60-GHz Transceivers for Wireless HD Uncompressed Video Communication in Nano-era CMOS Technology

Domenico Pepe¹ and Domenico Zito¹,²
¹Tyndall National Institute, Lee Maltings, Cork, Ireland.
²Dept. of Microelectronic Engineering, University College Cork (UCC), Cork, Ireland.
email to: {domenico.pepe, domenico.zito}@tyndall.ie

Abstract — This paper reports the system-level study of high-speed wireless system at 60 GHz for uncompressed HD video communications. The study is addressed to explore the implementation of 60-GHz transceivers in nano-scale CMOS technology. A model of the high data rate physical layer based on the specification released by the consortium WirelessHD® has been implemented in MATLAB® and the system simulations of the bit error rate have been carried out in order to derive the specifications of the building blocks of the 60-GHz transceiver. Finally, these specifications have been derived by taking into account the capabilities of the 65nm standard CMOS technology.

I. INTRODUCTION

In 2001, the Federal Communications Commission (FCC) allocated an unlicensed 7 GHz band in the radio frequency spectrum between 57 and 64 GHz for wireless communications [1]. This is the widest portion of radio-frequency spectrum ever allocated for wireless applications, allowing multi-gigabit-per-second wireless communications. Other countries worldwide have allocated the 60 GHz band for unlicensed wireless communications (Japan [2], Australia [3], Korea [4], Europe [5]), allowing a universal compatibility for the system operating in that band.

The recent advances in silicon technologies allows us nowadays to implement integrated transceivers operating at millimeter-waves, enabling the realization of a new class of mass-market devices for very high data rate communications [6].

One of the most promising applications that will benefit of the huge amount of bandwidth available in the 60 GHz range is the uncompressed high-definition (HD) video streaming. The reasons that make attractive the uncompressed video streaming are that compression at the transmitter and decompression at the receiver presents some drawbacks in wireless multimedia applications, as latency, degradation in the picture quality; moreover, the fact that the HD streaming is confined between two devices that employ the same compression technique. HD video signal has a resolution of 1920×1080 pixels, with each pixel described by three color components of 8 bits (24 bits per pixel), and a frame rate of 60 Hz. Thus, a data rate of about 3 Gb/s is required for the transmission of the sole video data, without considering audio data and control signals [7].

Several international standard organizations and associations of industrial partners are working to define specifications for millimeter-waves systems operating in the 60 GHz band [8-10]. The WirelessHD® consortium is an industry-led effort to define a worldwide standard specification for the next-generation wireless digital network interface specification for consumer electronics and personal computing products [10].

In this paper we report the results of the investigation regarding the possibility of realizing a fully integrated 60 GHz wireless transceiver in CMOS technology for uncompressed HD video transmission. In particular, we focus on the implications of the system specifications in terms of bit error rate required by the standard WirelessHD®.

This paper is organized as follows. In Section II, the standard developed by the WirelessHD® consortium is described and the specifications for the 60 GHz wireless interface are reported. In Section III, the architecture of a 60 GHz transceiver for uncompressed HD video communication is shown and analyzed. System simulations have been performed and the results obtained are illustrated. In Section IV, the specifications of the building blocks for the implementation in silicon of 60 GHz transceivers are derived and discussed. Finally, in Section V, the conclusions are drawn.

II. WIRELESSHD® STANDARD FOR UNCOMPRESSED HD VIDEO COMMUNICATIONS: HIGH RATE PHY

The WirelessHD® specifications have been architected and optimized for wireless display connectivity, achieving in its first generation implementation high-speed rates up to 4 Gb/s at ten meters for the consumer electronics, based on the 60 GHz millimeter-waves frequency band. WirelessHD® defines a wireless protocol that enables consumer devices to create a wireless video area network (WVAN) up to a possibility of streaming uncompressed HD video data, with a typical maximum range of 10m. The high rate PHY (HRP) is a PHY which supports multi-Gb/s throughput at distance of

This work has been supported in part by Science Foundation Ireland (SFI) under Grant 08/IN.1/I854.
Because of this, the HRP is highly directional and can only be used for unidirectional casting. WVANs consist of one Coordinator and zero or more Stations (see Fig. 1). The Coordinator schedules time in the channel to ensure that the wireless resources are prioritized and A/V streaming is supported. The Station may be the source and/or sink data in the network. The Coordinator device acts also as a Station in the WVAN and may behave as a source and/or sink of data [11].

The specifications required for the HRP PHY layer are shown in Table I.

The modulation scheme is a 16-QAM OFDM, with 512 subcarriers of which 336 data, 16 pilots, 157 nulls and 3 DC subcarriers, and a guard period of 64 times the FFT period. The 57-64 GHz band has been divided in four channels for the HRP, of which not all are available everywhere depending on the regulatory restrictions. A bit error rate (BER) of $4 \times 10^{-11}$ (quasi-error-free) is required in order to have a pixel error ratio less than $10^{-9}$ for 24 bit color. This is achieved by using a concatenated channel code made by an outer Reed-Solomon (224/216, Reed-Solomon) and an inner convolutional code, 4/5 and 4/7 for the least significant bits and the most significant bits respectively (in video communication, differently from data communication, the bits are not equally important: the most significant bits have more impact on the video quality [6], thus the most significant bits are coded with a more robust code (unequal error protection, UEP).

### III. 60 GHz HRP

The block scheme of the 60 GHz high rate physical layer is shown in Fig. 2. This system has been implemented in MATLAB® in order to perform system simulations.

The uncompressed video source data, after being processed by the MAC layer, are coded by a concatenated channel code made by an outer code (224/216, Reed-Solomon) and an inner convolutional code (4/5, 4/7 convolutional). This error protection scheme is fairly robust: in the case of the DVB-S standard systems, which have a similar scheme to that shown in Fig. 2, it can provide a quasi-error free BER of $10^{-10}$-$10^{-11}$ with non-corrected error rates of $10^{-1}$-$10^{-2}$ [12].

### Table I. HRP Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>1.76 GHz</td>
</tr>
<tr>
<td>Reference sampling rate</td>
<td>2.538 GS/s</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>512</td>
</tr>
<tr>
<td>Guard interval</td>
<td>64/Reference sampling rate</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>FFT period=Guard interval</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>336</td>
</tr>
<tr>
<td>Number of DC subcarriers</td>
<td>3</td>
</tr>
<tr>
<td>Number of pilots</td>
<td>16</td>
</tr>
<tr>
<td>Number of null subcarriers</td>
<td>157</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK,16QAM-OFDM</td>
</tr>
<tr>
<td>Outer block code</td>
<td>RS(224,216)</td>
</tr>
<tr>
<td>Inner code</td>
<td>1/3,2/3(EEP), 4/5+ 4/7(UEP)</td>
</tr>
</tbody>
</table>

After being coded, data are modulated. A raw data of 3.807 Gb/s is achieved by employing a 16QAM-OFDM modulation [10]. First the stream data is sent to the symbol mapper, which maps the input bits into the output modulation symbols (16QAM symbols, Gray code). Output data of the symbol mapper are then parallelized, and pilots, dc and null tones are added. Pilots are used for frame detection, carrier frequency offset estimation and channel estimation [13]. The central subcarriers are normally not used since they correspond to DC in the baseband. The outer subcarriers are usually unused in order to allow a low-pass filtering with a larger transition band after the digital to analog converter [13]. In the system we implemented in MATLAB® the pilot tones have been placed every 21 data subcarriers before and after the DC nulls. The resulting OFDM symbol in the frequency domain is shown in Fig. 3. An IFFT (size 512) operation is applied to the obtained symbol in order to have an OFDM symbol in which each subcarrier is modulated by 16QAM symbols from the mapper, DC, nulls and pilots. Then, a cyclic prefix is added at the beginning of the OFDM symbol by copying the last 64 samples of the symbols, in order to improve the immunity to inter-symbol interferences. Data stream is suddenly shaped by means of a square-root raised cosine filter, then upconverted at 60 GHz and transmitted.

On the receiver side, after the down-conversion and filtering, the cyclic prefix is removed from the OFDM symbol, and the FFT operation is carried of on the received stream. Since the output of the de-mapper is sensitive to the value of its input symbols, a block of channel estimation and gain correction has been implemented in MATLAB®. For each OFDM symbol received, the channel response is estimated by extracting the received pilot values and by dividing them to the expected values:

$$C(k) = \frac{P_{RX}(k)}{P(k)}$$

where $k$ is the pilot index, $P_{RX}(k)$ are the received pilot values and $P(k)$ the expected pilot value. The data subcarriers are then multiplied by the inverse of the coefficient $C(k)$ of the nearest pilot tone.
For the system simulations we considered an AWGN channel. BER simulations of the system shown in Fig. 2 have been carried out and the results are shown in Fig. 4. An input string of about 6,000,000 bits has been used as source for the 60 GHz system. The curves of the BER at the input of the baseband receiver, before and after the concatenated channel coded blocks, are shown in Fig. 4. By interpolating linearly the curve of the BER (that is a worsening condition with respect to the real case), we obtain a BER of $4 \times 10^{-11}$ for an energy per bit to noise power spectral density ratio ($E_b/N_0$) lower than 14 dB, that corresponds to a signal-to-noise ratio (SNR) of 16.74 dB, as calculated with (2).

$$\begin{align*}
\text{SNR} |_{\text{dB}} &= \frac{E_b}{N_0} |_{\text{dB}} + 10 \times \log_{10} k + 10 \times \log_{10} \left( \frac{dsc}{nFFT} \right) + \\
&+ 10 \times \log_{10} \left( \frac{nFFT}{nFFT + CP} \right) + 10 \times \log_{10} \left( \frac{kRS}{nRS} \right) + \\
&+ 10 \times \log_{10} \left( \frac{kCon}{nCon} \right)
\end{align*}$$

(2)

where $k = \log_2(M)$ and $M$ is the size of the modulation (16 in this case), $dsc$ is the number of data subcarriers (336), $nFFT$ the FFT size (512), $CP$ is the guard interval (64), $kRS/nRS$ is the Reed-Solomon coding rate (216/224) and $kCon/nCon$ is the convolutional coding rate (average of 4/5 and 4/7, i.e. 2/3).

IV. 60-GHz WIRELESS TRANSCIEVER SPECIFICATIONS

The recent advances in silicon technologies, in particular the latest CMOS generation with channel lengths lower then 90nm, i.e. nano-era CMOS, allows us nowadays to implement integrated transceivers operating up to the millimeter-waves [6].
where $K$ is the Boltzmann constant ($1.23 \times 10^{-23}$ W/K), $T$ is the antenna temperature (290 K), $B$ the occupied bandwidth (2 GHz) and $NF$ the receiver noise figure. In order to have a receiver sensitivity of at least -50 dBm [15], $NF$ is required to be lower than 8 dB. This value is achievable in latest CMOS processes, e.g. 65nm. Therefore, by taking into account the capabilities of the 65nm CMOS technology, if we consider for the Low Noise Amplifier (LNA) a gain of 15 dB and a noise figure of 6 dB [16, references therein], and for the mixer a gain of -2dB and a noise figure of 15 dB [17], the noise figure of the cascade of these blocks is equal to 6.5 dB.

At 60 GHz the path loss is very high. At 10m (this is the operating range required at least by the standard [10] the free space path loss amounts to

$$PL_{\text{db}} = \left( \frac{4\pi df}{c} \right)^2 \left( 10^\frac{d}{10} \right) = 88 \text{dB}$$

(4)

where $d$ is the operating range (10m), $f$ is the carrier frequency (60 GHz) and $c$ is the speed of light ($3 \times 10^8$).

Thus, it results that the power delivered by the power amplifier (PA) has to be quite high in order to provide a signal with adequate power at the receiver antenna. The typical antenna gain is expected to be 10 to 20 dB [15]. If we consider an antenna gain of 10 dB (both in transmission and reception) and $NF$ equal to 7 dB, in order to achieve an operating range of 10m, the output power delivered by the PA has to be at least 14 dBm. This is a quite high value for the CMOS implementation of the PA. Recently some example of PA with 1-dB compression point higher than 14 dBm has been reported in literature [18]. In spite of this, the PA has to be also very linear, since OFDM modulation presents a very high peak-to-average power ratio (the back-off amounts approximately to 10dB).

It is worth mentioning that the specifications of above are related to a transceiver with single-transmitter and single-receiver. In practice the overall transceiver could be implemented on silicon by exploiting multiple transceivers connected to an array of highly directional antennas [19, 20]. In this way, not only the antenna beam-form can be steered in order to improve the link between transmitter and receiver, but also the specifications of transmitters and receivers will result relaxed, since the power delivered will be $P$ ($N$ is the number of transceivers in parallel) times that delivered by a unit element, and the receiver noise figure will be reduced of $10 \times \log_{10} P$ dB. For instance, a number of more than 10 independent antennas and partial radio chains have been employed in a first solution appeared in the literature [20]. To be noted that the increase of the number of elements of the array will increase the power consumption of the overall communication system, thus a trade-off between performance and power consumption has to be taken into account for the optimal design of the wireless transceiver.

V. CONCLUSIONS

In this paper a wireless 60-GHz system for uncompressed video communication has been studied at a system level, and the possibility of realizing transceivers integrated in CMOS technology has been investigated. A model of the high rate physical layer based on the specification released by the consortium WirelessHD® has been implemented in MATLAB® and system simulations have been carried out. The implementation of 60-GHz wireless transceiver in a modern CMOS technology has been evaluated and discussed, showing that nano-scale CMOS technology represents a key enabler for the implementation by means of array approach.

REFERENCES