Hybrid M-FSK/DQPSK Modulations for CubeSat Picosatellites

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Abstract. *Conventional CubeSat radio systems typically use one of several basic modulations, such as AFSK, GMSK, BPSK, QPSK and OOK or switch between them on demand if possible. These modulations represent a balanced trade-off between good energy efficiency of high order M-FSK modulation and good spectral efficiency of high order M-QAM modulation. Utilization of modulations with the best energy efficiency is not possible due to strict limits on occupied frequency bandwidth. In this paper the proposed group of hybrid modulations and proposed hybrid modulator and demodulator are presented. Novel solution offer interesting possibilities of increasing spectral efficiency as well as energy efficiency of basic M-FSK modulation by embedding DQPSK symbols between two M-FSK symbols. Such group of hybrid modulations offers suitable properties for picosatellite, e.g. simple realization onboard the picosatellite, better energy and spectral efficiency, low PAPR, wide range of adaptation by changing the order of M-FSK, suitable for easy non-coherent demodulation, good immunity to Doppler effect with DM-FSK coding.*

Keywords

CubeSat, picosatellite communication system, adaptable modulation, hybrid modulation.

1. Introduction

Since 2009, the PilsenCUBE picosatellite is developed at the University of West Bohemia in Pilsen. One of our main goals is to enhance the usability of CubeSats picosatellites by increasing the data throughput on downlink (data transmission toward ground station). For this purpose it is necessary to use adaptation of transmission to actual space link channel conditions and to use a modulation with good energy efficiency and sufficient spectral efficiency.

For common modulations, increasing the energy efficiency decreases the modulation spectral efficiency, and vice versa [1]. Moreover, the modulations with high spectral efficiency (M-QAM) are complicated by needs of amplifying in linear amplifiers with low power efficiency [2]. That is why constant envelope modulations with a low peak to average power ratio (PAPR) are preferred in CubeSat projects [3].

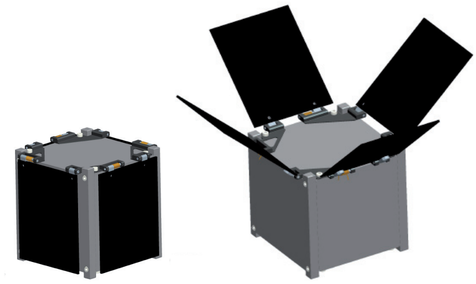

Fig. 1. PilsenCUBE picosatellite with deployable solar cells.

Therefore, for an adaptable communication system, we are limited to a small group of convenient modulations with an easy implementation using low power consuming picosatellite hardware. M-FSK modulations have a good energy efficiency and suitability for a non-coherent demodulation; however their spectral efficiency is poor [2]. Better utilization of signal space dimensionality can increase the spectral and also energy efficiency as it is presented in this paper.

2. Hybrid Modulation Design

Interesting ideas for increasing energy and spectral efficiency of modulations was found in [4], [5]. For these purposes, hybrid modulations (two parameters of carrier modulated at the same time) are used. In [4] the hybrid modulation M-FSK/QPSK and direct bit demodulation (DBD) receiver were described. In [5] hybrid M-FSK/QAM modulations were described. However, both solutions are not suitable for picosatellite communication system due to hardware complexity or signal complexity when the adaptation is required. The adaptation of communication system with hybrid modulation is presented in [6], but in this paper only switching between M-FSK and M-QAM is considered, true hybrid modulations (two parameters of carrier modulated at the same time) were not used. In this paper, true hybrid modulations are designed in relation to picosatellite system requirements and space link characteristics.

Our solutions can offer a simple hardware realization in picosatellite (based on memory addressing) with adaptation mechanisms, robustness to the space link behaviors (Doppler frequency shift, phase tracking difficulty, fading) and modern approach to the radio amateur receiver construction based on hardware frequency down conversion in common receivers followed by FFT signal processing in personal computer. This is important due to large number of radio amateur ground stations, which can co-operate around the world for picosatellite telemetry downloading. The FFT signal processing in PC after frequency down conversion is inspired by Dream open source project for software demodulation of Digital Radio Mondiale broadcasting (DRM) [7].

2.1 Increasing of Signal Space Usage

The basic M-FSK modulation (with a set of *M* orthogonal frequencies) creates an M-dimensional signal space. With increase of *M* the distances between symbols stay the same due to dimension ortogonality in comparison to the conventional M-QAM or M-PSK modulations, where the distances between symbols decrease as *M* increases because we stay in two dimensions. This leads to interesting behavior of M-FSK in comparison to M-QAM and M-PSK. With the same signal quality (E_b/N_0) increase of *M* decreases bit error rate, for M-QAM and M-PSK this has a reverse dependence. In other words, increasing the order of *M* has an increase in energy efficiency as consequence for M-FSK. However, as *M* increases, the spectral efficiency of M-FSK decreases. M-FSK modulation can also be imagined as a set of ASK modulations with on-off signaling at subcarrier orthogonal frequencies. More details for basic M-FSK, M-QAM and M-PSK modulation properties comparison can be found in [1] with a simple deduction.

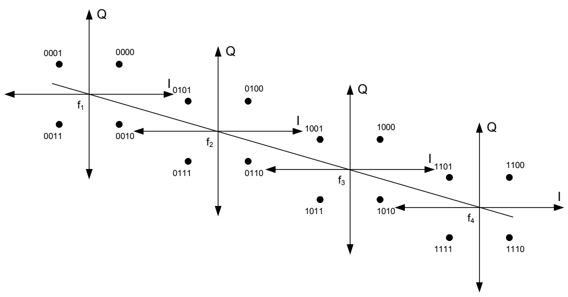

Fig. 2. Signal space of hybrid 4-FSK/QPSK modulation.

A better signal space utilization can be realized by antipodal or bi-orthogonal signaling on subcarriers. In the first case (antipodal signaling), a BPSK symbol is embedded between two symbols of M-FSK modulation. In the second case (bi-orthogonal signaling), a QPSK symbol is embedded between two neighboring symbols of M-FSK modulation. In [4] this is called hybrid M-FSK/QPSK modulation. With the same signal power and frequency bandwidth more bits can be transmitted, so the spectral efficiency and energy efficiency is increasing in comparison with conventional M-FSK.

For example, the hybrid 4-FSK/QPSK modulation has a signal space as presented in Fig. 2. During the symbol period, one of 16 different symbols can be transmitted. Differential coding can be realized on M-FSK side as well as on QPSK side of hybrid modulation to obtain possibilities of non-coherent demodulation.

2.2 Basic Hybrid M-FSK/DQPSK Modulation

The hybrid M-FSK/DQPSK modulation offers good possibilities of a simple realization of modulator onboard the picosatellite with a limited computing power. Our proposed modulator is based on memory addressing. In the memory, samples of a harmonic function are stored. Frequency changes are realized by increasing or decreasing the increment of memory addressing. Phase changes are realized by steps in memory addressing. The following modulator can realize a signal set of 4·M signals:

$$\begin{aligned}
s_{m,0}(t) &= \sqrt{\frac{2E_s}{T}}\cos\left[2\pi\left(f_c+(m-1)\Delta f\right)t+0\frac{2\pi}{4}\right],\\
s_{m,1}(t) &= \sqrt{\frac{2E_s}{T}}\cos\left[2\pi\left(f_c+(m-1)\Delta f\right)t+1\frac{2\pi}{4}\right],\\
s_{m,2}(t) &= \sqrt{\frac{2E_s}{T}}\cos\left[2\pi\left(f_c+(m-1)\Delta f\right)t+2\frac{2\pi}{4}\right],\\
s_{m,3}(t) &= \sqrt{\frac{2E_s}{T}}\cos\left[2\pi\left(f_c+(m-1)\Delta f\right)t+3\frac{2\pi}{4}\right],
\end{aligned} \tag{1}$$

$$\text{for} \quad m=1,\dots,M \quad \text{and} \quad 0\le t<T \quad \text{and} \quad \Delta f=\frac{1}{2T}.$$

This signal set contains all combinations of *M* orthogonal carriers of the FSK section of hybrid modulation and four discrete phase shifts of the embedded DQPSK section of hybrid modulation. Discrete phase shifts are differentially coded between two adjacent symbols.

In the designed memory based modulator, arbitrary M-FSK modulation, arbitrary M-PSK modulation, arbitrary DM-PSK modulation and arbitrary hybrid M-FSK/DQPSK modulation can be easily implemented.

Our proposed demodulator is based on the FFT analysis of received (and in frequency down converted) signals. The M-FSK part of hybrid modulation is demodulated by searching for the maximum amplitude in the FFT result, the DQPSK part of hybrid modulation is demodulated by comparing the phases in two adjacent symbols at frequencies given by the M-FSK demodulator.

2.3 Advanced Hybrid DM-FSK/DQPSK Modulation

At advanced hybrid DM-FSK/DQPSK modulation, differential coding of the M-FSK section is applied. This could be useful in channels with Doppler effect, e.g. underwater acoustic communication [8] or in satellite RF communication [9]. If the difference of Doppler frequency shift between two symbols is much smaller than the M-FSK frequency spacing, then this differentially coded modulation is robust with respect to the Doppler shift compensation error [10]. Concepts of our proposed modulator and demodulator for hybrid modulations are in Fig. 3 and Fig. 4.

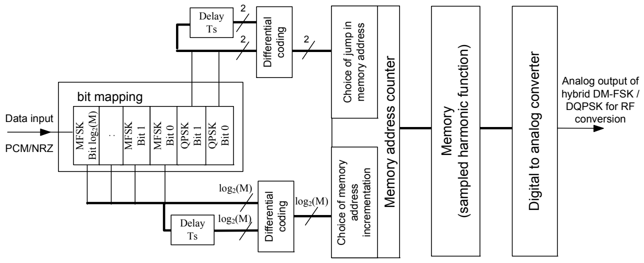

Fig. 3. Hybrid DM-FSK/DQPSK memory based modulator.

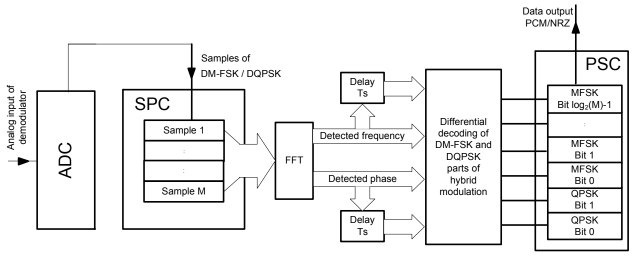

Fig. 4. Hybrid DM-FSK/DQPSK FFT based demodulator.

Hybrid modulators as well as hybrid non-coherent demodulators were realized in Matlab software and their performance in AWGN model of channel was tested.

3. Results for Hybrid Modulation

The proposed hybrid modulator and demodulator were realized in Matlab and evaluated by BER measurements in dependence on E_b/N_0 parameter for the AWGN channel model. In the proposed software modulator, there were conventional modulations 2-FSK up to 1024-FSK and DQPSK modulation (as a reference to hybrid modulation) realized. From the hybrid modulation groups, there were 2-FSK/DQPSK up to 1024-FSK/DQPSK modulations and D2-FSK/DQPSK up to D1024-FSK/DQPSK modulations realized. Software defined FFT based non-coherent demodulators were also realized in Matlab.

BER performances of conventional modulations are in Fig. 5 and Fig. 6. Performances of the hybrid modulations are shown in Fig. 7 and Fig. 8. The required E_b/N_0 for BER equal to 10^{-5} and BER equal to 10^{-3} in the AWGN channel together with spectral efficiency of all tested modulations are summarized in Tab. 1. The spectral efficiency is calculated for the null to null frequency bandwidth, for the orthogonal carriers with spacing for non-coherent demodulation.

For measured results of energy efficiency and results of spectral efficiency it was calculated how high data rates are possible for two limits of frequency bandwidth (20 kHz bandwidth related to receivers audio output – the signal processed in PC via sound card, 1.5 MHz bandwidth related to PilsenCUBE experimental radio) in dependence on the received signal quality C/N_0. This is enumerated for conventional as well as for proposed hybrid modulations.

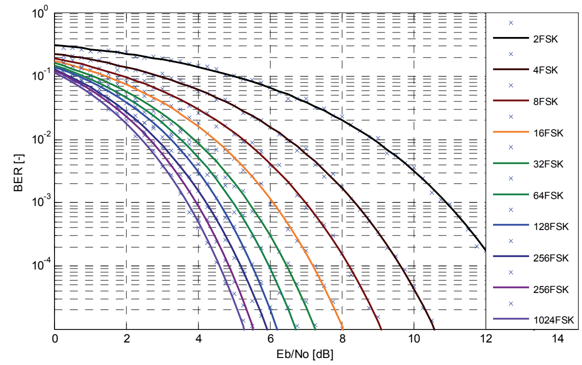

Fig. 5. Evaluation of conventional M-FSK modulations on the proposed hybrid M-FSK/DQPSK software modulator and demodulator.

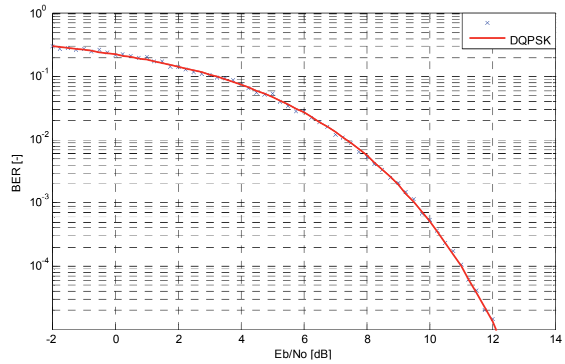

Fig. 6. Evaluation of conventional DQPSK modulation on the proposed hybrid M-FSK/DQPSK software modulator and demodulator.

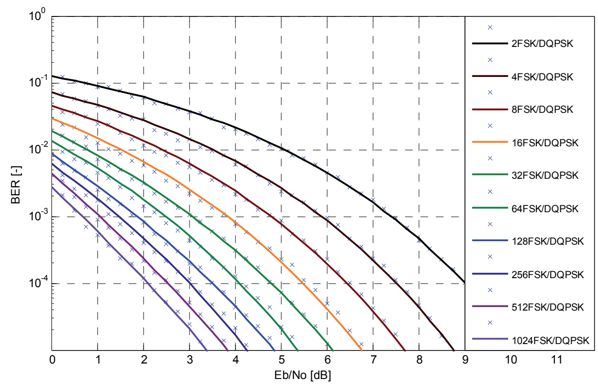

Fig. 7. Evaluation of hybrid M-FSK/DQPSK modulations on the proposed software modulator and demodulator.

The results show that the proposed hybrid modulations have better energy efficiency in comparison with the M-FSK modulation with corresponding spectral efficiency. Significant enhancement is noticeable for low order FSK modulations. For example, the 2-FSK modulation can be replaced by the 16-FSK/DQPSK modulation in the almost same bandwidth at more than 6.6 dB better energy efficiency (see Tab. 1).

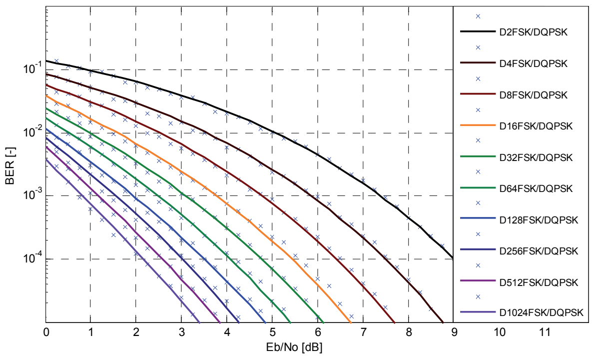

Fig. 8. Evaluation of hybrid DM-FSK/DQPSK modulations on the proposed software modulator and demodulator.

	E_b/N_0 [dB] ($BER=10^{-5}$)	E_b/N_0 [dB] ($BER=10^{-3}$)	Spectral efficiency [bit/s/Hz]
DQPSK	12.1	9.5	1.00
2-FSK	13.4	10.9	0.33
2-FSK / DQPSK	10.2	7.4	1.00
D2-FSK / DQPSK	10.2	7.4	1.00
4-FSK	10.6	8.4	0.40
4-FSK / DQPSK	8.8	5.9	0.80
D4-FSK / DQPSK	8.8	5.9	0.80
8-FSK	9.1	7.0	0.33
8-FSK / DQPSK	7.7	4.8	0.56
D8-FSK / DQPSK	7.7	4.8	0.56
16-FSK	8.0	6.1	0.24
16-FSK / DQPSK	6.8	3.8	0.35
D16-FSK / DQPSK	6.8	3.8	0.35
32-FSK	7.3	5.4	0.15
32-FSK / DQPSK	6.1	3.1	0.21
D32-FSK / DQPSK	6.1	3.1	0.21
64-FSK	6.7	5.0	0.09
64-FSK / DQPSK	5.4	2.5	0.12
D64-FSK / DQPSK	5.4	2.5	0.12
128-FSK	6.2	4.6	0.05
128-FSK / DQPSK	4.9	1.9	0.07
D128-FSK / DQPSK	4.9	1.9	0.07
256-FSK	5.9	4.2	0.03
256-FSK / DQPSK	4.3	1.5	0.04
D256-FSK / DQPSK	4.3	1.6	0.04
512-FSK	5.5	4.0	0.02
512-FSK / DQPSK	3.8	1.1	0.02
D512-FSK / DQPSK	3.8	1.2	0.02
1024-FSK	5.3	3.7	0.01
1024-FSK / DQPSK	3.4	0.7	0.01
D1024-FSK/DQPSK	3.4	0.8	0.01

Tab. 1. Results for all tested modulations on the proposed software defined modulator and demodulator.

Before reaching the channel frequency bandwidth limit, the proposed hybrid modulations offer a greater than 50% increase of data rate in comparison with M-FSK modulations (under the condition of the same received signal quality). After reaching the bandwidth limit, the proposed hybrid modulations offer a greater than 150% increase of the data rates. This is noticeable by comparing the results in Fig. 9 and Fig. 10 at the same C/N_0 (received signal quality).

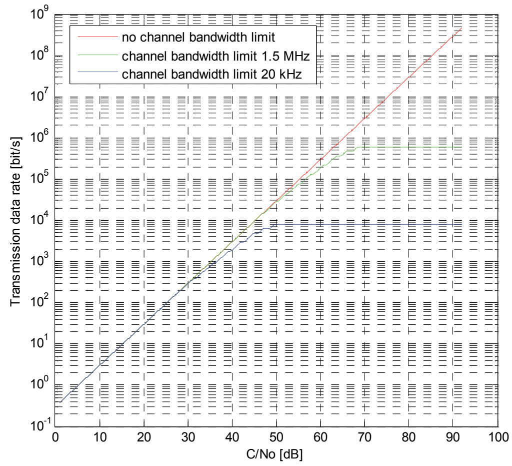

Fig. 9. Obtainable data rates at bandwidth limitations in dependence on C/N_0 – for a communication system implementing a conventional modulation 1024-FSK up to 2-FSK and DQPSK adaptation.

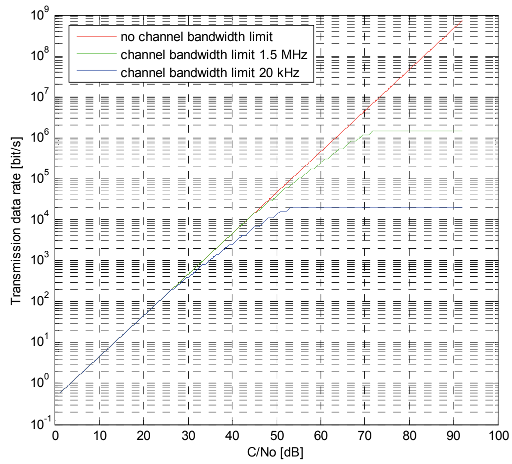

Fig. 10. Obtainable data rates at bandwidth limitations in dependence on C/N_0 – for a communication system implementing the proposed hybrid modulation 1024-FSK/DQPSK up to 2-FSK/DQPSK adaptation.

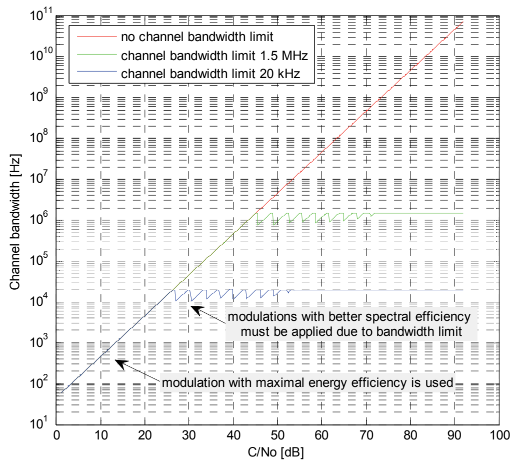

Fig. 11. Occupied frequency bandwidth related to data rates in Fig. 10 – for a communication system implementing the proposed hybrid modulation 1024-FSK/DQPSK up to 2-FSK/DQPSK adaptation.

In an adaptable communication system the modulation type is changed in dependence on the received signal quality. During a bad received signal quality period, a modulation with best energy efficiency is used (from implemented group of modulations). As the signal quality is increasing, the data rate is also increasing as well as the occupied frequency bandwidth. When the allowed frequency bandwidth is reached then the communication system has to switch to a more spectrally effective modulation for an increasing data rate and for keeping to the bandwidth limit (see Fig. 11).

4. Conclusion

The proposed novel modulator and demodulator with hybrid M-FSK/DQPSK and DM-FSK/DQPSK offer better energy efficiency as well as a better spectral efficiency in comparison with conventional M-FSK modulations. Hybrid modulations can be used for a CubeSat communication system with adaptation implementation, especially under the worst satellite link conditions (picosatellite elevation angle bellow 10°). At these elevations, the picosatellites on low Earth orbits stay for a high percentage time period, nevertheless the radio contact is possible [11]. The proposed hybrid modulations can ensure a better data rate than commonly used picosatellite CW beacons [12], [13] under these bad conditions.

When the bandwidth limit is not reached (due to low order of realized M-FSK part of modulation), then the proposed hybrid modulations offer a 50% increase of data rates in comparison with the conventional M-FSK modulation due to a better energy efficiency. When the bandwidth limit is fully used, then the hybrid modulations offer a 150% increase of date rates due to utilization of better energy efficiency as well as better spectral efficiency. The proposed hybrid modulations can also replace the very often used AFSK modulation. In this case, the 16-FSK/DQPSK modulation has a similar spectral efficiency with difference of energy efficiency approximately 6.6 dB for BER equal to 10^{-5} and 7.1 dB differences for BER equal to 10^{-3}.

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