AN ADAPTIVE ORIENTATIONAL BEAMFORMING TECHNIQUE FOR NARROWBAND INTERFERENCE REJECTION

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ABSTRACT

In this paper, we investigate and extend the linearly constrained minimum variance (LCMV) algorithm for conventional wideband beamforming system to the recently proposed orientational beamforming (OBF) system. An orientational LCMV (O-LCMV) algorithm is proposed. It is constructed on the orientation dimension, and an orientational constraint instead of directional constraint is used to guarantee an orientational gain for the desired signal. This perfectly solves the problem of rejecting an interference arriving from the same direction as the desired signal, which current adaptive directional beamforming algorithms cannot handle. Numerous simulations show that the O-LCMV algorithm for the OBF system works effectively regardless of the number of narrowband interferences (NBIs) or their DOAs if the NBIs have the same center frequency. As the number of different center frequencies of the NBIs increases, the performance degrades slightly.

***Index Terms*—** linearly constrained minimum variance, orientational beamforming system, tapped delay line

1. INTRODUCTION

Antenna arrays play an important role in a variety of applications such as communications, radar, sonar, and medical diagnosis [1–3]. These conventional arrays spatially filter a signal according to its direction through beamforming. Obviously, they are unable to spatially distinguish two identical signals coexisting in the same direction. To overcome this problem, a new spatial dimension named array orientation is explored, and the orientational beamforming (OBF) system is proposed [4]. The OBF system is beneficial when frequent direction of arrival (DOA) estimation is required. Besides, with the new spatial dimension, space-division can be done in both the direction dimension and the orientation dimension. Thus, it is expected to further improve the channel capacity of current space-division multiple access method.

However, the presence of strong interferences will deteriorate the performance of the OBF system. Although adaptive techniques have been extensively studied for the conventional directional beamforming system to reject interferences [5–7], similar adaptive methods for the OBF system have remained to be investigated. Among the adaptive techniques for the conventional wideband beamforming system, the linearly constrained minimum variance (LCMV) algorithm has been implemented for a wide range of applications [8–11]. The LCMV algorithm employs a tapped-delay-line (TDL) structure to compensate for the different phase shifts of different frequency components if pre-steering is not employed [8]. This limits its application in the conventional ultra-wideband (UWB) beamforming system. However, in the OBF system, the desired signals are always in phase under the orientation-matched condition, which provides more degrees of freedom to suppress interferences.

In this paper, we develop an orientational LCMV (O-LCMV) algorithm for the UWB OBF system, taking into account the similarities and differences between the conventional beamforming system and the OBF system. The linear constraints of the O-LCMV algorithm on the system's response to the desired signal are in the orientation dimension rather than the look direction dimension. Therefore, the O-LCMV algorithm works independently of the signal's direction and can effectively suppress an interference even if it has the same DOA as the desired signal. This capability cannot be handled by conventional adaptive directional beamforming methods. The performance of the O-LCMV algorithm under narrowband interferences (NBIs) is analyzed and studied through simulations.

2. SIGNAL MODEL

Array orientation is defined for pseudo-random arrays [4]. In a pseudo-random array, a reference line passing through its center of gravity (COG) is fixed. The orientation angle ψ is the angle measured anticlockwise from the true north to the reference line. As indicated, the rotation of an array around its COG changes its orientation rather than the signal's direction.

An OBF system consists of two pseudo-random arrays with the same configuration, a transmitting array $\mathcal{T}_x$ with an orientation ψ_T and a receiving array $\mathcal{R}_x$ with an orientation ψ_R. The same carrier-free UWB signal $p(t)$ is simultaneously transmitted by the antennas in $\mathcal{T}_x$. It is noticed that only when $\psi_T = \psi_R$, which is called the orientation-matched condition, the coexistence of the in-phase UWB signals is detectable at the receiving array, as shown in Fig. 1. By combining the in-

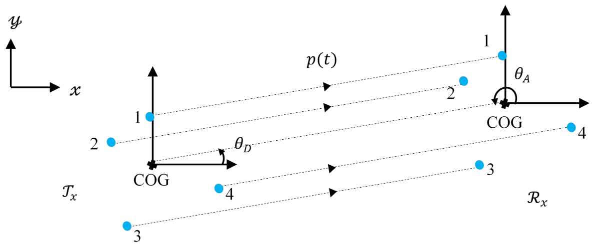


Fig. 1. An OBF system under the orientation-matched condition.

phase signals at receiving antennas, the desired pulse signal is enhanced by an orientational gain.

The UWB signal for each information bit is a monopulse employing biphase modulation [12], given by

$$p(t) = \sqrt{\varepsilon} \sum_{i=-\infty}^{\infty} b_i z(t - iT_b), \tag{1}$$

where ε is the pulse energy, $b_i = \pm 1$ represents the bit information, $z(t)$ is the pulse waveform with unit energy, and T_b is the bit duration, which is assumed to be much larger than the maximum time for a monopulse to pass through the receiving array, so that any inter-symbol interference is negligible.

Denote the signal's departure and arrival angles by θ_D and θ_A, as shown in Fig. 1. Then, the time delay of the pulse received by the r-th ($r = 1, 2, \ldots, M$) antenna with respect to the COG of $\mathcal{R}_x$ is

$$\tau_r(\theta_A, \psi_R) = q_r \cos(\beta_r + \psi_R - \theta_A)/c, \tag{2}$$

where c is the propagation speed, and the pair (q_r, β_r) determines the position of the r-th antenna in the polar coordinate system when $\psi_R = 0°$. Similarly, the time delay of the m-th ($m = 1, 2, \ldots, M$) radiated pulse with respect to the COG of $\mathcal{T}_x$ is $\tau_m(\theta_D, \psi_T) = q_m \cos(\beta_m + \psi_T - \theta_D)/c$. Since $\theta_D = \theta_A \pm 180°$ in line-of-sight (LOS) environments, $\tau_m(\theta_D, \psi_T) = -\tau_m(\theta_A, \psi_R)$ if $\psi_T = \psi_R$. Under this condition, the signal at the r-th receiving antenna is

$$\begin{aligned} x_r(t) =& p(t - \tau_p) + \sum_{m \neq r}^{M} p(t - \tau_p - \tau_m(\theta_D, \psi_T) - \tau_r(\theta_A, \psi_R)) \\ &+ \sum_{i=1}^{K_{int}} s_{ri}(t) + n_r(t) \\ =& d(t) + u_r(t), \end{aligned} \tag{3}$$

where τ_p is LOS propagation delay, $s_{ri}(t)$ is the i-th NBI detected at the r-th antenna, K_{int} is the number of NBIs, $n_r(t)$ represents additive white Gaussian noise, $d(t) = p(t - \tau_p)$ denotes the desired signal transmitted from the matched transmitting antenna, $u_r(t)$ denotes the summation of all the undesired signals including inter-channel effects, NBIs and noise. Note that the desired signal $d(t)$ is the same for all the receiving antennas under the orientation-matched condition.

Using vector notations $\mathbf{x}(t) = [x_1(t), x_2(t), \ldots, x_M(t)]^T$, $\mathbf{d}(t) = d(t)[1, 1, \ldots, 1]^T$, and $\mathbf{u}(t) = [u_1(t), u_2(t), \ldots, u_M(t)]^T$, the output signal with a set of associated weights $\mathbf{w} = [w_1^*, w_2^*, \ldots, w_M^*]^T$ is

$$\begin{aligned} y(t) &= \mathbf{w}^H \mathbf{x}(t) = \mathbf{w}^H \mathbf{d}(t) + \mathbf{w}^H \mathbf{u}(t) \\ &= d(t)\mathbf{w}^H \mathbf{1} + \mathbf{w}^H \mathbf{u}(t), \end{aligned} \tag{4}$$

where M is the number of antennas, $[\cdot]^T$ and $[\cdot]^H$ represent the transpose and Hermitian transpose, respectively, and $\mathbf{1}$ is an M-dimensional column vector with all entries equal to 1. From (4) we can see that $d(t)$ is enhanced by an orientational gain of $G = \mathbf{w}^H \mathbf{1} = \sum_{r=1}^{M} w_r$ as long as $\psi_T = \psi_R$ regardless of the signal's DOA.

3. THE O-LCMV ALGORITHM

In a directional array, phase shifts of different frequencies are different at receiving antennas for a signal arriving from a certain direction. Therefore, linear constraints are needed to guarantee the system's frequency response to the desired wideband signal, which consist of steering vectors corresponding to different frequency bins at the desired DOA. As the signal bandwidth increases, more linear constraints are needed, which reduces the available degrees of freedom for NBI suppression. Thus, a longer tap length is required in the LCMV algorithm to provide sufficient degrees of freedom.

The OBF system does not involve frequency information of the pulse signal because the desired signals are in phase at receiving antennas as long as $\psi_T = \psi_R$. No pre-steering delays are needed and TDLs are not required if no interference exists [13]. In the presence of strong NBIs, the original OBF system cannot work well. In this case, using TDLs can provide the OBF system with more degrees of freedom. Due to the in-phase arrival of the desired signals, these degrees of freedom are totally used to suppress NBIs. Therefore, the O-LCMV algorithm also employs a TDL structure as shown in Fig. 2, but usually a small tap length will be sufficient.

3.1. The O-LCMV Algorithm

With TDLs of length L, the M-dimensional signal vectors corresponding to different tap lengths are stacked to form an ML-dimensional stacked signal vector. After sampling with frequency f_s, the stacked signal vector and weight vector are

$$\begin{aligned} \bar{\mathbf{x}}[k] =& [x_1[k], \cdots, x_M[k], \cdots, \\ & x_1[k-L+1], \cdots, x_M[k-L+1]]^T \\ \bar{\mathbf{w}} =& [w_1^*, w_2^*, \cdots, w_M^*, \cdots, w_{(L-1)M+1}^*, \cdots, w_{LM}^*]^T, \end{aligned}$$

Then, the array output is

$$y[k] = \bar{\mathbf{w}}^H \bar{\mathbf{x}}[k]. \tag{5}$$

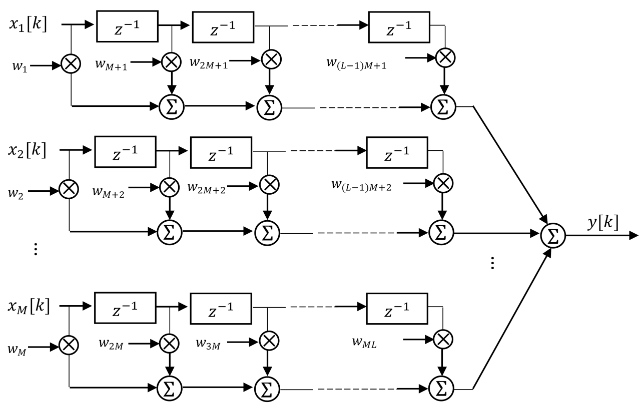


Fig. 2. Structure of the O-LCMV algorithm.

To suppress NBIs and recover the desired signal, the optimal weight can be obtained by solving the following constrained optimization problem if the signal is zero mean and stationary

$$\min_{\bar{\mathbf{w}}} \quad \bar{\mathbf{w}}^H \mathbf{R}_{\bar{\mathbf{x}}} \bar{\mathbf{w}}, \quad s.t. \quad \mathbf{C}^H \bar{\mathbf{w}} = \mathbf{h}, \tag{6}$$

where $\mathbf{R}_{\bar{\mathbf{x}}} = \mathrm{E}(\bar{\mathbf{x}}\bar{\mathbf{x}}^H)$ is the covariance matrix of the received signal, and $\mathbf{C}$ and $\mathbf{h}$ are the $ML \times L$ constraint matrix and L-dimensional desired gain vector given by

$$\mathbf{C} = \begin{bmatrix} 1 & \cdots & 1 & 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 1 & \cdots & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & 0 & \cdots & 1 & \cdots & 1 \end{bmatrix}^T \tag{7}$$
$$\mathbf{h} = \begin{bmatrix} G & 0 & \cdots & 0 \end{bmatrix}^T.$$

The constraints are to guarantee an orientational gain G for the desired signal under the orientation-matched condition, which does not involve the frequency value or the DOA of the desired signal due to the in-phase arrival of the desired signals. Therefore, the number of constraints is fixed at L regardless of the signal's DOA or bandwidth.

In the LCMV algorithm for conventional wideband beamforming system, the constraints are set to maintain the frequency response to the desired signal direction. Thus, the constraint matrix usually consists of steering vectors corresponding to the desired DOA at several frequencies of interest within the signal bandwidth. Therefore, the number of linear constraints is equal to the number of frequency bins N_f.

For the UWB impulse, the output signal fluctuates around the pulse instant value rather than zero. Consequently, minimizing the average output power will tend to offset the enhanced pulse signal, especially when the desired orientational gain is high and the available number of snapshots is small. Therefore, the O-LCMV algorithm employs an online leaning mode and updates the weight vector iteratively upon each arrival of the signal sample. We use the instant estimate of the correlation matrix $\hat{\mathbf{R}}_{\bar{\mathbf{x}}}[k] = \bar{\mathbf{x}}[k]\bar{\mathbf{x}}^H[k]$ in each iteration. To avoid the inversion of the input correlation matrix, the gradient-descent constrained least mean square algorithm is employed [8], and the weight vector is updated by

$$\bar{\mathbf{w}}[k+1] = \mathbf{D}(\bar{\mathbf{w}}[k] - \mu[k] y^*[k] \bar{\mathbf{x}}[k]) + \mathbf{Q}, \tag{8}$$

where $\mathbf{D} = \mathbf{I} - \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H$ and $\mathbf{Q} = \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{h}$, and $\mu[k] = 1/(\bar{\mathbf{x}}^H[k]\bar{\mathbf{x}}[k])$ is the step size in the k-th learning step.

With TDLs of length L, an M-antenna system has ML degrees of freedom. For the conventional wideband beamforming system without pre-steering, there are $ML - N_f$ degrees of freedom available for interference suppression. However, the O-LCMV algorithm has $(M-1)L$ degrees of freedom available. Therefore, the O-LCMV algorithm can provide more degrees of freedom for interference suppression when $N_f > L$, which is usually true for the UWB impulse.

3.2. Analysis on the O-LCMV algorithm

First, we analyze the dependence of the O-LCMV algorithm on the DOA of the NBI, represented by θ_i. We first consider the case with only one NBI. The following two situations are compared: 1) $\theta_{i1} = 0°$ and $\psi_{R1} = \psi_{T1}$; and 2) $\theta_{i2} = \Delta\theta_i$ and $\psi_{R2} = \psi_{T2}$. Since the orientation-matched condition is satisfied in both situations, the desired UWB signals at receiving antennas and the orientational gain in both situations are the same. Then, we consider the NBI. The time delay of the NBI at the r-th receiving antenna is $\tau_{ri}(\theta_i, \psi_R) = q_r \cos(\beta_r + \psi_R - \theta_i)/c$. Considering the two situations, we have $\tau_{ri}(\theta_{i2}, \psi_{R2}) = \tau_{ri}(\theta_{i1}, \psi_{R1})$ if $\psi_{T1} = \psi_{R1} = \psi_{R2} - \Delta\theta_i$. This indicates that the NBIs at receiving antennas in situation 2) are the same as those in situation 1) with a different matched orientation. Since both NBIs at receiving antennas and the orientational gain are the same in both situations, the two situations are equivalent. Therefore, we can conclude that if there is only one NBI, the O-LCMV algorithm can work regardless of its DOA. Since the adaptive OBF system is a linear system, the O-LCMV algorithm handles multiple NBIs in the same manner regardless of their DOAs. Therefore, in the following, we assume that the DOAs of NBIs are arbitrary, unless otherwise stated.

It is worth mentioning that the conventional LCMV algorithm for an M-element array can suppress at most $M-1$ NBIs with different DOAs if they have the same center frequency [14], no matter whether TDLs are used. However, the O-LCMV algorithm can effectively suppress more than $M-1$ NBIs if they have the same center frequency. This is obvious when all the NBIs have the same DOA. In this case, the summation of all the NBIs can be regarded as one NBI. Thus, these multiple NBIs can be successfully suppressed even if the number of NBIs is large. Since the O-LCMV algorithm works independently of the interference DOA, even though these NBIs have different DOAs, they can be successfully suppressed. Therefore, we can conclude that if all the NBIs have the same center frequency, the performance of the O-LCMV algorithm is independent of the number of NBIs or their DOAs. Consequently, the degrees of freedom of the OBF system is linked to the number of different center frequencies K_f of NBIs. Longer TDLs are needed if the NBIs have more different center frequencies.

4. SIMULATIONS AND DISCUSSIONS

We study the performance of the O-LCMV algorithm for a ten-element OBF system ($M = 10$) under NBIs. We assume the same SIR $= -20$ dB for each NBI. The sampling frequency is 40 GHz. The transmitted UWB impulses are generalized Gaussian pulses with $\varepsilon = 1$ and $T_b = 4.5$ ns. Since the OBF system is independent of the UWB signal direction, without loss of generality, the DOA of the desired UWB impulse is fixed at $\theta_A = 0°$. NBIs are passband white Gaussian signals with a fractional bandwidth of 3%. After adaptive OBF, the sign of the maximum absolute value of the output signal is used to determine the bit information. The tap length is fixed at $L = 10$ unless otherwise stated.

First, we consider the case with $K_f = 1$, where multiple NBIs have the same center frequency of 5 GHz. The DOAs of NBIs are different, among which one NBI has the same DOA as the desired signal. Fig. 3 shows the bit error rates (BERs) with different numbers of NBIs K_{int}. We can see that using the O-LCMV algorithm can significantly reduce the BER under each situation, and its performance curves with different K_{int} are almost overlapped. The results in Fig. 3 verify that the O-LCMV algorithm can successfully suppress an interference with the same DOA as the desired UWB impulse. Particularly, the O-LCMV algorithm can sufficiently suppress $K_{int} = 10$ NBIs with the same center frequency and different DOAs, in which case the LCMV algorithm cannot work well. This verifies our previous conclusion that the number of NBIs does not affect the performance of the O-LCMV algorithm if they all have the same center frequency.

Then, we investigate the situation where there are $K_{int} = 10$ NBIs with $K_f \geq 2$. Center frequencies of the NBIs are randomly selected within the bandwidth of the UWB impulse. The NBIs have different DOAs. We can see from Fig. 4(a) that when K_f increases from 1 to 10, the BER also increases slightly. The effect of increasing the TDL length on the performance under SNR $= 10$ dB is shown in Fig. 4(b). The BER decreases as tap length increases and stays unchanged when $L \geq 10$ for $K_f = 1$ and 2, and $L \geq 16$ for $K_f = 10$. However, the BERs for $K_f = 2$ and 10 are always higher than that when $K_f = 1$, independent of the TDL length. Therefore, increasing tap length cannot completely remove the effects of NBIs if they have different center frequencies.

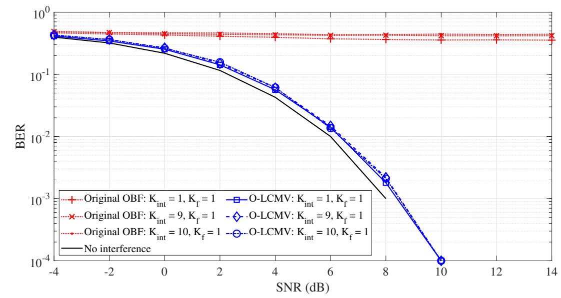
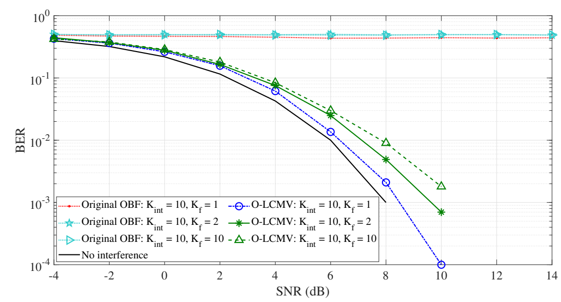
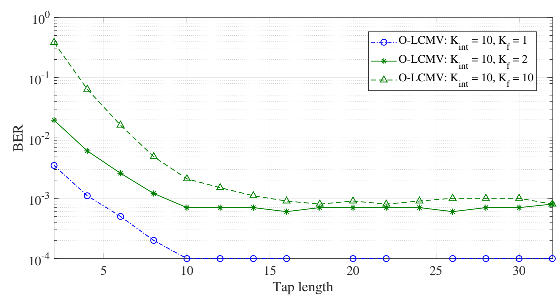


Fig. 3. BER performance when $K_f = 1$.



(a) BER versus SNR with $L = 10$.



(b) BER versus tap length under SNR $= 10$ dB.

Fig. 4. BER performance when there are $K_{int} = 10$ NBIs with $K_f \geq 2$.

5. CONCLUSION

In this paper, an O-LCMV algorithm for the OBF system to reject NBIs is presented. Constructed on the orientation dimension, the O-LCMV algorithm works regardless of the DOAs of the desired signal and NBIs. Thus, the O-LCMV algorithm can reject an NBI effectively when it has the same DOA as the desired signal, where the LCMV algorithm based on the direction dimension cannot work well. In addition, due to the in-phase arrival of the desired signals under the orientation-matched condition, the O-LCMV algorithm can provide more degrees of freedom for interference suppression. With M antennas, it can suppress more than $M-1$ NBIs if they have the same center frequency and different DOAs.

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