Thesis

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# Introduction

## The need for TTE:

### The use of the underground medium

Using the underground medium as a valid part of the battlefield is not unique to the recent years. Tunnels have served the Vietnamese in the Vietnam War both as a shelter and a stealth base to launch attacks against the American military. In Korea, one of the most probable scenarios to which the South Koreans and their counterparts are preparing for is an invasion launched from tunnels dug beneath the border between the two hostile states. Yet, the most actual case is the Israel-Gaza border where the tunneling warfare occupies a major role on both sides; Hamas on the attacker side and Israel on the defending side. It has reached a point where an entire all out clash’s outcome depends mainly on the underground warfare. As a result, huge technical and financial efforts are put to outrank the rival.

On the Homeland Security area, the underground medium has a presence too. Emergency services, often need to penetrate into closed underground spaces where no communication infrastructure is present such as collapsed buildings. Also in that domain, is the problem of illegal infiltration through the Mexico-USA border, where tunnels are sometimes used.

Yet, probably the area where the underground medium is most present is the civilian. The mining industry has suffered for hundreds of years from a bad reputation for its high rate of accidents and fatalities. Very often the accident itself is the cause for a communication failure which is usually wired. Recently, there is an interest in autonomous mining equipment [Brazil], requiring 2-way communication for operation and control.

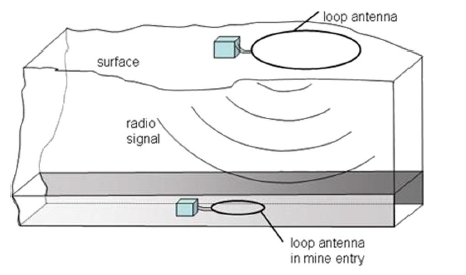
In all of these cases, we are facing the need for a reliable wireless ad-hoc communication ability.

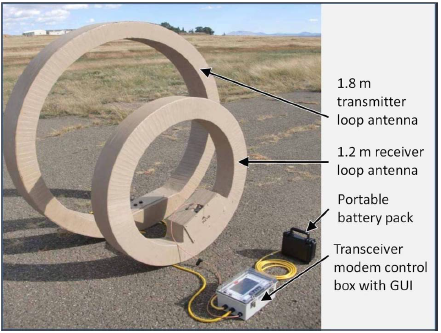
### TTE research and commercialization

Despite the old and proven need for Surface to Underground TTE wireless communication, up until late 2010’s, no such commercial nor military communication system had been developed. The capability of low frequency (ULF-VLF band) Electromagnetic Fields to penetrate through the ground has been proposed as early as 1890 by Nikola Tesla [Carrol]. However, in the 1970’s a research conducted by the US Bureau of Mines suggested that the required transmitted power, namely on the underground side, should exceed the safety allowable levels, thus making it impractical. [NIOSH].

From the 1970’s and on, there was only very little research in the field. Raab & Joughin suggested a signal processing techniques adapted to the VLF band on 1995, but only as late as mid 2000’s, after the launch of the semi commercial American NIOSH program we were able to witness more intensive research in that field (Raab, Brazil, Brakand& Damiano …), aiming to evaluate the channel characteristics (Brazil, 2016), and noise (Raab, 2010)

The advances in the communication technology from the 1990’s and on, namely the digital communications, digital signal processing and coding techniques, offered enhanced receiver performance allowing reduction of the transmitted power. A sponsored study was initiated by the American National Institute for Occupational Safety and Health (NIOSH) on 2007, in which participated 5 contractors: Lockheed Martin, E-spectrum, Stolar and Alertek. Its aim was to examine the feasibility of TTE wireless communication in the mining industry. All but one (E-Spectrum) adopted the Magnetic field approach: large Loop antennas (Coils in fact) communicating through a Quasi-Static Magnetic Field. The Magnetic field approach systems reached a distance varying between 180m to 300m with antenna diameters varying between 1.2m to 90m. For all 5 contractors, actual performance was significantly lower than what they had initially predicted. One reason is the fact that they had employed techniques borrowed from radio frequency communication systems, that may not fit the actual VLF channel impairments. A second one, is the fact that the noises evaluated during the researches of the 1970’s and 1980’s are probably much less intensive than those nowadays, mainly the man-made type. [NIOSH, p.6 left bottom]. Although not mentioned (apart from Ultra and Alertek), it seems and is quite logical view the time when the design took place, that most if not all contractors used standard single carrier techniques (FSK for Ultra and Alertek)



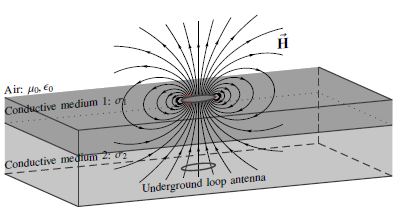


### VLF communication approach

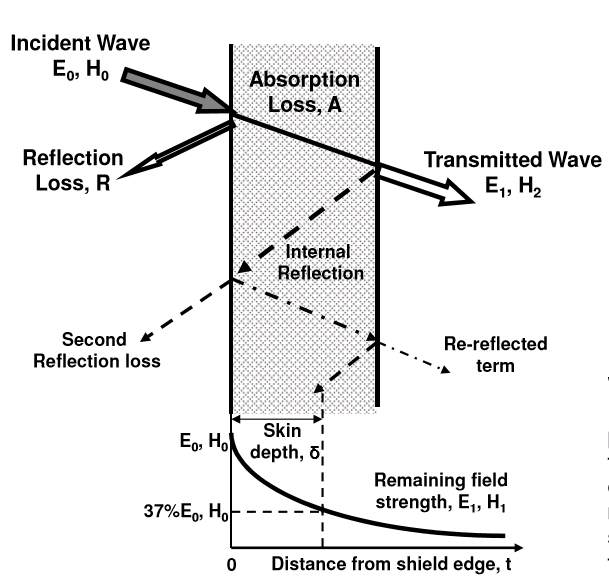
## Electromagnetic analysis of VLF band

### Transmission coefficient

A typical TTE link involves a surface based station residing in the free air and an underground station. The ground is not a homogenous and may be composed of several mediums that are conductive in general.



Suppose we transmit from the surface into the ground, the electric and magnetic fields will experience a reflection at the mediums’ boundary followed by an exponential decay with distance other than the polynomial decay already experienced in the non conductive medium.



The ratio between the incident and transmitted fields is

Where Z is the wave impedance of the medium. Assume that the air’s impedance is close to the free space’s (at far field);

The ground’s (conducting medium) impedance is calculated as follows

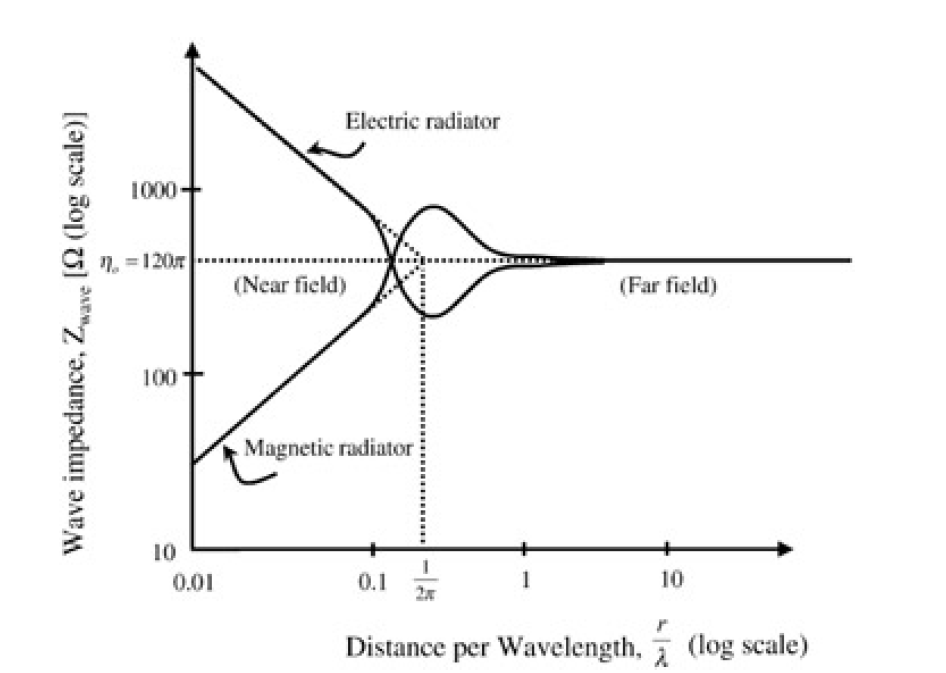
(see Clemmow, An introduction to ….section 5.3.2)

Where the , are the ground’s permeability (which is similar the free space’s; ) and conductivity. Example; for ,

The , and the transmission coefficient is

### Magnetic Versus Electric Radiators (Gibson p.47, high speed p.219). Near field

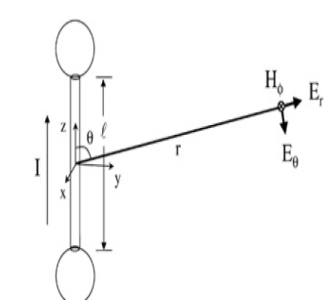
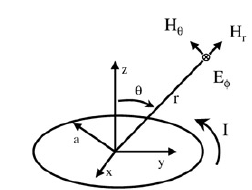
Free space wave impedance, in the above equations, is dependent on the radiator type and on the distance from it normalized by the wavelength. For a good (high) transmission coefficient we would need a low free space impedance.



For that to occur, the source needs to be a magnetic radiator and the boundary placed at a low electrical distance from the source

(p.219, High speed… )

Electric and magnetic radiators mentioned above are the electric and magnetic dipoles

Example: for a conducting medium with , and the boundary placed at () the (extrapolated from 0.01 at a rate of /5 per decade) The Transmission coefficient this time will be: .

In these 2 facts resides the concept of the TTE communication: a magnetic radiator operating in the near field, or equivalently- in the Very Low Frequency band. Another reason for operating on low frequencies is treated in greater details later on.

The term “Magneto Quasi Static communication” originates from the radiation source and the frequency band and not from the communicating fields. The magnetic radiator generates both magnetic and electric field.

### Magnetic Radiator: non conducting medium Field expressions (Gibson p.47

The EM fields emitted by a small loop antenna are:

If we define, and is the wave number. then;

### Magnetic Radiator: Conducting medium Field expressions

#### Complex wave number

The magnetic induction expression above was derived from;

Where is the magnetic vector potential function. As with all other functions, scalars and vectors, involved in Maxwell’s equations, it is also the solution of a wave equation:

(is the current density field vector). is the wave number and is defined:

In a conducting material we replace with , which leads to the following definition of the wave number on conducting medium;

. is the skin depth and will be discussed in greater detail later.

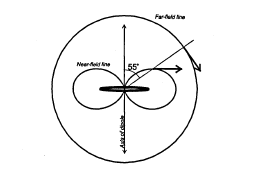
#### Complete expressions (2-18)

With the definition;

#### Far field approximation ( 2-20)

Under the assumption that , we could express the EM fields with:

Looking at the magnetic induction, we can see that in the near field it points to both radial and tangential directions, and as the distance increases, the tangential takes over the radial to become fully tangential in the far field



### Skin effect

In previous section we introduced the term . It appeared in the expression of the fields inside a conductor both in the complex and the real exponentials’ power. The accurate expression is:

But it is less useful than its approximations:

A good conductor: ,

A poor conductor: ,

Example: A medium with ,

#### Wave number interpretation

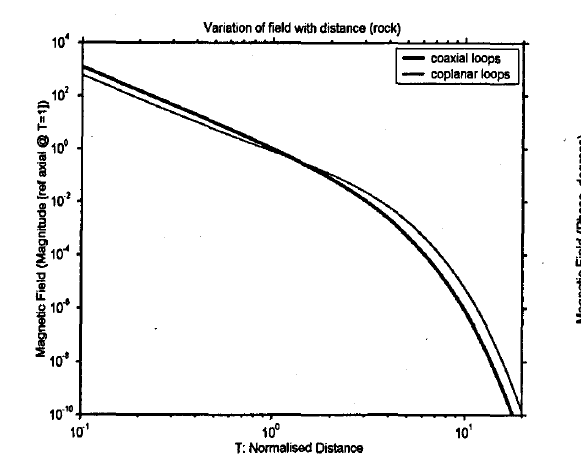
The term corresponds to the phase of a plane wave with a wave number of

#### Attenuation factor interpretation

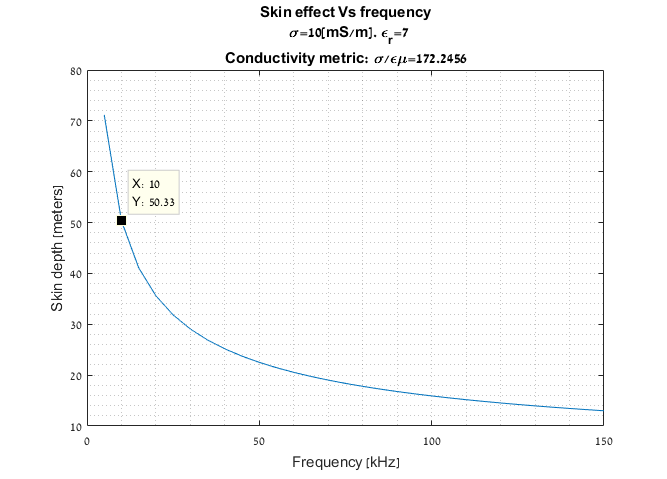
The term means an attenuation of the field amplitude at an exponential rate of . the range at which the attenuation reaches 8.7dB is called the “skin depth”. The exponential term becomes dominant the further we are from transmitter. In this zone, we can say that the signal is attenuated by 8.7dB at every skin depth.

#### Near field motivation of the TTE

The field amplitude versus the normalized range is shown below



In the expression of the field, the normalized range appears in inverse cube form at the denominator and as an exponential power. We can see that from about and on, the field amplitude attenuation is dominated by the exponent; the “skin effect” (Gibson p.56 bottom). This attenuation is far more intensive than the one caused by the inverse cube, thus motivating us to operate the TTE link in the “short distance” zone dominated by the inverse cube.



In the case of the curve above, at 10kHz we can be assured to be in the “inverse cube zone” at least up till 50m depth.

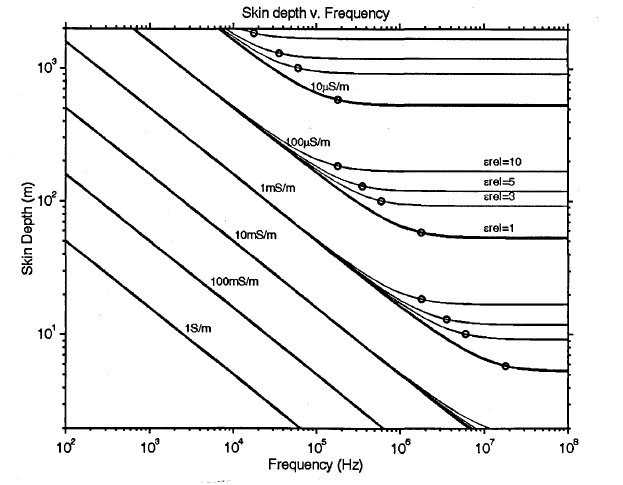
This fact is the 2nd main motivation for operating the TTE links in the near field, which corresponds to the VLF band

#### Ground as a conductor (p.54-55)

The conduction and the eventually the skin depth of a given medium depend of the material conductivity ( , permittivity () and permeability (). In general, the bigger of the material, the more it is conductive and the smaller is the skin depth. For communication purposes we are interested in operating in the inverse cube region of the field for as large distances as possible, thus, in large skin depths.

The conductivity of the soil can vary from to , depending on the moisture level. The factor of the permittivity () can vary between 7 and 43. The permeability of most materials does not vary much from that of the free space..

The following figure illustrates those dependencies.



#### Magneto quasi static & near field (Gibson, p.58)

Some of the literature claim that we should distinguish between the Magneto Quasi Static and Near Field zones.

The Quasi Static zone is defined as the distance from source where the condition holds. The expression of the field in that zone is (H without loss of generality):

We can see that it depends on range merely by an inverse cube relation.

The Near Field zone is where the skin depth exponential decay begins to have an effect. That zone comprises the distances where the condition holds. The field expression there is:

We can see that it resembles the complete expression apart from the term.

#### Wavelength in conducting materials

We already saw that the wavenumber of a signal in a good conducting material was (Gibson 2-15);

Since ,we can say that , which means that the wavelength in a conductor much shorter than its free space value.

example; . The , which derives that . In free space, , which means a ratio of more than 30.

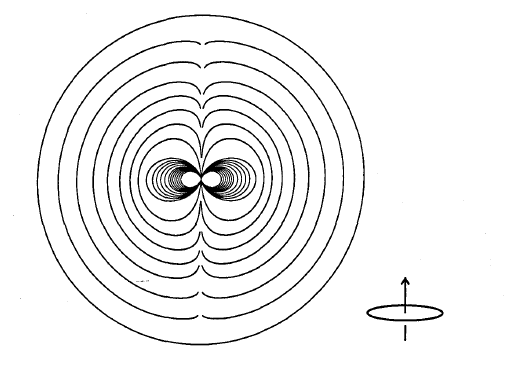
### Antennas

#### H-field and E-field antenna (p.102)

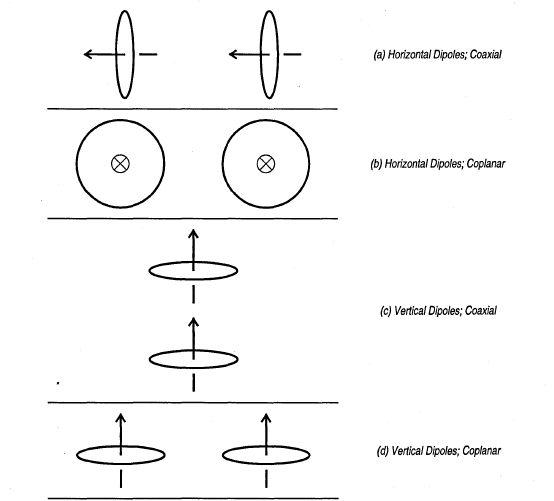
We must remember that both magnetic and electric radiators produce both magnetic and electric fields. Moreover, despite the fact that an electric radiator suffers from large attenuation at the air medium-conductive medium boundary, it may not be fully ruled out as a possible radiator. Varying the mutual positioning of the radiators could couple all field types from Tx antenna to Rx antenna .Hence, theoretically all 4 Tx-Rx combination ( H->H, E->E, H->E, E->H) are possible choices. The issue is treated in Gibson (chapter 4) that refers to Clemmow; the analysis presented there treats the SNR at the receiver antenna and not only the coupled signal. We will not bring the full reasoning, but summarize that the most natural combination is that of H-field antennas on both sides of the link.

#### Antennas orientation (Gibson 48, 49-50

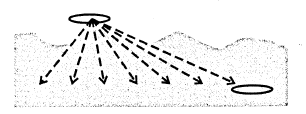
Based on the magnetic field expression we can draw the following field lines diagram



That diagram suggests that magnetic field coupling will exist in both co-axial and co-planar mutual positioning



A deployment of a TTE link will look as follows



#### From current loop to solenoid

The term , the magnetic moment, has appeared in the magnetic induction expression produced by a Tx antenna. Its value for a N windings solenoid is:

Where N is the number of turns, I is the current flowing in the solenoid and A is the Solenoid area.

## The choice of OFDM

The choice of the waveform to be used in the TTE communication system is a substantial issue. It should be the result of the multiple considerations:

* Channel model
* Noise model
* Required throughput
* Required distance
* Available spectrum
* Available HW and signal processing resources

We have chosen to use the Orthogonal Frequency Multiple Access (OFDM) technique and the reasoning is brought below

### Channel model [Brazil, Spain, Gibson]

#### Multipath

The issue of wavelength inside a conducting material was discussed earlier; it is much lower than free space wavelength. However, if we remain in the quasi-static or near field areas (close to transmitter), we can be assume that the link, Transmitter-Channel-Receiver, represent a lumped system. i.e; a system whose electrical length is much lower than the quarter of wavelength, whose spatial phase almost does not vary between the 2 circuit edges. This practically eliminates the possibility of multipath propagation [Spain, Gibson 2.4.3]. Nevertheless, it does not say that the channel may not be frequency selective.

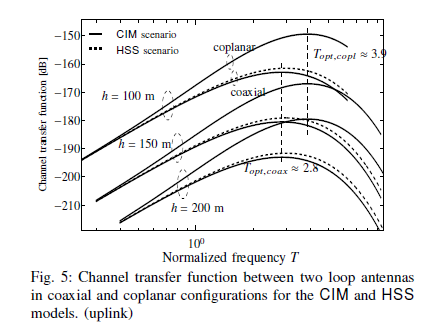
#### Optimum Frequency (Gibson 2.2.4)

Only few literature (e.g; Brazil, Spain, Gibson) has treated the subject.

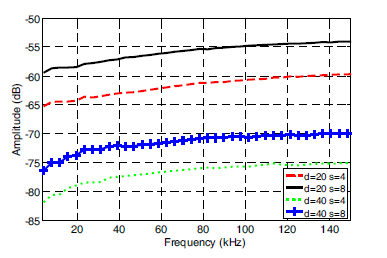
[Gibson] claims that on one hand the Electromotive force induced upon the Rx loop by the transmitted magnetic field is proportional to frequency. On the other hand, the conducting medium’s attenuation is also proportional to frequency. Therefore, we should expect a bandpass like shape of the frequency response. The peak is a solution of an optimization problem and achieved at , i.e at

example; . The , which results in

[Brazil] attempted to develop an analytical model, regarding the channel as a trans-admittance transfer function, achieving the same result as [Gibson] for coaxial antenna orientation and for coplanar antenna orientation



[Spain] suggested a measurement method, channel sounding, and actually performed it on 2 different depths.



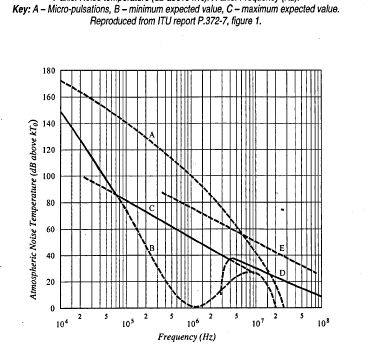
Although the peak response has not been reached and the conductivity is unknown, the results show a similar behavior to the expected ones given a reasonable conductivity of

It is clear that TTW channel model is very limited; partially because conductivity information is not always available but mainly because the soil is not homogenous [Brazil, p.170]. If we wish to know the exact channel response of a given link, we need to perform a specific measurement

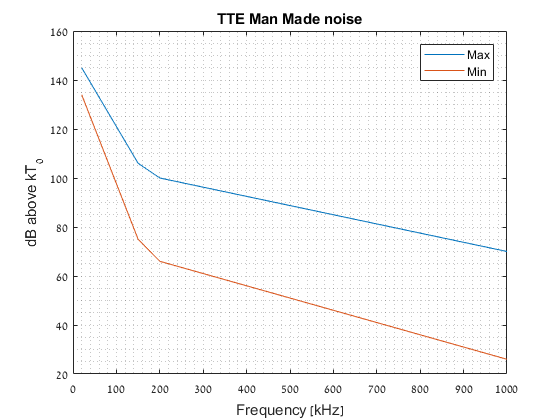
### Noise (Gibson p.158)

The noise sources in the VLF band, other than those related to the communication hardware, are of 2 types; atmospheric and man-made. Conventionally, their spectral density is measured in dB above rather than in pure power spectral density units such as dBm/Hz.

It appears that the atmospheric noise we are used to from radio communication, modeled as white whose power spectral density is is not the one that exists in the VLF band; it is higher than that and reaches the only towards . It is a superposition of Gaussian noise and impulse spikes.



Man made noise measurements results are brought in the same manner



However, they were carried out in the 1970’s and are probably not valid; they should be higher nowadays.

The noise level is, of course, higher on the surface than in the underground which makes the uplink reception tougher than downlink.

To summarize, we can say that TTE noise in the VLF band is not white, decreases with frequency and in general is higher than the RF band atmospheric noise. It may also change dramatically in time (the impulses).

### Waveforms in TTE communication systems

[Raab] from 1995 was the first to relate to the signal processing issue of a TTE communication system. He suggested MSK modulation combined with Adaptive Noise Cancelation.

Little is known on the systems developed within the NIOSH challenge. Two of them are known to have used FSK (Ultra) and PSK (Alertek) modulation. [Brazil] claims that even analog communication techniques were used. No information was given about ECC. [NIOSH] summarizes that the techniques and algorithms used were not adapted to the present (2010) TTE channels that had changed substantially from when they were characterized in the 1970’s, thus reaching performance that was much inferior to the predicted one. The impression is that very little is known on channel impairments as well as noise, and that there isn’t any certainty that the chosen communication and signal processing are the optimal ones.

### OFDM choice

Channel, noise, not known in 2005, flexible, better in dynamic channel, bandwidth is unlimited, disappointing results, MRC, PAPR reduction. Only cost- PAPR; we will reduce it

As mentioned before, the VLF TTE channel models that we have are unreliable. The same can be said on the VLF noise. Moreover, we know for sure that they are frequency selective. Moreover, all previous research and systems were based on the mining industry scenario, i.e; fixed stations with well known mutual positioning, good coaxial orientation of the antennas and possibly well characterized channel. This is not the case in the military scenario; the stations may move and not be optimally oriented to each other.

In general, much less relying on models and a lot more flexibility and much is required from a new technique. Based on all these, and the fact that the traditional communication techniques have provided disappointing performance, we suggest to use OFDM as our TTE communication waveform. It is less sensitive to channel selectivity; corrects quite easily poor channels on the Rx side. It is also flexible on the Tx side enabling selective modulation and coding depending on sub carriers quality. It is also easily combined with Rx diversity MIMO techniques to combat antenna orientation problem. If the channel is highly selective, this might have limited single carrier techniques’ bandwidth. OFDM de-couples the sub carriers and enables theoretically to communicate almost practically bandwidth

The main disadvantage of OFDM is its PAPR which might limit the range. We intend to use signal processing techniques to reduce that too.

# OFDM - General

## Need: Rx & Tx Selectivity

Along the years, communication systems have been challenged to provide higher data rates, to operate in increasingly difficult channel mediums and in increasingly densely occupied spectrum. The NLOS channels, in particular, confronted the communication system with highly frequency selective channels. All of the above created the need to provide waveforms with inherent frequency flexibility allowing both Tx and Rx chain to process the signal in frequency selective manner. The traditional single-carrier technology did come up with means of dealing with these impairments, with equalizers fora example, but this ability was limited to moderately selective channels and frequently did more harm than good

## Evolution of OFDM

OFDM and its ancestors are based on simultaneous transmission instead of serial transmission. A single carrier signal can be expressed as follows:



Where  is the pulse shaping function (usually belonging to the Raised cosine family),  is the n’th data symbol, and  is the symbol time. The separation between the consecutive symbols is in the time domain, and the pulse shaping function is such that enables the extraction of a given symbol form its predecessors and followers.

A multicarrier waveform is expressed as follows:



Where  are called the “sub-carrier” functions and are the data symbols, and  is again the symbol time. Here, the separation is achieved in the frequency domain

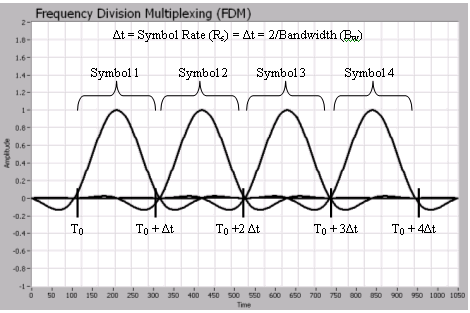
Naturally, in order to transmit the same amount of data symbols;



Hence, we can regard the multi carrier subcarriers as independent single-carrier waveforms, each spanning along a much longer duration in time that their corresponding true single carrier waveform. Longer duration means narrower bandwidth, which suggests why multi carrier waveforms deal better with frequency selective mediums.

### FDM

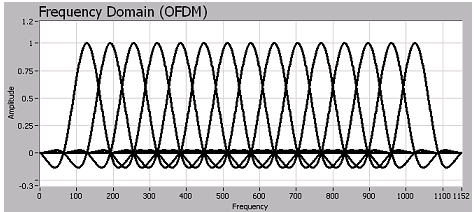
The basic waveform contains several sub carriers spectrally separated from each other. i.e; concatenated in such a way that a simple amplitude (e.g; brick wall, butterworth) filter bank can extract them with no significant loss of energy:



The implementation, however, is rather cumbersome and complex as it requires a bank of analog filters, frequency sources and mixers.

### Analog OFDM

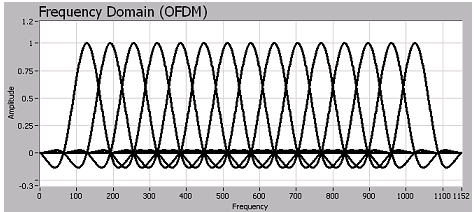
Orthogonal FDM uses the orthogonal Fourier basis for as the subcarrier family. That allows a denser arrangement, hence a better spectral efficiency



The analog implementation remains cumbersome

### Digital OFDM

The digital implementation of OFDM solves that problem of complexity of implementation as the simultaneous modulation/demodulation operations becomes IDFT/DFT operations. Those are naturally realized via the particularly efficient IFFT/FFT algorithms.



## Mathematical representation

### Tx

Additionally, it makes use of the DFT’s cyclic convolution property to easily estimate the channel and efficiently correct it.

### Other advantages

Ease of equalization, ease of channel estimation

## Mathematical representation

### Fourier basis

The complex Fourier basis is:



i.e; a family of functions completing an integer number of cycles within the time span 



They represent an orthonormal set over the interval :

### Transmission

The transmitted signal, is a linear combination of that basis with a QAM symbols stream as coefficients:



Substituting , we get:



The following figure demonstrates that procedure:

The symbol stream: multiplied by the above basis functions gives (real part)



Which look meaningless

### Tx: OFDM operation as IFFT

In discrete time, and the transmitted signal is:

Which is in fact;

### Rx: matched filtering as FFT

The receiver of OFDM has for goal to detect the series of symbols . That operation relies naturally on the orthogonality of the used functions basis, and consists of a filter bank matched to the transmitted one; . If the sampled received signal is , a long vector of time samples, then each of the bank’s branches, say , performs the following operation to extract an estimator of :

, which is in fact

And in general we can say that the whole series is demodulated by performing an DFT over the vector :

## Frequency domain

The frequency domain representation of a the complex Fourier basis function is;

It is a Dirichlet Kernel whose peak is placed at . Each of the kernels in the expression of the transmitted signal, the sum, has it nulls placed at , away from the peak, such that at each peak’s location a single kernel (=subcarrier) is contributing to the sum. Ideally, the DFT samples the DTFT at those peaks only.

It is convenient to regard the main lobe nulls of the leftmost and rightmost subcarrier as the signal’s boundaries. If we:

* observe the signal within instead of
* switch to physical frequency units:

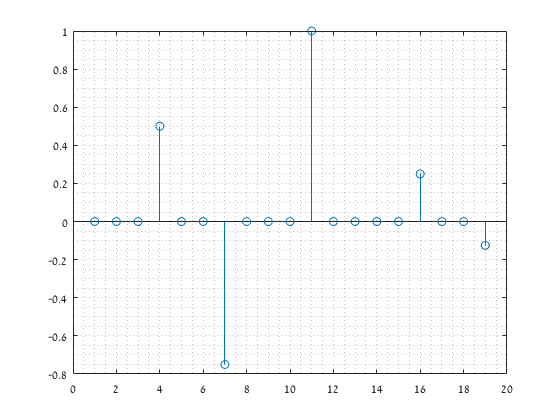
The peaks are at , and the extreme nulls are at and .

### Bandwidth, Fs, guard band, pilots, DC

## Guard Time and CP:

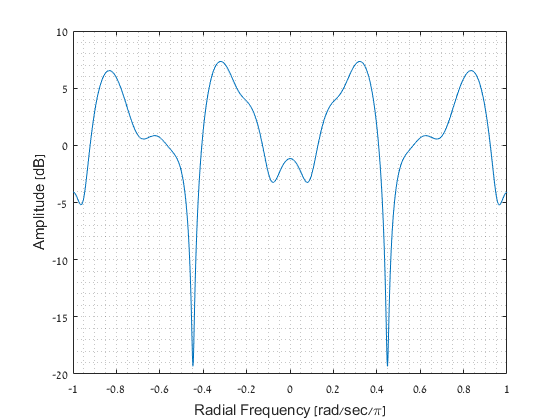
### ISI problem

A wireless channel is commonly modeled as a linear system, , that consists of a series of impulses, taps in the discrete domain;



Whose time domain support, its “memory”, is ;

From a physical point of view, each tap represents an electromagnetic path. In the frequency domain, the transfer function of such channel has the shape;



Such a channel is surnamed “frequency selective”.

If we ignore the addition of noise, the transmitted signal, is convolved with to give :

When 2 OFDM symbols are transmitted consecutively, ;

add visio illustration

The received sample corresponding to the 1st sample of the 1st symbol,, will be:

The one corresponding to the last sample,, will be;

We notice an “inter sample interference”, that we will later see that is harmless.

Since there is no gap between the transmission of the 2 OFDM symbols, the received sample corresponding to the 1st transmitted of the 2nd OFDM symbol, , will be:

The interfering samples this time belong to a different OFDM symbol. This phenomenon is named “Inter (OFDM) Symbol Interference”- ISI.

### Cyclic Prefix (CP): from Linear convolution to Circular convolution

A signal that goes through a wireless channel is enduring a linear convolution (if we ignore the noise addition)

We extend cyclically such that;

Where;

is defined as the cyclic extension, or cyclic prefix of . We assume that and constrain.

This time we transmit 2 consecutive extended OFDM symbols instead of . The linear convolution samples are;

1st sample involving a sample of

Last sample involving only samples of the cyclic extension of :

1st sample involving a sample of , belonging to the DFT block (i.e; that does not belong to its cyclic extension)

Last sample involving DFT block samples

The fact that assures that the vector involves only samples and in fact;

The circular convolution of with the channel.

### Role # 1: Frequency domain equalization

A well-known identity of the DFT transform pair is:

Therefore, suppose the receiver has prefect knowledge of the beginning of the OFDM symbol (say identify on previous section); if we dump the first samples of every OFDM symbol and feed the remaining samples to the DFT block that is part of the basic OFDM Rx chain, we get;

However,

Which is the original N-long QAM symbol series. On the other hand,

Is no other but the frequency domain representation of the wireless channel.

We have at the output of the DFT block;

From the point of view of a transmitted QAM symbol, neglecting the noise, passing through the wireless channel is merely multiplying by a complex scalar. This fact encompasses several benefits of the OFDM comparing to single carrier methods in frequency selective environment:

* Decoupling the QAM symbols from each other
* Ease of equalization
* Use of an already implemented block (the FFT)

### Role # 2: Guard Time- avoiding ISI

Beyond equalization, for a basic functioning of the OFDM Rx chain, the DFT block must operate on time domain samples that originate distinctively from a single transmitted OFDM symbol. Such problem is demonstrated in 2.5.1. For that purpose a Guard Time, a zeros sequence, needs to be inserted between every 2 consecutive symbols, that needs to contain at least samples.

However, we will show below that inserting the CP may resolve that problem too; in 2.5.2 we can see that the sequence is the only part of the received sequence that risks to be contaminated with the previous symbol’s samples. As these samples are dumped anyway, it turns that the CP is an effective Guard Time too

### Role # 3: Preservation of Orthogonality – avoiding ICI (Tse???)

The CP has yet another role. The whole OFDM idea relies on the orthogonality of the basis functions used; this requires that each one of accomplishes cycles across the samples processed in the DFT block. This demand holds also in the case of time-dispersive channel (frequency selective group delay) which may be caused by multipath. In figure ??? we see what can happen when 2 symbols are transmitted continuously. Loosing orthogonality is translated into an Inter Channel Inteference, as every contains some ingredient of QAM symbols other than .

Adding a cyclic extension, if longer than the channel’s delay spread, will resolve that problem too; all sub carriers delayed by all channel’s taps will accomplish integer number of cycles within the DFT processing interval.

## Time synchronization problems [Prasad]

In a typical OFDM receiver, a coarse timing synchronization block is incorporated. Let us assume a remainder of samples in the negative direction; instead of identifying the sequence to be processed by the DFT block as (here do not contain noise), we take the sequence . Let us also assume that; this implies that are not contaminated with previous OFDM symbol’s samples, and are only function of the channel and the current symbol.

Thanks to the cyclic extension concatenated to the left of the correct DFT sequence in the transmitter, the vector is merely a circular right shift of :

Using a known DFT identity, we get:

To give:

Which means that each QAM symbol will still experience a multiplication by a complex scalar, only somewhat different; a linear phase shift from leftmost () to the rightmost .

Since the equalizing task is already consists on a division by a complex scalar, no additional signal processing needs to placed for that purpose.

Still, the two assumptions made at the beginning of the development imply:

* The coarse synchronizer’s remaining error must zero or negative; . To ensure the negativity, a purpose error might be needed.
* The length of the CP must be greater than the maximum timing error added to the maximum channel memory (support) ;

## Frequency synchronization problems: effect on signal (Prasad, NPTEL, my summary)

When a frequency offset between Tx and Rx exists, the time domain received signal after CP dumping takes the form;

Where; , is the normalized frequency offset. The demodulation of such signal takes the form of:

Using the identity , we get;

We can see that in the case , that expression turns into

That we know well.

That expression shows that the DFT samples that DTFT transform of the Rx signal at instead of , and which causes two impairments to the SNR (other than already existing noise):

* The term has a maximum value of 1. This implies a signal level decrease, hence SNR decrease
* Inter Channel Interference: The term is the sum of the oscillations of the subcarriers Dirichlet Kernel other that the at the frequency

## Special subcarriers

### Guard bands

The baseband signal needs to be reconstructed and up converted or even up converted prior to reconstruction. Either way, these 2 procedures require interpolation. A practical interpolator is composed of upsampler and filter; for a reasonable complexity of the filter, some gap is needed between the Nyquist zone boundaries and the signal’s support. Additionally, as seen in 2.5, the leftmost main lobe is placed outside the Nyquist zone, and therefore is aliased.

Therefore, several subcarriers out of the total need to be allocated to zero amplitude subcarriers named “guard bands”.

What did I do in my case?

### Pilots

Some subcarriers are allocated for the purpose of channel estimation, and frequency/phase correction. These subcarriers are named “Pilots”, since they have amplitude and phase known to both transmitter and receiver. There exist several strategies of spreading them along the symbol, but the most common is a uniform spreading.

### DC

The DC subcarrier is allocated a zero in case the OFDM waveform is implemented in a Zero-IF radio. In this case, the LO signal participating in the down conversion is translated to DC frequency

## OFDM Frame

The OFDM frame is a time domain sequence of signal that carries data, and other pieces of information about the transmitter and the channel enabling correct demodulation. Communication standards such as 802.11a are very specific as to the content, the location and the length of the different subsets of the frame (see fig??). In our case, since we are not committed to any standard, there is much more flexibility. We decided to devote non data carrying sequence, the preambles, for timing synchronization, frequency offset estimation and channel estimation. The length of the frame is, among other considerations, dictated by the coherence time of the channel; this influences the validity of the channel information deduced by the receiver.

### Preambles

These sequences that are placed at the beginning of the frame, hence the term “preamble”. They are not standard OFDM symbols and generated differently than the data carrying symbols. The information that they carry is rather primitive but should be demodulated with great accuracy. We can control that accuracy by increasing their length or their power. They usually benefit of low PAPR, thus enabling to raise their verge power without increasing the maximum transmitted power set by the data sequence.

### Long Preamble

The long preamble is placed at the beginning the frame and it carries information from which we may derive the time and the frequency offset between the transmitter and the receiver. The algorithms are based on ideas raised by [Schmidl& Cox] and [Minn& Zeng], and rely on the good correlation properties of the PN sequences family. Its length is proportional to the accuracy of the estimation, hence the term “long”.

### Short preamble

The short preamble is placed right after the long one, and is there for the sake of channel and SNR estimation. It is exclusively composed of pilot subcarriers that are chosen to attain low PAPR, so we can amplify the average transmitted power.

# System, Magnetic and analog devices

This section describes the system engineering of our TTE communication link.

## Block diagram

## Design Concepts

### Software Defined Radio (SDR)

The transmitted signals are in the VLF band, specifically around . Despite the substantial decrease of wavelength in the soil conducting material, these can hardly be called “Radio Frequency” signals as the spatial phase of the signal is practically uniform across the link, as in lumped system. In that sense, the traditional Tx and Rx chains of communication systems consisting of software processed baseband signal connected via data converters (A/D, D/A) to high frequency analog hardware for further processing is cumbersome and totally unnecessary.

Therefore We decided to adopt the concept of Software Defined Radio; that in addition to the OFDM baseband processing, the IF chain will be also entirely realized in software and that the only analog hardware will be the indispensable Magnetic devices, the Tx Amplifier and the anti-aliasing filter required for sampling.

### SIMO 1x3

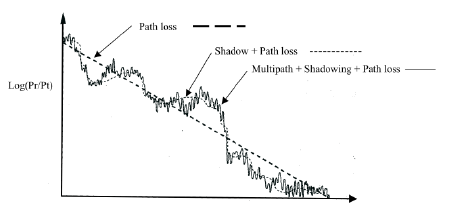
#### Direction sensitivity

We saw earlier (where) 2 options for the mutual orientation of the magnetic devices (the “antennas”) towards each other in terms of magnetic field coupling; the coaxial and less intuitive coplanar. [Gibson] states other orientations that have poorer coupling. In the case of mines when the 2 stations are fixed, it is rather easy to make sure the antennas are oriented as expected. In dynamic scenarios of communicating while moving and bending, it is practically impossible for the underground transceiver to correctly aim the axis or the plane of the surface transceiver.

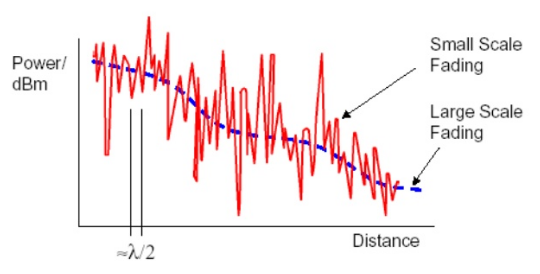
For that reason, we suggest a SIMO 1x3 (1 transmitter, 3 receiver) architecture based on a tri-axis Rx antenna combined with an appropriate signal processing- Maximum Ratio Combining, adopted from the fast fading channels radio channels signal processing.

#### Fading channels

The primary calculation of RSS (received signal strength) is based on the Friis formula, stressing that; . The broken line in the figure expresses that coonection.



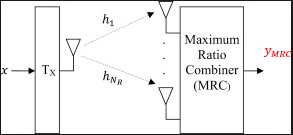
However, this describes well only cases of totally free-space mediums, which are extremely rare. Two other physical phenomenon are needed to explain the true behavior of RSS. The first is shadowing by obstacles bringing to a curve, that oscillates around the Large scale fading curve. It is sometimes named “Medium scale” fading. The other is due to the Multipath phenomenon, and is responsible for “fast” variations around the medium scale fading; its variance with distance is quite large comparing to the medium and large scale behaviors, hence its name; “Small Scale”. It is of an order of . The small scale fading is sometimes called “fast fading” when dealing with dynamic links where distance is linked to occurrence rate of the fading.



A typical receiver experiences the summation of all the three above; the red curve above.

#### SIMO 1x3 architecture and MRC algorithm

The fact that small scale fading is a random process together with the fact that a spatial separation totally realizable creates probabilistic independency gave birth to the architecture of SIMO; single transmitter and multiple receivers. The probabilistic independency makes that spaced RX antennas experience different signal amplitudes with high probability; spatial spacing means channel diversity. In general terms, the more antennas we have the lesser the probability we experience a negative destructive fading in all of them. An algorithm, Maximum Ratio Combining (MRC) that relies on that concept is nowadays widely employed in many communication systems. These communication systems typically operate in the L and S bands and their wavelength therefore is of the order of of centimeters.



This is, of course, not our case if only for the reason of the wavelength. However, we suggest to employ the SIMO concept to combat the problem of antenna orientation. We can suppose that the TTE RSS has a Large/Medium fading behavior and that the orientation problem resulting from movement of one of the stations may result in having a variable intensity with time on each of the axes. The MRC algorithm on his behalf should not change; it still needs to optimally combine the signals from all 3 axes without primarily knowing the one that is best oriented.

## Analog Hardware

The relatively low frequencies on which we operate constrain us to choose hardware and analyze its performance in terms of lumped systems; voltages, currents and fields.

### Magnetic devices

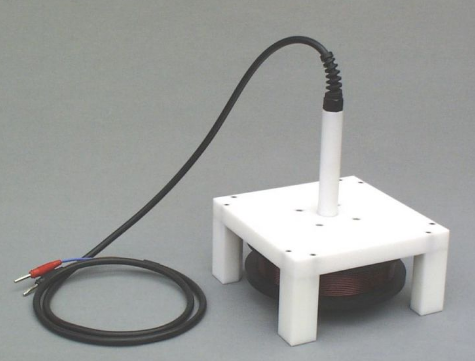
#### Tx

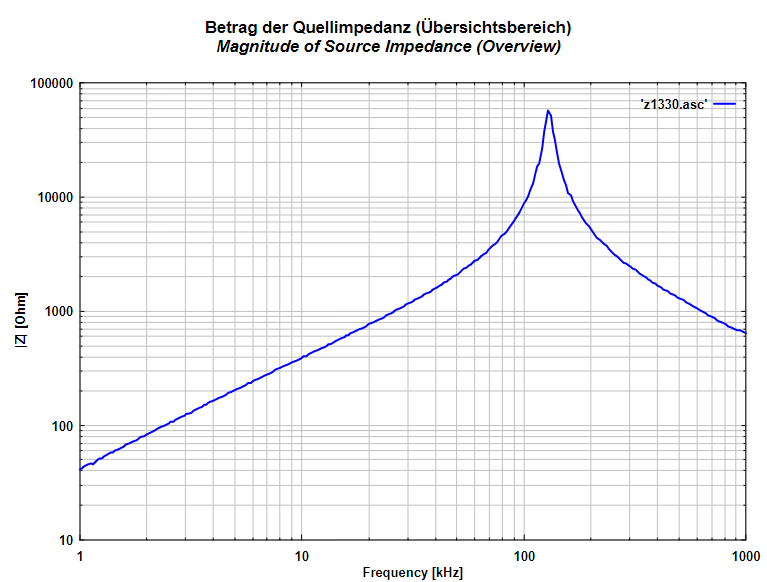
We used 2 radiating coils by Shwartzbeck, that are normally used for immunity testing

* FESP-5135
  + Diameter=0.5m
  + # of windings=20
  + Inductance= 485 uH
  + Frequency range=[0,300]kHz
  + Saturation current= 7 Amps



* FESP-5133 1330
  + Diameter=0.126m
  + # of windings=225
  + Inductance= 6.5 mH
  + Frequency range= [0,20]kHz
  + Saturation current= 20 Amps



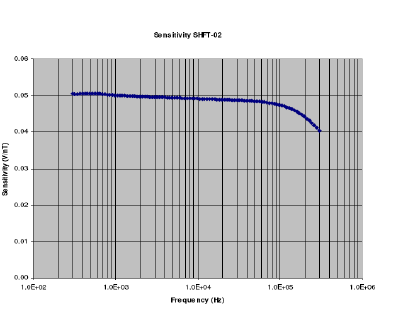


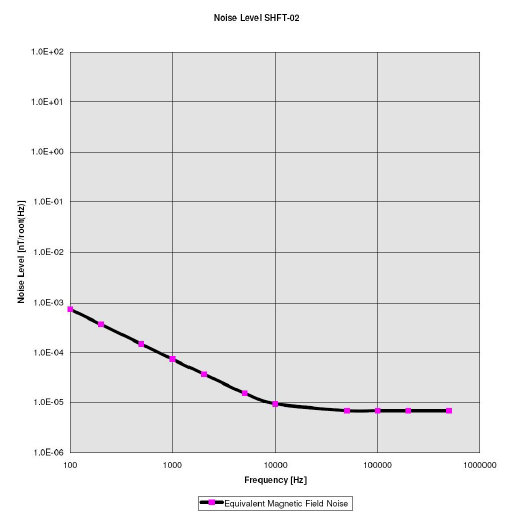
#### Rx

We used the SHFT-02e tri-axis active ( low noise amplifier is included ) magnetic antenna by Metronix:



* Frequency range=[1,300]kHz
* Output Sensitivity= 0.05V/nTesla
* Noise level= 8 nTesla/sqrt(Hz)





### Data Conversion

Because of Matlab to NI interface we need to work in Frames.

#### D/A



National Instruments NI USB-6212

* # of bits =16
* Fs,max=250ksps
* Vout,max=+/-10v

The noise floor level which is more of interest is not mentioned, but since the D/A is followed by a powerful amplifier, the D/A’s noise will have no effect on the total one

#### A/D

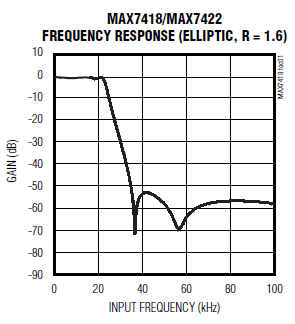


NI-9215 (in a cDAQ-9174 chassis)

* # of inputs=4
* 3 of bits=16
* Fs,max=100 ksps
* Vin,max=+/-10v

#### Reconstruction & Anti-aliasing filters

Maxim MAX7418



Can be used for both post D/A reconstruction filter and pre A/D Anti-Aliasing filter. In our case, since our system is the only one present in that frequency band, an Anti-Aliasing filter is sufficient.

### Tx Amplifier

AE Techron 2105



A high power amplifier. In his voltage output mode:

* Amplification, max=20V/V
* Frequency range=[0,20]kHz
* Vout,max=150 v
* Zout=28mOhm in series with 1uH

## System parameters and expected performance

### IF (Fc, bandwidth)

An important design issue was to choose the center frequency and the bandwidth. Several considerations should be taken into account:

* Channel transmission function
* Noise spectrum
* Analog hardware bandwidth
* Data Throughput requirement

We saw earlier on section 1.3 that the TTE transmission function reached an optimum at around 2.8 skin depths. Yet, [spain] showed that in a practical depth (20-40m) of soil with unknown conductivity the transmission function was monotonically increasing. The noise spectrum is monotonically decreasing. Hence, from these point of views the higher the operating frequency the better.

Data throughput considerations push us to require high bandwidth.

However, the chosen hardware, the Tx amplifier in particular constrain us to the band.

In order to remain well within the devices operating bandwidth without challenging its extremities we decided that:

### Link budget

Work with Setup\_calculations.m to calculate the SNR Ad Kedei VLF noise

### Throughput

## Preliminary measurements

June 2016

# OFDM Parameters

## Frame structure

## Guard bands, pilots

PAPR etc.

## Preambles

## CP

## N FFT

## Length of preambles

## Coding, QAM depth, data bins, needed Tframe

# Transmitter

## Block diagram

### OFDM

### IF

## Preambles enhancement

## PAPR reduction

## Analog HW compensation: inverse sinc, differentiator

AE Techron amp connected to inductor: . If we want to compensate that, can multiply the signal by a coefficient ; a differentiator!

# Receiver:

## Block diagram

## Equalizer types (see findings document)

## Timing synchronization

## Frequency& phase synchronization (=fine frequency correction)

## MRC MIMO

# Data Converters integration:

## Setting the Fs, Frec

## Synchronization

## Frequency error effect on signal integrity. My analysis (summary) and results

# Parameters& Simulations

Parameters: show calculation of Fs, Frec etc.

# Results- Field experiments

# References

[1]

D. Gibson, “Channel characterisation and system design for sub-surface

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Through the Earth Communications for Underground Mines. Carreno, Silva et al

[2] NIOSH – sponsored Research in Through the Earth Communications for Mines: a status report

Through the Earth Mine Communication systems. NIOSH

[3]

Through the Earth Communications: Breathrough solution for Miner safety. Carrol Technology group

# Signal processing for through-the-Earth radio communication, Raab& Joughin

High-Speed Digital System

Design—A Handbook of

Interconnect Theory and Design

Practices

**Amplitude-Probability Distribution Model for**

**VLF/ELF A tmospheric Noise (Field& Lewinstein)**