On Line-of-Sight Microwave Multicarrier Modulation Signature Area

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ABSTRACT – *The availability of line-of-sight (LOS) microwave digital systems which work at high transmission rates such as 155 Mbit/s, may be strongly limited by frequency selective fading effects. The main countermeasure techniques against the fading are equalization, diversity and error control coding. Under adverse geoclimatic conditions, the path length and/or the transmission rate may suffer restrictions even when countermeasures are used. The multicarrier modulation technique may be an alternative to tackle the effects of the fading. The performance analysis of multicarrier systems can be made based on the signature area. The aim of this work is to determine the signature area of orthogonal multicarrier systems suitable for microwave digital radio, and to determine the number of carriers necessary to obtain similar or better performance than single carrier coded modulation systems with adaptive equalization.*

KEY-WORDS: Digital radio; Multicarrier modulation; Signature area; Selective fading.

1. INTRODUCTION

The system signature or signature curve is the frequency response of the receiver to the signal distortion caused by frequency notches due to multipath fading. The signature shows the robustness of the equipment, in terms of bit error rate, when a frequency notch is inside of, or near to, the signal bandwidth boundaries, under some specific conditions.

The signature curve is a measurement made by setting up a test bench, which simulates a channel from Rummler's model or simplified three-path model, whose function can be written as [1; 2; 3; 4; 5; 6]

$$H(\omega) = a\{1 - b\exp[-j(\omega - \omega_0)\tau]\} \tag{1}$$

where a is the overall attenuation parameter, frequency independent, i.e., it represents a flat fading component; b is a shape parameter, defined by the ratio between the direct and secondary ray, and it determines the notch depth; ω is the angular frequency; ω_0 is the notch position in terms of its angular frequency and, finally, τ is the delay of the secondary ray. The notch depth, B, in *dB*, is given by

$$B = 20\log(1-b)\,. \tag{2}$$

The Figure 1 presents a test set block diagram for signature curve measurement [2]. The time delay τ is fixed, in practice, to 6.3 *ns* [1]. The secondary ray signal phase (φ) varies so that the notch may move in all extension of the signal bandwidth and its boundary vicinities. The notch depth is dynamically adjusted by the shape parameter (b), for a certain bit error rate (*BER*) condition, such as $BER = 10^{-3}$ or $BER = 10^{-6}$. This *BER* condition is generally named as *performance threshold* [1].

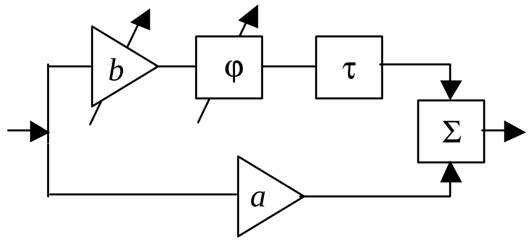

Figure 1. Fading simulation.

The delay τ assumes a positive value, when the secondary ray is delayed in relation to the direct ray, or τ is negative, when the direct ray is delayed in relation to the secondary ray. The shape parameter is in the interval $0 < b < 1$, when the amplitude of the secondary ray is smaller than that of the direct ray, and $b > 1$, otherwise. The channel response is said of *minimum phase* when $0 < b < 1$ and $\tau > 0$ and of *non-minimum phase* when $b > 1$ and $\tau > 0$ or when $0 < b < 1$ and $\tau < 0$. For single carrier modulation, the signature curve is usually obtained for both conditions, since the performance of some equalizers differs significantly from minimum to non-minimum phase condition [1].

Below the signature curve, the receiver will exhibit a very high and unacceptable *BER*. This situation establishes an *outage period* [3]. A typical signature curve and their rectangular approximation are presented in Figure 2.

The signature area may be obtained by rectangular approximation under the signature curve. The minimum phase signature area, S_M (in ns^{-2}), is computed according to

$$S_M = \frac{\lambda_a \times W}{\tau_r} \tag{3}$$

where W, in *GHz*, is the signature bandwidth; τ_r, in *ns*, is the reference delay, (typically, $\tau_r = 6.3$ *ns*) and l_a is the mean notch depth, converted from notch depth *B*, in *dB*, by

$$l_a = 10^{\frac{-B}{20}} . \tag{4}$$

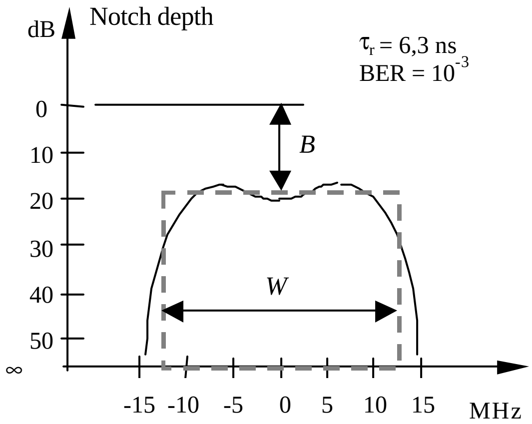

Figure 2. Typical signature curve.

The procedure to obtain the non-minimum phase signature area, S_{NM}, is identical to the minimum phase presented above. The system signature area is, in strict sense, an appropriate balance between the two situations. In practice, the minimum phase and non-minimum phase areas are averaged, i. e.,

$$S = \frac{S_M + S_{NM}}{2} . \tag{5}$$

2. TYPICAL SIGNATURE AREA FOR 155 MBIT/S SINGLE CARRIER MODULATION DIGITAL RADIO

The signature curve for single carrier modulation schemes are supplied by manufacturer of the receiver. Figures 3 and 4 present the 155 *Mbit/s* digital radio signature curves. The correspondent modulation schemes are the 64-TCM (Trellis Coded Modulation) and the 64-MLCM (Multilevel Coded Modulation). These schemes are suitable for 40 *MHz* width channel arrangements [7; 8].

Both receivers hold *time domain adaptive equalization* in order to compensate amplitude and phase distortions due to frequency selective fading. Figure 3 presents a minimum phase (full line) and non-minimum phase (dot line) signature curves. Note that there is no significant difference between the 64-MLCM and the 64-TCM and the areas are practically equivalent. In Figure 4, there is a significant difference between minimum phase (MP in the upper right corner) and non-minimum phase (NMP in the lower right corner). Thus, the areas are quite different. The equalizer used to produce the signature curve of the Figure 3, performs a very close response for minimum or non-minimum phase, whereas in the Figure 4, the signature curves show how an equalizer may produce substantially different responses for minimum and non-minimum phases. The dashed rectangle in both figures are the rectangular approximation used to compute the curve areas.

Note that both systems has the same magnitude order for signature area. Small differences may occur due equalizer performance and coded modulation schemes used.

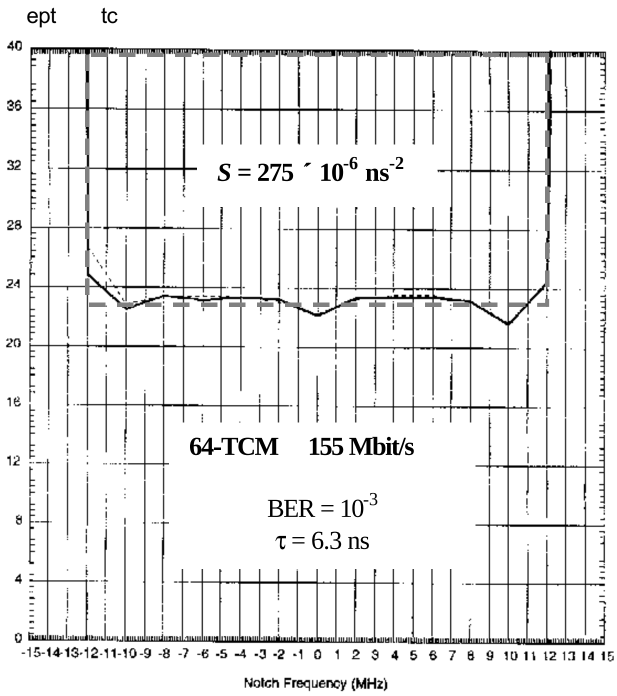

Figure 3. 64-TCM signature curve with adaptative equalization.

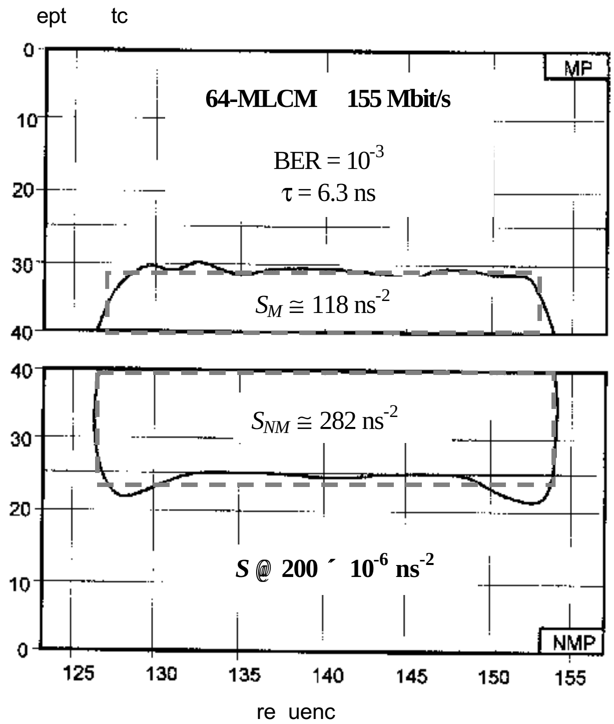

Figure 4. 64-MLCM signature curve with adaptive equalization.

3. SIGNATURE AREA FOR 155 MBIT/S MULTICARRIER MODULATION DIGITAL RADIO

The MCM scheme used to determine the signature area is an improved version of *time-limited orthogonal multicarrier modulation with waveform shaping* (*TLO-MCM*). This modulation technique presents a high bandwidth efficiency. For a considerable number of carrier, such as 64, its bandwidth is very close to the Nyquist bandwidth for double side band single carrier modulation, such as *M-PSK*, *M-ASK*, *M-QAM*. The bandwidth efficiency is approximately 1 *baud/Hz*. A detailed description of the *TLO-MCM* and its implementation are found in [9; 10; 11].

For the sake of comparison of the multicarrier schemes with *LOS* (*line of sight*) digital microwave radio with single carrier modulation, we are going to assume that:

1. The *LOS microwave radio* MCM schemes obey the channel arrangements authorized by regulatory agencies for a specific transmission rate.
2. The total transmission rate accommodates an *overhead* (typically about 10%) for synchronization, frame alignment, etc.
3. The occupied bandwidth for the MCM, for a given transmission rate, is smaller than or equal to the occupied bandwidth for the single carrier.
4. The *intercarrier interference* (*ICI*) due to the orthogonality damage brought by the selective fading is negligible, in order to its contribution to the bit error rate is despicable.

These assumptions hold for the following scheme:

a. The channel arrangements are for 40 *MHz* bandwidth channels.

b. The 155 *Mbit/s* nominal transmission rate plus 10% overhead implies to a total transmission rate of 170.5 *Mbit/s*. For convenience, a total transmission rate of 172.8 *Mbit/s* is adopted.

c. The MCM bandwidth is smaller than the single carrier modulation bandwidth, B, which is computed by

$$B = T_s^{-1} \cdot (1+\alpha) \qquad (6)$$

where T_S is the signaling period and α is the *roll-off factor* of the filter used to limit the bandwidth transmission. On the other hand,

$$T_s = \frac{\log_2 M}{R_b}\,, \qquad (7)$$

where R_b is the bit transmission rate and M is the number of symbols by carrier. Then, for R_b = 172,8 *Mbit/s*, M = 64 and α = 0,3; it is desirable that the MCM bandwidth be smaller than B = 37.44 *MHz*. Considering the 64-QAM, 64 subcarriers and the bandwidth efficiency approximately equal to 1, then the MCM bandwidth is 28.8 *MHz*.

d. The *intercarrier interference* (*ICI*) due to the orthogonality damage brought by selective fading is negligible if [10; 12]

$$C_\alpha = 2\pi \cdot \alpha_n \cdot B_n << 1 \qquad (8)$$

and

$$C_\beta = \frac{\beta_n}{T} << 1\,, \qquad (9)$$

where C_α and C_β are parameters that depend on the relative slope, α_n, and the group delay, β_n, respectively. B_n is the MCM subcarrier bandwidth and T is the MCM symbol period. B_n and T can be defined by

$$B_n = \frac{1}{T} \qquad (10)$$

and

$$T = N \cdot T_s \qquad (11)$$

where N is the number of subcarriers of MCM. Note that α_n and β_n are values of $\alpha(\omega)$ and $\beta(\omega)$, for $\omega = \omega_n$, respectively. The ω_n is the angular frequency for the n^{th} subcarrier of the MCM. Both $\alpha(\omega)$ and $\beta(\omega)$, are defined, respectively, as

$$\alpha(\omega) = \frac{1}{|H(\omega)|}\frac{d|H(\omega)|}{d\omega} \qquad (12)$$

and

$$\beta(\omega) = \frac{d\phi(\omega)}{d\omega} \qquad (13)$$

where the magnitude transference function of Rummler channel, $|H(\omega)|$, may be evaluated by:

$$|H(\omega)| = a \cdot \left\{\left[1+b^2\right] - 2 \cdot b \cdot \cos\left[(\omega-\omega_0)\cdot\tau\right]\right\}^{1/2} \,. \qquad (14)$$

The phase, $f(\omega)$, may be written as

$$\phi(\omega) = \tan^{-1}\left[\frac{b \cdot \mathrm{sen}(\omega\cdot\tau)}{1+b\cdot\cos(\omega\cdot\tau)}\right] \,. \qquad (15)$$

In this approach, it is possible to minimize the ICI, therefore the bit error rate becomes a function of the ISI only. Table 1 presents MCM systems with 64, 128 and 256 subcarriers with different notch depths. It can be verified that the both conditions imposed by (8) and (9) depend on the notch depth and on the number of subcarriers.

The performance of a MCM system can be analyzed under a frequency selective fading situation using a signal to interference ratio (SIR) for each subcarrier, χ_n, that can be obtained from the empiric expression [10]:

$$\chi_n = \left(\frac{T_s \cdot N \cdot |H(\omega_n)|}{\pi \cdot \tau \cdot a \cdot b} \right)^2 \quad (16)$$

where ω_n is the angular frequency of the subcarrier *n*.

Table 1 – Relative slope (α_n) and group delay (β_n) maximum values, for 64; 128 and 256 subcarries (*N*) as function notch depth (*B*).

N	**NOTCH DEPTH**					
	***B* = 20 dB**		***B* = 30 dB**		***B* = 40 dB**	
	C_a	**C_b**	**C_a**	**C_b**	**C_a**	**C_b**
64	0.084	0.026	0.277	0.087	0.874	0.28
128	0.042	0.013	0.139	0.043	0.437	0.14
256	0.021	0.006	0.069	0.022	0.218	0.07

From the signal to interference ratio, the symbol error rate of a M-QAM system, where *M* is a even power of two, can be evaluated by the expression [10]:

$$Ps_n = 2 \cdot \left(1 - \frac{1}{\sqrt{M}}\right) \cdot \text{erfc}\left(\sqrt{\frac{3}{2 \cdot (M-1)}\chi}\right) \times \left\{1 - \frac{1}{2} \cdot \left[1 - \frac{1}{\sqrt{M}}\right] \cdot \text{erfc}\left[\sqrt{\frac{3}{2(M-1)}\chi}\right]\right\} \quad (17)$$

Note that P_S is a function of χ, the signal to interference ratio, thus, this is the probability of symbol error for a given subcarrier with angular frequency ω_n.

For constellations which the symbol mapping is made by Gray code, the probability of bit error, Pb_n, is close estimate by:

$$Pb_n = \frac{Ps_n}{\log_2 M}. \quad (18)$$

The total bit error rate (BER), *Pb*, for the MCM scheme with an arbitrary number of subcarriers is obtained by using the mean value of the probability of bit error for each subcarrier. That is:

$$Pb = \frac{1}{M} \sum_{n=1}^{N} Pb_n \quad (19)$$

Figure 5 presents the total probability of bit error as a function of the subcarrier for two different notch depths. The spectral position of the notch coincides with the position of the 30th subcarrier of a MCM system with 64 subcarriers.

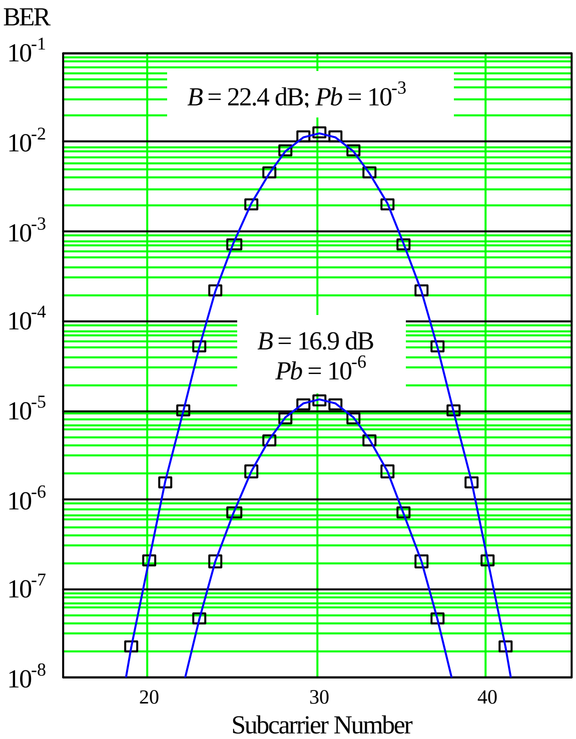

Figure 5. MCM (64 × 64-QAM) bit error rate as a function of a given subcarrier for two notch depths: 22.4 dB e 16.9 dB.

Therefore, the procedure to determine the signature area for any number of subcarriers can be summarized in the following steps:

1. Once the signature area as a function of ta notch depth (*B*) and of the reference delay (τ_r), is evaluated for an error rate threshold, it must be verified for a MCM scheme if the conditions imposed by (8) and (9) are satisfied.
2. For the total error rate, *Pb*, equal to the error rate threshold, the value of the notch depth that results in the error rate threshold, in the pass band and at the boundaries of the MCM spectrum, must be found for the values predefined of delay (τ_r) and flat fading (*a*), typically 6.3 ns and 1, respectively.
3. With the values obtained in the previous step, the signature area of the system can be evaluated by using the expressions (2), (3) and (4).

Figures 6 and 7 present the signatures obtained by computational analysis for a 64 × 64-QAM and 256 × 64-QAM MCM schemes, respectively. The results presented are for minimum phase. The MCM schemes present the same signature trace for minimum and non minimum phase [10].

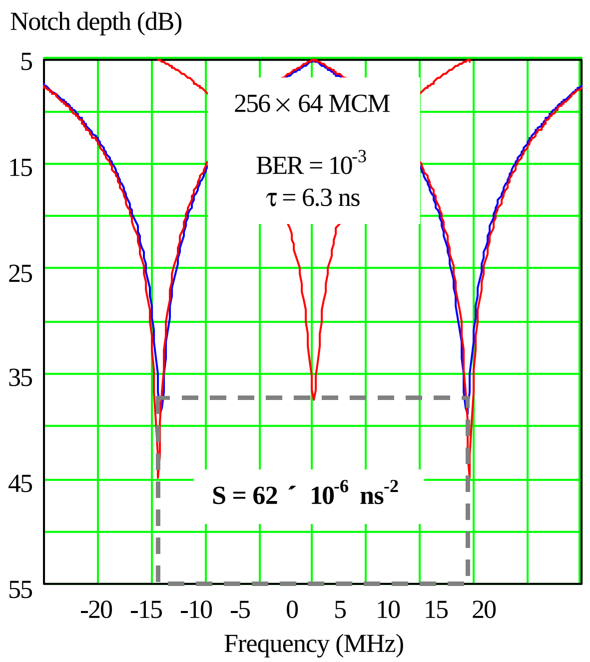

Figure 6. MCM – 64 × 64-QAM signature area.

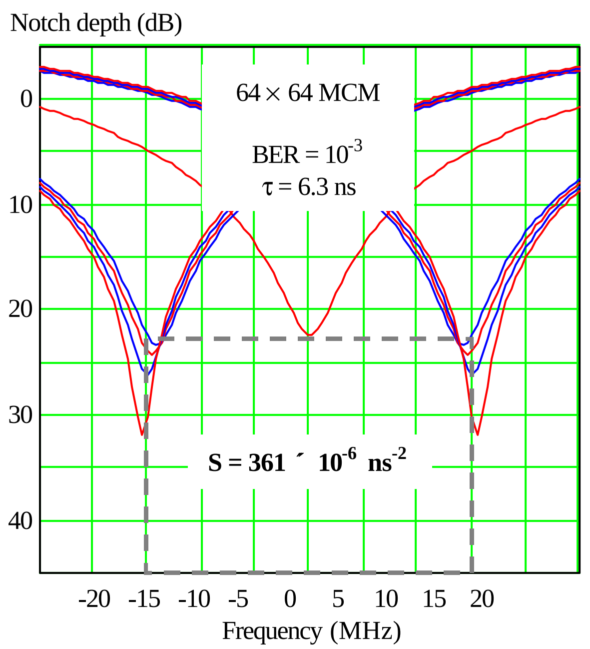

Figure 7. MCM – 256 × 64-QAM signature area.

Table 2. MCM signature áreas.

MCM	SIGNATURE AREA
64 ´ 64-QAM	361×10^{-6} ns^{-2}
128 ´ 64-QAM	148×10^{-6} ns^{-2}
256 ´ 64-QAM	62×10^{-6} ns^{-2}

Note that, according to figures 6 and 7, the MCM schemes present signature curves very similar with a rectangle. The notch depth that determines an error rate threshold is almost constant through the band. The limits of the signature bandwidth are defined by the abrupt increase of the notch depth when it approaches the subcarriers located at the boundaries of the MCM spectrum.

Table 2 shows the values of the signature area obtained for the 64 × 64-QAM, 128 × 64-QAM and 256 × 64-QAM MCM schemes.

4. Result Analysis

The results presented in the previous sections show that signature areas with values close to those presented by the best single carrier coded modulation with adaptive equalization can be obtained by using a MCM scheme with 64 subcarriers and Gray code, see figure 6.

According to figure 7 and table 2, for the number of subcarriers greater than 64, the signature area of the MCM scheme is significantly reduced.

Table 3 presents a brief of the results in decreasing order of signature areas and spectral efficiencies of the analyzed modulation. The transmission bit rate is 155 *Mbit/s*. Note also that there is a significant gain in bandwidth efficiency with the use of MCM schemes.

Table 3. Single carrier modulations and MCM signature area and bandwidth efficiency.

Modulation	Signature Area	Bandwidth Efficiency
64 ´ 64 MCM	361×10^{-6} ns^{-2}	5.38 bit/s/Hz
64-TCM [7]	275×10^{-6} ns^{-2}	3.88 bit/s/Hz
64-MLCM [8]	200×10^{-6} ns^{-2}	3.88 bit/s/Hz
128 ´ 64 MCM	148×10^{-6} ns^{-2}	5.38 bit/s/Hz
256 ´ 64 MCM	62×10^{-6} ns^{-2}	5.38 bit/s/Hz

5. Conclusion

This paper has shown that the signature areas with the same order of magnitude of those obtained by single carrier coded modulation schemes with adaptive equalization, can be obtained by using MCM schemes with 64 and over subcarriers. Note that the signature area is significantly reduced with 128 and 256 subcarriers. The signature areas of MCM schemes are evidently reduced by a factor of 2.4 when the number of subcarriers is increased from 64 to 128 and from 128 to 256. This signature area reduction reflects an increment in the notch depth of approximately 7.6 dB for an error rate threshold of 10^{-3}.

The MCM schemes has presented a better spectral efficiency than the single carrier coded modulation with adaptive equalization. This bandwidth gain would allow, for instance:

a. new division of the bands with canalization of 30 *MHz* instead of 40 *MHz*;
b. the use of the same 40 *MHz* channels for the transmissions at higher rates, by using subcarriers with greater constellations;
c. reduction of the signature area by using a coded modulation filling part or all the bandwidth that is not occupied by the MCM spectrum.

Notice also that, under the point of view of exclusively performance degradation imposed by the frequency selective fading, the use of MCM is gainful and it has a great development potential with the implementation of channel coding techniques.

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