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Strain Sensor and Accelerometer Communication Channels in Drill Pipes of Oil Wells: Delay Spreads and Eigenvalues

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Abstract

Wireless data communication between downhole equipment and surface platform in oil wells is of high importance for successful and cost effective drilling operations. In this letter two types of sensors, an accelerometer and a strain sensor are considered as receivers of modulated acoustic signals propagated through steel pipes of drill strings in oil wells. An accelerometer measures particle acceleration whereas a strain sensor measures fractional particle displacement. Using measured channel impulse responses, two important characteristics of wireless acceleration and strain channels, delay spreads and eigenvalues are studied. The experimental results show that strain channels exhibit smaller delay spreads and larger eigenvalues. Therefore, they can provide lower bit error probabilities and better communication performance for data transmission and telemetry. The results are useful for implementing improved systems for wireless data communication through drill strings in oil wells.

Keywords: Strain sensor; Accelerometer; Acceleration sensor; Acoustic communication; Wireless sensing; Channel modeling; Oil wells communication

Introduction

Establishing a communication link in deep oil wells to send information such as pressure, temperature, torque, etc., from downhole to the surface is a key part of drilling operations. Since having cables in harsh high-temperature wells whose depths are at least thousands of feet is costly and prone to failure, wireless communication is preferred. In this letter we focus on wireless communication via acoustic waves that can travel thru steel pipes of the drill string. The transmitter downhole includes a transducer that converts data-modulated electric signals to acoustic signals, which travel thru the long drill string and are received by some sensors. These sensors generate electric signals accordingly, which are then passed to a signal processing unit for data detection and demodulation.

Here we focus on two types of sensors, accelerometers and strain sensors, and study some properties of the propagation channels associated with them. An accelerometer measures particle acceleration along the drill pipes, whereas a strain sensor measures fractional particle displacement along the drill pipes. Since wireless channel parameters can significantly affect a communication system performance [1,2], here we study some characteristics of measured acceleration and strain wireless channels in a drill string testbed.

Definitions and measurements of acceleration and strain channels

If $u(x,t)$ represents particle displacement at a point x at time t on a pipe, then acceleration and strain there are temporal and spatial derivatives of the displacement, respectively, i.e., $a(x,t)=\partial^2 u(x,t)/\partial t^2$ and $s(x,t)=\partial u(x,t)/\partial x$ [3]. To measure acceleration and strain channel responses, we use PCB's accelerometer model 356B21 and PCB's strain sensor model 740B02, respectively. They serve as two communication receivers, mounted on one end of the drill string testbed. The transmitter is Etrema's actuator model CU18A, mounted on the other end of the drill string. The testbed is composed of four steel pipes whose lengths and diameters are 60 and 4 inches, respectively. They are connected via 3.5 inch couplings.

To measure acceleration and strain channel responses, the transmitter generated a one-second linear frequency modulated chirp signal that probed the drill string in frequency domain from 0.4 to 9.2 kHz. Since acceleration and strain are different physical quantities, they are measured by different units: m/sec^2 for acceleration and $1\,\mu=10^{-6}$ for strain, where $1\,\mu=10^{-6}$. By a simple commonly-used technique [4], we converted strain signals to acceleration-equivalent signals, to make the two sensors readouts comparable. At the end of the last pipe of the drill string testbed, the measured impulse responses of acceleration and strain channels, both expressed in m/sec^2, are shown in Figure 1.

Delay spreads of acceleration and strain channels

The measured channels demonstrate different behaviors. The acceleration impulse response appears to gradually grow and lasts longer, whereas the strain impulse response exhibits some sharp changes first and then dies faster. To verify and quantify these observations, we compute the channel delay spread, widely used to characterize wireless channels [1,2]. It basically measures the standard deviation of the signal arrival times in a channel with impulse response $h(t)$, defined as:

$$T_{ds}=\sqrt{<t^2>-<t>^2}\,, \tag{1}$$

where $<t^2>=\sum_m P_m t_m^2/\sum_m P_m$, $<t>=\sum_m P_m t_m/\sum_m P_m$ and $P_m=|h(t_m)|^2$. Figure 2 shows the delay spreads of acceleration and strain channels, with the accelerometer and strain sensor placed next to each other at various positions on the last pipe of the drill string testbed, where 0 cm refers to the end of the last pipe. It appears that

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multiple measured strain channels exhibit smaller delay spreads than the acceleration channels. The average delay spreads of strain and acceleration channels calculated over multiple measurements in Figure 2 are 11.6 and 18.1 milli sec, respectively. They corroborate the shorter duration of the strain channel impulse response observed in Figure 1 compared to the acceleration channel.

Eigenvlues of Acceleration and Strain Channels

To understand how different behaviors of acceleration and strain channels can affect a communication system performance, now we look at the eigenvalues of acceleration and strain channel matrices, which control system error probability. If a block of K transmitted symbols $\mathbf{S}$ is convolved with an M-tap channel whose impulse response is $h(t)$, then the received symbols block is given by $\mathbf{R} = \mathbf{HS} + \mathbf{N}$ [5], where $\mathbf{N}$ is the noise vector and $\mathbf{H}$ is the $(K+M-1)\times K$ banded channel matrix

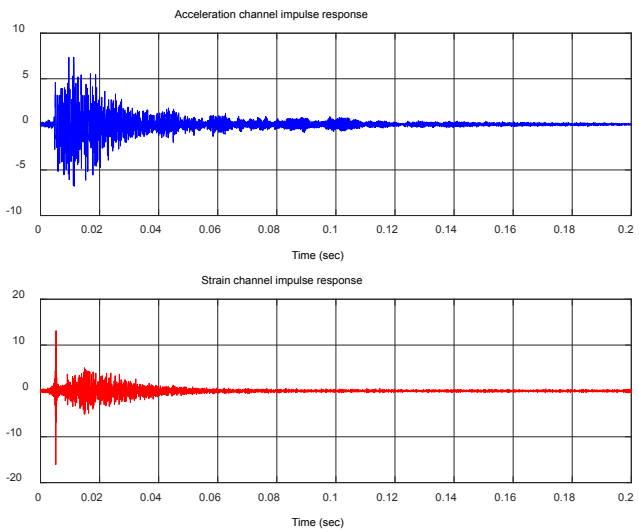

Figure 1: Measured impulse responses of acceleration (top) and strain (bottom) channels.

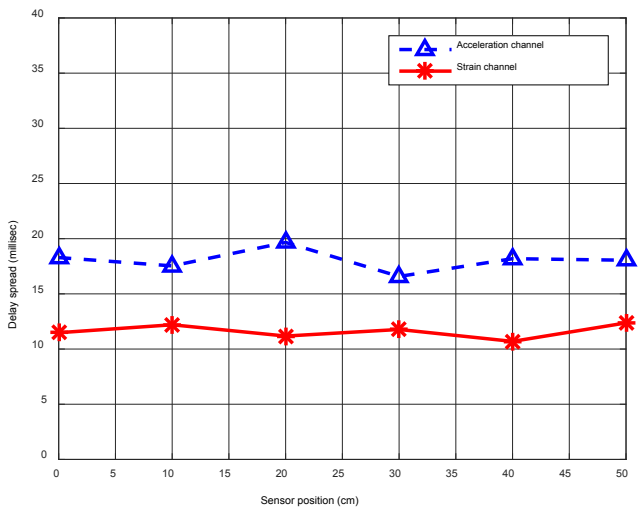

Figure 2: Delay spreads of acceleration and strain channels measured at various positions.

$$\mathbf{H} = \begin{bmatrix} h(0) & & \\ \vdots & \ddots & h(0) \\ & & \vdots \\ h(M-1) & \ddots & \\ & & h(M-1) \end{bmatrix}. \quad (2)$$

With $\mathbf{H}^{\dagger} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H$ as the pseudoinverse of $\mathbf{H}$ and ^{H} as transpose conjugate, the minimum variance unbiased estimate of the symbol vector $\mathbf{S}$ is $\hat{\mathbf{S}} = \mathbf{H}^{\dagger}\mathbf{R}$ [6]. While there are more advanced algorithms and equalizers for symbol recovery [2], here this basic equalizer is considered which allows to focus more on understanding the channel itself. Considering equi-probable binary phase shift keying (BPSK) ± 1 symbols transmitted in $\mathbf{S}$, the error probability averaged over K symbols is given by [7-9]:

$$P(e) = K^{-1}\sum_{\kappa=1}^{K} Q\left(\sqrt{2/\{\ddot{\mathbf{E}}\}_{\kappa\kappa}}\right), \quad (3)$$

where Q is the normal probability integral. Additionally, $\{\mathbf{\Lambda}\}_{\kappa\kappa}$ is the κ-th diagonal element of the symbol estimation error covariance matrix $\mathbf{\Lambda} = E[(\hat{\mathbf{S}}-\mathbf{S})(\hat{\mathbf{S}}-\mathbf{S})^H]$, related to the channel matrix $\mathbf{H}$ as follows [6]:

$$\mathbf{\Lambda} = \sigma^2(\mathbf{H}^H\mathbf{H})^{-1}, \quad (4)$$

where σ^2 is the power of additive noise. Eigenvalues of the Gram channel matrix $\mathbf{H}^H\mathbf{H}$ play a key role in system performance. Small eigenvalues indicate an ill-conditioned matrix whose inverse can have large elements, i.e., large values for $\{\mathbf{\Lambda}\}_{\kappa\kappa}$ in (3). Since Q is a decreasing function, this means a large error probability $P(e)$. Figure 3 shows eigenvalues of the measured Gram matrix $\mathbf{H}^H\mathbf{H}$ of the acceleration and strain channels whose measured impulse responses are shown in Figure 1. For each channel, eigenvalues are sorted in an ascending order, normalized such that the largest eigenvalue for each channel is 1. We observe that most of the eigenvalues of the strain channel are greater than those of the acceleration channel, resulting in a better-conditioned Gram channel matrix $\mathbf{H}^H\mathbf{H}$ for the strain channel. As explained above, this means smaller error probability, when communicating through the strain channel. To examine this using

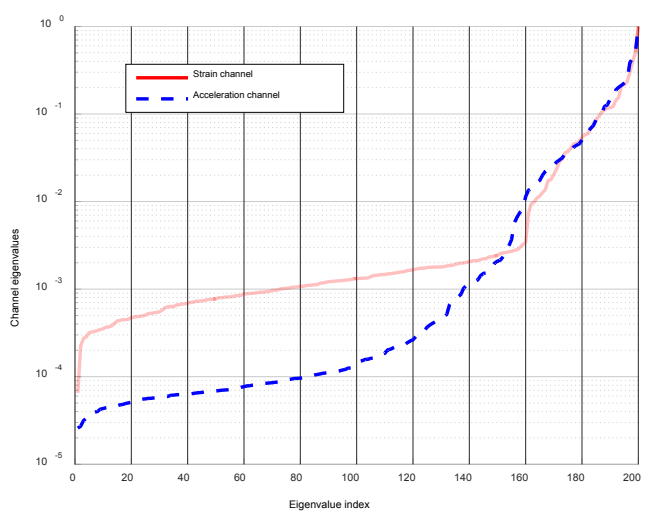

Figure 3: Measured eigenvalues of acceleration and strain channels.

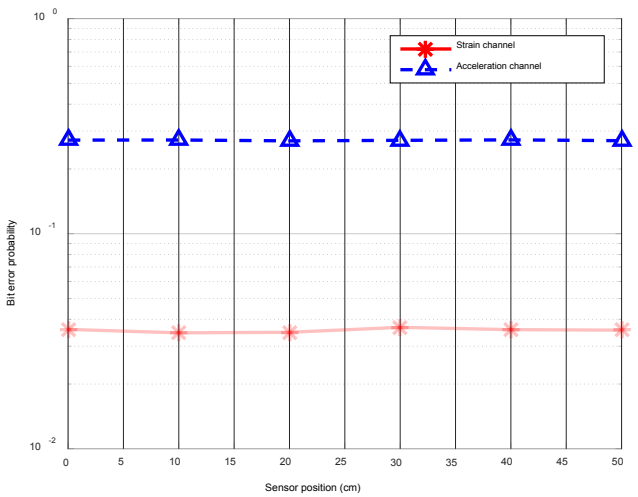

Figure 4: Bit error probability in acceleration and strain channels measured at various positions.

our measurements, BPSK bit error probabilities are shown in Figure 4 for a signal-to-noise ratio (SNR) of 16 dB, where the two receivers, an accelerometer and a strain sensor, are placed next to each other at various positions on the last pipe of the drill string testbed. We observe that the strain sensor receiver provides smaller error probabilities and better communication performance, compared to the accelerometer receiver. This can be attributed to the different behavior of the strain channel, i.e., larger eigenvalues and smaller delay spread discussed in this letter.

Conclusion

In this letter two different sensor types are used as receivers for wireless acoustic communication through drill strings in oil wells: an accelerometer and a strain sensor. To understand the system performance using these receivers, delay spreads and eigenvalues of the channels associated with these sensors are studied using experimental data.

It is observed that the measured strain channel impulse responses show smaller delay spreads and larger eigenvalues, compared to the measured acceleration channel impulse responses. These features are shown to contribute to smaller bit error probabilities for the strain channels. Such channels are promising for improved communication and telemetry via drill strings in oil wells.

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