A Comparative Study of Multichannel and Single Channel Accelerometer Sensors for Communication in Oil Wells

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***Abstract*—Transmission of information from the downhole of oil wells to the drilling platform on the surface is a key part of drilling operations for oil exploration and extraction. Important data such as temperature and pressure collected by sensors near the drill bit are needed to be modulated on acoustic signals, to travel thru drill strings. On the surface, accelerometers which convert acoustic signals to electric signals can be used to receive and demodulate the data. In this paper, we study the performance of multichannel and single channel accelerometers used as uphole communication receivers. Using experimental results from a drill string communication testbed, we show that one tri-axial accelerometer can provide nearly uncorrelated signals, compared to two single channel accelerometers. Having uncorrelated signals at the uphole receiver provides diversity which in turn can result in an increase in the communication system performance.**

***Index Terms*—Drill string communication, oil wells, multichannel reception, diversity, channel correlations, borehole communication, accelerometers.**

I. Introduction

To extract oil from underground reservoirs, wells whose depth might be at least several thousand feet, are needed to be drilled. Drilling for oil wells is a complex and costly operation. For safe, fast and cost-effective drilling, the drilling engineer needs to receive information about downhole parameters such as pressure, temperature, drilling direction and torque, and so on, in real time. This requires a communication link from the downhole to the uphole drilling platform.

There are several methods utilized for borehole communication [1]. Electromagnetic waves can offer large bandwidth. However, in borehole communication they are highly attenuated. Another method establishes a communication link between downhole and uphole using cables. This system provides high data rates, but is very costly, highly prone to failures, and interrupts the drilling. The other method is the mud-pulse technology [2], where pulses of mud are used to transmit information bits. While this can work without interrupting the drilling, it is a very slow system whose data rate is only about few bits per second. Data transmission via acoustic signals thru drill strings is an emerging method that can offer high data rates, without interrupting the drilling operation. Acoustic signals can travel thru various types of media ranging from water [3] to solids such as drill strings, and are promising carries of information in oil well communication systems.

A drill string is composed of a series of steel pipes, connected via tool joints. Due to the different cross sections of pipes and tool joints and the resulting mismatch between them, this structure creates many back and forth reflections of the transmitted signal. This in turn results in a complex multipath structure for the drill string channel impulse response, which typically has large delay spreads [4]. There are several papers that have studied and proposed models for the drill string channel, such as [5]-[8].

Signal reception using multichannel devices and multiple receivers is known as a useful means to improve communication system performance in multipath environments [9]. However, in various propagation environments such as acoustic channels [10] and radio frequency channels [11], there might be some correlations between multiple channels of a receiver which may affect the system performance. These possible correlations need to be well understood, before deploying a multichannel receiver.

Single channel accelerometers have been widely used for signal reception in drill string communication systems. One can envision using more than one single channel accelerometer for multiple signal reception. Another alternative for multiple signal reception is using a multichannel accelerometer which measures and provides several different acceleration signals, as explained in the next section. The goal of this paper is to study these two multi-reception schemes in drill string communication systems, to understand and compare possible levels of correlations between the channels.

The technical challenge is that because of many back and forth signal reflections between tool joints throughout the drill

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string, analytical modeling and simulation of signal propagation in drill strings are complex tasks and involve partial differential equations with proper boundary conditions [1]. These become more complicated when there are multiple sensors and multichannel sensors, with some possible correlations, which are the focus of this paper. Therefore, as a plausible approach, we resort to experiments to obtain a picture of possible correlations among various acceleration signals in drill strings.

The rest of this paper is organized as follows. In Section II various types of acceleration signals are introduced and equations for received signals resulted from convolution of transmitted signal with drill string channel impulse responses are provided. The experimental testbed is presented in Section III, whereas drill string channel impulse response measurements are provided in Section IV. Section V discusses correlations among various types of measured channels and how they affect the system performance. Concluding remarks are given in Section VI.

II. Acceleration Signals Sensed by Accelerometers

Let an acoustic transducer be placed on one end of a drill string, which generates the signal $\gamma(t)$, via converting information from electric form to acoustic waves. These acoustic waves travel thru the drill string, and are sensed by an accelerometer at the other end of the drill string. The accelerometer is a sensor that converts acoustic waves to electric signals. The multichannel sensor that we consider in this paper is a tri-axial accelerometer which measures accelerations of local vibrations at a single point in three orthogonal directions *x*, *y*, and *z*. Let $u_x(t)$, $u_y(t)$ and $u_z(t)$ be the time-varying local displacements due to vibrations at a single point at the end of the drill string, where the accelerometer is mounted. With acceleration as the second derivative of displacement with respect to time [1], the three acceleration signals can be written as

$$a_i(t) = \partial^2 u_i(t) / \partial t^2 , \quad i = x, y, z . \tag{1}$$

The vector nature of the tri-axial sensor that measures orthogonal components of acceleration resembles the vector sensor receiver in [3] which measures orthogonal particle velocity components.

Let the three drill string channel impulse responses which correspond to the tri-axial accelerometer receiver be represented by $h_x(t), h_y(t)$ and $h_z(t)$. Upon transmitting the signal $\gamma(t)$, the three received signals can be written as

$$r_i(t) = h_i(t) \oplus \gamma(t) + n_i(t) , \; i = x, y, z , \tag{2}$$

where $\oplus$ stands for convolution and $n_i(t)$ represents noise in the *i*-th channel. In the next section we present our drill string communication testbed, and then in Section IV we show how the three channel impulse responses in (2) can be obtained

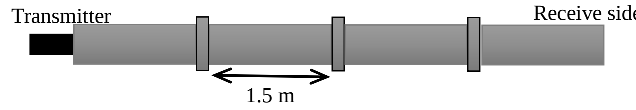

Fig. 1. The drill string testbed, not drawn to scale. The transmitter (black rectangle) is on the left, whereas accelerometers are going to be mounted on the right, at the end of the last pipe.

from the acceleration measurements of the sensor given in (1).

III. The Drill String Testbed

The drill string testbed consists of four steel pipes connected via tool joints, schematically shown in Fig. 1. The length and diameter of each pipe are 60 and 4 inches, respectively (about 1.5 m and 10 cm, respectively). The length of each tool joint is 3.5 inches (about 9 cm). The transmitter is a magnetostrictive transducer that can generate vibrations up to 20 kHz. The actual testbed and the transmitter are shown in Fig. 2. In Fig. 3 the mounted tri-axial accelerometer is shown on the receive side.

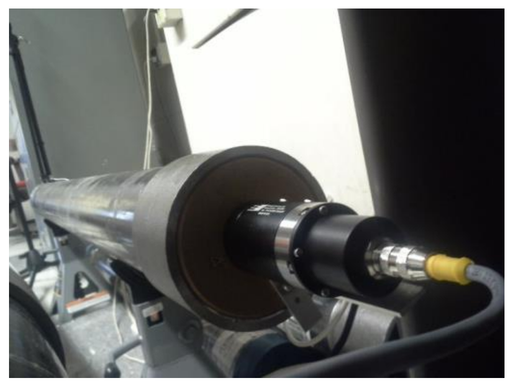

Fig. 2. The transmit transducer mounted along the drill string testbed axis.

Fig. 3. The tri-axial accelerometer mounted on the receive side.

IV. Drill String Channel Impulse Responses

To measure the drill string channel impulse responses sensed by accelerometers, the drill string is excited by a linear frequency modulated chirp signal of duration 1 sec. over the frequency range of 0.4 to 9.2 kHz. The chirp signal is generated by a computer, amplified by a power amplifier and then applied to the transmit transducer. At the receive side, signals measured by the accelerometers are collected and sampled at a rate of 40 ksamples/sec using a multichannel analog-to-digital converter and then fed into another computer. Cross-correlation of the received signals with the original chirp signal provides measurements of the channel impulse responses in the drill string.

For the tri-axial accelerometer, sensitivity per channel is $\beta = 10$ milliV/g, where g = 9.8 m/sec^2 is the gravity acceleration, whereas for the single channel accelerometer we have $\beta =$ 100 milliV/g. To account for different sensor sensitivities, the readouts of the accelerometers, which are in milliV, are multiplied by the factor g/β, which converts their units to m/sec^2. The three channel impulse responses $h_x(t), h_y(t)$ and $h_z(t)$ measured by the tri-axial accelerometer are shown in Fig. 4. The channel impulse responses $h_1(t)$ and $h_2(t)$ measured by two adjacent single channel accelerometers are shown in Fig. 5.

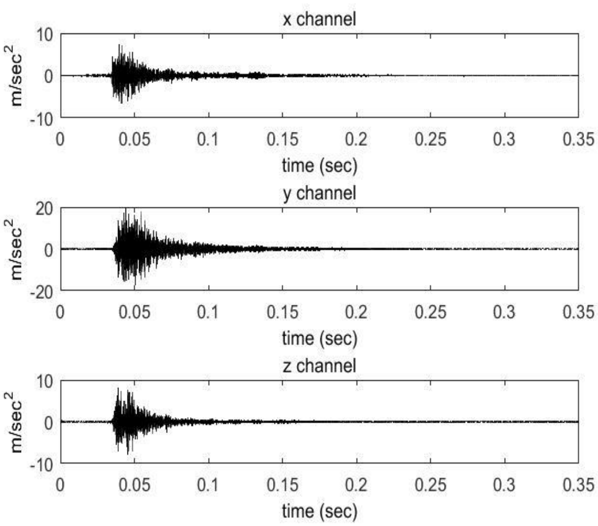

Fig. 4. Drill string channel impulse responses measured by a tri-axial accelerometer.

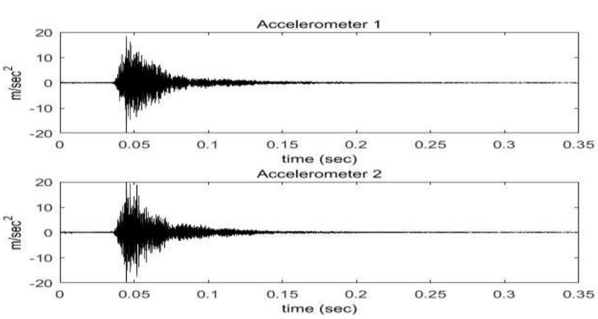

Fig. 5. Drill string channel impulse responses measured by two single channel accelerometers.

TABLE I
MEASURED CHANNEL CORRELATION MAGNITUDES FOR TWO RECEIVERS: RECEIVER A IS A TRI-AXIAL ACCELEROMETER, WHEREAS RECEIVER B CONSISTS OF TWO SINGLE CHANNEL ACCELEROMETERS.

Receiver A		Receiver B	
Correlation of $h_x(t)$ and $h_y(t)$	0.25	Correlation of $h_1(t)$ and $h_2(t)$	0.73
Correlation of $h_x(t)$ and $h_z(t)$	0.25		
Correlation of $h_y(t)$ and $h_z(t)$	0.1		

V. CHANNEL CORRELATIONS AND SYSTEM PERFORMANCE

In this section we calculate channel impulse response correlations for two different receivers. Receiver A is a tri-axial accelerometer, whereas receiver B is composed of two single channel accelerometers.

After converting real passband channel impulse responses to complex baseband equivalents, correlation magnitudes between channels of the above two receivers are calculated and listed in Table I. It appears that channels in the tri-axial accelerometer are nearly uncorrelated, whereas the two single channel accelerometers are highly correlated. This indicates that the multichannel accelerometer can serve as a better communication receiver, compared to two single channel accelerometers.

To better understand how a high correlation level among channel impulse responses with complex multipath structures can affect communication system performance, one can look at the condition number and eigen spectrum of the matrix $\mathbf{H}^\dagger\mathbf{H}$, where $\mathbf{H}$ is the entire system channel matrix and † stands for transpose conjugate. These metrics can be used to compare the performance of multichannel equalization in communication receivers utilizing different channels [12] [13]. In another paper we use bit error rate to compare the performance of receivers utilizing different types of accelerometers.

Let $\mathbf{H}_i$, $i = x, y, z, 1, 2$, be the i-th banded channel matrix whose dimension is $(K+M-1)\times K$ [12]

$$\mathbf{H}_i = \begin{bmatrix} h_i(0) & & \\ \vdots & \ddots & h_i(0) \\ h_i(M-1) & \ddots & \vdots \\ & & h_i(M-1) \end{bmatrix}. \quad (3)$$

where M is the number of channel taps and K is the number of transmitted symbols. Similarly to [12], the entire system channel matrices for the tri-axial accelerometer system, receiver A, and the system with two single channel accelerometers, receiver B, are given by

$$\mathbf{H}_{\mathrm{A}} = \begin{bmatrix} \mathbf{H}_x \\ \mathbf{H}_y \\ \mathbf{H}_z \end{bmatrix}, \qquad \mathbf{H}_{\mathrm{B}} = \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{H}_2 \end{bmatrix}. \tag{4}$$

The condition number of a matrix is the ratio of its largest singular value to the smallest singular value. A large condition number indicates that the channel matrix is nearly singular, which translates into more difficult and less effective equalization [12]. For $K = 100$ transmitted symbols, conditions numbers for $\mathbf{H}_{\mathrm{A}}^{\dagger}\mathbf{H}_{\mathrm{A}}$ and $\mathbf{H}_{\mathrm{B}}^{\dagger}\mathbf{H}_{\mathrm{B}}$ according to (4), calculated using Matlab, are 9.8×10^3 and 18.7×10^3, respectively. The smaller condition number for the tri-axial accelerometer system, receiver A, can be attributed to its nearly uncorrelated channels, as listed in Table I. On the other hand, the high channel correlation in Table I for the system with two single channel accelerometers, receiver B, can be related to the larger condition number. Typically, a smaller condition number such as system A's results in more effective equalization and a lower bit error rate [12].

Better performance of the tri-axial accelerometer, system A, can be viewed from another angle. In Fig. 6 eigenvalues of $\mathbf{H}_{\mathrm{A}}^{\dagger}\mathbf{H}_{\mathrm{A}}$ and $\mathbf{H}_{\mathrm{B}}^{\dagger}\mathbf{H}_{\mathrm{B}}$ are plotted for the two systems A and B, respectively. Eigenvalues for each system are normalized such that the largest eigenvalue is 1. We observe that the eigenvalues of the tri-axial accelerometer receiver are greater than those of the receiver which consists of two single channel accelerometers. As discussed in [12], performance of a system with larger eigenvalues is better, due to more effective equalization. This reflects the usefulness of the tri-axial receiver which benefits from co-located yet nearly uncorrelated channels listed in Table I.

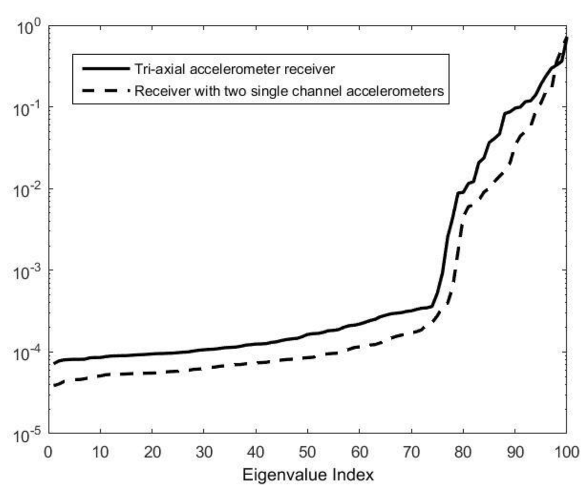

Fig. 6. Normalized sorted eigenvalues of $\mathbf{H}_{\mathrm{A}}^{\dagger}\mathbf{H}_{\mathrm{A}}$ and $\mathbf{H}_{\mathrm{B}}^{\dagger}\mathbf{H}_{\mathrm{B}}$ for two receivers: Receiver A is a tri-axial accelerometer, whereas receiver B consists of two single channel accelerometers.

VI. CONCLUSION

In this paper two types of receivers for communication via drill strings in oil wells are studied. The first one is a tri-axial multichannel accelerometer which measures acceleration signals in three orthogonal dimensions, whereas the second one is composed of two single channel accelerometers. Analysis of measured channel impulse responses collected from our drill string testbed, presented in the paper, reveals that the tri-axial acceleration channels are nearly uncorrelated, whereas the single channel accelerometers are highly correlated. This indicates that the tri-axial receiver is capable of providing diversity gain and therefore better performance, relying on its orthogonal channels. This is further demonstrated in the paper, by looking at the multichannel eigen spectrum, which shows the usefulness of the tri-axial receiver.

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