Generalised differential encoding for underwater acoustic communication

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ABSTRACT

We study the efficacy of a generalised form of differential encoding of binary phase shift keyed (BPSK) signals transmitted through a shallow underwater acoustic communication channel. Using simulations involving a fixed source and a receiver moving about with the surface waves, we show that no advantage arises from using the generalised differential encoding methods. On the contrary, the best results in our study arise from simple second-order differential BPSK (DBPSK) signalling. This is in contrast to an earlier study that showed the promise of the generalised differential encoding methods via simulations. The previous study did not address the issue of inter-symbol interference (ISI), whereas we include ISI. It appears that the added complication of removing ISI significantly reduces the benefits of generalised differential encoding.

INTRODUCTION

It has long been recognised that the ocean presents severe challenges to those seeking to communicate acoustically through water. Many approaches have been investigated with varying degrees of success (Kilfoyle and Baggeroer 2000). In this paper, we restrict our attention to the problem of communicating from a fixed source to a receiver that moves about with the waves. Such motion leads to problems with symbol synchronisation and time-varying Doppler shifts. In addition, we consider communication through shallow water, which introduces ISI as copies of signals propagate along different ray paths (multipaths) and combine at the receiver.

Gini and Giannakis (1998) recently proposed a class of differential encoding methods that includes and generalises such methods as DBPSK modulation. In their work they showed that it is theoretically possible to do better than DBPSK, by improved compensation for nonlinear signal distortions arising from the motion of transmitters and/or receivers. Their study concentrated on examples from electromagnetic communication, such as between a satellite and a ground station, and their simulations demonstrated fewer symbol errors for certain generalised differential encoding/decoding schemes and simulation parameters. The problem of ISI was not addressed by Gini and Giannakis, but was discussed by them as an area for future study.

In the present work we investigate whether similar performance gains may be obtained for underwater acoustic communication. To this end, we set up a simulation that involved a shallow channel with a fixed source and a receiver moving about a fixed position with wave-like perturbations. For quite moderate receiver motion, such as would be expected in calm seas, we show that the generalised differential encoding schemes do not yield an improvement in signalling performance. On the contrary, the best results in our simulation arise from the ordinary DBPSK method.

BACKGROUND

Our model environment consists of a uniform, stationary body of water of depth 50 m, with speed of sound 1500 m/s, density 1000 kg/m^3 and attenuation 2.5 dB/km at 15 kHz. This acoustic medium overlies a uniform solid half-space of density 1600 kg/m^3, compressional (P)-wave speed 1515 m/s, P-wave attenuation 0.5 dB/λ, shear (S)-wave speed 100 m/s and S-wave attenuation 1 dB/λ. A fixed acoustic monopole point source is at lateral co-ordinates (x,y)=(0,0) and depth z=47 m, while a receiver moves about a mean position (x,y,z)=(1500,0,2) with wave-like perturbations.

A stochastic model was developed for the wave-like receiver motion, with wave periods of several seconds and amplitudes of about half a metre, deemed typical of calm seas. We envisage a stationary source, anchored just off the sea floor, transmitting to a receiver buoy hanging off the side of a boat. Due to the motion of the waves, the receiver moves about a nominal mean position. A typical time series trace of the perturbations in the receiver's motion is given in figure 1.

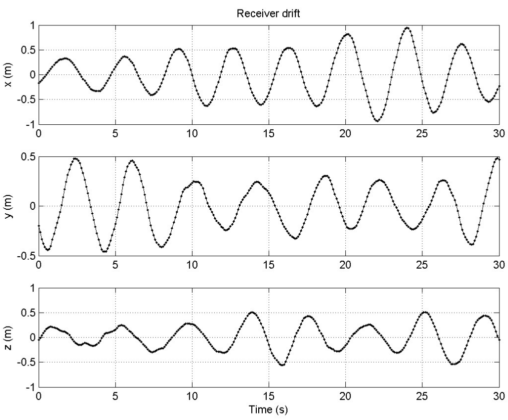

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Figure 1. Typical plots of receiver (x,y,z) perturbations.

The fixed source emitted a constant tone at the carrier frequency 15 kHz, and this was modulated by binary-phase-shift keying at 3 kbps. Both the carrier and modulation cycles were synchronised to begin with a phase offset of zero at time zero. There were five carrier wave cycles per bit. A synthetic time series was produced at the moving receiver location at a sampling rate of 240 kHz, or 16 times the carrier rate. Classical ray tracing was used to model the propagation of sound through the channel, using 24 rays only (Frisk 1994).

In addition to the time series synthesized at the moving receiver, a noise-free reference time series was synthesized at a hypothetical receiver located at the mean receiver position. This reference series was introduced to mimic the 'tail' estimate of an ordinary decision-feedback equalizer (DFE) (Sklar 2001). The reference series was produced using just 23 of the 24 rays, omitting the direct-path ray.

For both time series, sampling began after a delay equal to the propagation delay along the direct path connecting the source and the mean receiver position. This provided symbol synchronisation at the reference position (the mean receiver position).

BPSK modulation consists of a baseband alphabet of symbols -1 and +1, representing binary digits 0 and 1, respectively (Sklar 2001). A pseudorandom number generator was used to produce a stream of random binary 'message' symbols from the alphabet {-1,1}, with each symbol being equally likely. This stream was subsequently differentially encoded using one of the generalised differential encoding methods of Gini and Giannakis (1998), using the so-called ml-HIM (multilag high-order instantaneous moment) transformations.

The second-order ml-HIM encoder consists of the input-output relationship

$$w_d(n) = w(n) w_d(n - m_1), \tag{1}$$

where {w(n)} is the set of input symbols, n is the discrete-time index at the symbol rate 3 kbps, m_1 is the (positive) lag and $\{w_d(n)\}$ is the sequence of output symbols. If we set m_1=1 and apply equation (1) to BPSK inputs {w(n)}, we produce ordinary DBPSK outputs {wd(n)} (Sklar 2001).

The third-order ml-HIM encoder consists of the input-output relationship

$$w_d(n) = w(n) w_d(n - m_1) w_d(n - m_2) w_d(n - m_1 - m_2), \tag{2}$$

where m_2 is an additional lag, chosen for causality to be greater than or equal to m_1 (Gini and Giannakis 1998). In the case of BPSK inputs {w(n)} and lags m_1=m_2=1, the output sequence $\{w_d(n)\}$ is the *doubly* differential BPSK, or DDBPSK output (Gini and Giannakis 1998).

White zero-mean Gaussian noise was added to the time series synthesized at the moving receiver position, and the noise-free reference time series was subsequently subtracted. This provided a crude implementation of a decision-feedback equalizer, using for an estimate of the channel the noise-free time series at the mean receiver position (Sklar 2001).

The output of the 'equalizer' was processed using inverse forms of (1) and (2). For the second-order ml-HIM in (1), the inverse of (1) is

$$x_2(n; m_1) = x(n) x^*(n - m_1), \tag{4}$$

where {x(n)} is the time series at the receiver, after subtraction of the reference signal, and where the asterisk denotes complex conjugate. The third-order inverse of (2) is

$$\begin{aligned} x_3(n; m_1, m_2) &= x(n) x^*(n - m_1) x^*(n - m_2) \\ &\times x(n - m_1 - m_2). \end{aligned} \tag{5}$$

The outputs of (4) or (5) are quantized to the nearest BPSK symbol in the complex plane, either -1 or 1. By comparing this with the original message, a count of bit errors was made.

RESULTS

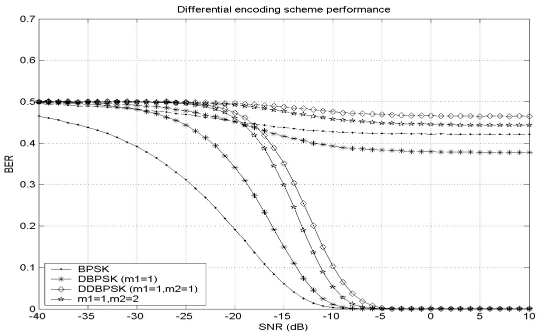
Simulations were conducted on time series records of 30 seconds duration, using encoding methods (1) and (2), with m_1 chosen from {1,2,3,4} and m_2 from {m_1,…,4}. The bit-error rate (BER) was computed at each signal-to-noise ratio (SNR) in {-40,-39,…,10}, where SNR (in dB) was given by

$$SNR = -20 \log_{10}(r_0 \sigma), \tag{3}$$

where r_0 is the reference distance from the fixed source to the mean receiver position, in metres, and σ is the standard deviation of the additive complex Gaussian noise.

In figure 2 below are eight curves of BER versus SNR, divided into two sets of four differential encoding methods: BPSK (no encoding); DBPSK (second-order ml-HIM with m_1=1); DDBPSK (third-order ml-HIM with m_1=1 and m_2=1); and third-order ml-HIM with m_1=1 and m_2=2. The set of four curves that have BER above 0.3 at every SNR correspond to those in which the receiver was moving; and the other set of four curves that have BER approaching 0 at high SNR are reference curves, in which there was no receiver motion.

Altogether there were 15 different methods studied, these being BPSK; second-order ml-HIM (m_1 in {1,2,3,4}); and third-order ml-HIM (m_1 in {1,2,3,4} and m_2 in {m_1,…,4}). Curves for 11 of the 15 methods are not shown in figure 2, as those data sets plotted very close to one of the curves shown. We chose to display only the data for the ml-HIM methods having the smallest lag indices m_1 and m_2.



Source: (Author 2005.)

Figure 2. Relative performance of differential encoding schemes. Solid curves are for the reference case of a stationary receiver; dashed curves are for a moving receiver.

DISCUSSION

We note immediately from figure 2 that none of the differential encoding methods copes well with the receiver motion, with error rates at about 0.38 or higher at all SNRs. Thus, even with mild wave-like motion of the receiver, the ml-HIM did not compensate well for the errors introduced by the mismatch between the received signal (the noisy time series at the moving receiver position) and the reference time series (the noise-free time series at the mean receiver position, with the omission of the direct-path ray).

As discussed by Gini and Giannakis (1998), the reference curves are as expected. We observe that the best results are from no differential encoding at all (the BPSK curve), and that DBPSK has a higher BER than BPSK at each SNR. Likewise, DDBPSK has a higher BER than DBPSK at each SNR. By using the concept of generalised differential encoding, we can do better than DDBPSK, by selecting lags other than the lags m_1=1 and m_2=1 of DDBPSK. Indeed, this is shown by the curve for m_1=1 and m_2=2, which lies between that of DBPSK and DDBPSK in the receiver-stationary case. So, in this ideal case, the assertions of Gini and Giannakis hold true.

A different picture emerges, however, when we allow receiver motion in our simulations. The upper four curves of figure 2 demonstrate clearly that, even with ideal 'knowledge' of the channel (that is, we have available the noise-free direct-path-omitted time series at the mean receiver position), we are unable to compensate well for the signal distortion with differential encoding. We note that the best performance comes from the use of ordinary DBPSK encoding, and that this is only marginally better than using no encoding at all (BPSK). Of note, too, is that DDBPSK produces the worst performance, with slightly better results from the use of the generalised third-order ml-HIM, with m_1=1 and m_2=2. This is in line with the observation of Gini and Giannakis that selecting different lags, other than the conventional ones for DBPSK and DDBPSK, may produce better compensation of motion-induced signal distortion.

It may be that the generalised differential encoding methods perform better for a manoeuvring submarine, which might undergo less perturbation in motion. Waves are always present, however, and some perturbation of the order of at least half a metre over several seconds, as these simulations used, would be present in most vessels in motion. Conversely, lowering the carrier frequency would be expected to provide improved performance, since the wavelength would be higher. For a carrier rate of 15 kHz, the wavelength in water was 0.1 m, and perturbations of receiver motion were thus over many wavelengths. At a carrier frequency of 1.5 kHz, the wavelength would be 1 m, and the same perturbation would only now be over a single wavelength or so.

CONCLUSIONS

We showed, via simulation, that the promised gains of the generalised differential encoding techniques of Gini and Giannakis (1998) do not pan out well, at least under the assumptions used in our paper. To improve the performance of the generalised differential encoding methods may require the incorporation of channel coding, or a proper decision-feedback equalizer (unlike the form used in our simulations). Future work on trials data is planned, to further investigate the efficacy of the generalised differential encoding and decoding schemes of Gini and Giannakis to underwater acoustic communication.

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