Channel Estimation in Through-The-Earth Communications with Electrodes

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Abstract— One of the main points in the design of a communication system is to know the channel behaviour for a given frequency band in terms of amplitude and phase. Free space communications channels have been characterized thoroughly for a large range of frequencies. But in the field of Through-The-Earth (TTE) communications, the work about channel characterization found in the literature is very scant and focused in magnetic propagation (induction loops). This paper presents a method of channel characterization for TTE communications with electrodes, and the tests and results done in real field measurements.

1. INTRODUCTION

TTE communication systems have been developed for establishing communication in confined areas as tunnel, mines or caves. Due to rock conductivity, electromagnetic waves suffer from skin effect attenuation. Because of that, TTE communication works in VLF-LF range. There are two possible medium access solutions: current injection by means of ground electrodes [1] and magnetic induction by inductive loops. In current injection a pair of electrodes is located underground and other pair in surface.

In TTE communication not only it is necessary to study the electrical noise present. A channel characterization is of paramount importance at time to model and simulate a communication system. A channel sounding allows obtaining the parameters of the channel impulse response expression $h(t)$, considering in this case a time invariant channel. The channel transfer function states that for a given input $x(t)$, the output $y(t)$ is the convolution of $x(t)$ and the impulse response $h(t)$. Knowing $h(t)$, it would be possible to predict the distortion that the receiver will suffer and to design equalizers or matched filters to compensate it.

On the other hand, if $h(t)$ is not known, a large number of parameters (channel attenuation, SNR, phase distortion) critical in system design are left to trial and error, which effectively multiplies time needed to design such systems and most important, designed systems are usually far from optimum.

The characterization of TTE communication channel with inductive loop has been studied theoretical and experimentally [1, 2]. In the electrodes case, several studies in the literature offer theoretical formulae that model the communication channel with electrodes. However, they are valid for big electrodes, with emitter and receiver in surface and with a large separation between them. This situation is not suitable for TTE communication system where the electrodes separation is relatively small, also its size. Moreover, the electromagnetic waves travel though the rock in this case.

For the channel object of study, electrodes effect is also considered, since it is not possible to isolate its impact in the measurements. Furthermore, in a real TTE communication application the electrodes contribution in the channel will be present. The electrode impedance generally presents a very high value that limits the current injected and so after the electric field generated [3]. In this paper a basic channel characterization method developed for TTE communication applications with electrodes is presented. This method has been applied in several locations, presenting here a couple of measurements done in surface.

2. CHANNEL SOUNDING METHODS

Many methods for communication channel estimation have been developed. They are based on setting $x(t) = \delta(t)$ (Dirac delta function). The output $y(t)$ is directly the impulse response $h(t)$. In practice, it is not possible to obtain a true delta (infinite amplitude and infinitesimal duration). Therefore, the measurement methods try to approximate an impulse function. They are grouped in two kinds of methods: Those that implement the estimation in time domain and those that work in frequency domain. A comparative of them does not show clear advantages of one method with regard to the other [4].

2.1. Time Domain Methods

The Periodic Pulse method excites the channel with a short-duration RF-pulse to approximate the delta function [6, 7]. This method was very used in the past. Another method, the Pulse Compression Technique states that a linear system impulse response can be estimated supplying it with white noise [8]. The impulse response can be obtained from the cross correlation between channel input and output. Deterministic signal with noise characteristics are employed as the pseudo-noise (PN) sequences. Their self-correlation offers a sharp peak in the zero-shift. This method has been employed in underground channel estimation with induction loop [1].

The Swept Time Delay Crosscorrelation method or Sliding Correlator Technique employs PN sequences but the signal in receptor is generated by a clock slightly slower than in emitter [10]. This method is employed in wireless channel sounding, since it allows measuring the amplitude and phase delay of different multipath signals. A comparative of different methods in time domain is done in [7], concluding that the method that employs the PN sequences is the most adequate for wideband radio channels.

2.2. Frequency Domain Methods

Some examples of the frequency domain method for underground communications in tunnels are shown in [11]. In this kind of methods, generally a Vector Network Analyser (VNA) is used to measure the parameter $S_{21}(f)$ at different frequencies, obtaining the channels frequency response. Main advantage of this method is that present a simple implementation. But it requires a wired reference signal common to emitter and receiver and sweep time is long. Solutions for the wired reference consider the use of synchronization between emitter and receiver by means of high precision clocks or with GPS receivers. Another solution employs a VNA without a direct connection, sending a triggering signal to the frequency analyzer. Another approximation is given by the digital down-conversion method, which is based on bandpass sampling the receiver signal with a sampling frequency twice the information bandwidth.

3. METHOD DEVELOPED

The channel sounding method developed is grouped in the frequency domain methods. In the emitter, a variable frequency tone is generated for a number of discrete frequencies in the band of interest. Receiver is in charge of estimating the amplitude and phase of the received tones, giving as a result an estimation of $S_{21}(f)$. But in order to do this a common reference is needed and a wired one is not appropriate in the case of TTE communications. Therefore, a solution to obtain a phase reference in receiver is required. In order to solve this, a fixed frequency sinusoidal tone is generated together with the sweep frequency signal, acting the first as a reference signal. Both tones (reference and sweep) are phase synchronized and have the same amplitude. This allows measuring the phase and amplitude variation at the different swept frequencies. As the emitter output power can be easily measured, the result is basic channel estimation in terms of amplitude and phase. Due to the low frequencies used (VLF-LF), neither multipath nor signal delays are considered.

The measurement equipment employed in transmission is formed by a PC which generates the transmission tones and does the control, an arbitrary signal generator and a pair of electrodes. In reception, signal is captured with a pair of electrodes connected to a low noise amplifier. After the amplification, signal is digitalized by a high rate A/D converter connected to the PC via USB port. The sampling frequency in generator and ADC is set to 2 MHz, the maximum allowed by ADC. All the instrument control as well as the data processing is implemented in Matlab scripts.

The frequency band to study is in the range of 3–150 kHz. These frequencies are a compromise between minimum bandwidth needed and signal generator output capability. Test signals are generated with the help of an IDFT (Inverse Discrete Fourier Transform) of 512 points in order to obtain orthogonal tones. The reference tone frequency is 3906.25 Hz which is the result of dividing the sampling frequency (2 Msps) by the IDFT size (512 points). Sweep tone frequency is calculated as integer multiples of the reference frequency ($n = 2.40$).

Sweep tone changes its frequency value every ten seconds. The emitter transmits the sweep continuously until the user stops the application, in a circular way. The receiver samples every second capturing a signal for 131 ms (2ˆ18 points) in order to limit the errors caused by the sampling

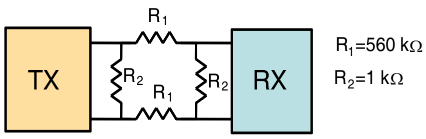

Figure 1: Calibration network.

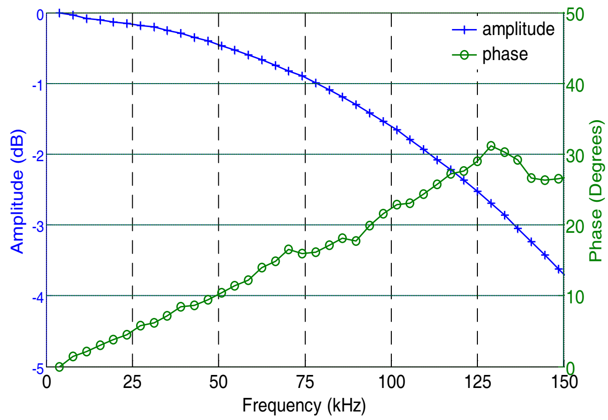

Figure 2: Calibration network frequency response.

operation. A Lagrange Interpolation is implemented as suggested in [12] to obtain a synchronized sampled signal. Although this solution would be applied, an error in data phase measurement will appear due to the linear interpolation applied and the A/D converter quantization [13]. This error increase with the frequency swept. Future studies will try to solve this inconvenient.

A DFT is latter calculated with the 262144 (2ˆ18) sample points, a power of two multiple of the emitter IDFT points (512×512). Thus, both the errors introduced by FFT computation and channel noise in receiver are minimized. As the frequential positions of the scanning are known in receiver, the relative amplitude and phase values for these samples are stored. For every frequency point only nine correct measurements are available (out of ten). This is due to the time needed in the emitter to store the signal in signal generator. The outliers that overcome 1 dB from the average of the nine samples are discarded, applying a new average that will be stored as correct value for each frequency.

The calculation of channel response is evaluated offline applying the LS (Least Squares) algorithm. According to this method, the frequency channel response follow the expression (1), with X a diagonal matrix with the value for each frequency sample ($x_1, \ldots, x_k$) generated with the IDFT and Y the k frequency samples in the receiver. The measurement system has been calibrated with a resistance network shown in Fig. 1 in order to correct the measurement method systematic errors. It has been applied the Self-Calibration Measuring Technique (SCMT) [24].

$$\hat{H}_{LS} = X^{-1}Y \tag{1}$$

The frequency response of the network measured is drawn in Fig. 2. It can be seen that the generator does not present constant amplitude with frequency nor the phase response is zero, as it would be in an ideal system. This error is compensated in the measurements offline. As it has been commented before, the phase measurement presents some errors due to the desynchronization of generator and sampler frequencies. The phase trend has been represented in previous figure smoothing the response obtained.

The random errors are limited applying an average of the maximum values in the frequency sounding and the DFT method as proposed in [12].

4. EXPERIMENT CONDITIONS

Although the channel sounding has been developed to characterize the communication for underground applications, to prove that the method work and the results are consistent, it has been firstly tested in surface communication, presenting the results in this paper. The emitter and receiver present a four meters gap between the electrodes. The electrodes employed are steel bars, improving the contact with salty water and the wires used in emitter had no loops (minimum resistance and inductance).

As the electrodes impedance depends heavily on frequency [3], the soil injected current would not present a constant value for all the frequencies. However, it is of interest to know not only the isolated channel response but also with the load effect. So that it can be considered the effect of a total transmission channel that includes the electrodes. On the other hand, the impedance

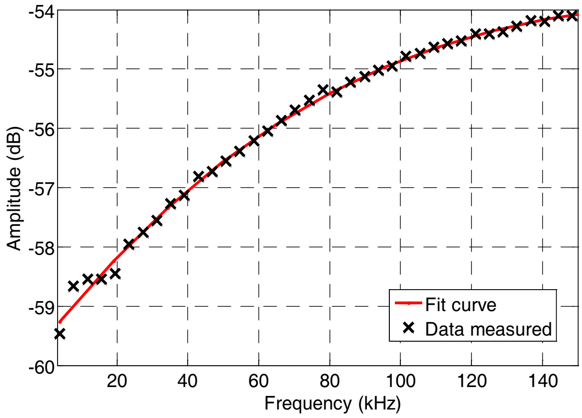

Figure 3: TTE channel frequential response amplitude.

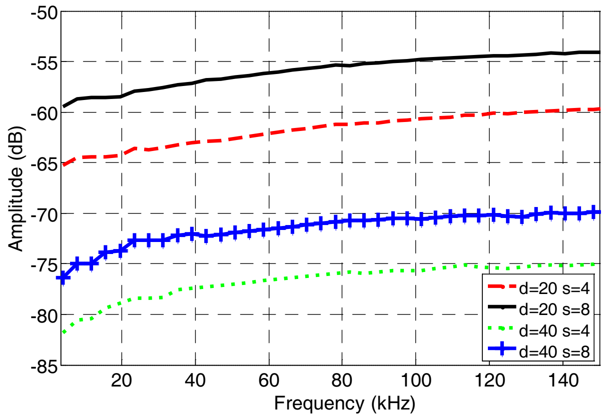

Figure 4: TTE channel frequential response with the distance (d) and the span (s).

between the electrodes has been measured in previous studies [3] having obtained an impedance characterization and being able to isolate the channel response offline.

The measurements presented in this paper were taken in Walqa Technological Park (Huesca) in December 2009. The soil in this location is composed by four meters of gravels lying and sandstone and clay of Miocene with an aquifer in the contact surface.

For the experiments, the span between the electrodes in the emitter was fixed to four meters in order to avoid modifications in the emitter impedance, and in the receiver was set to 4, 8 and 12. For the separation between emitter and receiver were considered 20 meters at first and 40 m later.

5. RESULTS

The channels amplitude frequency response for TTE communications in surface is shown in Fig. 3. Due to the low accuracy in phase measurements, it has only been considered the amplitude channel response. These results are enough for TTE radio applications using amplitude modulations. For data transmission with phase modulations it will be necessary to characterize also the phase channel response in future tests.

It can be seen in previous figure that the amplitude response increases with frequency. This effect is a combination of the electrodes system impedance and the channel behaviour. The channel response has not been isolated from this value since this is the real situation that a TTE communication system with electrodes will find. In Fig. 4 it is shown the response for two different distances and electrode spans of receiver.

Analysing the results it can be appreciated that doubling the distance translates into a 16.5 dBV attenuation. Relative to variation in span, doubling its value to 8 m, increased received signal in 6 dBV. A further increase in span (12 m) resulted in a smaller 3.5 dBV increase. It should be noted that increasing the span also increases the perceived noise.

6. CONCLUSIONS

A variation of a frequency domain method has been used to estimate the impulse channel response. The test results reveal that channel attenuation rises very fast with distance and can be partially compensated with the span distance between electrodes. Unfortunately, the method used does not allow a precise phase measurement as is. Future work will be focused in a more accurate phase channel response measurement, correcting the errors due to the jitter of emitter and receiver clocks in order to have a complete channel description. Moreover, the channel sounder will be applied in underground locations in order to obtain a TTE channel characterization in different terrains.

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