Acoustic Signal Dispersion and Distortion by Shallow Undersea Transmission Channels

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Abstract

The undersea littoral is an adverse medium for acoustic signal transmission to horizontal ranges of many water depths. Reflections and scattering in the bounded, nonhomogeneous channel disperse the arrival of received signal energy with a prolonging effect called multipath spread. Motion of the reflectors and scatterers disperses the frequencies of the received signal with a bandwidth broadening effect called Doppler spread. This paper examines the oceanographic causes and acoustic effects of the doubly-spread channel. Dispersion and distortion phenomena are evaluated according to relationships between the spread parameters and the signal parameters. This categorization, along with considerations of received signal-to-noise ratio, provides a context for identifying digital communications strategies for the shallow-water undersea acoustic channel.

1. Introduction

In littoral seas 10 to 200 meters deep, wireless signaling technology is needed to link underwater stations separated by horizontal ranges greater than five kilometers. For many applications, accessing atmospheric transmission channels by way of surface buoys is impractical or unacceptable. Most forms of undersea signal radiation are inadequate. Electromagnetic waves suffer high transmission loss because of the high conductivity of seawater. Extremely-low-frequency lateral electromagnetic waves show promise for low data rates, but require large transmitter apertures and power sources. Optical waves, including those produced by blue-green lasers, are rapidly attenuated. Seismic waves are overly dependent on local geology.

Sonic pressure waves provide the best impedance match to the environmental channel. Nature affirms the use of sound energy as evidenced by the many marine biosonar and bioacoustic systems selectively evolved for feeding and reproduction. To advance digital acoustic telemetry and ranging capabilities for autonomous undersea systems, the U.S. Navy has initiated exploratory development of "telesonar" signaling [1].

The difficulties with communicating acoustically in shallow water arise primarily from dynamic interference effects induced by inhomogeneities and nonstationarities of the bounded, multipath medium. Spatiotemporal variability and complex boundaries distort the propagating wavefront, disperse the received energy in time and frequency, and cause signal fluctuations in both amplitude (*i.e.* fading) and phase. Even for unreflected propagation, kinetic channel inhomogeneities produce scintillations similar to the atmosphere's effect on starlight. With horizontal channel geometries, dispersion and distortion are compounded by severe refraction and multiple boundary interactions. Also hindering signal demodulation are the dynamic noise background and transmission loss by spatial spreading and absorption. These impediments historically have limited acoustic telemetry in littoral water to vertical, ducted or short-range horizontal channels.

Advent of the low-power, low-cost, digital signal processor (DSP) has fostered application of modern communication theory to ocean acoustic signaling [2]. Now it is practical to overcome impairments of the long-range horizontal medium with methods developed in the 1960s for telephony, space communications, and Rayleigh fading channels [3,4]. Indeed, rates exceeding 10 kbit/s have been achieved in certain horizontal undersea channels [5].

This paper examines the shallow undersea transmission channel and categorizes dispersion and distortion phenomena according to the relative time and frequency parameters defining the signal waveform and the channel spread.

2. Transmission channel

The essence of the physical transmission channel includes propagation mechanisms, boundary interactions, and noise phenomena. These time-variant and space-variant processes determine received signal dispersion, signal distortion, and signal-to-noise ratio (SNR).

2.1 Propagation

Communication systems are commonly based on electromagnetic-wave propagation through media such as the atmosphere (radio), wire (electricity), and fiber (light). By contrast, underwater sound is a mechanical transmission of energy in the form of pressure waves propagating through an elastic medium. The transmitter converts electric energy to acoustic energy, thereby projecting sound into the compressible undersea environment. Transducer radiation is described in spherical coordinates by a beam pattern representing the mean-square pressure at a reference distance r_0 = 1 m from the theoretical point-source origin. An omnidirectional projector radiates uniformly at all angles with a vector intensity I_{omni}. A directional projector radiating the same total acoustic power and aligned with the axis of maximum intensity I_0 toward the receiver provides gain (in decibel units) according to the transmitting directivity index $DI_T = 10 \log I_0/I_{omni}$.

As the acoustic wavefront expands into the undersea environment to range r, geometric spreading reduces the signal intensity I_r. A commonly applied estimate of spatial transmission loss for shallow-water channels is $TL_{spa} = 10 \log I_r/I_0 \approx 15 \log r$. This rule provides a realistic compromise between spherical spreading by r^2 in an unbounded free field and cylindrical spreading by r in an ideal planar waveguide. Further attenuation by volume scattering occurs upon incidence with suspended particulates, entrained bubbles, and biomass abundantly present in nearshore waters. Section 2.2 describes additional transmission losses at the sea surface and seafloor.

As early as World War I, narrowband submarine communication was performed by on-off keying rudimentary moving-coil transducers. Quantitative evidence for the coherence of a broad bandwidth appeared in the 1940s, when a series of experiments involving small underwater explosions showed that a shock-induced pressure wave retained a rise time of T = 20 μs at the propagation range r = 1,000 m [6]. Preservation of this sharp leading edge implies that the useful sonic bandwidth of the observed channel, viewed as a filter, is $W = 1/T$ = 50 kHz. The flat response to a broad acoustic spectrum indicates the potentially large communications capacity of seawater channels. At the very short range r = 60 m, a 1-MHz acoustic band provided a record-setting digital throughput of 500-kbit/s [7]. But the useful spectrum diminishes with increasing range because seawater cumulatively absorbs sound roughly in proportion to the square of the frequency. The dominant absorption mechanism at frequencies between 5 and 100 kHz is acoustic energy conversion to heat by ionic relaxation of $MgSO_4$ salt molecules. Absorption therefore causes additional transmission loss, $TL_{abs} = \alpha r \times 10^{-3}$. The 10^{-3} factor allows range r to be in units of meters while the frequency-dependent and mildly temperature-dependent absorption coefficient α is conventionally expressed in units of dB/km. Empirical formulae yield absorption coefficients at 20°C of α = 0.5 dB/km at f = 10 kHz and α = 2 dB/km at f = 20 kHz, for example. Even within the useful propagating band, absorption will differentially attenuate the frequency components of a spread-spectrum or other wideband signal.

Traveling orders of magnitude slower than familiar electromagnetic signals, ocean acoustic waves propagate at the nominal speed c = 1500 m/s, and require nearly seven seconds to reach a notional range of r = 10,000 m. Sound speed in seawater increases with temperature, salinity, and pressure. In littoral waters, these variables are governed by large-scale circulation and seasonal forcing, and influenced by wind, upwelling, daily temperature cycles, mixing, tides, surface waves, internal waves, evaporation, precipitation, and runoff. The ensuing medium is inhomogeneous and stratified, producing sound-speed variations that distort the acoustic wavefront. The net result is time-dependent, range-dependent, and strongly depth-dependent acoustic refraction.

The expanding wavefront is often illustrated as a set of emanating rays depicting discrete propagation paths governed by Snell's law of refraction. A ray intersecting the receiver location is an eigenray. If several eigenrays exist for the transmitter-receiver geometry, the transmission medium is a multipath channel, with asynchronous convergence and interference of geometrically distinct arrivals at the receiver. Some eigenrays comprise many slightly divergent and reconvergent micropaths created by nonuniform refraction at small-scale inhomogeneities. Since shallow water is a bounded medium, most of the multipath structure results from specular boundary reflections.

Signaling range is ultimately limited by the propagation pattern. Knowledge of the oceanography in the intended operating environment is essential for anticipating the availability of a reliable acoustic path. Oceans are predominantly characterized by a warm, wind-mixed, surface layer overlying a thermocline of increasingly colder water with depth. Such temperature gradients produce sound-speed profiles that refract sound rays downward. In the deep ocean, isothermal conditions prevail at depths exceeding z = 1,000 m where sound is refracted upward by the influence of pressure. Refraction toward the depth of sound-speed minima results in a duct known as the deep sound channel. In littoral seas, however, the shallow seafloor generally rules out long-range, ducted propagation. Bottom-limited downward refraction produces bottom-to-bottom paths favoring acoustic modems placed near the seafloor. Here modems are more likely to be connected by waterborne signal energy propagating along refracted direct paths, long-range refracted bottom-bounced paths, and surface-reflected paths. Furthermore, the shadow zones existing beyond the convergence of downward reflected and refracted energy do not occur near the bottom.

2.2 Boundaries

Transmission is strongly dependent on the acoustic characteristics of the sea surface and seafloor. Incident propagating energy is reflected, scattered, and absorbed in varying proportions, producing a weakened specular reflection and a spatially distributed redirection of scattered sound. Sensitivity to boundary roughness is proportional to signal frequency because scattering features increasingly distort the signal wavefront as the signal wavelength is shortened. A criterion for the acoustical roughness or smoothness of a boundary is the Rayleigh parameter, $\rho = k\Gamma \sin\theta$, where k is the acoustic wave number $2\pi f/c$, Γ is the boundary trough-to-crest height variation at the localized region of eigenray incidence, and θ is the grazing angle [8]. If $\rho << 1$, the surface is primarily a reflector and yields a coherent wavefront reflection at the specular angle equal to the angle of incidence. When $\rho >> 1$, the scattering is incoherently distributed in space.

The sea surface is a high-impedance interface between the liquid acoustic channel and the pressure-releasing air above. Absorption does not occur at this boundary, but reflection and scattering patterns can exhibit rapid time variability. If the surface is roughened by wind waves such that $\rho \geq 1$, the "specular" reflection actually comprises many component micropaths scattered forward from evolving sets of momentarily aligned facets or corrugations on some large elliptic region of the boundary. Motion of a finite sea-surface scattering element imposes a Doppler shift $\Delta f = 2f(v/c)\sin\theta$, where f is the signal frequency and v is the vertical component of the surface velocity. The instantaneous reflectors have assorted vertical motions, so that each forward-scattered waveform is subject to a distribution of Doppler shifts related to the power spectral density of the sea surface. Hence the reflected waveform experiences a phase reversal, loses energy to out-of-beam scattering, and acquires a Doppler-smeared frequency band. In summary, forward scattering from the sea surface is time-variant and sensitive to the acoustic frequency, grazing angle, and sea state.

The redistribution of bottom-scattered energy depends on the acoustic frequency, grazing angle, bottom composition, and bottom slope. Geoacoustic properties differ dramatically within littoral seabeds, depending on the varying composition of seawater, clay, silt, sand, gravel, moraine, chalk, limestone, and basalt (here listed in increasing order of sound speed). Irregular bathymetry and sediment deposition are attributable to faults and fractures created by continental-margin geophysics, and from now-submerged terraces and canyons formed during the last ice age by reduced sea levels. Above some critical grazing angle sound penetrates the bottom and is converted to bottom-borne energy or is reradiated as waterborne energy. Penetration into the bottom is generally greater in the summer than in the winter because sea-surface warming increases the temperature gradient and strengthens downward refraction. Bottom absorption is a significant cause of transmission loss, irretrievably reducing the net signal energy reaching the receiver. For frequencies above 5 kHz, bottom-borne energy is absorbed within an effective acoustic penetration depth of about ten meters. An advantage of absorption is the alleviation of complexities from bottom-borne propagation. Above 5 kHz, therefore, bottom relief is the significant influence on received signal energy. In shallow water, irregular or sloping bathymetry produces three-dimensional eigenrays. Forward scattered sound is spatially distributed amongst the many boundary-induced micropaths, including reradiated energy from sound that has penetrated the bottom.

For transmitter and receiver near the sea surface or at intermediate depths, the multipath structure is usually stable and successfully modeled by ray theory. The bottom interaction occurs at discrete, localized sites and the relatively steep grazing angles allow sound waves to reflect coherently, despite partial absorption by the bottom. Near-surface modems can suffer image interference between the nearly synchronous arrival of parallel eigenrays having approximately the same intensity, one reflected at the nearby surface and the other not reflected.

For transmitter and receiver at or near the seafloor, the wavefront includes small bottom-grazing angles where the reflected waves are perturbed by an angle-dependent phase shift [9]. These phase shifts affect the many three-dimensional micropaths joining near-bottom stations, and the net boundary effect is diffuse, noncoherent smearing of received signals. For frequencies above a few kilohertz, the seafloor is often assumed to be a solid half-space supporting only shear waves and forming a rigid boundary where the pressure field is maximum and acoustic particle velocity is small. Under this assumption, a receiver near the bottom would sense all compressional propagating modes of the fluid waveguide, and be influenced by evanescent bottom-boundary interface waves and reradiated energy from bottom-borne shear waves. If the seafloor is fluid or elastic, however, sound wave interference could result from the nearly coincident image reflection from the bottom [10]. With downward refraction, a pair of modems at some height above the bottom would have clustered multipath arrivals, with each cluster comprising four parallel eigenrays formed by image reflections from the seafloor in the vicinity of neither, both, or either modem.

Horizontal propagation in shallow water involves repeated interaction of the wavefront with rough boundaries. Propagation is further complicated by the time-varying nature of the sea surface and the range-varying nature of the seafloor. Thus the bounded shallow-water channel is an imperfect waveguide. For a wide range of propagation angles and frequencies, acoustic energy is trapped as discrete, frequency-dependent modes. The channel impulse response is normally dominated by a sparse pattern of discrete multipath arrivals. Complications arise from nonstationarities and nonhomogeneities of the boundaries. Within the shallow waveguide, propagation modes may also oscillate because of hydrodynamic sea-surface waves and internal waves, further disrupting channel stationarity. These time-variant and space-variant influences smear the impulse response and make it time-dependent.

2.3 Noise

Littoral acoustic channels are impacted by dynamic noise mechanisms both natural (biologics, waves, wind, rain) and man-made (distant shipping, local traffic, industry). These produce fluctuating background levels with a dynamic range of 60 dB over seasonal time scales. A contributor to in-band noise is incoherent signal reverberation. Likewise, co-channel multiple-access interference can elevate the noise level. Distortion can result from these interference sources to the extent that they correlate with the desired signal. Otherwise, ambient noise is an additive effect rather than a distortive effect, but its presence prevents signal demodulation if the SNR is inadequate. Demodulators that adaptively remove signal distortion are particularly inhibited by low SNR. Directional transmitters and receivers improve SNR by increasing the correlated received signal power relative to the uncorrelated omnidirectional noise.

Sonic frequencies below 1 kHz are known to offer optimal propagation in shallow-water environments [11], but the decreased signal attenuation does not offset the elevated ambient noise arriving from many distant sources. Telemetry signals must have sufficient energy to overcome range-dependent and frequency-dependent transmission loss, $TL(r,f)$, and frequency-dependent ambient noise level, $NL(f)$. The sonar equation permits analysis of these phenomena to identify optimal signaling frequencies for the intended horizontal range, r [8]:

$$SNR(r,f) \;=\; SL(f) - TL(r,f) - NL(f) \tag{1}$$

For flat transmitter source-level spectra with $SL(f) = constant$, the frequency band with highest $SNR(r,f)$ emerges as the minima of the summed spectra of $TL(r,f)$ and $NL(f)$ phenomena for the littoral waters. Equation (1) favors increasingly higher frequencies with decreasing range, r. For transmission to ten-kilometer ranges, $SNR(r)$ is maximum for the spectral region around $f = 8$ kHz.

3. Spreading

The transmitter digitally encodes the data message using block codes or convolutional codes. The encoding provides redundant binary information enabling the receiver to more reliably decode the data message despite noise and interference introduced by the channel. Next the transmitter modulates the digitally encoded information by mapping it into analog waveforms compatible with the physical channel. A transmitted waveform has time duration, T, and frequency bandwidth, W. The product TW is a measure of processing gain available to an energy detector. Define R as the transmission rate of a waveform sequence. Direct-sequence spread-spectrum modulation utilizes the entire available channel bandwidth with each waveform and transmits consecutively with time interval $T = 1/W = 1/R$. Thus $TW = 1$ for direct-sequence modulation. Frequency-hopped spread-spectrum modulation is less bandwidth efficient but allows greater design flexibility in choosing transmitted signal duration T, transmitted signal bandwidth W, and transmission rate R.

3.1 Multipath spread and Doppler spread

The receiver responds to energy from a given waveform over an interval of duration $T+L_{max}$ and at frequencies of bandwidth $W+B_{max}$. L_{max} and B_{max} are the maximum extent of channel-induced multipath spread and Doppler spread, respectively, of the received waveform. In practice, $T+L_{max}$ and $W+B_{max}$ are the interval and band over which the received signal exceeds some power threshold relative to received noise levels. Because the undersea channel often produces multipaths resolvable in the time domain, multipath spread L_{eff} and Doppler spread B_{eff} associated with the resolvable multipath may be measured and used as the effective spread parameters associated with that multipath subchannel.

Multipath spread is the added duration of the received waveform by the arrival of transmitted energy in the form of specular multipath reflections and forward scattering. Therefore L is a measure of channel time dispersion. The channel coherence bandwidth W_{coh} is the bandwidth over which the channel or subchannel is "flat" and passes all spectral components with approximately equal gain and linear phase. For totally scattered channels with no resolvable multipath, an estimate of the channel coherence bandwidth is $W_{coh} \approx 1/L_{max}$. For resolvable multipaths, the estimate is $W_{coh} \approx 1/L_{eff}$. Multipath spread and coherence bandwidth describe the time-dispersive nature of the channel but offer no direct information about temporal variability.

Time-dependent variations in the channel are impressed upon the signal as Doppler shifting of spectral components and an overall broadening of the signal band. Time-variant channel phenomena include motion of the source or receiver themselves, motion of the sea surface, motion of volume scatterers, and motion of refracting nonhomogeneites such as internal waves. The largest range of positive and negative frequency deviations observed at the receiver for a given spectral line of the original signal is the Doppler spread, a measure of channel frequency dispersion. The channel coherence time, during which the channel is stable and the impulse response is essentially invariant, is estimated by $T_{coh} \approx 1/B$. For example, if channel Doppler spread is $B = 20$ Hz, then impulse-response measurements of the channel separated by $1/B > 0.05$ s are uncorrelated.

The channel may be represented as a time-variant linear filter $h(\tau,t)$ describing the response of the channel at time t to an impulse applied at time t-τ. Instantaneous multipath spread is the duration of $h(\tau,t)$ at fixed t. Instantaneous Doppler spread is the time variation of the channel at fixed t, and can be measured by the rate of variations of $h(\tau,t)$. Because τ and f are Fourier conjugate variables, the measurement is conveniently obtained in the frequency domain as the bandwidth of $H(f,t)$ at fixed t.

The maximum observed spread is useful for generally characterizing the channel. L_{max} and B_{max} are, respectively, the maximum duration over all t of $h(\tau,t)$ and the maximum bandwidth over all t of $H(f,t)$.

3.2 Spread factor

Channels spread in both time and frequency are called doubly spread. In general, such channels exhibit both time-selective and frequency-selective fading. Stated alternatively, the fading is neither time-invariant nor frequency flat. The ionosphere and troposphere are doubly spread electromagnetic channels where multipath and Doppler spread are caused principally by scatterers moving randomly within the medium. The undersea acoustic channel, on the other hand, introduces random spread principally at boundary scatterers. Multipath propagation is otherwise slowly varying and largely deterministic. Insofar as the deterministic component of the spread can be tracked or adapted to, receivers must contend only with random scattering by the boundaries. Moving from deep ocean to shallow ductless waters, the channel begins to resemble the random scattering model as the eigenray structure degenerates to purely reverberant transmission.

For conservative, distortionless signaling without tracking or adaptation, the doubly spread channel constrains the signal design:

$$\begin{array}{l} T >> L_{max} \text{ prevents } h(\tau,t) \text{ distortion} \\ 1/T >> B_{max} \text{ prevents } H(f,t) \text{ distortion} \end{array} \quad \Rightarrow \quad L_{max} << T << 1/B_{max} \tag{2}$$

$$\begin{array}{l} W >> B_{max} \text{ prevents } H(f,t) \text{ distortion} \\ 1/W >> L_{max} \text{ prevents } h(\tau,t) \text{ distortion} \end{array} \quad \Rightarrow \quad B_{max} << W << 1/L_{max} \tag{3}$$

Conditions (2) cannot be jointly satisfied unless $B_{max}L_{max} < 1$. Conditions (3) represent a dual requirement that $B_{max}L_{max} < 1$ in order to choose the bandwidth of a distortion-resistant signal. If tracking and adaptation are employed with coherent demodulation when $B_{max}L_{max} < 1$, then $T \approx 1/W$ may be specified to achieve a bandwidth-efficient single-carrier serial transmission with direct-sequence modulation.

Therefore an appropriate measure of channel adversity is the spread factor, identified as the product of multipath and Doppler spread, $B_{max}L_{max}$. For a noise-free channel, condition $B_{max}L_{max} < 1$ implies the channel is underspread and instantaneous measurements of the channel impulse response are meaningful. Otherwise, for $B_{max}L_{max} > 1$, the channel is overspread and measurement of the channel impulse response is ambiguous [12].

A tracking or adapting demodulator with knowledge of a sparse multipath structure or knowledge of constant Doppler shifts can use that information to function in nominally overspread channels. In that case, deterministic slowly-varying dispersion of a resolvable multipath or induced by relative modem motion may be measured or predicted. The effective multipath spread L_{eff} and effective Doppler spread B_{eff} may be used to obtain the effective spread factor, $L_{eff}B_{eff}$. For such a demodulator, the effective spread factor is confined to the area covered in the time- and frequency-spreading plane rather than the gross rectangular spreading area defined by

$L_{max}B_{max}$ [13]. For example, if the channel impulse response contains discrete resolvable multipath arrivals with intervening periods of negligible response, L_{eff} would exclude time periods with negligible response. However, adaptation to time-variant channels requires high SNR to reduce the detrimental effects of intersymbol interference (ISI) without being impeded by residual estimation errors.

3.3 A doubly-spread undersea acoustic channel

As a hypothetical illustration of spreading estimation for ocean channels, consider acoustic transmission between a pair of submerged modems at depths $z_1 = z_2 = 200$ m, separated by range $r = 1.0$ km. For simplicity, a constant sound speed $c = 1500$ m/s renders an isovelocity, nonrefractive medium. Signal transmission begins at time t_0. A direct path arrives at $t_d = t_0 + [(z_1\text{-}z_2)^2+r^2]^{½} / c$, and a reflected path strikes the surface with grazing angle $\theta = \arctan[(z_1+z_2)/r] = 22°$ and arrives at $t_s = t_0 + [(z_1+z_2)^2+r^2]^{½} / c$. Neglecting additional multipaths and reverberation, the multipath spread is $L_{max} = t_s\text{-}t_d = 0.051$ s.

Now estimate Doppler spread by examining the interaction of the reflected path with the dynamic sea surface. A surface wave with period p and trough-to-crest height Γ has vertical velocity $v = d[(\Gamma/2)\sin(2\pi t/p)] / dt = \pi\Gamma/p \cos(2\pi t/p)$. For waves with average period $p = 8.6$ s and average height $\Gamma_{avg} = 4.1$ m (empirically corresponding to waves driven by 30-knot winds), the sea surface would experience vertical surface velocities $-1.5 < v < 1.5$ m/s. For a hypothetical carrier frequency $f = 20$ kHz, the Doppler spread is $B_{max} = 2\ \Delta f = 30$ Hz. This conservative estimate neglects additional spread from larger-than-average waves (*e.g.*, the average height of the highest 10% of waves developed by 30-knot winds is $\Gamma = 8.5$ m) and from the compound surface reflections of longer multipaths (*e.g.*, the surface-bottom-surface path).

The spread factor of the hypothetical channel is $L_{max}B_{max} = 1.5$. Because highly processed, high-SNR tracking or adaptive demodulators recognize deterministic spreading features such as the two stable modeled eigenrays, an estimate of the effective spread factor is based solely on the area occupancy of the delay-Doppler surface during a finite observation time. For these more complex receivers, however, the degrading spread from refracted micropaths and boundary scattering must be modeled to avoid overly optimistic spreading assumptions and to account for SNR degradation. Statistically distributed beams are a possible way of extending ray theory to account for these phenomena. Eigenrays are first modeled in the usual way, and are then augmented with a probability density function describing the spatial distribution of acoustic energy about the ray. Interactions with complex scattering surfaces may then be mathematically modeled according to theoretical redistribution functions. The net received energy is summed as a time-dependent response of the recombined "eigenbeams."

4. Distortion

Multipath spread and Doppler spread are each responsible for a different type of signal distortion. Fourier transforms can be used to examine dispersion and distortion, but the use of spread estimates provides a convenient way of categorizing these effects and identifying signaling methods to overcome them.

4.1 Time-dispersive channels

A channel nondispersive in frequency (B=0) is a linear time-invariant system. Such is a noncirculating, mirror-flat ocean with no transmitter-receiver motion and no moving scatterers. A slowly time-varying channel (BT<0.01) may also be so modeled if demodulation is adaptive. The response of a frequency-nondispersive channel to a sinusoid is the summation over all eigenrays of the input sinusoid scaled by a constant attenuation and delayed by a constant phase. The received signal is the superposition of contributions from all the reflectors and scatterers forming the channel. Wideband signals in such a channel suffer frequency-dependent gains and phase shift across the signal band. If $W > 1/L$, the constructive and destructive combinations of reflected returns enhance certain frequency components and attenuate others. Hence, the signal frequencies are affected differently by the channel, and the distortion effect is frequency-selective. Frequency selectivity caused by $W > 1/L$ occurs even if $T > L$; here the received waveform has negligible time spreading but may have an altered structure compared to that of the transmitted signal. If $W < 1/L$, the time-dispersive channel behaves as though it is nondispersive and is frequency-nonselective. Lastly, a time-dispersive, frequency-nondispersive channel with $WL << 1$ is frequency nonselective. .

4.2 Frequency-dispersive channels

Doppler spread accounts for temporal variations in the channel, and the associated distortions are time-selective variations in signal strength. Pure Doppler shifts produced solely by a constant transmitter-receiver range rate do not necessarily result in distortion. Channels dispersive only in frequency (L=0) are the duals of channels dispersive only in time. For a frequency-flat fading channel, if the signal bandwidth is much less than the Doppler spread, $W << B$, then the channel appreciably spreads the transform of the signal. But if $B << 1/T$, the channel is slowly fading and alters the received signal by only a scale factor and a carrier phase shift. Hence, a channel dispersive only in frequency behaves nondispersively and without distortion if $BT << 1$. When $BT >> 1$, the signal is always distorted by the channel, and is dispersed when $B/W >> 1$.

4.3 Doubly-dispersive channels

For doubly spread channels, dispersion-induced fading is both time-selective and frequency-selective. The effect of the channel on the transmitted signal therefore depends on the signal structure, bandwidth, and duration. Table 1 categorizes the gross occurrence of distortion and dispersion on the received signal according to the relative values of T, W, L, and B.

BT	WL	B/W	L/T	Distorted	Time Dispersed	Frequency Dispersed	Remarks
<<1	<<1	<<1	<<1	No	No	No	Implies BL<<1
<<1	>>1	<<1	<<1	Yes	No	No	Implies BL<<1 and TW>>1
<<1	>>1	<<1	>>1	Yes	Yes	No	
>>1	<<1	<<1	<<1	Yes	No	No	Implies BL<<1 and TW>>1
>>1	>>1	<<1	<<1	Yes	No	No	Implies TW>>1
>>1	>>1	<<1	>>1	Yes	Yes	No	Implies BL>>1 and TW>>1
>>1	<<1	>>1	>>1	Yes	No	Yes	
>>1	>>1	>>1	<<1	Yes	No	Yes	Implies BL>>1 and TW>>1
>>1	>>1	>>1	>>1	Yes	Yes	Yes	Implies BL>>1

Table 1: Received signal characteristics [14].

4.4 Intersymbol interference

ISI results when consecutive symbols arrive simultaneously at the receiver via a time-dispersive channel. ISI is negligible if $T >> L$. ISI is avoided if the waveform interval includes a guard time larger than the multipath spread, $1/R > T+L$, thus clearing the channel. Furthermore, since signal waveforms separated in time by at least 1/B are statistically independent, the waveform rate can be increased without incurring ISI if $1/R > T+L+1/B$.

A means of increasing R is by introducing additional transmission bands. Statistical independence is obtained by choosing a guard band $\Omega > W+B+1/L$. The frequency separation between the spectra of adjacent waveforms thereby exceeds the coherence bandwidth of the channel. When a high rate with limited bandwidth is required, resolving interfering symbols is possible only by tracking or adapting to channel dispersion at the demodulator. Tracking or adaptation can only occur with an effectively underspread channel.

If the channel is overspread ($BL > 1$), it is not possible to assign waveform parameters simultaneously satisfying $W << 1/L$ and $T << 1/B$ and $TW \approx 1$. Thus adaptive coherent demodulation cannot be achieved. On the other hand, if $TW \approx 1$ and the signal has long duration $T >> L$, then the signal bandwidth is much smaller than the coherence bandwidth $W << 1/L$ even in an overspread channel. Alternatively a signal with $W >> 1/L$ will resolve the multipath components and provide LW resolvable signal components. Overspread channels may therefore be overcome by transmitting encoded data with waveforms occupying different time-frequency cells separated by at least T_{coh} and W_{coh}. The waveforms will fade independently and diversity coding will allow the receiver to retrieve the encoded information.

5. Conclusions

A signaling philosophy for doubly-spread undersea channels should include appropriate strategies for tolerating or removing dispersive and distortive effects.

Coherent demodulation of a serial stream of phase-encoded symbols has recently been shown to yield surprisingly high bit rates in certain ocean environments by probing, sampling, tracking and adapting to channel fluctuations. To compensate for signal perturbations, the demodulator relies on high SNR, high symbol rates, adaptive equalization, and phase-locked tracking. This reliance imposes the need for high transmit power and sophisticated signal processing. Signal demodulation fails when the channel is effectively overspread unless augmented with vertical beamforming to directionally resolve effectively underspread subchannels. Therefore, this approach has limited applicability for channels severely impaired by dispersion and noise.

If lower bit rates are acceptable, orthogonal signal waveform sets may be implemented with intersymbol guard times and guard bands sufficient to resist intersymbol interference. Such signals tolerate overspread channels and may be noncoherently demodulated without tracking and adaptation. Other benefits include reduced signal power, reduced processing, and reduced reliance on spatial beamforming. Transmission security and networking are accommodated by the associated low SNR, block or convolutional encoding, and frequency-hopped spread-spectrum modulation.

Environmental adaptation and improved channel efficiency are achieved by tracking deterministic and slowly varying channel parameters, such as stable multipaths and Doppler shifts. This use of channel memory supports refined signal parameters and optimized demodulation. Likewise, bidirectional links allow transmission power control to produce sufficient but not excessive received SNR. Lastly, redundant transmission in time, frequency and space statistically improves signaling performance by providing channel diversity.

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