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Ultra wideband impulse beamforming: It is a different world

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Abstract

Aim of this contribution is to closer investigate the behavior of a delay and sum beamformer for impinging ultra wideband (UWB) signal wavefronts. Because the duration of UWB signals is shorter than the travel time to cross the array, several atypical properties can be observed. For example, the grating lobes disappear, the sidelobe level is constant and the peak gain is squared compared to conventional narrow- or broadband beamforming.
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1. Introduction

Beamforming for ultra wideband (UWB) impulse signals holds some special properties that are different from the narrowband (NB) case. Such features can be illustrated by the so-called beampattern. Several definitions of beampatterns are known; we will present three cases and investigate one of them in detail. While the mainlobe width remains unchanged for UWB and NB signals, a striking discrepancy is given by the absence of grating lobes in the UWB beampattern. Hence, the spacing of the array elements is not longer limited by half of the wavelength, were we consider the wavelength of a broadband pulse as the wavelength corresponding to its virtual center frequency, so that high resolution can be achieved with only a few array elements simply by increasing the element spacing. A further surprising property is that the use of unequal prefilters or weighting for the individual antennas increases the sidelobe level. This is also in clear contrast to the narrowband case. Although these results are valid for general broadband pulse shaped signals, we will focus on UWB impulse beamforming. Note that the more technical derivations have been included in the appendix (Section 8).

2. Ideal UWB impulse beamforming

Consider the case of a linear equispaced array, consisting of N equidistant omnidirectional antennas. If c is the propagation speed, Φ the angle of incidence of a time-limited impulse signal $s(t)$ measured with respect to broad-side direction and d the distance between two sensors, then the signal recorded at the nth sensor is given by

$$y_n(t) = s\left(t + n\frac{d}{c}\sin(\Phi)\right) = s(t + n\tau_\Phi),\quad n = 0\ldots N-1, \tag{1}$$

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where $\tau_\Phi = (d/c)\sin(\Phi)$. The ideal *delay and sum* or *time-delay* beamformer produces

$$y(\Phi, \Theta, t) = \frac{1}{\sum h_n} \sum_{n=0}^{N-1} h_n y_n(t - n\tau_\Theta), \tag{2}$$

where $\tau_\Theta = (d/c)\sin(\Theta)$ are the *steering delays*, Θ the *steering angle* and h_n the weighting coefficients.

In order to achieve a *time-independent* beampattern the total energy

$$\mathrm{BP_{TE}}(\Theta, \Phi) = \frac{\left(\int_{-\infty}^{\infty} |y(\Phi, \Theta, t)|^2 \, \mathrm{d}t\right)^{1/2}}{\left(\int_{-\infty}^{\infty} |s(t)|^2 \, \mathrm{d}t\right)^{1/2}} \tag{3}$$

of the beamformer output has been proposed, or, alternatively

$$\mathrm{BP_{max}}(\Theta, \Phi) = \frac{\max_t |y(\Phi, \Theta, t)|}{\max_t |s(t)|} \tag{4}$$

(see [1–4] and the references cited therein). The normalization by the impulses energy or maximum modulus is not always included in the literature, but it is very convenient to discuss the relations between the different beampattern definitions. The formal advantage of Eq. (3) is to allow some meaningful analytical calculations; however, even for selected UWB pulses, the derivation of an exact closed form of the total energy as well as the max-operator based beampattern is not known yet. Moreover, the infinite integration interval is not only rather unrealistic, but especially for rapidly vanishing UWB impulses may lead to erroneous interpretations. However, note that for special cases, approximate expressions for the beampattern have been already developed [5].

In this paper, we investigate an alternate and in or opinion reasonable definition of a time-invariant beampattern:

$$\mathrm{BP}(\Theta, \Phi) = \frac{\max_t \left(\int_{t-T/2}^{t+T/2} |y(\Phi, \Theta, \tau)|^2 \, \mathrm{d}\tau\right)^{1/2}}{\max_t \left(\int_{t-T/2}^{t+T/2} |s(t)|^2 \, \mathrm{d}\tau\right)^{1/2}}, \tag{5}$$

where the integration interval T is equal to the UWB impulse duration. This does not present a limitation, since the beampattern is generally dependent on the pulse shape. Observe that $\mathrm{BP}(\Theta, \Phi)$ is related to the impulse energy; hence, it allows meaningful physical interpretations.

The first observation concerning the beampattern definitions is that for narrowband signals, all three beampatterns are equal. Hence, the discussion has to focus on the broadband impulse case. It is easily seen that if T goes to infinity, (5) converges to (3), and if T tends to zero, (5) approaches (4). Hence, all three beampattern definitions are closely related. In Fig. 1, the space–time diagram of $|y(\Phi, \Theta, \tau)|^2$ for a typical UWB impulse arriving at 90°is shown. Integrating over the whole temporal axis gives the beampattern according to (3), taking the maximum over time results in (4), and performing a short-time integration before the maximum search gives (5). The short–time integrated space–time diagram is shown in Fig. 2. Finally, in Fig. 3, the three beampatterns are shown together. They have approximately the same mainlobe width and share

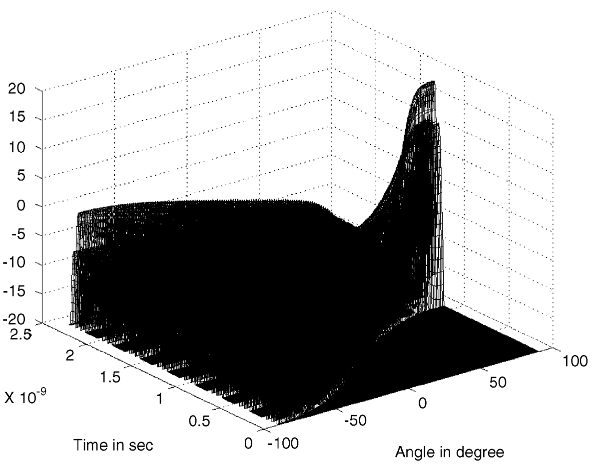

Fig. 1. Space–time diagram of beamformer output for impulse $g(t)$ arriving at 90°on array 1 with eight elements at distance λ.

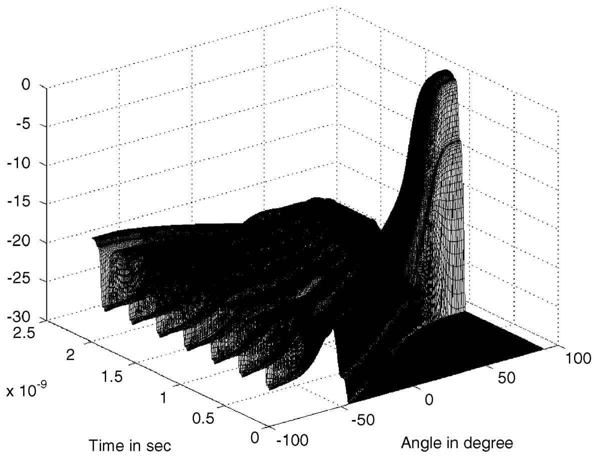

Fig. 2. Space–time diagram of short-time integrated beamformer output for impulse $g(t)$ arriving at 90°) on array 1 with eight elements at distance λ.

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