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Array design considerations for exploitation of stable weakly dispersive modal pulses in the deep ocean

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ABSTRACT

Modal pulses are broadband contributions to an acoustic wave field with fixed mode number. Stable weakly dispersive modal pulses (SWDMPs) are special modal pulses that are characterized by weak dispersion and weak scattering-induced broadening and are thus suitable for communications applications. This paper investigates, using numerical simulations, receiver array requirements for recovering information carried by SWDMPs under various signal-to-noise ratio conditions without performing channel equalization. Two groups of weakly dispersive modal pulses are common in typical mid-latitude deep ocean environments: the lowest order modes (typically modes 1–3 at 75 Hz), and intermediate order modes whose waveguide invariant is near-zero (often around mode 20 at 75 Hz). Information loss is quantified by the bit error rate (BER) of a recovered binary phase-coded signal. With fixed receiver depths, low BERs (less than 1%) are achieved at ranges up to 400 km with three hydrophones for mode 1 with 90% probability and with 34 hydrophones for mode 20 with 80% probability. With optimal receiver depths, depending on propagation range, only a few, sometimes only two, hydrophones are often sufficient for low BERs, even with intermediate mode numbers. Full modal resolution is unnecessary to achieve low BERs. Thus, a flexible receiver array of autonomous vehicles can outperform a cabled array.

1. Introduction

A broadband acoustic wave field can be represented as a superposition of modal pulses [1,2], which are broadband contributions to the wave field corresponding to fixed mode numbers. Stable weakly dispersive modal pulses (SWDMPs) are special modal pulses that are characterized by negligible dispersion and weak scattering-induced broadening. To appreciate the difference between SWDMPs and typical modal pulses, assume that the wave field is excited by a point source whose time history consists of two cycles of a carrier frequency. In that wave field the information carried by a SWDMP is a delayed replica of the transmitted signal, two cycles of the carrier frequency. In contrast, in the same wave field dispersion causes most other (typical) modal pulses to unravel into frequency-modulated sweeps whose duration grows with increasing

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range. The anomalous absence of unraveling of the SWDMPs leads to potentially important underwater acoustic communications applications. The received SWDMP waveform is to a good approximation a replica of the transmitted signal, thereby eliminating (under ideal circumstances) the need to equalize. The difference in behavior between SWDMPs and typical modal pulses can be explained by the fact that SWDMPs have the special property that the waveguide invariant for that mode number, evaluated at (or very near) the center frequency, is equal to zero. The extraction of a modal pulse, weakly dispersive or not, requires mode filtering. This paper investigates, using theoretical arguments and numerical simulations, the receiver array design requirements necessary to extract, from an acoustic wave field, an accurate estimate of a SWDMP, and, in turn, the information carried by it.

Simulations are performed in a nearly stratified ocean environment using a typical mid-latitude sound speed profile, in which two groups of weakly dispersive modal pulses commonly occur. The first group is the lowest order modes (modes 1–3 at 75 Hz are considered in the paper). The second group consists of intermediate order modes (around mode 20 at 75 Hz) whose waveguide invariant is near-zero. Broadband acoustic wave fields are simulated at ten equally spaced ranges between 50 km and 500 km with a point source transmitting a phase-modulated binary sequence. The resulting wave fields are mode processed using various receiver array configurations. The modal pulses are demodulated to estimate the transmitted binary sequence. Signal distortions lead to inter-symbol interference (ISI) and are quantified by the bit error rate (BER) (the percentage of incorrectly detected bits), which is a convenient measure of the performance. No a priori receiver training or channel equalization is performed. To estimate uncertainties due to environmental variations, which in turn cause variations in the modal shapes, all simulations and post-processing steps are repeated 10 times with different realizations of the sound speed perturbation field.

One question that motivated this analysis is: Under what conditions can the information carried by a SWDMP be recovered with small errors (as measured by BERs) if the corresponding modes are not fully resolved? In the environments considered in this paper, which closely resemble a typical mid-latitude deep ocean sound speed profile, approximately 40 hydrophones are needed to resolve the first 10 modes at 75 Hz [3–6]. It turns out that low BERs can often be realized when the modes comprising a SWDMP are not fully resolved. It is shown that, for the lowest order modes, a surprisingly small number of hydrophones at fixed depths, sometimes as few as three, is needed to achieve low BERs at ranges up to 400 km. For the SWDMPs corresponding to modes 19 and 20 as few as 34 hydrophones at fixed depths may be needed to achieve low BERs. It is also shown that only two or four hydrophones may be sufficient to achieve low BERs for SWDMPs for low and intermediate mode numbers, respectively, if the receiver depths are optimally chosen depending on the horizontal distance to the source. Of course, one cannot expect an adequate resolution of any modes with only two hydrophones, or mode 20 at 75 Hz with only four hydrophones, but full modal resolution turns out to be unnecessary to achieve low BERs. With this analysis a portable and flexible receiver array composed of autonomous underwater vehicles (AUVs) will, in some instances, have superior communications performance to cabled arrays.

Since SWDMPs experience little propagation-induced distortion, they are useful in communications applications [7,8]. The underwater acoustic channel is a challenging communications media due to the constantly fluctuating ocean environment and due to multipath propagation which results in large channel delay spread [9]. In a deep ocean long-range acoustic communication system, a signal consisting of a sequence of symbols experiences significant ISI (up to several seconds or hundreds of transmitted symbols [10]), which precludes achieving reliable high-speed data transmissions. A common solution is to design a receiver that compensates for the ISI and employs a decision feedback equalizer (DFE) [9]. However, large channel delay spread increases the complexity of the required DFE [11].

An important milestone in long-range underwater acoustic communications is the work of Freitag and Stojanovic [12]. The authors processed the acoustic data transmitted over 3250 km range using an adaptive multi-channel DFE with integrated phase tracking and Doppler compensation and showed that the joint use of 20 hydrophones allowed near symbol-rate communications (37.5 bps). At this long range the channel spread is on the order of several seconds requiring many equalizer taps, but the computational complexity is partially mitigated by the low symbol-rate.

It is demonstrated in this paper that the extraction of information carried by SWDMPs prior to equalization reduces the channel delay spread by exploiting the physics of the underwater sound channel and the properties of the acoustic wave field, thus reducing the complexity of the DFE. Note that mode processing differs from reduced complexity equalization. The latter is designed to invert the distortions due to propagation through the channel. The mode-processed wave field, however, is still a solution to the acoustic wave equation. One possible extension of this analysis, which is outside of the current scope, is to revisit the receiving array requirements if modal analysis is combined with the equalization method presented in [12]. A disadvantage to our approach is that SWDMPs might not exist in a given environment for the ranges considered. While SWDMPs exist in many ocean environments, they are not ubiquitous.

SWDMPs are related to weakly divergent beams [7]. Weakly divergent beams were described theoretically in [13] and later in [14,15] and they have been observed experimentally in the North Atlantic at ranges up to 3500 km [16–18] and in the Norwegian Sea at ranges up to 1000 km [19]. The connection between weakly divergent beams and SWDMPs arises from ray-mode duality: the asymptotic equivalence of acoustic wave fields described using rays or as a superposition of normal modes [20,21]. Here we demonstrate that information carried by SWDMPs, even corresponding to intermediate mode numbers, can be recovered with a few hydrophones with their positions well-predicted by the asymptotic ray-mode duality results.

The remainder of the paper is organized as follows. Section 2 provides an example demonstrating that only two hydrophones could be sufficient to extract the information carried by a SWDMP corresponding to an intermediate order mode