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Waveform Design for Energy Efficient OFDM Transmission

Homayoun Nikookar

Abstract

In this chapter, a green radio transmission using the binary phase-shift keying (BPSK) modulated orthogonal frequency-division multiplexing (OFDM) signal is addressed. First, the OFDM transmission signal is clearly stated. For a specified performance of the system, the least transmit power occurs by the optimal OFDM shape, which is designed to minimize the average inter-carrier interference power taking into account the characteristic of the transmit antenna and the detection process at the receiver. The optimal waveform is obtained by applying the calculus of variations, which leads to a set of differential equations (known as Euler equations) with constraint and boundary conditions. Results show the transmission effectiveness of the proposed technique in the shaping of the signal, as well as its potential to be further applied to smart context-aware green wireless communications.

Keywords: green radio transmission, multicarrier, OFDM, signal design, optimization

1. Introduction

The advancements in the field of wireless communication have led to many exciting applications such as mobile internet access, health care and medical monitoring services, smart homes, combat radios, disaster management, automated highways, and factories. With each passing day, novel and advanced services are being launched even while existing ones continue to flourish. Wireless services have now found applicability in other sectors too including health care, transportation, security, logistics, education, and finance. Demand for wireless services is thus expected to grow in the foreseeable future. However, with the increasing popularity of wireless services (such as the 5G and the future 6G), the requirements on prime resources such as green transmission and radio spectrum are put to a great test. Recent studies have shown that the energy costs account for as much as half of a mobile service provider's annual operating expenses. Therefore, making the communication equipment more efficient in relation to its power consumption not only has implications with regard to environmental pollution and the level of CO₂ emission, but also makes economic sense and can eventually reduce the cost of wireless services (for providers and users).

In this regard and given the 10% of the world's energy consumption due to the information and communication technology (ICT) industry [1], energy efficiency has become one of the key performance indicators (KPI) in the design and implementation of radio systems.

The theme of green radio communications is to design energy-efficient wireless communication techniques and protocols, which optimally utilizes available resources and minimize power consumption. Various strategies are employed for the design of energy-efficient wireless systems; among them are energy-efficient new radios [2, 3], minimization of interference [4], and optimal resource allocation [5]. In this chapter, we would like to design a signal for energy-efficient OFDM transmission. As can be seen from Section 4, we will reduce the power dissipation of the transmitter and consequently the level of CO₂ emission of the radio system by optimal design of a waveform for transmission that minimizes inter-carrier interference of the OFDM system. In this way for reaching the same performance level of the provided communication services, a lower power level will be required for transmission, which leads to a green wireless radio system. As the reduction of the inter-carrier interference level is the basis for the optimization of OFDM signal, the approach explained in this chapter falls in the category of green radio by minimization of interference mentioned above.

The rest of the chapter is organized as follows. In Section 2, the basics of the OFDM transmission being provided. In Section 3, the data detection procedure in the receiver is mathematically explained. This procedure is further needed for the maximization of the detection performance of the system. Waveform design and the optimization procedure using calculus of variations and the Lagrange multiplier are detailed in Section 4, and the results are discussed. Conclusion remarks appear in Section 5.

2. OFDM transmission

Multicarrier technique, also called orthogonal frequency-division multiplexing (OFDM), used among others in the DAB (Digital Audio Broadcasting), DVB (Digital Video Broadcasting), and 5G wireless communication systems, is a modulation method that is used for the high-speed data communications. In this technique, transmission is carried out in parallel on different orthogonal frequencies (known as subcarriers). By orthogonality, we mean different frequencies—that are used for transmission—do not influence each other. Because of the orthogonality of subcarriers, data on different frequencies do not interfere with each other and subsequently, a higher performance can be achieved with this transmission technique. This technique is desirable for the transmission of digital data through multipath fading radio channels. Since by parallel transmission, the deleterious effect of fading is spread over many bits; therefore, instead of a few adjacent bits completely destroyed by the fading, it is more likely that several bits only be slightly affected by the channel. The other advantage of this technique is its spectral efficiency. In OFDM, the spectra of subchannels (subcarriers) overlap each other while satisfying orthogonality, giving rise to the spectral efficiency. Because of the parallel transmission, in the OFDM technique, the transmit symbol duration is increased. This has the added advantage of this method to work in the radio channels having impulsive noise characteristics. The other advantage of the OFDM method is its implementation with the fast Fourier transform (FFT) algorithm, which provides efficient full digital implementation of the modulator and demodulator. A detailed study of OFDM for wireless personal communications and its comparison with other modulation methods can be found in [6].

In the serial data transmission sequences of data are transmitted as a train of serial pulses. However, in the OFDM parallel transmission, each bit of a sequence of M bits modulates a subcarrier. A simple block diagram of the OFDM transmitter is shown in **Figure 1**. The input data with the rate R are divided into the M parallel

Figure 1.
 Block diagram of the OFDM system.

information sequences with the rate R/M . Each sequence modulates a subcarrier. In the OFDM method, the frequency of the m th subcarrier is

$$f_m = f_0 + \frac{m}{T}, \quad m = 0, 1, 2, \dots, M-1 \quad (1)$$

where f_0 is the lowest frequency, which can be considered zero without loss of generality, M is the number of subcarriers, and T is the OFDM symbol duration. The OFDM transmitted signal is written as

$$s(t) = \frac{1}{\sqrt{M}} \sum_{i=-\infty}^{\infty} \sum_{m=0}^{M-1} b_m(i) e^{j2\pi f_m t} g(t - iT) \quad (2)$$

where $b_m(i)$ is the symbol of the m th subchannel at time interval iT , and for the BPSK modulation is ± 1 and $g(t)$ is the shape of the transmitter filter that is nonzero in $(0, T)$, which in this chapter we will try to optimize its shape. The factor $1/\sqrt{M}$ in (2) is used in order to keep the power of the OFDM signal constant disregarding the number of subcarriers. For the interval $(0, T)$, the OFDM signal can be expressed as follows:

$$s(t) = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} b_m(0) e^{j2\pi f_m t} g(t), \quad 0 \leq t < T \quad (3)$$

In the transmitter, the abovementioned OFDM signal is sent to the antenna for transmission through the radio channel. Since the OFDM transmission is a very wideband transmission technique, the transmit antenna will influence this signal. The impact of the antenna in the transmission band can be modeled as a differentiator [7]. Accordingly, the transmitted signal is written as follows:

$$x(t) = \frac{d}{dt} s(t) = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} b_m(0) [j2\pi f_m e^{j2\pi f_m t} g(t) + e^{j2\pi f_m t} \dot{g}(t)], \quad 0 \leq t < T \quad (4)$$

where $\dot{g}(t) = \frac{d}{dt} g(t)$. The above Eq. (4) can be simplified as

$$x(t) = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} b_m(0) e^{j2\pi f_m t} [j2\pi f_m g(t) + \dot{g}(t)], \quad 0 \leq t < T \quad (5)$$

3. Data detection procedure in the OFDM receiver

Now noting the block diagram of the OFDM system, **Figure 1** and assuming an ideal channel and no noise, in the receiver for the detection of the k th bit, the following operation is done:

$$z_k = \int_0^T x(t) e^{-j2\pi f_k t} dt = \int_0^T \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} b_m(0) e^{j2\pi f_m t} [j2\pi f_m g(t) + \dot{g}(t)] e^{-j2\pi f_k t} dt \quad (6)$$

The decision variable z_k can be written as follows:

$$z_k = \frac{1}{\sqrt{M}} \int_0^T b_k(0) [j2\pi f_k g(t) + \dot{g}(t)] dt + \frac{1}{\sqrt{M}} \sum_{m=0, m \neq k}^{M-1} b_m(0) e^{j2\pi (f_m - f_k) t} [j2\pi f_m g(t) + \dot{g}(t)] dt \quad (7)$$

The first part of (7) is the useful signal for detection of bit b_k and the second term is the inter-carrier interference (ICI), that is,

$$ICI = \frac{1}{\sqrt{M}} \int_0^T \sum_{m=0, m \neq k}^{M-1} b_m(0) e^{j2\pi (f_m - f_k) t} [j2\pi f_m g(t) + \dot{g}(t)] dt \quad (8)$$

As our data bit modulation is BPSK, we are only interested in the real part of the first term of (7). Furthermore, by ignoring the ICI term the decision variable becomes

$$z_k = \frac{1}{\sqrt{M}} \int_0^T b_k(0) \dot{g}(t) dt \quad (9)$$

So, for the best detection performance, we would like to have

$$\int_0^T \dot{g}(t) dt = 1 \quad (10)$$

This is a normalized constraint that will be used later on in finding a solution to the optimization problem.

4. Waveform design and optimization procedure

In this chapter, we would like to design the waveform $g(t)$ to have the least transmit power while having the best data detection performance. This can be achieved by minimizing the power of interference. In this way, when the power of ICI is minimized the least transmit power will be needed to provide a specified data detection performance. In the following, the power of ICI is obtained. Since the mean of BPSK data is zero, $E(b_m) = 0$, using Eq. (8) the variance of the ICI interference is written as follows:

$$\sigma_{ICI}^2 = \frac{1}{M} \int_0^T \int_0^T \sum_{m=0, m \neq k}^{M-1} \sum_{n=0, n \neq k}^{M-1} \overline{b_m(0) b_n^*(0)} e^{j2\pi (f_m t - f_n u)} e^{j2\pi f_k (t-u)} [j2\pi f_m g(t) + \dot{g}(t)] [-j2\pi f_n g(u) + \dot{g}(u)] dt du \quad (11)$$

Since the BPSK-modulated data bits on different carriers are assumed to be independent, that is, $E[b_m b_n^*] = \delta_{m,n}$, and by using the properties of Dirac delta function, Eq. (11) reduces to

$$\sigma_{ICI}^2 = \frac{1}{M} \int_0^T \sum_{m=0, m \neq k}^{M-1} (4\pi^2 f_m^2 g^2(t) + \dot{g}^2(t)) dt \quad (12)$$

By changing the order of integral and summation we have:

$$\sigma_{ICI}^2 = \frac{1}{M} \sum_{m=0, m \neq k}^{M-1} \int_0^T (4\pi^2 f_m^2 g^2(t) + \dot{g}^2(t)) dt \quad (13)$$

Using Eq. (1) and by denoting

$$A_m = \frac{2\pi m}{T} \quad (14)$$

The power of ICI interference becomes

$$\sigma_{ICI}^2 = \frac{1}{M} \sum_{m=0, m \neq k}^{M-1} \int_0^T (A_m^2 g^2(t) + \dot{g}^2(t)) dt \quad (15)$$

Therefore, our index function to minimize can be written as follows:

$$J_{min} = \int_0^T (A_m^2 g^2(t) + \dot{g}^2(t)) dt \quad (16)$$

We would like to find the optimal waveform by minimizing (16) and with respect to the constraint of Eq. (10).

By consideration of this restriction and using the Lagrange multiplier, the *augmented functional* for minimization is written as follows:

$$J_a(g(t), \dot{g}(t), p(t), t) = \int_0^T [A_m^2 g^2(t) + \dot{g}^2(t) + p(t)(\dot{g}(t) - \dot{\nu}(t))] dt \quad (17)$$

$$J_a(g(t), \dot{g}(t), p(t), \dot{\nu}(t), t) = \int_0^T f_a(g(t), \dot{g}(t), p(t), \dot{\nu}(t), t) dt$$

$$f_a(g(t), \dot{g}(t), p(t), \dot{\nu}(t), t) = A_m^2 g^2(t) + \dot{g}^2(t) + p(t)(\dot{g}(t) - \dot{\nu}(t)) \quad (18)$$

where $p(t)$ is the Lagrange multiplier and according to (10)

$$\dot{\nu}(t) = \dot{g}(t) \quad (19)$$

The optimal waveform $g_*(t)$, (subscripts with * indicate the optimal waveforms), which is the extremal for the augmented functional J_a in (17), is the solution of the Euler differential Equation [8]:

$$\frac{\partial f_a}{\partial g}(g_*(t), \dot{g}_*(t), p_*(t), \dot{\nu}_*(t), t) - \frac{d}{dt} \left(\frac{\partial f_a}{\partial \dot{g}}(g_*(t), \dot{g}_*(t), p_*(t), \dot{\nu}_*(t), t) \right) = 0$$

$$\frac{\partial f_a}{\partial \dot{\nu}}(g_*(t), \dot{g}_*(t), p_*(t), \dot{\nu}_*(t), t) - \frac{d}{dt} \left(\frac{\partial f_a}{\partial \dot{\nu}}(g_*(t), \dot{g}_*(t), p_*(t), \dot{\nu}_*(t), t) \right) = 0 \quad (20)$$

Figure 2.
The optimal energy efficient OFDM waveform for different values of M .

By calculation of the Euler equation, we obtain the following differential equations:

$$\ddot{g}_*(t) - A_m^2 g_*(t) = 0 \quad (21)$$

$$\frac{d}{dt} \left(\frac{\partial f_a}{\partial \dot{v}} (g_*(t), \dot{g}_*(t), p_*(t), \dot{v}_*(t), t) \right) = \dot{p}_*(t) = 0 \quad (22)$$

The solution for Eq. (21) is as follows:

$$g_*(t) = C_1 e^{A_m t} + C_2 e^{-A_m t} \quad (23)$$

By using the boundary conditions $g(0) = 0$, and $g(T) = 1$ we have

$$C_1 = -C_2 = \frac{1}{2 \sinh(A_m T)} \quad (24)$$

Accordingly, the optimum waveform $g_*(t)$ for minimal interference, which leads to a minimal transmit power becomes the following:

$$g_*(t) = \frac{\sinh A_m t}{\sinh(A_m T)} \quad (25)$$

where A_m is a constant which is a function of the subcarrier number of the OFDM and the OFDM symbol duration T , see Eq. (14). Therefore, for a specified performance the *hyperbolic sine* (*sinh*) is the best shape for energy-efficient OFDM transmission. In **Figure 2**, the optimal waveform for different values of M is plotted.

5. Conclusion

In this chapter, we designed an optimal shape for energy-efficient OFDM transmission. We started with the formulating of the OFDM transmit signal and its shaping taking into account the behavior of the transmit antenna in the broad bandwidth of the OFDM signal and its detection at the receiver. The energy-efficient optimal waveform was obtained by minimizing the inter-carrier interference power level in the data detection process, which subsequently gives the best performance of the system. Results show that the *sinh* shape needs the least transmit

energy to provide the specified performance. It has to be mentioned that the design framework presented in this chapter (i.e., minimization of ICI power that requires the least transmit power) can directly be applied to other design criteria such as security, spectral efficiency, performance, of OFDM wireless communication networks by merely changing the objective function. However, in this process, the desirable properties of the OFDM signal must be translated into realizable objective functions with constraints, a task that might be quite challenging.

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