An Adaptive, Soft-Decision Multiuser Receiver for Underwater Acoustical Channels

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Abstract
An underwater acoustic local area network (ALAN) is being deployed which permits two-way data telemetry between many high-rate, ocean-bottom sensors and a central, surface-deployed receiver in the 10-40kHz vertical acoustical channel [1]. The ocean-bottom nodes initiate the transmission process by requesting data channel time slots through a common narrowband request channel. Request packets overlap in time and frequency in this scenario, and the throughput and average transmission delay rely heavily on the successful resolution of the request channel collisions. This paper describes the design and performance of a request channel receiver capable of resolving collisions between several asynchronous and cochannel packets. The receiver algorithm differs from: standard capture schemes (by demodulating the data from both strong and weak transmitters), conventional spread-spectrum receivers (by overcoming the near-far problem), and existing multiple-access demodulation techniques (by adapting to the number of interfering signals, and the unknown phase, Doppler, amplitude and timing of each signal in the collision). The receiver demodulates the collided packets by decision-directed techniques, it differs from known decision-directed multiple-access receivers [2] [3] [4] through a novel method of estimating the interference for each user which minimizes error propagation due to inaccurate tentative decisions [5] [6]. An in-water experiment illustrates that this technique is extremely desirable for collision resolution in underwater acoustic local area networks, and also for underwater autonomous vehicles with both sidescan sonar as well as acoustic telemetry links.

1. Introduction
In this work we shall focus on a congested acoustic channel, involving the data telemetry in the vertical channel from many ocean-bottom sensors to a central, surface-deployed receiver, as described in Figure 1. In typical ALAN deployments, each battery-powered data modem is high-rate, the peak-to-average duty cycle of each sensor is quite high, the average round trip propagation time exceeds 5 seconds, and the time-varying nature of the acoustic environment precludes global synchronization. Efficient orchestration of this network should be dynamic, allow the modem to shut down when not required, and yet minimize handshaking. For these and other reasons, static time- and frequency-division, polling or probing techniques are not of interest. Instead, it is preferable that the ocean-bottom node initiate the transmission process, without regard to other users, by sending a relatively short request packet through an asynchronous, common request channel. Carrier-sensing techniques are useless due to the long propagation delays, and acoustic congestion takes the form of request packet collisions between ocean-bottom modems, which must be resolved at the central receiver for data channel scheduling. In this case, the collision resolution must proceed with some fixed upper bound on the demodulation delay, in order to establish time-out conditions for retransmission of requests.

This work addresses one technique for resolving the collision of inband and asynchronous packets, with the goal of demodulating both strong and weak signals within a fixed amount of time. We shall address the particular case of coherent, binary phase shift keying (BPSK) for each data packet. The transmitting waveforms are assumed to be known by the central receiver for all modems, but the amplitude, Doppler, fine synchronization, and phase are a priori unknown and slowly time-varying. (In the ALAN receiver, the originator of each packet, as well as course synchronization is determined through header information, and is assumed to be known in this work.)
for ease of exposition.) The algorithm must estimate and track the unknown parameters for each signal, and demodulate the short request packets of each user. This work is presented in the following manner: the system model is described in Section 2 in terms of the collision of inband, asynchronous packets. In this section we also described the proposed adaptive receiver structure, which makes joint decisions for the data of all overlapping symbols by constructing an interference estimate for each before detection. Section 3 explores the theoretical performance and the comparison to previously published schemes in the low thermal noise regime, for perfect channel estimates. Performance is intuitively yet precisely described by the fraction of the received signal-to-noise power ratio (SNR) of a given user which is expended to combat interference. It is shown that the proposed technique wastes far less signal energy for a given user to combat interference than algorithms of similar (linear) complexity and decoding delay (e.g., the two-stage detector [3]), and approaches the performance of dynamic programming (sequence) detectors with unbounded demodulation delay and exponential complexity. The effectiveness of this scheme is demonstrated in Section 4 via experimental data taken south of Marthas Vineyard, MA in August, 1991. In this example a collision is resolved between two independent acoustic telemetry systems operating simultaneously in the same frequency band. In particular, the near-far resistance of this algorithm is demonstrated as the relative strength of these signals differ by 10dB, and yet both are demodulated without errors.

2. System Model

In a K-user baseband multiple-access channel, the kth user modulates a preassigned, (unit energy) waveform sk(t) by the sequence of symbols {bk(j)} via linear modulation (we shall assume bk(j) = ±1 in this work). Since communication proceeds without synchronism between transmitters, the delay of the kth user relative to a common reference is denoted by rk. Without loss, we reorder the users so that τ1 = 0 ≤ τ2 ≤ ... ≤ τK < T. Each signal is passed through a different channel. It will be demonstrated in Section 4 that the aggregate output signal from the vertical acoustical channel is well-modeled as

\[ r(t) = n(t) + \sum_{k=1}^{K} \sum_{i} b_k(i) \sqrt{w_k(i)} e^{j\theta_k(i)} s_k(t - r_k(i) - iT) \]

where \( \theta_k(i) \) models the instantaneous phase at the receiver due to Doppler and initial phase offsets, \( w_k(i) \) represents the received signal energy sequence, and \( r_k(i) \) represents the slowly time-varying relative delay, due to initial asynchronism and Doppler compression. In this work we consider n(t) to be a wide-sense stationary Gaussian random process with zero mean and power spectral density which has level \( \sigma^2 \) across the aggregate signal passband.

Any multiuser receiver uses knowledge of the received signal set \( \{s_k(t)\} \), the symbol alphabets, and an interval observation of the noisy aggregate signal r(t) to produce estimates of the symbol sequences for K users. The receiver also may estimate the phase, Doppler, relative delay, and signal strength of each user. Provided accurate channel estimates (after a short training period), the sufficient statistics for the data sequences \( \{b_k(i)\} \) are given by the symbol rate samples of the matched-filter output vector y(i), as shown in Figure 2.

There exist a variety of techniques for making decisions on \( \{b_k(i)\} \) given \{y(i)\} and accurate channel estimates. Of interest in this work is to identify a collision resolution technique which approaches the performance of the maximum likelihood receiver [7] without its exponential demodulation complexity and unbounded decision delay. Decision-driven schemes, such as decision feedback and 2-stage multiuser detectors, exhibit bounded decision delays and polynomial complexity (depending on the technique for tentative decisions) and have been analyzed for known channel parameters [2][3][5]. A well-documented problem with data-driven detection is error propagation, which is of particular concern in this time-varying channel. It has been demonstrated, for example, that the 2-stage detector suffers from low near-far resistance due to error propagation [5]. As we show in the next section, the proposed algorithm retains the simplicity of decision-directed detection schemes, while exhibiting performance which is uniformly superior over all relative energies to the 2-stage detector.

The matched-filter output for user 1 will contain multiple-access interference (MAI), a linear combination of the partial cross-correlations between s1(t - iT) and all overlapping waveforms. The partial cross-correlations between the waveforms of user 1 and 2, for example, are denoted by \( \rho_{12} \) and \( \rho_{21} \),
and are given by

$$\rho_{21}(\tau_2(i)) = \int_{\tau_2(i)}^{\tau_2(i) + T} s_1(t) s_2(t - \tau_2(i)) dt$$

$$\rho_{12}(\tau_2(i)) = \int_{\tau_2(i)}^{\tau_2(i) + T} s_1(t) s_2(t - \tau_2(i)) dt.$$  

Due to asynchronous transmission, two consecutive symbols of user 2 interfere with a given symbol of user 1, and \( \rho_{12} \) denotes the amount of interference due to the latter symbol of user 2.

The proposed receiver is described in Figure 2, and is motivated by the case of 2 asynchronous users. In this case the matched-filter output for user 1 corresponding to \( b_k(0) \) is

$$y_1(0) = \tilde{r}_1(0) + b_1(0) \sqrt{w_1(0)} e^{j\theta_1(0)} + I_1(0)$$

where the interference term is

$$I_1(0) = b_2(-1) \sqrt{w_2(-1)} e^{j\theta_2(-1)} \rho_{21}(\tau_2(-1)) + b_2(0) \sqrt{w_2(0)} e^{j\theta_2(0)} \rho_{12}(\tau_2(0)).$$

The proposed receiver estimates the interference for each matched-filter output through soft-decisions as

$$\tilde{I}_1(0) = g(y_2(-1)) \sqrt{w_2(-1)} e^{j\theta_2(-1)} \rho_{21}(\tau_2(-1)) + g(y_2(0)) \sqrt{w_2(0)} e^{j\theta_2(0)} \rho_{12}(\tau_2(0)).$$

where \( 2g(\cdot) - 1 \) is a cumulative distribution function which may depend on the received signal estimates of each user. As illustrated in Section 3, the near-far resistance of the collision resolution algorithm is strongly influenced by the choice of \( g(\cdot) \).

As shown in Figure 2, the vector sequence \( z(i) = y(i) - \tilde{I}(i) \) is used together with the channel estimates to form final decisions for the data. Final decisions may be determined by a variety of schemes, although in Section 4 the final decisions are made by hard-limiting each component, \( b(j) = \text{sgn}(z(j)) \).

The final decisions as well as the matched-filter outputs are used to update channel estimates for each user, as shown in Figure 2. Although this multiuser receiver does not require particular channel estimators, we have utilized causal maximum likelihood estimators for amplitude, Doppler shift, synchronization and phase, assuming isolated transmission of each user, in the experimental section. This suboptimal estimation strategy takes advantage of one particular attribute of this channel - packets involved in collisions almost surely have portions which are received without cochannel interference. The proposed estimation strategy allows for simple, causal, and rapid acquisition of the channel parameters during the isolated portion of the first packet involved in a collision, and accurate cancellation of the subsequent interference for the second packet.

3. Performance of Collision Resolution Algorithms

For simplicity, we focus on 2 inband and asynchronous users. Since the multiple-access interference is often the dominant noise term in the demodulation of the data of user 1, say, we are often interested in the symbol error rate for user 1 as the background thermal noise vanishes (sufficiently large signal-to-noise ratio, SNR1). With any successful demodulation strategy, it is expected that the symbol error rate should vanish exponentially with the inverse thermal noise level. For example, the error rate for equally-likely, binary antipodal signaling and optimal demodulation of an isolated user in background Gaussian noise is

$$P_{e,1} = Q(\sqrt{SNR}_1) \leq 1/2e^{-SNR_1/2}$$

where the upper bound is exponentially tight. Motivated by this form, we would like to express the performance of any multiuser demodulation strategy in terms of the error rate exponent, or asymptotic multiuser efficiency (AME) for user 1, \( \eta_1 \), such that

$$\lim_{\sigma \to 0} -\log P_{e,1} = \frac{1}{\eta_1^{SNR_1/2}}.$$  

Comparing the previous two expressions, \( \eta_1 \) represents the effective attenuation of the signal energy for user 1, relative to isolated transmission and optimal demodulation, required to eliminate MAI. Thus \( 0 \leq \eta_1 \leq 1 \), and is positive when the error rate for user 1 decays exponentially fast as the noise level vanishes. If \( \eta_1 = 0 \) for any relative signal strength, then the error rate does not decay exponentially fast for vanishing background noise, and we say that the receiver has a near-far resistance of zero. Alternatively, when \( \eta_1 = 1 \) the receiver wastes no energy in resolving collisions.

The AME for 2 asynchronous users has been found for an increasing number of detectors, including the
maximum likelihood sequence detector [7], the zero-forcing (decorrelating) detector [8], the 2-stage detector with hard tentative decisions [5], and most recently, the soft-decision detector proposed in this work [6]. It should also be noted here that the AME for the MMSE multiuser detector [9] corresponds with that in [8], and the AME for the sequential multiuser detector employing the stack algorithm (with infinite stack memory) [10] corresponds to that in [7]. We have plotted the AME for user 1 for all analyzed detectors in Figure 3, for the particular case of strong correlation among the waveforms. It should be noted here that we have compared the AME assuming perfect channel estimates. In Figure 3, the AME curve corresponding for hard tentative decisions is taken from [5], and the two soft-decision detector curves are derived in [6]. The soft-decision curve labeled "best" corresponds to the nonlinearity \( g(x) \) of the class

\[
g(x) = \begin{cases} 
-1, & \text{if } x < d \\
\frac{x}{d}, & \text{if } -d \leq x \leq d \\
+1, & \text{otherwise}
\end{cases}
\]

which maximizes the AME for a given relative energy \( w_2 \). In addition, we have also shown the AME for a nonlinearity of the same class using \( d = \sqrt{w_2} \max(|p_{12}|, |p_{21}|) \). The latter is nearly optimal among the class for a wide range of conditions [6]. Note that the AME of the proposed detector is uniformly higher than the similar detector employing hard tentative decisions, uniformly better than conventional detection, and approaches the asymptotic performance of the optimal strategy for strong interferers. It should be noted that considerably higher AME may be obtained with soft decisions based on decorrelated inputs [6].

4. Multiuser Demodulation Experiment

The multiuser receiver described in Section 2 was evaluated on recorded inwater data. For this demonstration, two acoustic modems were programmed to transmit 700 bit BPSK data packets. The transmitters were configured to transmit repeatedly in an asynchronous fashion. Each packet is initiated by a transmitter-specific 13-bit address, followed by a 4-bit silent period. The silent period is normally used by the receiver to initialize decoding and channel estimation, and provide a minimum of data buffering at the receiver. The two modems were deployed at a range of 2000 m in deep water south of Martha's Vineyard, MA, on 24-25 August, 1991, with the weather at sea state 5, and with 6'-8' seas. Both the transmitters and the shipborne receiver were roughly omnidirectional.

The baseband transmitted waveforms \( s_k(t) \) have a spreading factor of 3. Figures 4 through 6 illustrate the degree of interference cancellation with a 10dB imbalance of signal energy. (In Figures 4 and 5 we have removed the data symbols in order to illustrate clearly the improvements in channel estimates. Thus, in a single-user channel with no Doppler and no modulation, there would be no rotation of the matched filter outputs in the complex plane.) Figure 4 illustrates the difficulty of estimating the Doppler and phase of each user using the raw matched filter outputs. Note in particular, the phase trajectory of the weak user in Figure 4. While it appears that the phase noise for the weak user is white, a closer inspection reveals that the phase trajectory noise is strongly correlated with the symbol values. Figures 5 presents the instantaneous phases after interference compensation (at the output of the summing junctions, \( z(j) \)) and show a dramatic improvement in the estimated phase trajectories for the weak user. Only residual multiple access interference and thermal noise contaminate the observations, and it is clear that estimators of amplitude, timing, phase and Doppler using these outputs would rival those for truly isolated transmission. Figure 6 illustrates the scatter plots with data of the weak user (inner pair) and strong user (outer pair). Initial scatter in the constellation is due to the fact that we employed causal estimators, which converged within several bits to the steady state value.

5. References


Figure 1. The ALAN network.

Figure 2. Soft-decision multiuser receiver.