# Acoustic Channel Model for Adaptive Downhole Communication over Deep Drill Strings

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***Abstract*—For reducing costs in drilling technology, seismic prediction while drilling (SPWD) is envisioned. SPWD needs a fast data link bringing up the seismic data from bottomhole to the ground. In this paper, we propose a flexible and easy-to-use acoustic channel model for long drill strings. The model enables efficient design of adaptive OFDM communication links and prediction of achievable data rates for variable string dimensions. We describe acoustic wave propagation by the S-parameters of the drill string modelled as a series of alternating short and long resonators due to segments of constant acoustic impedance. All segments have been parametrised and the final channel is a concatenation of all its segments. We verify the new model by comparison with measurements on a 55 m long drill string. By using our model, the properties of a manifold of real drill pipes with variable dimensions can be predicted. We investigate the impact of length variations typical for rough drilling applications. For efficient communications over 1.5 km, length variations of the screwed tool joints should be limited to a few centimetres while the pipe length may vary up to one meter.**

***Keywords - acoustic communications; channel model; OFDM; S-parameters;***

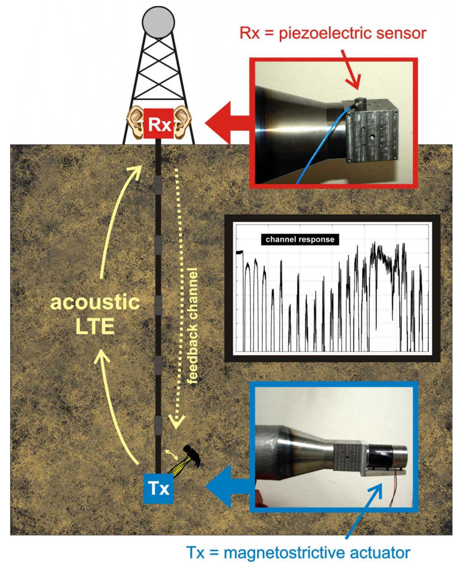


Figure 1. Acoustic communications over drill strings: A magnetostrictive actuator is used as transmitter, screwed drill pipes form the transmission channel and a piezoelectric sensor is used as receiver.

## I. Introduction

To reduce costs of geothermal energy, deep wells drilling needs higher success rates. The exploration risk can be lowered in the future if the advance of the drill bit is scouted by seismic prediction while drilling [1]. The drill direction can be controlled in this way towards water-bearing fault zones. Complex seismic data need to be transmitted from the bottom of the hole to the ground enabling a suitable control of the drill direction.

Nowadays, drillers use mud-pulse telemetry [2], where data are modulated onto the mud flow transporting also the borehole cutting to the ground. Clearly, very low data rates of few bit/s can be realized in this way. In the literature, several approaches for increasing the data rate are discussed, such as by using cable, electromagnetic or acoustic waves. However, for our application (see Fig. 1) acoustic transmission in combination with high resolution OFDM [5, 6] is exploited to achieve maximum data rate.

Due to very high costs and complexity of any drilling, measurements are only seldom feasible and hence a good and flexible channel model is of evident importance to design an adaptive OFDM communication system optimally. Moreover, since the transmission properties depend on several parameters of each segment in the string, besides the total number of segments, we need a channel model to predict the achievable data rate as a function of string lengths. First approaches to calculate the channel response of a drill string are based upon finite difference methods applied to the differential equations used but yielding a less flexible solution [9]. This is alleviated in [11] with the introduction of the transfer matrix method shifting the solution from the time into the frequency domain. In this paper, the analogy to the electrical wave is exploited and the drill string is described by S-parameters which are commonly used in the frequency domain and well known from radio frequency (RF) techniques. This has the great advantage that frequently available microwave design tools can be applied to the problem.

The paper is organized as follows. A tractable channel model for acoustic communications over the drill string is developed and verified in section II. In section III, the qualification of standard drill pipes is investigated and in section IV the influence of length and diameter variations are discussed, followed by the conclusions in section V.

## II. The Acoustic Drill String Channel

### A. Channel Model

The mathematical description of a guided acoustic wave ends with a wave equation solved numerically so far [9]. Here, we exploit the direct analogy to the well-known electrical wave equation in RF engineering to come to a more tractable channel model using acoustic impedances.

The drill string is modelled as a series of alternating short and long resonators defined by segments of constant acoustic impedance, see Fig. 2. The pipe and the screwing denoted as tool joint are both modelled as elements of a transmission chain where each element is described by a 2x2 scattering matrix $S$ commonly used in RF engineering. The drill string is considered as a 2-port device where $S_{11}$ and $S_{22}$ measure reflection while $S_{12}$ and $S_{21}$ measure transmission in the forward and reverse directions, respectively.

The long thin pipes and the short thick tool joints show different impedance characteristics. According to [10], the acoustic impedance is nearly proportional to the respective cross-sectional area. However, to determine the S-parameters of all components separately, a characteristic impedance is necessary (in RF usually 50 Ohm). For convenience, this characteristic impedance is set to the impedance $Z_1$ of the thin pipe, yielding that all reflections are concentrated at the ends of the thick pipes. To obtain the S-parameters for one segment, we assume that the segment is symmetric in forward and reverse direction, and use the following equations to describe the elements of the chain (with Mason-Rule e. g. [14])

$$S_{11} = S_{22} = \frac{b_1}{a_1}\Big|_{a_2=0} = r \cdot \left(1 - \frac{(1-r^2)\cdot e^{-2\cdot j\cdot\gamma\cdot L}}{1 - r^2\cdot e^{-2\cdot j\cdot\gamma\cdot L}}\right) \quad (1)$$

$$S_{21} = S_{12} = \frac{b_2}{a_1}\Big|_{a_2=0} = \frac{(1-r^2)\cdot e^{-j\cdot\gamma\cdot L}}{1 - r^2\cdot e^{-2\cdot j\cdot\gamma\cdot L}}. \quad (2)$$

$$S_{i/o} = \begin{pmatrix} -r_{i/o} & t_{i/o}\cdot e^{-j\cdot\gamma\cdot L_{i/o}} \\ t_{i/o}\cdot e^{-j\cdot\gamma\cdot L_{i/o}} & r_{i/o}\cdot e^{-j\cdot 2\cdot\gamma\cdot L_{i/o}} \end{pmatrix} \quad (3)$$

where $r = 0$ for the thin pipe $\mathbf{S_1}$ and $t = \sqrt{1-r^2}$ in Fig. 2, $r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$ for the thick pipe $\mathbf{S_2}$ and $\gamma = \frac{2\pi\cdot f}{v_{ac}} - j\cdot\alpha$.

The three model parameters $L$, $r$ and $\alpha$ can be interpreted as the length of the segment, the reflection and the attenuation, respectively. Reflection scales from 0 to 1 and it is related to the ratio of cross-sections [10]. For acoustic absorption, literature values for steel pipes range between 10 and 40 dB/km.

Since all individual components can be described using the equivalent S-parameters, the overall channel characteristics is obtained as a serial concatenation of all individual ones. For describing this mathematically, we introduce so-called T-matrices related to the S-matrices as

$$\mathbf{T} = \frac{1}{S_{21}}\begin{pmatrix} S_{12}S_{21} - S_{11}S_{22} & S_{11} \\ -S_{22} & 1 \end{pmatrix} \quad (4)$$

where the concatenation $\mathbf{T}_{pipe}$ of all $N$ segments provides us with the resulting channel frequency response taken from the $S_{21}$ parameter of the overall chain as

$$\mathbf{T}_{pipe} = \prod_{n=1}^{N}\mathbf{T}_n, \qquad S_{21} = \frac{1}{(T_{22})_{pipe}}. \quad (5)$$

Along with intermediate reflections within the short tool joints and the longer drill pipes, all reflections over the entire

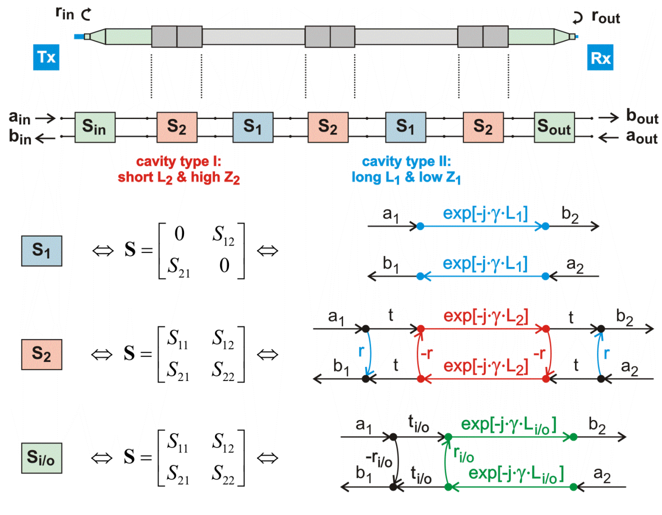


Figure 2. Model for the drill string composed of two types of resonators and its representation by S-parameters. Arbitrary reflection factors $r_{in}$ and $r_{out}$ are assumed at the ends. The characteristic impedance is $Z_1$.

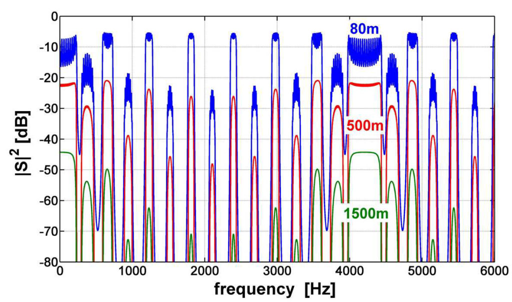


Figure 3. Modeled channel frequency responses corresponding to drill strings of 80 m, 500 m and 1,500 m length composed of 5 inch drill pipes each 30 feet long. An attenuation of 20 dB/km and 75% end reflections are assumed.

length of the string form a very complex acoustic resonator. At the ends of a drill string, mounts for transmitters and receivers are attached causing additional reflections, see green areas in Fig. 2. The impact of those end resonances depends largely on the attenuation of the drill string. The longer the string, the less important they are.

## B. Comparison of Model and Measurement

By using this new channel model, the properties of the acoustic drill string channel can be described. In the following, we have parametrized it using $v_{ac} = 5\ km/s$ for the speed of sound, $\alpha = 20\ dB/km$, $L_1 = 28\ ft$, $L_2 = 2\ ft$, $\frac{Z2}{Z1} = 4.5$, $L_{in} = L_{out} = 14\ ft$, $r_{i/o} = 0.82$.

For intuition of the results in Fig. 3, we consider short and long cavities. Long cavities occur between the tool joints and they cause the typical pass- and stop-bands in the frequency response clearly observed in Fig. 3. Further, short cavities are built within each tool joint and their resonances imply that transmission is better around 0, 4.2 and 8.4 kHz etc. while it is worse around 2.1, 6.3 kHz, etc.. Another way to describe the drill string is to imagine that it consists of a series of long thin pipes with frequency dependent reflectors in between (tool

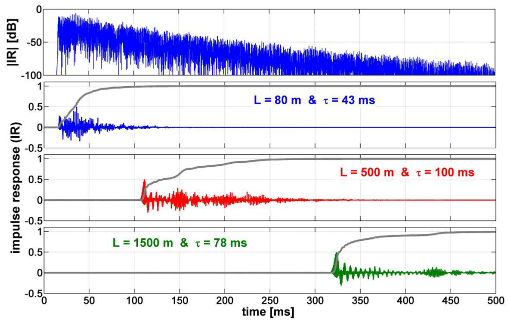


Figure 4. Impulse responses evaluated from the channel frequency responses whereas the one for 80 m is also shown with a logarithmic scale. Also depicted is the aggregate power (gray) and out of it the 90% time delay $\tau$ is determined.

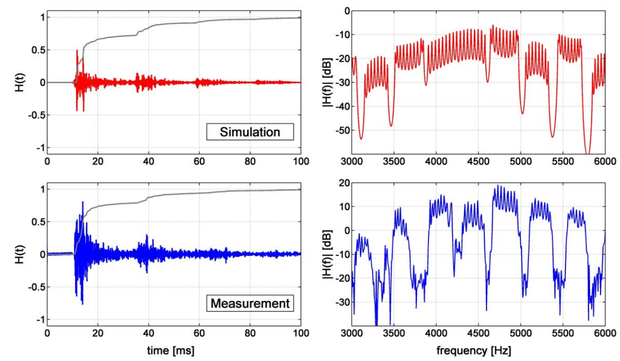


Figure 5. Modelled (top) and measured (bottom) impulse responses (left) and the corresponding channel frequency responses (right) for a 55 m drill string [13].

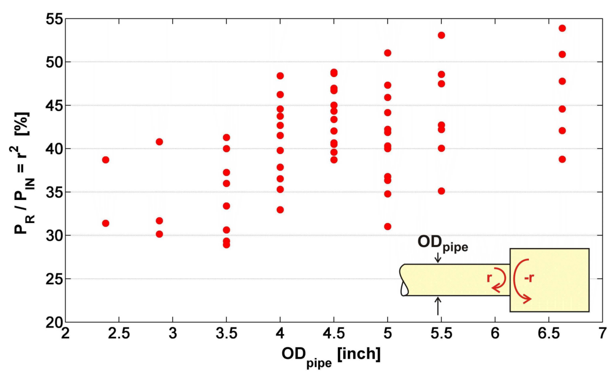


Figure 6. Acoustic reflection at a transition from pipe to tool joint for standard drill pipes, in which $OD_{pipe}$ denotes the outer diameter of the pipe. For every diameter $OD_{pipe}$ are different tool joints possible yielding different transmission performances.

joints). For certain frequencies the reflections of all reflectors simultaneously vanish and the whole drill string becomes transparent yielding an optimal situation for data transmission. In between of such optimal frequencies the reflectors show maximum reflection coming along with maximum attenuation.

The longer the string, the more the signal is attenuated in general. Moreover, the width of the pass-bands suitable for communication gets reduced. Clearly, if the string gets long, two major spectral regions of interest remain, one close to zero and another around 4.2 kHz in our example. Higher frequencies, e.g. around 8.4 kHz, are also possible, but are more sensitive to length variations of the cavities.

The complex frequency characteristic corresponds to an infinite impulse response revealing the rich multi-path nature of the acoustic drill string channel. It has an approximately exponential overall decay shown in Fig. 4.

In Fig. 5, we compare our model and a measurement taken at a 55 m long drill string made of eight pipes of 20 feet length and 5 inch boring plus half a pipe at both ends where transmitter and receiver are mounted [13]. The principal properties of the impulse response are well modelled, and the typical multi-path structure of the acoustic drill string channel is reproduced very well. In the frequency response, the number of peaks in each pass-band corresponds to the number of pipes. In the measurements, there is an additional comb enclosed due to end reflections so that sometimes less peaks are observed.

## III. Standard Drill Pipes

Most drill pipes are produced according to a standard where the pipe diameter is classified [12]. Pipe diameters of 2-3/8, 2-7/8, 3-1/2, 4, 4-1/2, 5, 5-1/2 and 6-5/8 inch are common. Furthermore, each drill pipe can be manufactured in 4 quality grades and with different tool joints to adapt it to a variety of applications. One main quality factor for acoustic application is the reflection at transitions from pipe to tool joint. The lower the reflection is, the more suited is the channel response for data transmission. Hence, Fig. 6 shows the reflection of one transition for common standard drill pipes.

Fig. 7-top shows the frequency response for a 2000 m long drill string with the lowest (29%) and the highest reflection (54%) according to Fig. 6. A lower reflection produces higher pass bands and the bandwidth of them is greater, too. Altogether, roughly the double bandwidth can be allocated for data transmission compared to the case with the highest reflection. Around the first resonance frequency of the tool joints, of about 5.3 kHz, both allow nearly perfect data transmission, but with the lower reflection the bandwidth is about 30% greater.

Drill pipes are commonly equipped with a small thickening behind each tool joint called elevator upset (compare inset of Fig. 7-bottom) for stable handling purposes. For acoustic waves this area acts as an additional matching between the pipe and tool joint acoustic impedances improving the channel response as can be seen in Fig. 7-bottom.

## IV. Length and Diameter Variations of Drill Pipes

In an ideal case, all drill pipes are identical, but in reality at least three dimensions of a drill pipe can typically vary as shown at the top of Fig. 8. A variation of the pipe length denoted by $\Delta L_{pipe}$ of maximum 3 feet is already allowed according to the standard [12] but pipes from the same production interval are typically very similar. The drill pipes suffer from screwing them on and off. Due to the high stress additional thread cuttings are sometimes necessary yielding a reduction of the tool joint length $\Delta L_{joint}$. Furthermore,

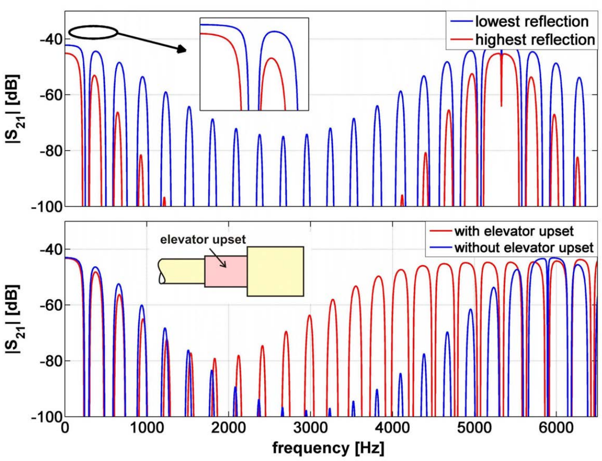


Figure 7. Simulations of a drill string of 2000 m long and without reflections at the ends. Top: lowest possible reflection ( 29%) according to Fig. 6 and the highest one (54%). The inset shows the first two pass-bands in detail. Bottom: simulation with and without elevation upset. The inset shows the location of the elevation upset. A reflection at one tool joint of 40% is assumed.

the drilling process causes a steady scratching of the tool joints against the casing or formation which reduces the diameter ($\Delta D_{joint}$). The last issue corresponds to a reduction of the acoustic impedance of the tool joints, meaning that the impedance difference of the pipes decreases and a slight improvement of data transmission may be expected.

However, for achieving a high data rate it is evident the necessity of transmission bandwidth for frequencies greater than 1 kHz to avoid the strong drilling noise. Fig. 8 suggests that this may only be achieved with very low length variations $\Delta L_{joint}$ of the tool joint of some few centimetres, whereas the pipe length can vary up to a meter.

Fig. 9 shows details for $\Delta L_{joint} = \pm 1cm$ and $\Delta L_{pipe} = \pm 40cm$ from Fig. 8 revealing the strong fading. Therefore, a high-resolution OFDM system with a subcarrier separation smaller than 3 Hz is required to nearly hold the flat fading condition. For the still remaining faults, a forward error correction may be included. Our currently adapted acoustic LTE-system [8] has a subcarrier separation of 15 Hz, but an advanced version including the feature of carrier aggregation available on LTE-Advance can reach subcarrier separations of 1 Hz and below, sufficient for this application.

## V. Conclusions

In this paper, the analogy between electrical and acoustic wave was exploited to describe acoustic wave transmissions over a drill pipe. Therefore, a new channel model based upon S-parameters, well known from the RF-technique, was developed and verified by a measurement over a 55 m drill string. Due to its definition in the frequency domain, it can be easily adapted to strong fading conditions which are typical for real drill string applications. An investigation of length variations revealed that the length of the screwed tool joints must be accurate by a few centimetres whereas the long pipe may vary up to a meter to achieve useful channel characteristics.

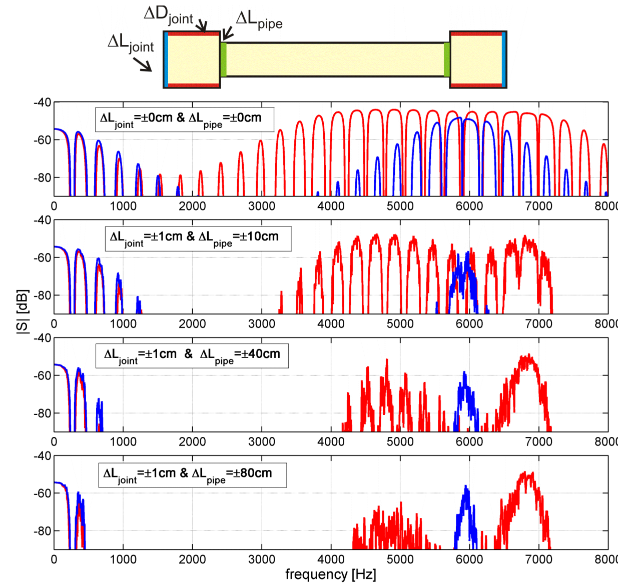


Figure 8. Simulations considering length variations of the pipe $\Delta Lpipe$ and tool joint $\Delta Ljoint$. The distributions of the length are assumed to be white. At the top, a sketch is included showing $\Delta Lpipe$ and $\Delta Ljoint$ (same simulation parameters as in Fig. 7-bottom but with end reflection of 75%).

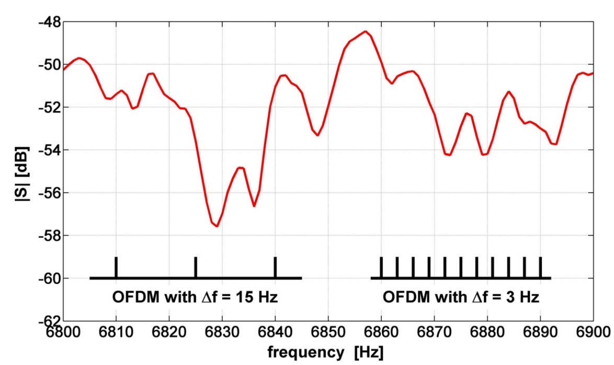


Figure 9. Detail of the curve for $\Delta Lpipe = \pm 40$ cm and $\Delta Ljoint = \pm 1$ cm of Fig. 8 in the high frequency range showing a strong frequency-selective fading. Indicated are also the OFDM subcarrier spacings for our current acoustic LTE system and the advanced one.

Standard drill pipes suit generally for this application but the useful bandwidth can differ by a factor of two. To enhance the data rate further, MIMO-processing shall be implemented in future research and the channel model will be adapted therefore.

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