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To cite this version:
Christophe Bernard, Pierre-Jean Bouvet, Antony Pottier, Philippe Forjonel. Multiuser Chirp Spread Spectrum Transmission in an Underwater Acoustic Channel Applied to an AUV Fleet. Sensors, MDPI, 2020, 20 (5), pp.1527. 10.3390/s20051527. hal-02903378

HAL Id: hal-02903378
https://hal.archives-ouvertes.fr/hal-02903378
Submitted on 21 Jul 2020

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Multiuser chirp spread spectrum transmission in an underwater acoustic channel applied to an AUV fleet

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Abstract: The objective of this paper is to provide a multiuser transmission technique for underwater acoustic communication in the framework of Autonomous Underwater Vehicle (AUV) fleet. By using a variant of an Hyperbolically Frequency Modulated (HFM) signal, we describe a new family of transmission techniques called MultiUser Chirp Spread Spectrum (MU-CSS) that allows a very simple matched filter based decoding. These techniques are expected to provide good resilience against multiuser interference while keeping good robustness to the Underwater Acoustic (UWA) channel impairments like Doppler shift. Their implementation for the UWA scenario are described, and performance results over a simulated shallow water UWA channel are analysed and compared against the conventional Code-Division Multiple Access (CDMA) and Time-Division Multiple Access (TDMA) transmission. Finally, feasibility and robustness of the proposed methods are verified over the underWater AcousTic channEl Replay benchMARK (Watermark) fed by several channel responses from sounding experiments performed in a lake.

Keywords: Underwater communications; multiple access; chirp spread spectrum; direct sequence spread spectrum; code division multiple access (CDMA); time division multiple access (TDMA).

1. Introduction

The UWA channel is one of the most challenging channels for data communications. Due to the low celerity of acoustic waves \(c = 1500 \text{ m.s}^{-1}\), UWA channels are characterized by extensive multipath effects and large Doppler spreads. Moreover frequency dependent attenuation, temporal variations and background noise limit the achievable data rate considerably [1][2]. On the other hand, AUVs are used for several marine applications such as in military field with anti-submarine warfare, science field with wreck exploration, or in industrial field with offshore energy research. Nowadays the concept of several AUVs working together within a fleet is an on-going research axis [3]. UWA communication with an AUV fleet is used to control vehicles (downlink) or to gather data from vehicles (uplink). The quality and reliability of communications is essential, mainly in shallow water areas for which the multipath effect is stronger, leading to extensive intersymbol interference.

Multiuser communication protocols in an UWA channel can be divided into two categories, random or deterministic protocols. In random protocols, data rate cannot be predicted in advance due to the phenomenon of collisions between different users. A classical examples of random protocol is ALOHA [4] and its variants [5] which use the long propagation delays to reduce the number of collisions and consequently to increase the data rate. An other example of random protocol is the Carrier Sense Multiple Access (CSMA) method [6] which is based on channel listening to avoid collisions. On the other side, deterministic protocols perform deterministic assignments of channel resources to the users so that their activity on the channel is predictable. The method we propose in
this paper aims at building a new set of mutually orthogonal waveforms to be assigned to the users
of an UWA channel, so as to separate them easily at the receiver side. This falls consequently in the
class of deterministic protocols. Traditional methods for deterministic, multiuser, UWA transmissions
are inspired by radio communications and adapted to the UWA channel. As examples, we can
cite the TDMA [7], Frequency Division Multiple Access (FDMA) [8], CDMA [9] and Multi-Carrier
Code-Division Multiple Access (MC-CDMA) [10] transmissions. Typically, FDMA is considered
inefficient since UWA channel has limited bandwidth and exhibits large Doppler spread that requires
guard frequency bands between users leading to data rate wasting. MC-CDMA transmission schemes
suffer from both time/frequency selectivity of UWA channel and multiple-access interference, and
require complex iterative equalizers. Consequently, in the following we will focus only on TDMA and
CDMA multiple access strategies. TDMA allows several users to share the same frequency channel by
dividing the signal into different time slots. Each user uses alternatively its own time slot to transmit
data without interfering with other users. However, as the number of users increases, the waiting
time per user increases and the user data rate decreases. In CDMA transmission, the different users
transmit information data simultaneously through a different spreading sequence for each user. The
disadvantage of this method lies in the multiuser interference provided by the non-orthogonality
of spreading sequences especially when the user communication channel is selective in time or in
frequency. Moreover such effect is increased when the interference power is much larger than the
received signal power. This phenomenon is well known in mobile communication networks as the
near-far problem. To cope with interference terms in CDMA, advanced equalization schemes can be
invoked, such as multiuser detection [11] or Multi-User Multiple-Input Multiple-Output (MU-MIMO)
technique combined with Passive Phase Conjugation (PPC) [12], but at the prize of an higher decoding
complexity and a limited number of users. Recently, the authors of [13] proposed an alternative of
CDMA and TDMA by using chirp waveforms for UWA multiuser communication. To reduce the
multiuser interference, the Virtual Time Reversal Mirror (VTTRM) technique is used with a Fractional
Fourier Transform (FrFT) at the reception. However, this method requires an estimate of the different
channels and is limited to 4 users because of interference.

In this paper, we describe a new transmission scheme based on Chirp Spread Spectrum (CSS)
entitled MU-CSS that we originally introduced in [14]. The basic idea consists in building a set of
mutually orthogonal chirp-based waveforms which will be resistant to Doppler spread and Doppler
shift. The objective is on the one hand to take benefit from the robustness of chirps against UWA
channel impairments and, on the other hand, to use orthogonality to separate multiple users at the
receiver side, using a simple matched filter. With respect to [14], we derive three new methods to build
MU-CSS that optimize mutual orthogonality between waveforms. By assuming an uplink scenario
where a fleet of $N_u$ AUVs in motion needs to transmit data to a receiver situated at the sea surface,
we provide performance comparison of each method over simulated and experimental replay channels.

The paper is organized as follows: System model and state of the art of multiuser transmissions
are introduced in Section 2. The proposed MU-CSS multiuser schemes are presented in Section 3.
Performance results of the proposed schemes against conventional multiuser transmissions are carried
out in Section 4 by using shallow water UWA channel simulator derived from [15,16] and in Section 5
by using Watermark replay channel [17] fed by experiments conducted in Ty-Colo lake, Saint-Renan,
France. Finally, conclusions are drawn in Section 6.

In the following, $|| \cdot ||_2$ denotes the euclidean norm, $\langle , \rangle$ the scalar product, $\mathbb{E}\{ \cdot \}$ denotes the
statistical expectation, $(\cdot)^*$ the complex conjugate and $u * v$ denotes the convolution product between
$u$ and $v$. 
2. Multiuser transmission

2.1. System model

2.1.1. Transmitted signal

Let $d_{i,k}$ be the $k$-th symbol transmitted by the $i$-th user, we assume that $d_{i,k}$ belong to a unit-amplitude Phase Shift Keying (PSK) alphabet, and are differentially encoded such that:

\[ d_{i,k} = d_{i,k-1} \cdot b_{i,k} \quad \text{with} \quad i \in [1, N_u], k \in [2, N_s] \]  

where $b_{i,k}$ is the original PSK data symbol, and $d_{i,0}$ is set to 1. Beforehand, the data symbols $b_{i,k}$ are protected by a Forward Error Correction (FEC) code followed by a random interleaver. In the following, the FEC code type will be an half-rate convolutive code with code generator $(133, 171)$. Moreover, $N_u$ denotes the number of users and $N_s$ the number of data symbols per frame. The choice of Differential Phase Shift Keying (DPSK) is motivated by the rapid fluctuation of UWA channel and thus allows to avoid the use of channel equalizers at the receiver side, which are sensitive to outdated channel estimations [18]. Thus, in a UWA communication channel with large delay spreads and rapid time variations, differential modulation are demonstrated to provide interesting performance and even outperform coherent modulation under certain conditions [19].

Let $g_i(t)$ the transmit waveform associated to user $i$ and $T_s$ the symbol duration, the baseband transmit signal for user $i$ can be written as:

\[ s_i(t) = \sum_{k=1}^{N_s} d_{i,k} g_i(t - kT_s) \]  

2.2. Underwater multiuser channel

By assuming that users are mobile with relative motion $v_i$, positive values of $v_i$ denote motion away from the receiver, while negative values denote motion toward the receiver, the received baseband signal is given by:

\[ r(t) = \sum_{i=1}^{N_u} \int_{-\infty}^{+\infty} h_i(\tau, t) s_i((1 - a_i)(t - \tau)) e^{2\pi f_c a_i(t - \tau)} d\tau + n(t) \]  

with $f_c$ the carrier frequency and $a_i = \frac{v_i}{c}$ the Doppler scale factor. The UWA channel impulse response for the $i$-th user at time $t$ is denoted by $h_i(\tau, t)$ and $n(t)$ represents the additive noise assumed Gaussian and zero-mean.

2.2.1. User decoding

When the Doppler shift can be estimated at the receiver, the Doppler effect is usually removed prior to decoding by resampling the received baseband signal and compensating phase rotation as follows [1]:

\[ z_i(t) = r \left( \frac{t}{1 - a_i} \right) e^{-j2\pi f_c a_i(t - \tau)} \]  

By assuming perfect time synchronization, information data of the $i$-th user can be estimated by matched filtering $z_i(t)$ with the transmitted waveform of user $i$, followed by integration over a symbol duration [20]:
\[
\hat{d}_{i,k} = \max_{k \frac{T_s}{2} \leq t \leq k \frac{T_s}{2} + \frac{T_s}{2}} \left[ \int_{-\infty}^{+\infty} g_i^*(-u)z_i(t-u)du \right] 
\]

\[
= \int_{-\frac{T_s}{2}}^{\frac{T_s}{2}} g_i^*(t)z_i(t+kT_s)dt 
\]

\[
= \gamma_{i,k} d_{i,k} + \eta_{i,k} + w_{i,k} 
\]

where \( \gamma_{i,k} \) denotes the bias of the decoder, \( \eta_{i,k} \) the multiuser interference terms and \( w_{i,k} \) the additive noise terms, exact expression of these three terms is provided in the appendix A.

### 2.3. Conventional multiuser transmission schemes

#### 2.3.1. CDMA

The objective of CDMA is to break up a finite transmission spectrum so that multiple users can access it at the same time. To accomplish time multiplexing, a code, chosen in a set of mutually orthogonal spreading codes, is assigned to each user [21]. For the \( i \)-th user, the transmitted waveform is expressed by:

\[
g_i(t) = c_i(t) = \sum_{l=0}^{N_{SF}-1} c_{i,l}\phi(t-lT_c) 
\]

with \( [c_{i,1}, c_{i,2}, ... , c_{i,N_{SF}}] \) the spreading code of length \( N_{SF} \), \( T_c \) the chip duration, \( N_{SF} \) the spreading factor and \( \phi(t) \) the pulse shaping filter chosen as a Square Root Raised Cosine (SRRC) filter [20]. Since, we are in an uplink scenario, CDMA system is asynchronous, and spreading codes are chosen as Pseudo-Noise (PN) sequences generated pseudo-randomly such that their autocorrelation functions tend to Dirac functions as \( N_{SF} \) grows, so that the mutual cross-correlation tends to zero.

At the receiver side, if \( T_s > \tau_{\text{max}} \) where \( \tau_{\text{max}} \) denotes the Root Mean Square (RMS) channel delay spread, and if the communication channel is constant over a symbol duration \( T_s \), the autocorrelation properties and quasi-orthogonality between users of PN codes leads the term \( \eta_{i,k} \) in (7) to become negligible compared to \( \gamma_{i,k} \) and thus allow to decode each user separately [20].

#### 2.3.2. TDMA

![Figure 1. Scheme of TDMA.](image)

In a TDMA approach, the users are time-multiplexed as depicted in Fig. 1. The time slot assigned to one user is made of a frame slot of \( N_uT_s \) seconds followed by a guard interval of duration \( T_g \) so as to absorb multiuser interference. In order to deal with frequency selectivity of the UWA channel, Direct Sequence Spread Spectrum (DSSS) signalling with the same modulation parameters as CDMA is chosen for each user such that TDMA and CDMA approaches are equivalent in the single user scenario. The baseband received signal and the decoding process are given by particularizing (2) and (8) respectively with \( N_u = 1 \). One can note that more spectral efficient transmission scheme could be chosen for TDMA (see [22] for example) but at the price of higher complexity at the receive side. Moreover, higher spectral efficiency signaling scheme would make difficult the comparison with CDMA especially in the single user case.
3. MU-CSS scheme

3.1. Generalities

By the use of frequency swept signals, which are resilient to the detrimental effects of the UWA channel, the CSS modulation technique offers robust performance with a very simple matched filtering-based decoder that makes such a communication scheme particularly adapted to the UWA communication channel [23,24]. In the CSS system, a broad spectrum is occupied to modulate the information in order to achieve high processing gain and multipath resolution to the detriment of the spectral efficiency. In the following, we construct 3 multiuser schemes based on CSS signaling and more precisely on HFM signal given by:

\[ x(t) = \begin{cases} \cos(-2\pi(k \log(1 - \frac{t}{t_0}) + \frac{f_h + f_l}{2})) & \text{if } -\frac{T_s}{2} \leq t \leq \frac{T_s}{2} \\ 0 & \text{otherwise} \end{cases} \]  

(9)

with \( t_0 = \frac{T_s (f_h + f_l)}{f_h - f_l} \), \( k = \frac{T_s f_h f_l}{f_h - f_l} \), \( f_i \leq f_h \) and \( T_s \) the duration of the HFM signal, whose instantaneous frequency is provided in figure 2 with \( f_h = B/2 \) and \( f_l = -B/2 \) where \( B = 4 \text{ kHz} \) and \( T_s = 7.75, 15.75, 31.75 \text{ ms} \).

![Figure 2. Instantaneous frequency of HFM waveform with BT<sub>s</sub> = 31, 63, 127.](image)

The basic idea of MU-CSS consists in building an orthogonal basis of signals \( e_i(t) \) thanks to the Gram-Schmidt process where the waveform \( e_i(t) \) is assigned to \( i \)-th user with \( i \in \{1, N_u\} \). The initial orthogonality between waveforms is brought by the combination of the HFM signals with orthogonal spreading sequences that are chosen as a Walsh-Hadamard codes [21]. The set of spreading codes allows users to be differentiated at the receiver side while HFM waveform provides robustness against Doppler and delay spreads.

3.2. MU-CSS Gram-Schmidt Iterated

In this method, an iterative process is used to improve the mutual orthogonality between the chirp waveforms, as well as the immunity against channel impairments.

Let \( e_i^{(l)}(t) \) denotes the waveform corresponding to the \( i \)-th user with \( i \in \{1, 2, ..., N_u\} \) at iteration \( l \in \{1, N_{IT}\} \). The process is based on the Gram-Schmidt method [25], as follows, for \( i > 0 \):

\[ e_i^{(l)}(t) = c_i(t) + a_i^{(l)} e_i^{(l-1)}(t) \]  

(10)
where:

\[
a_i^{(l)} = -\frac{\langle c_i(t), e_{i-1}^{(l)}(t) \rangle}{||e_{i-1}^{(l)}(t)||^2_2} = -\frac{\int_0^{T_s} c_i(t)e_{i-1}^{(l)}(t)dt}{||e_{i-1}^{(l)}(t)||^2_2}
\]  

(11)

with \( c_i(t) \) given by equation (8). At the first iteration, we set \( e_0^{(l)}(t) = x(t) \) where \( x(t) \) is defined in (9) and for \( l > 1, i > 0 \):

\[
e_i(t) = e_i^{(l-1)}(t)
\]  

(12)

The final waveform assigned to each user is obtained after \( N_{IT} \) iterations of the above mentioned process by setting \( g_i(t) = e_i^{(N_{IT})}(t) \). The orthogonality between the different waveforms and the choice for the value of \( a_i^{(l)} \) are justified in the appendix B, using the Gram-Schmidt procedure.

3.3. MU-CSS Gram-Schmidt multiplication

In this method, the combination with the HFM is made by multiplying it with the spreading sequence, while applying the Gram-Schmidt iteration process to ensure orthogonality. We start from:

\[
e_i(t) = c_i(t) + a_i e_{i-1}(t) \quad \text{with} \quad i \in [1, N_u].
\]  

(13)

with \( a_i \) defined in (11). Then we build:

\[
\tilde{e}_i(t) = \tilde{e}_i(t) + \beta_i \tilde{e}_{i-1}(t)
\]  

(14)

where \( \tilde{e}_0(t) = \tilde{e}_0(t) = x(t) \) (this signal will be excluded from the set later) and for \( i > 0 \):

\[
\tilde{e}_i(t) = x(t)e_i(t)
\]  

(15)

Moreover:

\[
\beta_i = -\frac{\langle \tilde{e}_i(t), \tilde{e}_{i-1}(t) \rangle}{||\tilde{e}_{i-1}(t)||^2_2} = -\frac{\int_0^{T_s} \tilde{e}_i(t)\tilde{e}_{i-1}(t)dt}{||\tilde{e}_{i-1}(t)||^2_2}
\]  

(16)

The final waveform assigned to each user is obtained by setting \( \tilde{g}_i(t) = \tilde{e}_i(t) \).

3.4. MU-CSS Gram-Schmidt insertion

In this last variant, we combine the previous method with the insertion of an HFM signal at regular intervals such as:

\[
e_i(t) = \begin{cases} 
  x(t) & \text{if } i = kp \text{ with } k \in \mathbb{N}^* \\
  x(t)e_i(t) & \text{else}
\end{cases}
\]  

(17)

with \( p \) the insertion step. The idea is to try to improve the robustness of the different waveforms. To impose orthogonality between spread signals, we simply apply equations (13) and (14) and finally get \( \tilde{g}_i(t) = \tilde{e}_i(t) \).
4. Simulation results

4.1. Underwater acoustic channel simulator

For the simulation comparisons, we consider the UWA channel simulator provided by [15] based on a stochastic model. The time-varying transfer function for the $i$-th user is given by:

$$H_i(f, t) = \bar{H}_i(f) \sum_p h_{i,p}(f, t) e^{-j2\pi f \tau_{i,p}(t)}$$  \hspace{1cm} (18)

with $\bar{H}_i(f)$ the transfer function of direct path, $h_{i,p}$ the relative path gain, $\gamma_{i,p}(f, t)$ represents the scattering coefficient modeled by a complex-valued Gaussian processes whose statistics reflects the time coherence of the channel, and $\tau_{i,p}(t)$ denotes time-varying delay of the $p$-th path and can be expressed as:

$$\tau_{i,p}(t) = \bar{\tau}_{i,p} - (\bar{a}_i + a_{i,p})t$$  \hspace{1cm} (19)

where $\bar{\tau}_{i,p}$ is the average delay of path $p$ and $\bar{a}_i$ represents the mean Doppler shift induced by the motion of $i$-th AUV relatively to the receiver. In the following we will assume that $\bar{a}_i$ is known at the receiver side and compensated. Moreover, $a_{i,p}$ is the residual Doppler factor that captures resulting motion-induced time scaling on the $p$-th path. Coefficients $a_{i,p}$ are assumed to be constant over a frame and to follow a zero-mean Gaussian distribution with variance $\sigma_a^2$. Time variations of $\gamma_{i,p}(f, t)$ and $\tau_{i,p}(t)$ lead to Doppler spread effects [15].

4.2. System parameters

The chosen model represents a short range UWA transmission with a 10 m water depth at a center frequency of 23 kHz over a 4 kHz bandwidth. Each AUV are supposed at a same depth of 1 m. At the beginning of the simulations, the range between each AUV and the receiver is randomly selected in the interval $[0.1, 1]$ km modeling a fleet situating in a circular area (Fig. 3). Channel model parameters are summarized in Table 1 whereas transmission system parameters are provided in Table 2. The symbol duration is set according to the channel delay spread such that $T_s > \tau_{\text{max}}$ and is fixed identical for all
protocols. Evolution of simulated channel impulse response \(|h_i(\tau, t)|\) over one frame is provided in figure 4.

\[ h_i(\tau, t) \]

\[ 0 \leq \tau \leq \tau_{\text{max}} \]

\[ t \in [0, T_s] \]

\[ T_s \]

\[ \tau_{\text{max}} \]

\[ \text{SNR} \]

\[ \text{v}_i \]

\[ \sigma_a \]

\[ 4.3. \text{Orthogonality verification} \]

To verify the orthogonality of the proposed waveform, we compute the Signal-to-Interference-plus-Noise Ratio (SINR) obtained after matched filtering. Following (7), for user \(i\), we have:

\[
\text{SINR} = \frac{\mathbb{E}\left\{ |\gamma_{l,k}|^2 \right\}}{\mathbb{E}\left\{ |\hat{d}_{l,k}|^2 \right\} + \mathbb{E}\left\{ |w_k|^2 \right\}}
\]

(20)

Simplifying (A4), (A5) and (A8) in the case of static AUV motion (i.e. \(a_i = 0\)) and channel delay spread very small compared to the symbol duration (i.e. \(T_s \gg \tau_{\text{max}}\)), the last equation becomes:

\[
\text{SINR} = \frac{\left| \int_{-\infty}^{+\infty} g_i^*(t) h_i(t, \tau) g_i(t - \tau) d\tau \right|^2}{\left| \sum_{j=1}^{N_u} \int_{-\infty}^{+\infty} g_j^*(t) h_j(t, \tau) g_j(t - \tau) d\tau \right|^2 + \mathbb{E}\left\{ \left| \int_{-\infty}^{+\infty} g_i^*(t) n(t) dt \right|^2 \right\}}
\]

(21)

\[ T_s \]

\[ \tau_{\text{max}} \]

\[ \mathbb{E}\left\{ |\gamma_{l,k}|^2 \right\} \]

\[ \mathbb{E}\left\{ |\hat{d}_{l,k}|^2 \right\} \]

\[ \mathbb{E}\left\{ |w_k|^2 \right\} \]

\[ \left| \int_{-\infty}^{+\infty} g_i^*(t) h_i(t, \tau) g_i(t - \tau) d\tau \right|^2 \]

\[ \left| \sum_{j=1}^{N_u} \int_{-\infty}^{+\infty} g_j^*(t) h_j(t, \tau) g_j(t - \tau) d\tau \right|^2 \]

\[ \mathbb{E}\left\{ \left| \int_{-\infty}^{+\infty} g_i^*(t) n(t) dt \right|^2 \right\} \]
Table 2. System parameters.

| Symbol | Signification                        | Value               |
|--------|--------------------------------------|---------------------|
| $M$    | Modulation order                     | 2 (DBPSK)           |
| $N_s$  | Number of symbols per frame          | 200                 |
| $N_f$  | Number of frames                     | 5000                |
| $C$    | FEC code type                        | Convolutive code    |
| $g_C$  | FEC code generator                   | $(133, 171)_6$      |
| $R_C$  | FEC code rate                        | $\frac{1}{2}$      |
| $T_g$  | Guard interval time                  | 15 ms               |
| $T_b$  | Duration of the chirp signal         | 7.75 ms             |
| $T_C$  | Chip duration                        | 0.25 ms             |
| $N_{SF}$ | PN length code                | 31                  |
| $N_{IT}$ | Number of iterations            | 1000                |
| $p$    | Insertion step                       | 7                   |
| $\alpha$ | Pulse shaping filter roll-off factor | 0.25                |
| $T_s$  | Symbol duration                      | 7.75 ms             |

In figure 5, we compute numerically the SINR by using (21) and the system parameters depicted in table 2 over an Additive White Gaussian Noise (AWGN) channel and also over the time-varying UWA channel with static users described in Section 4.1. Comparisons are performed between MU-CSS, CDMA and TDMA transmissions. At $N_u = 1$ user, since there are no interference terms, all the transmission techniques have the same SINR after matched filter decoding, which is equal to channel Signal-to-Noise Ratio (SNR) added to the spreading gain in the case of AWGN channel. Naturally, as the number of users increases, SINR decreases due to the growing importance of the interference terms, excepted for the TDMA case for which interference terms are absent whatever the number of users, thanks to time multiplexing. In both AWGN and UWA channels, MU-CSS transmissions outperform CDMA demonstrating that Gram-Schmidt based construction method provides good orthogonality properties for MU-CSS waveforms. This SINR gap is mainly explained by the use of PN sequences in CDMA that are not perfectly orthogonal (but only quasi-orthogonal) while MU-CSS employs waveforms that are orthogonal owing to the Gram-Schmidt process. Obviously, this SINR gap could be erased in AWGN by the use of orthogonal codes like Walsh-Hadamard sequences for CDMA, however such codes are not suitable in the uplink scenario.

Figure 5. Average SINR for different waveforms over AWGN and time-varying UWA channel with static users, SNR = 30 dB.
4.4. Performance metrics

As performance metrics, we consider the average effective data rate per user defined for each transmission technique as follows:

\[
D_{CDMA}^e = \frac{R_C \log_2 M}{N_{SF} T_c} \cdot (1 - \text{FER}) \quad \text{[bps]} \quad (22)
\]

\[
D_{TDMA}^e = \frac{R_C \log_2 M}{N_u N_{SF} T_c + (N_u - 1) T_g} \cdot (1 - \text{FER}) \quad \text{[bps]} \quad (23)
\]

\[
D_{MU-CSS}^e = \frac{R_C \log_2 M}{T_h} \cdot (1 - \text{FER}) \quad \text{[bps]} \quad (24)
\]

where \( M \) is the size of the DPSK constellation, \( R_C \) is channel coding rate and FER is the Frame Error Rate. A frame is considered erroneous when at least one bit per frame after channel decoding is erroneous.

4.5. Static channel

In a first step we consider a static UWA channel leading to only frequency selective fading. This yields constant parameters \( \gamma_p(f, t) \) and \( \tau_p(t) \) in time, in equation (18). Frame Error Rate (FER) performance and effective data rate of each transmission technique over the modeled shallow water acoustic channel are provided in Fig. 6.

In the single-user scenario, the 3 transmission techniques have a FER of 0 and as expected, the FER of TDMA remains unchanged when the number of users increases. Above 4 users, the interfering terms of the CDMA, expressed in equation (7) by the quantity \( \eta_{i,j,k} \), make impossible the decoding of each user. On the other side, the largest number of users that can be handled by the MU-CSS is 8 or 9 depending on the method. The fact that MU-CSS outperforms CDMA is mainly explained by the better orthogonality properties of the MU-CSS waveforms.
4.6. Time varying channel and static users

In a second step, we consider a time-varying channel model where Doppler spread effect is provided in the equation (18) by $\gamma_i(f, t)$ and $\tau_{ip}(t)$ coefficients. In this scenario, we assume that all users are static yielding to $\bar{a}_i = 0$ in relation (19). Performance over time varying channel with static users is depicted in Fig. 7.

Doppler spread effect provided by multipath time-variations leads to an FER increase of both CDMA and MU-CSS transmissions, while TDMA decoding performance still remains error free. In fact, TDMA transmission is not affected by multiuser interference but only UWA channel time and frequency selectivity while CDMA and MU-CSS suffers from multiuser interference in addition to the UWA channel selectivity. The MU-CSS transmissions have the best effective data rate compared to CDMA because the HFM signal makes the spreading signals resistant against channel impairments such as Doppler spread. Among the MU-CSS transmission technique, the Gram-Schmidt iterated method appears to be slightly less robust than the other methods.

4.7. Time varying channel and mobile users

In a last step, we consider, a time varying channel model with mobile AUV whose speed is randomly selected in the interval $[-2, 2]$ m/s at each frame and for each user. The motion induced Doppler shift is assumed to be perfectly known and compensated at the reception for each user $i$. According to (4), since each user has different speed, Doppler compensation of user $i$ will increase power of interference terms. However, in practice, Doppler shift is unknown and must be estimated prior to decoding [26].

Performance over time-varying UWA channel with mobile users is carried out in Fig. 8. In the single-user scenario, the three transmission techniques provide an FER of 0% and, as expected, FER of TDMA remains unchanged when the number of users increases. Both CDMA and MU-CSS transmissions are severely impacted by motion-induced Doppler shift, since Doppler shift correction for an user also applies to other users according to equation (4). However MU-CSS transmissions still outperforms CDMA, which might be explained by the MU-CSS construction that provides both an orthogonality enhancement and a better robustness against Doppler shift. Beyond 6 users, the TDMA approach is more efficient in terms of data rate.
5. Experimental results

5.1. Channel sounding

5.1.1. Ty-Colo lake of Saint-Renan (France)

The sounding experiments took place in July 2019 at the lake of Ty-Colo, Saint Renan, France. The depth of the lake is around 5 m and up to 10 transmission ranges between $[47, 364]$ m were sounded successively with one hydrophone at the receiver side as depicted in Fig. 9. Each channel sounding was performed during 3 min 30s, using a 255-Maximal Length Sequence (MLS) probe signal [27] centered on $f_c = 27$ kHz over a 6 kHz bandwidth. Fig. 10 provides an example of the delay-Doppler spread extracted from the successive estimated Channel Impulse Response (CIR). Estimated channel delay spreads and Doppler spreads are reported in Table 3.

5.2. Watermark replay channel

To simulate a real experiment, we consider in this section the Watermark channel [17] which is a replay channel simulator driven by measurements of the time-varying CIR. The principle of the simulator consists of distorting input waveforms by convolving them with measured channels. To
To simulate a multiuser communication, we sum the output of several Watermark channel fed by different
CIRs and delayed by relative range of each user. The operation of channel replay for a static multiuser
communication in the Single Input Single Output (SISO) case can be expressed in baseband as:

$$ r(t) = \sum_{i=1}^{N_u} \int_{-\infty}^{+\infty} \hat{h}_i(\tau, t)s_i(t - \tau - \bar{\tau}_i)d\tau + n(t) $$

where $s_i(t)$ is the input signal, $\hat{h}_i(\tau, t)$ is the recorded CIR of the $i$-th user, $\bar{\tau}_i$ is communication delay
between the $i$-th user and the receiver and $n(t)$ is a Gaussian noise.

For a mobile multiuser communication, the Doppler shift is simulated by resampling and
phase-rotating the transmitted signal as follows:

$$ r(t) = \sum_{i=1}^{N_u} \int_{-\infty}^{+\infty} \hat{h}_i(\tau, t)s_i((1 - a_i)((t - \tau - \bar{\tau}_i))e^{j2\pi f_c a_i(t-\tau)}d\tau + n(t) $$

In the following, the Doppler shift will be known by the receiver and compensated by the relation (A1).

Ty-Colo lake channels parameters are summarized in Table 3 whereas transmission system parameters
are provided in Table 2.

### Table 3. Watermark channel parameters.

| Symbol | Signification                  | Value     |
|--------|--------------------------------|-----------|
| $f_c$  | Center frequency               | 27 kHz    |
| $f_s$  | Sampling frequency             | 96 kHz    |
| $B$    | Signal bandwidth               | 4 kHz     |
| $D_i$  | Transmission range             | [47, 364] m |
| $z_w$  | Water depth                    | 5 m       |
| SNR    | Signal to noise ratio          | 10 dB     |
| $\tau_{max}$ | RMS channel delay spread [20] | [4.31, 7.27] ms |
| $\sigma_{max}$ | RMS channel Doppler spread [20] | [0.86, 2.51] Hz |

Figure 10. Delay-doppler spread function for the Ty-Colo lake.
5.3. Performance results

5.3.1. Static users

Fig. 11 provides performance of multiuser transmission techniques over the Watermark channel fed by the Ty-Colo lake channel soundings. It can be noticed that the FER, and consequently the effective data rates, are worse than in simulation. This can be mainly explained by the fact the experimental soundings are very shallow water ($\approx 5$ m) leading to much more important multipath effect and, as consequence, to higher multiple access interference terms. Meanwhile, FER performance of MU-CSS transmissions are still better than CDMA ones up to 6 simultaneous users (except the case $N_u = 4$ where the CDMA is slightly ahead). Beyond this threshold, TDMA transmission is more suitable despite its low data rate due to a large number of users.

5.3.2. Mobile users

In Fig. 12, AUVs motion is emulated by adding motion-induced Doppler scale at the output of Watermark channel. For each frame, speed value of each AUV is randomly selected in the interval $[-2, 2]$ m/s. We can see that the performance of all access schemes are degraded excepted TDMA. From 1 up to 6 users, the MU-CSS transmissions remain globally more interesting in term of effective data rate. As seen in simulation, the MU-CSS with Gram-Schmidt insertion method is confirmed in experiments to provide highest robustness among all MU-CSS construction methods. Beyond 6 users, the TDMA is demonstrated to be more advantageous.

6. Conclusion and future works

In this paper, we have proposed a new multiuser transmission technique based on HFM signal denoted MU-CSS in the context of UWA communication within an AUVs fleet. By using the Gram-Schmidt orthogonalization, we derived three construction methods for MU-CSS allowing a very simple matched filter decoding scheme at the receiver side. Simulation comparisons against traditional CDMA with single user decoding over static and time-varying shallow water UWA models demonstrate a superior effective data rate for the proposed MU-CSS scheme even if the number of users is large and even if users are in motion, as for an AUV fleet. Experimental results with Watermark channel replay fed by channel soundings confirm the superiority of MU-CSS transmissions in a realistic scenario. The MU-CSS is demonstrated to be globally superior to CDMA up to 6 users. Beyond, the traditional TDMA approach is demonstrated to be more efficient. The MU-CSS approach...
and especially associated with the Gram-Schmidt construction method offers a set of waveforms providing good orthogonal properties even in UWA uplink channel, so that such waveforms does not require complex multiuser decoding scheme at the receiver side. Thereby, MU-CSS transmission techniques constitute an interesting alternative to asynchronous CDMA for UWA network.

In a future work, we will consider multi-channel decoding for MU-CSS in order to improve the number of users to be correctly decoded simultaneously, and also taking into account real Doppler-shift estimation and impact to decoding performance when AUVs have different speeds and directions.

Funding: This research was partly funded by Thales DMS France in the framework of the WAVES laboratory. The APC was funded by L@bISEN Yncréa Ouest.

Author Contributions: Software, C. Bernard; writing–original draft preparation, C. Bernard and P.-J. Bouvet; writing–review and editing, A. Pottier and P. Forjonel.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix. Calculation of $\gamma_{i,k}$, $\eta_{i,k}$ and $w_{i,k}$

The receive baseband signal after Doppler pre-processing can be expressed as:

$$z_i(t) = r \left( \frac{t}{1-a_i} \right) e^{-j2\pi f_c \left( \frac{a_i}{\tau_i} \right) t}$$

Combination of (2) and (7) yields:

$$\gamma_{i,k} = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} h_i \left( \tau, \frac{t+kT_s}{1-a_i} \right) g^*_i(t) g_i \left( t-(1-a_i)\tau \right) e^{-j2\pi f_c a_i/T} T d\tau dt$$

**Figure 12.** Average FER performance versus number of users for the Ty-Colo lake replayed channel with mobile users (left) and average effective data rate per user versus number of users for the Ty-Colo lake replayed channel with mobile users (right).
\[
\eta_{i,k} = \sum_{n=1, n \neq k}^{N_k} d_{i,n} \int_{-\infty}^{+\infty} h_i \left( \tau, t + \frac{kT_s}{1-a_i} \right) g_i^*(t) g_i(t - \tau - (n - k)T_s) e^{-j2\pi f_c \frac{kT_s}{1-a_i}} d\tau dt 
\]

\[
+ \sum_{j=1}^{N_k} \sum_{n=1}^{N_k} d_{j,n} \int_{-\infty}^{+\infty} h_j \left( \tau, t + \frac{kT_s}{1-a_i} \right) g_j^*(t) g_j \left( 1 - a_j \right) \left( t + \frac{kT_s}{1-a_i} - \tau \right) - nT_s \right) e^{-j2\pi f_c \frac{kT_s}{1-a_i}} d\tau dt 
\]

and

\[
w_{i,k} = e^{-j2\pi f_c \frac{kT_s}{1-a_i}} \left( \int_{-\infty}^{+\infty} g_i^*(t) n \left( \frac{t + kT_s}{1-a_i} \right) e^{-j2\pi f_c \frac{kT_s}{1-a_i}} dt \right) 
\]

**Appendix. Justification of the MU-CSS Gram-Schmidt construction process**

To have the orthogonality between the different \(e_i(t)\), we use a variant of the Gram-Schmidt process [25], which is a method for orthogonalizing a set of vectors in an inner product space. The inner product is defined by \(\langle f(t), g(t) \rangle = \int_{-\infty}^{+\infty} f(t) g^*(t) dt\). Let \(\{c_1(t), c_2(t)\}\) a set of linearly independent vectors. We add the vector \(e_0(t)\) to the previous family and we build an orthogonal family from vector \(e_0(t)\). By the Gram-Schmidt process, we have:

\[
e_1(t) = c_1(t) + a_1 e_0(t) 
\]

Using orthogonality, the previous equation gives:

\[
\langle c_1(t), e_0(t) \rangle + a_1 ||e_0(t)||^2 = 0 
\]

\[
\Leftrightarrow a_1 = -\frac{\langle c_1(t), e_0(t) \rangle}{||e_0(t)||^2} = -\frac{\int_{-\infty}^{+\infty} c_1(t) e_0^*(t) dt}{||e_0(t)||^2} 
\]

For the last vector, the Gram-Schmidt process gives:

\[
e_2(t) = c_2(t) + \beta e_0(t) + a_2 e_1(t) 
\]

We take \(\beta = 0\) because that is enough to have orthogonality and we obtain:

\[
e_2(t) = c_2(t) + a_2 e_1(t) 
\]

Using orthogonality, the previous equation becomes:

\[
\langle c_2(t), e_1(t) \rangle + a_2 ||e_1(t)||^2 = 0 
\]

\[
\Leftrightarrow a_2 = -\frac{\langle c_2(t), e_1(t) \rangle}{||e_1(t)||^2} = -\frac{\int_{-\infty}^{+\infty} c_2(t) e_1^*(t) dt}{||e_1(t)||^2} 
\]

By generalization, we deduce the equation (10).
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