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Novel four-dimensional direct sequence spread spectrum waveform design based on prolate spheroidal wave functions

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Key words: Direct sequence spread spectrum; Prolate spheroidal wave functions; Chip waveform; Spectral efficiency; Anti-interference

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Motivation

- Low spectral efficiency and poor energy concentration of conventional rectangular chip waveforms used in spread spectrum modulation make it difficult to meet the high-rate and high-sensitivity reception requirements of future systems. To address this issue, this study proposes a spread spectrum chip waveform design method based on prolate spheroidal wave functions (PSWFs), which enhances signal dimensionality and spectral efficiency under finite time–bandwidth product constraints.

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Main idea

- By introducing PSWFs into the spread spectrum chip waveform design and proposing a PSWF-based method for constructing a 4D chip waveform set, the waveform dimension and spectral efficiency of spread spectrum systems are enhanced.
- By introducing equivalent low-pass processing, an equivalent low-pass PSWF spread spectrum system model is developed, where signal processing employs a “baseband+ in-phase/quadrature (I/Q) dual-channel” approach, effectively reducing implementation complexity.

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Method

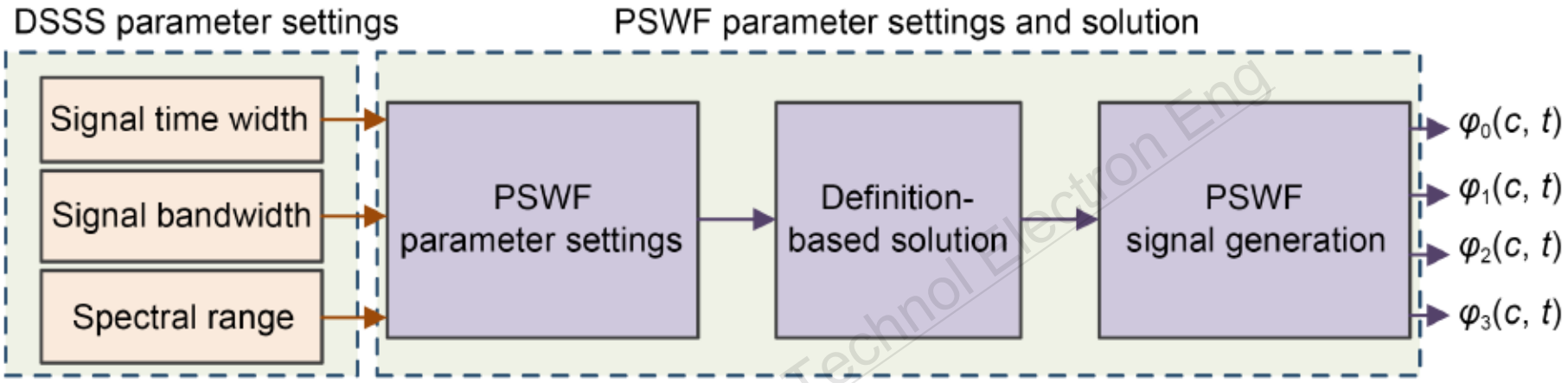


Fig. 1 Construction of the 4D PSWF code-sheet waveform set based on definitional formulas

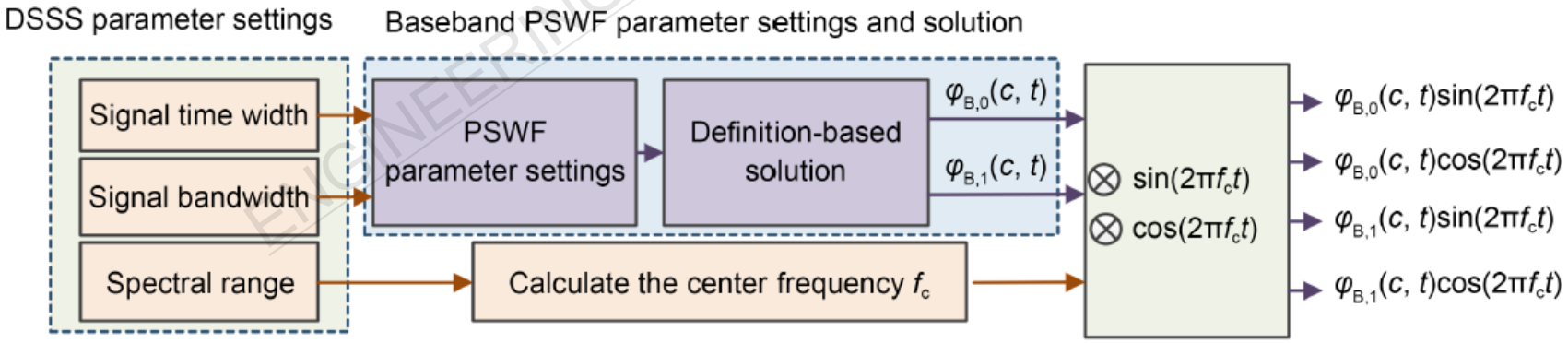


Fig. 4 Construction schematic of the 4D PSWF code-piece signal set based on equivalent LPFs. ⊗ denotes multiplication

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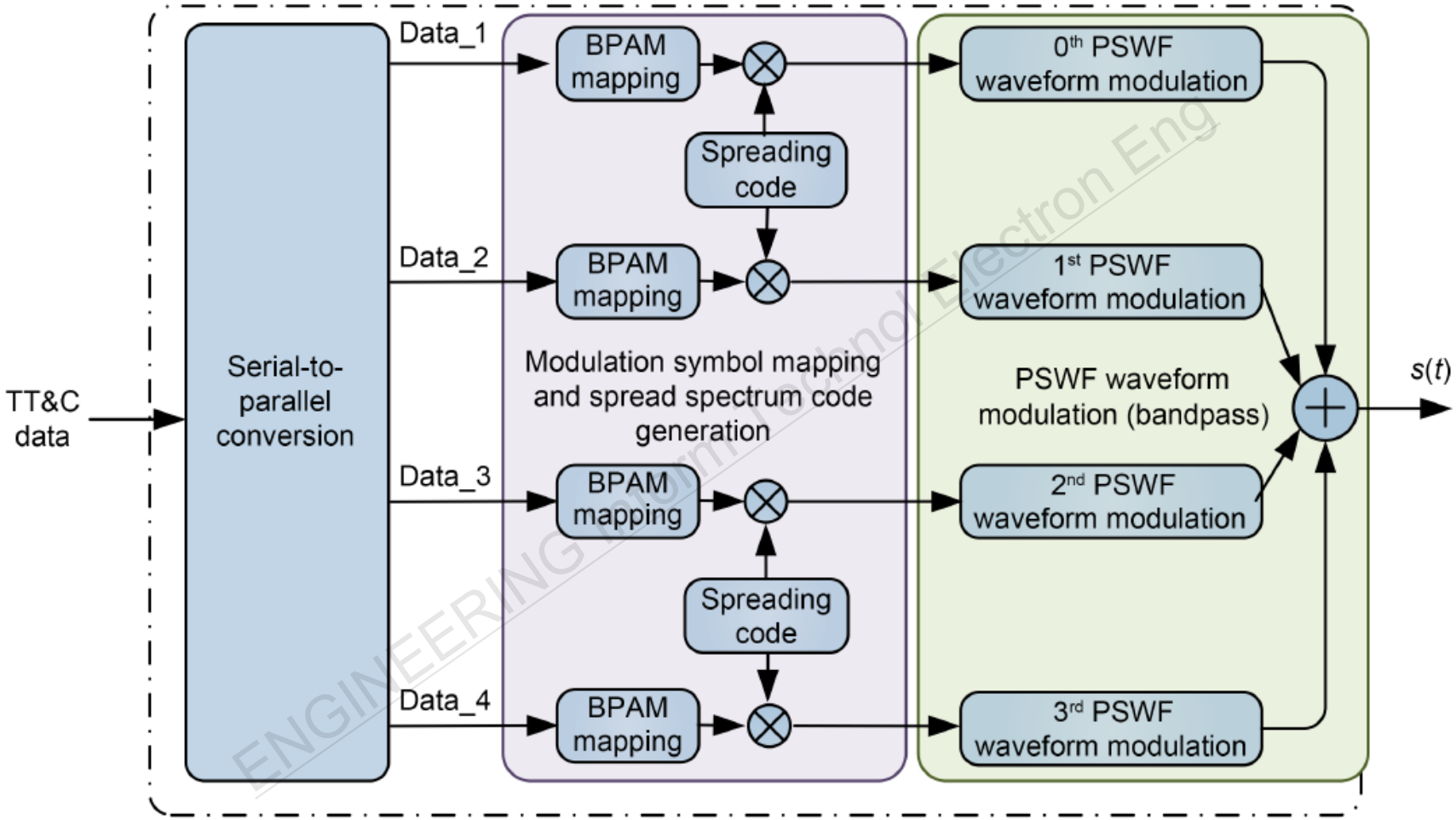


Fig. 6 Modulation model of the 4D unified spread spectrum TT&C system based on PSWF waveform modulation

Method

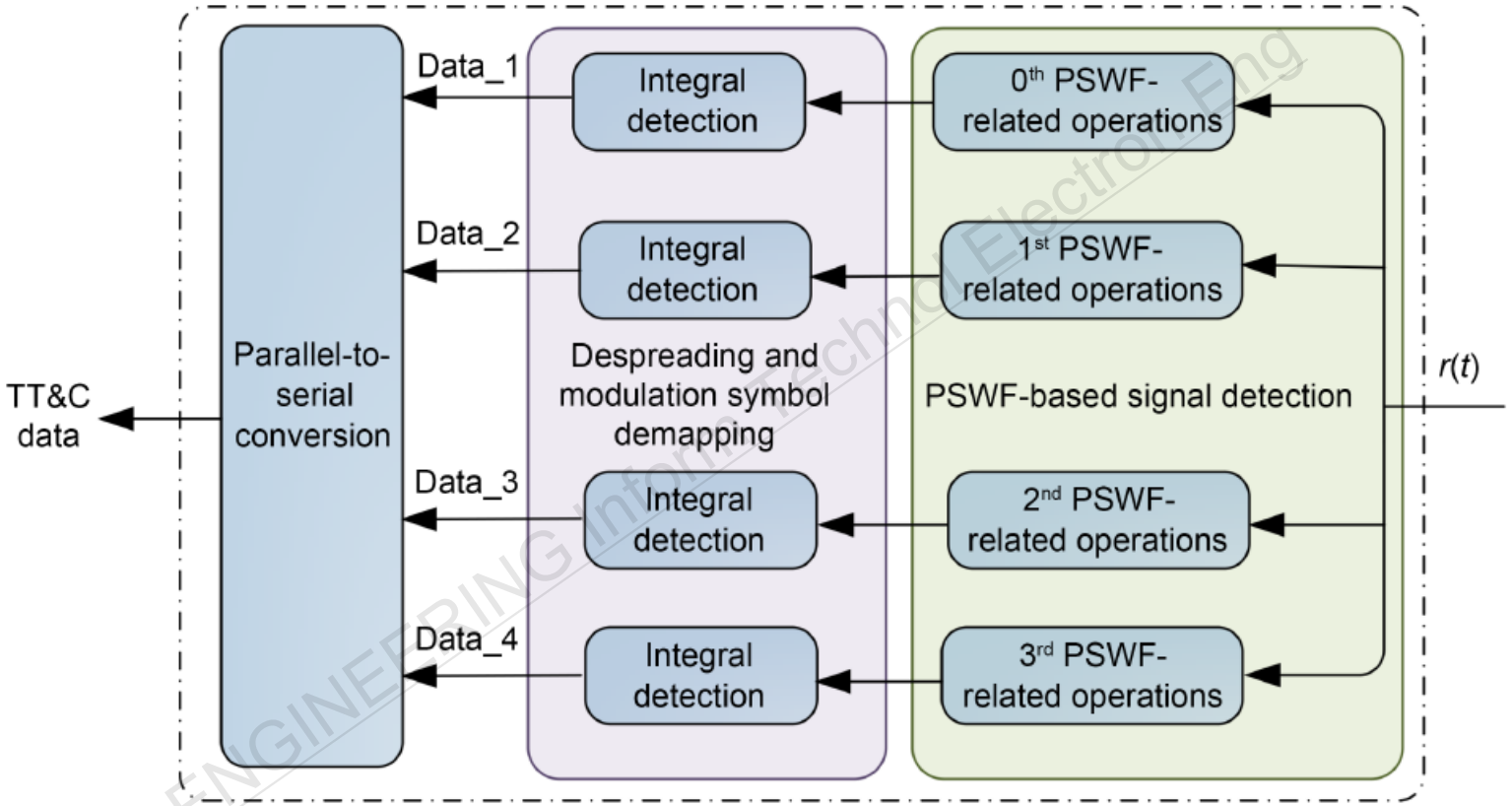


Fig. 7 Block diagram of the spread spectrum signal demodulation model based on PSWF code sequence waveform

Method

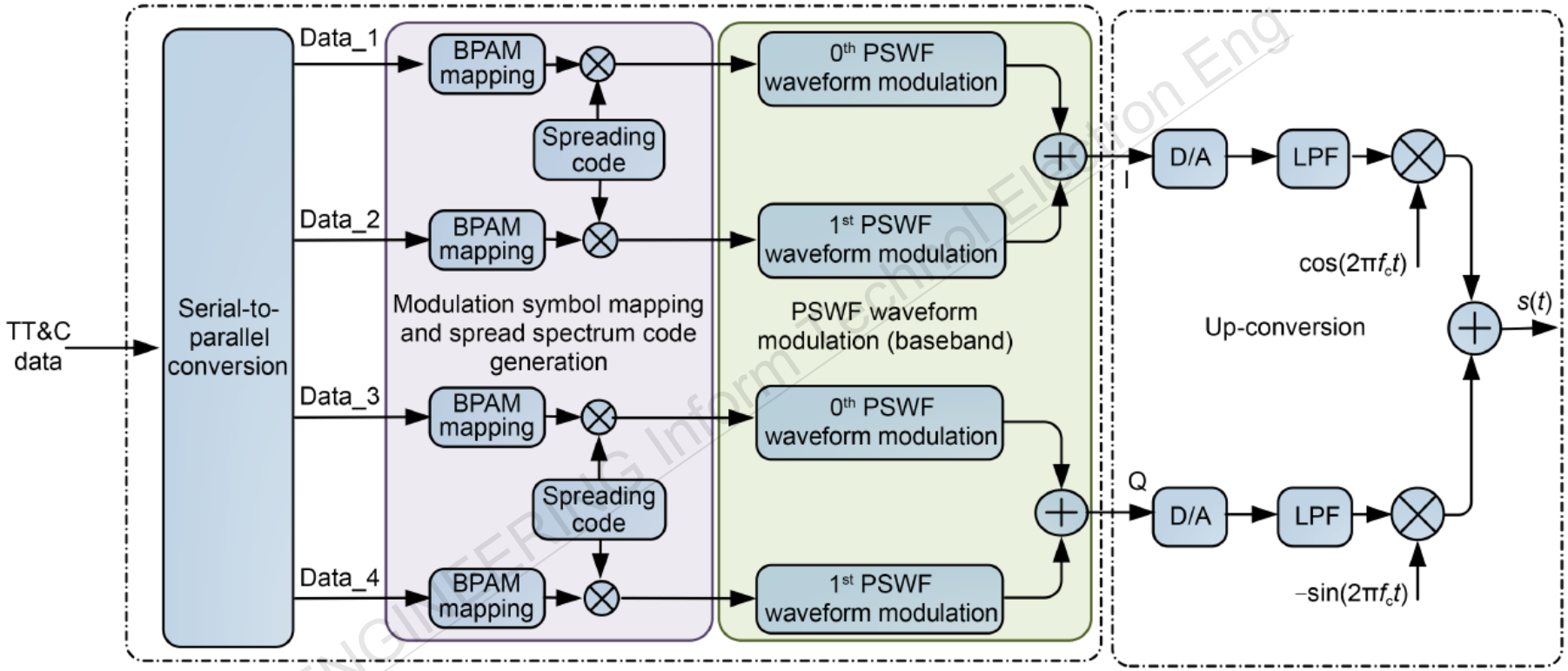


Fig. 8 Block diagram of the PSWF spread spectrum modulation based on equivalent LPFs. D/A: digital-to-analog. ⊕ denotes addition

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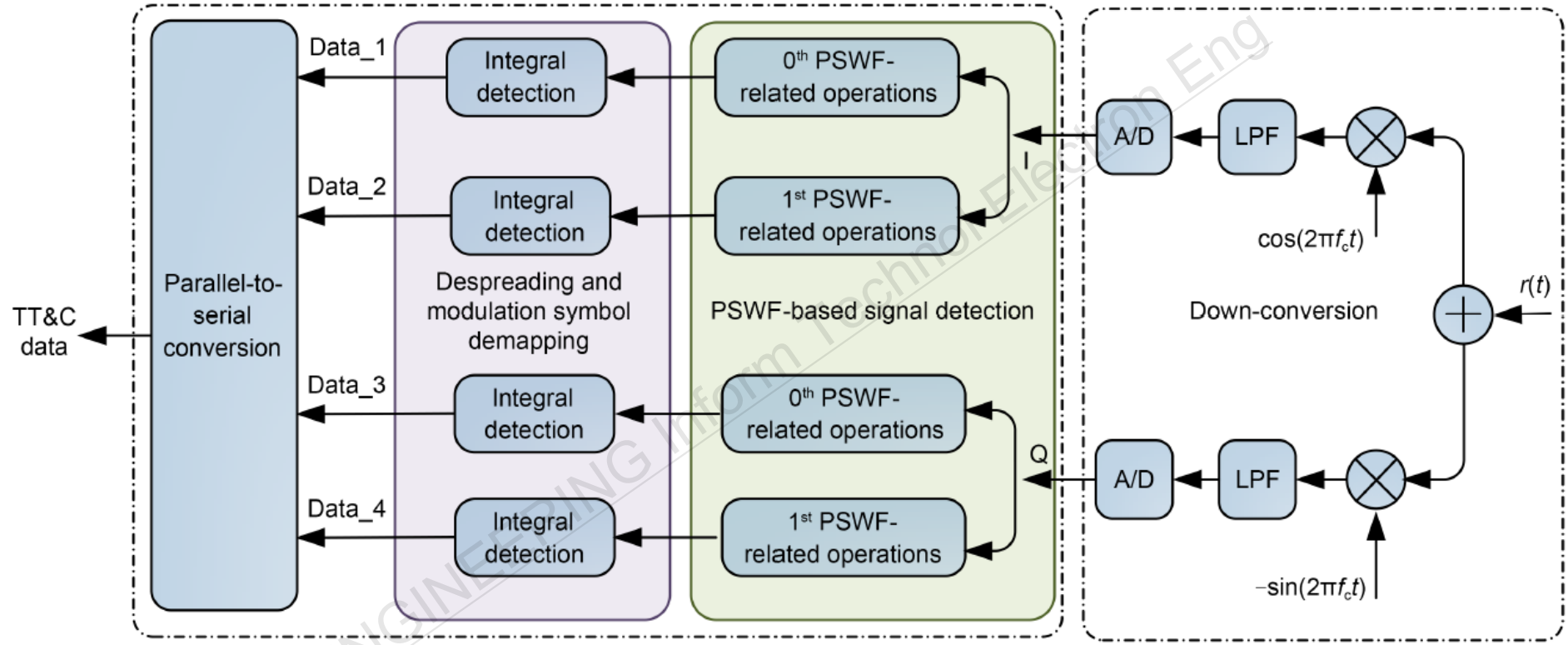


Fig. 9 Block diagram of the PSWF spread spectrum signal demodulation based on equivalent LPFs. A/D: analog-to-digital

Results

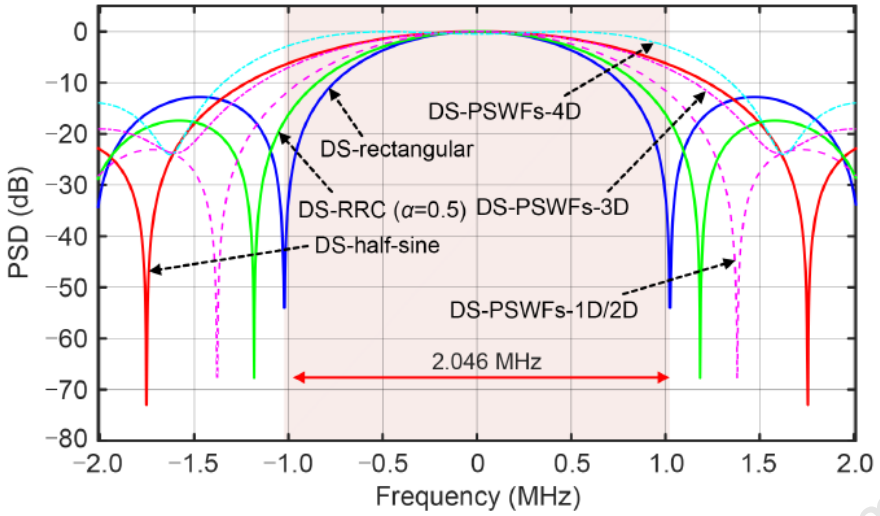


Fig. 10 Power spectrum diagrams of different spread spectrum modulati signals. PSD: power spectral density

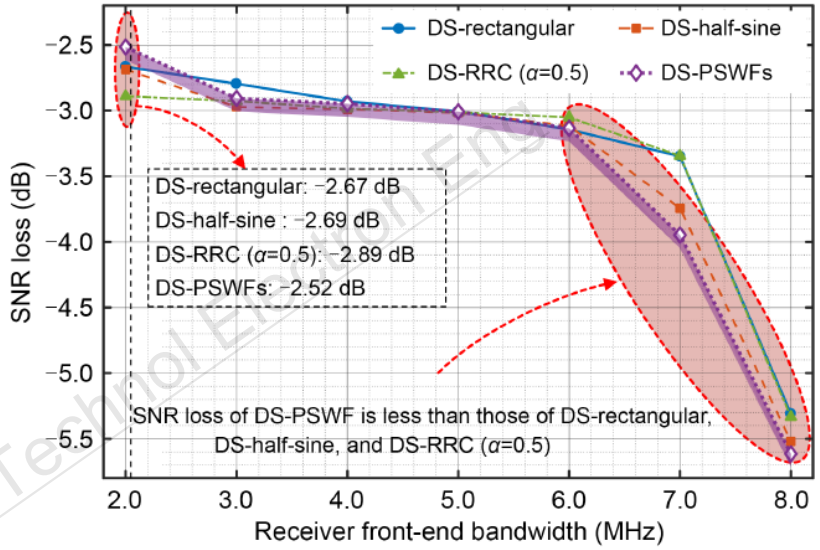


Fig. 11 SNR loss due to the receiver filter bandwidth

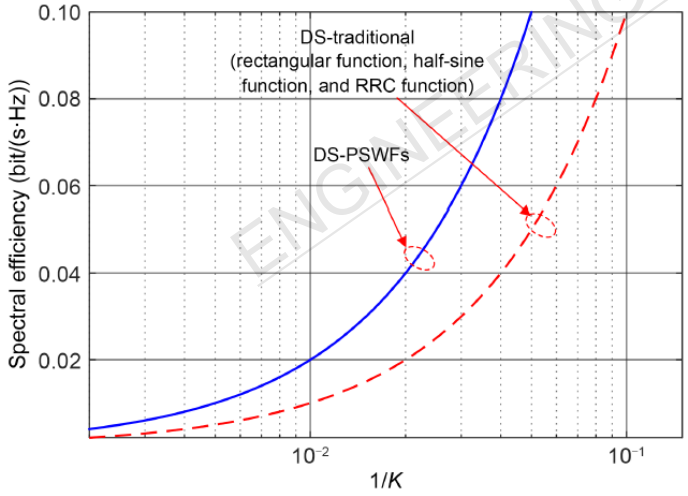


Fig. 12 Relationship between the spread spectrum modulation spectral efficiency and the inverse of spread factor K

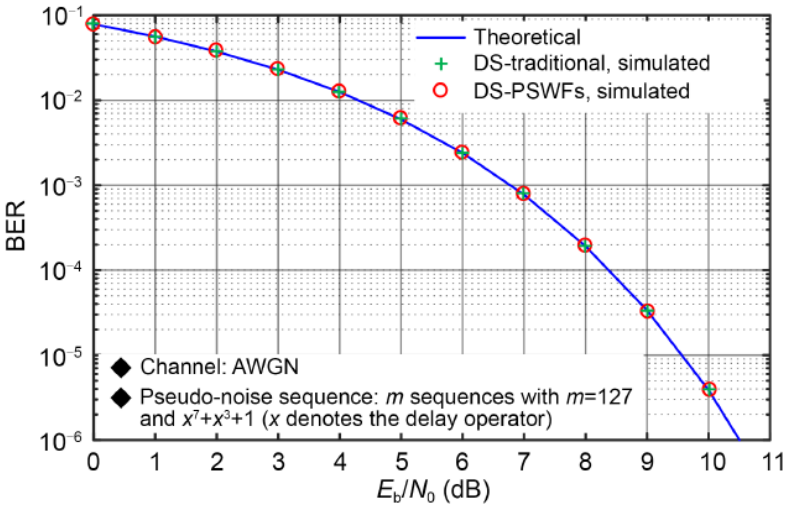


Fig. 13 Theoretical and simulated BER curves

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Results

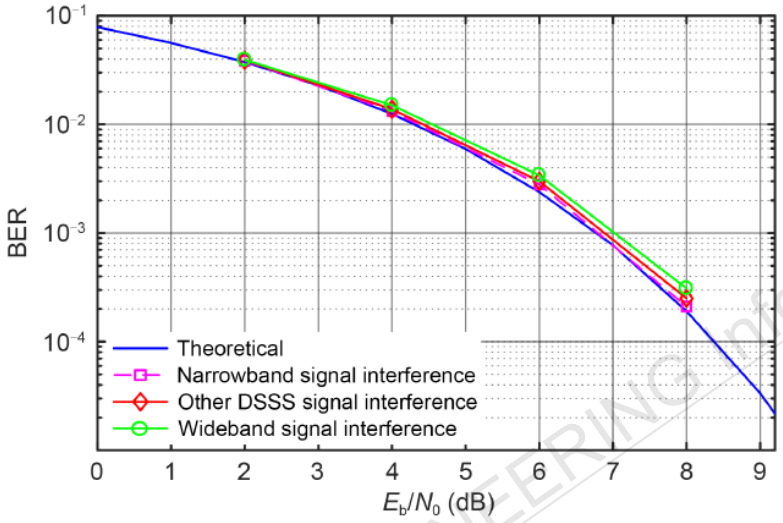


Fig. 14 Error rate simulation curves for system anti-interference capability

Table 1 Comparison of design parameters

Parameter type	Traditional spread spectrum	4D PSWF-based spread spectrum modulation
Chip waveform	Rectangular window, rised-cosine function, half-sine pulse, etc.	4D PSWF-based code waveform
Chip waveform dimension	1 (baseband) 2 (bandpass)	2 (baseband) 4 (bandpass)
Chip length (s)	1/1.023e-6	1/1.023e-6
Bandwidth (MHz)	2.046	2.046
Information transmission efficiency (bit/s)	2000	2000
Chip symbol duration (s)	0.001	0.002
Chip bit count (bit)	1023	2046

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Conclusions

To address the issues of low chip waveform dimensionality and insufficient spectral efficiency in conventional direct sequence spread spectrum systems, this study proposes a 4D spread spectrum chip waveform design method based on PSWFs and constructs a corresponding spread spectrum modulation system implementation model. The simulation results demonstrate that the proposed waveform achieves approximately double the spectral efficiency of conventional waveforms while maintaining comparable error performance. It also exhibits robust anti-interference and anti-interception capabilities under narrowband, broadband, and co-channel spread spectrum signal interferences.

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