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Differential orthogonal frequency division multiplexing communication in water pipeline channels

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Abstract: The problem of information transmission through water pipelines is addressed and a class of methods based on differentially encoded orthogonal frequency division multiplexing (OFDM) is proposed. Specifically, two methods are investigated; one based on conventional differential encoding with an estimation of the average time of arrival and another based on double encoding. Results show that the first approach improves performance in the low signal to noise ratio (SNR) region, while the second is better suited at high SNR. Adopting these techniques closes the performance gap between differential OFDM systems and coherent OFDM systems while retaining the benefits of computational simplicity.

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1. Introduction

Acoustic communication in water pipeline channels encounters unique challenges compared to the open-area underwater acoustic (UWA) communication environment (e.g., oceanic channel). While general UWA channel characteristics include large delay spread, fast time variation, and Doppler distortion, water pipeline channels with sensors mounted in fixed locations have features that include frequency dependent delay spread, high attenuation, and low Doppler even with water flow (Jing *et al.*, 2018). The probability density function of the acoustic noise in the water pipe channel has been shown to follow a heavy tail distribution and can be characterized by an α-stable process. The heavy tail components are negligible at frequency higher than 10 kHz. Consequently, the acoustic noise can be considered Gaussian at frequencies >10 kHz (Dubey *et al.*, 2019).

Coherent orthogonal frequency division multiplexing (OFDM) and differential OFDM communication systems have been extensively studied for oceanic UWA communication systems (Wang *et al.*, 2012; Aval and Stojanovic, 2015; Zhang *et al.*, 2017; Tadayon and Stojanovic, 2019). Differential OFDM in this paper refers to differential encoding in the frequency domain where the characteristic of channel invariance between adjacent carriers is utilized. Differential encoding can also be applied in the time domain, but will not be addressed here. Differential OFDM is an alternative to coherent OFDM with the advantage of low complexity because no explicit channel estimation is required. Coherent OFDM has previously been investigated for water pipeline channels (Li *et al.*, 2018), in which the frequency dependency of delay spread was explored, and an adaptive OFDM algorithm was designed based on the estimation of the delay spread on all subcarriers. In contrast, differential OFDM for water pipelines has not been well explored. Due to the varying phase difference between the channel coefficients of adjacent subcarriers, direct application of differential OFDM algorithms to the water pipeline channel will lead to residual phase rotations in the post-detection constellation. This will deteriorate the system performance as measured by bit error rate (BER) and/or the mean squared error (MSE).

This work presents the performance of differential OFDM communication systems and addresses the constellation rotation problem. Two algorithms are proposed to improve the system performance. The first is based on conventional differential encoding but relies on estimating the average time of arrival (ToA). The second is based on double encoding the transmitting symbol

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stream to overcome the problem of phase rotation. The paper is structured as follows: Sec. 2 includes the system model of differential OFDM system and the two proposed algorithms, Sec. 3 presents the experimental results, and Sec. 4 concludes the work.

2. System model

Differential OFDM communication system design is described in detail in Aval and Stojanovic (2015), and we briefly review the system model here. We consider an OFDM system with bandwidth BW and N carriers, so that the carrier spacing is $\Delta f = BW/N$. The lowest carrier frequency is denoted f_0, and the nth carrier is specified as $f_n = f_0 + n\Delta f$, $n = 0, 1, \ldots, N-1$. Each carrier transmits a differentially encoded data symbol d_n, and the data symbol is modulated by a phase shift keying (PSK) scheme with unit amplitude. d_n is differentially encoded across subcarriers with the original data symbol b_n by the following relationship $d_n = d_{n-1}b_n$, $n = 1, 2, \ldots, N-1$, with $d_0 = 1$. The transmitted signal in one OFDM block can be written as

$$s(t) = \mathrm{Re}\left(\sum_{n=0}^{N-1} d_n e^{j2\pi f_n t}\right),\ t \in [0, T], \tag{1}$$

where T represents the duration of one OFDM block. After down-conversion and FFT demodulation, the signal received on the nth carrier is $y_n = H_n d_n + w_n$, where H_n is the channel coefficient and w_n is zero-mean noise. In a properly designed OFDM system, the carrier spacing is narrow enough such that the channel coefficient of adjacent carriers are approximately the same, i.e., $H_n \approx H_{n-1}$. Differential detection can then be accomplished by forming an estimate $\hat{b}_n = y_n/y_{n-1}$ and choosing the nearest data point $\tilde{b}_n$ as the decision on the data symbol b_n.

The channel coefficient can be written in a polar form as $H_n = |H_n|\angle\theta_n$, where $|H_n|$ and θ_n are the magnitude and phase of the channel coefficient, respectively. For signals traveling across a water pipeline, the assumption $H_n \approx H_{n-1}$ is true only under perfect timing synchronization which leaves no residual error. However, the modal nature of multipath propagation in the pipeline channel (Jing *et al.*, 2018) is likely to yield a residual delay error after front-end synchronization. When that is the case, the channel coefficient phase will exhibit rotation, such that $\theta_n = \theta_{n-1} + \Delta\theta$, where the phase difference is related to the residual delay. In order to improve the performance of differential OFDM system in such condition, two algorithms are proposed to solve this problem.

2.1 Phase adjustment by estimating the average ToA

One solution to the phase problem is to estimate the phase difference between adjacent channel coefficients. The phase difference on each subcarrier can be calculated by $\Delta\theta_n = 2\pi\Delta f\tilde{\tau}$, where $\tilde{\tau}$ is the average ToA of the narrow band impulse response of a frequency band with center frequency at f_n and a narrow bandwidth $\Delta\tilde{f}$. The impulse responses can be obtained by sending pilots to estimate the channel coefficients and taking the IFFT of the channel coefficients of each narrow sub frequency bands. The phase difference on each carrier is $\Delta\hat{\theta}_n = \angle y_n/y_{n-1}$ and the average phase difference $\Delta\hat{\theta} = [1/(N-1)]\sum_{n=1}^{N}\Delta\hat{\theta}_n$. Incorporating the estimate of the average phase difference, the data symbol estimate becomes

$$\hat{b}_n = \frac{y_n}{y_{n-1}} e^{-j\Delta\hat{\theta}}, \tag{2}$$

and the decision on b_n is made by choosing the data point $\tilde{b}_n$ nearest to $\hat{b}_n$.

2.2 Double differential encoding

The second solution is implementing double encoding at the transmitter side. Instead of transmitting the differentially encoded symbol d_n, a double-differentially encoded symbol c_n is transmitted, where $c_n = c_{n-1}d_n$, $n = 1, 2, \ldots, N-1$, and $c_0 = 1$. The relation between the intermediate symbol d_n and the original data symbol b_n remains the same, which is $d_n = d_{n-1}b_n$, $n = 1, 2, \ldots, N-1$, with $d_0 = 1$. Again we assume the adjacent channel coefficients are similar $H_{n+1} \approx H_n \approx H_{n-1}$ and the noise component is negligible, so that the symbol can be detected through the estimate

$$\hat{b}_n = \frac{y_n y_{n-2}}{y_{n-1}^2}, \tag{3}$$

and choosing the nearest data point $\tilde{b}_n$ as the decision on the data symbol b_n. In double differential encoding, the phase difference will be canceled.

3. Experimental results

In order to validate the feasibility of differential OFDM in water pipeline channels and to verify the effectiveness of the proposed algorithms, the water pipeline channel in a laboratory environment was measured. The channel transfer function of a steel pipeline filled with static water was measured by a vector network analyzer. The pipeline was 5.8 m long with 6.5 cm diameter, and two acoustic transducers were placed at 2.87 m separation. The measured channel is a static channel with no Doppler, and measurements also show that the Doppler effect will remain insignificant with water flow. Channel noise has been studied previously (Dubey *et al.*, 2019) and found to be Gaussian at frequencies higher than 10 kHz. Consequently, the measured steel-pipeline water channel together with additive complex Gaussian noise is used as the simulated communication channel. The channel bandwidth BW is chosen to be 10 kHz from 20 to 30 kHz for data communication, and the delay spread is around 12 ms. The channel is sampled at 80 kHz. A 20 ms cyclic prefix is inserted between OFDM symbols for all simulation scenarios.

3.1 Constellation diagram results

Figures 1 and 2 show constellation diagrams for the received QPSK symbols of coherent OFDM and differential OFDM communication techniques. Each figure part shows all N received QPSK symbols from all subcarriers in one OFDM symbol. In Fig. 1(a), the received constellation for the coherent OFDM technique is shown while the remaining results are for differential OFDM systems. We use MSE to reflect the deviation of the received symbols from the ideal location and it is defined by

$$MSE = \frac{1}{N}\sum_{n=0}^{N-1} |b_n - \hat{b_n}|^2. \quad (4)$$

Pseudo-random sequences were generated for the experiments. For each MSE measurement, 40 960 QPSK symbols (81 920 bits) were transmitted through the channel.

The constellation diagrams of differential OFDM systems rotate clockwise, and the received constellation rotates further from the ideal location when the number of subcarriers decreases, i.e., the frequency spacing between adjacent carriers increase. The performance of differential OFDM improves when the number of subcarriers N increases, and when $N = 4096$ the $MSE = -20.56$ dB.

Both the proposed algorithms are effective in terms of addressing the rotation issue of the received constellation diagram as shown in Fig. 2. For this 10 kHz channel, 128 evenly separated pilot tones are selected for the ToA estimation. While the two methods exhibit distinctive performance differences at different SNR, at 30 dB SNR, estimating the ToA provides the best MSE performance. On the contrary, at 50 dB SNR, doubly encoding the transmitting symbol shows outstanding MSE performance.

3.2 Received MSE performance

The relationship of average MSE versus SNR for the two proposed approaches are compared in Fig. 3. Differential OFDM with ToA estimation outperforms conventional differential OFDM across the entire range of SNR because it corrects the residue phase rotations. However, the performance of differential encoding innately suffers from the small difference between adjacent channel coefficients. When SNR is high enough, the noise influence on the system performance becomes negligible compared to the error caused by the difference between adjacent channel coefficients. Consequently, the MSE performance of differential encoding saturates at high SNR. When the number of subcarriers N increases, the coherence between adjacent tones improves. Hence, we observe the performance gap among differential OFDM with different N.

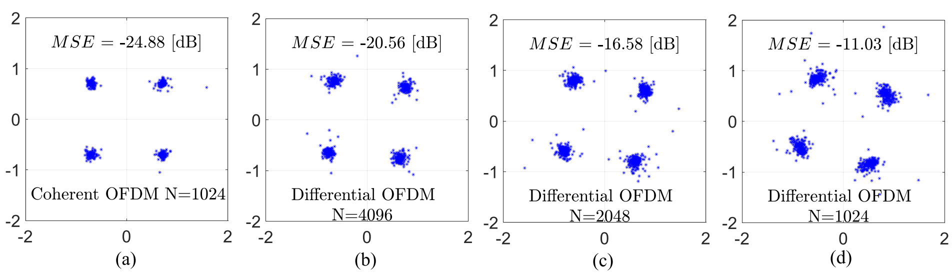

Fig. 1. (Color online) Received constellation diagrams of coherent OFDM and differential OFDM system at 30 dB received SNR.

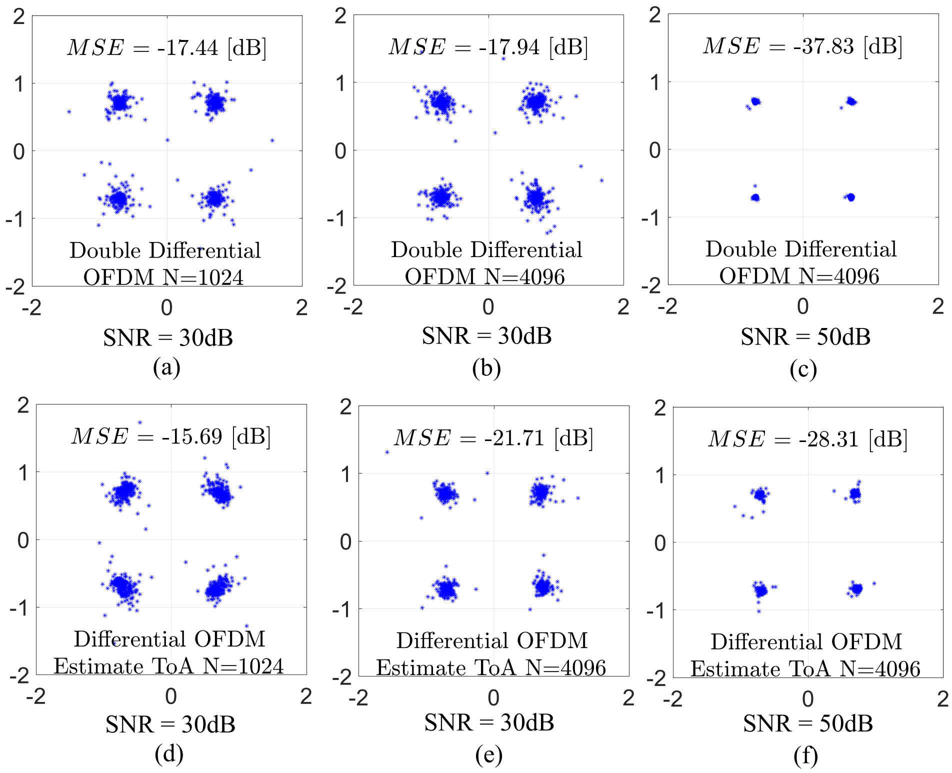

Fig. 2. (Color online) Received constellation diagrams of differential OFDM system with ToA estimation and doubly encoded differential OFDM system.

Double differential OFDM performs poorly in the low SNR region because the algorithm is more sensitive to the noise, which is expected given the fact that it involves not only quadratic noise components but higher-order components as well, while at high SNR, the MSE continues to improve with increase in SNR without saturation. The reason for such behavior is that double encoding incorporates adjacent subcarriers on both sides and cancels phase and amplitude errors caused by the difference between adjacent channel coefficients. The double differential algorithm has the best performance at high SNR. In Jing *et al.* (2018), the SNR in a water pipeline channel in a laboratory environment was found to be $\mathrm{SNR} = 63[\mathrm{dB}] - 0.98[\mathrm{dB/m}]z$, where z is the channel length. 50 dB SNR can be achieved at 10 m distance, and if a transducer that was specifically tuned for transmission (projector) were used, then it would have been possible to achieve longer distance for 50 dB SNR in pipeline.

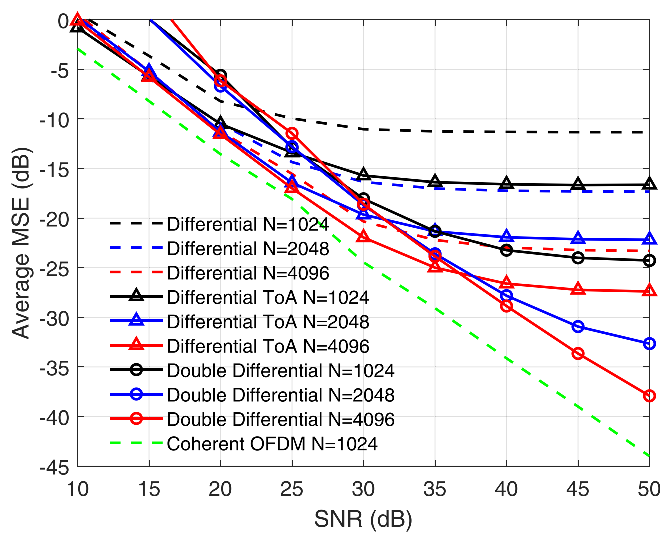

Fig. 3. (Color online) Average MSE performance versus received SNR.

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4. Conclusion

Differential OFDM is shown to be a viable technique for communication in water pipeline channels, and the two proposed algorithms can effectively improve the system performance. Both methods are effective for addressing the rotation of the constellation diagrams. Compared to the conventional differential OFDM system, the estimation of average time of arrival can improve MSE performance at all input SNRs. However, MSE performance saturates at high SNR. Doubly encoded differential OFDM is very sensitive to noise. The system performs poorly at low SNR, but at high SNR the MSE performance will not saturate and get closer to the performance of a coherent OFDM system.

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