# Impact of RF Circuit Imperfections on Multi-carrier and Single-carrier based Transmissions at 60 GHz

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***Abstract*— Circuit technology for 60 GHz is still limited, and impairments due to radio frequency (RF) circuit imperfections must be taken into account. Therefore, the candidate transmission schemes, in addition to multi-path fading, should be fairly resistant to RF circuit imperfections. In this paper, a performance comparison of multi-carrier (MC) and single-carrier (SC) based transmission schemes in the presence of DAC/ADC imperfections and amplifier nonlinearities, is carried out. It is shown that the SC scheme has substantially lower front-end requirements than its MC counterpart, while having the same overall system complexity.**

***Index Terms*— OFDM, SC-FDE, DAC, ADC, amplifier nonlinearities.**

## I. Introduction

Multi-carrier (MC) and single-carrier (SC) schemes are two practical alternatives for high data rate communication in the 60 GHz band, and are currently under consideration by the IEEE 802.15.3c task group. Both schemes provide effective mitigation of inter-symbol-interference (ISI) with reasonable implementation complexity. However, their sensitivity to RF circuit impairments in 60 GHz transmission scenarios is not yet fully investigated. A number of comparisons between MC and SC schemes can be found in literature [1]–[4]. The SC scheme was shown to have a lower complexity when used over short distances in asymmetric digital subscriber lines (ADSLs) [1]. SC has a lower peak-to-average-power ratio (PAPR), and is more resistant to frequency offset errors as compared to the MC scheme [2]. The block based processing for the SC scheme is known to achieve maximum diversity, irrespective of the block length [2], and therefore outperforms the MC scheme in un-coded scenarios. For code rates $R_c \leq 1/2$, both schemes have the same performance in multi-path fading channels [2]. This is also confirmed, still assuming an ideal front-end, for 60 GHz transmission scenarios [3]. The SC scheme was shown to require a lower input back-off (IBO) for the high power amplifier (HPA) in IEEE 802.11 transmission scenarios [4]. The operating parameters for 60 GHz RF circuits are expected to be different from IEEE 802.11 due to a large number of sub-carriers and more severe multi-path conditions.

In this paper, the impact of RF circuit imperfections on MC and SC schemes is investigated. The RF imperfections taken into account are: quantization, due to digital-to-analog and analog-to-digital converters (DACs and ADCs), and nonlinearities due to HPA. The power penalty for SC and MC schemes, i.e., the signal-to-noise ratio (SNR) degradation as a function of bit error rate (BER) for various DAC/ADC word lengths and HPA input back-off (IBO) values, is presented. It is shown that for a given number of DAC/ADC bits and for a certain amplifier IBO, SC scheme has a substantially lower SNR degradation, while having the same overall system complexity. Therefore, the SC scheme appears to be more suited for low cost transceiver implementation in 65 nm CMOS technology, that is under investigation for 60 GHz front circuit fabrication.

The remaining paper is organized as follows: Section II gives the used 60 GHz channel model and the system models for the MC and SC based transceivers. The transfer characteristics of various RF circuit impairments and their impact on MC and SC based transceivers is outlined in Section III. Conclusions are drawn in Section IV.

## II. System and Channel Model

A brief overview of orthogonal frequency division multiplexing (OFDM) based MC schemes [2], block based SC schemes with frequency domain equalization (FDE) [5], and a 60 GHz channel model [6], is presented in this section.

### A. Channel Model

A line-of-sight (LOS) time invariant tapped delay line (TDL) channel model, based on wideband measurements at 60 GHz [6], is used for performance evaluation. The channel coefficients $h_n$, given in [6], are modeled as complex numbers with a uniformly distributed phase between $[0, 2\pi)$. This channel has an average root mean square (RMS) delay spread of $\overline{\tau}_{rms} = 7$ ns and an average maximum delay spread of $\overline{\tau}_{max} = 70$ ns. The channel coherence bandwidth $B_c$ is given as $B_c = 0.063/\overline{\tau}_{rms} = 9$ MHz.

### B. Multi-carrier based System Design

The OFDM symbol samples are denoted by $\left(X_0^{\mathcal{M}}, \ldots, X_{N-1}^{\mathcal{M}}\right)$, where $X_k^{\mathcal{M}} = \frac{1}{N}\sum_{n=0}^{N-1} x_n e^{j2\pi kn/N}$, $N$ is the number of OFDM symbol samples, and $\mathbf{x} = (x_0, x_1, \ldots, x_{N-1})$ is the vector of mapped data symbols. To avoid inter-block interference (IBI), the OFDM symbol is extended with a cyclic prefix (CP) of $L$ samples. Assuming an ideal front end, the components of the received vector $\hat{\mathbf{x}}^{\mathcal{M}}$, after CP removal, FFT operation and equalization in the presence of noise, are given by $\hat{x}_m^{\mathcal{M}} = x_m + N_m/H_m$, where $H_m = \sum_{n=0}^{N-1} h_n e^{-j2\pi mn/N}$, and $N_m = \sum_{k=0}^{N-1} n_k e^{-j2\pi mk/N}$. The noise component $n_k$ represents additive white Gaussian noise (AWGN), with single sided power spectral density (PSD) $N_0/2$ per dimension. The equalized symbol vector $\hat{\mathbf{x}}^{\mathcal{M}}$ is then passed to a maximum likelihood (ML) detector which operates on a symbol by symbol basis. The parameters of the 60 GHz OFDM based transceiver are summarized in Table I. The performance of a MC-QPSK and MC-8PSK system for an ideal front end is shown in Figure 1(a).

TABLE I
MC AND SC SYSTEM PARAMETERS

| | MC | SC |
|---|---|---|
| Carrier frequency | 60 GHz | 60 GHz |
| Modulation scheme | QPSK / 8PSK | QPSK / 8PSK |
| Channel bandwidth | 1 GHz | 1 GHz |
| # of sub-carriers / block length | 1024 | 1024 |
| Cyclic prefix length ($L$) | 100 | 100 |

### C. Single-carrier based System Design

In a SC system, the mapped data symbols $\mathbf{x} = (x_0, x_1, \ldots, x_{N-1})$ are extended with a CP of $L$ samples, prior to transmission. Assuming an ideal front end, the components of the received vector, $\hat{\mathbf{x}}^{\mathcal{S}}$ after CP removal FFT, channel equalization and IFFT operation, are $\hat{x}_m^{\mathcal{S}} = x_m + \frac{1}{N}\sum_{k=0}^{N-1}(N_k/H_k)\, e^{j2\pi km/N}$. The samples of the estimated data vector $\hat{\mathbf{x}}^{\mathcal{S}}$ are then passed to an ML detector. The system parameters for a 60 GHz SC based system design are also given in Table I. The performance of a SC-QPSK and SC-8PSK system for an ideal front end is shown in Figure 1(a).

### D. System Complexity

Denoting $N_{\mathrm{MA}}$ as the number of multiply and accumulate (MA) operations required for one block of length $N$, it is shown in [1], that for an FFT/IFFT operation $N_{\mathrm{MA}} = 0.75N\log_2 N$. The simple channel equalization strategy outlined in the previous section can be performed by 3 real multiplications per sample, i.e., $3N$ real multiplications per block. The complexities of OFDM and SC are summarized in Table II. In an OFDM system, both the transmitter ($T_x$) and the receiver ($R_x$) have comparable computation complexity, whereas for SC the complexity is solely concentrated at the receiver side. Therefore, in terms of implementation complexity, MC is a better candidate for broadcast systems whereas for symmetric links both schemes have the same overall computational cost.

TABLE II
COMPLEXITY OF MC AND SC BASED SYSTEMS

| MC | SC | MA operation block | $N_{\mathrm{MA}}$ |
|---|---|---|---|
| $T_x$ | $R_x$ | IFFT | $0.75N\log_2 N$ |
| $R_x$ | $R_x$ | FFT | $0.75N\log_2 N$ |
| $R_x$ | $R_x$ | Equalization | $3N$ |
| | | Total | $1.5N\log_2 N + 3N$ |

## III. RF IMPAIRMENTS: MODELS AND CONSEQUENCES

This section briefly outlines the RF device models and then investigates their impact on SC and MC schemes. A detailed description of RF models can be found in [7], [8], and the references therein.

### A. DAC: Model and Consequences

A thermometric coded DAC, in which each element consists of a resistor divider is considered [7]. The resistor noise is modeled as AWGN with zero mean and variance

$$\sigma_R^2 = 4 \cdot 1.38 \times 10^{-23} \cdot T \cdot R \cdot B, \qquad (1)$$

where $T$ is the temperature in Kelvin (K), $R$ the resistance in Ohm ($\Omega$) and $B$ the the equivalent noise bandwidth in Hz. Assuming a room temperature of 300 K, a combined resistance of 50 $\Omega$ and a circuit operating at 1 GHz, we get $\sigma_R^2 = 8.2 \times 10^{-10}$ V$^2$. The normalized transfer characteristic of a 3 bit DAC is shown in Figure 2(a).

For a MC scheme, employing a real DAC, the transmitted vector $\mathbf{X}^{\mathcal{MD}}$ has components $X_p^{\mathcal{M}} + q_p^{\mathcal{MD}} + r_p$ that are an addition of the ideal signal $X_p^{\mathcal{M}}$ with a uniformly distributed quantization noise $q_p^{\mathcal{MD}}$, and a zero mean AWGN component $r_p$ with variance $\sigma_R^2$. The quantization noise $q_p^{\mathcal{MD}}$ is uniformly distributed between $\left(-b \cdot \Delta^{\mathcal{MD}}, +b \cdot \Delta^{\mathcal{MD}}\right)$, where $\Delta^{\mathcal{MD}} = \max\left\{\max|\Re(X_p^{\mathcal{M}})|, \max|\Im(X_p^{\mathcal{M}})|\right\}$, $b = 1/(2^{N_{DAC}} - 1)$, and $N_{DAC}$ denotes the number of DAC bits. The operators $\Re(.)$ and $\Im(.)$ denote the real and imaginary part of a complex signal. It is assumed that no signal clipping occurs. For a SC based system, the elements of the transmitted vector $\mathbf{x}^{\mathcal{SD}}$ are given by $x_p^{\mathcal{S}} + q_p^{\mathcal{SD}} + r_p$. The quantization noise $q_p^{\mathcal{SD}}$ is uniformly distributed between $\left(-b \cdot \Delta^{\mathcal{SD}}, +b \cdot \Delta^{\mathcal{SD}}\right)$, where $\Delta^{\mathcal{SD}} = \max\left\{\max|\Re(x_p^{\mathcal{S}})|, \max|\Im(x_p^{\mathcal{S}})|\right\}$. In a MC system, $\mathbf{X}^{\mathcal{M}}$ has a high dynamic range (due to the summation of multiple orthogonal sub-carriers), whereas in case of a SC scheme $\mathbf{x}^{\mathcal{S}}$ has a relatively low dynamic range. Therefore, $\Delta^{\mathcal{MD}} > \Delta^{\mathcal{SD}}$ and thus a higher number of bits are required in a MC system to reduce the impact of quantization noise. The SNR degradation (or power penalty) $\Delta_{SNR}$, at the input of the ML detector, is the ratio of the ideal front end SNR to the SNR in the presence of RF impairment(s). Figure 1(b) shows $\Delta_{SNR}$ as a function of BER for SC and MC schemes using QPSK and 8PSK constellations and different $N_{DAC}$ values. For a maximum power penalty of 1 dB at a BER of $10^{-4}$, SC-QPSK and SC-8PSK schemes

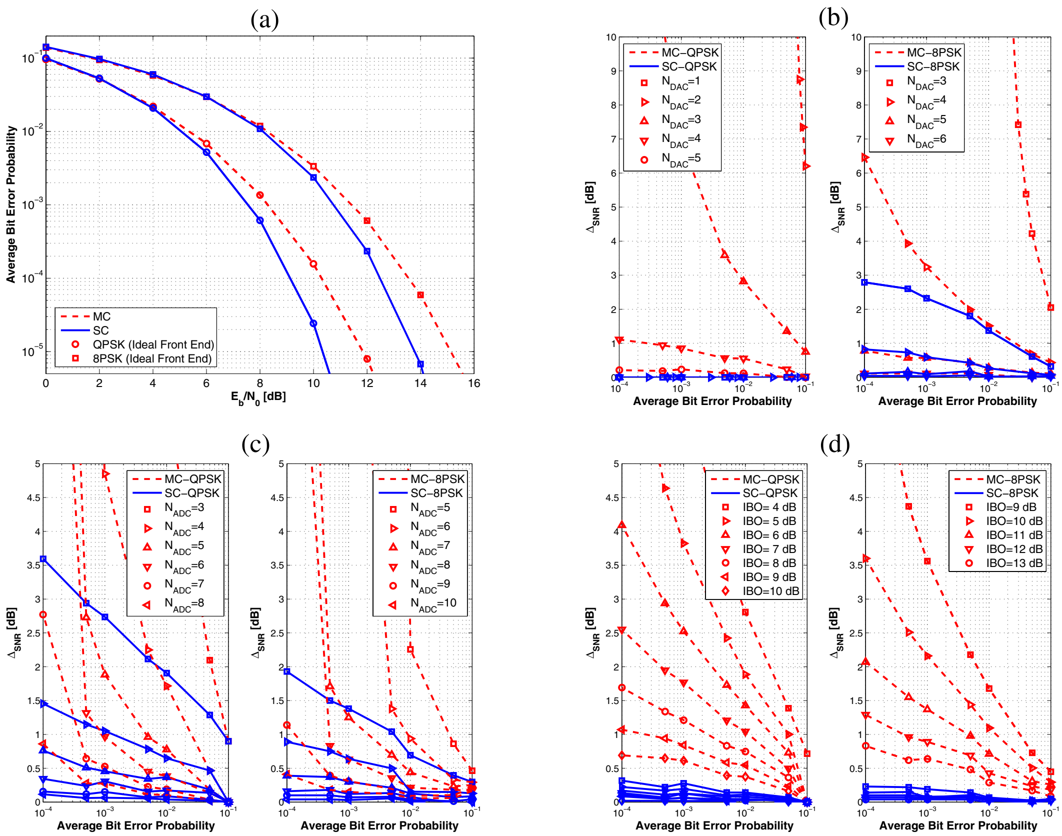


Fig. 1. Performance of SC and MC transceiver using QPSK/8PSK for (a) ideal front end, (b) various number of DAC bits, (c) various number of ADC bits, and (d) various HPA IBO values.

require 1 and 4 bits whereas both MC-QPSK and MC-8PSK require 5 bits of DAC resolution.

### *B. ADC: Model and Consequences*

A Flash ADC based on behavioral modeling [7] with transfer characteristics as shown in Figure 2(b), is considered. The voltage references of ADC comparators are assumed to be created by a number of resistance dividers with noise variance given in (1). The resistance noise gives rise to differential non-linearities (DNLs). Each ADC comparator, is assumed to have an offset variance of 0.05 $V^2$ and a maximum operating voltage of 1 V.

The received vector, for a MC based transceiver, using a real ADC, after CP removal is given as $\mathbf{X}^{\mathcal{M}} \otimes \mathbf{h} + \mathbf{q}^{\mathcal{MA}}$, where $q_p^{\mathcal{MA}}$ are the samples of the quantization noise and $\otimes$ denotes the circular convolution operation. In case of a SC based system, the received vector, after analog to digital conversion and CP removal is $\mathbf{x} \otimes \mathbf{h} + \mathbf{q}^{\mathcal{SA}}$. The received signal in case of the MC transmission has a higher dynamic range as compared to the SC scheme and thus a higher number of quantization levels and ADC bits $N_{ADC}$ are required. Figure 1(c) shows the plot of $\Delta_{SNR}$ against BER for various values of $N_{ADC}$ using SC and MC schemes employing QPSK and 8PSK constellations. Assuming that a BER of $10^{-4}$ with a maximum allowed $\Delta_{SNR}$ of 1 dB is required, SC-QPSK and SC-8PSK schemes require 5 and 6 bits whereas MC-QPSK and MC-8PSK need 8 and 10 bits.

### *C. Amplifier Nonlinearity: Model and Consequences*

The input amplitude to output amplitude (AM/AM) and input amplitude to the output phase (AM/PM) relations for a nonlinear amplifier, when supplied with a complex input signal $a = |a|\, e^{j\phi_a}$ are given by [8] $f(a) = \frac{\alpha_f}{1+\beta_f|a|^2}$ and $g(a) = \frac{\alpha_g|a|^2}{1+\beta_g|a|^2}$, respectively. The amplifier output is thus given by $a_{out}(a) = af(a)e^{jg(a)}$. Assuming that the maximum input voltage is limited to $\max(|a|) = a_{\max} = 1/\sqrt{\beta_f}$, then the output saturation voltage is given by $\max(a_{out}) = \alpha_f a_{\max}/2$. The parameters $\alpha_f, \beta_f, \alpha_g$ and $\beta_g$ are device specific and are usually found by performing a minimum mean square curve fitting procedure. The IBO of an amplifier is given as $\text{IBO} = \frac{a_{max}^2}{<P_{in}>}$, where $< P_{in} >$ denotes the average input power. Typical values for the amplifier model parameters are taken to be $\alpha_f = 1, \beta_f = 0.25, \alpha_g = \pi/50$ and $\beta_g = 0.25$ [8]. The input/output relations for the given power amplifier parameters are shown in Figure 2(c), and are in good agreement with proposed 60 GHz HPA/LNA amplifier designs [9].

The components of the received MC vector $\hat{\mathbf{x}}^{\mathcal{MN}}$, after CP removal and equalization in the presence of a

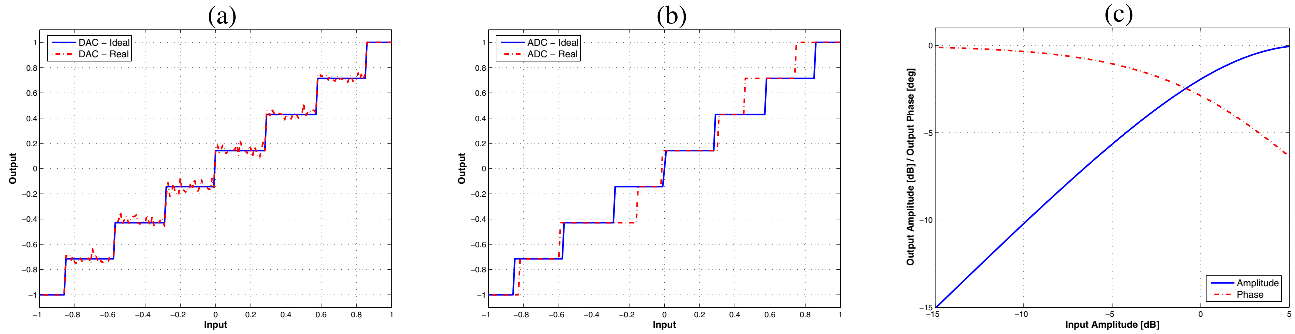


Fig. 2. Transfer characteristics for (a) DAC, (b) ADC, and (c) HPA

nonlinear HPA are given by $J_0 x_m+\sum_{n=0,n\neq m}^{N-1} x_n J_{n-m}+N_m/H_m$, where $J_h=\sum_{k=0}^{N-1}\mathcal{T}_{X_k^{\mathcal{M}}} e^{j2\pi hk/N}$ and $\mathcal{T}_{X_k^{\mathcal{M}}} = \left(X_k^{\mathcal{M}}\right) f(X_k^{\mathcal{M}}) e^{jg(X_k^{\mathcal{M}})}$. The received signal vector $\hat{\mathbf{x}}^{\mathcal{SN}}$ elements in case of a SC based system at the output of the IFFT block are given by $\mathcal{T}_{x_k^{\mathcal{S}}} x_m + n_m/H_m$, where $\mathcal{T}_{x_k^{\mathcal{S}}} = \left(x_k^{\mathcal{S}}\right) f(x_k^{\mathcal{S}}) e^{jg(x_k^{\mathcal{S}})}$. The received MC signal is affected by ICI which thus results in the clustering of the signal constellation points, whereas a SC signal, due to the absence of ICI term only has the effect of constellation rotation and contraction. The simulation results for SC and MC based systems using QPSK and 8PSK constellation and employing a nonlinear HPA are illustrated in Figure 1(d). Assuming that a BER of $10^{-4}$ with a maximum allowed power penalty $\Delta_{SNR}$ of 1 dB is required, then the SC-QPSK and SC-8PSK scheme require 4 dB and 9 dB of IBO whereas the IBO for MC-QPSK and MC-8PSK schemes is 10 dB and 13 dB, respectively.

### *D. System Parameter Summary*

The RF system parameters for the SC and MC schemes using QPSK and 8PSK constellations at a BER of $10^{-4}$ with a maximum allowed power penalty $\Delta_{SNR}$ of 1 dB are summarized in Table III. The ADC and DAC values are given in bits whereas the IBO values are specified in dB. It can be seen that an un-coded SC system, while having the same implementation complexity, requires a lower number of ADC and DAC bits and a lower IBO for the HPA.

TABLE III
MC AND SC CIRCUIT OPERATION PARAMETERS

| Modulation | Transc. | $N_{DAC}$ | $IBO_{HPA}$ | $N_{ADC}$ |
|---|---|---|---|---|
| QPSK | MC | 5 | 10 | 8 |
| (BER= $1\times10^{-4}$) | SC | 1 | 4 | 5 |
| 8PSK | MC | 5 | 13 | 10 |
| (BER= $1\times10^{-4}$) | SC | 4 | 9 | 6 |

## IV. CONCLUSIONS

In this paper, a comparison of SC and MC transmission schemes for 60 GHz systems, in the presence of RF circuit imperfections, was presented. DAC, ADC and HPA models, that are in accordance with 60 GHz transceiver circuits, were used. For both schemes the SNR degradation in terms of operating parameters such as the number of bits in DAC/ADC and input back-off requirements for HPA was determined. It was shown that while having the same overall system complexity, the SC scheme suffers from a considerably lower SNR degradation. The SC schemes offer a good trade-off in terms of circuit parameters and system performance, therefore they are more suited for the implementation of low cost and power efficient wireless communication systems operating in the 60 GHz band.

## ACKNOWLEDGEMENT

This work was supported by IOP GenCom under SiGi Spot project IGC.0503.

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