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OFDM Communication Method for a Parametric Loudspeaker

パラメトリックスピーカーに適した OFDM 通信方式

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1. Introduction

Digital acoustic communication in air is an important technology for wireless communication and broadcasting with mobile devices like a smartphone. The main advantages of acoustic communication are the ease of implementation of modulation-demodulation schemes and the use of existing hardware in mobile devices (such as loudspeakers and microphones). However, the sound emitted in multi-user communication scenario causes signal interference. Thus, we focus on the use of parametric array loudspeaker (PAL) for acoustic communication shown in **Fig. 1**. When a PAL emits an ultrasonic signal amplitude-modulated by the transmission signal $x(t)$, the sound $z'(t)$ is demodulated due to the nonlinearity of the air and received by the microphone. Then, received sound $z'(t)$ contains the fundamental and the 2nd harmonic of the signal $x(t)$ [1]. As a communication method considering nonlinear acoustic channel, a technique using minimum shift keying (MSK) has been proposed [2]. This is a single carrier scheme and effectively uses 2nd harmonics during demodulation.

Orthogonal frequency division multiplexing (OFDM) is a communication scheme that encodes digital data on multiple carrier frequencies. The main advantage of OFDM over single carrier scheme is its robustness in multi-path channels with reasonable computational complexity [3]. As shown in Fig.1 (b), it is assumed that the sounds reflected on the floor are also received as well as the direct sounds. However, when applying the conventional OFDM scheme to communication with nonlinear channel, the communication quality is significantly degraded [4]. Thus, to improve reliability of acoustic communication in multi-path and nonlinear environments, we propose OFDM communication method suitable for a PAL, and the feasibility is experimentally confirmed.

2. Proposed OFDM communication scheme

Fig. 2 shows the block diagram of the proposed OFDM communication system. Let T denote OFDM signal length and let T_g denote guard interval length. The entire OFDM signal length is $T+T_g$. Then, the subcarrier frequencies f_n are located at

$$f_n = n \cdot \frac{1}{T} (n = k, k+1, \ldots, k+N-1) \qquad (1)$$

where N and k are the total number of subcarriers and index of start frequency in the baseband, respectively. Then, we define $\boldsymbol{F}_{\mathrm{A}}$ and $\boldsymbol{F}_{\mathrm{N}}$ as non-overlapping sets of active and null subcarriers respectively that satisfy $\boldsymbol{F}_{\mathrm{A}} \cap \boldsymbol{F}_{\mathrm{N}} = \{k, k+1, k+2, \ldots, k+N-1\}$. The total number of active subcarriers is defined as M.

Then, let d_n denote a complex symbol converted from binary messages. OFDM baseband signal $x(t)$ is given as

$$x(t) = \sum_{n \in F_{\mathrm{A}}} d_n \exp\left(j 2\pi \frac{n}{T} t\right) \;, t \in [-T_g, T]. \qquad (2)$$

When a PAL emits an ultrasonic signal $y(t)$ [$=(1+m\,x(t)) \cdot \sin(2\pi f_c t)$], where m and f_c are the modulation index ($0 \leq m \leq 1$) and carrier frequency, the audible signal $z(t)$ can be received as

$$z(t) = P\left\{2m \frac{\partial^2}{\partial t^2} x(t) + m^2 \frac{\partial^2}{\partial t^2} x^2(t)\right\} \qquad (3)$$

where P is a value determined by parameters such as the gain of amplifiers, the sound speed and the air density. As shown in Eq. (3), received sound $z(t)$

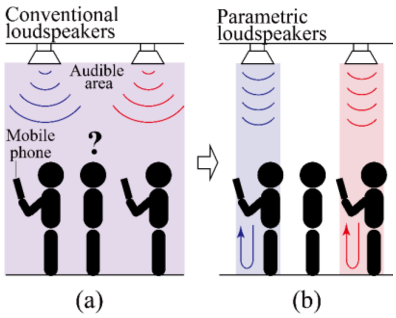

Fig. 1 (a) conventional method and (b) proposed method of acoustic communication.

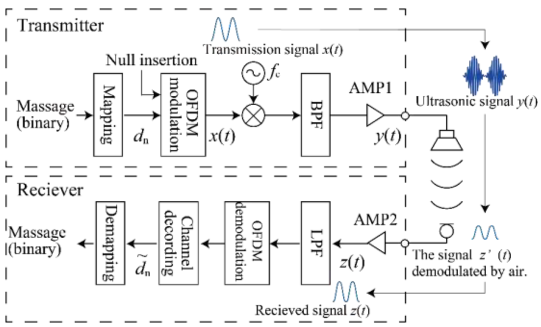

Fig. 2 Block diagram of proposed OFDM communication system.

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contains the fundamental (first term) and 2nd harmonic sound (second term). Assuming that $x(t)$ consists of only two frequencies f_1 and f_2, the intermodulation between f_1 and f_2 is given by sum and difference frequencies: f_1+f_2, $2f_1$, $2f_2$, f_1-f_2 and f_2-f_1. We propose design policies [1] and [2] of active subcarriers set $\boldsymbol{F}_\mathrm{A}$ in order to avoid overlapping intermodulation with active subcarriers.

[1] Subcarrier allocation
: Index $\boldsymbol{F}_\mathrm{A}$ of active subcarriers are odd.

[2] Frequency band range
: The maximum index of $\boldsymbol{F}_\mathrm{A}$ is less than twice the minimum index of them. [$k < (k+N-1)/2$]

3. Experiment in an anechoic chamber

3.1 Experiment procedure

We evaluated the performance of the proposed subcarrier allocation design in two experiments in an anechoic chamber. The transmitter consists of a PC with software (MATLAB, Mathworks), digital to analog converter (DAC) (USB-6212, National Instruments), a power amplifier (AMP1: AP20d, FOSTEX) and a PAL consisting of 49 emitters (T40-16, Nicera). The receiver consists of a microphone (C9767, DB products limited), an operational amplifier (AMP2: JRC4580), analog to digital converter (ADC) (USB-6212). First, the computer calculates the OFDM signal $y(t)$ and the transmitter emits an ultrasonic signal with a PAL. Second, the signal is demodulated due to the nonlinearity of the air and received by the microphone. Finally, the messages are demodulated by the receiver. In this experiment, the distance between a PAL and a microphone was 1 m. OFDM signal length T was 8 ms (the frequency spacing $1/T$=125 Hz), and the guard interval T_g was 8 ms. Sampling rate f_s and carrier frequency f_c were 100 kHz and 40 kHz, respectively. Modulation method was quadrature phase-shift keying (QPSK). We measure the relationship between the energy per bit to noise power spectra density (E_b/N_0) and bit error ratio (BER). **Fig. 3** shows the BER results. E_b/N_0 is a parameter when comparing the BER performance among different digital modulation schemes regardless of band-width.

3.2 Experiment results

We confirmed the performance of [1] subcarrier allocation when the frequency band range was constant [frequency band B=1~9.785 kHz ($\boldsymbol{F} \cap \boldsymbol{F}_\mathrm{N}$ = {8,9,10,…,79})]. Frequency sets of active subcarriers were as follows.

- Case 1: Dense ($\boldsymbol{F}_\mathrm{A}$= {8, 9, 10, …, 78, 79})
  Data rate: 9000 bps
- Case 2: Odd ($\boldsymbol{F}_\mathrm{A}$= {9, 11, 13, …, 77, 79})
  Data rate: 4500 bps [proposed]

The BER result [Fig. 3 (a)] indicates that the proposed method [Case 2] (red line) designed by the policy [1] reduces the BER in the region of high power (E_b/N_0>3 dB).

We also confirmed the performance of [2] frequency band range when active subcarriers are densely located. Frequency sets of active subcarriers were as follows.

- Case 3: B=2 ~ 7.875 kHz, ($\boldsymbol{F}_\mathrm{A}$= [16, 17, …, 63])
  Data rate: 6000 bps
- Case 4: B=4 ~ 7.875 kHz, ($\boldsymbol{F}_\mathrm{A}$= [32, 33, …, 63])
  Data rate: 4000 bps [proposed]

The BER result [Fig. 3 (b)] indicates that the proposed method [Case 4] (purple line) designed by the policy [2] reduces the BER. Furthermore, the worst BER result is conventional method [Case 1] (blue line). It is suggested that, the intermodulation components overlap with more active subcarriers than other methods.

4. Conclusion

By focusing the property that the parametric loudspeaker emits the 2nd harmonic, we proposed the idea of subcarrier allocation: [1] odd subcarrier and [2] frequency band range [$k<(k+N-1)/2$], and the feasibility was experimentally confirmed. BER results indicate that the proposed OFDM method can communication without degrading BER performance even if a parametric loudspeaker emits a high power.

Reference

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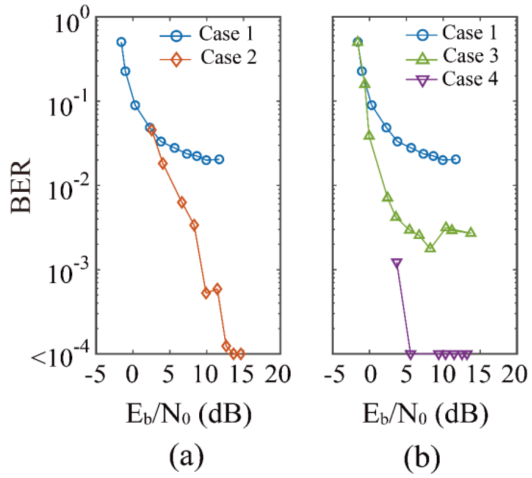

Fig. 3 E_b/N_0 vs BER results. (a): Performance of [1] and (b): performance of [2].