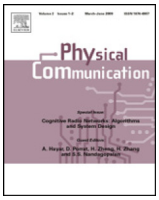
Physical Communication 18 (2016) 15–27

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom



Full length article

Further results on multicarrier MFSK based underwater acoustic communications

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ARTICLE INFO

Article history:
Received 24 March 2015
Received in revised form 22 September 2015
Accepted 7 December 2015
Available online 2 January 2016

Keywords:
Underwater acoustic communications
OFDM
MFSK
Impulsive noise
Narrowband interference

ABSTRACT

Multicarrier M-ary frequency shift keying (MFSK), a parallel transmission of multiple MFSK data streams, is one basic reference scheme for underwater acoustic communications due to low-complexity incoherent processing at the receiver and ease of implementation. In this paper, we provide some further results for multicarrier MFSK based on the recent development of coherent orthogonal frequency division multiplexing (OFDM) schemes. Specifically, we adopt an OFDM based representation, develop a residual Doppler shift compensation approach at the receiver, and present different ways of computing the soft likelihood information for multicarrier MFSK transmissions in combination with nonbinary channel coding. As compared with coherent OFDM, simulation and semi-experimental results show that multicarrier MFSK has consistent performance in channels with different numbers of paths and in environments with different types of external noise.

1. Introduction

The underwater acoustic channel is commonly regarded as one of the most challenging channels for communication [1]. Lacking a widely adopted channel model, acoustic communication algorithms are often developed based on experimental data validation, and performance results from different experiments are often not directly comparable because the system performance depends on the site geometry and environmental conditions [1,2]. On the signal processing level, the major challenges are due to the large delay spread and fast time variation of the propagation paths [1,2]. Based on different principles, a variety of digital modulation schemes have been studied and tested for underwater acoustic communications over the past three decades [1,3]. Broadly speaking, they fall into two main categories, as illustrated in Fig. 1.

- Single carrier approaches. Direct sequence spread spectrum (DSSS) (e.g., [4–6]) as well as sweep-and-spread carrier (S2C) schemes [7] transmit information sequence in a signal band that is larger than the information rate. Lowering the spectrum efficiency much less than 1 bit per second per Hz (bit/s/Hz), robust performance could be achieved in low signal to noise ratio (SNR) applications or acoustic channels with a large number of propagation paths. Without spread spectrum operations, phase-coherent transmissions often operate at spectrum efficiency around one bits/s/Hz (e.g., 0.5–2 bit/s/Hz). An effective equalizer is needed at the receiver side, and there are a plethora of receivers developed (e.g., [8–11]). Recently, multi-input multi-output (MIMO) techniques have been adopted to increase the spectrum efficiency to several bits/s/Hz (e.g., [12–15]).

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http://dx.doi.org/10.1016/j.phycom.2015.12.001
1874-4907/

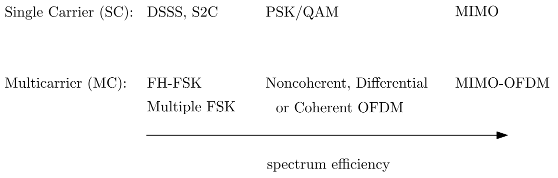

Fig. 1. The overview of underwater acoustic communication methods.

- Multicarrier approaches. There are multiple frequency points, or subcarriers, available in the signal band. Frequency hopped frequency-shift-keying (FSK) hops a FSK-modulated symbol to a different frequency point at each symbol interval [16]. As a spread spectrum scheme, it has an efficiency much lower than 1 bit/s/Hz. Multiple FSK data streams could be transmitted in parallel to increase the data rate, where the center frequency of each data stream could be fixed or could hop within the signal band [17–19]. Orthogonal-frequency division multiplexing (OFDM) uses closely packed orthogonal subcarriers, where the superposition of parallel subcarriers is implemented based on the discrete Fourier transform. On top of OFDM, noncoherent modulations such as on–off keying (OOK) [20] and coherent modulations such as phase-shift-keying and quadrature-amplitude-modulation (e.g., [21–25]) on each subcarrier, or differential modulation can be adopted across OFDM subcarriers [26,27]. The spectrum efficiencies are typically around one or two bits/s/Hz. MIMO-OFDM further increases the spectrum efficiency to several bits/s/Hz through parallel transmissions in the spatial domain (e.g., [28,29]).

Note that different schemes have different characteristics on data rate, operational SNR ranges, and receiver complexities. Hence a particular application will have its own favorite among the available choices.

In this paper, we focus on the multicarrier MFSK scheme. Intuitively, the transmission consists of multiple M-ary FSK data streams in parallel, with each data stream located at a different center frequency [17–19]. Consistent with this intuitive idea, we choose to adopt the OFDM based implementation, where the subcarriers are overlapping but orthogonal to each other; hence another suitable name for this particular implementation is OFDM-MFSK. The key motivation for this paper is to leverage the insights learned from the progresses made on coherent OFDM (see e.g., [25] and references therein) to the transceiver design of the noncoherent multicarrier MFSK scheme. The specific contributions of this paper are as follows.

- We present a method for residual Doppler shift compensation at the receiver to reduce the intercarrier interference (ICI). Different from existing approaches, the proposed method does not require the existence of null subcarriers [22] or pilot tones [19].
- We evaluate the performance of the OFDM-MFSK scheme with nonbinary channel coding with two different ways to compute the log-likelihood ratio (LLR). Matching the size of the M-ary modulation with the size of Galois field avoids the bit to symbol mapping and vice versa. It also avoids the need to estimate the channel amplitude and the noise variance in one presented method of the LLR computation.
- We compare the performance of OFDM-MFSK with that of coherent OFDM in the presence of different types of external noises, including Gaussian noise, impulsive noise, and partial-band partial-block-duration noise. Performance results show that the OFDM-MFSK scheme exhibited its consistency over OFDM-BPSK in two aspects: consistency against different numbers of paths in a multipath channel, and consistency over different types of external noise.

To our knowledge, these issues have not been explicitly addressed in the literature for the multicarrier MFSK scheme. The study in this paper hence contributes to further understanding of this legacy scheme.

The rest of the paper is organized as follows. Section 2 presents the transmitter design and the PAPR reduction method. Section 3 presents the receiver design, with the Doppler shift compensation and the coupling with nonbinary channel coding. Sections 4 and 5 contain simulation and experimental results, respectively. Conclusions are drawn in Section 6.

2. Transmitter design

In this paper, we adopt an implementation of multicarrier MFSK where overlapping OFDM subcarriers are used to carry MFSK symbols. The presentation here will follow the zero-padded (ZP) OFDM structure in [22]. Consider one OFDM block with symbol duration T, hence the subcarrier spacing is $1/T$. Assume that there are K subcarriers in total over a signal band $B = K/T$. The kth subcarrier is located at the frequency

$$f_k = f_c + \frac{k}{T}, \quad k = -\frac{K}{2}, \ldots, \frac{K}{2} - 1, \tag{1}$$

where f_c is the center frequency. Let T_g denote the zero-padding interval and $T_{bl} = T + T_g$ the total block duration corresponding to one ZP-OFDM block. With $d[k]$ as the information symbol on the kth subcarrier and $\phi[k]$ a phase rotation term to be specified later, the transmitted signal is

$$\tilde{x}(t) = \sum_{k=-K/2}^{K/2-1} e^{j\phi[k]} d[k] e^{j2\pi f_k t} g(t) \tag{2}$$

where $g(t)$ is the rectangular pulse shaping filter: $g(t) = 1/T$ for $t \in [0, T]$ and $g(t) = 0$ elsewhere.

Now, we specify how the information bits are mapped to the data symbols $\{d[k]\}$. Suppose that there are N_g parallel MFSK transmissions in one OFDM block and a channel code of rate r_c is used. If a binary code is used, $r_c N_g \log_2 M$ information bits will be coded into $N_g \log_2 M$ bits, which will be divided into N_g groups. For the ith group, let $\{l_0, \ldots, l_{M-1}\}$ denote the subcarrier indexes used by MFSK. Based on the value of $\log_2 M$ coded bits, one of $d[l_0], \ldots, d[l_{M-1}]$ will be one and the rest will be zeros. In this paper, we adopt the nonbinary channel codes from [30]. Operating over Galois field GF(M), $r_c N_g$ information symbols are mapped to N_g coded symbols, and each coded symbol is used to choose one frequency out of M choices for transmission. Matching the size of the MFSK