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ISSUE FEATURE

# Siliconization of 60 GHz

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**S**ilicon-based RF and microwave technology has had a dramatic impact on the world of wireless technology. We can now access voice/data and entertainment in virtually every corner of the globe—with everything from short range Bluetooth and WiFi networks to cellular and satellite networks—to meet different range and throughput requirements. A laptop computer without wireless capability is unthinkable today, whereas, ten years ago, these technologies were in their infancy. What do the next ten years hold? What gaps in wireless technology exist even today? Perhaps the most obvious missing link is between the various devices that we carry with us, such as cellular phones or personal digital assistants (or smart phones if you prefer), digital cameras, music and video players (such as the ubiquitous iPod), laptops, and

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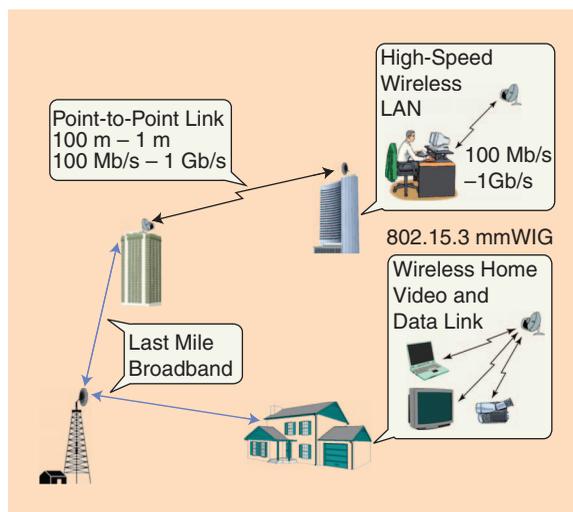
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peripherals such as external hard drives and monitors. The case of the mobile smart phone is particularly important since the existing wireless connectivity is either too slow and power hungry (Bluetooth) or designed and optimized for longer ranges (WiFi). What is missing is a wireless universal connectivity that can support high data rates demanded by large data rate multimedia applications. Wireless technology has been conspicuously absent from MP3 music players (such as Apple's iPod), which are ideal candidates for downloading music and video. While ultrawideband (UWB) technology using the 3–10 GHz band promised to fulfill these needs, it fell short in many ways, and, today, most of the start-up companies pursuing UWB have folded.

Now many are making the same promises about 60-GHz technology, so it is interesting to briefly explore the similarities and differences among these technologies. The UWB spectrum offered 7 GHz of bandwidth in the United States, but, when you consider a global UWB solution, the bandwidth is smaller (6–10 GHz) due to regulatory restrictions. More importantly, the allowed power transmission in this band is severely restricted by the Part 15 spectrum emission mask (24.3 dBm/MHz). By contrast, the maximum transmission power in the 60-GHz band is orders of magnitude higher. In the United States, up to 39 dBm equivalent isotropically radiated power (EIRP) can be transmitted (due to the oxygen absorption in this band). Most UWB standards channelized the band into 500-MHz chunks, which limits the power even further, whereas most 60-GHz standards use channels with over 1.5 GHz bandwidth. These differences translate into much higher capacity and much longer range communication in the 60-GHz band compared to the UWB band. This is true even after the differences in propagation loss are taken into account. In fact, for the same aperture, a much higher gain antenna can be realized at 60 GHz compared to, say, 5 GHz due to the shorter wavelength. There are also clear disadvantages to operation at 60 GHz arising from the line-of-sight (LOS) nature of the channel. Interestingly, there are some similarities between UWB and 60 GHz in that both require a sophisticated baseband processor to handle the long delay spread relative to the symbol duration, which requires equalization or orthogonal frequency-division modulation (OFDM). Moreover, the wideband modulation requires a very fast analog-to-digital converter (over 1 GHz), which can be a big source of power consumption if a high dynamic range signal is digitized directly. Techniques to lower the dynamic range of the baseband signal using mixed-signal techniques can benefit both kinds of systems.

## Applications of 60 GHz

Figure 1 shows many scenarios where a high-speed Gb/s link can enhance the modern user's experience.



**Figure 1.** Potential applications for a high data rate 60-GHz link.

For example, the wireless LAN network today is limited to about 100 Mb/s, while the wired Ethernet cables are operating today at 1 Gb/s and will move to higher speeds in the near future. Many homes are converting to an optical connection which will offer high bandwidths to homes and offices, and users will demand a similar performance boost in their networks.

One of the most exciting applications for UWB technology was a wireless USB-like connection. The ubiquity and simplicity of USB has transformed the computer industry. Users today buy peripherals and connect them to their PCs without having to worry about making the right connection. This is an example of a great success story in the PC industry. If we can similarly deliver a wireless USB-like connection with 60 GHz, the flexibility and ease of use will enhance the experience even further. Once users become accustomed to an untethered USB experience, there will be no turning back to cables.

While existing applications will benefit from the higher speeds offered by 60 GHz, there are many emerging applications that will fundamentally change the way we use technology. Consider the hypothetical 60-GHz-enabled iPhone, shown in Figure 2, which could use the 60-GHz connection to download movies from a kiosk (perhaps at a train station or airport), transmit video to a larger screen for easier viewing (wireless docking), and connect to external peripherals such as hard disks and wired and optical networks. If such a device is realized with reasonable power consumption, we see that it can truly displace the laptop computer for most users.

Now that analog TV has been discontinued in the United States, many users are upgrading their television sets to flat panel high-definition television (HDTV) screens. While the enhanced resolution and picture quality of digital TV is an exciting step forward, we have also taken a step backward by introducing



**Figure 2.** A high data rate 60 GHz link will enable universal untethered connectivity between consumer electronics and business devices. (From [20]. With kind permission of Springer Science and Business Media.)

unnecessary complexity, accompanied by a rat's nest of cables, into the life of the end user. Each user has to connect several devices to the TV (an antenna, a DVD player, a game player such as an Xbox or Playstation, a DVR/cable set-top box, video cameras). As people convert to high-definition multimedia interface (HDMI), the number of cables reduces to the number of devices, as opposed to many setups that use component video and audio separately. While HDMI cables are inexpensive (unfortunately many are fooled into believing that the expensive cables are necessary and enhance quality), once a wireless solution is made available, it will be compelling to most users. It gives users the freedom to put devices where it is most convenient and to include mobile devices that can stream content to the TV (mobile phones, digital cameras, DVRs, netbooks/laptops, etc).

Just as MP3 revolutionized the Internet and the music industry, we are now observing a similar transformation with video (and the popularity of Web sites such as YouTube). Disappointed by the limitations of current cable TV set-top boxes, many users are turning to the Internet for video content (television and videos). The Internet allows flexibility to share content and, most importantly, to move content from one device to another seamlessly. Many devices are vying to become the central hub of entertainment in the home theatre (Sony Playstation, Xbox, Apple TV), but most are limited in their ability to universally play content from any device, particularly at the high resolution offered by HD video sources today. What is sorely lacking is a high throughput wireless connection that works universally with all devices. While some are trying to use the existing 802.11abgn networks to do this, there are fundamental issues (Shannon's Theorem) with

the amount of bandwidth and, hence, network capacity, which favors a high bandwidth solution such as 60 GHz. Moreover, the ability to send uncompressed data from a device to a display is a great advantage since it reduces the computational burden in video decompression. It also solves a common problem of dealing with encryption and incompatible codecs.

### Technology Choices

Silicon technology has all but displaced gallium arsenide (GaAs) and other technologies for RF applications in the low GHz regime. A few niche applications, such as power amplifiers, remain as a stronghold but are also under threat by several upstarts in high-volume, low-power applications (mobile phones). For those with faith in Moore's law, this was an inevitable consequence in scaling. Transistors became small enough and, consequently, fast enough to operate into the gigahertz frequencies.

From a technology and performance perspective, silicon is not the obvious choice for 60-GHz systems. Many non-silicon-based III-V technology choices come to mind that offer higher mobility and an insulating substrate (high  $Q$  passives) and, thus, high-frequency operation at moderately short channel lengths. Unfortunately, these technologies are expensive and have low manufacturing yields, thus they offer limited integration possibilities. Furthermore, these processes are not expected to scale in cost. If you believe 60 GHz is a high volume market, as is clearly evident from the potential applications that will enjoy 60 GHz, then silicon is in fact the obvious choice. Moreover, in price-sensitive consumer applications, complimentary metal-oxide-semiconductor (CMOS) is the right choice.

But CMOS technology is not without problems. In addition to the well-known technical problems, such as lower performance (lower surface mobility of electrons, higher noise, lower gain, and a conductive substrate) and higher sensitivity to temperature, there are also economic challenges facing CMOS. After decades of unabated geometry scaling, today there is a lot of resistance to continue due to the prohibitively high costs (which only the microprocessor market has been able to endure) and an exponential increase in the leakage power of nanoscale digital circuits (which the microprocessor industry cannot tolerate). With the increased cost of scaled CMOS, one may wonder if there is a place for other technologies, especially close relatives such as silicon germanium (SiGe) bipolar CMOS (BiCMOS). Many argue that SiGe can realize the same performance as CMOS using older lithographic nodes, which are cheaper to manufacture. While this is certainly true, fortunately, we have already crossed the threshold, and today's high-volume CMOS technologies such as the 90-nm node are capable of good performance at 60 GHz and are beginning to reduce in cost as the industry moves to 65 nm, 45 nm, and

even 32 nm. In fact, the performance boost of scaling CMOS is beginning to wane to fight leakage currents (higher threshold voltages in transistors, which translates into lower overdrive and lower speed) and other short-channel effects (mobility reduction to high field effects, higher gate/source/drain resistance due to thinner metal and junctions and smaller contacts, and lower quality passive devices due to the use of thinner metal and insulation layers). Moreover, the complexity of designing a chip in scaled CMOS has increased due to design for manufacturing rules, which require regularity in the layouts and densities of metal and junctions in the layout.

Given these various conditions, the best process option for 60-GHz CMOS appears to be 90- or 65-nm nodes. Measurements on 90-nm transistors at the Berkeley Wireless Research Center show an  $f_T$  exceeding 100 GHz (post-layout measurement) and an achievable  $f_{max}$  over 200 GHz. At 60 GHz, we have measured a maximum stable gain of 8.5 dB and a unilateral gain over 12 dB. The minimum achievable noise figure of such devices is 3–4 dB (measured indirectly). The output power capability of a single device is about 10 mW. Using these numbers to estimate the range of a 1-GHz channel 60-GHz link, we arrive at: +10 dBm – PathLoss > –84 dBm (kTB) + 4 dB (NF) + 10 dB (signal-to-noise-ratio), or PathLoss < 80 dB. We have assumed low-gain antennas in this calculation, which is a valid assumption for a small portable device. This path loss corresponds to a distance of ~4 m LOS.

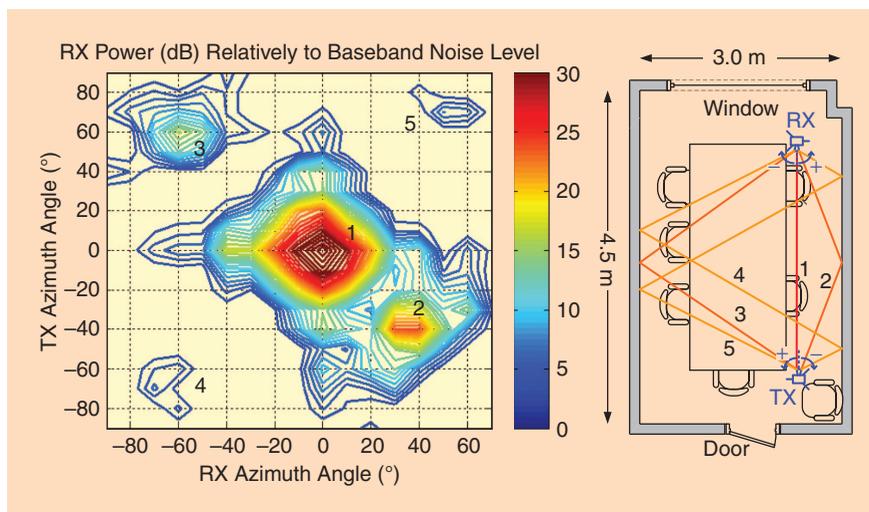
Another important and related issue is the cost of packaging and testing. In most of today’s military millimeter-wave systems, the cost is dominated by these factors, and the die cost is a much smaller consideration. Keep in mind, though, that these low volume applications do not provide sufficient incentives to explore low-cost packaging options. Moreover, these applications are very performance-sensitive and would not compromise on the package if it resulted in a small decrease in performance. Consumer applications in contrast are so price-sensitive that this consideration completely outweighs other concerns. Given this constraint, it is expected that very-low-cost solutions for the packaging will be developed. To lower the cost of testing, it is imperative that circuit functionality is tested at baseband or at the digital interface, as millimeter-wave testing equipment is costly and more difficult

(sensitivity to cable displacement or compression, for instance) using built-in self-test (BIST). For example, if a transceiver is put into loop-back mode, it can test the functionality of the entire chip.

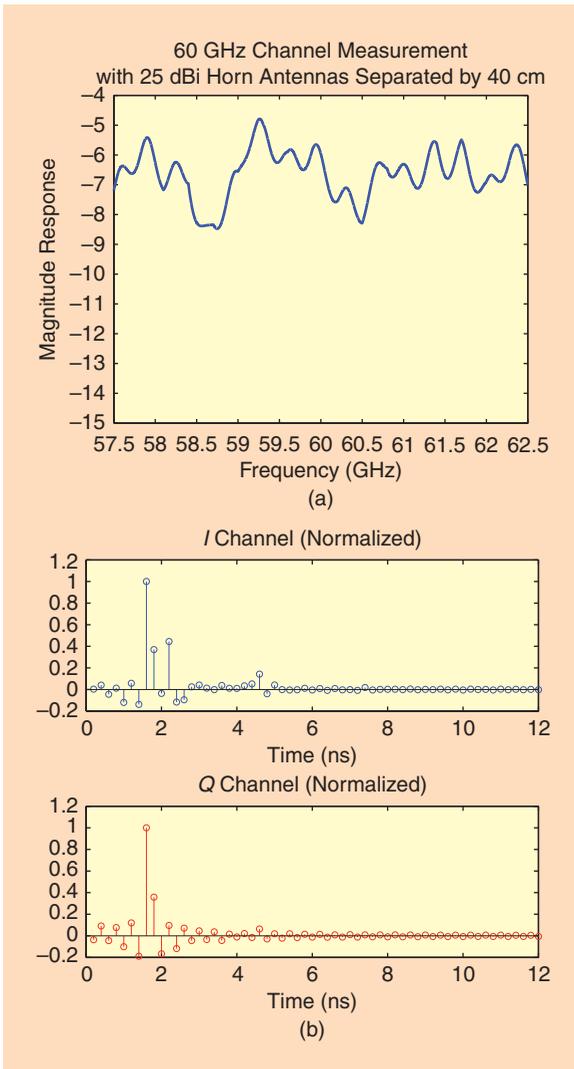
### 60 GHz Propagation

In narrowband systems, multipath propagation manifests itself as flat fading in the band. Propagation at 60 GHz, on the other hand, has a long delay spread of about 100 ns (seen, for example, in the IEEE 802.15.3c library channel model), which translates into frequency-selective fading over the band of interest (say a 1 GHz bandwidth). The most common way to deal with this kind of wireless channel is to use OFDM or multicarrier modulation. Unfortunately, OFDM is not an easy solution to adopt for 60 GHz owing to the high peak-to-average power ratio of the transmitted signal, the requirement for a high resolution analog-to-digital converter (ADC) and low phase noise voltage-controlled oscillator (VCO), and a highly linear receive path. In high-speed links, a mixed-signal equalization approach is utilized where a finite impulse response (FIR) filter is used to subtract out intersymbol interference, effectively equalizing the channel impulse response. Given the long delay spread at 60 GHz, this requires hundreds of FIR taps in the filter, which is costly in terms of silicon area and power consumption.

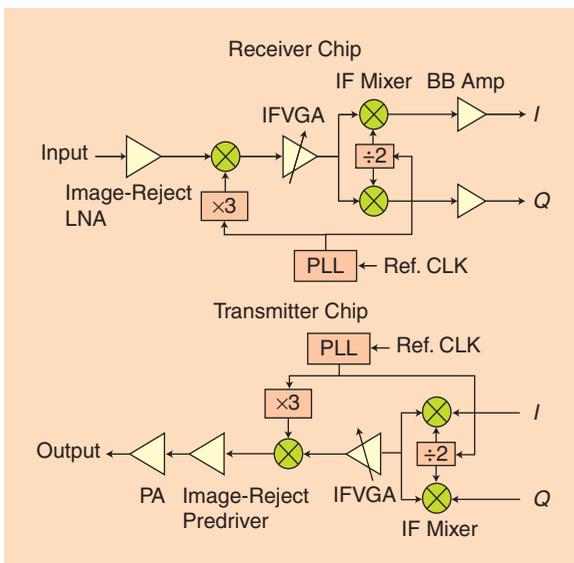
If we measure the actual 60 GHz channel, we observe that the propagation is quasi-optical, and simple ray tracing can be used to understand the multipath profile [1]. With careful measurements, one can observe several clusters of multipath propagation, as shown in the conference room measurement shown in Figure 3, and each cluster is easily identified as a LOS or non-LOS (NLOS) wave component that bounces off of walls, ceilings, or other objects. Each reflection results in approximately 10 dB of signal



**Figure 3.** The measured 60 GHz channel in a conference room setting. The measurements clearly show evidence of quasi-optical propagation, e.g., simple to resolve multipath reflections. From [1].



**Figure 4.** The 60 GHz channel response measured using highly directive 25 dBi horn antennas in the (a) frequency domain and (b) time domain [13].



**Figure 5.** Block diagram of IBM's SiGe 60 GHz front-end [5].

power loss and reaches the receiver with an easily identifiable angle of arrival. If a directive antenna is employed, the antenna's spatial selectivity reduces the delay spread considerably ( $\sim 10$  ns) as signals arriving after or before the strongest path come from different directions. A typical channel measurement using directive antennas, performed at the Berkeley Wireless Research Center, is shown in Figure 4, both in the frequency domain and the time domain. We can clearly see that the delay spread is shorter than 10 ns, and frequency selectivity is on the order of 100 MHz, with fades as deep as 5 dB. In such a case, use of a mixed-signal baseband with modest ADC resolution is possible, and this approach has been pursued [2] where a 1 Gb/s I/Q baseband with a complex decision feedback equalizer (DFE) and 4-bit ADC was demonstrated with a power of 55 mW, capable of resolving up to 32 ns of delay spread.

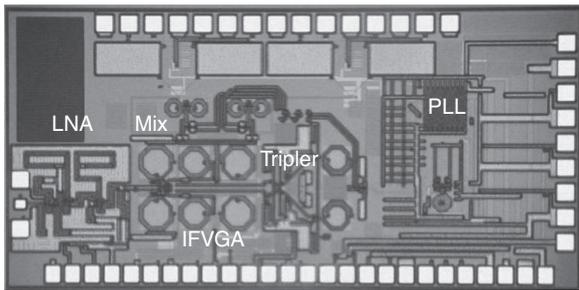
To overcome the high path loss and delay spread of the 60 GHz channel, we see that high-gain (high-directivity) antennas are necessary. Directive antennas are usually physically large (such as a horn antenna), and require precise alignment. For mobile applications, sectorized antennas or phased arrays are much more convenient, providing gain without requiring alignment by the user. Phased arrays and high-gain antennas are probably the only practical ways to enable longer-range 60-GHz communication. Other benefits include spatial power combining, which allows one to reduce the transmitted power per element, which may help to realize higher efficiencies.

Phased arrays have been an active research topic, with many demonstrations in SiGe and CMOS [3], [4]. Most of the phased arrays demonstrated to date suffer from very high power consumption and most are demonstrated in SiGe. The realization of a low power large array in CMOS at 60 GHz is still an outstanding problem to be solved.

## 60-GHz Transceiver Demonstrations

Many research groups are actively working on silicon-based 60-GHz building blocks and full transceivers. The research team at IBM demonstrated full transceiver front-ends in a SiGe BiCMOS (0.13- $\mu\text{m}$ ) technology [5].

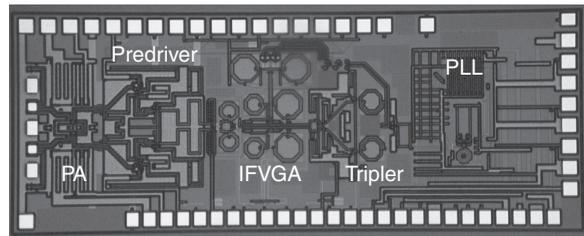
A block diagram of the two-chip transceiver chipset is shown in Figure 5. A dual-conversion superheterodyne radio architecture was selected over a homodyne approach due to its lower carrier feed-through in the transmitter and better I/Q quadrature accuracy. A die photograph of the receiver is shown in Figure 6. The die size is  $3.4 \times 1.7$  mm<sup>2</sup> to the outside of the pad frame. The low-noise amplifier (LNA) is at the lower left, and the spiral inductors in the receiver mixer and intermediate frequency (IF) variable gain amplifier (IF VGA) are visible to the right of the LNA. The frequency tripler is in the center, and the phase locked loop (PLL) occupies the right third of the chip. The chip contains



**Figure 6.** Chip microphotograph of IBM's 60 GHz receiver [5].

more than 300 NPN transistors, more than 1,000 field-effect transistors (FETs), and more than 90 transmission lines and inductors. On-wafer measurements were made on the full receiver, including the PLL. The Rx power conversion gain is 38–40 dB and the NF is 5–6.7 dB. The image rejection is 30–40 dB, the third-order input-referred intercept point IIP3 is –30 dBm, and input  $P_{1dB}$  is –36 dBm. The receiver consumes 195 mA from 2.7 V, 50 mA of which is in the baseband output buffers. The receiver and transmitter PLL measurements show a VCO phase noise of –115 to –120 dBc/Hz at 10 MHz offset with a root mean square (RMS) jitter less than 1.5° integrated over 0.1–1 GHz.

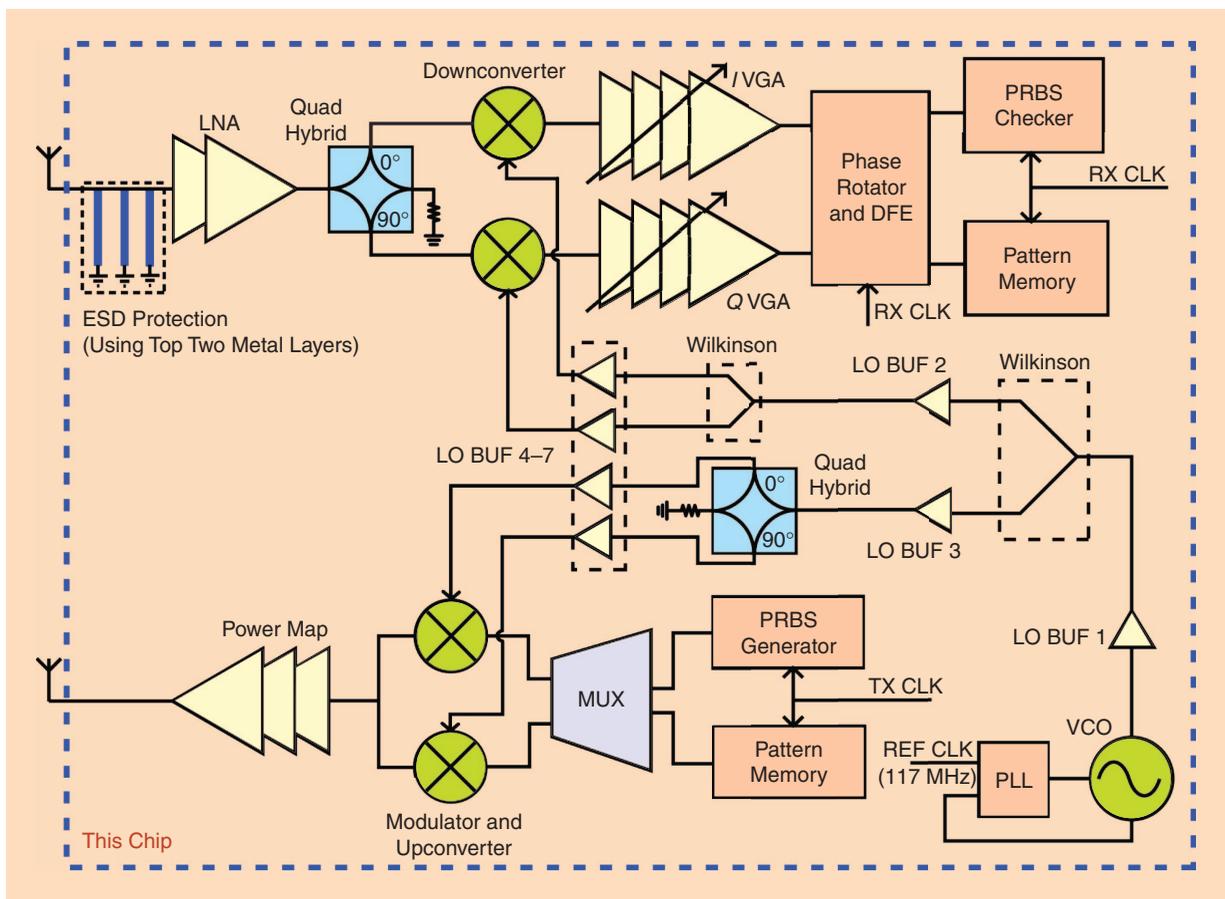
A die photograph of the transmitter is shown in Figure 7. The die size is  $4.0 \times 1.6 \text{ mm}^2$ . The PA and the differential output pads are on the left, adjoined to the right



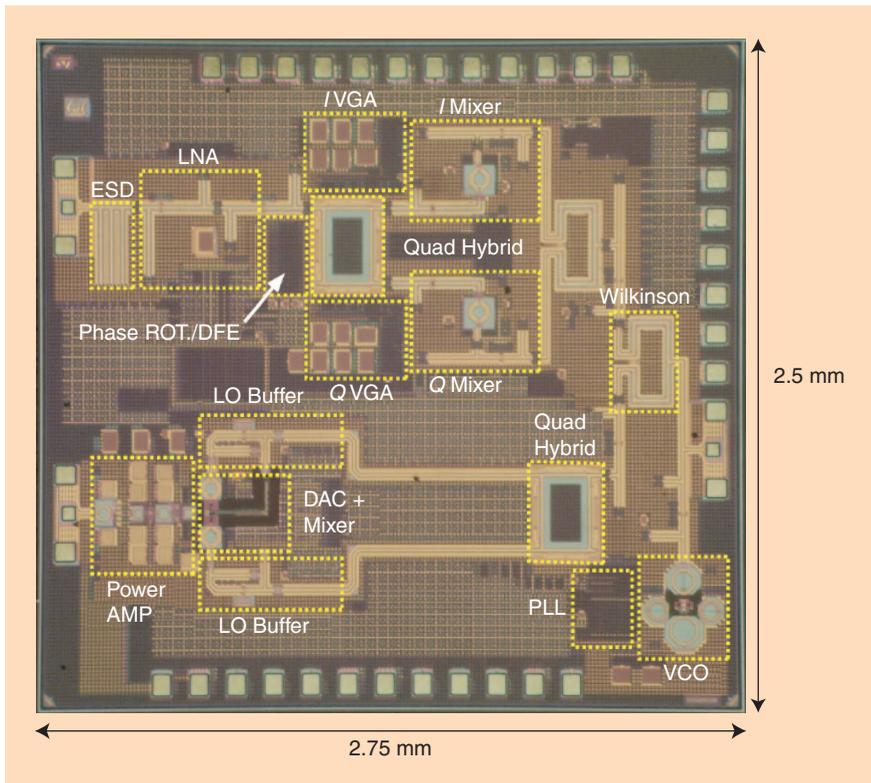
**Figure 7.** Chip microphotograph of IBM's 60 GHz transmitter [5].

by the predriver, IF-to-RF mixer, IFVGA, and frequency tripler. The PLL occupies the right third of the chip, and the baseband-to-IF mixer contains the two spiral inductors at the top center. The transmitter chip contains more than 300 NPN transistors, more than 1,000 FETs, and more than 170 transmission lines and inductors. The transmitter conversion gain is 42–36 dB.  $P_{1dB}$  is +10 to +12 dBm while  $P_{sat}$  is +16 to +17 dBm and the conversion gain is 34–37 dB. With no dc offset correction applied, the external I/Q quadrature accuracy is within  $\pm 2^\circ$ . At  $P_{1dB}$ , the transmitter consumes 190 mA from 2.7 V and 72 mA from 4 V (PA).

Research on CMOS millimeter-wave circuits is also very active, with many demonstrations of front-end receivers [6] and even complete transceivers [7]–[10]. At the Berkeley Wireless Research Center, we have



**Figure 8.** Block diagram of the Berkeley Wireless Research Center's 60 GHz CMOS transceiver [13].



**Figure 9.** Chip microphotograph of the Berkeley Wireless Research Center's 60 GHz CMOS transceiver [13].

demonstrated a fully integrated transceiver in 90 nm CMOS technology [11]. A block diagram of the transceiver is shown in Figure 8. Electrostatic discharge structures are absorbed into the LNA matching network, whereas the transmitter naturally benefits from the electrostatic discharge protection provided by the output transformer. On-chip quadrature couplers were used to produce I/Q signals in the receive path and I/Q LO signals in the transmit path. An on-chip PLL generates a 60-GHz LO from a 117 MHz reference frequency using a push-push oscillator (core running at 30 GHz), which obviates the need for a 60-GHz divider. The receive path uses transmission lines extensively for impedance matching and interconnect, whereas lumped transformers are employed in the transmitter. The transformers are also used to convert signal-ended LO signals to differential form for the Gilbert mixers and combine the power of two transistors in the output PA. The chip also includes a high-speed mixed signal baseband with 5 GHz bandwidth in each I/Q channel.

The transceiver chip has dimensions of  $2.5 \times 2.75$  mm<sup>2</sup> (Figure 9). It operates from a 1.2 V supply and



**Figure 10.** SiBEAM's WirelessHD compliant 60 GHz chipset. (Image courtesy of SiBEAM.)

consumes 170 mW in transmit mode and 138 mW in receive mode. The PA is operated from a 1-V supply to improve reliability and has a simulated small signal gain of 14 dB at 60 GHz. CW measurements verify that the PA can deliver +11 dBm of saturated output power with a peak PAE of 14.6%. The receiver is a modification of a direct-conversion receiver demonstrated in [12]. The previous design had a measured noise figure of less than 6.2 dB across the 60-GHz band. The addition of the electrostatic discharge structure and other modifications are expected to increase the noise figure of the receiver by approximately 1.2 dB. The VCO has a measured tuning range from 60–64 GHz and has a phase noise of  $-112$  dBc/Hz at a 10-MHz offset from the 60-GHz carrier. Electrostatic discharge measurements

confirm that the structures provide up to 400-V machine model (MM) protection.

Wireless testing was performed using a pair of 25 dBi horn antenna. The antennas were placed approximately 1 m apart for testing purposes. Due to the high data rates for which this transceiver was designed, data generation and checking were performed on-chip with pseudo-random bit sequence (PRBS) generators/checkers and a pattern memory both on the transmit and receive side. The highest data rate achieved was 4 Gb/s using quadrature phase-shift keying (QPSK) over the wireless channel. While, in theory, the transceiver should operate up to 10 Gb/s, the realized chip suffered from higher than expected I/Q mismatches. More details about the transceiver can be found in [13].

SiBEAM has demonstrated and is currently shipping the first multigigabit 60-GHz all-CMOS phased array system delivering 4 Gb/s in 10-m non-LOS environments [14]. The fully integrated chipsets enable the first WirelessHD compliant systems in the market, supporting uncompressed and lossless wireless audio/video streaming of up to 1,080 p/60 resolutions and frame rates with a wired equivalent robustness of less than a  $10^{-10}$  bit error rate. Figure 10 shows a chipset in a typical implementation. The two chip sets achieve complete antennas-to-bits integration, requiring minimal additional support hardware for integration into existing consumer electronics equipment (Blu-ray and HD DVD players and HD set-top boxes and displays). The radio chip's packaging includes integrated 60-GHz antennas,

simplifying board and system design by containing all high-frequency routing within the CMOS die and chip package. Achieving full 10 m NLOS coverage at the required data rates requires many independent antennas and partial radio chains. Thus, this fully integrated radio chip, containing all radio chains and antennas, represents a significant advance in the degree of parallelism achieved at the RF level for high-volume consumer wireless communications products.

## Standardization

There are currently many standards for 60-GHz wireless communication, including IEEE 802.15.3c [16], IEEE 802.11ad (a high-speed WLAN network) [17], the ECMA-387 standard [18], WirelessHD [15], and the WiGig standard [19]. Each standard is formed by a different community of potential users of the technology, such as consumer electronics companies (WirelessHD) versus the PC industry (WiGig). Most of the standards are focusing on very high speed communication (1–5 Gb/s) to enable wireless HDMI replacement.

Unfortunately the process of standardization is highly political and controversial, often to the detriment of the technology and ultimately to the consumers. This was certainly the case for UWB technology and may have contributed to the delay of products and to the eventual downfall of UWB. It is imperative that the same mistakes are not made with 60 GHz. Even though different standards are needed for different applications, interoperability between the standards is key. For instance, a simple single carrier low range link should be the fall-back mode for all the different 60-GHz radios. A single carrier is preferred, even though it may have a shorter range due to multipath effects, because it can be easily integrated into small low-power portable devices. This is in stark contrast to systems using OFDM, which require high power for the ADC and digital baseband processor (FFT operation).

## Conclusion

Silicon based 60 GHz is a promising technology for high data rate communication. Gordon Moore is best known for his Law predicting the continued exponential growth in the number of transistors fabricated in silicon integrated circuits. In the same paper, though, he also predicted that someday the same trend may benefit microwave and millimeter-wave phased arrays. Today, with the convergence of high-speed silicon technology and the market demands for high data rates driven by high-definition video, 60 GHz is at the right place at the right time. Key challenges moving forward include power and size reduction to enable adoption in mobile devices and interoperability between the standardization efforts to ensure a universal 60-GHz communication link, much like today's wired USB cables. If 60 GHz is widely deployed in consumer electronics devices, we may have to coin a new millimeter-wave Moore's Law.

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## References

- [1] A. Maltsev, R. Maslennikov, A. Sevastyanov, A. Khoryaev, and A. Lomayev, "Experimental investigations of 60 GHz wireless systems in office environment," *IEEE J. Select. Areas Commun.*, vol. 27, no. 8, Oct. 2009.
- [2] D. A. Sobel and R. W. Brodersen, "A 1Gbps mixed-signal analog front end for a 60 GHz wireless receiver," in *Proc. IEEE Symp. VLSI Circuits*, June 2008, pp. 156–157.
- [3] A. Babakhani, X. Guan, A. Komijani, A. Natarajan, and A. Hajimiri, "A77-GHz phased array transceiver with on-chip antennas in silicon: Receiver and antennas," *IEEE J. Solid-State Circuits*, vol. 41, no. 12, pp. 2795–806, Dec. 2006.
- [4] K. Scheir, S. Bronckers, J. Borremans, P. Wambacq, and Y. Rolain, "A 52GHz phased-array receiver front-end in 90nm digital CMOS," in *ISSCC Dig. Tech. Papers*, Feb. 2008, pp. 184–185.
- [5] S. K. Reynolds, B. A. Floyd, U. R. Pfeiffer, T. Beukema, J. Grzyb, C. Haymes, B. Gaucher, and M. Soyuer, "A silicon 60-GHz receiver and transmitter chipset for broadband communications," *IEEE J. Solid-State Circuits*, vol. 41, no. 12, pp. 2820–2831, Dec. 2006.
- [6] A. Parsa and B. Razavi, "A 60GHz CMOS receiver using a 30GHz LO," in *ISSCC Dig. Tech. Papers*, Feb. 2008, pp. 190–191.
- [7] S. Pintel, S. Sarkar, P. Sen, B. Perumana, D. Yeh, D. Dawn, and J. Laskar, "60GHz single chip 90 CMOS radio," in *ISSCC Dig. Tech. Papers*, Feb. 2008.
- [8] J. Lee, Y. Huang, Y. Chen, H. Lu, and C. Chang, "A low-power fully integrated 60GHz transceiver system with OOK modulation and on-board antenna assembly," in *ISSCC Dig. Tech. Papers*, Feb. 2009, pp. 316–317.
- [9] A. Tomkins, R. A. Aroca, T. Yamamoto, S. T. Nicolson, Y. Doi, and S. P. Voinescu, "A zero-IF 60GHz transceiver in 65nm CMOS with > 3.5Gb/s links," in *IEEE CICC Dig.*, San Jose, CA, Sept. 2008, pp. 471–474.
- [10] C.-H. Wang, H.-Y. Chang, P.-S. Wu, K.-Y. Lin, T.-W. Huang, H. Wang, and C.-H. Chen, "A 60-GHz low power six-port transceiver for gigabit software-defined transceiver," in *ISSCC Dig. Tech. Papers*, Feb. 2007.
- [11] C. Marcu, D. Chowdhury, C. Thakkar, L.-K. Kong, M. Tabesh, J.-D. Park, Y. Wang, B. Afshar, A. Gupta, A. Arbabian, S. Gambini, R. Zamani, A. M. Niknejad, and E. Alon, "A 90 nm CMOS low-power 60GHz transceiver with integrated baseband circuitry," in *ISSCC Dig. Tech. Papers*, Feb. 2009, pp. 314–315.
- [12] B. Afshar, Y. Wang, and A. M. Niknejad, "A robust 24mW 60 GHz receiver in 90 nm standard CMOS," in *ISSCC Dig. Tech. Papers*, Feb. 2008, pp. 182–183.
- [13] C. Marcu, D. Chowdhury, C. Thakkar, J.-D. Park, L.-K. Kong, M. Tabesh, Y. Wang, B. Afshar, A. Gupta, A. Arbabian, S. Gambini, R. Zamani, E. Alon, and A. M. Niknejad, "A 90 nm CMOS low-power 60GHz transceiver with integrated baseband circuitry," *IEEE J. Solid-State Circuits*, to be published.
- [14] J. M. Gilbert, C. H. Doan, S. Emami, and C. B. Shung, "A 4-Gbps uncompressed wireless HD A/V transceiver chipset," *IEEE Micro*, vol. 28, no. 2, pp. 56–64, Mar./Apr. 2008.
- [15] WirelessHD. [Online]. Available: <http://www.wirelesshd.org>
- [16] IEEE 802.11 Working Group, Wireless PAN Task Group 3c. (2009). Millimeter Wave Alternative PHY. [Online]. Available: <http://www.ieee802.org/15/pub/TG3c.html>
- [17] IEEE 802.11 Working Group. Very high throughput in 60 GHz. [Online]. Available: [http://www.ieee802.org/11/Reports/tgad\\_update.htm](http://www.ieee802.org/11/Reports/tgad_update.htm)
- [18] Standard ECMA-387. (2008, Dec.). High Rate 60 GHz PHY, MAC and HDMI PAL [Online]. Available <http://www.ecma-international.org/publications/standards/Ecma-387.htm>
- [19] Wireless Gigabit Alliance. [Online]. Available: <http://wirelessgigabitalliance.org/>
- [20] A. M. Niknejad and H. Hashemi, Eds., *mm-Wave Silicon Technology: 60 GHz and Beyond*, Springer, 2008. 