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# Broadband Orthogonal Modulation Technology for Terahertz Inter-satellite Communication of Low-Earth-Orbit Satellites from the Perspective of Software-defined Radio

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**Abstract:** Benefiting from the ultra-wide continuous bandwidth of 0.1-10 THz and strong beam directivity, the terahertz frequency band has become an important research direction for high-speed inter-satellite communication. Nevertheless, broadband orthogonal modulation faces great difficulties in bandwidth expansion, spectrum flatness maintenance, phase-noise suppression, nonlinear compensation and other aspects. Based on the Software-Defined Radio (SDR) architecture, this paper proposes a complete broadband orthogonal-modulation scheme for the 220 GHz terahertz transmitting link of low-earth-orbit inter-satellite communication. Research results show that within the GHz-level bandwidth range, the proposed method can realize favorable spectrum constraint and sidelobe suppression; constellation stability meets the requirements of high-order QAM modulation. Adaptive spectrum-shaping compensation smooths the power spectrum and improves Error Vector Magnitude (EVM). The research outcomes provide systematic technical references for the engineering design of broadband reconfigurable modulation modules in transmitting systems for LEO inter-satellite terahertz communication.

**Keywords:** Terahertz communication; Broadband orthogonal modulation; Software-defined radio; Inter-satellite link

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## 1. System requirement analysis and overall architecture

### 1.1. Requirement analysis for LEO inter-satellite terahertz communication links

The operating environment and performance characteristics of LEO inter-satellite THz links are prominent. From the perspective of link budget, free-space propagation loss in the THz band is far larger than that in the microwave band; high-gain narrow-beam antennas must be adopted to compensate for link-budget losses. In terms of platform constraints, LEO satellites generally orbit at altitudes of 500-2000 km, and the relative inter-satellite movement speed can reach several kilometers per second. Therefore, platform vibration and attitude disturbances exert significant impacts on beam pointing [1]. In terms of communication performance,

inter-satellite links shall simultaneously satisfy three requirements: high data rate, low bit-error rate and low latency.

For LEO inter-satellite THz transmitting links, typical characteristic requirements are put forward for baseband and modulation modules:

(1) Instantaneous signal bandwidth can reach several GHz, typically 1-5 GHz;
(2) Support multiple modulation modes including 16QAM, 64QAM, 256QAM or broadband OFDM/QAM;
(3) Sampling rate ranges from 2 GS/s to 4 GS/s, and the I/Q sampling rate shall be higher than 2 GS/s;
(4) Resolution is 10-12 bit, and the precision of I/Q digital-to-analog conversion shall be no less than 10 bit;
(5) In terms of spectrum performance, power-spectrum sidelobe suppression shall be no less than 30 dB;
(6) For modulation precision, the Error Vector Magnitude (EVM) after pulse-shaping filtering shall be better than -25 dB;
(7) For reconfigurability, the SDR module shall support on-line switching of modulation formats, bandwidth and bit rates.

The above requirements jointly constitute the constraint boundaries for the design of the broadband orthogonal-modulation scheme.

## 1.2. Overall system-architecture design

According to the above requirement analysis, the transmitting system for LEO inter-satellite terahertz communication designed in this paper consists of three major parts: the on-satellite terminal, the on-board terahertz communication payload, and the ground receiving terminal [2]. Data from various on-board service payloads are fed into the communication-processing module via configurable 10/25/50 Gbit/s interfaces. Data distribution, scheduling and relay forwarding are realized through high-speed switching and networking units. Afterwards, LDPC channel coding, MIMO processing and baseband I/Q modulation are executed by high-speed modem and MIMO-processing units [3]. Then I/Q signals are sent to the modulator for up-conversion, and output to the 220 GHz terahertz antenna through a 220 GHz RF transceiver module (including frequency synthesis, frequency multiplication, power amplification, mixing, filtering and other components), aiming at inter-satellite or satellite-ground links.

The reconfigurability constitutes the advantage of SDR in baseband processing. Modulation modes, bandwidth parameters, coding schemes and so on can be flexibly configured without hardware replacement. Relevant studies have shown that FPGA-implemented baseband-processing modules support rapid switching of bit rates and frame structures under a throughput of 2-5 Gbit/s [4].

## 1.3. Core challenges of broadband orthogonal modulation

Under GHz-level bandwidth, broadband orthogonal modulation exhibits characteristics different from narrow-band systems. First, the matching problem between sampling rate and bandwidth. Conventional I/Q modulation generally adopts fixed sampling rates such as 30.72 MHz. However, THz links operate under multi-GHz bandwidth; thus the sampling rate needs to be increased by more than two orders of magnitude, which brings great difficulties to digital baseband generation, interpolation filtering and data conversion. Second, pulse-shaping filtering is complex to implement. Conventional Root-Raised-Cosine (RRC) filters require high orders to complete time-domain convolution operations under GHz-level bandwidth. Real-time processing can hardly be satisfied even at millisecond or microsecond time scales [5–7]. Third,

frequency-stability issues of THz oscillators. Frequency-synthesis and frequency-multiplication links in the THz band introduce large frequency offsets and phase noise, which severely affect constellation-point phases for high-order QAM modulation and may even lead to demodulation errors in severe cases. Fourth, non-ideal radio-frequency front-end amplitude-frequency response. Gains of THz frequency-multiplication chains and power-amplifier devices vary with frequency, showing slanted and rippled distributions, which result in non-smooth transmitted-signal power spectra and degraded modulation quality [8].

## 2. Key technologies for broadband orthogonal modulation

### 2.1. Adjustable-bandwidth digital-baseband generation framework

Aiming at the problem that fixed sampling rates of conventional I/Q modulation cannot adapt to GHz-level bandwidth requirements, this paper proposes a target-bandwidth-adaptive digital-baseband generation framework [9]. Its core idea is: given target bandwidth $B$, the system automatically selects the sampling rate $f_s = k \cdot B$, where $k \in [2,4]$. This design enables the sampling rate to scale linearly with the target bandwidth, avoids unnecessary power consumption and processing burden brought by fixed high sampling rates, and meanwhile satisfies the basic requirements of the Nyquist sampling theorem for band-pass signals [10]. Under typical configurations: a 0.5 GHz bandwidth corresponds to a 1.5-2 GHz sampling rate; a 1 GHz bandwidth corresponds to a 3-4 GHz sampling rate; a 3 GHz bandwidth corresponds to a 6-12 GHz sampling rate.

From the perspective of engineering implementation, multi-stage interpolation structures are adopted in the digital-baseband generation module to raise sampling rates and satisfy the requirements of GHz-level broadband modulation. Interpolators can adopt multi-stage structures of CIC (Cascaded-Integrator-Comb) plus FIR, or RRC interpolation-shaping structures. The CIC structure features high resource efficiency, while the RRC interpolation-shaping structure delivers better spectrum controllability. After sampling-rate improvement via interpolation, time-domain resolution of baseband signals is enhanced, laying necessary time-domain-sampling foundations for subsequent high-precision orthogonal modulation [11].

### 2.2. Broadband pulse-shaping filter designed in the frequency domain

Pulse-shaping filtering suppresses out-of-band leakage and meets spectral-mask requirements. Under GHz-level broadband conditions, conventional time-domain RRC filters are difficult to design. To obtain sufficient stop-band attenuation and appropriate transition bands, FIR filters require hundreds or even thousands of taps. The computational complexity of time-domain convolution increases exponentially with filter order, failing to satisfy real-time-processing requirements under GHz sampling rates [12–14].

This paper adopts a frequency-domain shaping scheme to replace time-domain RRC filtering. Its basic idea: directly design the target frequency response $H(f)$in the frequency domain; transform time-domain signals into the frequency domain via Fast Fourier Transform (FFT); multiply them by$H(f)$; then convert them back to the time domain through inverse FFT. Design parameters of frequency-domain filters include target bandwidth $B$ and transition-band roll-off factor $\alpha$ (usually 0.05-0.2). The frequency response remains flat within the pass-band and smoothly decreases to the stop-band in the transition band following raised-cosine or raised-cosine-like functions. The core advantage of the frequency-domain scheme lies in its independence from filter order: the computational complexity of FFT is $O(NlogN)$, far lower than $O(N \cdot L)$

for time-domain FIR (where $L$ denotes filter order). Millisecond-level or even sub-millisecond computation latency can be achieved for GHz-level signal processing.

2.3. High-speed I/Q orthogonal-modulation architecture

I/Q orthogonal modulation constitutes one of the means to improve spectral efficiency. Its mathematical expression is: where $I(t)$ and $Q(t)$denote the in-phase and quadrature baseband signals respectively, and $\omega_{LO}$ stands for the local-oscillator angular frequency.

$$s_{IF}(t) = I(t)cos(\omega_t) - Q(t)sin(\omega_{LO}t)$$

For high-speed implementation, the following key points shall be considered for the I/Q modulation architecture. First, time-domain alignment of dual-channel signals. Strict timing synchronization must be guaranteed for the I-channel and Q-channel signals before they reach the mixer. Any timing error will cause I/Q imbalance, resulting in elliptical constellations and deteriorated EVM. Second, orthogonality of local-oscillator signals. The local-oscillator output is split into two paths: one is fed directly into the I-channel mixer; the other passes through a 90° phase shifter before entering the Q-channel mixer. Phase-shifting precision directly affects the orthogonality of the quadrature-carrier pair. Third, denoising after mixing. Mixed products contain sum-frequency and difference-frequency components. Low-pass filters are used to suppress high-frequency components, and band-pass filters are adopted to restrict signal bandwidth and suppress out-of-band noise. Finally, broadband intermediate-frequency signals satisfying radio-frequency-link requirements are obtained. When intermediate-frequency signals need to be up-converted to terahertz carriers, intermediate-frequency signals can be sent to subsequent frequency-multiplication or mixing links to generate terahertz radio-frequency outputs.

## 3. Adaptive compensation and simulation verification

### 3.1. Adaptive-carrier-calibration I/Q modulation

Frequency offset and phase noise of THz-band oscillators degrade modulation precision. THz signals are generally generated by microwave local-oscillator frequency-multiplication chains. Frequency offset and phase noise of the local oscillator are amplified step-by-step in the multiplication process, so that frequency stability and phase purity of THz carriers are far inferior to those of microwave local oscillators. Phase noise corresponds to random carrier-phase variations, manifested as angular-direction spreading of constellation points on constellation diagrams; frequency offset brings overall rotation of constellation points.

This paper proposes the Adaptive Carrier-calibration I/Q Modulation (AC-IQM) method. A phase-noise model is introduced in the digital domain to accurately simulate and compensate for THz-oscillator behaviors. The phase-noise process can be modeled as:

$\varphi(t+1)=\varphi(t)+\Delta\varphi+v(t)$ where $\Delta\varphi$ denotes the frequency-offset step; $v(t) \sim N(0,\sigma_\varphi^2)$ represents random phase jitter driven by Gaussian white noise. This model can characterize both deterministic frequency offset and stochastic phase-noise physical mechanisms simultaneously.

After phase-noise compensation in the digital domain, the modulated signal can be expressed as:

$$s(t) = I(t)cos(2\pi f_c t + \varphi(t)) - Q(t)sin(2\pi f_c t + \varphi(t))$$

By estimating $\varphi(t)$ and performing inverse rotation in the digital domain, the impacts of phase noise on

modulation quality can be effectively suppressed.

### 3.2. Adaptive spectrum-shaping compensation

Non-ideal amplitude-frequency response of THz radio-frequency front-ends constitutes another difficulty for broadband modulation. After cascading devices such as frequency-multiplication chains, power amplifiers and filters, gains exhibit linear tilts of several decibels with frequency, superimposed with in-band ripples caused by cavity resonance and parasitic parameters. Non-flat amplitude-frequency responses result in non-flat main lobes of transmitted-signal power spectra, i.e. low gain at edge frequency bands and high gain at central frequency bands, which degrade EVM and demodulation performance at the receiving terminal.

The Adaptive Spectrum-shaping Compensation (ASC) method proposed in this paper compensates for amplitude-frequency distortions introduced by radio-frequency front-ends in the digital domain. Its main procedures are as follows:

(1) Measure or estimate the amplitude-frequency response $G(f)$ of the THz front-end, i.e. the ratio between actual power spectrum $PSD_{actual}(f)$ and ideal power spectrum $PSD_{ideal}(f)$;

(2) Design the compensation function: $C(f) = G(f)^{\beta}$ where $\beta \in [0.3,0.7]$ is the compensation-intensity factor, which controls the aggressiveness of compensation to avoid new distortions induced by over-compensation;

(3) Pre-compensate baseband signals in the digital domain:

$$S_{out}(f)=C(f)\cdot S_{in}(f)$$

Essentially, ASC pre-carves spectrum shapes complementary to channel distortions in the digital domain before signals enter digital-to-analog conversion, so that output spectra after passing through radio-frequency channels restore flatness. This method requires no hardware modification and is fully implemented by software, conforming to SDR design concepts.

### 3.3. Simulation experiments and result analysis

MATLAB-based simulations are adopted to systematically verify the above-mentioned schemes. Identical frequency-domain and time-domain parameter settings are applied in simulations. The frequency range from -1.5 GHz to 1.5 GHz is used to plot baseband power spectra before and after shaping. The time range from 0 ns to 700 ns with 2000 sampling points generates structured broadband I/Q signals and IF waveforms superimposed with high-frequency carriers. Two-hundred complex points are adopted for constellation diagrams: ideal constellations are used for modulation-precision comparison; constellations with simulated noise demonstrate phase perturbation and compensation effects. THz-channel distortions are simulated by 3-dB linear tilts and small-amplitude ripples of device frequency responses.

Simulation results verify scheme effectiveness from three dimensions.

In terms of spectrum shaping: pre-shaping signals feature wide power spectra with sidelobe suppression of only about -15~-20 dB and lack smooth transitions at spectral edges. After broadband frequency-domain shaping filtering, spectra are well confined within target bandwidths, transition bands become smooth, sidelobe suppression is improved above -30 dB, spectra become flatter and out-of-band leakage decreases. For time-domain modulation: the obtained time-domain waveforms $I(t)$ and $Q(t)$ are smooth broadband random waveforms with identical amplitude statistical characteristics, which proves consistency of I/Q signals after interpolation and shaping. IF signals manifest GHz-level high-speed carriers superimposed with

baseband-envelope modulation at nanosecond scales, verifying the validity of broadband orthogonal modulation and the phase-noise model. In terms of modulation precision: ideal constellations achieve EVM of -30 dB with compact constellation-point distribution and clear clustering boundaries. After introducing phase noise, EVM drops to approximately -25 dB, point clouds spread to a certain extent with more severe angular-direction diffusion, which is consistent with the feature that THz phase noise is mainly transmitted to channels via phase perturbations. After ASC compensation, point-cloud scattering caused by channel distortions is obviously mitigated; amplitude-direction and phase-direction errors are reduced, and EVM is further improved.

It can be concluded that the proposed scheme guarantees favorable spectrum and constellation stability under shaping, up-conversion and phase-noise perturbations. Under channel-distortion conditions, ASC restores flat spectra and greatly improves EVM. This indicates that frequency-domain pre-compensation can enhance modulation quality of THz broadband links without hardware equalizers [15].

## 4. Conclusion

Targeting the 220 GHz high-speed LEO inter-satellite terahertz link, this paper puts forward a broadband orthogonal-modulation design method based on the software-defined-radio architecture. A complete system architecture including on-board switching, baseband processing, terahertz transceivers and antenna links is established. By adaptively adjusting sampling rates at the baseband terminal according to target bandwidths, favorable spectrum constraints and sidelobe-suppression effects are obtained under GHz-level bandwidths. Frequency-domain shaping replaces conventional RRC filtering. Carrier calibration overcomes carrier distortions caused by frequency drift and phase noise. Moreover, the adaptive spectrum-shaping-compensation method is proposed to correct front-end gain tilts and in-band ripples. Simulation results show that the proposed scheme maintains favorable spectrum and constellation stability under shaping, up-conversion and phase-noise perturbations. ASC can restore spectral flatness and significantly improve EVM in the presence of channel distortions. Along with the trend of unified on-board SDR architectures and gradual advancement of on-orbit tests for terahertz-communication modules, the scheme in this paper provides systematic references for the engineering-oriented design of broadband reconfigurable modulation modules in transmitting systems for LEO inter-satellite terahertz communication.

## Disclosure statement

The authors declare no conflict of interest.

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