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Determination of the Underwater Channel Characteristics to Improve a Multiband OFDM Communication

[1]Mahmoud Abdellaoui, [1]Nejah Nasri, [1]Bilel Gassara,
[1]Nacer Kachouri, Mounir Samet and [2]Thierry Val
[1]LETI-ENIS, ISECS-R.Menzel chaker Km 0.5 B.P.868-3018, Sfax, Tunisia
[2]ICARE IUT Blagnac Toulouse-France

Abstract: In this study, transducer system for wireless underwater communication is presented and discussed that utilizes multi-band Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a topic of great interest for wireless underwater communication since it offers the potential of achieving higher transmission data rates compared to single carrier approaches. For wireless underwater communication applications, the frequency dependent attenuation links the maximum available bandwidth with the desired transmission distance. As the problem of bandwidth and a range restriction due to frequency dependent transmission loss and multi-path spreading leads to Inter-symbol Interference (ISI) and large Doppler shifts and spreads (Inter-carrier Interference ICI): these parameters are crucial to improve wireless underwater communication. Additional to the parameters above mentioned, the battery powered network nodes limits the life time of the OFDM transceiver. For thus, the power efficiency is a desirable characteristic for wireless underwater communication. The goal of this study is to survey the determination and evaluation of the parameters of an OFDM transceiver for underwater communication based on the simulated channel characteristics.

Key words: Underwater communication, phenomenological channel model, OFDM, ISI/ICI, bandwidth, transceiver

Introduction

As in each wireless communication systems, the bandwidth allocation is a significant factor to determine the system efficiency. In the case of underwater wireless communication systems, these resources (propagation velocity, frequency band, power consumption, binary speed) are severely limited. The attenuation level depends on the distance and the transmission frequency of the acoustics signals. The bandwidth employed in underwater wireless systems requires also a considerable attention on the data redundancy during the construction of the frames. The underwater wireless communication channel has variable characteristics according to time and strongly depends on the distance between the emitter and the receiver. The propagation velocity of the acoustic waves depends on the local temperature, salinity and pressure in the medium; these three factors vary considerably according with the depth (Urick, 1983). In this study, the propagation velocity of the acoustic signals is 1500 $m\ s^{-1}$. This is very small compared to a propagation velocity of the radio signals in free space is $3.10^8\ m\ s^{-1}$. The underwater wireless communication systems undergo also many effects like: diffraction of the waves and roches, salinity effect of the medium of the propagation conditions, the loss energy by diffusion in volume, the strong levels on noise, effect thermo-cline for systems whose communication is done vertically (on a same level of difference in temperature, the water layer behaves like reflectors)

Corresponding Author: Mahmoud Abdellaoui, LETI-ENIS, ISECS-R.Menzel chaker Km 0.5 B.P.868-3018, Sfax, Tunisia

(Berkhovskikh *et al*., 1982). Surface and sea-bed induce propagation by multiple ways which is a major defect of the wireless communication systems: a multitude of signals arrives at the receiver which must then reconstitute the initial signals. The multiple ways generates an inter symbol interference on the received acoustic signal. To solve the effect of the phenomenon, the multi-carrier modulation OFDM on the encoder block is used instead of the MFSK HADAMARD coding (Scussel *et al*., 1997). The encoder block is composed with general cyclic redundancy check generator concatenated by convolutional encoder, inter-leaver and HADAMARD code generator.

The wireless underwater (WUW) channel differs from radio channels in many respects. The available bandwidth of the WUW channel is limited and depends on both range and frequency. Within this limited bandwidth, the acoustic signals are subject to time varying multi-path, which may results in severe inter-symbol interference and large Doppler shifts and spreads, relative to radio channels. These characteristics restrict the range and bandwidth for reliable communications. Also, since the ocean-bottom instruments are battery powered, power efficiency is a desirable characteristic for WUW. Special attention should be given to these facts when designing a network protocol (Stojanovic, 2005).

The provisioning of energy is a major constraint in underwater wireless systems. This constraint is due to the difficulties encountered to change the batteries of underwater stations. The change of the underwater stations batteries requires the recovery of equipment; this operation takes a significant time, stalls the system and is expensive. For thus, we should optimize the energy consumption and the proposed circuit was designed aimed on the optimized performance of each building block. In fact, the values of the multi-carrier frequencies, transmission distance and power consumption, are crucial to improve the wireless underwater communication.

Under Water Channel Simulations

For the design of such communication systems, the transmission conditions of the underwater medium have to be taken into account. One of the major constraints is the attenuation of acoustic signals in water due geometrical spreading and to frequency dependent absorption. This phenomena is discussed in existing literature in the field of underwater acoustics, but the absorption coefficient to thorp's expressions (Stojanovic, 2005; Coppens *et al*., 1982), aren't taken into account the diffraction, diffusion and dispersion. The achieving efficient communication in the underwater environment is challenging due to severe distortions that affect the transmitted signals as they undergo multiple reflections and refractions in their propagation path. In the other hand, the channel characterization is extremely important in underwater communication because multi-path propagation may induce channel responses lasting hundreds of milliseconds. Unlike terrestrial OFDM applications, frequency-selective channels have to be explicitly considered. For thus, we proposed a modified model that determine the power consumption of the network. By using this model, we can determine the transmission loss within the water medium in dependence on transmission distance and frequency.

The present study discuss modifications done to the mathematical model to represent the under water channel for the underwater wireless communication. Because the bad choice of the channel characteristics restrict the efficiency multi-band OFDM wireless transceiver. Then, we give a description of network design and the method to determine the power consumption dependent transmission loss within the water medium in dependence on transmission distance and frequency by using a proper model.

Phenomenological Model of Underwater Channels

The attenuation coefficient is derived from a variety of factors. A fresh water case will be considered first and the more complicated saltwater case (water mixture: freshwater, seawater and

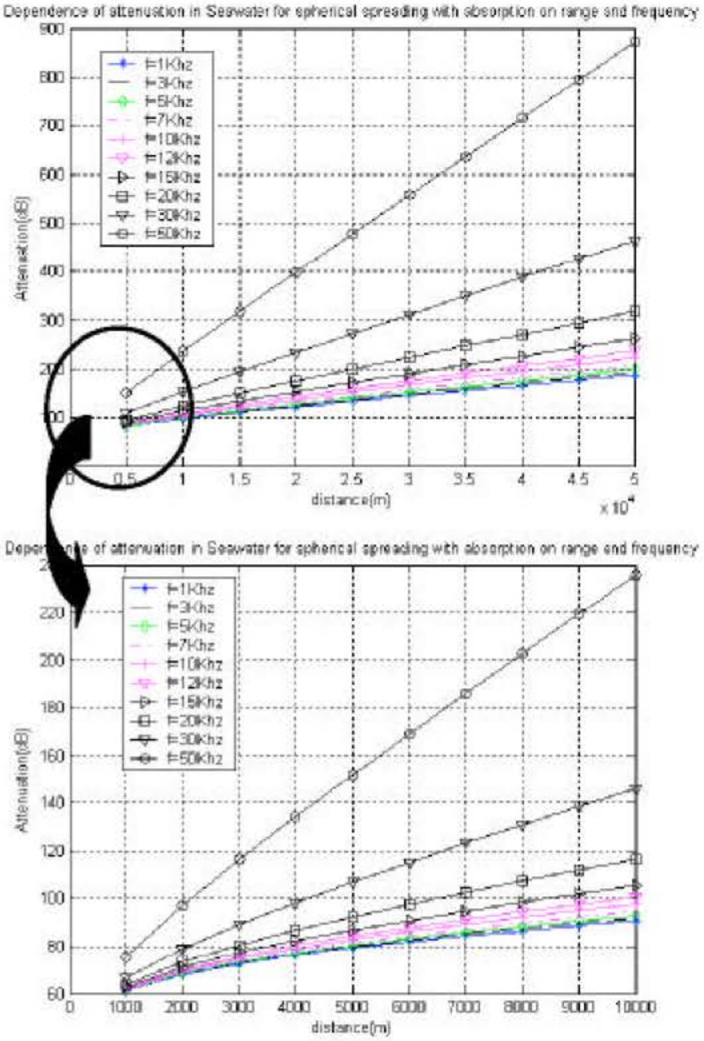


Fig. 1: Attenuation vs distance

chemical products (Magnesium sulfate $MgSO_4$, the Sodium chloride, Boric acid BOH_3 and other molecular compound found in seawater)) will be built on from there, taking in to account both shear and bulk viscosity. A phenomenological underwater channel model based on the Wong method (Wong, 2005) and Coppens method (Coppens *et al*., 1982) together, is the employed model in this study. This modified model represents accurately the sea layer by taking into account the majority of the underwater channel physics parameters. Especially, the diffraction and diffusion effects are not considered in the other models.

So, the transmission loss in underwater channels is defined by the following expression:

$$\mathrm{TL} = \mathrm{ad} + 20\log(\mathrm{d}) \tag{1}$$

Where: TL: Transmission Loss (dB).
a(f): is the absorption coefficient's expressed as following as:

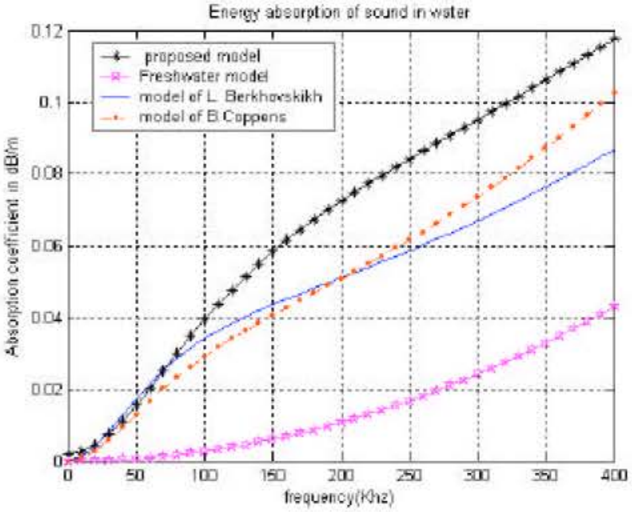


Fig. 2: Absorption coefficient vs frequency of three models

$$a(f)_{(dB/m)} = f^2\left[2.692\times10^{-13} + \frac{7.858\times10^{-2}}{f^2+1.226\times10^{10}} + \frac{1.481\times10^{-4}}{f^2+1.522\times10^{6}}\right] + 0.0018 \qquad (2)$$

d: is the transmission distance (m).
f: is the sub-carrier frequency (Hz).

Under Fig. 1, we deduct that the attenuation variation is directly proportional to the distance between the two communicating nodes (Emitter/Receiver) and the transmission loss difference for various frequencies is significant:

For the low frequencies (from 1 to 20 KHz), the path loss is less than 120 dB for a distance varying from 1 to 10 Km and do not exceed 300 dB for a distance of 50 km.

For the high frequencies (more than 20 KHz), for a distance of 50 km, the path loss achieve 900 dB at f = 50 KHz and 450 dB at f = 30 KHz. For thus, we limit to low frequencies.

Figure 2 shows the absorption versus frequency for a few underwater channel models. The proposed model, seeing that's taken into account all sorts of the underwater channel physics parameters and effects, have an absorption coefficient larger than the other models.

Network Design and Power Consumption

An underwater acoustic communication network is considered which consists of a large number of nodes operating in a shallow water environment at a depth of approximately 50-100 m (Proakis, 1995). In this study, the nodes that are mounted on the bottom (at depth = 1000 m; consequently the propagation velocity is assumed at 1500 m s^{-1}) are replaced by an Emitter/Receiver which are separated by distance d that must be determined precisely. The network is constrained by power consumption, because the acoustic modems are battery powered, as are the sensor processors. The goal of the network design is to achieve a good trade off between the quality of service and the power consumption. In particular, a good quality of service includes maximum information (maximum available bandwidth) through output at minimum delay with the desired transmission distance. One of the network design goals is to minimize the power consumption while providing reliable

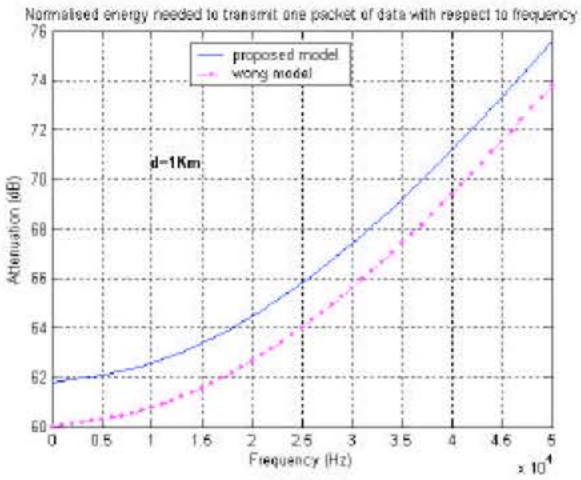


Fig. 3: Normalized energy needed to transmit one packet of data with respect to the frequency

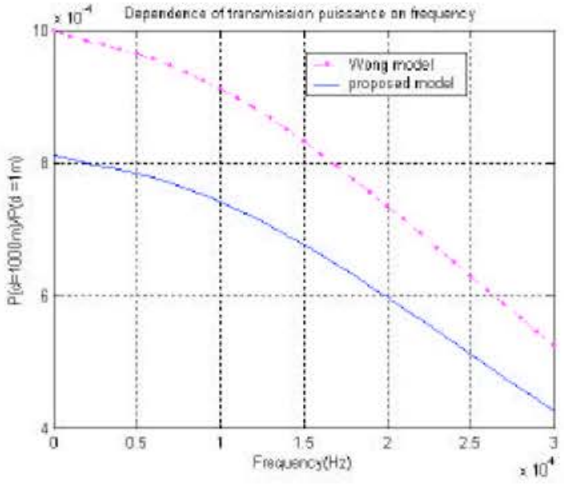


Fig. 4: Dependence of transmission puissance on frequency for range = 1 km

connectivity between the emitter and the receiver. To quantify the power consumption of the network, we investigate a simplified case in which emitter and receiver are arranged linearly. To determine the energy needed for transmission of a single data packet of duration T_p from an emitter at distance d to the receiver, we assume that a required quality of reception is achieved if the received power level is P_0. To achieve a power level P_0 at the input to the receiver at distance d, the transmitter power needs to be $P_E = P_0 \times TL\ (f, d)$, where TL (f, d) is the transmission loss calculated at distance d in meter for f in Hertz. To transmit a data packet from emitter to receiver over a distance d, the total consumed power from transmission is:

$$E = P_E \times T_p = P_0 \times T_p \times TL\ (f, d). \tag{3}$$

The transmitted data packet, who's formed the frames, has realized by the media access protocol based on the modified version of the Multiple Access with Collision Avoidance protocol (MACAW),

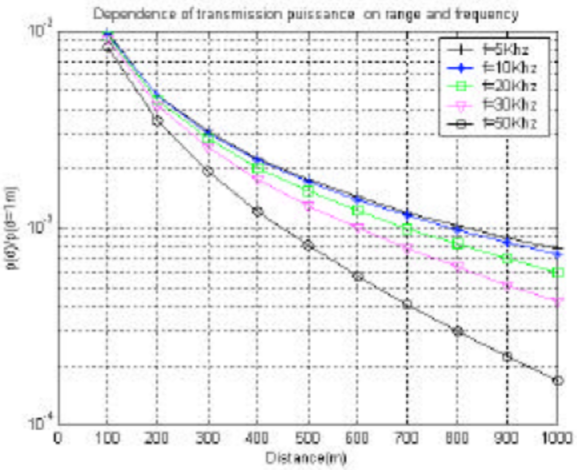


Fig. 5: Dependence of transmission puissance on frequency and range

which uses Request to Sent (RTS), Clear to Sent (CTS), data exchange. The carrier since multiple access with collision avoidance protocol appears efficient and adapted for underwater communication. This protocol can be associated with the RTS/CTS option to resolve the hidden node problem. We notice, when no activity is detected on the channel, the emitter waits for an inter-frame space and senses the medium again. And when the medium remains free, the emitter emits the data packet over the channel. If the medium is busy, the emitter waits for a random time before actuating the described above for transmitting the data packet.

Figure 3 shows the attenuation graph according to the frequency and the distance of 1 Km. The emission power required to transmit a packet of data decrease to any great extend (ratio of 10^{-3}) with many frequencies, for a distance of 1 km. For transmitting the packet of data from emitter to receiver, the total energy received and detected by the receiver after 1Km is 0,1mW for the emission power is 0,1 W.

Figure 4 presents the standardized energy (E/P_0T_0) according to the frequency of transmission to transmit one packet of data between the emitter and the receiver.

Figure 5 presents the normalized energy according to the distance with many frequencies.

Figure 6 shows the consumed power from transmission with the desired distance and frequency. In this simulation, the total sensor data rates is taken into account for two different values: 2400 and 100 bits/s. The protocol whence the received probability of the correct packet is considered at 0,96; consequently and according to the input data rates, each packet is retransmitted (2,5/1,2/0,31/0,1) times.

Figure 6a represents the consumed power that's varying to 100 mW with 2400 bits/s input data rates, in which emitter and receiver are arranged linearly and are separated at distance d = 1000 m, for the depth of approximately 1000 m.

In Fig. 6b, we preserve the same circumstances of simulation, but we reduce the input data rates to 100 bits/s and the depth to its shallow value 100 m. Therefore the maximum value of the consumed power is 42 mW.

Bandwidth, ISI, ICI and Their Influence on the OFDM Transceiver Performance

For wireless underwater communication application, the frequency dependent attenuation links the maximum available bandwidth with the desired transmission distance. The available bandwidth of

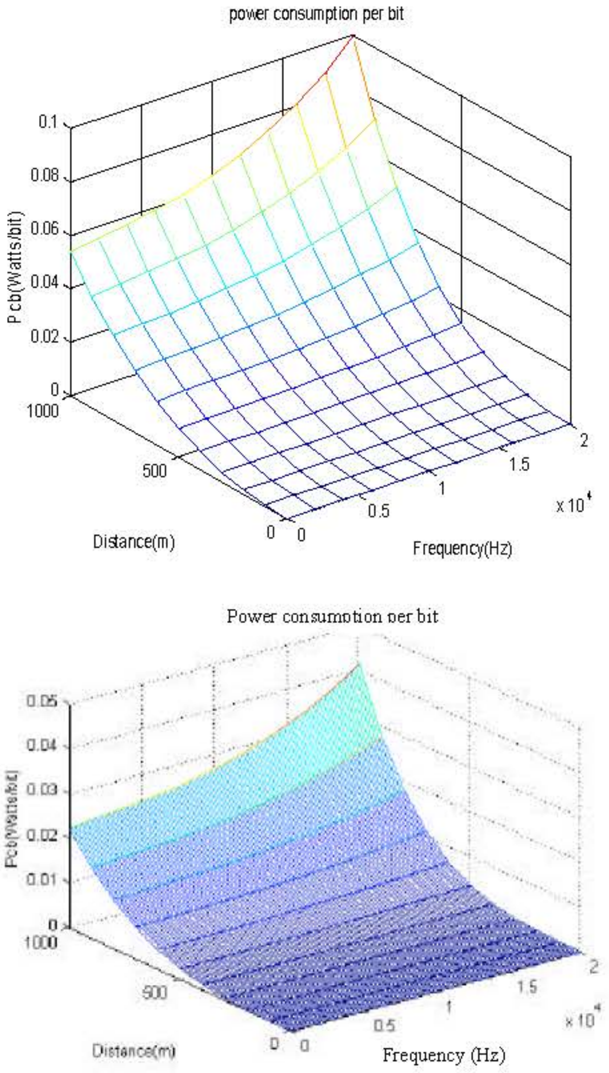


Fig. 6: Consumed power with transmission distance and frequency

the underwater communication channel is limited and depends on both range and frequency. Within this limited bandwidth, the acoustic signals are subject to time varying multi-path, which may result in severe inter-symbol interference and a large Doppler shifts and spreads, relative to radio channels. These characteristics restrict the range and bandwidth for reliable communications. Additional to the bandwidth and a range restriction due to frequency dependent transmission loss, multi-path spreading leads to inter-symbol interference, where subsequent transmitted symbols can overlap in time at the receiver position. Furthermore, deviations from the nominal carrier frequencies of the OFDM modulation, caused by Doppler, can lead to an over lap of the sub-bands of the OFDM signal which is called inter-carrier interference. Both ISI and ICI can have significant influence on the receiver performance. Both effects increase the Bit Error Rate (BER) in the communication link. Thus, modulation schemes for underwater communications must combat multi-path effects for optimum performance. Above all, we present the main considerations to choose the used OFDM structure. Then, we present an approach for estimating and determination the bandwidth of the OFDM transceiver taken into account the ISI and ICI effects.

Design Considerations and OFDM Transceiver Structure

Calling in of sum advanced (characteristics) for OFDM communication: Multi-carrier modulation performs well in dispersive channels as aquatics channels. When combined with guard interval and cyclic prefix, OFDM eliminates inter symbol interference and inter carrier interference and overcame fading by using forward error correction coding. The channel estimate can be incorporated in to a soft decision Viterbi decoder in a bit-interleaved coded modulation fashion to get more coding gain and have the system operate in lower signal to noise ratio. In a multi-band OFDM system, OFDM symbols are interleaved along different frequency bands, hence yielding frequency diversity as well. Another advantage of OFDM is its capability to capture multi-path energy with a simple fast Fourier Transform, where rake correlator fingers should be used to exploit multi-path diversity.

In the Estimator for carrier frequency offset in an OFDM system, slot elements in an OFDM block symbol are weighted in terms of their received energies.

On the subject of the Peak to Average Power Ratio (PAPR) of a multi-carrier signal, we emphasize that low values of the autocorrelation coefficients represent only a sufficient condition for a small value of the PAPR of the signal. Therefore, the autocorrelation coefficients of the generating sequences cannot serve as a basis for comparison of PAPR of the corresponding signals.

The phenomena of the Inter-Carrier Interference (ICI), caused by Doppler spreading in an OFDM system when the angle of arrival of the received signal is not uniformly distributed, can be taken into account. An expression of the ICI power is derived by taking into account the probability density function of the AOA (Bingham, 1990).

Significant Doppler shift may be induced in acoustic wave forms event by relatively slow emitter/transmitter motion caused by waves and currents. Performance studies for terrestrial OFDM have shown that accurate tracking of average Doppler is required to ensure low Inter-carrier Interference (ICI). Average and differential Doppler compensation has not been studied in detail for single-carrier communication, but it will likely play an important role in underwater OFDM system. An approach based on simple ray propagation models will be used to predict the evolution of Doppler in each path and guide the tracking algorithm (Gomes *et al*., 2004; Barroso, 2004).

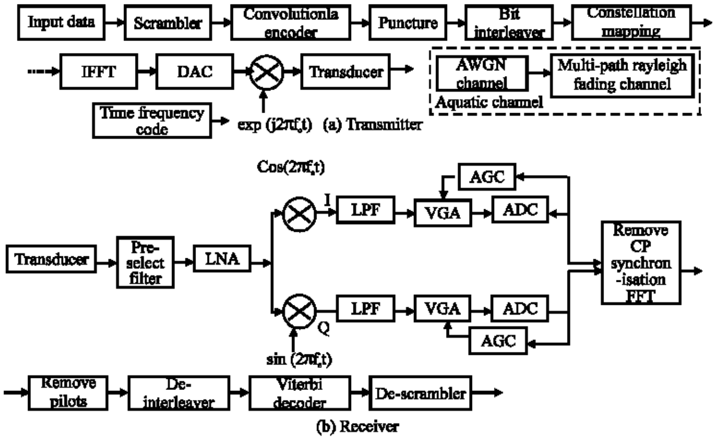


Fig. 7: The multi-band OFDM UWB transceiver for the underwater communication

Considering all the design considerations above-mentioned and in accordance with the simulation parameters results that can be used as initial values for this wireless communication, our proposed multi-band OFDM UWB wireless transceiver of underwater communication is shown in Fig. 7.

The proposed system will have: a scrambler to make data look random eliminating long runs of ones and zeros as well as repetitive patterns. A convolutional encoder to realize the error correction coding scheme. An interleaver to spread burst errors in time. A QPSK modulation mapper to achieve higher bit-per-symbol. Time frequency codes are utilized to interleave data sequences in different bands, there by achieving spread-spectrum communications. An important concern regarding the multi-band OFDM UWB wireless transceiver for the underwater communication is its requirement of a transducer at the transmitter side. This transducer allows to transform electrical waves into sound waves and inversely. It is directly connected to an AWGN channel (added noise to the useful signal) and multi-path Rayleigh fading channel.

Simulation Results and Discussion

After the determination of the transmission loss within the water medium in dependence on transmission distance and frequency by using a proper model. And by considering that the most important characteristic of UWB system is its capability of operating in power limited regime which his value is estimated and determined above mentioned. Then, using Shannon's equation for the channel capacity (Shannon 1949):

$$C = B\log\left[1+\frac{BS_0}{BN_0}\right] \text{Bits/sec} \tag{4}$$

Where C is the channel capacity (Bits/seconds)

B is the available bandwidth (Hz)

S_0 is the signal power spectral density (watt/Hz)

N_0 is the noise single side (watt/Hz)

In addition to the transmission loss, we also defined a Rayleigh random variable that represents fading. When received power of a packet is calculated, two Gaussian random variables with zero mean and unit variance are generated and the Rayleigh fading coefficient is calculated. The resulting number is multiplied by the received power after loss. Since we make this calculation for the entire packet, this is equivalent to simulating a quasi-stationary channel.

The background noise of the system is fixed throughout the simulations. Under the simulation results of relative Signal to Noise Ratio (SNR) versus frequency (from 0 to 20 KHz) with several transmission distance (d = 1 km, d = 5 km, d = 10 km, d = 50 km and d = 100 km) that's in completely harmony and in a good agreement with Stojanovic simulation results (Stojanovic, 2005), so the SNR's varying between 70 and 50 dB from a maximum distance of 10 km, with several frequencies from 1 to 20 KHz. As for that, the noise level is calculated to achieve 70 dB SNR at maximum range. This SNR level ensures 10^{-3} Bit Error Rate on AWGN channel and multi-path Rayleigh fading.

And we consider, for a UWB wireless underwater communication, the bandwidth will likely be much higher than the data rate, so that the system can operate at very low Signal to Noise Ratio (SNR). This means that a UWB wireless underwater communication network will be able to achieve high data rates with relatively low transmit power. A key point is that in this regime, the capacity increases almost linearly with power, whereas in the bandwidth limited regime (high SNR), capacity increases only as the logarithm of signal power (which means that a linear increases in data rate requires exponentially more power). This fact also highlights the importance of a power efficient modulation format in the design of a UWB system. The disadvantages of the approach that the power efficiency

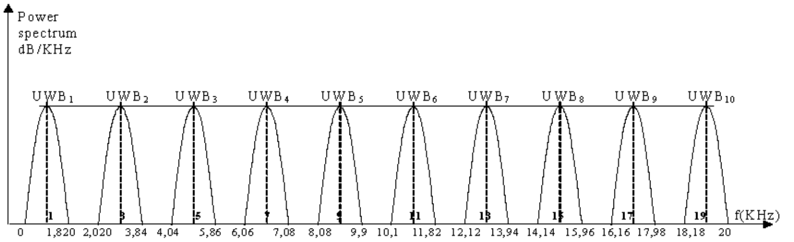


Fig. 8: The band plan for the multiband OFDM UWB wireless underwater communication

Table 1: OFDM channel characteristics

Transmit power (mW)	SNR (dB)	BER	Multiplying factor $[1+BS_0/BN_0]$	Channel capacity (Bits/s)	Band-width (Hz)
100	70 dB for f = 1 KHz at d = 1 km	10^{-3} for $E_s/N_0 = 18$ dB	1.135	100	1820
			1.462	300	1820
			4.564	1200	1820
			20.830	2400	1820

directly translates to a corresponding reduction in throughput. In addition, the use modulation improves BER performance under multi-path conditions using more robust techniques to combat fading and ISI. This modulation product to be a robust scheme for underwater data transmission. In the encoder block used in this study, the HADAMARD code increases the effective receiver BER by providing additional coding gain. The coding gain, provided by the HADAMARD code, allows one or two tones to fade without significant impact on the receiver BER. The HADAMARD scheme provides a significant decrease in BER for increasing levels of SNR per Bit. ISI is reduced only by providing a mechanism to avoid symbol overlap due to multi-path delay. Considering all the indications above mentioned, the results of OFDM underwater communication parameters, with the channel characteristics, are summarized in the Table 1.

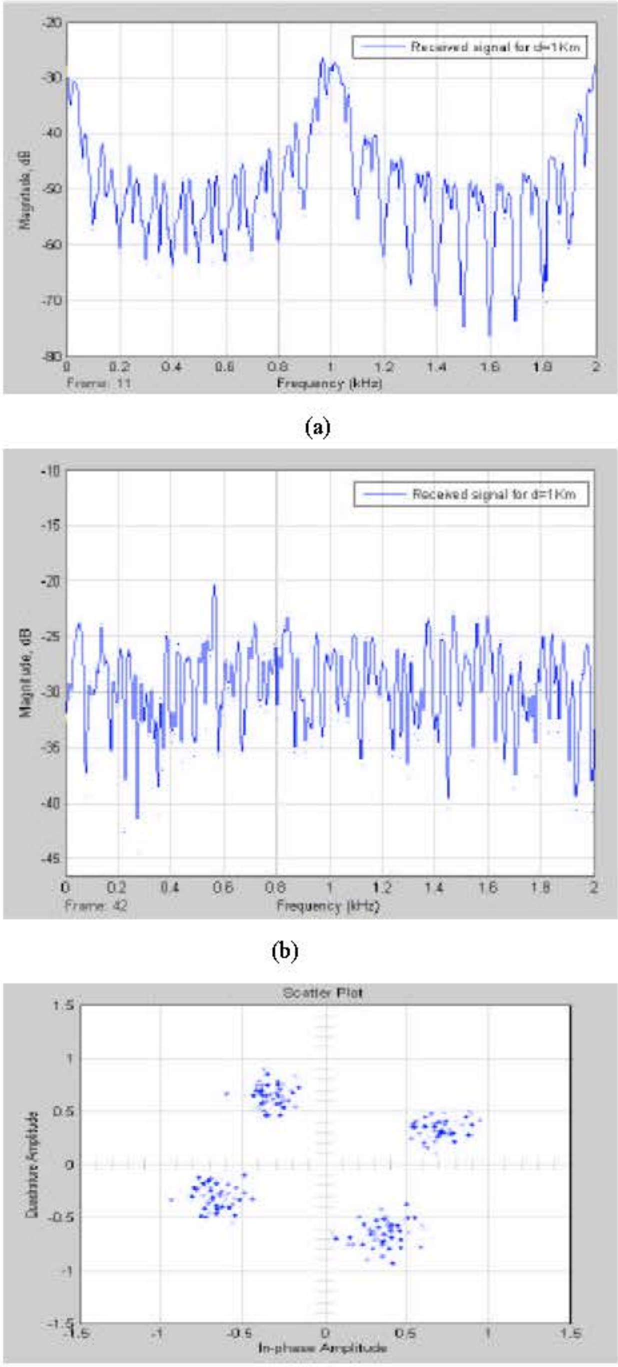
In this OFDM transceiver, the whole (0-20) KHz bandwidth is split up into 1820 Hz sub-bands (10 Ultra-Wide-Bands) with 200 Hz guard interval. Single carrier (central frequency) is employed in each sub-band, as illustrated in the Fig. 8.

In OFDM modulation for wireless UWB underwater communication, the message stream is divided into many parallel lower rate streams that modulate a set of partially overlapping orthogonal carriers. Since longer symbols are less sensitive to multi-path equalization (using a time frequency code or a highly complex filters,...) requirements may be considerably relaxed on each sub-carrier.

The OFDM underwater communication system for middle distance (d = 1 km) is based on the use of QPSK modulation and the encoder block, which is composed with general cyclic redundancy check generator concatenated by convolutional encoder, inter-leaver and HADAMARD code generator, to achieve the high bandwidth efficiency.

Figure 9a shows the received signal of one carrier among the tens used in the OFDM Wireless underwater communication, through the underwater channel that's represented with AWGN channel and Multi-path Rayleigh Fading channel. This response represents a party of the transmission data, arrives along a many clearly defined ways different of one another.

Figure 9b represents the received signal, in the case, how the Doppler coefficient increases (using in the MATLAB modeler tool: toolbox) and the HADAMARD coding provides a significant decrease in the BER for increasing the level of the SNR; in a way, we decrease the value of the added noise to the useful signal and we increase the multi-path Rayleigh Fading channel, seeing that, the underwater channel is represented with AWGN channel and multi-path Rayleigh Fading channel.



(a)

(b)

(c)

Fig. 9: Received signal for 1 km transmission distance and constellation scope for QPSK modularion

Figure 9c shows the constellation scope for QPSK modulation with the multi-path and the noise effects: instead of to have condensed points, we have a scatter of points. The recognizable rotation of the QPSK constellation is due to the multi-path spreading leads to ISI, where subsequent transmitted symbols can over lap in time at the receiver's position. Furthermore, deviations from the nominal carrier frequencies of the OFDM modulation, caused by Doppler, can lead to an overlap of the sub-bands of the OFDM signal (ICI effects).

Conclusions

This study provided a comprehensive study of a multi-band OFDM UWB wireless transceiver for underwater communication. Our contribution consists in the determination of the important parameters to get better the wireless underwater communication by using a phenomenological underwater channel model. Furthermore, the multi-band OFDM UWB transceiver was studied by using an optimal structure.

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