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APPLICATION OF OPTIMAL AMPLITUDE-PHASE MODULATION SIGNALS IN CHANNELS WITH DOPPLER FREQUENCY SHIFT

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Abstract. The paper addresses the problem of improving the spectral efficiency of radio communication systems operating in channels with Doppler frequency shift by employing optimal signals with amplitude-phase modulation. The relevance of the study is driven by the need for high data rate transmission in low-Earth orbit satellite communication systems, where conventional signals based on RRC pulses exhibit significant energy losses when the symbol rate is increased. A synthesis technique for optimal shaping pulses is proposed, based on the criterion of out-of-band emission suppression under given constraints on the cross-correlation coefficient that determines the BER performance. A computer simulation model of the transmission channel is developed, taking into account carrier frequency instability, timing synchronization offset, and Doppler shift modeled with time-scale transformation. Numerical simulations for 64APSK constellation and coding rate 4/5 demonstrate that the use of optimal signals with doubled symbol rate provides a spectral efficiency gain of up to 12.7% compared to RRC-based signals when the occupied bandwidth is estimated by the 99% energy concentration criterion. The associated energy penalties range from 3 to 4 dB depending on the satellite elevation angle, which is attributed to the need for wider receiver front-end bandwidth under Doppler-induced spectral distortions. It is shown that the choice of the cross-correlation coefficient enables a trade-off between BER performance and spectral efficiency. The obtained results confirm the feasibility of optimal signals in satellite communication systems with high spectral efficiency requirements and limited link power budgets.

Keywords: optimal signals, APSK, Doppler shift, spectral efficiency, satellite communications, FTN, DVB-S2X

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ПРИМЕНЕНИЕ ОПТИМАЛЬНЫХ СИГНАЛОВ С АМПЛИТУДНО-ФАЗОВОЙ МОДУЛЯЦИЕЙ В КАНАЛАХ С ДОПЛЕРОВСКИМ СМЕЩЕНИЕМ ЧАСТОТЫ

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Аннотация. Рассмотрена задача повышения спектральной эффективности радиотехнических систем передачи сообщений в каналах с доплеровским смещением частоты на основе применения оптимальных сигналов с амплитудно-фазовой модуляцией. Актуальность исследования обусловлена необходимостью обеспечения высоких скоростей передачи данных в системах связи с низкоорбитальными космическими аппаратами, где традиционные сигналы с формирующими импульсами типа RRC демонстрируют значительные энергетические потери при попытке увеличения символьной скорости. Предложена методика синтеза оптимальных амплитудных импульсов на основе критерия минимизации внеполосных излучений при заданных ограничениях на коэффициент корреляции, определяющий помехоустойчивость приема. Разработана компьютерная имитационная модель канала передачи, учитывающая нестабильность несущей частоты, сдвиг временной синхронизации и доплеровское смещение, моделируемое с учетом масштабирования временной шкалы сигнала. В ходе численного моделирования для сигнального созвездия 64APSK и скорости кодирования 4/5 установлено, что применение оптимальных сигналов с удвоенной символьной скоростью обеспечивает прирост спектральной эффективности до 12,7% по сравнению с RRC-сигналами при оценке полосы частот по критерию концентрации 99% энергии. При этом энергетические потери составляют 3–4 дБ в зависимости от угла возвышения космического аппарата, что обусловлено необходимостью расширения полосы пропускания приемных трактов в условиях доплеровских искажений. Показано, что выбор значения коэффициента взаимной корреляции позволяет управлять компромиссом между помехоустойчивостью и спектральной компактностью сигнала. Полученные результаты подтверждают целесообразность использования оптимальных сигналов в системах спутниковой связи с высокими требованиями к спектральной эффективности и ограниченным энергетическим бюджетом радиолинии.

Ключевые слова: оптимальные сигналы, APSK, доплеровский сдвиг, спектральная эффективность, спутниковая связь, FTN, DVB-S2X

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Introduction

The efficiency of radio communication systems is determined by their spectral and energy performance relative to the Shannon limit [1, 2]. Approaching this limit is achieved, among other techniques, through the application of Faster-Than-Nyquist (FTN) concepts [3–6]. The fundamental

idea of FTN signaling is to increase the symbol rate R , i.e., to pack a larger number of modulation symbols into a limited time resource. In general, increasing the symbol rate R leads to a higher degree of non-orthogonality of the transmitted signals, which may result in significant degradation of BER performance.

These effects raise the question of how to approach the Shannon limit when using FTN technology. By approaching the Shannon limit, we mean increasing the spectral efficiency $R_b/\Delta F$, where ΔF is the occupied frequency bandwidth and $R_b = R \cdot \log_2(M)$ is bit rate (M is channel alphabet size, which determines the number of bits per symbol), while minimizing energy losses. It is known that increasing the symbol rate to $R > 1.1/T$ with RRC pulses leads to a sharp deterioration in BER performance [7, 8], which prevents the desired approach to the Shannon limit.

Additional opportunities for reducing energy losses are provided by the use of optimal spectrally efficient signals [7–9]. Such signals, depending on the chosen optimization criterion, allow synthesizing shaping pulse waveforms of various durations under constraints on BER performance (correlation properties) and the peak-to-average power ratio (PAPR) of the radiated oscillations [10, 11]. The use of optimal signals ensures a proximity to the Shannon limit. Evaluations of these performance metrics have been considered for channels with constant parameters and limited frequency bandwidth under additive white Gaussian noise (AWGN) with power spectral density $N_0/2$. However, evaluations of the spectral and energy efficiency of optimal signals have not been performed for communication channels involving Doppler frequency shift (for example, low-Earth orbit satellite communication systems). This work fills this gap, and **its aim** is to analyze the spectral and energy performance of a radio communication system using optimal APSK signals in the presence of Doppler shift.

Representation of optimal signals with APSK

In general form, a sequence of N APSK signals of duration $T_a = LT$, $L \in \mathbb{N}$ with amplitude A_0 and carrier frequency f_0 , can be written as [7, 8, 10]:

$$y(t) = \operatorname{Re} \left\{ A_0 \sum_{k=0}^{N-1} c^{(k)} a(t - k\xi T) \exp \left(j2\pi \left\{ f_0 + \Delta f(f_{s(f)}, t) \right\} t \right) \right\}, \quad (1)$$

where $0 \leq t \leq NT$, $a(t)$ is shaping pulse function, $c(k)$ is the channel alphabet symbols transmitted at symbol rate $R = 1/\xi T$, $0 < \xi \leq 1$, $\Delta f(f_{s(f)}, f)$ is the Doppler frequency shift.

The Doppler frequency shift $\Delta f(f_{s(f)}, f)$ is determined by the position of the low-Earth orbit (approximately 500 km) small satellite (CubeSat) relative to the ground station and depends both on the satellite velocity and on the bandwidth (shape) of the spectrum $S(f)$ of the shaping pulse.

As shown in [7, 8, 10], the shaping pulse $a(t)$ can be chosen as an optimal function obtained according to the criterion of a fixed out-of-band emission decay rate under constraints on BER performance (correlation properties). We can write the functional as:

$$\arg \min_{a(t)} J, \quad J = \frac{1}{2\pi} \int_{-\infty}^{\infty} g(f) |S_a(f)|^2 df, \quad g(f) = f^{2n}, \quad n = 1, 2, 3, \dots, \quad (2)$$

$$S_a(f) = \int_{-\frac{T_a}{2}}^{\frac{T_a}{2}} a(t) \exp(-j2\pi ft) dt,$$

where $g(f)$ is function, which assigns a certain weighting coefficient to each part of the spectrum. Obviously, the values of function should be as small as possible within the required frequency band and as large as possible outside it. The most convenient choice for the nuisance function is an even-degree

parabola $g(f) = f^{2n}$, where $n = 1, 2, 3, \dots$ is a parameter determining the degree of out-of-band emission suppression.

The function $a(t)$ can be represented on a symmetric time interval using a limited Fourier series:

$$a(t) = \frac{a_0}{2} + \sum_{k=1}^{m-1} a_k \cos\left(\frac{2\pi}{T_a} kt\right). \quad (3)$$

The following constraints must be taken into account:

- Boundary conditions on the pulse shape:

$$a^{(k)}(t) \Big|_{t=\pm T_a/2} = 0, \quad k = 1 \dots (n-1);$$

- Normalized energy constraint:

$$\int_{-T_a/2}^{T_a/2} a^2(t) dt = 1;$$

- BER performance constraint (K_0 is the threshold cross-correlation coefficient, η is determined by the modulation scheme):

$$\eta \max_{k=1 \dots (L-1)} \left\{ \int_{k\xi T}^{LT} a(t) a(t - k\xi T) dt \right\} < K_0.$$

The shapes of optimal amplitude pulses and their corresponding energy spectra (Fig. 1) were obtained using an iterative optimization technique [7, 8, 10]. The optimal pulses were designed for 64APSK modulation, pulse duration $8T$, out-of-band decay rate $n = 2$, symbol rate $R = 2/T$, and coding rate $4/5$. The correlation coefficient constraint ranged from $K_0 = 0.001$ to $K_0 = 0.050$. The time-domain and frequency-domain representations of RRC pulses ($\beta = 0.35$) are shown for comparison in Fig. 1.

The symbol rate for optimal signals is twice as high. Obviously, the spectrum width of such optimal signals is also wider than that of signals based on RRC pulses. However, the out-of-band emission level is controllable for optimal signals and turns out to be lower compared to RRC signals. This feature is important for multi-channel satellite communication systems with frequency-division multiplexing of several information channels.

It is necessary to choose a criterion for determining the occupied frequency bandwidth ΔF to evaluate the degree of spectral efficiency approaching the Shannon limit. It should be noted that the quantitative results of the proximity to the Shannon curve depend significantly on the choice of this parameter. One option is the energy concentration criterion in the frequency domain, e.g., at the 85% or 99% level.

Table 1 presents the estimated occupied bandwidth ΔF . Table 2 shows the corresponding spectral efficiency $R_b/\Delta F$ values for the cases of bandwidth determination by 85–99% energy concentration. The estimates were obtained for 64APSK modulation without error-correcting coding and pilot symbols.

As can be seen from Table 2, there is a significant dependence of spectral efficiency on the choice of occupied frequency bandwidth. Optimal signals provide the maximum difference in spectral efficiency equal to 12.7% relative to RRC signals in case of bandwidth determination by the 99% energy concentration level. At the same time, the BER performance in channels with constant parameters and AWGN is approximately the same [7].

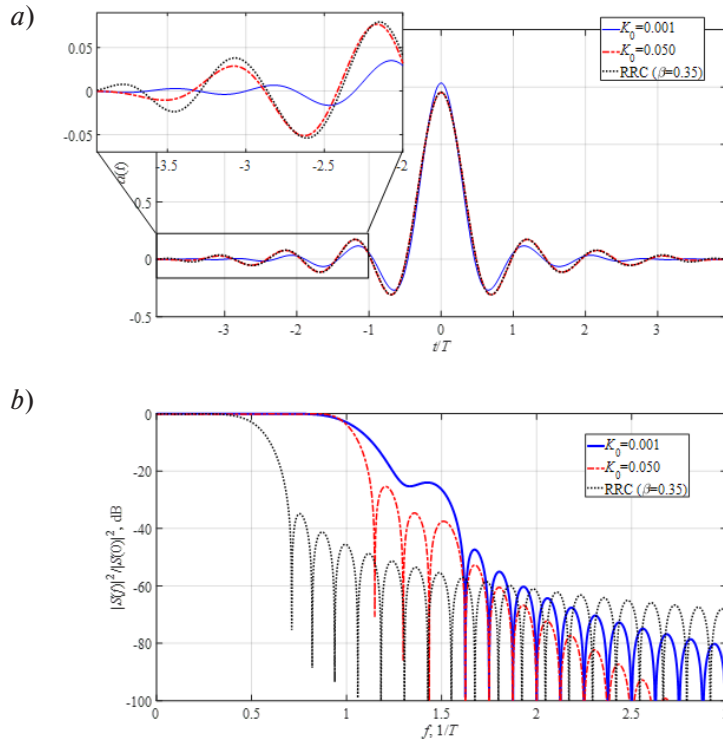


Fig. 1. Optimal pulses (a) and corresponding energy spectra (b)

Table 1

Occupied frequency bandwidth ΔF by energy concentration level

	RRC, $R = 1/T$	Optimal signals, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$\Delta F_{99\%}, 1/T$	1.155	2.203	2.065	2.059	2.059	2.049
$\Delta F_{95\%}, 1/T$	1.024	1.973	1.912	1.907	1.905	1.895
$\Delta F_{90\%}, 1/T$	0.935	1.826	1.798	1.793	1.791	1.784
$\Delta F_{85\%}, 1/T$	0.867	1.709	1.698	1.694	1.692	1.686

Table 2

Spectral efficiency $R_b/\Delta F$ for ΔF determined by energy concentration

	RRC, 64APSK, $R = 1/T$	Optimal signals, 64APSK, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$R_b/\Delta F_{99\%}, (\text{bit/s})/\text{Hz}$	5.195	5.447	5.811	5.828	5.828	5.857
$R_b/\Delta F_{95\%}, (\text{bit/s})/\text{Hz}$	5.859	6.082	6.276	6.293	6.299	6.332
$R_b/\Delta F_{90\%}, (\text{bit/s})/\text{Hz}$	6.417	6.572	6.674	6.693	6.700	6.726
$R_b/\Delta F_{85\%}, (\text{bit/s})/\text{Hz}$	6.920	7.022	7.067	7.084	7.092	7.117

Another option for determining ΔF is the criterion based on the normalized energy spectrum level. Table 3 presents the bandwidth values calculated at the -60 dB and -70 dB levels of the normalized energy spectrum of optimal signals for various values of the cross-correlation coefficient K_0 . As can be seen from comparing Tables 1 and 3, when the bandwidth is determined by the energy spectrum level, the bandwidth values are more than twice as large as those obtained using the energy concentration criterion.

Table 3

Occupied frequency bandwidth ΔF by levels of the normalized energy spectrum

	RRC, $R = 1/T$	Optimal, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$\Delta F_{-60 \text{ dB}}, 1/T$	$3.74/T$	$3.84/T$	$5.30/T$	$4.92/T$	$3.74/T$	$3.56/T$
$\Delta F_{-70 \text{ dB}}, 1/T$	$6.72/T$	$4.54/T$	$6.90/T$	$6.16/T$	$4.436/T$	$3.98/T$

Table 4 presents the spectral efficiency values for ΔF determined by the energy spectrum level. Comparing the spectral efficiency values (Tables 2 and 4), it is evident that the numerical spectral efficiency decreases by a factor of 2–3 when the bandwidth is determined by the energy spectrum levels.

Table 4

Spectral efficiency $R_b/\Delta F$ for ΔF determined by levels of the normalized energy spectrum

	RRC, 64APSK, $R = 1/T$	Optimal, 64APSK, $R = 2/T$				
		$K_0 = 0.001$	$K_0 = 0.010$	$K_0 = 0.025$	$K_0 = 0.032$	$K_0 = 0.050$
$R_b/\Delta F_{-60 \text{ dB}}, (\text{bit/s})/\text{Hz}$	1.60	3.13	2.26	2.43	3.21	3.37
$R_b/\Delta F_{-70 \text{ dB}}, (\text{bit/s})/\text{Hz}$	0.89	2.64	1.73	1.94	2.69	3.01

Computer simulation model for CubeSat with Doppler frequency shift

We evaluate the spectral and energy efficiency of data transmission in the presence of Doppler frequency shift using a model of signal transmission from a CubeSat to a ground receiving station. The block diagram of the model is shown in Fig. 2. The model is based on the DVB-S2X digital television signal transmission standard [12, 13].

At the transmitting module, information bits enter the coding block, where concatenated coding is performed using BCH codes with parity bits and LDPC codes at a coding rate of 4/5. This coding rate is chosen as a compromise between error-correction capability and the requirement to achieve high data rates (exceeding 1 Gbit/s). The encoded bits are fed to the bit interleaving blocks and bit-to-symbol mapping blocks. The 64APSK constellation is used because further increasing the channel alphabet size significantly raises the requirements for receiver synchronization algorithms and the link budget. The subsequent blocks (Fig. 2) insert pilot symbols into the message packet preamble for synchronization and perform scrambling to ensure uniform energy distribution across symbols.

Further processing in the transmitting module consists of forming the optimal signal according to the specified symbol rate $R = 1/\xi T$, where ξ is the time-domain compression factor, and the selected shaping pulse (RRC or optimal).

The channel simulation block accounts for Doppler frequency shift. The threshold signal-to-noise ratio is chosen as 15 dB, meaning that the required BER = 10^{-6} must be achieved at $E_b/N_0 < 15$ dB. The satellite position is described by the elevation angle φ (Fig. 3).

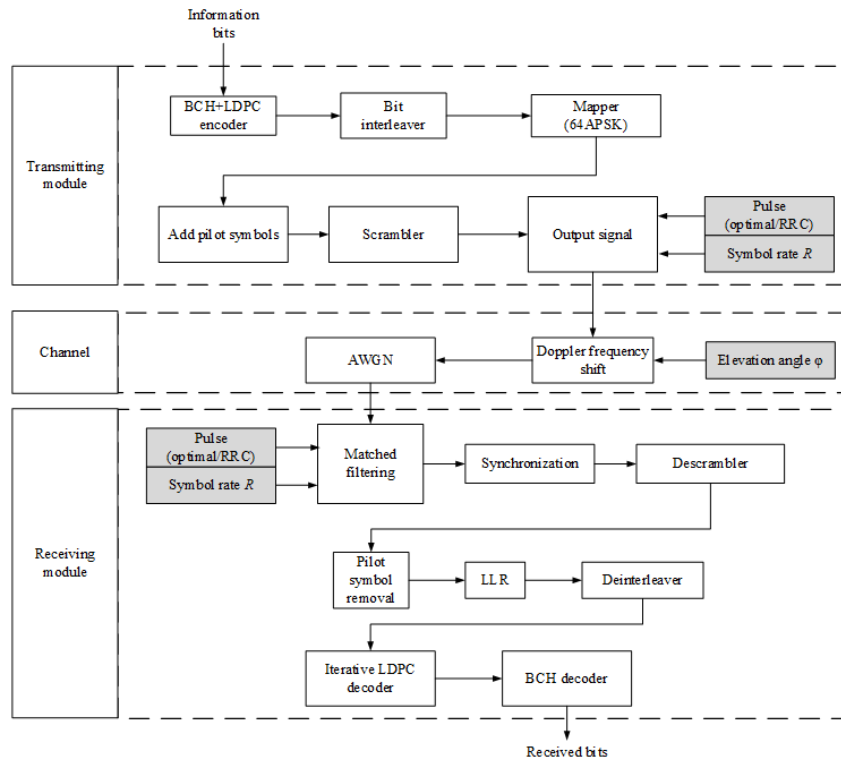


Fig. 2. Block diagram of the computer simulation model

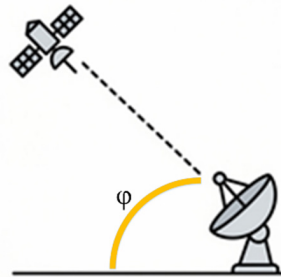


Fig. 3. Illustration of the CubeSat elevation angle

It should be noted that applying a Doppler frequency shift model based on a single frequency offset for all spectral components is insufficient when analyzing high-speed transmission systems based on the DVB-S2X protocol. Therefore, the motion of the satellite transmitter relative to the ground receiver must be modeled by time-scale transformation, equivalent to a change in the signal waveform (compression or stretching of the time representation) [14–17].

Mapping between the transmitter time scale and the receiver time scale is established based on modeling the distance variation between the receiver and transmitter. The corresponding arrival time at the receiver side is determined for a given transmission instant. Then the inverse problem is solved: for each sample on the uniform receiver time grid, the corresponding time instant at the transmitter side is found.

The received signal value is reconstructed by linear interpolation between adjacent samples of the transmitted realization since the receiver samples are formed on a uniform time grid and the corresponding time instants at the transmitter side generally do not coincide with the original samples.

The computer simulation model accounts for frequency instabilities of the transceiver module oscillators: carrier frequency offset, carrier frequency instability, and transmission start time offset.

The received signal is fed to the DVB-S2X demodulator block. The input signal processing employs matched filtering according to the selected pulse shape and symbol rate. Subsequently, symbol synchronization is performed using the Gardner algorithm. Next blocks are frame synchronization to locate the pilots, coarse and fine frequency synchronization. After descrambling and pilot symbol removal, soft log-likelihood ratio (LLR) estimates are computed. The obtained LLR stream is fed to the iterative LDPC decoding block. No more than 20 decoding iterations are used to enable processing speeds exceeding 1 Gbit/s [18, 19]. The received information bits are assembled after BCH decoding. Table 5 lists the parameters of the computer simulation model.

Table 5

Parameters of the computer simulation mode

Satellite orbit altitude	500 km
Carrier frequency	8 GHz
Satellite elevation angle	$\varphi = 0$ to $\varphi = 90^\circ$ (corresponds to Doppler shift from 180 kHz to 0, respectively)
Modulation scheme	64APSK
Coding rate	4/5
Number of decoding iterations	20
Pulse type	optimal / RRC
Carrier frequency offset	2 MHz
Carrier frequency instability	2 ppm
Time offset	31 samples

BER performance of optimal signals in the presence of Doppler frequency shift

Let us consider the results of BER performance evaluation in the presence of Doppler frequency shift based on computer simulations. As an example, we evaluate the BER performance using optimal signals for an elevation angle $\varphi = 60^\circ$ between the satellite and the ground station (Fig. 4). At least 10^8 information bits were transmitted for each signal-to-noise ratio point for BER computation. RRC signals were generated with symbol rate $R = 1/T$, while optimal signals were generated with symbol rate $R = 2/T$.

The following conclusions can be drawn from Fig. 4. First, for signals based on RRC pulses, achieving $\text{BER} = 10^{-6}$ requires value of signal-to-noise ratio of no more than $E_b/N_0 = 10.3$ dB. At the same time, the required value E_b/N_0 for optimal signals ranges from 13.1 to 14.5 dB depending on the choice of the correlation coefficient K_0 . Second, the energy losses for optimal signals amount to approximately 3–4 dB relative to RRC-based signals. These losses are caused by the need for a wider passband of the receiving station input filters, especially in the presence of carrier Doppler shift and spectral distortions.

The signal-to-noise ratio required to achieve the target error probability also changes as the elevation angle changes. Table 6 presents the values of E_b/N_0 (dB) required to achieve $\text{BER} = 10^{-6}$ for elevation angles ranging from 0 to 90 degrees (Fig. 3). These values lie within a 3.35 dB range (from 12.65 to 16.00 dB).

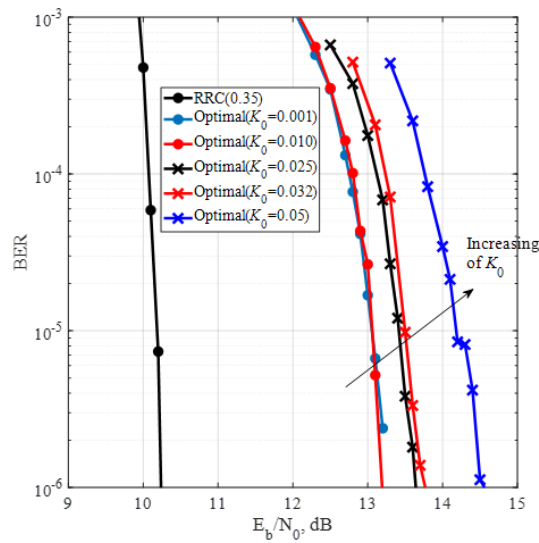
Fig. 4. BER performance of optimal signals for elevation angle $\varphi = 60^\circ$

Table 6

Values E_b/N_0 (dB) for BER = 10^{-6}

	$\varphi = 0^\circ$	$\varphi = 30^\circ$	$\varphi = 60^\circ$	$\varphi = 75^\circ$	$\varphi = 89^\circ$
$K_0 = 0.050$	13.85	14.05	14.55	14.85	16.00
$K_0 = 0.032$	13.08	13.32	13.80	14.05	15.10
$K_0 = 0.025$	13.03	13.18	13.65	13.86	14.75
$K_0 = 0.010$	12.68	12.92	13.20	13.40	14.01
$K_0 = 0.001$	12.65	12.91	13.19	13.40	14.00

Conclusions

The use of optimal APSK signals with doubled symbol rate $R = 2/T$ provides a spectral efficiency gain of approximately 12.7% compared to the case of RRC pulse usage for case of frequency bandwidth determination by the 99% energy concentration level.

It is shown that quantitative estimates of spectral efficiency critically depend on the method of determining the frequency bandwidth ΔF . When the bandwidth is determined by the energy spectrum levels, the spectral efficiency of optimal signals appears to be more than 2–3 times higher than that of RRC-based signals.

The energy efficiency of optimal signals in the presence of Doppler frequency shift is lower than that of RRC-based signals by 3–4 dB. This difference is explained by the fact that optimal signals require a wider passband of the receiving ground station input filters, especially in the presence of carrier Doppler shift and spectral distortions. The required E_b/N_0 for optimal signals ranges from 13.1 to 14.5 dB depending on the chosen correlation coefficient K_0 , which confirms their applicability in radio communication systems using small satellites.

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