Waveform Adaptive Algorithm for Air-Ground Channels Based on OFDM/OQAM Systems (Postprint)

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Abstract

Traditional waveform adaptive design for Orthogonal Frequency Division Multiplexing/Offset Quadrature Amplitude Modulation (OFDM/OQAM) systems primarily optimizes waveforms for channel models with non-exponential delay power spectra and non-U-shaped Doppler power spectra; however, in practice, waveform adaptive design yields different channel matching criterion coefficients for different channel models. By combining the characteristics of ground-to-air channel models and extended Gaussian functions, a novel waveform adaptive design algorithm for OFDM/OQAM systems is proposed based on conventional SINR-optimized OFDM/OQAM system waveform adaptive algorithms. This algorithm introduces a channel matching coefficient , establishes the relationship between waveform time-frequency domain spacing and the channel' s maximum multipath delay as well as maximum Doppler shift through a channel matching criterion, and subsequently combines the traditional SINR optimization function to calculate spreading factor parameters, which are fed back to the transmitter to adjust the filters at both the transmitter and receiver, thereby achieving waveform adaptation. Simulation results demonstrate that the introduction of the channel matching coefficient yields an improvement of over 1.0 dB in system bit error performance under both 4QAM and 16QAM modulation.

Full Text

Preamble

Title: Waveform Adaptive Algorithm for OFDM/OQAM System under Air-Ground Channel

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Abstract: The conventional adaptive waveform design of orthogonal frequency division multiplexing/offset quadrature amplitude modulation (OFDM/OQAM) systems primarily optimizes waveforms for channel models with non-exponential delay power spectra and non-U-shaped Doppler power spectra. However, in practice, waveform adaptive design yields different channel matching criterion coefficients for different channel models. This paper proposes a novel OFDM/OQAM waveform adaptive design algorithm by combining the characteristics of air-ground channel models with extended Gaussian functions (EGF) and building upon traditional signal-to-interference-plus-noise ratio (SINR) optimization approaches. The algorithm introduces a channel matching coefficient to establish the relationship between waveform time-frequency spacing and the channel' s maximum multipath delay and maximum Doppler shift. Combined with the traditional SINR optimization function, the algorithm calculates the optimal filter extension factor parameters, feeds them back to the transmitter, and adjusts the filter banks at both transmitter and receiver to achieve waveform adaptation. Simulation results demonstrate that the introduction of channel matching coefficient provides more than 1.0 dB improvement in system bit error rate performance under both 4QAM and 16QAM modulation.

Keywords: air-ground channel; OFDM/OQAM; waveform adaptive algorithm; extended Gaussian function

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0 Introduction

As a candidate modulation scheme for the 5G physical layer, OFDM/OQAM (offset quadrature amplitude modulation based orthogonal frequency division multiplexing) employs prototype pulse filters with excellent time-frequency localization properties–specifically, extended Gaussian functions (EGF). This enables the system to achieve robust resistance against both inter-symbol interference (ISI) and inter-carrier interference (ICI) without requiring a cyclic prefix (CP). The EGF' s adjustable time-frequency characteristics further allow the system to design appropriate pulse shaping functions for enhanced interference mitigation.

Current waveform adaptive pulse shaping design methods fall into two categories. The first category optimizes filter parameters based on inherent filter characteristics, including least-squares (LS) algorithms, Minimax algorithms for minimizing maximum stopband ripple, and interference energy minimization algorithms. These methods minimize filter sidelobe interference in the frequency domain to optimize OFDM/OQAM pulse shaping functions. Time-frequency localization (TFL) optimization designs pulse shaping functions by optimizing the Heisenberg parameter that characterizes the filter’ s time-frequency concentration. However, these approaches do not incorporate actual channel characteristics and are unsuitable for waveform adaptive algorithms in wide-sense stationary uncorrelated scattering (WSSUS) channels.

The second category combines channel characteristics with signal-to-interference-plus-noise ratio (SINR) optimization to obtain optimal filter parameters. Kozek et al. proposed a design framework for non-orthogonal pulse shapes and established a channel matching criterion between filter and channel characteristics. Schafhuber et al. introduced an SINR optimization method but did not integrate waveform matching criteria into pulse function design. References [7,8] derived two WSSUS channel models from the channel scattering function—one with uniform delay and Doppler power spectra, and another with exponential delay and U-shaped Doppler power spectra—and redefined waveform matching criteria for both models. Reference [9] validated the SINR optimization algorithm under WSSUS channels using DVB-T and DRM channel models. Reference [10] analyzed the energy concentration properties of pulse shaping functions through ambiguity functions, clarifying their impact on filter extension factors in waveform adaptive algorithms. Goto proved that the scattering function remains constant for WSSUS channels with uniform delay and Doppler power spectra, designing pulse shaping functions based on ambiguity function energy concentration. However, these studies focused on OFDM systems without considering OFDM/OQAM system characteristics, where waveform adaptive design produces different channel matching criterion coefficients due to time-frequency lattice relationships, channel models, and EGF filters.

This paper proposes an OFDM/OQAM waveform adaptive algorithm that integrates EGF filters with air-ground channel models. The algorithm derives the channel matching coefficient for WSSUS channel models and formulates a binary optimization function for SINR, enabling calculation of optimal SINR values and corresponding filter parameters.

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1 Channel Model

The WSSUS channel model is commonly employed for time-varying multipath channels in mobile communications. It exhibits uncorrelated characteristics in the delay domain and Doppler frequency shift domain , while maintaining wide-sense stationary properties in the time domain t and frequency domain f. The second-order statistical properties are determined by the scattering function. Previous OFDM waveform adaptive research has categorized WSSUS channels into two models:

Model 1: Time-frequency doubly dispersive channels with uniform delay power spectrum and uniform Doppler power spectrum.

Model 2: Time-frequency doubly dispersive channels with exponential delay power spectrum and U-shaped Doppler power spectrum.

The statistical characteristics of the air-ground channel studied in this paper are summarized in Table 1. The channel parameters include the delay slope, and the minimum and maximum elevation angles of the aircraft. The Parking state exhibits Rayleigh fading with delay and Doppler power spectra following the COST207 standard’ s typical urban environment. The Taxi state shows Rician fading with spectra following the COST207 rural environment. Both En-Route and Arrival states follow Rician distributions. As shown in Table 1, all delay power spectra follow exponential distributions, while all Doppler power spectra follow U-shaped distributions. According to the WSSUS channel model classification, the air-ground channel belongs to Model 2.

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2 Waveform Adaptive Design

WSSUS channels exhibit rapid time-frequency fading characteristics, necessitating real-time adaptation of EGF filters in OFDM/OQAM systems. The adjustable time-frequency properties of EGF filters make waveform adaptive design particularly crucial in WSSUS channels. Figure 1 illustrates the waveform adaptive algorithm design framework.

[Figure 1: see original paper]

As shown in Figure 1, the binary random information sequence generated by the source enters the channel after modulation. The receiver obtains the channel’ s maximum multipath delay and maximum Doppler shift parameters through channel estimation. The waveform adaptive algorithm module then calculates the filter parameters and transmits them to the transmitter via a feedback link, enabling the transmitter to adjust the pulse shaping functions at both ends.

2.1 OFDM/OQAM System Model

The introduction of EGF filters equips OFDM/OQAM systems with robust ISI and ICI resistance without CP. Therefore, this paper establishes the waveform adaptive algorithm based on the OFDM/OQAM system. Due to the real-domain orthogonality property of EGF filters, OFDM systems must employ OQAM modulation, where OFDM symbols are transmitted through real and imaginary branches. Assuming T is the OFDM symbol period, with and representing the subcarrier spacing in the frequency domain and the time offset between adjacent OQAM real-valued symbols in the time domain, respectively, the system’ s time-frequency expression is given by Equation (3).

The equivalent baseband transmitted signal of the time-domain OFDM/OQAM system is expressed as Equation (4), where M denotes the number of subcarriers and a , represents the nth real-valued OFDM/OQAM symbol on the mth subcarrier. The filter basis function for the mth subcarrier and nth symbol at time-frequency lattice point (m,n) is denoted by g , (t), which is the EGF pulse shaping function.

Real-domain orthogonality is expressed through the inner product of transmit and receive filter basis functions as Equation (5), where · denotes the inner product operation, {·} represents the real part operation, and is the Kronecker delta. The real-domain orthogonality condition yields a real symbol when m=m' and n=n' , and an imaginary symbol otherwise.

The ambiguity function of the EGF filter is given by Equation (6), where is the filter extension factor. The channel' s maximum multipath delay and maximum Doppler shift are denoted by and , respectively. The channel matching criterion depends on filter functions and channel characteristics. For example, in OFDM systems based on Gaussian filters, the channel matching coefficient is 1 for channel model 1 and 2/3 for channel model 2.

2.2 Proposed Waveform Adaptive Algorithm

This paper integrates the air-ground channel model into the OFDM/OQAM waveform adaptive algorithm by introducing a waveform matching coefficient to determine the matching relationship between the EGF function and channel characteristics. Consequently, the conventional expression can be reformulated as Equation (8), where W and W_f represent the filter' s time and frequency energy distribution parameters, respectively, describing the filter' s energy dispersion along the time and frequency axes.

Through channel estimation, and can be obtained, and the waveform time-frequency spacing and can be expressed as functions of , , and . Combining Equations (3) and (8) yields the relationship shown in Equation (9).

In the SINR-optimized waveform adaptive design method, the SINR expression is given by Equation (10), where E is the energy of the real-valued symbols, S_H(,) is the channel scattering function (using Model 2), and A_g(,) is the ambiguity function value of the EGF filter. Generally, in OFDM/OQAM systems employing EGF filters with excellent time-frequency concentration, ISI and ICI interference for the desired symbol primarily originate from adjacent symbols. Therefore, Equation (10) can be simplified to Equation (11).

The EGF filter function and its ambiguity function are defined as in Equation (6). For the IOTA function, the parameters are real coefficients, and the function exhibits isotropic attenuation characteristics in both time and frequency domains.

The waveform adaptive algorithm design flowchart is shown in Figure 2. According to Equation (11), the SINR is a binary expression of the waveform matching coefficient and filter extension factor , i.e., SINR(,). By calculating max SINR(,) within the given ranges of (0.5 2) and (1 2), the optimal EGF filter parameters for the current channel model can be obtained and fed back to the transmitter to adjust the filter banks at both transmitter and receiver, achieving waveform adaptation.

The air-ground channel model parameters are configured using the SPIRENT-VR5 spatial channel simulator. In wireless multipath transmission systems based on the Weyl-Heisenberg framework under time-frequency doubly selective fading channels, spectral efficiency improves with higher QAM orders, but system performance degrades accordingly. Therefore, this paper adopts a compromise between spectral efficiency and system performance using 4QAM and 16QAM modulations. The system parameter settings are detailed in Table 2.

[Figure 2: see original paper]

The simulation results of SINR versus and are shown in Figure 3.

[Figure 3: see original paper]

Figures 3(a)-(d) present the waveform adaptive algorithm results for the four air-ground channel states: Parking, Taxi, En-Route, and Arrival. The X-axis represents the filter extension factor , the Y-axis denotes the channel matching coefficient , and the Z-axis shows the SINR. From these results, the optimal (,) pairs for each state can be obtained:

- Parking: (,) = (1.5, 1.537×10)
- Taxi: (,) = (2.0, 1.876×10)
- En-Route: (,) = (1.9, 2.908×10)
- Arrival: (,) = (1.5, 1.480×10)

For classical-EGF (=1), the optimal parameters are: - Parking: (1.0, 1.937×10) - Taxi: (1.0, 2.876×10) - En-Route: (1.0, 4.108×10) - Arrival: (1.0, 1.780×10)

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3 Simulation Results

This section compares the system performance of IOTA filters, classical-EGF pulse shaping functions (without), and -EGF pulse shaping functions (with) under air-ground channel conditions. The system parameters are configured as shown in Table 2.

Using the optimal filters derived above, the bit error rate performance curves for OFDM/OQAM systems with 4QAM and 16QAM baseband modulation are presented in Figures 4 and 5, respectively. The equivalent extension factor is defined as _eq = 2 / . The case =1 represents classical-EGF filter simulation results (optimization based solely on filter extension factor), while 1 represents -EGF filter performance (optimization considering both and).

[Figure 4: see original paper]

[Figure 5: see original paper]

The results demonstrate significant performance improvements:

For 4QAM modulation: - Parking state: -EGF achieves approximately 2.9 dB gain over classical-EGF at SNR=9 dB - Taxi state: approximately 1.7 dB gain at SNR=9 dB - En-Route state: approximately 1.4 dB gain at SNR=15 dB - Arrival state: approximately 1.7 dB gain at SNR=12 dB

For 16QAM modulation at SNR=30 dB: - Parking state: -EGF provides approximately 17.5 dB gain - Taxi state: approximately 7.0 dB gain - En-Route state: approximately 2.1 dB gain - Arrival state: approximately 2.0 dB gain

These results confirm that the introduction of channel matching coefficient yields substantial performance gains in OFDM/OQAM system bit error rate compared to classical-EGF functions.

4 Conclusion

This paper proposes an OFDM/OQAM waveform adaptive algorithm that integrates the WSSUS air-ground channel model with EGF function characteristics. The algorithm derives optimal channel matching coefficients and filter extension factors for air-ground channel scenarios. Simulation results demonstrate that the introduced channel matching coefficient not only adapts to WSSUS channels with exponential delay power spectra and U-shaped Doppler power spectra but also provides significant performance improvements over classical-EGF functions, making it more suitable for WSSUS channel models similar to air-ground channels.

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