Evaluation of Time-Staggered MIMO FMCW in HFSWR

Jan Oliver Hinz*, **Thomas Fickenscher****, **Anshu Gupta****, **Martin Holters***, **Udo Zölzer***

*Department of Signal Processing and Communications
Helmut Schmidt University, Holstenhofweg 85, 22043 Hamburg, Germany
email: jan.hinz@hsu-hh.de

**Department of High-Frequency Engineering
Helmut Schmidt University, Holstenhofweg 85, 22043 Hamburg, Germany

Abstract: *This paper evaluates the performance of the time-staggered (TS) multiple-in-multiple-out (MIMO) Frequency Modulated Continuous Wave (FMCW) radar approach and compares it to a conventional phased-array approach to obtain a proof-of-concept. The approach combines stretch processed FMCW and colocated MIMO radar by using multiple time-staggered chirps. The advantages of forming virtual antenna elements can be seen as a flexible solution regarding antenna configuration for a mobile or space-limited High-Frequency Surface Wave Radar (HFSWR).*

1. Introduction

High Frequency Surface Wave Radar (HFSWR) is used in the field of oceanography and maritime surveillance, because it allows ranges up to some hundred kilometers over conducting sea water. Frequency Modulated Continuous Wave (FMCW) in combination with stretch processing is a popular choice with advantages listed in [1]. Typical shore-based HFSWRs [2] operate a uniform linear array (ULA) receiving array of up to 16 elements with $\lambda/2$ spacing and thus can easily extend to a length of a kilometer. The evaluated time-staggered (TS) multiple-in-multiple-out (MIMO) FMCW approach presented in [3] takes advantage of the combination of a dense array and a sparse array to synthesize virtual antennas based on a given transmitter and receiver arrangement.

Critical is the issue of signal separation at the receiver. In contrast to the time-multiplex FMCW approach of [4], where only one transmitter is active at each time instant, here the signals are transmitted simultaneously and thus have to be separated in the frequency domain. This paper is aimed at evaluating the performance of the TS MIMO FMCW approach, where particularly crucial points in the receiver processing are illustrated. First the developed signal model for TS-MIMO FMCW signals is presented, second the signal separation process at the receiver is illustrated. Third the simulation parameters for the performance evaluation are given and simulation results are shown. Finally a conclusion is drawn.

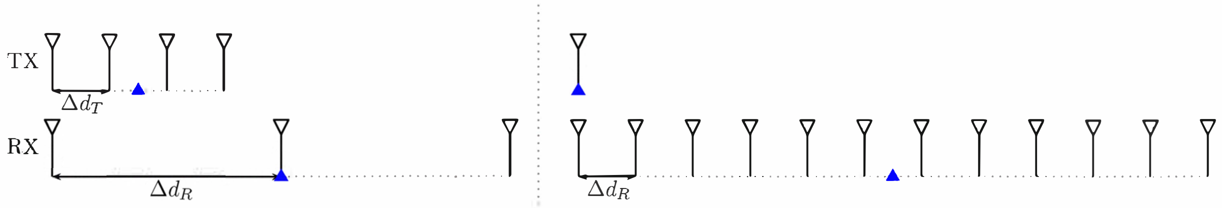

Figure 1: 4x3 (left) and 1x12 (right) transmit and receive array with array references

2. Signal model for TS-MIMO FMCW

To be able to proof the concept of TS-MIMO FMCW a radio-frequency (RF) simulation is required. Due to the chosen TS concept in combination with stretch processing the separation of the different transmitters is carried out in the analog domain in the receiver RF-front-end. The selected antenna configuration can be seen in Fig. 1 and consists of a dense transmitter array (TX) with $M_T = 4$ elements and a colocated sparse receiver array (RX) with $M_R = 3$ elements. Still other configurations are possible. To model the received signals the following four delays are involved, assuming a potential target situated in the far-field at an angle α from boreside. The first delay is the round-trip time from the reference point of the transmitter array via the target to the reference point of the receiver array as given by

$$\tau_r = \frac{2R}{c}, \tag{1}$$

where R is used to denote the target range and c is used to denote the speed of light.

The additional delay τ_{tx} between each transmitter element with respect to the transmitter array reference point is dependent on the distance $d_t[m_t]$ of each element m_t from the reference point and the target angle α as described in

$$\tau_{\text{tx}}[m_t] = \frac{d_t[m_t]}{c} \sin(\alpha) \qquad \forall\, m_t. \tag{2}$$

The same applies to the additional delay τ_{tx} at the receiving elements as shown in

$$\tau_{\text{rx}}[m_r] = \frac{d_r[m_r]}{c} \sin(\alpha) \qquad \forall\, m_r, \tag{3}$$

in which $d_r[m_r]$ denotes the distance of one particular receiving element m_r from the receiving array's reference.

In the TS-MIMO FMCW approach each transmitter element transmits its signal at an additional time offset $\Delta\tau_{\text{to}}$, where the minimum time offset $\Delta\tau_{\text{to}}$ between elements is equal to the round-trip delay τ_{max} at maximum range R_{max}. On the other hand $(M_T - 1) \cdot \tau_{\text{to}}$ is required to be smaller than $T/2$, where T is used to denote the chirp duration. The delay at et each element follows $\tau_{\text{to}}[m_t] = (m_t - 1) \cdot \Delta\tau_{\text{to}}$. The received signal at one particular receive antenna $r[m_r]$ is composed of the superposition of the Doppler-shifted and delayed target responses from each transmit element. For one target and one time instant this leads to a total delay τ_{total} of

$$\tau_{\text{total}} = \tau_r + \tau_{\text{rx}}[m_r] + \tau_{\text{tx}}[m_t] + \tau_{\text{to}}[m_t] \tag{4}$$

In case the target is moving radially towards or away from the radar this only affects τ_r, while $\tau_{\text{rx}}[m_r]$, $\tau_{\text{tx}}[m_t]$ as well as $\tau_{\text{to}}[m_t]$ remain unaffected.

3. Receiver processing

As illustrated in Fig. 2, at each receiver element a separation of the reflected and superimposed transmitter waveforms is performed. This is commonly known as stretch processing (SP) and mixes each receiver element signal with the M_T appropriately delayed $[0 \ldots (M_T - 1) \cdot \Delta\tau_{\text{to}}]$ FMCW reference waveforms (REF m_t). An even more important point is the following analog lowpass filtering (LPF) to suppress the mixing products with the other $(M_T - 1)$ waveforms. The characteristic of the analog lowpass filter needs to fulfill

$$f_{\text{pass}} = \tau_{\text{max}} \cdot \frac{B}{T} \tag{5}$$

$$f_{\text{stop}} = \Delta\tau_{\text{to}} \cdot \frac{B}{T}, \tag{6}$$

under the condition that $\Delta\tau_{\text{to}} \geq \tau_{\text{max}}$, where f_{pass} and f_{stop} are used to denote passband frequency and stopband frequency, respectively. To reduce the requirements of the analog lowpass $\Delta\tau_{\text{to}}$ is usually chosen to to be several times τ_{max}. Finally the signal is passed to an analog-to-digital converter (ADC). This is performed equally for all receive elements, leading to a total of $M_T \cdot M_R$ signals. To form beams into certain directions, a delay-and-sum MIMO beamformer is used, it compensates the phase delays of equations (2) and (3) and applies windowing. After the

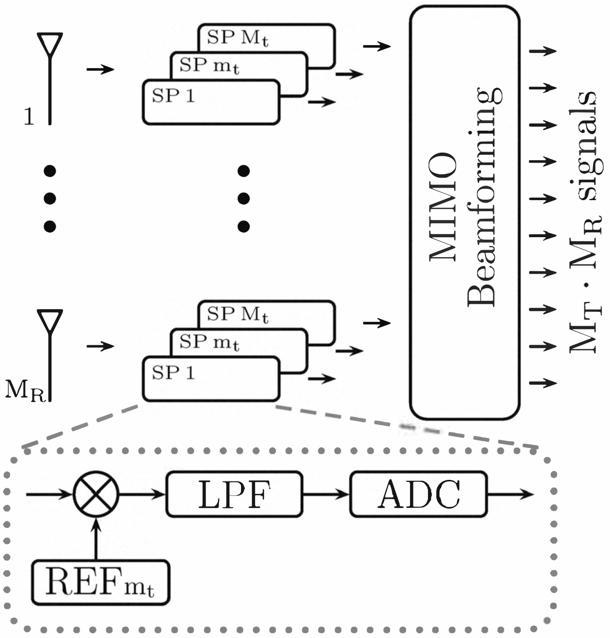

Figure 2: TS-MIMO FMCW receiver structure: Stretch processing for each transmitter/receiver combination, followed by the MIMO beamformer

MIMO beamformer, the range and Doppler-transforms are carried out to produce the Range-Doppler (RD) map.

4. Simulation Results

For the simulation the radar operating frequency is chosen to be 3 MHz with a chirp duration of $T = 0.5\,\mathrm{s}$, a bandwidth of $B = 100\,\mathrm{kHz}$ and a total of $N_c = 28$ chirps in one coherent processing interval (CPI). The time offset $\Delta\tau_{\mathrm{to}}$ is chosen to be three times the round-trip time at maximum range. The MIMO transmitter element spacing Δd_t is chosen to be $\lambda/2$, whereas the receiver array element spacing Δd_r is chosen to be $M_T \cdot \Delta d_t$ to obtain a virtual Nyquist array. As already indicated in Fig. 1 the number of elements are chosen to be $M_T = 4$ and $M_R = 3$. The used simulation sampling frequencies are $f_{\mathrm{sRF}} = 6.4\,\mathrm{MHz}$ $f_{\mathrm{sBB}} = 2048\,\mathrm{Hz}$. Using equations (5) and (6) this leads to the following requirements for the analog lowpass: $f_{\mathrm{pass}} = 266\,\mathrm{Hz}$ and $f_{\mathrm{stop}} = 800\,\mathrm{Hz}$. In this case a Butterworth filter of fourth order with the cut-off frequency f_c set to f_{pass} is used. The simulated radar scenario consists of two targets with ranges $R_1 = 80\,\mathrm{km}$ and $R_2 = 140\,\mathrm{km}$, target angles $\alpha_1 = 0°$ and $\alpha_1 = -40°$ as well as radial velocities $v_1 = 0\,\mathrm{m/s}$ and $v_2 = 20\,\mathrm{m/s}$. The first evaluation is carried out in terms of beampattern for the conventional phased-array (single transmitter and a long-dense receiver array of size $M_T \cdot M_R$) and the virtual array formed by the proposed TS-MIMO FMCW, which is presented in Fig. 3. As one can see in Fig. 3 the beampattern look almost identical: the directivity in the main beam and the expected sidelobe level from the Dolph-Chebyshev weighting of -40 dB is maintained with only minor differences in the null positions of the sidelobe pattern.

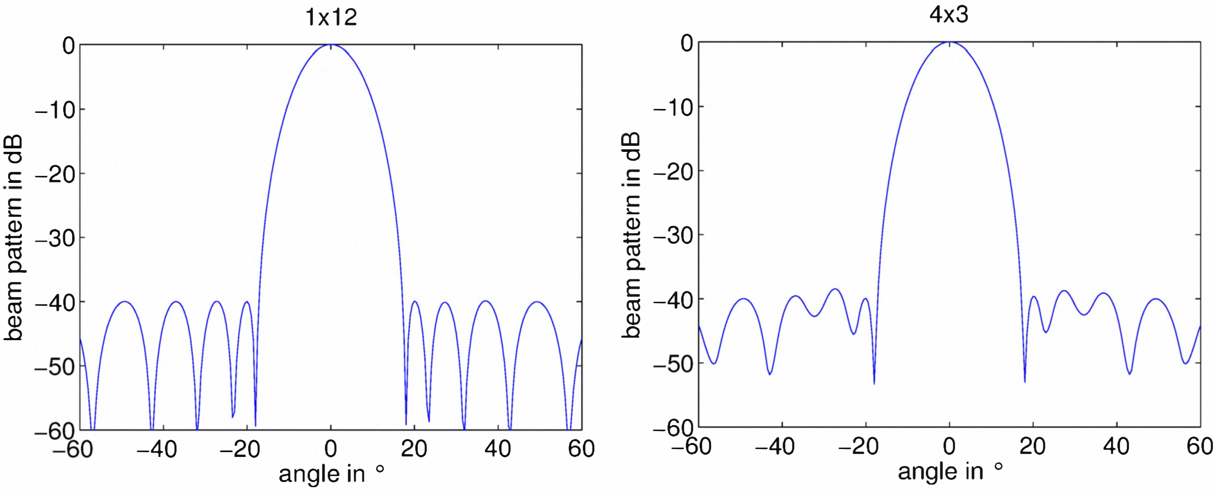

Figure 3: Beampattern for conventional 1x12 phased array (left) and 3x4 virtual TS-MIMO array(right)

In Fig. 4 a comparsion in terms of RD map is presented, when the beamformer is steered to an angle of $-40°$ to boreside. Again Dolph-Chebyshev windowing with $-40\,\mathrm{dB}$ sidelobe level is applied. Target two can be clearly identified at the expected position in the conventional phased-array case (left) as well as TS-MIMO FMCW case (right). It should be noted that the performance is similar even tough the the radial speed of the target is chosen to be much higher than a typical ship target. The RD map of target one shows similar outcome but is not shown here.

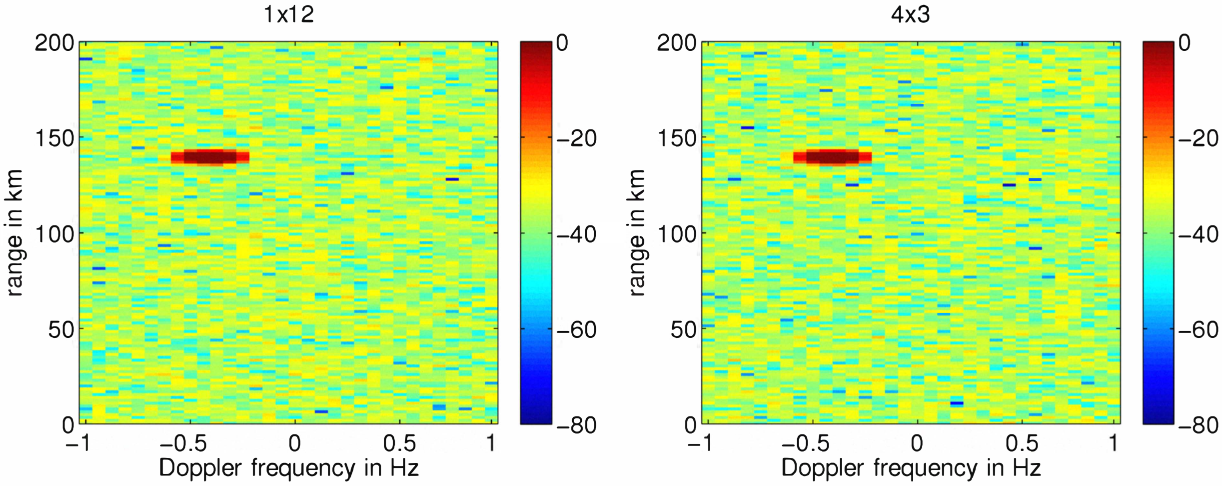

Figure 4: Simulation results 1x12 (left) and 4x3 (right), RD map with look angle of -40 °

5. Conclusion

In the paper we have presented the signal model of TS-MIMO FMCW as well as an evaluation of performance in terms of beampattern and RD map. From a comparison with a conventional phased-array of equal size we can conclude that the presented approach offers comparable results. Due to the flexible antenna configuration and the simulateous transmitter operation it is a potential candidate for a mobile os space-limited FMCW HFSWR.

References

[1] A. Stove, "Linear FMCW radar techniques," *IEE Proceedings of Radar and Signal Processing*, vol. 139, no. 5, pp. 343 –350, Oct. 1992.

[2] A. Dzvonkovskaya and H. Rohling, "CFAR Target Detection Based on Gumbel Distribution for HF Radar," in *International Radar Symposium (IRS) 2006*, May 2006, pp. 1 –4.

[3] T. Fickenscher and A. Gupta, "Element-Space Spatially Waveform Diverse FMCW Radar Distributed on Naval Formation," in *German Microwave Conference GEMiC 2011, Darmstadt, Germany*, Mar. 2011, (in press).

[4] R. Feger, C. Wagner, S. Schuster, S. Scheiblhofer, H. Jager, and A. Stelzer, "A 77-GHz FMCW MIMO Radar Based on an SiGe Single-Chip Transceiver," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 5, pp. 1020 –1035, May 2009.