System-on-a-Chip Radio Transceivers for 60-GHz Wireless Body-Centric Communications

Domenico Zito and Domenico Pepe

Abstract The 60-GHz band, previously forgotten because of the attenuation due to the resonance of the oxygen molecule, was recently reconsidered for building very short range wireless communication systems, including wireless body-centric networks. The 60-GHz radio channel has the potential to overcome some of the main limitations encountered in the implementation of body-centric communication systems in the industrial, scientific and medical (ISM) bands at lower frequency in the radio frequency spectrum. In particular, compared to the systems operating at lower frequencies, the 60-GHz radio channel offers the potential for supporting multi-gigabit per second communication rates, security, and low interference with adjacent wireless body-centric networks, and high level of miniaturization of the antennas.

Keywords 60 GHz · Body-centric · On-body · Off-body · Wireless communication · System-on-chip · Transceiver · CMOS · Phased array

The 60-GHz band, previously forgotten because of the attenuation due to the resonance of the oxygen molecule, was recently reconsidered for building very short range wireless communication systems, including wireless body-centric networks. The 60-GHz radio channel has the potential to overcome some of the main limitations encountered in the implementation of body-centric communication systems in the industrial, scientific and medical (ISM) bands at lower frequency in the radio frequency spectrum. In particular, compared to the systems operating at lower frequencies, the 60-GHz radio channel offers the potential for supporting multi-gigabit per second communication rates, security, and low interference with adjacent wireless body-centric networks, and high level of miniaturization of the antennas.

In this frame, the opportunity to realize such systems is directly dependent on the possibility to implement system-on-a-chip (SoC) radio transceivers. This chapter reports some of the main design challenges and perspective for the implementation of

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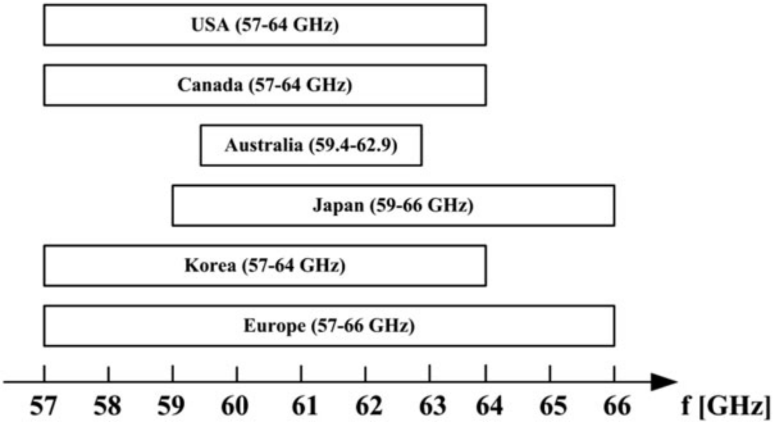


Fig. 1 Worldwide allocations of 60-GHz unlicensed bands

SoC radio transceivers enabling wireless body-centric communications. In detail, it focuses on the feasibility of SoC transceivers in nano-scale complementary metal oxide semiconductor (CMOS) technology. Section 1 reports an introduction to 60-GHz band and its applications. Section 2 introduces wireless body-centric communications, technology challenges, and opportunities. Section 3 reports a preliminary feasibility study of SoC transceivers by taking into account the main characteristics of the radio channel and the main limitations of the nano-scale CMOS technology. The co-integration with wearable millimeter-wave antennas for on- and off-body communications (integration with textile, miniaturized flexible antennas, etc.) will be considered as well. Finally, the conclusions are drawn in Section 4.

Introduction

In 2001, the Federal Communications Commission (FCC) allocated an unlicensed 7-GHz wide band in the radio-frequency (RF) spectrum from 57 to 64 GHz for wireless communications [1]. This is the widest portion of RF spectrum ever allocated in an exclusive way for wireless unlicensed applications, allowing multi-gigabit-per-second wireless communications. Other countries worldwide have allocated the 60-GHz band for unlicensed wireless communications [2–5], allowing in principle a universal compatibility for the systems operating in that band. Figure 1 shows the 60-GHz frequency band allocations in USA, Canada, Japan, Australia, Korea, and Europe.

The 60-GHz band is very attractive for its reduced coverage range, which is limited to a few meters as a result of the dramatic attenuation of the signal propagation. This is primarily due to the high path loss at 60 GHz. This reduced coverage range allows several wireless personal area networks (WPANs) to operate closely with low interference.

Moreover, at the millimeter-waves (mm-waves) it is possible to implement very directional antennas, thus allowing the implementations of highly directional communication links. Line-Of-Sight (LOS) communication may help in alleviating the design challenges of the wireless transceivers. All together, these characteristics of the 60-GHz radio channel have attracted the interests of both industry and academy.

One of the most promising applications that will benefit from the huge amount of bandwidth available in the 60-GHz range is the uncompressed High-Definition (HD) video communication [6]. The reasons that make the uncompressed video streaming attractive are that the compression and decompression (codec) in transmitters and receivers, respectively, exhibit some drawbacks such as latency which is unacceptable in real time applications (e.g., videogames), and compatibility issues between devices that use different codec techniques. To date, this research has reached a considerable level of maturity, and the first commercial products are appearing on the market [7].

In addition to the previous mass-market applications, it is also interesting to consider the potential opportunity offered by wireless body-centric networks [8, 9]. These emerging applications have attracted the interests of several research groups worldwide. To date, most of the research efforts have been limited to antennas and propagation, and addressed to scenarios for military applications [10].

The feasibility of 60-GHz SoC transceivers for wireless body-centric communications is still not addressed. The feasibility for wireless uncompressed video communications has reached an advanced level of development, mainly limited to fixed communication infrastructures (e.g., home video, etc.), demonstrating the feasibility in advanced microelectronic technologies. In spite of all this, the idea of translating these developments directly into wireless body-centric communications could be unsatisfactory, since these last applications require ad hoc developments characterized by high mobility (i.e., wearable devices), and thereby very low power consumptions that can be supported by light batteries.

Moreover, despite the development of military applications which can rely on large investments, the opportunity to justify the development and fabrication costs of SoC implementations in advanced microelectronic technologies would require a potential market of several million units. With this in mind, it is interesting considering the hypothesis that this emerging technology, currently explored for military applications, could be extended also to a number of civil applications, allowing a justification of costs and advancing of technology for the benefits of humanity. In particular, for the increasing needs of communication, sensing, and networking for biomedical and environmental applications. Despite it could be not easy to figure out the details of the possible future civil applications, it is still possible to envisage application scenarios for the future challenges of the information and communication society, such as smart cities [11], augmented reality [12], personalized health [13], sport and fitness [14], emergency operators [15], and any other potential needs of interfacing electronic systems, communication, and data infrastructures (e.g., wireless local area networks, cellular phone networks, satellite networks, cloud computing networks, etc.) with the biological and environmental systems, supporting mobility, continuity, and diversity of services in a variety of scenarios including urban (i.e., hospitals [16]) and rural environments.

Therefore, considering that the feasibility of wireless body-centric communications is dependent on the feasibility of SoC transceivers, currently not addressed by the research community, our objective in this chapter is to introduce and then accelerate the research and development of this interesting frontier of the emerging wireless applications. In particular, on the basis of the latest advances of the microelectronic CMOS technology [17–19]—today superior to all the other commercial technologies and capable of providing transistors with maximum cut-off in excess of 300 GHz and low noise figure (NF) (e.g., lower than 2 dB at 60 GHz)—we report hereinafter a preliminary feasibility of SoC transceivers in nano-scale CMOS technology in support of the needs of 60-GHz wireless body-centric communications.

Wireless Body-Centric Communications

The continuing miniaturization of electronic devices, together with the development of wearable computing technologies, leads toward the realization of a series of devices that can be carried on the human body [8]. Before stepping into the details of the specific design challenges for the SoC implementations of radio transceivers in nano-scale CMOS technology, it is worth summarizing in short the typical scenarios of the body-centric wireless communications.

In particular, the concept of wireless body area networks (WBANs) consists in a network of several sensors placed around the human body that can communicate information via wireless link. These sensors can monitor several vital parameters (ECG, EEG, glucose level, etc.) and transmit the information through a wireless link to a central node. In some cases, the sensor itself may use RF contactless sensing technologies [16], which remove the need of contact, reduce the encumbrance, and improve the wearability [20–23]. As mentioned earlier, the main advantages of exploiting the 60 GHz wireless link are the very high data rates of multi-Gb/s for short range applications, covertness, high frequency reuse, reduced interference, narrow antenna beam width, and small antenna size [10, 24]. We can distinguish three levels of communication [8] (see Fig. 2):

- *In-body* wireless transceivers are implanted in the body and most of channel is inside the body (for example a sensor placed on a broken bone to monitor its recovering). In Fig. 2a, the in-body sensor is represented with an orange spots, the central node with blue spots, and the wireless link between them with orange arrows.
- *On-body* wireless transceivers are placed on the surface of the body or on a wearable garment. This can be the case of external sensors as respiratory and heart-rate monitors [25, 26], EEG, motion detectors, etc. In this case most of the channel is on the surface of the body. In 2 and 2b, the sensors are represented by the green spots, while the central nodes by the blue spots. The on-body wireless link is represented by the green arrows.
- *Off-body* wireless transceivers are placed on the surface of the body, but they communicate outside the body, to a central node worn by other persons (e.g., as

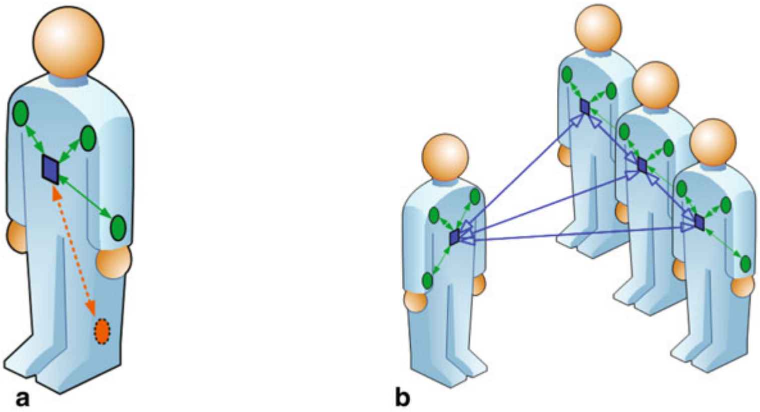


Fig. 2 **a** Scenario for in-body (*orange link*, *dashed circle* and *line*) and on-body (*green links*, *solid circles* and *lines* with *filled arrows*) wireless communications. **b** Scenario for on-body (*green links*) and off-body (*blue links*, *solid squares* and *lines* with *empty arrows*) wireless communication. Here, the devices in *blue* operate as coordinators

in [10], therein limited to military applications), or to an external communication infrastructure of the surrounding environment (not shown). In Fig. 2b, central nodes and their off-body wireless links are represented by the blue spots, while on-body sensors and their on-body wireless links are in green.

Preliminary Feasibility Analysis of 60-Ghz System-on-a-Chip Transceivers for Wireless Body-Centric Networks

In this Section we report the link budget analyses for 60-GHz wireless transceivers for wireless body-centric communications (see Fig. 2), compliant to the millimeter-wave High Rate Wireless Personal Area Networks standard IEEE 802.15.3c-2009 [27]. The results of the link budget analyses are exploited to carry out some preliminary evaluations on the feasibility of SoC transceivers by taking into account the capabilities and limitations of the modern nano-scale CMOS technologies and the latest advances in wearable textile antennas.

The IEEE 802.15 WPAN Task Group 3c (TG3c) [27] provides a reference for systems operating in the RF spectrum 57–66 GHz in United States (57–64 GHz), Canada (57–64 GHz), Australia (59.4–62.9 GHz), and Europe (57–66 GHz). This standard specifies that the RF spectrum 57–66 GHz is divided in four channels of 2.16 GHz, as shown in Table 1 (not available in all countries, depending on the RF spectrum allocation for 60 GHz unlicensed wireless communication by the regulatory agencies).

The standard supports a variety of modulation and coding schemes, that support up to 5 Gb/s. For the high-data rate physical layer (HRP), the modulation parameters

Table 1 Millimetre-wave physical layer channelization

Channel number.	Start frequency	Stop frequency
1	57.240	59.400
2	59.400	61.560
3	61.560	63.720
4	63.720	65.880

Table 2 High-data rate physical layer (HRP) modulation parameters

Parameter	Value
Bandwidth	1.76 GHz
Reference sampling rate	2.538 GS/s
Number of subcarriers	512
FFT period	Ref. sampling rate/number of subcarriers
Guard interval	64/reference sampling rate
Symbol duration	FFT period + guard interval
Number of data subcarriers	336
Modulation	16QAM-OFDM

are specified as in Table 2. Convolutional channel coding may be employed to attain the desired Bit Error Rate (BER). For instance, let us assume that we are interested in achieving a quasi-error free communication (BER $> 10^{-11}$) between two on-body transceivers. For a system employing the modulation parameters as shown in Table 2, with forward error correction made by Reed–Solomon (216/224) block code and inner convolutional code (2/3), a signal-to-noise ratio (SNR) at the input of the receiver equal to 17 dB is required [28].

For the low-data rate physical layer (LRP), the modulation parameters are specified as in Table 3. The LRP supports largely lower data rates than the HRP, up to a maximum of 10.2 Mb/s.

In the United States the maximum effective isotropic radiated power (EIRP) limits imposed by the Federal Communication Commission (FCC) [1] are 27 dBm for indoor applications and 40 dBm for outdoor applications [27], while in Japan and Australia those limits are set equal to 57 and 51.8 dBm [27]. In Europe those limits are set to 25 dBm and 40 dBm for indoor and outdoor applications, respectively [29].

Table 3 Low-data rate physical layer (LRP) modulation parameters

Parameter	Value
Bandwidth	92 MHz
Reference sampling rate	317.25 MS/s
Number of subcarriers	128
FFT period	Ref. sampling rate/number of subcarriers
Guard interval	28/reference sampling rate
Symbol duration	FFT period + Guard interval
Number of data subcarriers	30
Modulation	BPSK-OFDM

On-Body High Rate Line-of-Sight Communication

Let us consider the scenario shown in Fig. 2a. The radio communication occurs within a maximum of 2 m (i.e., a reasonable maximum distance between devices) around the human body.

The literature reports 60-GHz wearable textile antennas with antenna gain (G_{ANT}) of 12 dB [30].

As for the achievable performance of millimetre-wave CMOS transceiver, Chen and Niknejad [31] report a 60 GHz power amplifier with 1-dB output, compression point higher than 15 dBm, and Mitomo et al. [32] report a complete receiver with a total NF of 14 dB.

Thus, consider a CMOS transceiver with the following performance, achievable with modern nano-scale CMOS technologies:

- transmitted power P_{TX} equal to 15 dBm
- receiver NF equal to 14 dB
- signal bandwidth equal to 1.76 GHz centered at 60 GHz.

Then, the receiver sensitivity (S) amounts to:

$$S = -174\ \mathrm{dBm/Hz} + \mathrm{NF} + 10 \times \log_{10}(BW) + \mathrm{SNR} = -50\ \mathrm{dBm} \tag{1}$$

The free space path loss (PL) amounts to:

$$PL = 20 \times \log_{10}\left({}^{\lambda}\big/_{(4\pi d)}\right) = 74\ \mathrm{dB} \tag{2}$$

where $\lambda = f/c = 5$ mm ($f = 60$ GHz, $c = 3 \times 10^8$ m/s) and $d = 2$ m.

In the case of LOS communication, the received power (P_{RX}) is equal to:

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} + 2 \times G_{\mathrm{ANT}} - PL = -35\ \mathrm{dBm} \tag{3}$$

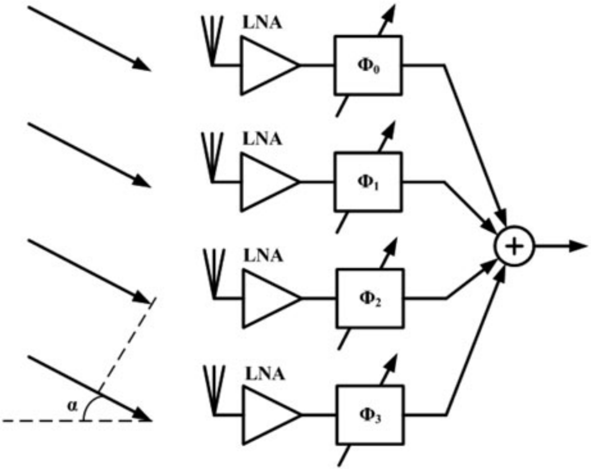
Thus, the loss margin (LM) left for shadowing, body loss, polarization mismatch, and other losses, is equal to:

$$LM = P_{\mathrm{RX}} - S = 15\ \mathrm{dB} \tag{4}$$

On-Body High Rate Nonline-of-Sight Communication

In the previous section, we considered on-body LOS communication. In spite of this, the case offers an opportunity to derive some considerations, this communication scenario is quite unrealistic since the position of each on-body transceiver relative to the others varies as a consequence of the human body movements. Therefore, a more appropriate scenario would be to consider the case in which omni-directional

Fig. 3 A four-element phased array receiver. Φ_i are the phase shifters, α is the angle of incidence of the EM radiation with respect to the receiver



antennas ($G_{ANT} = 1$) [33] are employed in order to allow a non-LOS communication. Moreover, the considerations that could be derived for this communication scenario could be extended in part also to the case of off-body communication (see Fig. 2b).

In the case of on-body non-LOS communication, we can easily verify that we are not able to match the desired specifications anymore, and that a minimum P_{TX} of 24 dBm ($P_{TX} = S - PL = -50 + 74 = 24$ dBm) is required in order to have the desired SNR at a distance of 2 m from the transmitter, without any loss margin left.

In order to meet the initial requirements also by employing omni-directional antennas, a phased array approach could be adopted. The overall transceiver can be implemented on silicon by integrating multiple parallel transceivers on the same silicon die, connected to an array of antennas (see Fig. 3). In this way, not only the antenna beam-form can be steered (by selecting appropriately the value of the phase shifting Φ of each path) in order to improve the link between transmitter and receiver, but also the specifications of transmitters and receivers are more relaxed, since the power delivered will be N times that delivered by a unit element and the receiver NF is reduced of $10 \times \log_{10} N$ dB (N is the number of transceivers in parallel). For instance, a number of more than ten independent antennas and partial radio chains have been employed in this; the first solution recently appeared in the literature [34].

Let us suppose to have a SoC phased array transceiver made by N transmitters and N receivers in parallel, with $N = 10$. In this case, the total transmitted power is equal to:

$$P_{TX} = 15 \text{ dBm} + 10 \times \log_{10}(N) = 25 \text{ dBm} \tag{5}$$

The equivalent receiver NF is equal to:

$$\text{NF} = 14 \text{ dB} - 10 \times \log_{10}(N) = 4 \text{ dB} \tag{6}$$

The total receiver sensitivity amounts to:

$$S = 174 \text{ dBm/Hz} + \text{NF} + 10 \times \log_{10}(BW) + \text{SNR} = -60 \text{ dBm} \tag{7}$$

The received power is equal to:

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} - PL = -49\ \mathrm{dBm} \tag{8}$$

Thus, in this case, we have again a *LM* left for shadowing, body loss, polarization mismatch, and other losses, that is equal to:

$$LM = P_{\mathrm{RX}} - S = 11\ \mathrm{dB} \tag{9}$$

On-Body and Off-Body Low Rate Communication

Let us consider now the case in which a high data rate is not required, and thus the 60 GHz transceivers can communicate by exploiting the LRP. Let us suppose that the transceivers are equipped with omni-directional antennas. Therefore, the following considerations apply to both on-body and off-body communication scenarios. Let us suppose also that SNR requirements are the same as for the HRP case (this is a worsening condition: the use of a simpler modulation scheme in LRP with respect to HRP relaxes largely SNR requirements to achieve a certain BER). In this case it is possible to realize the wireless communication even by means of single transceivers, because of the reduced minimum sensitivity due to the smaller communication bandwidth ($BW = 92$ MHz) of the LRP with respect to the HRP (and hence less noise floor).

$$S = -174\ \mathrm{dBm/Hz} + \mathrm{NF} + 10 \times \log_{10}(BW) + \mathrm{SNR} = -63\ \mathrm{dBm} \tag{10}$$

The received power is

$$P_{\mathrm{RX}} = P_{\mathrm{TX}} - PL = -59\ \mathrm{dBm} \tag{11}$$

Thus, even with a single transmitter and receiver, in this case we could still have a *LM* left, equal to:

$$LM = P_{\mathrm{RX}} - S = 4\ \mathrm{dB} \tag{12}$$

Conclusions

In this chapter we presented the opportunity offered by the emerging wireless body-centric networks, envisaging their applications to a number of possible future civil applications, beyond the current interests limited to military applications. In particular, we addressed the opportunities of implementing SoC transceivers in support of the needs required by the wireless body-centric networks, be they for on-body or off-body communication scenarios. In detail, we focused on the feasibility through preliminary analyses considering the characteristics of the 60-GHz radio channel, international standard regulations, current performance and limitations of nano-scale CMOS technology, and integrated circuits designs, as well as the performance of wearable antenna designs.

From the preliminary feasibility analyses reported herein it is possible to derive that the performance available at the state of the art for CMOS millimeter-wave wireless transceivers and millimeter-wave wearable antennas may offer concrete opportunities to realize wireless body-centric networks by exploiting the 60-GHz frequency band. However, the results of these preliminary considerations on feasibility should be revised in the light of the on-field experimental validations and observations in presence of shadowing, body loss, and other nonidealities, which may have a significant impact on the operation of the wireless body-centric communications.

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