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SINGLE-CARRIER FREQUENCY DIVISION MULTIPLE ACCESS FOR UNDERWATER ACOUSTIC COMMUNICATIONS

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Abstract: *A single-carrier frequency division multiple access (SC-FDMA) scheme for transmission through underwater acoustic channel is proposed in this paper. A uniform distributed mode is used for the subcarrier mapping at the transmitter side. A single user scenario is considered where empty subcarriers between each two successive occupied subcarriers are considered as a guard interval. This enables to increase the receiver robustness against Doppler spread compared to traditional single-carrier transmission schemes. Adaptive linear frequency-domain equalization is considered at the receiver. Results show that the proposed scheme outperforms the single-carrier frequency-domain equalization transmission scheme (SC-FDE) in terms of bit error rate (BER) and mean square error (MSE).*

Keywords: *SC-FDMA, uniform distributed mapping, frequency-domain equalization (FDE), underwater acoustic channel, Doppler compensation.*

1. INTRODUCTION

Underwater acoustic (UWA) communication systems suffer from the frequency selectivity of the multipath propagation, which causes inter-symbol interference (ISI). The UWA channel is also time-variant, yielding a Doppler spread [1]. In order to combat frequency and time selectivity of the UWA channel, advanced signal processing and robust equalization techniques have to be used. Single-carrier frequency division multiple access (SC-FDMA) is a promising technique for high data rate uplink communications [2]. SC-FDMA is a modified form of orthogonal frequency division multiple access (OFDMA). Performance and complexity of SC-FDMA are similar to those of OFDMA. The advantage of SC-FDMA over OFDMA is its reduced peak-to-average power ratio (PAPR) that makes it suitable for transmission from terminals with low battery-life [3], thanks to its inherent single-carrier structure. SC-FDMA is adopted by the 3GPP as the uplink for the 4th generation mobile system, long term evolution (LTE) [4]. SC-FDMA uses cyclic prefix (CP)-based frequency-domain equalization (FDE) at the receiver [4]. The CP insertion prevents the transmitted signal from inter-block interference (IBI). The FDE is an interesting alternative to the time-domain equalization (TDE) and both have the same theoretical performance. The computational complexity of the FDE is increasingly lower than the TDE as the channel delay spread is larger in terms of symbol duration [5, 6]. The subcarrier mapping consists in allocating to each user a subset of subcarriers out of N total subcarriers in the SC-FDMA bandwidth either localized or distributed [4]. To the best of our knowledge, the only work related to SC-FDMA transmission in UWA channel is given in [7] where authors design the localized SC-FDMA receiver using 4 users. The uniform distributed SC-FDMA was not investigated and its application in such a channel is a challenging task.

In this paper, we propose a single user SC-FDMA transmission scheme with a uniform distributed sub-carriers mapping for transmission in UWA channel. Performance is analyzed through transmissions over a time-variant UWA channel in the Brest harbor, France from quay to quay over a distance of about 850 meters in shallow water. A multiple input frequency-domain adaptive linear equalizer (MI-FD-ALE) is considered at the receiver. Results of simulations and experiments are given in terms of BER and MSE.

2. SYSTEM MODEL

A single user transmits an SC-FDMA signal using the uniform distributed subcarrier mapping. This user occupies the entire bandwidth non-continuously resulting on zero-amplitude subcarriers between each two successive occupied subcarriers. The information data bits are mapped into QPSK symbols using the gray mapping. At the output of the SC-FDMA modulator, the resulting data stream is modulated on a carrier frequency f_c . An acoustic signal is generated via the transducer to be transmitted through the UWA time-varying channel. When the pass-band digital received signal is centered on a relatively low carrier frequency, an all-digital reception can be applied. Since the received signal is band-limited, an oversampling is performed at the rate $1/T_s$ where T_s is chosen to fulfill the sampling theorem conditions. The down-conversion is performed digitally and the optimum sampling is realized from a sample rate converter. The resulting all-digital receiver is depicted in Fig. 1.

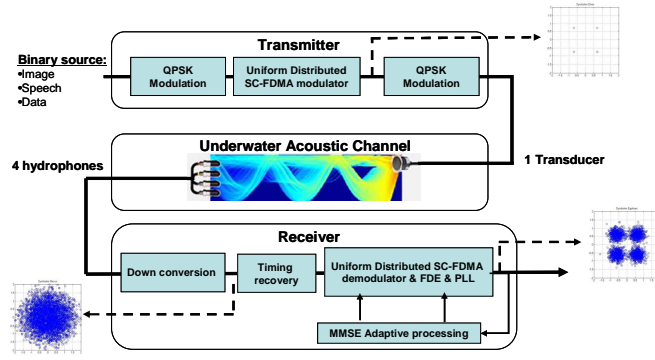


Fig. 1. UWA transmission scheme

In wide-band transmissions, such as UWA communications [8], the Doppler effect introduces a scaling of the symbol period that must be taken into account in the design of the timing recovery scheme. To restore the transmitted signal, the optimum sampling time depends not only on the propagation delay observed at the antenna, but also on a common Doppler shift function of the relative speed between the transmitter and the receiver and the propagation wave velocity. At the receiver side, the optimum sampling time is unknown and must be estimated. Initial compensation of common Doppler shift is performed, based on the estimation of the relative velocity measured using a short preamble [9] transmitted at the beginning of the frame. Then, a non data aided (NDA) timing recovery scheme is designed to compensate residual Doppler shifts due to the time-variation in the relative speed. Note that the preamble is also used to realize the transmission detection and frame synchronization process.

3. SINGLE USER SC-FDMA TRANSMISSION

The proposed scheme is depicted in Fig. 2. A single user SC-FDMA transmission is considered in this paper using the uniform distributed mapping mode. The remaining empty subcarriers are assigned zero amplitude. As only one user is transmitting in the entire bandwidth, the inter-user interference (IUI) is avoided. The QPSK modulation symbols are grouped into blocks of size M symbols. The blocks are transformed in the frequency-domain (FD) via a discrete Fourier transform (DFT). The entire bandwidth of the SC-FDMA system which contains N subcarriers is divided into U subsets each of M subcarriers where U is the bandwidth spreading factor ($M=N/U$). Let denote by u ($u=0, \dots, N_u - 1$) the user index where N_u is the number of users. The maximum number of users that can transmit simultaneously in the entire bandwidth is equal to U . A subcarrier mapping is performed where the DFT outputs are assigned to M among N subcarriers. An N -point inverse DFT is applied to generate the time-domain blocks followed by a parallel to serial converter and CP insertion. The CP insertion consists in adding at the beginning of each block the last N_{CP} symbols of the same block. N_{CP} has to be equal to or greater than the maximum channel delay spread in terms of symbol duration. At the output of the SC-FDMA modulator, the symbols $\{s_n^{(u)}\}$ of the u -th user are passed through a pulse shaping filter $g(t)$ where a symbol duration T is given to each symbol and are then modulated on a carrier-frequency f_c with carrier phase uncertainty ψ followed by a digital to analog converter (DAC). The resulting analog electrical signal is transduced to an analog acoustic wave via a transducer to be transmitted in the UWA channel.

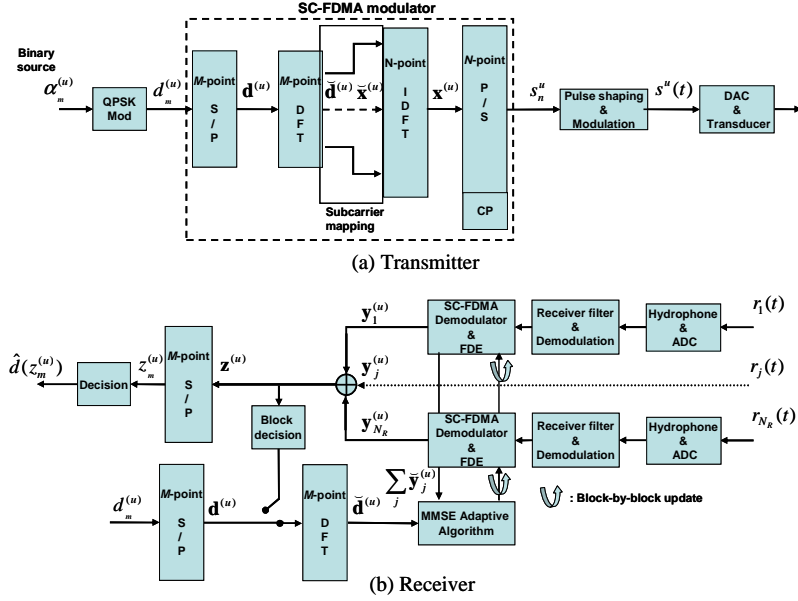


Fig. 2. SC-FDMA transmission scheme

Let $s^{(u)}(t)$ be the transmitted signal corresponding to the user u ,

$$s^{(u)}(t) = \text{Re} \left\{ e^{j(2\pi f_c t + \psi)} \sum_{n=0}^{N-1} s_n^{(u)} g(t - nT) \right\} \quad (1)$$

3.1 Uniform distributed Subcarrier mapping

There are two subcarrier mapping modes in SC-FDMA: the localized mapping and the distributed mapping. In the localized mapping, the M -point DFT outputs are mapped to consecutive subcarriers. In the distributed mapping, the M -point DFT outputs are spread over the entire bandwidth non-continuously which is robust against frequency selective fading and offers additional frequency-diversity gain compared to the localized mode. On the other hand, the localized mapping is less sensitive to IUI than the distributed mapping is. Uniform distributed mapping consists is an equal-spacing subcarrier allocation. In Fig. 3, we give an example of the uniform distributed mapping with $N=6$, $U=2$ and $M=3$. Note that the user symbol duration at the input of the SC-FDMA modulator T_{user} is defined as a product of the symbol duration in SC-FDMA signal and the bandwidth spreading factor ($T_{user} = TU$). At the transmitter side, the uniform distributed mapping is done as follows,

$$\tilde{x}_q^{(u)} = \begin{cases} \sum_{m=0}^{M-1} d_m^{(u)} e^{-j\frac{2\pi}{M}mv} & \text{for } q = vU \\ 0 & \text{else} \end{cases} \quad (2)$$

where ($v=0, \dots, M-1$) and ($q=0, \dots, N-1$) are indices on the subcarriers bins. We also define ($m=0, \dots, M-1$) and ($n=0, \dots, N-1$) the indices on the time-domain block symbols. After the N -point IDFT, the n -th symbol of a block is given by the following equation,

$$x_n^{(u)} = \frac{1}{U} d_{n \bmod M}^{(u)} \quad (3)$$

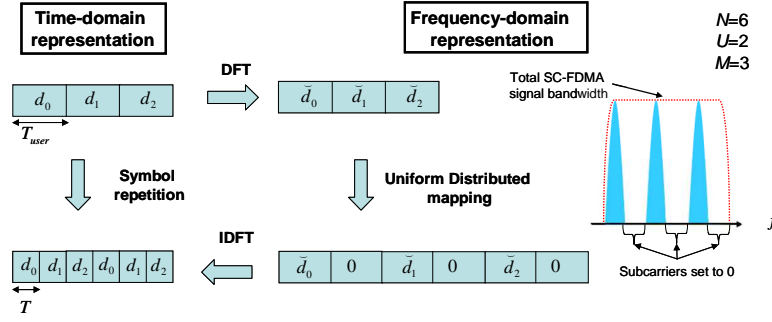


Fig. 3. Time and frequency domain representations of uniform distributed mapping

According to (3) and as illustrated in Fig. 3, the uniform distributed SC-FDMA is equivalent to a U -times symbol repetition in the time-domain of the SC-FDMA modulator input symbols. This can offer a time-diversity gain in the presence of Doppler shift in the time-varying UWA channel. The uniform distributed mapping has a lower PAPR compared to non-uniform distributed and localized mapping modes [3].

3.2. SC-FDMA multiple-input frequency-domain adaptive linear equalizer

The received acoustic signal is transduced to an electrical analog signal via a hydrophone followed by an analog to digital converter (ADC). After demodulation and filtering, the received signals are modelled as multiple outputs of a discrete time channel. The n -th sample received by the j -th antenna can be written as follows,

$$r_{j,n} = \sum_{u=0}^{N_u-1} \sum_{l=0}^{L-1} h_{j,n}^{(u)}(l) s_{n-l}^{(u)} + w_{j,n} \quad (4)$$

where $w_{j,n}$ is an additive white Gaussian noise (AWGN) with zero-mean and variance σ_w^2 and $h_{j,n}^{(u)}(l)$ ($l=0, \dots, L-1$) are the L coefficients of the multipath time-varying channel corresponding to the u -th user at the j -th antenna with ($j=1, \dots, N_R$) and N_R is the number of receiver antennas. As in the example of Fig. 3, we consider that the single user is transmitting on the subcarrier subset indexed by $p = 0$.

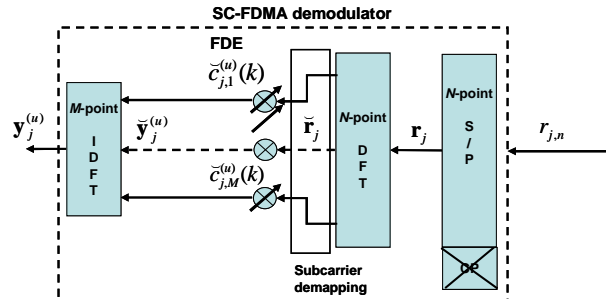


Fig. 4. SC-FDMA demodulator

At each input j , the received symbols are grouped into blocks \mathbf{r}_j of size N . An N -point DFT is performed resulting in N orthogonal streams followed by a subcarrier demapping to select the user M -size blocks. The CP are removed and a serial to parallel conversion is performed to form symbol blocks. The CP insertion allows a circular convolution between the transmitted signal $s^{(u)}(t)$ and the channel impulse response (CIR) $h_j(t)$. The circular property of the received signal $r_j(t)$ combined with the FD structure of SC-FDMA make the FDE the best alternative to traditional TDE.

A multiple input frequency-domain adaptive linear equalizer (MI-FD-ALE) is proposed. The multiple inputs are used to obtain a higher average SNR at the receiver output. The k -th equalizer coefficients block $\tilde{\mathbf{c}}_j^{(u)}(k)$ for the user u at input j are computed based on the minimization of a common mean square error (MSE) in the FD between all inputs, with respect to $\tilde{\mathbf{c}}_j^{(u)}$. The equalizer coefficients are updated on a block-by-block basis using the least mean square (LMS) algorithm. This means that the coefficients of the equalizer are kept fixed over the entire block duration. At the beginning of the transmission, the update process is based on a data-aided (DA) mode to allow convergence to the optimal response. Then, the update is done in a decision directed (DD) mode in order to track the channel time-variation. We define the FD error block as follows,

$$\tilde{\mathbf{e}}^{(u)}(k) = \sum_{j=1}^{N_R} \tilde{\mathbf{R}}_j(k) \tilde{\mathbf{c}}_j^{(u)}(k) - \tilde{\mathbf{D}}^{(u)}(k) \quad (5)$$

where $\tilde{\mathbf{R}}_j(k)$ is a diagonal matrix containing the M elements of the k -th block $\tilde{\mathbf{r}}_j(k)$ at the j -th input, $\tilde{\mathbf{D}}^{(u)}(k)$ is a diagonal matrix containing the M -point DFT of the k -th preamble symbol block $\tilde{\mathbf{d}}^{(u)}(k)$ during the DA training mode and the M -point DFT of the decision block at the equalizer output $\hat{d}\{\mathbf{y}^{(u)}(k)\}$ during the DD tracking mode.

$$\tilde{\mathbf{c}}_j^{(u)}(k+1) = \tilde{\mathbf{c}}_j^{(u)}(k) - \mu \tilde{\mathbf{R}}_j^H(k) \tilde{\mathbf{e}}^{(u)}(k) \quad (6)$$

where H stands for complex conjugate transpose and μ is the adaptation step size.

4. SIMULATION RESULTS

The proposed scheme is compared to the SC-FDE transmission system where the entire bandwidth is occupied. Therefore, the transmission duration in the case of SC-FDMA is U times greater than the transmission duration in SC-FDE for the same transmitted data stream. The proposed scheme is simulated over two frequency-selective time-invariant channel models with one receiver antenna ($j = 1$). Fig. 5 shows the BER vs. E_b/N_0 for Porat and Proakis B channel models, respectively, where E_b is the average energy per data bit and N_0 is the one-sided noise power spectral density. Porat and Proakis B channel models have a medium and strong frequency-selectivity, respectively. The results show the performance of frequency-domain adaptive linear equalizer (FD-ALE) in SC-FDMA and SC-FDE. Two values of U are tested ($U=2$ and $U=3$). The genie LE is the lower theoretical bound of the MMSE linear equalizer and is computed using an ideal equalizer with infinite length and perfectly known CIR. SC-FDMA performs better than SC-FDE and offers an additional gain that gets higher as the channel selectivity increases. The zero-amplitude subcarriers inserted between occupied subcarriers in the uniform distributed SC-FDMA make the channel frequency response less selective than it is in the SC-FDE. In Fig. 5. (a), when the BER is about 10^{-5} , a gain in E_b/N_0 of about 1 dB is given for the cases of SC-FDMA with $U=2$ and $U=3$ compared to SC-FDE. When the frequency-selectivity increases, that is the case in Fig. 5. (b), this gain becomes more

important and is equal to 5 dB for a BER equal to 10^{-2} . This gain increases by increasing the bandwidth spreading factor at the price of a reduction in the user throughput.

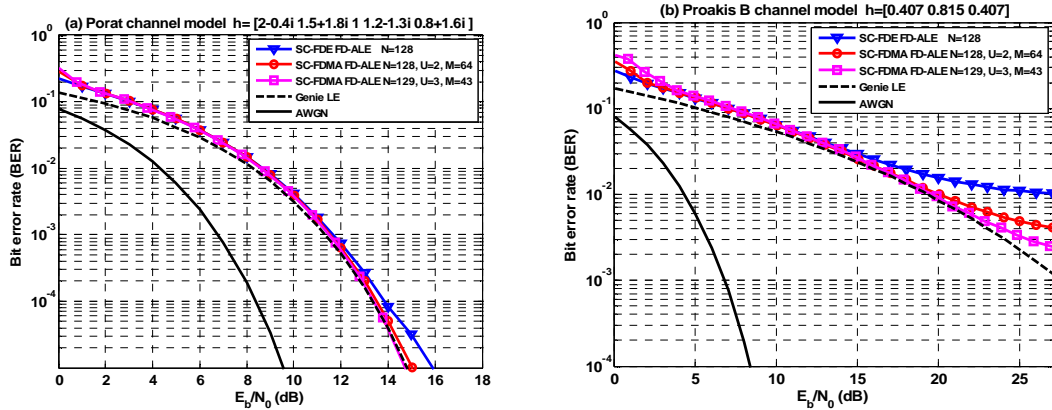


Fig. 5. BER vs. E_b/N_0

5. REAL UNDERWATER EXPERIENCE

The transmission was conducted in the Brest harbor, France from quay to quay over a distance of about 850 meters in shallow water with a carrier frequency of about 18 kHz and a data rate of about 6 kbps. The experience configuration is given in Fig. 6 and the signal transmission design is given in Fig. 7. The transducer and hydrophones were fixed but they drifted in the water due to the movement of the waves which, added to the UWA channel movement, results in a certain relative speed between the transducer and hydrophones.

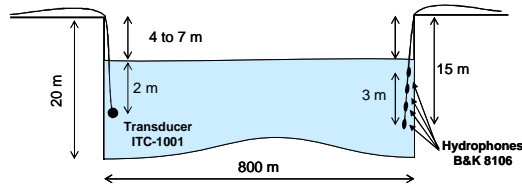


Fig. 6. Experience configuration

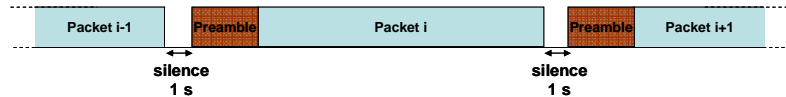


Fig. 7. Frame definition

The BER for the FD-ALE in SC-FDMA and SC-FDE transmissions is given in Tab. 1 for a fixed value of N and different values of U (1, 2, 4). The SC-FDMA scheme performs better than SC-FDE. This improvement becomes more important when the number of zero-amplitude subcarriers increases. A BER equal to 0 is achieved in the case of $U = 4$.

N	SC-FDE $M=N$ ($U=1$)	SC-FDMA $M=N/2$ ($U=2$)	SC-FDMA $M=N/4$ ($U=4$)
64	$1.3 \cdot 10^{-4}$	$1.5 \cdot 10^{-5}$	0
128	$2 \cdot 10^{-4}$	$7.4 \cdot 10^{-5}$	0

Tab. 1 BER of SC-FDMA vs. SC-FDE BER

In Fig. 8, we show the instantaneous MSE. In the SC-FDMA transmission, the FD-ALE converges faster and achieves an MSE larger than that in SC-FDE. When N increases from 64 to 128, the MSE achieved by the FD-ALE keeps roughly the same in both SC-FDMA schemes, while it gets degraded in the SC-FDE scheme.

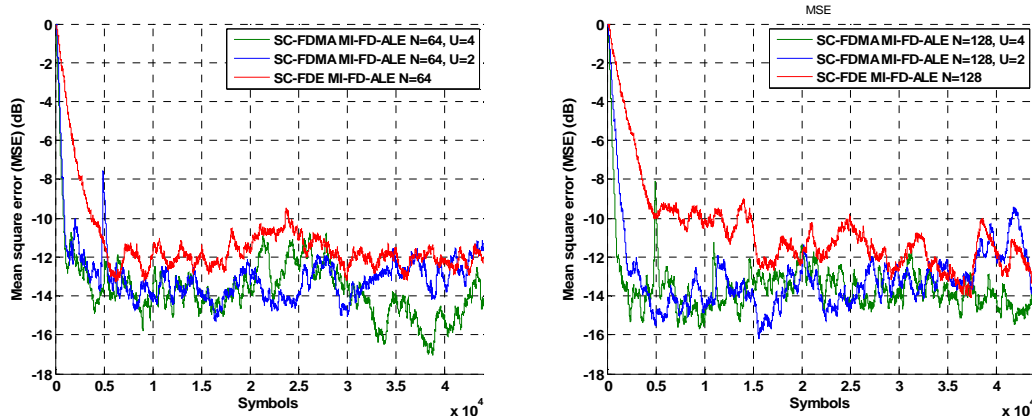


Fig. 8. Instantaneous mean square error (MSE)

6. CONCLUSION

A uniform distributed SC-FDMA scheme using the MI-FD-ALE for a single user is proposed in this paper. The adaptive process allows tracking time-variation in the UWA channel in a decision directed mode. The proposed scheme offers an additional gain in terms of BER and achieved MSE compared to the SC-FDE scheme. The proposed scheme is more robust than SC-FDE in the presence of Doppler shifts and may offer an additional gain in frequency-selective channels.

7. ACKNOWLEDGEMENTS

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