DATA COMMUNICATION ALONG THE DRILL STRING USING ACOUSTIC WAVES

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ABSTRACT

A new method of wireless data telemetry in oil well services uses compressional acoustic waves to transmit data along the drill string. Coded wave trains are produced by an acoustic transducer, travel through the drill string and are subsequently decoded to recover the data. Normal drilling operations produce in-band acoustic noise at multiple sources at intensities comparable to the transducer output while propagation through the long drill string further degrades the signal. In this paper, we will describe a theoretical channel model and based on this model demonstrate that a single receiver system has a capacity of several hundreds bits per second in such noisy drilling conditions. We analyze two-receiver scheme that exploits the fact that the dominant noise source and the signal propagate in opposite directions. We show that with two receivers this dominant noise can be cancelled, which results in a significant improvement in the capacity over the single receiver.

1. INTRODUCTION

The success in finding the oil reserves depends, in part, on real-time (while-drilling) information acquired by multiple sensors placed close to the drill bit. This information, if transmitted to the surface, can be used to optimize the drilling by adjusting the direction of drilling or to determine the proximity of oil in the formation. Currently, two telemetry methods are used. In wireline telemetry, the measurements are converted into electrical signals and sent up a coaxial cable. However, using the electrical cable is not acceptable while drilling because drill string is formed by adding 10-15m sections as the hole is advanced. Either electrical connections are required every 10-15m or the drilling has to stop for the cable to be tripped out in order to add a new pipe segment. Both approaches are impractical [3]. Alternatively, the measurements could be converted into frequency- or amplitude-modulated mud pulses which can be used while drilling but either achieves very low data rates - typically less than 10 bits/s and provides only one way communication: from the drill bit to the surface [3].

A new method of wireless data telemetry uses compressional acoustic waves to transmit data up and down the drill string. Many physical constraints present challenges for this type of acoustic telemetry. Acoustic wave propagation through the drill string encounters attenuation and scattering due to the acoustic impedance mismatch at the pipe joints. The mismatch results in a lossy, non-flat transfer function [3]. The bit and surface in-band sources of noise result in low signal-to-noise ratio. Limited power available at the downhole transmitter also restricts communication data rate. Note that compressional waves can be used to communicate from the surface to the drill bit. The model for this downlink communication has a form similar to the uplink system shown in figure 1, but the channel transfer function is, in general, different.

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2. MODEL FOR THE ACOUSTIC DATA TRANSMISSION IN THE DRILL STRING

Normal drilling operations produce in-band acoustic noise at multiple sources at intensities comparable to the transducer output. During the drilling, the drill bit crushes the formation and creates compressional acoustic waves that propagate in the drill string. However, since drill string consists of many pipe segments, compressional acoustic waves also partly reflect at the pipe joints. Consequently, this periodic structure of the drill string results in a frequency response which has multiple stopbands and passbands. Finally, surface noise, the result of the surface drilling operations, further degrades the signal sent by the transducer. We use the idealized model as depicted on the Figure 1 to analyze the performance of acoustic telemetry. The model is assumed to be linear, as in [3].

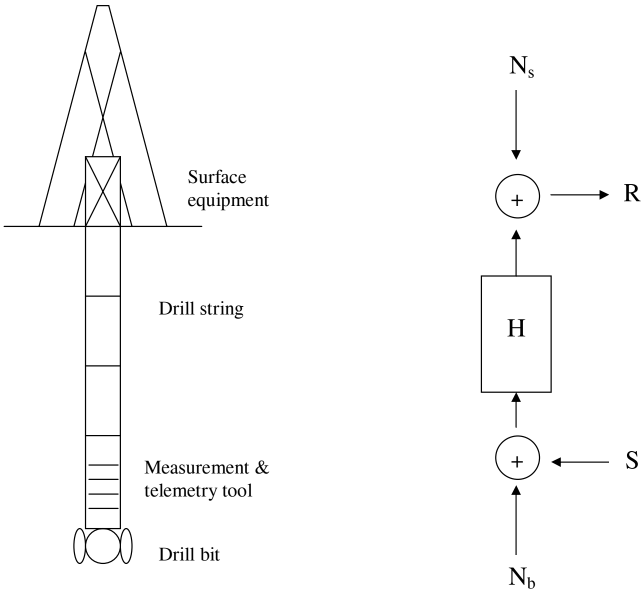

Fig. 1. The figure to the left depicts a simplified model of an oil rig with derrick on the surface, drill string, composed of jointed pipes, stretching from the surface down to the drill bit. The figure to the right shows idealized oil rig system model used in analysis of the acoustic telemetry data rates. S denotes the telemetry signal; R denotes received signal; N_b denotes the bit noise; N_s denotes the surface noise; and H denotes the uplink drill string channel model.

3. CAPACITY CALCULATION

We here consider the case of uplink telemetry signal $s(t)$ contaminated by the bit noise $n_b(t)$ and transmitted to the surface. The following notation is used: $N_b(f)$ denotes the bit noise PSD (power spectral density); $N_s(f)$ denotes the surface noise PSD; and $H(f)$ denotes the drill string frequency response (transfer function). For a drill string of several thousand feet of length, $H(f)$ exhibits small gains ($|H(f)| \ll 1$) with many passbands and stopbands due to the multiple reflections of the acoustic waves in the drill string. Furthermore, attenuation even in the passbands becomes more severe as the length of the drill string increases. We assume both noise sources to be additive and Gaussian. Finally, after imposing the constraint on the average transmit power $E[s^2(t)] = P$, we let $S(f)$ denote the input power spectrum that meets this constraint ($P = \int S(f)df$). The expression for the uplink capacity over the frequency band B is given by [8, 10]:

$$C_{UL} = \int_B \log_2 \left(1 + \frac{S(f)}{N_b(f) + N_s(f)|H(f)|^{-2}}\right) df \text{ bits/s} \tag{1}$$

For a given bandwidth B, the capacity depends on the SNR-like quantity inside the logarithm. The denominator inside the logarithm shows that the surface noise is, in effect, greatly amplified by $|H(f)|^{-2}$ because $|H(f)|^{-2} \gg 1$. Therefore, if $N_b(f)$ and $N_s(f)$ are of the same order of magnitude, the capacity formula shows that the dominant noise component in the capacity formula is the surface noise because of the amplification factor $|H(f)|^{-2}$. Taking into account currently available power and bandwidth limitations, an uplink capacity on the order of 1000 bits/sec can be reached for a drill string approximately 2 km in length. Expression similar to (1) can be derived for the uplink case.

4. DIRECTIONAL SIGNAL ENHANCEMENT

Considering the fact that the bandwidth, the channel, the signal power and the noise sources are given, one can mistakenly assume that nothing can be done to improve the capacity of the uplink channel. However, we demonstrate here that two receivers can be used to completely remove the surface noise. The key idea is to take the advantage of the fact that compressional acoustic waves travel in two directions inside the drill string. Then, by employing two receivers, surface noise which propagates in the opposite direction from the signal can be perfectly suppressed. Unlike the traditional array processing, where the SNR is increased by using more sensors to decrease the noise, here we show that - under ideal conditions - two receivers can *completely* suppress the surface noise. Sampling and quantization, however, do introduce the errors in the directional signal enhancement.

4.1. Two Receiver System

We consider for simplicity the case where first-order wave reflections at the pipe ends are taken into account. The result generalizes when multiple reflections are considered. See Figure 2 for the detail of the model. Here, r_1 and r_3 represent reflection coefficients at the top and the bottom part of the pipe segment on which the receivers are located. We consider the received signal expression shown in Figure 2 in the frequency domain:

$$\begin{aligned} Y_1(f) =& X(f)(1 + r_1 e^{-j2\pi f 2\tau_1}) + \\ & N_s(f)(1 + r_3 e^{-j2\pi f 2(\tau_2+\tau_3)}) \\ Y_2(f) =& X(f)(e^{+j2\pi f\tau_2} + r_1 e^{-j2\pi f(2\tau_1+\tau_2)}) + \\ & N_s(f)(e^{-j2\pi f\tau_2} + r_3 e^{-j2\pi f\tau_2+2\tau_3)}) \end{aligned} \tag{2}$$

By solving this system for $X(f)$, we get:

$$X(f) = (H_2(f)Y_2(f) - H_1(f)Y_1(f))/D(f) \tag{3}$$

where

$$
\begin{aligned}
H_1(f) =& e^{-j2\pi f\tau_2} + r_3 e^{-j2\pi f(\tau_2+2\tau_3)} && (4)\\
H_2(f) =& 1 + r_3 e^{-j2\pi f2(\tau_2+\tau_3)} && (5)\\
D(f) =& (e^{+j2\pi f\tau_2} + r_1 e^{-j2\pi f(2\tau_1+\tau_2)}) && (6)\\
& (1 + r_3 e^{-j2\pi f2(\tau_2+\tau_3)}) &&\\
& - (1 + r_1 e^{-j2\pi f2\tau_1})(e^{-j2\pi f\tau_2} + r_3 e^{-j2\pi f(\tau_2+2\tau_3)}) &&
\end{aligned}
$$

We conclude that even when the reflections are included in the two-receiver model, surface noise can be completely suppressed by combining the outputs of the two receivers - after applying appropriate filters. Surface noise cancellation significantly improves the uplink capacity, as can be seen from the expression (1).

4.2. Digital Considerations: Sampling and Quantization

As shown in the preceding section, frequency-domain analysis of continuous signals demonstrates that the array processing with two receivers perfectly cancels surface noise. In the case of sampled signals, only processing delays which are integer multiples of the sampling interval can be obtained. In general, these digital delays do not correspond to the actual propagation delays. This mismatch between digital and actual propagation delays results in imperfect surface noise cancellation, as shown in figure 4.

In order to reduce the error of digital delays, we approximate fractional delays by allpass filters. Each delay $\tau = nT_s + \delta$ consists of an integer multiple of sampling period, nT_s, and a fractional delay, $0 \leq \delta < T_s$. The fractional delay δ can be approximated by the first-order allpass filter.

$$H_\delta(z) = \frac{a + z^{-1}}{1 + az^{-1}} \text{ where } a = \frac{1 - \delta/T_s}{1 + \delta/T_s} \qquad (7)$$

approximates the fractional delay δ. Specifically, terms of the form $e^{-j2\pi f\tau}$ in expressions (4)-(6) are expressed as

$$e^{-j2\pi f_D n} H_\delta(e^{j2\pi f_D})$$

where f_D denotes digital frequency. The approximation is very accurate at low frequencies. Better higher order allpass filter fractional delay approximations are given by modified Thiran's design technique [13, 14] which trades computational complexity for accuracy. Figure 3 shows the outputs of the two receivers in the frequency domain. Figure 4 demonstrates the improvement with directional processing with allpass filter correction over the integer delays. The two-receiver scheme can be viewed as an attenuation of the surface noise. If both the bit and the surface noise are attenuated by some attenuation factors $|G_b(f)|^2$ and $|G_s(f)|^2$

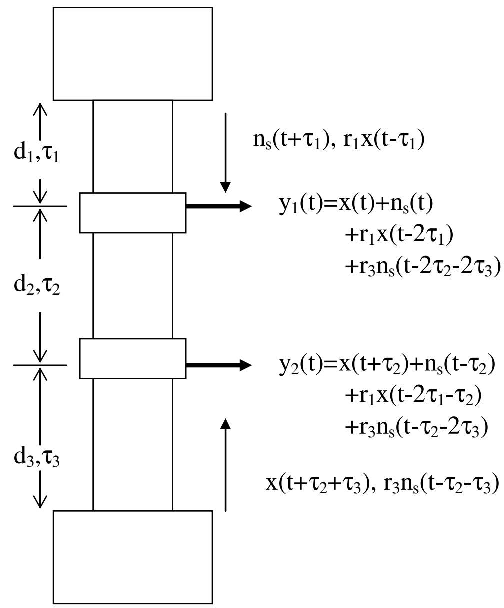

Fig. 2. Two receivers on the first pipe at the top of the drill string record two signals, n_s and x, and their reflections. Time origin (delay equal to zero) is set at the top receiver. Different delays between the two signals at two receivers can be exploited to completely suppress the surface signal n_s and reflections. This case illustrates how directional signal suppression works even with reflections included.

the corresponding capacity expression (in bits/sec) becomes

$$C_{UL} = \int_B \log_2 \left(1 + \frac{|G_b(f)|^2 S(f)}{Q(f)}\right) df \qquad (8)$$

where $Q(f) = |G_b(f)|^2 N_b(f) + |G_s(f)|^2 N_s(f)|H(f)|^{-2}$.

5. CONCLUSIONS

Acoustic telemetry is capable of achieving data rates which are two orders of magnitude higher than the mud pulse telemetry. However, for very long drill strings this is no longer true due to the severe attenuation which, in effect, makes the surface noise dominant. We show that by simple signal processing with two receivers, capacity can be significantly improved over the single receiver case by suppressing the surface noise. We are currently studying the sensitivity of our two-receiver signal processing scheme. In particular, we are considering how well the two-receiver scheme operates when the knowledge of the acoustic wave propagation in the drill string - concerning the reflection coefficients and delays - is imprecise.

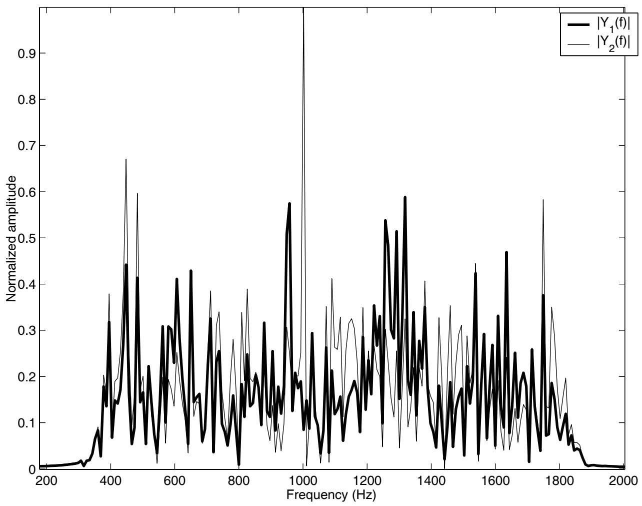

Fig. 3. An upward propagating 1 kHz signal sine wave, is mixed with downward propagating surface noise. Outputs of two receivers are shown in the frequency domain. We note that at one of the receivers 1 kHz signal is not distinguishable from the noise.

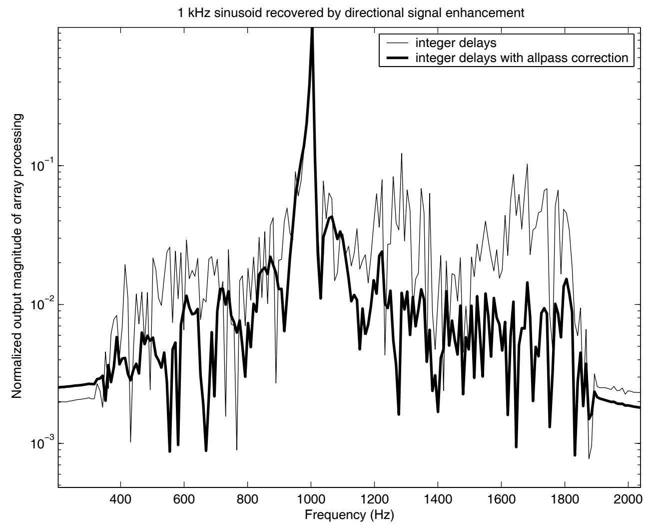

Fig. 4. Signal, an upward propagating 1 kHz sine wave, is mixed with downward propagating surface noise. After directional signal enhancement, the sinusoid is recovered by using two different schemes: one where delays are integer multiples of the sampling period (integer delays); and the other one where the integer delays are corrected with allpass filter fractional delay approximation. We note that the allpass correction reduces the error in the directional noise suppression.

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