This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE CCNC 2010 proceedings

Comparison of Power Amplifier Non-linearity Impact on 60 GHz Single Carrier and OFDM Systems

Alexander Maltsev, Artyom Lomayev,
Alexey Khoryaev, and Alexey Sevastyanov
Wireless Standards and Technology Group
Intel Corporation, Nizhny Novgorod, Russia
alexander.maltsev@intel.com

Roman Maslennikov
Wireless Competence Center
N.I. Lobachevsky State University of Nizhny Novgorod
Nizhny Novgorod, Russia
roman.maslennikov@wcc.unn.ru

Abstract— **This paper presents a detailed analysis of the impact of power amplifier (PA) non-linearity on the performance of single carrier (SC) and OFDM systems in 60 GHz spectrum. The efficiency of the considered systems was analyzed by estimating values of the power amplifier output backoff needed to meet the requirements on the transmit spectrum mask (TSM) compliance and error vector magnitude (EVM). Different models of the PA including an experimentally measured model for the 60 GHz PA were considered. It was estimated that for many types of modulations and PA models, SC system can have up to 1.5 dB higher output power than OFDM system. However, for the experimental PA model accounting for amplitude modulation-phase modulation distortion in addition to amplitude modulation – amplitude modulation distortion, the difference between the OFDM and SC output power levels was minimal, and OFDM even had approximately 1 dB better performance than SC for the BPSK modulation. A potential improvement in the transmit power due to application of digital predistortion techniques was estimated for both systems to be in the range from 1.5 to 3.4 dB.**

Index Terms — **power amplifier non-linearity impact, RF impairments, OFDM, single carrier, 60 GHz**

I. Introduction

Wireless communication systems operating in the 60 GHz frequency band are an area of active investigations in the last years because of the availability of 7 GHz of spectrum for unlicensed operation [1]. 60 GHz Wireless Personal and Local Area Networks (WPANs and WLANS) are capable of providing multi-Gbps performance for applications like uncompressed high definition video transmission, Gigabit wireless Ethernet, high speed synchronization between devices, and many others.

Effective design of 60 GHz wireless indoor systems is contributed by many factors with a proper selection of the modulation scheme being one of them. Two main candidate modulation schemes are considered for application in the millimeter-wave systems – single carrier (SC) modulation and orthogonal frequency division multiplexing (OFDM). The two schemes have both advantages and disadvantages relatively to each other. A comparison between the two modulations involves investigations of many different factors with the power amplifier non-linearity impact being one of the most important factors.

It is well known that SC systems have lower peak-to-average power ratio (PAPR) than OFDM systems giving SC systems some advantage in terms of the power amplifier (PA) backoff required to keep signal distortions due to PA non-linearity below the maximum allowed level. However, an informed selection between SC and OFDM modulation schemes requires knowledge of quantitative advantages in terms of PA backoff level of one modulation scheme over the other with taking into account specific 60 GHz WPAN / WLAN systems parameters and 60 GHz power amplifier models. In addition, the degradation due to PA non-linearity may be partially compensated by different digital predistortion techniques. Hence, the PA backoff levels for SC and OFDM systems after digital predistrotion application are also an important characteristic of the modulations comparison.

This paper presents results of the PA non-linearity investigation for SC and OFDM systems in the 60 GHz WPAN / WLAN scenario. Specific models of 60 GHz PAs are considered to evaluate both in-band and out-of-band signal distortions due to PA non-linearity and draw qualitative and quantitative conclusions on OFDM and SC systems impact.

The remainder of the paper is organized as follows. Section II presents details about the system model used including OFDM and SC systems parameters, and the considered PA models. Section III describes the evaluation criteria used for PA non-linearity distortion characterization. Section IV provides results of the performed analysis. Section V concludes the paper.

II. System Model

A. OFDM and SC Parameters

A summary of OFDM and SC systems parameters used in this work for PA non-linearity impact analysis are given in Table I. The selected values are typical for 60 GHz WPAN and WLAN system characteristics that are proposed in different specifications. The single carrier system with frequency domain equalization (SC-FDE) [2] was considered. Parameters of the SC and OFDM systems were selected so that to make throughputs of the two systems to be the same to allow for a fair comparison.

To model PA non-linear distortions, eight times interpolation of the transmitted and received signals was used. For the OFDM system, the interpolation at the transmitter and the decimation at the receiver were performed by applying the FFT of a larger size. For the SC system, the interpolation and decimation procedures were done with help of oversampled square root raised cosine (SRRC) filters applied at the transmitter and the receiver.

TABLE I
OFDM AND SC SYSTEMS PARAMETERS

Parameter	OFDM	SC
Sample rate	2.0 GHz	1.5 GHz
FFT size	512	512
Number of data subcarriers	384	512
Guard interval size	1/4 - 128 samples	1/4 - 128 samples
Symbol duration	320 ns (including GI)	426.6 ns (including GI)
Subcarrier spacing	3.9 MHz	2.9 MHz
Modulations	BPSK, QPSK, 16-QAM	BPSK, QPSK, 16-QAM
Interleaver	802.11a-like bit interleaver	block symbol interleaver
FEC scheme	convolutional coding $\{133_8, 171_8\}$ with code rates ½ and ¾	convolutional coding $\{133_8, 171_8\}$ with code rates ½ and ¾
Throughput	0.6 Gbps (BPSK ½) – 3.6 Gbps (16QAM ¾)	0.6 Gbps (BPSK ½) – 3.6 Gbps (16QAM ¾)

B. Power Amplifier Models

Non-linearity distortion of PAs is described by their amplitude modulation – amplitude modulation (AM/AM) and amplitude modulation – phase modulation (AM/PM) characteristics.

In this work, several models of PAs were considered. The first model is based on experimental measurements of the 60 GHz PA described in [3]. This model introduces AM/AM and AM/PM distortions in accordance with the following formulas:

$$y = F_{AM-AM}(x) = \frac{Gx}{\left(1+\left|\frac{Gx}{V_{SAT}}\right|^{2p}\right)^{\frac{1}{2p}}} \quad (1)$$

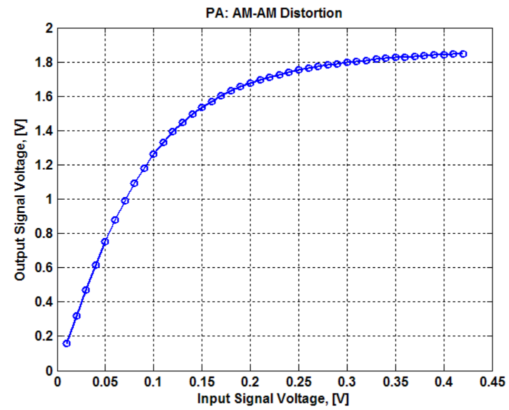
$$\theta = F_{AM-PM}(x) = \frac{Ax^q}{\left(1+\left(\frac{x}{B}\right)^q\right)} \quad (2)$$

where x is an amplitude of the input PA signal, y is an amplitude of the output PA signal, θ is a phase of the output PA signal, and parameters of the model are equal to: $G = 16$, $V_{SAT} = 1.9$ V, $p = 1.1$, $A = -345$, $B = 0.17$, and $q = 4$.

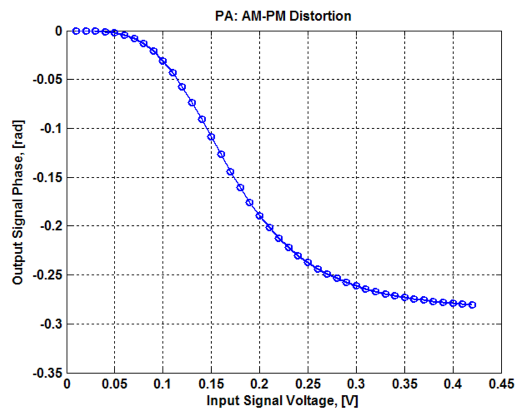
Model (1-2) was used by the IEEE 802.15.3c 60 GHz WPAN standardization group for PA impact evaluation. This model is referred to hereafter as the 'IEEE model'. The AM/AM $F_{AM-AM}(x)$ and AM/PM $F_{AM-PM}(x)$ characteristics of the model are plotted in Fig. 1 (a) and (b) respectively.

The AM/AM distortion function $F_{AM-AM}(y)$ of 'IEEE model' is known as the Rapp's model of the PA [4]. The Rapp's model is widely applied for PA non-linearity impact analysis in wireless systems. However, the Rapp's model only includes AM/AM distortions. In this work, the Rapp's model with parameters $p = 1.1$, $p = 2$, $p = 3$, and $p = 100$ was used for analysis in addition to the 'IEEE model'.

For the Rapp's PA model with high p, the AM/AM curve transforms into the 'ideal clipping' characteristic comprising a pure linear dependence between input and output signals below



(a)



(b)

Fig. 1. AM/AM (a) and AM/PM (b) characteristics of the PA model [3] used by the IEEE 802.15.3c group for PA non-linearity impact evaluation.

the PA saturation level and constant output amplitude for signals above the saturation level. Since many predistortion algorithms apply a signal transformation to have the effective AM/AM characteristic of the PA and predistrotion scheme to be close to the 'ideal clipping' characteristic, results for the Rapp's model with high p may be considered as an estimate of the results for the system employing a digital PA predistortion algorithm. In this work, the Rapp's model with $p = 100$ was used to estimate performance characteristics of PA with digital predistortion scheme.

III. CRITERIA FOR PA NON-LINEARITY IMPACT ANALYSIS

Non-linear distortion of the PA leads to appearance of additional interference both in the frequency band of the transmitted signal and in the adjacent frequency bands.

The in-band interference due to PA non-linearity may be considered as an additional noise source that contributes to the total noise budget of the communication system. The in-band interference is usually characterized by the error vector magnitude (EVM). The EVM is calculated as a normalized average power of the error vector between ideal and actually transmitted signal constellation points. The requirements for maximum allowable EVM level depend on the modulation and coding scheme (MCS) used by the communication system. More robust MCSs operating in lower SNR region may tolerate higher levels of the EVM than less robust ones. Specific requirements for the EVM of different MCSs considered in this

TABLE II

MAXIMUM EVM LEVELS FOR DIFFERENT MCSS

MCS	Relative constellation error (EVM), dB
BPSK ½	-5
QPSK ½	-10
QPSK ¾	-13
16-QAM ½	-16
16-QAM ¾	-19

work and the EVM measurement procedure were taken in accordance with IEEE 802.11a standard [5]. The EVM requirements for the analyzed MCSs are listed in Table II.

The out-of-band interference appearing due to non-linear distortions of the transmitted signal does not impede the given communication system performance but may harm the communication systems operating in the adjacent frequency channels. To guarantee that the out-of-band interference is below the maximum allowable level, a transmit spectrum mask (TSM) is defined and the spectrum of the output signal has to be below the TSM.

In this work, the TSM from the IEEE 802.11a standard [5] was taken as a basis and then scaled in the frequency domain by 100 times to account for the increase from 20 MHz channel bandwidth of the OFDM system in the IEEE 802.11a standard to 2 GHz channel bandwidth of the OFDM system in this work. As a result, the following TSM definition was used

0 dBr (dB relative to the maximum spectral magnitude of the signal) for bandwidth not exceeding 1800 MHz;

-20 dB at 1100 MHz frequency offset;

-28 dB at 2000 MHz frequency offset;

-40 dB at 3000 MHz frequency offset and above.

The same transmit spectrum mask was used for the OFDM and SC systems.

The estimation of the transmitted spectrum was done by calculation of the transmitted signal power spectrum density (PSD). The important parameters of the spectrum measurements are the resolution and video filter bandwidths. In this work, the bandwidth of the resolution filter was equal to the OFDM system subcarrier spacing of 3.9 MHz and the bandwidth of the video filter was taken equal to 2.5 kHz providing almost ideal averaging of the measured PSD.

The PA non-linearity impact was assessed by the maximum transmit power that can be maintained by the communication system while simultaneously meeting both the EVM and TSM requirements. The transmit power was measured as a negative backoff of the PA output power (output backoff – OBO) relatively to the saturation level. Maximum OBOs for the OFDM and SC systems using different MCSs were calculated for different PA models to compare these systems with respect to the PA non-linearity impact. The results were obtained with the help of numerical simulations.

IV. RESULTS OF ANALYSIS

A. Error Vector Magnitude (EVM) Results

EVM characteristics as a function of the PA OBO were calculated by simulations for different PA models and different

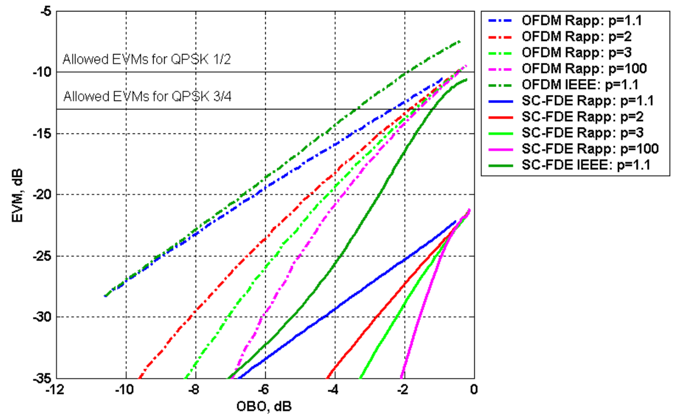


Fig. 2. EVM as a function of the OBO for OFDM and SC systems using QPSK modulation for different PA models.

modulations (BPSK, QPSK, 16-QAM). For OFDM systems, the EVM does not depend on the modulation type, but for SC systems such dependence exists with the highest EVM corresponding to the 16-QAM constellation.

As an example, Fig.2 shows the EVM results for the QPSK modulated OFDM and SC systems. The required EVM levels, also plotted in Fig. 2, allow to determine the maximum OBOs for each system and PA model as intersection points with the EVM curves. Fig. 2 shows that the SC systems have the EVM significantly below than for the OFDM systems for the Rapp's PA model with different value of parameter *p*. However, the 'IEEE model', additionally including the AM/PM distortion, increases the EVM level of the SC systems by approximately 10 dB for the OBO region close to the saturation and making the EVM performance of SC comparable to that of OFDM system.

TABLE III

OBO NEEDED TO MEET EVM REQUIREMENTS

MCS	PA model	OFDM OBO, dB	SC OBO, dB
BPSK 1/2	IEEE, p=1.1	0.00	0.00
	Rapp's p=1.1	0.00	0.00
	Rapp's p=2	0.00	0.00
	Rapp's p=3	0.00	0.00
	Rapp's p=100	0.00	0.00
QPSK 1/2	IEEE, p=1.1	-1.90	0.00
	Rapp's p=1.1	-0.49	0.00
	Rapp's p=2	-0.47	0.00
	Rapp's p=3	-0.45	0.00
	Rapp's p=100	-0.44	0.00
QPSK 3/4	IEEE, p=1.1	-3.37	-1.18
	Rapp's p=1.1	-2.30	0.00
	Rapp's p=2	-1.81	0.00
	Rapp's p=3	-1.66	0.00
	Rapp's p=100	-1.56	0.00
16QAM 1/2	IEEE, p=1.1	-4.77	-3.00
	Rapp's p=1.1	-4.05	-1.69
	Rapp's p=2	-3.09	-1.15
	Rapp's p=3	-2.80	-0.99
	Rapp's p=100	-2.57	-0.88
16QAM 3/4	IEEE, p=1.1	-6.13	-3.91
	Rapp's p=1.1	-5.75	-2.96
	Rapp's p=2	-4.30	-1.99
	Rapp's p=3	-3.90	-1.70
	Rapp's p=100	-3.48	-1.49

A summary of the OBOs sufficient to meet EVM requirements is given in Table III. One may see that for the BPSK modulation there is no gain of the SC over the OFDM since both systems meet EVM requirements even for OBOs close to the saturation level. For other modulations, the advantage of the SC is from 0.4 to 2.3 dB for the QPSK and from 1.5 to 2.8 dB for the 16-QAM.

As expected, the Rapp's model with p = 100 ('ideal clipping') provides the minimum EVM for all configurations of both the OFDM and SC systems.

B. Transmit Spectrum Mask (TSM) Compliance Results

OBOs required to meet the TSM requirements were calculated for the OFDM and SC systems by numerical simulations. The transmit signal PSD depends on the modulation type for the SC systems and different OBOs are required when using different modulation levels. For the OFDM system, the transmit signal spectrum does not depend on the used modulation and the same OBO can be used with all types of modulations.

Fig. 3 shows the TSM and transmit signals PSDs for the QPSK-modulated SC system with different PA models. Fig. 4 plots the same used TSM and transmit signal PSD for the OFDM system also with different PA models.

A summary of the OBOs that should be used in order for the considered systems configurations to meet the TSM requirements is given in Table IV.

It can be seen that in terms of the TSM requirements the OFDM has an OBO gain over SC for the case of BPSK modulation for the 'IEEE model' of the PA and Rapp's model with p = 1.1. In addition, for the case of the 16-QAM modulation and the Rapp's PA model with p = 100, the OBOs for the OFDM and SC are almost equal. For all other cases, the SC has an OBO gain over the OFDM but it is not higher than 1.5 dB.

C. Total Impact of PA Non-linearity

As described above, the EVM and TSM requirements have to be met by the communication system simultaneously. Hence, two OBO values originated from the EVM and TSM requirements need to be found and the minimum OBO has to be selected in order to meet both constraints. Table V gives a summary of the completed investigation by indicating a type of the OBO restriction (EVM or TSM) for different MCSs of the OFDM and SC systems for all the considered PA models. In addition, a gain of the SC over the OFDM is calculated in the last column of Table V.

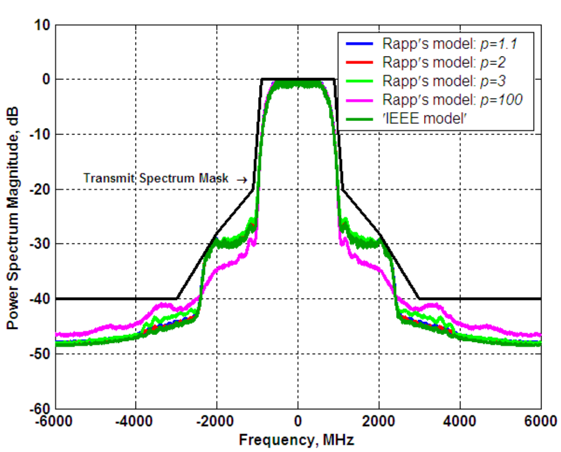


Fig. 3. Transmit spectrum mask and spectra of SC system with QPSK modulation for different models of the PA.

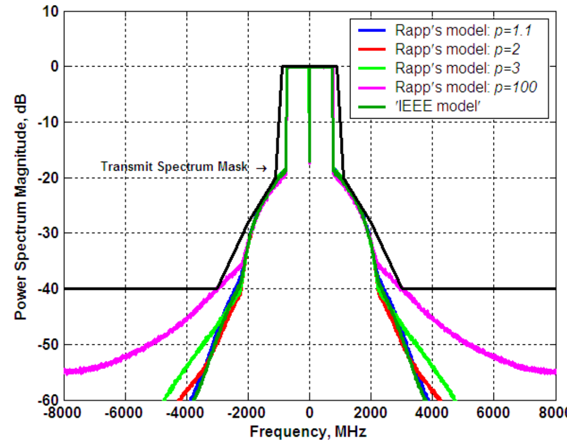


Fig. 4. Transmit spectrum mask and spectra of the OFDM system for different models of the PA.

It can be seen from Table V that the TSM is a limiting factor for all MCSs of the OFDM system except for 16-QAM ¾ and for all MCSs for the SC. The absolute OBO values are from -3.1 to -6.1 dB for the OFDM and from -1.8 to the -4.7 dB for the SC systems. The OFDM has approximately 1 dB gain over the SC for the BPSK when considering the 'IEEE model' of the PA and Rapp's PA model with p = 1.1. For other configurations, the SC can meet both the EVM and TSM restrictions at higher level of the transmit signal OBO. However, the gains of the SC system over the OFDM are not significant and the difference in the OBO does not exceed 1.5 dB and is below 1 dB for many system configurations. For the 'IEEE model' of the PA, the difference is the required OBOs between the SC and OFDM systems is minimal and does not exceed 0.5 dB for all modulations except for 16-QAM ¾.

As expected, the Rapp's PA model with p = 100 ('ideal clipping' model) provides the maximum OBO for all OFDM and almost all SC systems configurations. The OBO gain for the Rapp's model with p = 100 over the 'IEEE model' was found to be from 1.9 to 2.7 dB for the OFDM system and from 1.5 to 3.4 dB for the SC system. This improvement may be considered as an estimate of the transmit power increase that can be achieved by applying ideal digital predistortion techniques.

TABLE IV

OBO REQUIRED TO MEET TSM REQUIREMENTS

PA model	OFDM OBO, dB	SC BPSK OBO, dB	SC QPSK OBO, dB	SC 16-QAM OBO, dB
IEEE, p=1.1	-5.00	-5.93	-4.58	-4.68
Rapp's p=1.1	-4.73	-6.12	-4.58	-4.53
Rapp's p=2	-3.58	-3.37	-2.53	-3.16
Rapp's p=3	-3.22	-2.5	-1.8	-2.62
Rapp's p=100	-3.14	-2.5	-1.68	-3.16

TABLE V
SUMMARY OF PA NON-LINEARITY IMPACT RESULTS FOR 60 GHZ OFDM AND SC SYSTEMS

MCS	PA model	OFDM limitation	OFDM min OBO, dB	SC limitation	SC min OBO, dB	SC gain over OFDM, dB
BPSK 1/2	IEEE, p=1.1	TSM	-5.00	TSM	-5.93	-0.93
	Rapp's p=1.1	TSM	-4.73	TSM	-6.12	-1.39
	Rapp's p=2	TSM	-3.58	TSM	-3.37	0.21
	Rapp's p=3	TSM	-3.22	TSM	-2.50	0.72
	Rapp's p=100	TSM	-3.14	TSM	-2.50	0.64
QPSK 1/2	IEEE, p=1.1	TSM	-5.00	TSM	-4.58	0.42
	Rapp's p=1.1	TSM	-4.73	TSM	-4.58	0.15
	Rapp's p=2	TSM	-3.58	TSM	-2.53	1.05
	Rapp's p=3	TSM	-3.22	TSM	-1.80	1.42
	Rapp's p=100	TSM	-3.14	TSM	-1.68	1.46
QPSK 3/4	IEEE, p=1.1	TSM	-5.00	TSM	-4.58	0.42
	Rapp's p=1.1	TSM	-4.73	TSM	-4.58	0.15
	Rapp's p=2	TSM	-3.58	TSM	-2.53	1.05
	Rapp's p=3	TSM	-3.22	TSM	-1.80	1.42
	Rapp's p=100	TSM	-3.14	TSM	-1.68	1.46
16QAM 1/2	IEEE, p=1.1	TSM	-5.00	TSM	-4.68	0.32
	Rapp's p=1.1	TSM	-4.73	TSM	-4.53	0.20
	Rapp's p=2	TSM	-3.58	TSM	-3.16	0.42
	Rapp's p=3	TSM	-3.22	TSM	-2.62	0.60
	Rapp's p=100	TSM	-3.14	TSM	-3.16	-0.02
16QAM 3/4	IEEE, p=1.1	EVM	-6.13	TSM	-4.68	1.45
	Rapp's p=1.1	EVM	-5.75	TSM	-4.53	1.22
	Rapp's p=2	EVM	-4.30	TSM	-3.16	1.14
	Rapp's p=3	EVM	-3.90	TSM	-2.62	1.28
	Rapp's p=100	EVM	-3.48	TSM	-3.16	0.32

V. CONCLUSION

This paper presented results of the power amplifier (PA) non-linearity impact analysis for the OFDM and SC systems when applied to the operation in the 60 GHz frequency band. The experimental 'IEEE model' [3] and traditional Rapp's model [4] of PA were considered. Systems tolerance to PA non-linearity was estimated in terms of the output power decrease relatively to the PA saturation level (output backoff – OBO) required for meeting Error Vector Magnitude (EVM) and Transmit Spectrum Mask (TSM) constraints.

It was demonstrated that for most combinations of the modulation and coding schemes (MCSs) and PA models, the SC system has an advantage in terms of the required OBO over the OFDM system. The absolute values of the minimum OBO for both systems were estimated in the range from –6.1 to –1.7 dB. The power level increase that can be tolerated by the SC system while still meeting the TSM and EVM requirements was found to be up to 1.5 dB higher than for the OFDM system. The minimum difference (below 0.5 dB for all the MCSs except for the 16-QAM ¾) between the SC and OFDM performance was observed for the measurements based 'IEEE model' of the PA including AM/PM distortions in addition to the AM/AM distortions of the Rapp's model. For the "IEEE" model and BPSK modulation, the maximum power of the OFDM was found to be even 1 dB better than for SC. Comparing the TSM and EVM imposed requirements, the requirements for the TSM dominated over the EVM requirements for all the MCSs of the SC system and for all the MCSs of the OFDM system except for the 16-QAM ¾ modulation.

The potential OBO gain from digital predistortion techniques was estimated to be in the range from 1.9 to 2.7 dB for OFDM and from 1.5 to 3.4 for SC.

The detailed analysis performed in this work has demonstrated that in respect to the PA non-linearity impact, the 60 GHz SC has advantage over OFDM for most of the MCSs and PA models. However, the achievable advantage from 0 to 1.5 dB of SC over OFDM is not significant and cannot be considered as an essential factor for most 60 GHz WPAN/WLAN applications.

VI. REFERENCES

[1] P. Smulders, H. Yang, I. Akkermans, "On the design of low-cost 60-GHz radios for multigigabit-per-second transmission over short distances", *IEEE Comm. Mag.,* Dec 2007, pp. 44-51.

[2] F. Pancaldi *et al*, "Single-carrier frequency domain equalization," *IEEE Signal Processing Mag.*, Sept 2008, pp. 37-56.

[3] IEEE doc.: 802.15-06-0477-00-003c, Chang-Soon Choi et al, "RF impairment models for 60 GHz-band SYS/PHY simulation".

[4] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSK/OFDM signal for a digital sound broadcasting system," *Proc. ECSC-2*, Oct. 1991, Liege, Belgium, pp. 179–84.

[5] IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications – 2007.