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Two-Dimensional Spreading waveform for Adaptive Rate Acoustic Underwater Communication

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Abstract—Autonomous Underwater Vehicles (AUVs) are becoming a part of the ocean navigation ecosystem, and their applications deal with seafloor mapping, channel sounding, surveillance, submarine volcanism survey or mine warfare. During a mission, it is of great importance, through a reliable acoustic wireless communication link, that ships or surface buoys receive live data from an AUV and exchange information data with it. Furthermore, the communication range can vary during a mission. Thus, this paper addresses the challenging topic of designing a modem, to transmit information; to an AUV, by emphasizing on the adaptivity and robustness of the link. The designed modem combines multi-carrier signal and 2D spreading and is called MC-SS-2D. A variable length spreading sequence combined with OFDM creates a flexible design that uses frequency diversity, time diversity and adds a processing gain to transmit at various distances. The modem was tested using rayleigh channels as well as experiments in a water tank and at sea using the IROMI platform.

Index Terms—AUV, MC-SS, Doppler, Underwater Acoustic Communications, Doppler filter bank, Adaptive bit rate, 2D spreading, at sea transmissions

I. INTRODUCTION

Recent advances in underwater technology enabled the use of AUVs for both civil and military applications [1]. Most application of AUVs deal with seafloor mapping, channel sounding, surveillance, submarine volcanism survey or mine warfare. Through a reliable acoustic wireless communication link, AUVs collect live data or exchange information data with ships or surface buoys. Communication requirements are very dependent on the target application and the associated scenario. For example, military applications need secure "private" communication link for the data confidentiality or security particularly when the data is highly sensitive. Furthermore, an underwater acoustic modem should be reliable and robust for efficient transmission and information exchange. Underwater acoustic channel is often considered as one of the harshest communication medium because it is characterized with time-variable multipath propagation [2]. In addition to

this, available bandwidth is usually very limited and the latency is large [3]. During mission, distance between ship or buoy and AUV may vary. Therefore, the modem should be able to adapt its parameters to fit the situation and keep a robust communication. We propose to use spreading codes as part of the downlink broadcast from the buoy to the AUV, thus creating a private communication channel. Knowledge of the spreading sequence (SS) is required to communicate directly with the AUV. Spreading codes also help making the communication more reliable and less affected by jamming. By changing the spreading factor (SF), a processing gain can be added making the communication more robust at low SNR. In this paper, a multi-carrier spread spectrum with 2D spreading (MC-SS-2D) downlink modem for AUVs applications is presented. MC-SS-2D combines spreading and multi-carrier signal. It is a generalization of the MC-SS modem using spreading only in the frequency domain [4], [5]. Adding a variable length SS to an OFDM signal, creates a flexible solution that provides frequency diversity, time diversity and adds a processing gain to transmit at various distances. In this paper, the MC-SS-2D modem emitter and receiver are described as well as the methods used for channel and Doppler estimation. Furthermore the modem performances are tested using a multipath blockfading channel. Finally, results from transmissions in a water tank and at sea are analysed.

II. SYSTEM MODEL

A. Multi-carrier spread spectrum

Depending on the mission or real scenario, distance between the buoy and the AUVs can vary a lot ranging from less than a kilometer to tens of kilometers. Therefore, the modem needs to be able to adapt its characteristics in such a way that the communication between the buoy and the AUVs stays stable and reliable. Multi-carrier spread spectrum (MC-SS) combines spreading and multi-carrier signal. Multiple combinations of spreading and OFDM have been proposed [4], [5]. To have both frequency and time diversity, the proposed modem uses a 2D OVFSF spreading code \mathbf{C} [6]. Coding matrix \mathbf{C} has a size

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of $Q \times M$ where M designs the SF in the time domain and Q is the SF in the frequency domain. Q must be a divisor of the number of subcarriers K . Thereby, $I = \frac{K}{Q}$ QPSK symbols can be sent on 1 MC-SS-2D symbol.

$$\mathbf{C} = \begin{pmatrix} c_0 & \dots & c_m & \dots & c_{M-1} \\ \vdots & & \vdots & & \vdots \\ c_{qM} & & c_{qM+m} & & c_{qM+M-1} \\ \vdots & & \vdots & & \vdots \\ c_{(Q-1)M} & \dots & c_{(Q-1)M+m} & \dots & c_{QM-1} \end{pmatrix} \quad (1)$$

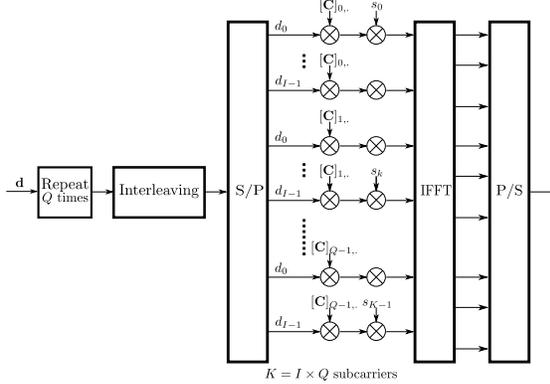


Fig. 1. MC-SS 2D transmitter structure.

MC-SS-2D transmitter structure is shown in figure 1, where $\mathbf{d} = [d_0, \dots, d_{I-1}]$ represents I QPSK symbols for 1 MC-SS-2D symbol, K is the number of subcarriers, $[C]_{q,l}$ is the q^{th} line of \mathbf{C} and $\mathbf{s} = [s_0, \dots, s_{K-1}]$ is a scrambling code. As one can be shown in figure 1, QPSK data symbols $\mathbf{d} = [d_0, \dots, d_{I-1}]$ are first repeated Q times and then interleaved. Interleaving is used to maximize the distance between two chips of the same QPSK symbols in the frequency domain (the distance between two symbols d_0 in Fig. 1 for instance) and therefore to increase the frequency diversity. Indeed, frequency diversity is present if channel coefficients affecting two chips of the same data symbols are independent. Each of K subcarriers is then multiplied by one line of the matrix \mathbf{C} . The spreaded symbols are scrambled with a complex sequence \mathbf{s} before being modulated on different subcarriers using inverse FFT. With this scheme, the SF can be modified in both time and frequency domains giving this scheme flexibility in how it uses time and frequency diversity. Furthermore, setting $M = 1$ or $Q = 1$, scheme of the MC-SS waveform with spreading only in the frequency domain or time domain is obtained. If both M and Q are equal to 1, an OFDM waveform is obtained. Figure 2 represents the corresponding receiver structure. After FFT, received signal for 1 MC-SS-2D symbol is given by:

$$r_{k,m} = d_{k\%I} c_{\lfloor \frac{k}{I} \rfloor M+m} s_k \check{h}_{k,m} + w_{k,m} \quad (2)$$

where $k \in \{0, \dots, K-1\}$ is the subcarrier index and $m \in \{0, \dots, M-1\}$ is the time index representing all OFDM

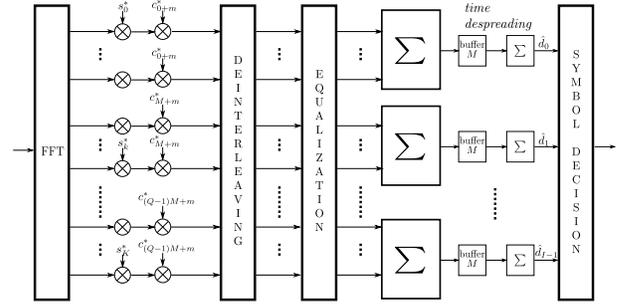


Fig. 2. MC-SS 2D receiver structure.

symbols for 1 MC-SS-2D symbol, $\%_0$ is the modulo symbol and $\lfloor \cdot \rfloor$ is floor function. Function $\check{h}_{k,m}$ is the frequency response of the channel affecting one subcarrier and $w_{k,m}$ is an additive noise. To retrieve QPSK symbols, 5 steps are needed. First, received signal is multiplied by conjugate of the scrambling code. Then, to perform the despreading process, each subcarrier is multiplied by the conjugate of the correct spreading code. Before summing in frequency and time to despread the signal, subcarriers are reordered and equalized. Like in OFDM, equalization is done by multiplying each subcarrier by conjugate of channel frequency response. Channel estimation is detailed in section II-C. Finally despreading is done in the frequency domain by summing Q subcarriers and in the time domain by summing M consecutive OFDM symbols.

B. Doppler Estimation

In underwater acoustic communications (UAC), the Doppler deeply affects the received signal. Unlike radio communications, in UAC, Doppler not only creates a shift of the carrier frequency but also a time compression/dilatation [7]. Doppler d for a constant speed v between transmitter and receiver can be approximated by:

$$d = 1 - \frac{v}{c} \quad (3)$$

The method described in [7], [8] allows one to jointly estimate the Doppler, detect and synchronize the signal. This method uses a pilot signal and a bank of matched filters. Each filter in this filter bank is a unique time compression/dilatation of a pilot signal. By correlating the filter bank with the received samples, Doppler can be estimated as equal to the compression/dilatation of the filter with the maximum correlation peak. Once estimated, Doppler is compensated by resampling the signal. This maximum correlation peak can be used for synchronization but also for detection by comparing it to a threshold defined by CA-CFAR method [9]. The pilot signal is generated in a similar way as the data signal and is therefore a MC-SS symbol with $M = 1$. To increase its difference with the data signal, a distinctive scrambling sequence is used for the pilot signal. The frame structure is a pilot signal followed by MC-SS symbols. Using this method, the modem

can estimate a Doppler speed v up to $\pm 10\text{m.s}^{-1}$. Currently, the Doppler factor is estimated once per frame and supposed constant during the frame. This may need improvement and will be discussed in part V.

C. Channel estimation

As shown in figure 2, channel needs to be equalized on each subcarrier. Channel estimation is realized using complex pilots p . Pilots are allocated to subcarrier in both time and frequency as depicted in figure 3. The number of pilots in the frequency and time domains should be chosen according to respectively the coherence bandwidth and the coherence time of channel.

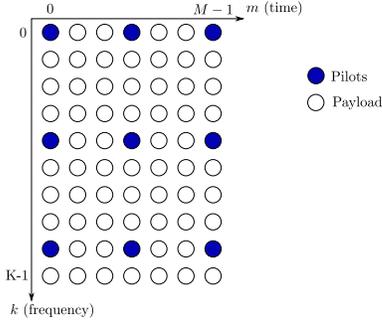


Fig. 3. Pilots repartition

Using a least-square (LS) method, $\hat{h}_{k,m}$ can be estimated on pilot subcarriers as follows:

$$\begin{aligned} \hat{h}_{k_p, m_p} &= \frac{r_{k_p, m_p} C_{\left[\frac{k_p}{T} \right] M + m_p}^* S_{k_p}^*}{p} \\ &= \frac{p \check{h}_{k_p, m_p} + w_{k_p, m_p}}{p} = \check{h}_{k_p, m_p} + \eta_{k_p, m_p} \end{aligned} \quad (4)$$

where k_p and m_p are the frequency and time indexes of subcarriers containing a pilot and η_{k_p, m_p} is an additive noise. To obtain an estimated of channel frequency response for data subcarriers, an interpolation is performed. Since 1 MC-SS-2D symbol needs to be received to retrieve data, interpolation is done in 2D using both time and frequency knowledge. Once interpolated, $r_{k,m} \hat{h}_{k,m}^*$ realizes channel equalization.

III. SIMULATION USING BLOCKFADING RAYLEIGH CHANNELS

The MC-SS-2D waveform was tested and compared to the MC-SS waveform on a multi-path Rayleigh block fading channel. While this channel is not representative of an UAC, it is helpful to compare the modem performances with theoretical BER (bit error rate).

A MC-SS-2D is composed of M OFDM symbols. For each OFDM symbols, an impulse response is generated independently from other impulse responses. One impulse response is composed of ℓ_h independent coefficients generated at chip time where each coefficient represents a path and its magnitude in time follows a Rayleigh distribution. Knowing the distribution of the channel, the theoretical error probability can be

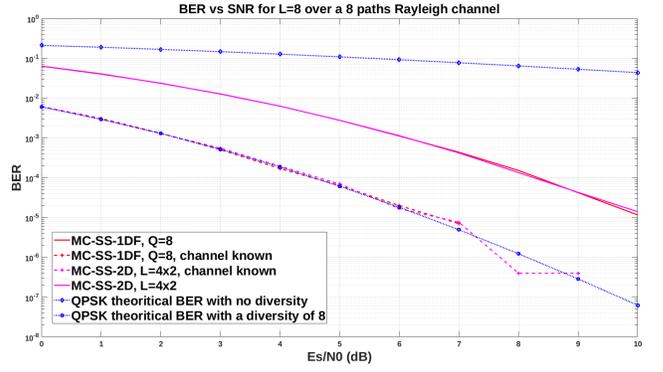


Fig. 4. Simulation results over a 8 paths Rayleigh block fading channel with a spreading factor of $L = 8$

derived. It corresponds to the probability error on a Rayleigh channel using a diversity of L . Therefore, according to [10]:

$$P_e = \left[\frac{1}{2} \left(1 - \sqrt{\frac{\gamma}{1+\gamma}} \right) \right]^L \sum_{\ell=0}^{L-1} \binom{L-1+\ell}{\ell} \left[\frac{1}{2} \left(1 + \sqrt{\frac{\gamma}{1+\gamma}} \right) \right]^\ell \quad (5)$$

For the simulations on the Rayleigh block fading channel, different spreading factors have been tested. A 2D OVFSF spreading code [6] was used for the MC-SS-2D waveform. MC-SS-2D and MC-SS were both simulated with channel knowledge and channel estimated with a least-square estimation using dedicated subcarriers as pilot. With channel knowledge, MC-SS-2D performances are equivalent to equation (2) as displayed in Fig. 4. Results shows that MC-SS-2D and MC-SS have similar performances with a small spreading factor as seen in Fig. 4. However, as the spreading factor increases, MC-SS-2D shows better results by distributing its chips in both frequency and time domain. Indeed, with a large spreading factor, distance between two chips of the same data symbol for the MC-SS waveform becomes smaller than the coherence bandwidth impacting the frequency diversity. MC-SS-2D solves this issue thanks to its flexibility.

IV. TRANSMISSIONS IN A WATER TANK

A. Experiment setup

The MC-SS-2D waveform has been validated through experimentation in a water tank. Sound file containing MC-SS-2D data signals were generated. No channel coding was added. Furthermore, pilot signals were regularly inserted in order to estimate the Doppler factor (and carrier frequency offset) and to synchronize the receiver. Fig. 5 and 6 shows the communication chains used for the transmitter and receiver. For those transmissions, the modem parameters must be choosed wisely especially the length of the cyclic prefix. Indeed, the water tank being small, there are a lot of strong reflection meaning that the delay spread can be quite long. Fig. 7 shows the impulse response in the water tank. As one can see, its impulse response is quite long and a delay spread

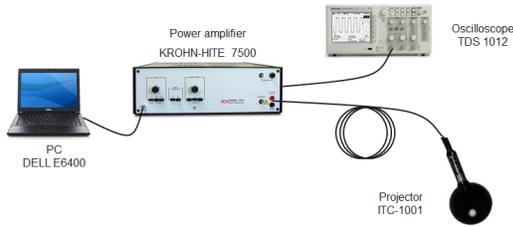


Fig. 5. Transmitter acoustic communication chain

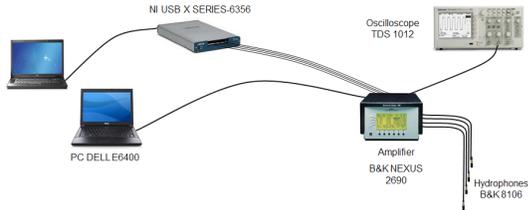


Fig. 6. Receiver acoustic communication chain

of around 30ms is present. Thus, the cyclic prefix should be longer than 30ms.

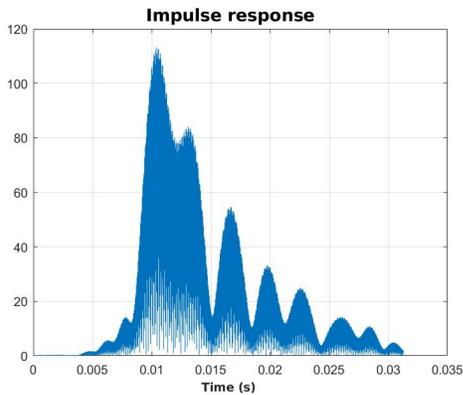


Fig. 7. Water tank impulse response

B. Results

Spreading factor ($Q \times M$)	BER	Bit rate (bps)	bits sent
OFDM	0.1	2460	1230336
4×2	0.0072	410	204928
4×4	0.00033	246	122880
16×4	0	71	35424

TABLE I
BER OF THE TRANSMISSIONS IN THE WATER TANK

Table I shows the results obtained for 3 different spreading factors and an OFDM signal. For each spreading factor, a 500s file is being sent. Signals are transmitted on a carrier frequency of $25.05kHz$ and with a bandwidth of $8kHz$. A SNR of approximately 8db was observed. It was computed by measuring the power without and with the signal. As expected, the larger the spreading factor is, the better are the

performances. Furthermore, results obtained are encouraging as channel coding could remove the last few errors obtained. In this case scenario, results show concrete improvement over OFDM. The proposed waveform shows flexibility and robustness. It can adapt to a wider range of channel than MC-SS by exploiting both time and frequency diversity. Results on a Rayleigh block fading channel shows that theory error rate are reached when channel estimation is perfect. Performances with large spreading factors are better with MC-SS-2D compared to MC-SS. Finally, tests in a water tank show promising results. In order to validate the modem, further performances tests were made at sea using the IROMI platform.

V. TRANSMISSIONS AT SEA

A. LMAIR-IROMI platform

The "laboratoire marin d'acoustique et d'imagerie de la rade" (LMAIR) or Maritime laboratory for acoustic and imaging of the roadstead of Brest consist of 3 relocatable marine platforms [11]. Each platform is equipped with 5 hydrophones, 4 HTI96-MIN hydrophones working in the 20-30kHz bandwidth and one HTI99-HF operating from 2Hz to 250kHz. It also has an acoustic source Neptune D26BB (10 - 50 kHz). Each platform can therefore act as a transmitter or SIMO receiver. They also have solar panels that allows them to 6 minutes of transmissions every hour. Furthermore, an authorized user can access each platform individually by logging into a specific web page. From that page, he can upload a wav file and either start the receiver or the transmitter. The LMAIR aims to be an experimental laboratory that can be accessed at any time. This laboratory would be situated at the sea test base near Brest, France. While the platform is not currently available all the time, a test drive experiments was setup for a few days. This allowed us to realize some transmissions at sea with the presented modem. 2 buoys were deployed at sea according to Fig. 8 with a distance of 1772,26m

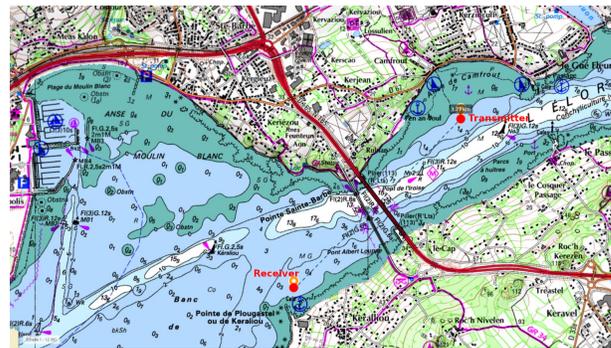


Fig. 8. Buoy position at sea

The transmission conditions met during the experiments were very rough. As seen on the Fig. 8, transmission are done in very shallow water (depth less than 10m) meaning a lot of strong multipath were expecting. After the first tests, the main bottleneck for the modem was found to be the Doppler spread

which was greater than 10Hz. Weather also was not kind with wind above 100km/h.

B. Results

The modem was adapted to handle these transmissions conditions as best as possible. The number of subcarriers was chosen to handle the Doppler spread by increasing the subcarrier spacing. The parameters used were the following:

- 21-29 kHz frequency passband
- 128 subcarriers leading to a 62,5Hz subcarrier spacing
- 12ms prefix cyclic
- 60 to 120s transmissions
- No error correction is added

While the buoy are not moving, Doppler is still expected due to sea movement and slight carrier offset. Therefore, the method to synchronize the signal and estimate the Doppler must be regularly used. In order to regularly estimate the Doppler and keep synchronization, the signal structure presented in Fig. 9 was used.

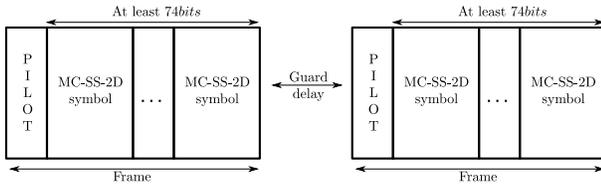


Fig. 9. Signal structure

In Fig. 9, each frame has as many MC-SS-2D symbols as necessary to have at least 74 bits. Each frame starts with a signal pilot. This pilot is an OFDM symbol. It uses 512 subcarriers and a different scrambling sequence. Using this pilot signal, the receiver can realize the synchronization and the Doppler estimation. Using 512 subcarriers creates a longer pilot (around 76ms). Some tests were realized using a pilot signal with 128 subcarriers but detection and synchronization were too unstable. Each frame is separated by a 28ms guard delay.

Table II shows some of the results obtained during this week of testing. 3 sensors were used on the receiver. For the transmission where $L = 16 \times 16$, power was divided by 2 to test transmission at lower SNR. Transmissions lasted 60s except for $L = 16 \times 16$ which lasted 120s.

$L = Q \times M$	BER 1	BER 2	BER 3	bits sent
OFDM	0.3695	N/A	0.0698	130000
2×2	0.00055	0.0012	0	51264
4×2	0.0402	0.0521	0.00042	28480
4×4	0.0026	0.0048	0	15520
8×1	0.07	0.4643	0.0074	28480
16×16	0.2546	0.0061	0.0385	1976

TABLE II
BER OF THE TRANSMISSIONS AT SEA

During the experiment, a Doppler speed varying between $-1m.s^{-1}$ and $1m.s^{-1}$ was measured. For the OFDM transmission, on the second sensor, some frames were not detected and

a BER could not be obtained. OFDM without coding cannot properly receive the signal, hence the high BER. Results show that the modem can work at sea. Near free error results were obtained with a spreading factor as little as $L = 2 \times 2$. There are however a few points that can be improved. First results can drastically change by using one sensor or another. Hence, SIMO seems like a mandatory addition to the modem. Furthermore, while the pilot signal provided a solid estimation of the Doppler factor, the modem did not have anything to follow the evolution of the Doppler during a frame. For small spreading factor, this did not affect performances since the Doppler was not changing enough. However, for larger spreading factor, it significantly increased the BER. For instance, for the first sensor with $L = 4 \times 4$, removing all doppler estimation barely changes the result. A method to follow the evolution of the Doppler would greatly improve results for bigger spreading factor. While these results are interesting to test the proper functioning of the modem and study its current limitations, they are not helpful to compare different spreading factors. Indeed, they are far too many inconsistencies within the testing conditions:

- Channel always changes and can be more favorable to one transmission
- Unexpected boats can cut the communication link
- Hydrophones failures

Tests realized in a control environment such as a water tank or a simulation are for more accurate to compare performances between 2 spreading factors.

VI. CONCLUSION

In this paper, a modem designed for AUVs applications is presented. This modem combines multi-carrier signal and 2D spreading. The obtained waveform is called MC-SS-2D and is a generalization of the MC-SS waveform. A variable length spreading sequence combined with OFDM creates a flexible design that uses frequency diversity, time diversity and adds a processing gain to transmit at various distances. Modem performances were compared to theoretical ones using a multipath blockfading Rayleigh channel. The modem was also experimentally studied using a water tank and at sea using a platform called LMAIR. Results in a water tank shows the effectiveness of SF to improve the error rate at low $\frac{E_s}{N_0}$. Robustness and adaptivity of the modem is interesting for AUVs applications where the communication needs to be reliable even if the communication range vary. The modem looks to yield near error free performances during transmissions at sea with small spreading factors despite having no channel coding. Some limitations of the current design were revealed by the tests on the LMAIR platform especially the lack of Doppler tracking. Further potential improvements for this modem such as channel coding and improving Doppler tracking are being looked upon.

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