeds the aperture of the physical array. This is possible when information from every transmitter–receiver pair is utilized. The main challenge when applying the MIMO principle lies in accurate separation of transmitter pulses at the receiver. This can be achieved using code division multiplexing (CDM), time division multiplexing (TDM) or frequency division multiplexing (FDM) [3]. CDM enables simultaneous transmissions within the same frequency band and time window by assigning distinct coding schemes to each transmitter. In this way, the ping rate is comparable with SIMO configuration and supports long-range applications. However, imperfect pulse separation can cause inter-channel interference known as crosstalk, which decreases detection performance and may introduce ghost target artifacts [4]. In TDM non-overlapping time slots are assigned to each transmitter while maintaining the same frequency band. This approach to separation reduces crosstalk and enables pulse distinction. However, this way of transmission reduces the overall ping rate of the MIMO system. Additionally, during pulse transmission temporal changes in the acoustic channel may appear, limiting its use to short- and medium-range applications. FDM separates pulses by allocating different frequency bands to each transmitter within the same time window. While this method allows for perfect pulse separation, it reduces the range resolution, introduces spatial ambiguities in the beampattern and is sensible to frequency-dependent propagation effects [5]. Therefore, FDM is unsuitable for coherent MIMO signal processing and is not considered here.

In this work, we present a comparison between CDM, TDM, and propose a combined approach for signal processing in MIMO sonar systems. Combining CDM and TDM should provide a high overall ping rate of the sonar system while at the same time reduce the crosstalk. Multiple scenarios with targets at different distances, various number of transmitter and different pulse types are simulated. More specifically, we investigate the pulse separation methods with linear frequency modulated (LFM), LFM sequence [2], LFM chain [6] and orthogonal frequency-division multiplexing (OFDM) signals for two and four transmitters. We analyse the performance of each method based on their point-spread function (PSF) and the generalised integrated sidelobe level (GISL). The simulation results are further validated through additional experiments conducted in a harbour environment.

2. SIMULATION SETUP

The simulation covers six scenarios of using CDM and TDM as shown in Figure 1. The first scenario resembles a pure CDM case where the two signals overlap completely in time. The second scenario involves a 10 ms delay between the two signals. In the third scenario, the second signal starts immediately after the first one finishes. The fourth, fifth, and sixth scenarios explore increasing gaps of 10 ms, 20 ms and 30 ms between the signals, respectively. For a considered processing range of 30 m the final two scenarios represent fully separated signals in time.

The MIMO sonar system is simulated to match the experimental hardware specifications, including a sampling frequency f_s of 192 kHz, a center frequency f_c of 50 kHz and a bandwidth

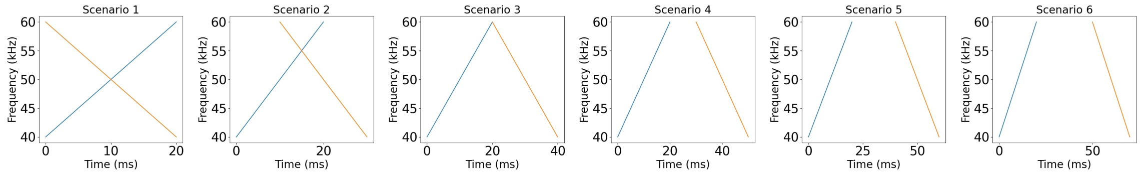


Figure 1: CDM-TDM scenarios considered in the simulation and experiment. Scenario 1 is pure CDM while the subsequent scenarios add a further time delay of 10 ms between the pulses. Blue line represents LFM-Up and orange line LFM-Down pulse.

B of 20 kHz. The receiving antenna is a linear array with 32 channels. We simulate the scenarios with two and with four transmitters with a spacing of half a wavelength and centered at the origin of the receiver. All scenarios are simulated with LFM sequence (LFMS), LFM chain (LFMC) and OFDM pulses, which are designed based on previous work [4, 7]. In addition, the two transmitter setup also uses a LFM-Up pulse for the first and a LFM-Down pulse for the second transmitter. All pulse length T are set to 20 ms.

A point target is simulated at 2 m, 5 m and 10 m distance at an azimuth direction of 0°. The simulation also accounts for bottom and surface reverberation. Ambient noise is modeled as normally distributed, incoherent white noise.

3. MEASUREMENT SETUP

The measurement takes place in the fishing harbour in Bremerhaven, Germany nearby the Institute for the Protection of Maritime Infrastructures of the German Aerospace Center (DLR). The basin has depth of approximately 6 m and a width of 50 m. The sonar system, consisting of a 32-channel receiver antenna and one transmitter at each end of the receiver, was installed on the quay wall at the depth of 2 m. The estimated speed of sound c in the water is 1480 m/s. A air-filled sphere was placed as a target in front of the sonar at ranges R of 2 m, 5 m and 10 m at a depth of 2 m. The same six CDM-TDM scenarios with all four pulse types as in the simulation are considered in the experiment.

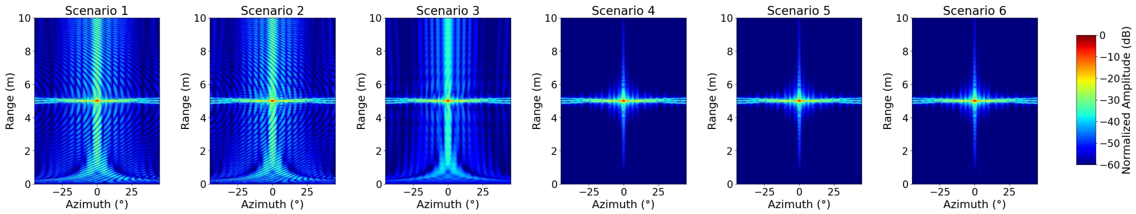
4. RESULTS

All scenarios are qualitatively analysed based on the output of the beamformer. From this we further calculate the GISL of the target beam signal $s_{TB}(r)$ as

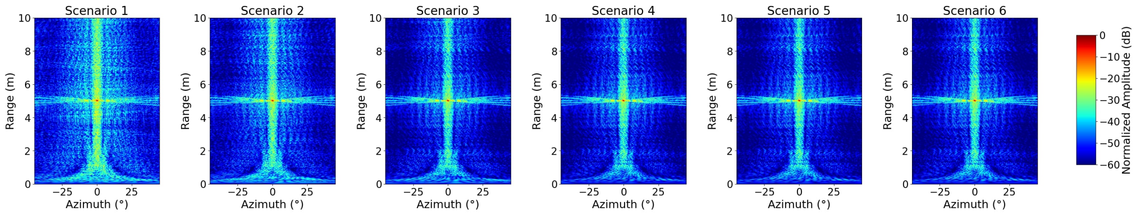
$$\text{GISL}^{(p)}(s_{TB}(r)) = \left(\frac{\int_{\Omega_{SL}} |s_{TB}(r)|^p dr}{\int_{\Omega_{ML}} |s_{TB}(r)|^p dr} \right)^{\frac{p}{2}} \tag{1}$$

to compare the scenarios quantitatively. With p set to 2, this corresponds to the integrated sidelobe level, which is commonly used for sonar pulse form optimization [8]. The area of the mainlobe Ω_{ML} is defined as

$$\Omega_{ML} = \left[R - \frac{c}{2B}, R + \frac{c}{2B} \right] \tag{2}$$



(a)



(b)

Figure 2: Simulated PSF for the six CDM-TDM scenarios obtained for configuration with (a) two transmitters with LFM-Up and LFM-Down pulses and (b) four transmitters with LFMC pulses. Point target located at 5 m and 0°.

and the area of the sidelobe Ω_{SL} as

$$\Omega_{SL} = \left[R - \frac{cT}{2}, R + \frac{cT}{2}\right] \setminus \Omega_{ML}. \tag{3}$$

Since due to movements of the target in the water its exact position is unknown in the measurement, we estimate it by first searching for the beam with the highest intensity. Afterwards, the position of the maximum within this beam in a range of ± 0.5 m around the setup range (2 m, 5 m or 10 m) is taken as the final target position.

Figure 2 compares the simulated PSF of all six scenarios for a target at 5 m for a MIMO sonar with two transmitters using the LFM-Up and LFM-Down pulses and a MIMO sonar with four transmitters using the LFMC pulses. In both cases it can be seen that for a larger time delay between the signals the crosstalk in the area around the target beam is reduced.

Figure 3 shows the simulated PSF of all considered pulse types for the scenarios 1, 4 and 6 with a MIMO sonar with two transmitters. The selected scenarios represent the case of pure CDM, a mixture of CDM and TDM without complete separation in time and complete separation in time. Especially the LFMS and LFMC pulses suffer from high crosstalk. Adding time delay between these pulses can efficiently reduce the crosstalk. As expected the best result is achieved for the complete separation of the signals in time. Furthermore, the overall noise background can be reduced by combining CDM with TDM.

Figure 4 displays the results of the corresponding experimental measurements for the same setup and scenarios as in Figure 3. For all setups the target is present in the direction in front of the MIMO sonar. However, only for the LFMC pulses the point target is clearly visible. Here the positive effect of combining CDM with TDM can be seen. When considering a not complete separation in time the crosstalk is reduced. Additionally, due to the short distance to the target effects from temporal changes in the acoustic channel are limited.

Table 1 and 2 list the GISL obtained during simulation studies and practical experiments for all investigated scenarios and pulse types for a MIMO sonar with two transmitters. The simulation shows an improvement in GISL for all pulse types when TDM is combined with CDM. In many cases a time shift of 20 ms between the pulses (scenario 3) is already sufficient to

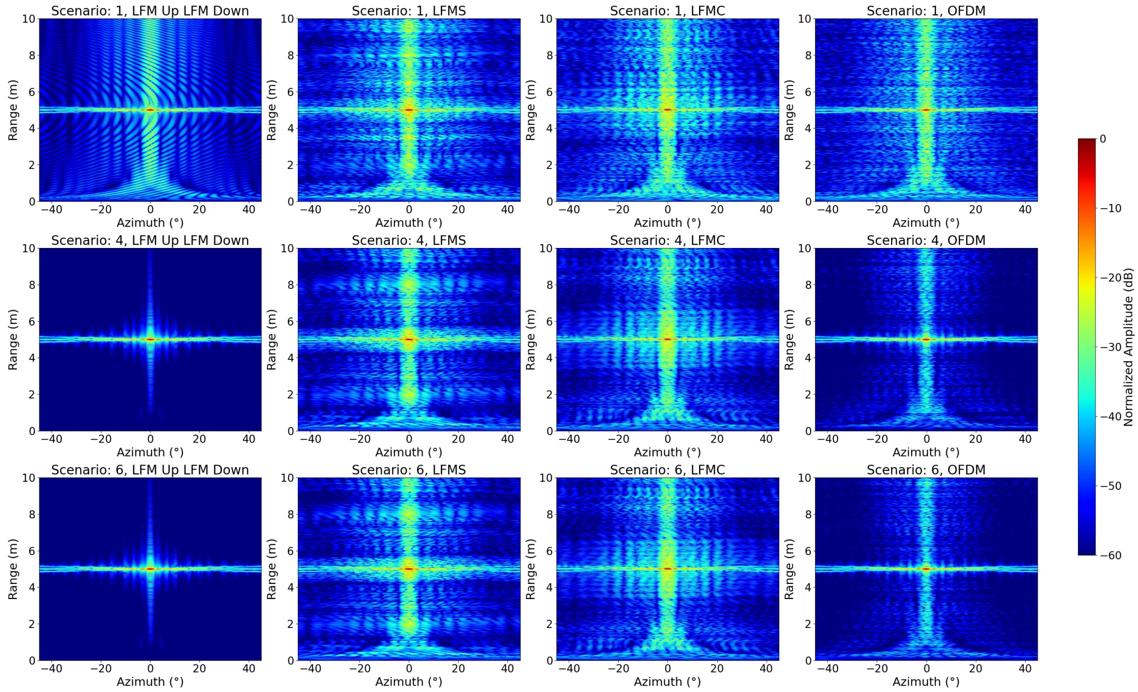


Figure 3: Simulated PSF for all considered pulse types obtained for a configuration of two transmitters the three CDM-TDM scenarios 1, 4 and 6. Point target located at 5 m and 0°.

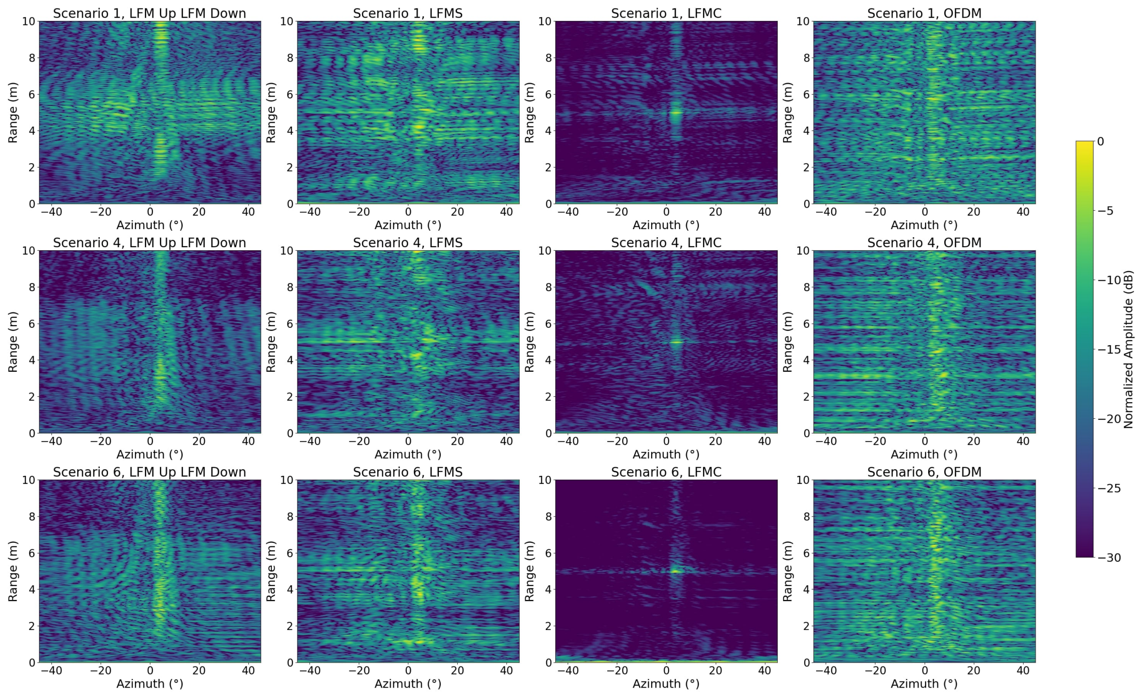


Figure 4: Beamformer output in the experiment for all considered pulse types obtained for a configuration of two transmitters the three CDM-TDM scenarios 1, 4 and 6. Point target located at 5 m and 0°.

Pulse type	Target range in m	GISL in dB for scenario					
		1	2	3	4	5	6
LFM-Up & LFM-Down	2	-28.1	-28.8	-29.9	-31.4	-32.5	-32.5
	5	-30.2	-30.8	-32.1	-33.8	-35.3	-35.3
	10	-31.4	-32.1	-33.4	-35.4	-37.4	-37.4
LFMS	2	-24.7	-24.7	-25.7	-26.4	-26.5	-26.5
	5	-26.7	-26.5	-27.9	-28.6	-28.7	-28.7
	10	-27.9	-28.1	-29.1	-29.8	-29.9	-29.9
LFMC	2	-24.8	-24.9	-26.1	-26.7	-26.8	-26.8
	5	-24.4	-24.5	-25.0	-25.5	-25.6	-25.6
	10	-26.5	-26.4	-27.6	-28.4	-28.5	-28.5
OFDM	2	-26.3	-26.9	-28.7	-29.8	-30.5	-30.5
	5	-28.3	-29.5	-30.8	-32.4	-32.8	-32.8
	10	-30.3	-30.1	-32.3	-33.4	-34.6	-33.9

Table 1: Performance of the CDM-TDM scenarios based on the GISL from the simulations.

Pulse type	Target range in m	GISL in dB for scenario					
		1	2	3	4	5	6
LFM-Up & LFM-Down	2	-4.1	1.2	-5.4	-1.0	-6.3	-7.4
	5	1.4	-1.6	2.5	-3.4	-1.0	-3.3
	10	0.0	-2.7	-2.4	1.4	-4.1	-1.9
LFMS	2	-1.8	-4.2	-2.4	-5.7	-8.2	-5.4
	5	-2.7	0.6	-3.0	-0.2	-4.1	-4.8
	10	-4.3	-1.1	-5.5	-3.4	-4.6	-2.3
LFMC	2	-15.0	-16.2	-15.9	-17.3	-20.1	-19.4
	5	-19.7	-14.1	-20.5	-16.8	-20.6	-22.5
	10	-4.4	-5.9	-2.8	-3.0	-5.7	-6.6
OFDM	2	-3.2	-1.1	-1.8	-3.5	-4.7	-8.8
	5	-4.9	-6.4	-2.2	-4.5	-6.5	-6.1
	10	-8.1	-6.1	-4.0	-5.3	-3.6	-8.5

Table 2: Performance of the CDM-TDM scenarios based on the GISL from the experiments.

achieve the same performance as with complete pulse separation. Compared to the simulations, the experiments show higher values for the GISL. The reason for this is the idealised nature of the simulation, which does not take all possible acoustic phenomena and noise sources into account. In general, the experimental results does not show the same clear behaviour of the GISL for the different scenarios. However, especially for the case of LFMC, for which the target is clearly visible, the performance improves with adding a larger time delay between the pulses.

5. CONCLUSIONS

This work has analysed the effect of combining TDM and CDM for pulse separation in a MIMO sonar system. A broad range of simulated setups with varying extend of time division, array configuration and pulse types have been conducted. Furthermore, these setups have been investigated through experiments in a harbour environment. For short range applications, adding a time delay between transmitted signals can reduce the crosstalk of the MIMO system. This positive effect already applies for short time delays that do not involve complete separation of the signals in time and thus allow for higher ping rates compared to pure TDM. Further work needs to extend the simulation in order to include more acoustic phenomena and allow for temporal changes in the acoustic channel.

REFERENCES

[1] J. Li, P. Stoica, *MIMO Radar Signal Processing*, (John Wiley & Sons, 2009).

[2] Y. Pailhas, J. Houssineau, E. D. Delande, Y. Petillot, D. E. Clark: "Tracking underwater objects using large MIMO sonar systems" in *2nd Underwater Acoustics Conference and Exhibition*, (Rhodes, 2014).

[3] Y. Pailhas, Y. Petillot: "Wideband CDMA Waveforms for Large MIMO Sonar Systems" in *2015 Sensor Signal Processing for Defence (SSPD)*, (Edinburgh, 2015).

[4] S. Schröder, J. Reermann, S. Barnes, D. Kraus, A. Kummert: "Study on pulse form design for monostatic MIMO sonar systems" in *OCEANS 2023 - Limerick*, (Limerick, 2023).

[5] D. Cohen, D. Cohen, Y. C. Eldar: "High Resolution FDMA MIMO Radar", *IEEE Transactions on Aerospace and Electronic Systems* **56(4)**, 2806–2822 **(2020)**.

[6] S. Schröder, J. Reermann, M. Stephan, D. Kraus, A. Kummert: "Experimental demonstration of the angular resolution enhancement of a monostatic MIMO sonar" in *6th Underwater Acoustics Conference and Exhibition*, (virtual, 2021).

[7] S. Schröder, J. Reermann, S. Barnes, D. Kraus, A. Kummert: "Pulse form optimization for MIMO sonar systems" in *International Conference on Underwater Acoustics 2024*, (Bath, 2024).

[8] D. A. Hague: "Adaptive Transmit Waveform Design Using Multitone Sinusoidal Frequency Modulation", *IEEE Transactions on Aerospace and Electronic Systems* **57(2)**, 1274-1287 **(2021)**.