A WFMT Downlink Transmitter for Low Earth Orbit Satellite

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Abstract: - This paper discusses the performance of the Satellite Downlink Transmitter that uses a Wavelet based Filtered Multi-Tone (WFMT) modulation. The novel WFMT modulation was proposed for improving characteristics of OFDM multicarrier systems but also can be successfully used in satellite communications. In this paper, we discuss the advantages of WFMT modulation in comparison with OFDM so as low sensitivity to narrowband RF interference and lower Peak-to -Average Power Ratio. It is shown that modern GaAs Solid-State Power Amplifiers are well suited for transmission of multicarrier signals. An effect of non-linear distortion on power added efficiency (PAE) of the RF Power Amplifier is discussed. Effect of clipping of WFMT signal on the error performance is described. It is shown that error correction block codes can significantly improve PAR characteristics of the communication system. The Power Efficiency of WFMT Satellite Transmitter is significantly higher that in case of OFDM.

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Key Words: - FMT, WFMT, filter-bank, Satellite, transponder, PAR, Reed Solomon.

1. Introduction

The Low Earth Orbit (LEO) satellites are used for such applications like Earth Observation, Personal Communication and Internet Access. The major advantage of the LEO Satellites is a low output power (about 1~10 W) of a downlink transmitter and as result the low cost and weight of the satellite.

It is well known that a multicarrier modulation provides better immunity of communication system to narrowband interferences and impulse noise but transmits more peak power.

A low power efficiency of the multicarrier downlink transmitter makes using of the multicarrier modulation in GEO Satellites impossible, but in the case of LEO Satellites, the multicarrier modulation may be used for wide range of applications.

In last years, a big progress in the technology of Solid-State-Power Amplifiers (SSPA) has been made. The modern SSPA uses semiconductor devices on basis of Gallium Arsenide, which can operate at higher frequencies than silicon devices.

The maximum continuous output power of a single GaAs FET ranges from a few watts to several tens of watts. The limiting factor is the generation of heat. The thermal limit for the maximum power is inversely proportional to the square of the frequency. A typical GaAs FET at C-band might have a maximum output power between 100 and 150 W, while at X-band it is about 10 W [14]. Higher power may be obtained by assembling modules using standard combining techniques. However, the number of parallel modules is limited by combination losses. A modern solid-state technology is the microwave monolithic integral circuits (MMIC). This device combines active GaAs FETs and passive elements that are placed on a small chip.

The modern SSPA provides very low non-linear distortions. Figure 1 demonstrates AM/AM and AM/PH characteristics of Ka-band GaAs SSPA [14].

During the last years, a great progress has been made in research and developing of Solid-State Power Amplifiers for multicarrier communication systems like Wi-Fi and WiMAX. These amplifiers have low non-linear distortion and work with output back off about 7dB. The efficiency of SSPA was improved by using several new techniques. One of these techniques is described in [15]. This paper discusses a GaN WCDMA amplifier, which uses an envelope tracking bias system to achieve high linearity and efficiency. A measured overall power

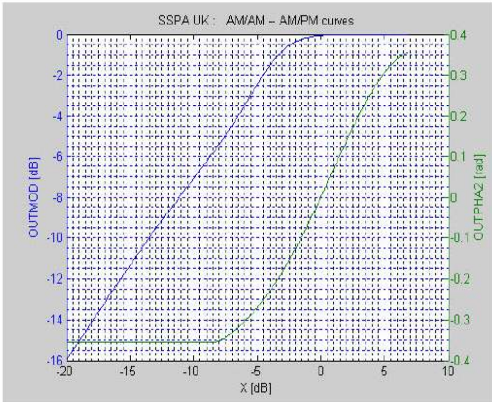

Figure 1. AM/AM and AM/PH characteristics of the GaAs SSPA

added efficiency (PAE) reached 50% for average output power 37 W. Another paper shows E-class switching SSPA that has drain efficiency 88% and output power 10 W in 2GHz frequency [13]. Figure 2 illustrates an output power and power added efficiency (PAE) of the proposed E-class SSPA.

Several new semiconductor technologies were proposed [14], [15]. Wide bandgap transistors such as the gallium n-electron mobility transistors (GaN HEMTS) were recently introduced commercially. The GaN devices wide bandgap increases the breakdown field by five times and the power density by a factor of 10 to 20, compared with GaAs-based amplifiers. The GaN devices are also highly efficient because they can operate at a higher voltage 24-35V, compared to 5-8V for GaAs based devices. In addition, GaN devices built on SiC substrate have a thermal conductivity 10 times higher than those fabricated from GaAs. The GaN HEMTs can also work at higher temperatures, which reduces the need for cooling and allows for more compact module design.

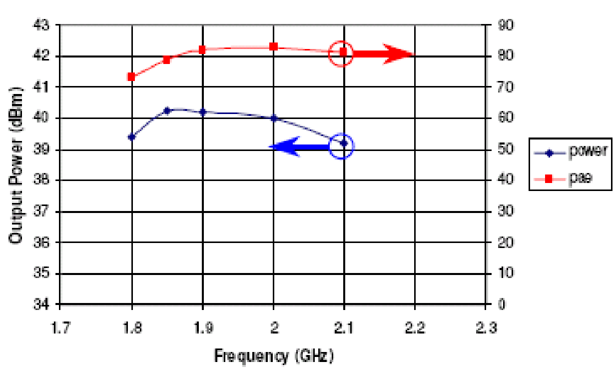

Figure 2. Output power and PAE of the E-class Power Amplifier

Apart from offering smaller size, GaN transistors have low capacitances, very high gain as well as capability of being operated over wide bandwidths.

The commercial available linear GaN HEMT power amplifiers for WiMAX applications were described in [14]. This article discusses the design and implementation of two linear Class-A/B amplifiers using high voltage Cree GaN transistors. Both designs, operating with peak powers of 15 and 100 watts, demonstrate the multicarrier capability of wide bandgap transistors whilst simultaneously providing high linearity over greater than 16 dB dynamic range. In addition, the transistors exhibit the excellent drain efficiency. Figure 3 illustrates a good linearity and an efficiency of the SSPA for 12-watt average output power on 3.6 GHz frequency [14].

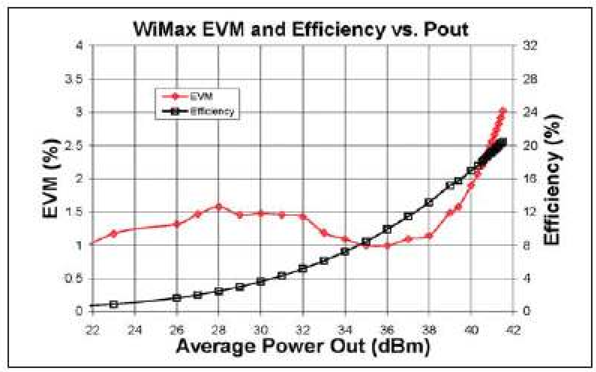

Figure 3. Error Vector Magnitude (EVM) and drain efficiency of the 12 watt WiMAX amplifier

As we see, the modern Solid State Power Amplifiers may be successfully used in the downstream transmitters of the LEO Satellites.

2. Multicarrier Modulation: OFDM, FMT, and WFMT

An Orthogonal Frequency Division Multiplexing (OFDM) Modulation was recently proposed for local area mobile wireless networks, such as WiFi and HIPERLAN-2. By implementing an Inverse Fast Fourier transform (IFFT) at the transmitter and a Fast Fourier Transform (FFT) at the receiver, OFDM transmits data over a number of ISI free sub-channels placed on orthogonal frequency carriers [1].

Although OFDM enables simple equalization, it introduces the following well-known problems.

- The peak-to-average power ratio (PAR) of the transmitted multicarrier signal is large

(about 15 dB), which requires using components with very low nonlinear distortions.
- Because information symbols are transmitted on orthogonal sub-carriers, OFDM is very sensitive to the frequency offset between transmitter and receiver oscillators, to the Doppler effect, and to the phase noise.

The Filtered Multi-Tone (FMT) Modulation was proposed by a group of researches from IBM as alternative technology for xDSL [2]. This technology is based on a Wavelet theory and uses complex filter-banks for synthesis and analysis of a multi-channel signal. The theoretical aspects of FMT Modulation for Wireless Application were developed by Cambridge University [3] and Udine University [4]. It was shown that in many cases FMT modulation guarantees better performance than OFDM.

A major drawback of FMT is a high realization complexity. To improve this disadvantage a Wavelet based Filtered Multi-Tone Modulation (WFMT) was developed by Data-JCE Electronics Ltd in 2002 – 2003 [5].

The Wavelet based Filtered Multi-Tone Modulation is a version of the Filter-bank modulated communication system described in detail in [8], [9], [10], in which the synthesis and analysis of sub-channel wavelets have corresponding provided by IFFT and FFT cores. Unlike OFDM, the number M of sub-channels in WFMT system is significantly less than N - the number of IFFT/FFT points. Each sub-channel wavelet is generated in this case from K harmonics (IFFT/FFT points) so there is a simply expression for the number of sub-channels:

$$M \le \frac{N}{K} \qquad (1).$$

As was shown in [7], the number of harmonics K defines a quality of generated wavelets, in particular the Inter-Symbol Interference (ISI) between wavelets and a bandwidth of sub-channels.

4. A PAR reduction, clipping, and error-correction coding in WFMT Systems

One of the major advantages of the WFMT technology is the low level of the Power-to-Average Power Ratio (PAR) that limits the transmitter power efficiency. As was shown in [10] the PAR of the WFMT signal is significantly less than the PAR of the OFDM signal. Figure 4 illustrates the PAR of a multicarrier system as a function of the number of sub-channels M.

As it is clear from the expression (1), WFMT system has a significant lower number of sub-channels M than the OFDM System, which uses the same IFFT core. Therefore, each WFMT sub-channel has wide bandwidth $W = KF$, where $F = 1/T$ is the distance between OFDM carriers.

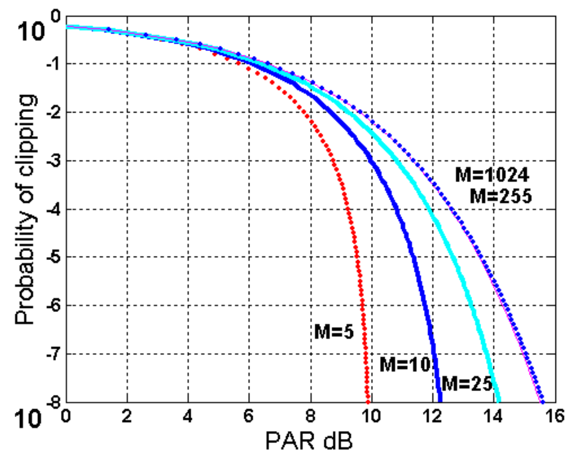

Figure 4. Peak-to-Average Power Ratio of WFMT system with circular constellation diagram

A Clipping of high amplitude peaks is a simple and effective way to reduce PAR in multicarrier systems. [11]. However, clipping causes distortion of the transmitted signal. In general, clipping will cause in-band and out-of-band distortion. It has been shown that out-of-band distortion can be removed using a simple filter [11]. The remaining in-band distortion has an effect on the transmitted signal as adding like-noise component- clipping noise. This clipping noise can be modelled as an additive noise at transmitter. Figure 5 shows a block diagram of a multicarrier system with clipping. It is clear that the transmitted signal $S(t)$ can be written as sum of non-clipped signal $S_0(t)$ and the clipping noise $\varepsilon(t)$:

$$S(t) = S_0(t) + \varepsilon(t). \qquad (3)$$

The clipping process cuts peaks of the original multicarrier signal. Therefore the clipping noise is a sequence of short pulses following with different time intervals. These pulses after passing over communication channel $C(f)$ are processed by a receiver of a multicarrier system. The multicarrier receiver comprises M sub-channel filters $G(f)$.

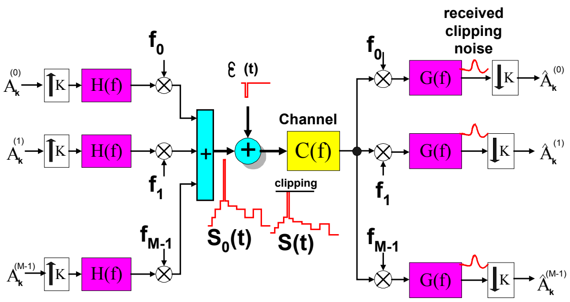

Figure 5. Multicarrier system with clipping

The clipping noise generates on the output of each sub-channel filter $G(t)$ a sequence of impulses $\psi(t)$, which have the length τ which are significantly longer than the length τ_0 of clipping noise pulses $\varepsilon(t)$.

$$\tau = \tau_0 + \Delta T , \qquad (4)$$

where ΔT is a length of the impulse response $g(t)$.

Suppose that $G(f) = 1$ for $0 < f < W$ and $G(f) = 0$ for $f > W$, where W is a bandwidth of the low-pass sub-channel filter $G(f)$.

In this case:

$$g(t) = Sin(2\pi Ft)/2\pi Ft , \quad (5)$$

The most part of energy of $g(x)$ is placed in an interval $-2\pi < x < 2\pi$ and ΔT may be coarse defined as:

$$\Delta T \approx 2/W . \qquad (6)$$

The length of the clipping noise pulses τ_0 can be defined correspondingly by using a full bandwidth B of the multicarrier system:

$$\tau_0 = 2/B = 2/MW . \quad (7)$$

Now we can define the relation Ω between the lengths of transmitted τ_0 and received τ clipping noise pulses.

$$\Omega = \frac{\tau}{\tau_0} = M + 1 , \qquad (8)$$

Note that for the OFDM System the number of sub-channels M is the same as the number of IFFT points: $M_{OFDM} = N$, and the expression (8) can be rewritten as:

$$\Omega_{OFDM} = N + 1 \quad , \quad (9)$$

$$\Omega_{WFMT} = \frac{N}{K} + 1; \qquad (10)$$

Figure 6 illustrates a timing diagram of the clipping pulses in the WFMT and OFDM systems. The short pulses of the clipping noise $\varepsilon(t)$ are generated by limiter schematics in the multicarrier transmitter. These pulses have a length τ_0 and a probability P_{CN}.

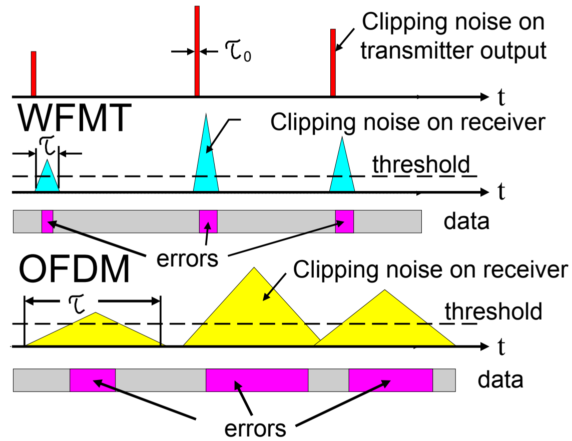

Figure 6. Time diagram of clipping noise in the OFDM and WFMT systems.

Each pulse of the clipping noise produces an impulse in the receiver of the multicarrier system. The length of the received impulse depends on the bandwidth of the sub-channel. Therefore, the same clipping pulse provides significantly more errors in the OFDM system than in the WFMT system. We start the investigation of this effect from a simple hypothesis.

Suppose that a non-clipped signal $S_0(t)$ is a normal process, then:

$$P_{CN} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-CR}^{+CR} e^{-x^2/2} dx , \quad (11)$$

where CR is a clipping ratio, $CR = CL/\sigma$, CL - clipping level and σ^2-variance (power) of $S_0(t)$.

It is clear that the peak-to average power ratio of the clipped signal $S(t)$ is:

$$PAR = 10\log(CR). \quad (12)$$

Now we can define an expression for probability of data error P_E in the multicarrier system:

$$P_E = \Omega P_{CN} . \qquad (13)$$

Let us use an error correction code to improve the performance of the multicarrier system, for example the Reed-Solomon Code $RS(n,m,r)$, which generates a sequence of $n-$ coded bytes from $m-$information bytes, and can corrects $r-$ of an erroneous bytes. We define for this code a code density DE as:

$$DE = m/n \ , \qquad (14)$$

and the maximal probability of error that may be corrected - P_{MAX} :

$$P_{MAX} = r/n = \frac{1}{2}(1 - DE); \ (15)$$

The number of clipping noise pulses that may be corrected by one block of the $RS(n,m,r)$ code Z is:

$$Z = P_{MAX} / P_E = \frac{1 - DE}{2 P_{CN} \Omega}; \quad (16)$$

Now we can calculate the probability P_Z of the appearance of Z pulses during one block of the $RS(n,m,r)$ code. Of course, this probability is the same as the probability of non-corrected data error on output of Reed-Solomon decoder. Since the number of clipping pulses is the same in the transmitter and receiver of the multicarrier system we can write:

$$P_Z = (P_{CN})^Z = (P_{CN})^{\frac{1-DE}{2\Omega P_{CN}}} \ . (17)$$

Note, that P_{CN} depends only on a clipping ratio CR, and DE is constant, which is defined by the Reed-Solomon Code. A parameter Ω depends only on the bandwidth of sub-channel (8). Therefore the expression (17) gives relations between probability of error in coded and clipped signal and Peak-to-Average Power Ratio (PAR) in the multicarrier system. Figure 7 illustrates this dependence for a different number of the sub-channels of a multicarrier system. In this case a circular constellation diagram was used for QAM symbols.

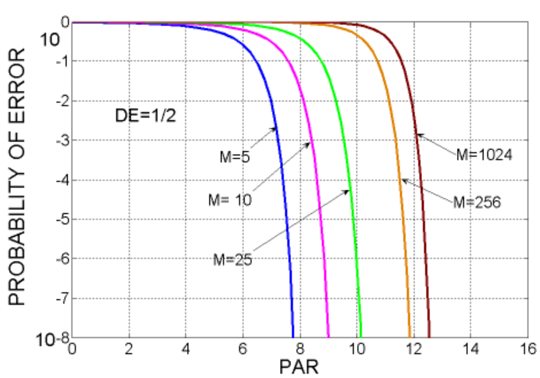

Figure 7. The Peak-to-Average Power Ratio and Probability of error in a multicarrier system with the Reed Solomon correction coding and circular constellation of QAM symbols

As for the case of non-coded transmission, the form of constellation diagram is very important for PAR characteristics of the multicarrier system. The square constellation diagram of QAM modulator increases PAR by ~2 dB both for the case of non-coded system and for case of error-correction coding and clipping of the multicarrier signal. Figure 8 shows this fact.

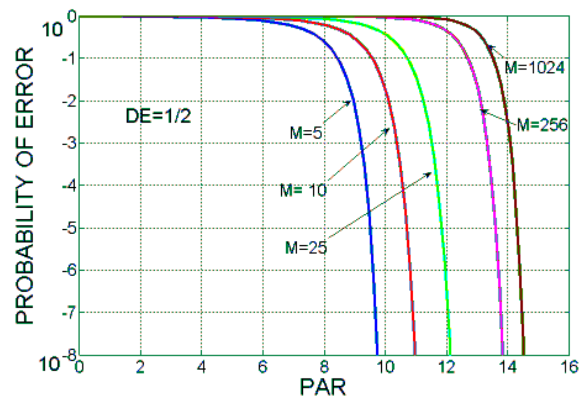

Figure 8. The Peak-to-Average Power Ratio in a multicarrier system with the Reed Solomon correction coding and square constellation diagram of a QAM modulator.

It is interesting that the code density DE of the error-correcting RS code has a small impact on the PAR performance of a multicarrier system. Figure 9 demonstrates a PAR characteristic of the WFMT system with $M = 5$ for different code densities of the Reed Solomon Code $DE = 1/2$, 2/3, 3/4, 7/8, 9/10. As we can see, the difference in PAR for different codes does not exceed 1 dB.

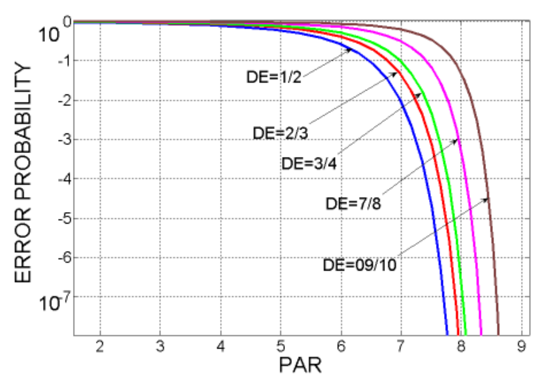

Figure 9. Peak-to-Average Power Ratio of WFMT system with circular constellation diagram and different error-correcting codes

5. Conclusions

In the last years a big progress in developing new technologies in the fields of wireless communications and the solid-state power amplifiers has been made. This progress gives a possibility to use a novel method of multicarrier transmissions based on WFMT modulation in Downstream Transmitters of LEO Satellites.

The main disadvantage of the multicarrier modulation is the high timer domain Peak-to-Average Power Ratio (PAR), which limits Downstream Transmitter power efficiency. The Downstream Transmitter power efficiency is one of the main parameters of the satellite communication system, which defines the size and cost of the satellite.

There are two ways to improve the downlink transmitter power efficiency:

1. To decrease the Peak-to-Average Power Ratio of the transmitted multicarrier signal.

2. To increase the power efficiency of the SSPA by using amplifiers of the AB-class or using E-class RF switching amplifiers.

The modern GaAs AB-class Solid State Power Amplifiers have a power efficiency of 15~20% in the case of transmission of WiMAX multicarrier signal in contrast to A-class SSPA, which have power efficiency of no more than 5%.

Using of the WFMT modulation gives addition increasing the downstream transmitter power efficiency by decreasing the Peak-to Average Power Ratio by 4~4.5 dB in comparison with OFDM modulation.

An efficient method of PAR reduction in multicarrier systems comprises of clipping the transmitted signal and using error-correcting block codes.

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