MIMO Surface Wave Radar Using Time Staggered FMCW Chirp Signals

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Abstract—**In order to distinguish between different signal paths, full orthogonal waveforms for each transmit antenna element is desirable for the concept of MIMO radar. We investigate time staggered Frequency Modulated Continuous Wave (FMCW) chirp signals with an individual successive temporal delay larger than the maximum round-trip time of the radar signal. This concept is superior compared to those using time division multiplexing or multiple carrier frequencies in terms of unambiguous Doppler and bandwidth requirement, respectively. This is in particular important for long range marine surveillance using high-frequency surface wave radar where the frequency band is very congested and fast boats or helicopters have to be detected.**

Keywords-high-frequency radar; MIMO radar; FM radar; array signal processing; radar signal processing

I. INTRODUCTION

Transmitting different signals on multiple TX antennas while keeping these signals separable at reception is the major characteristic shared between all multiple-input multiple-output (MIMO) radar systems [1]. One advantages of this approach is that it is possible to synthesize virtual antenna positions resulting in a larger number of effective antenna array elements. This is of particular interest for High-Frequency (HF) radar as large antenna arrays are very costly. Synthesis of virtual antenna elements for FMCW MIMO radar using the concept of time division multiplexing (TDM) as well as using multiple carrier frequencies have been reported in [2] and [3]. However these concepts suffer from several drawbacks. Assuming a given coherent integration time *CIT* and M individual transmit elements the former approach results in a reduction of the number of Doppler bins, and, thus, in a reduction of the maximum unambiguous Doppler frequency by a factor of M^{-1}. On the other hand, the multiple carrier frequencies approach results in an increased bandwidth requirement by a factor of M. Both drawbacks are very undesirable for HF radar where the spectrum is very congested and in particular with the application of long range maritime surveillance where fast boats or helicopters have to be detected. Thus these approaches are impractical for implementation.

Recently, mobile FMCW HF Surface Wave Radar (SWR) distributed among a naval formation has gained research interest [4]. An antenna array distributed among a naval formation will be sparse in nature, i.e. the inter-element spacing between antennas located on different ships will be more than one-half of a wavelength ($\lambda/2$). Beamforming in sparse arrays typically results in gratinglobes which have the same magnitude response as the mainlobe and are indesirable for a HF SWR system. Using the concept of effective aperture [5] a virtual dense receive array without gratinglobes can be realized. This concept is most efficient when combined with the MIMO approach where complex weights can be applied to the individual signal paths between each transmit and receive antenna array element. As target detection of ships is clutter limited but not limited by internal noise sensitivity penalty of spatially waveform diverse radar is of no consequence in this application.

In this paper we present a FMCW MIMO radar concept using time staggered chirp signals as transmitted waveform which avoids all the aforementioned drawbacks of the TDM concept as well as those of the multiple carrier frequencies concept. At the receiver the baseband signals are separable in the frequency domain. In order to distinguish between the signals originating from different transmit antenna array elements the temporal delay between the time staggered chirps of the individual transmit antenna array elements has to be larger than the maximum round-trip time of the radar signal.

II. CONCEPT OF PROPOSED FMCW MIMO RADAR

Fig. 1(a) displays an example of a MIMO radar with M=5 transmit elements with inter-element spacing $d=\lambda/2$ and a uniform sparse receive array with N=3 elements. A quasi-monostatic or even a bistatic architecture can be considered. Communication between the individual platforms of this distributed radar system can be provided via satellite communication or via a line-of-sight communication between all platforms which can be established via microwave or optical links.

In order to apply the MIMO concept it is necessary to individually weight the amplitude and phase of the MxN signals of the combination of each transmit antenna array element i and each receive antenna array element k. Fig 1(b) displays the time shifted FMCW chirp signals with chirp rate

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α and respective instantaneous transmitter frequency f_{ti} as individual waveform for each element i (i=1,…, M)

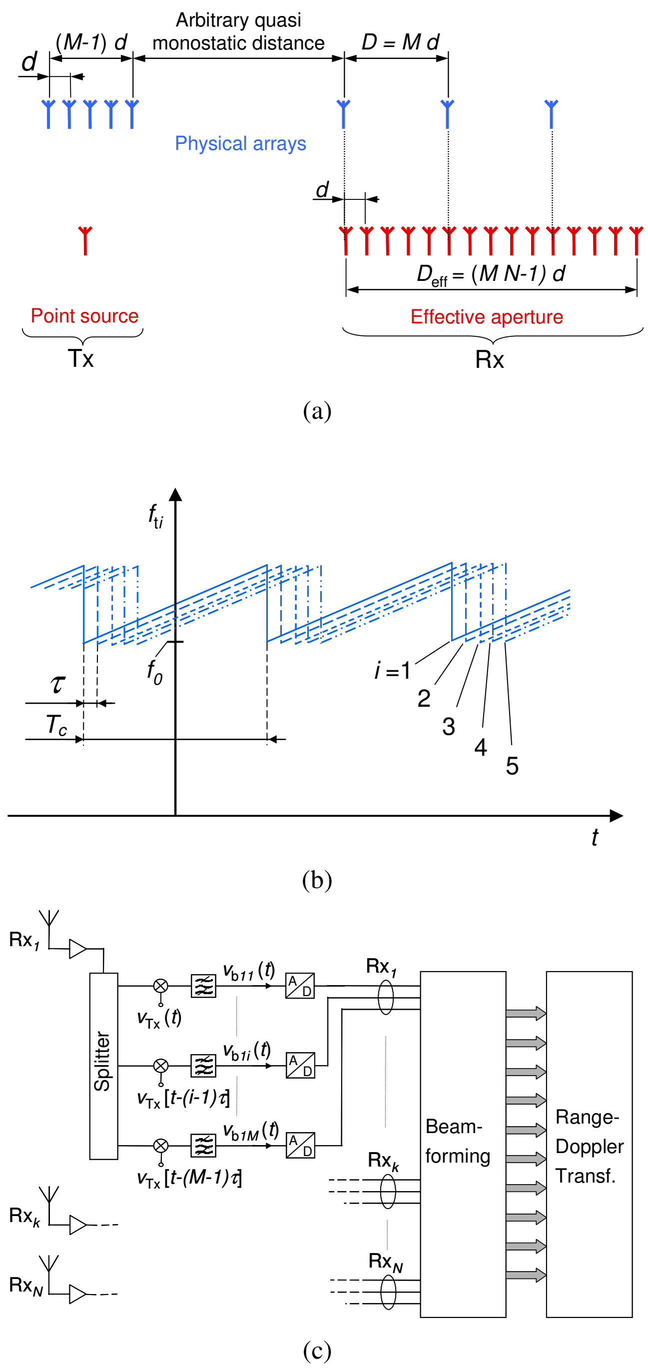


Figure 1. FMCW MIMO radar: (a) example of geometrical arrangement of M=5 element transmit array and N=3 element sparse receive array with corresponding virtual effective aperture, (b) timing of individual transmit chirp signals (not drawn to scale violating the constraint $(M\text{-}1)\tau << T_c$), and (c) block diagram of hardware and software functions to distinguish between individual signal paths $Tx_i - Rx_k$.

$$f_{ti}(t) = f_0 + \alpha[t-(i-1)\tau] \qquad (1)$$

where f_0 denotes the start frequency of the chirps. In order to distinguish in the frequency domain between the signals originating from different transmit antenna array elements of a quasi-monostatic radar the temporal delay τ has to be chosen according to $\tau > \tau_d$, where τ_d is the maximum round-trip time of the signals given by

$$\tau_d = 2\frac{R_{max}}{c} \qquad (2)$$

with c denoting the speed of light in vacuum and R_{max} the maximum usable range. For a HF SWR system R_{max} is limited due to the attenuation of the surface wave. Assuming R_{max} = 200 km results in $\tau_d \leq$ 1.33 ms. Thus, constraints due to maximum unambiguous range are not a problem and $(M\text{-}1)\tau << T_c$ can be fulfilled using repetition frequencies T_c^{-1} which allow for unambiguous Doppler covering the speed of ships. Note that for graphical reasons Fig 1(b) is not drawn to scale and the constraint $(M\text{-}1)\tau << T_c$ is not fulfilled.

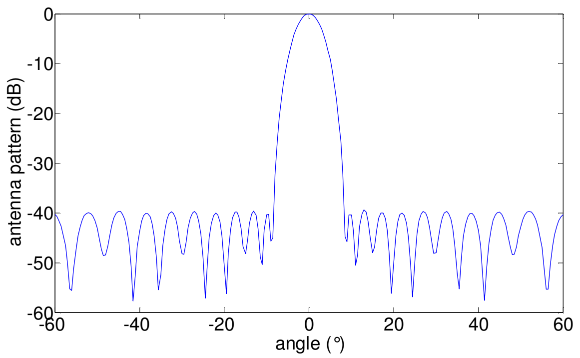
The signal of each receive array element (Fig. 1(c)) is splitted after amplification and downmixed with the individual transmit chirp signals with instantaneous frequency f_{ti}. With adequate bandpass filters the beat signals $v_{bi,k}(t)$ originating from each combination of transmit element i and reveive element k can be obtained separately. Filtering could be omitted if the individual transmit elements would radiate sequentially. Effectively this would be the TDM concept. However, it reduces the rate between successive range transforms by a factor of M^{-1} and, thus, the maximum resolvable Doppler frequency.

III. Results and Discussion

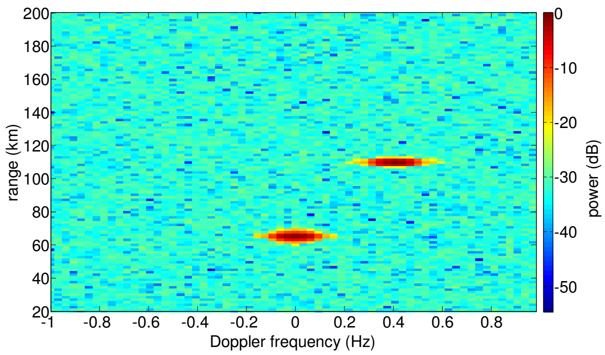
We consider a MIMO radar with M=8 transmit elements and N=3 receive elements synthesizing a virtual linear array with an effective aperture of MxN = 24 elements with Chebyshev weighting (side lobe level SSL=40 dB) and spacing $d=\lambda/2$. The element pattern are assumed to be omnidirectional. The starting frequency and the bandwidth of the chirp signals are f_0=3 MHz (λ=100m) and $B=\alpha T_c$=100 kHz, respectively. Assuming a maximum range of 200 km we obtain a maximum round-trip time of τ_d = 1.33 ms and, thus, chose the successive delay of the time staggered chirps τ = 4ms. Further parameters are a repetition frequency of T_c^{-1} = 2 Hz and CIT = 18 s resulting in a maximum unambiguous Doppler frequency of +/-1 Hz and a Doppler resolution of 0.0556 Hz, respectively.

Simulations were carried out considering the RF signals in the time domain and the processing chain displayed in Fig. 1(c). Fig. 2(a) displays the pattern of the virtual array for a look angle of θ_{look} = 0°. The pattern was generated by simulating a single stationary target varying in azimuth from θ = -60° to +60°. The pattern of the virtual effective aperture is identical with that obtained for a physical array of identical geometrical arrangement and a length of 1150 m with same element characteristics and same beamformer. The half power beamwidth (HPBW) at boresight is 6°. As a further proof of concept Fig. 2(b) and Fig. 2(c) show the range-Doppler map for $\theta_{look} = 0°$ and +20° for a scenario of 3 targets with an radar cross section (RCS) of 35 dBsm with range, azimuth and speed as given in table I. As expected, all targets are displayed correctly. The maximum delay of $(M\text{-}1) \times \tau = 28$ ms between the chirps of the individual transmit elements is negligible for an application where it is assumed that a target does not move out of a range-Doppler cell within the coherent integration time of 18 s.

For long range maritime surveillance a mobile surface wave MIMO radar would be advantageous with one platform



(a)



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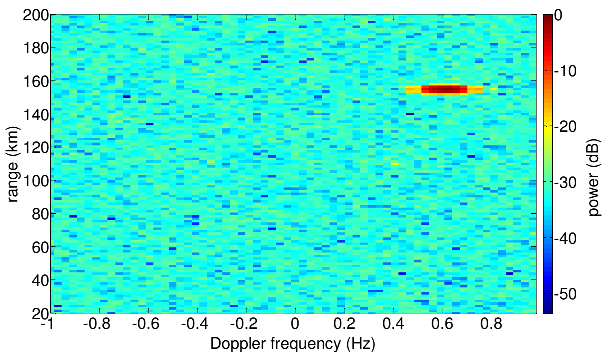
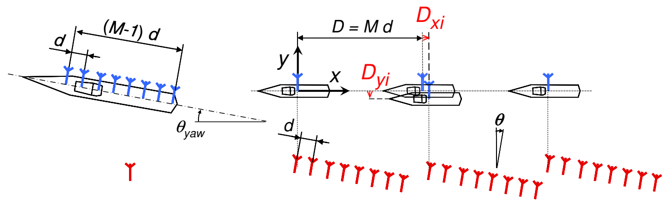


(c)

Figure 2. Simulated data of FMCW MIMO radar for M=8 and N=3: (a) antenna pattern of virtual array at $\theta_{look} = 0°$, (b) range-Doppler map for $\theta_{look} = 0°$, (c) range-Doppler map for $\theta_{look} = -20°$.

TABLE I. TARGET SCENARIO FOR RANGE-DOPPLER CALCULATION

	Range / km	Azimuth / °	Radial speed / ms^{-1}
Target I	65	0	0
Target II	110	0	-20
Target III	155	-20	-30



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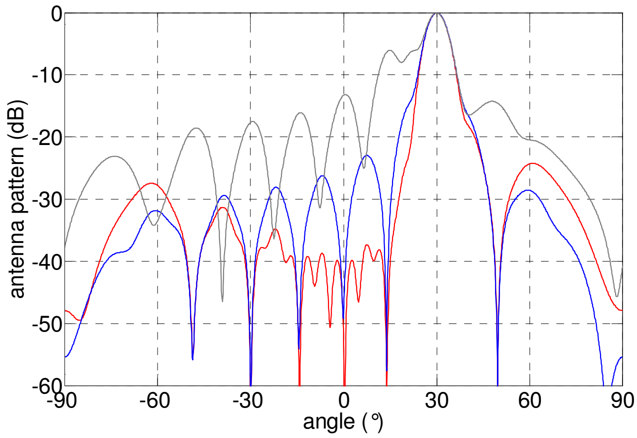

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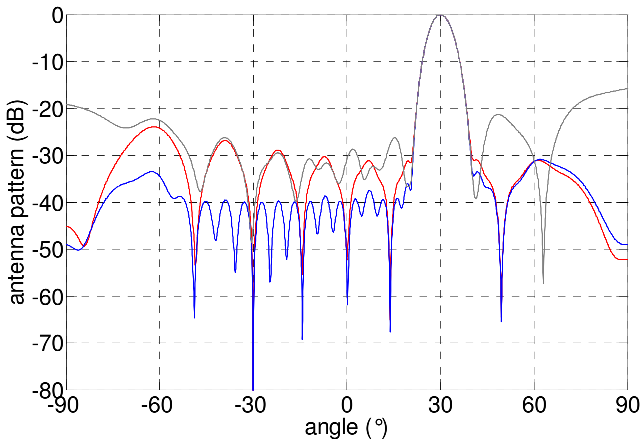

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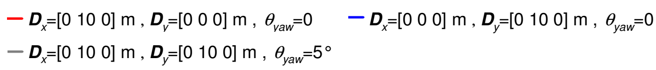

Figure 3. Mobile surface wave MIMO radar: (a) example of distortion of effective aperture due to θ_{yaw} as well as surge D_{xi} and sway D_{yi}, of individual Rx platform i = 1…3, resulting antenna pattern of effective aperture for various patterns of misalignment (b) without and (c) with phase correction.

hosting the M transmit elements and N platforms hosting one receive element each (ref. Fig. 3(a)). Swell and wind can cause some misalignment of the geometrical antenna arrangement as are uncertainties in the actual position of each antenna element. This will cause a distortion of the virtual effective aperture. Fig. 3(b) displays the resulting distorted antenna patterns for various values of the parameter of yaw angle $\theta_{1\mathrm{yaw}}$ (Tx ship) and the individual surge (vector $\mathbf{D}_x$) as well as sway (vector $\mathbf{D}_y$) of the Rx platforms i=1..3. Surge and sway of the Tx platform has no impact on the virtual effective aperture as there is no impact due to a possible yaw of the Rx platforms. From Fig. 3(b) it can be concluded that a misaligned inter-ship formation pattern as well as non-synchronous roll of Rx platforms has severe impact on antenna pattern of effective aperture which results in mainlobe broadening and in increased sidelobe level.

However, if the actual antenna positions are known or the signals from ships of opportunity are used for an adaptive algorithm for a look angle dependant phase compensation of the individual phase errors of each virtual antenna element mainlobe broadening is resolved and sidelobe level is decreased significantly (Fig. 3(c)).

IV. Conclusion

The concept of MIMO radar using time staggered FMCW chirp signals as transmitted waveform has been proved. This approach is superior to those MIMO FMCW radar concepts using TDM or multiple carrier frequencies in terms of higher unambiguous Doppler and bandwidth requirement, respectively. Furthermore, compared to the TDM approach, all transmitters are radiating continuously, and, thus, in the case of limiting internal noise, signal to noise ratio is increased by a factor equal to the number of transmitting elements. Compared to the conventional non-MIMO approach using transmit array beamforming target signal power is reduced by a factor equal to the number of transmitting elements. However, in HF band the receiver is external noise limited and, thus, sensitivity penalty of spatially waveform diverse radar is of no consequence in such application. Furthermore, it has been proven that a dynamic compensation of the pattern distortion of the effective aperture caused by misaligned receivers can be achieved.

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