A 4-GBPS UNCOMPRESSED WIRELESS HD A/V TRANSCEIVER CHIPSET

WIRELESS TRANSMISSION OF UNCOMPRESSED LOSSLESS HD VIDEO PROVIDES HIGHER IMAGE QUALITY WITH LOWER LATENCY AND COST THAN COMPRESSED-CONTENT TRANSMISSION. HOWEVER, IT REQUIRES DATA RATES OF ABOUT 4 GBPS FOR 1080P RESOLUTION, EXCEEDING THE CAPABILITIES OF EXISTING WIRELESS TECHNOLOGIES. USING THE 60-GHZ BAND AS DETAILED BY THE WIRELESSHD SPECIFICATION, SIBEAM'S CHIPSET MAKES SUCH DATA RATES ECONOMICALLY ACHIEVABLE.

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•••••• The proliferation of HD content and associated source and display devices has fueled end users' desire to flexibly connect all of their consumer electronics (CE) systems with minimal effort. The In-Stat market research company projects that worldwide sales of devices with a high-speed digital A/V interface will grow to 495 million units in 2009 (InStat, *HDMI-DVI Report*, Nov. 2007; http://www.instat.com). Imagine the full quality of a wired audio/video (A/V) connection for uncompressed lossless high-definition (HD) 1080p resolution, coupled with the ease of use, ease of placement, and unified control capabilities of a fully interconnected wireless system. SiBEAM has developed the world's first chipset capable of achieving this goal, using 60-GHz wireless transmissions.[1]

Benefits of uncompressed wireless A/V

There are many advantages of using uncompressed wireless A/V content delivery instead of conventional compressed delivery. First, as Figure 1 shows, a compressed wireless system requires an encoder and a decoder. These significantly increase system cost, necessitating extra circuitry, and often requiring additional external memory to serve as a compression or decompression buffer. Compression can also negatively affect the user's experience by increasing latency and decreasing image quality. Latency can render interactive applications such as gaming unusable and, in many cases, can even affect simple operations such as remote-control channel changing. Decreased image quality can be particularly objectionable as displays increase in size and resolution. Additionally, unless the compression codec and over-the-air formats are standardized, interoperability and content protection problems can result. Finally, if the compressed wireless system operates in the same bands as heavily deployed wireless LAN data networking (such as the 2.4- or 5-GHz bands), interference can be a problem.

Even if the content enters the source device in compressed form (as in a set-top box or disc player), it must be decompressed and then recompressed for rendering of the source device's on-screen display. Additionally, if the source device's native compressed format is used for transmissions, sink devices must contain the decoders for all

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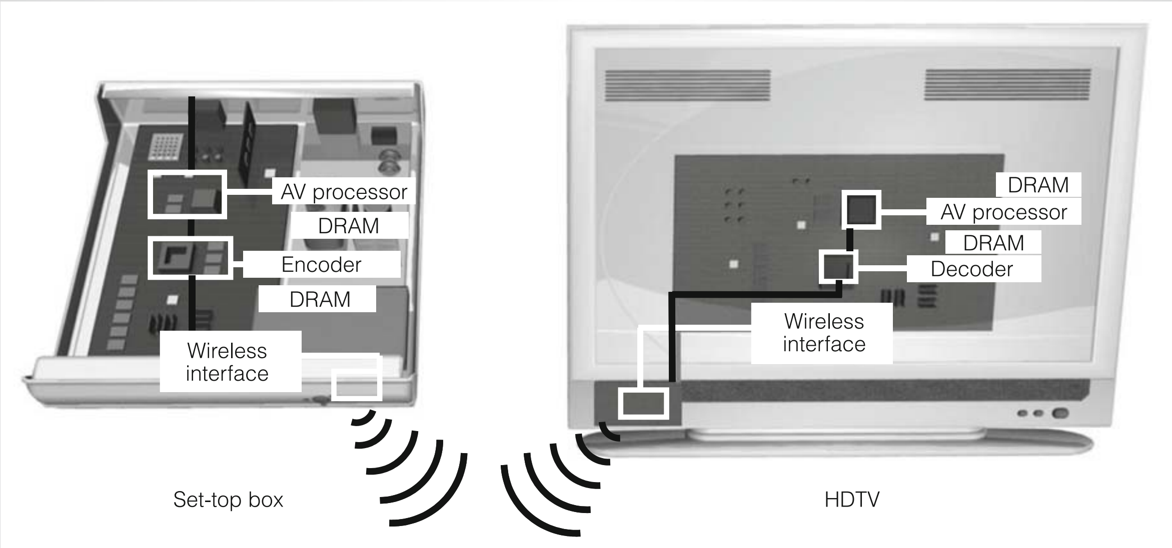

Figure 1. Typical wireless A/V system using compressed transmission.

potential source devices (camcorders, set-top boxes, HD DVD and Blu-ray players, and so forth). It is particularly challenging to anticipate the codecs required in future sources, since the lifetime of sinks is typically longer than that of sources.

As Figure 2 shows, using uncompressed wireless transmissions eliminates the need for a video encoder (compressor) and decoder (decompressor), significantly reducing system cost and complexity. By sending content without compression, the system preserves the best image and audio quality and adds no encoder-generated latency. By using a band not already occupied by many data-networking devices, such as the 60-

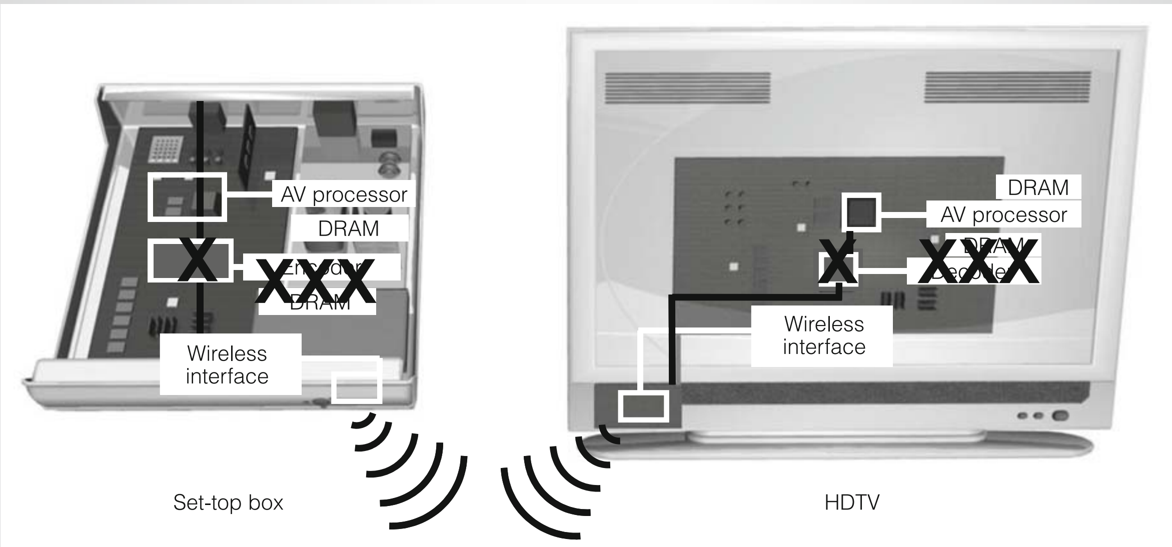

Figure 2. Wireless A/V system using uncompressed transmission.

Table 1. Comparison of various high data rate specifications.*

Specification	Total spectral availability (GHz)	Maximum allowed transmission power (EIRP**) (mW)	(dBm)	Maximum data rate (Mbps)	Channel bandwidth (MHz)	bps/Hz needed for 4 Gbps
WirelessHD	7.00	10,000	40	~4,000	~2,000	~2
IEEE 802.11n	0.67	160–3,200	22–35	289	20	200
				600	40	100
Ultrawideband (UWB)	1.5–7.5	0.1	−10	480	520	8

* Maximum allowed transmission power and UWB spectral availability vary by regulatory domain.
** Effective isotropic radiated power.

GHz band, wireless transmissions encounter less interference. Finally, a specification incorporating wireless physical layer (PHY), media access control (MAC), A/V, and content protection, such as the WirelessHD specification we describe here, provides interoperability and content protection.

WirelessHD consortium and specification

The WirelessHD Special Interest Group (http://www.wirelesshd.org), formed in 2006, includes as members Intel, LG Electronics, Matsushita Electric Industrial (Panasonic), NEC, Samsung Electronics, SiBEAM, Sony, and Toshiba. It created the WirelessHD specification, a next-generation wireless interface specification for HD media streaming and transmission between fixed-location and portable CE devices. WirelessHD is the first HD digital wireless interface for simplified media streaming and HD content portability supported by the CE and technology industries.

The WirelessHD specification's key characteristics include

- high interoperability supported by major CE device manufacturers;
- uncompressed HD video, audio, and data transmission, scalable to future HD A/V formats;
- high-speed wireless, multigigabit technology in the unlicensed 60-GHz band;
- smart-antenna technology to overcome line-of-sight constraints of 60-GHz secure communications;
- device control for simple operation of CE products; and
- error protection, framing, and timing control techniques for a quality consumer experience.

The WirelessHD specification makes seamless wireless interconnection and interoperation of a wide array of CE devices in a wireless video area network (WVAN) possible. Integrated device control and non-line-of-sight smart-antenna techniques allow simple and intuitive operation in various environments. Uncompressed audio and video allow the highest quality user experience, without the increased cost and latency and decreased quality of many compression technologies.

Obtaining very high wireless data rates

The High-Definition Multimedia Interface (HDMI) can deliver uncompressed video but requires interconnection via a web of unsightly and expensive cables. In contrast, wireless interconnection untethers the display and other A/V components, allowing clean placement out of the immediate proximity of their sources. It also enables mobility of portable devices. However, supporting uncompressed HD content requires data rates of 3 to 5 Gbps, which far surpass those supported by wireless technologies such as IEEE 802.11n and ultrawideband (UWB), which support only about 0.5 Gbps, as Table 1 shows.

Supporting very high data rates requires either very high spectral efficiency or lots of spectrum because the data rate is calculated as follows:

$$\text{Raw data rate (bps)} = \text{spectral efficiency (bps/Hz)} \times \text{bandwidth (Hz)}$$

Increasing spectral efficiency through MIMO techniques such as spatial multiplexing typically leads to higher cost and reduced range and robustness because it requires multiple concurrent paths between the transmitter and receiver and hardware to separate data traveling over these paths. Increasing bandwidth requires operation in a large frequency spectrum band, which for sufficient range and robustness must allow reasonable transmission power.

Fortunately, 7 GHz of unlicensed spectrum is available worldwide in the 60-GHz band, allowing up to 10 W of effective isotropic radiated power (EIRP). If this spectrum is divided into channels of 2 GHz each, a system needs a spectral efficiency of only 2 bps/Hz to deliver data at 4 Gbps. In contrast, an 11n system requires 100 bps/Hz to deliver the same 4-Gbps data rate even in its wider 40-MHz mode, and a UWB system needs 8.0 bps/Hz to achieve the same data rate in its 520-MHz channel. UWB is further constrained by regulations to transmit at most only 0.1 mW of power (up to 100,000 times less than is available in the 60-GHz band) and is approved for use only in limited geographical regions. This power limitation severely impacts the obtainable operation range.

Challenges and solutions for 60-GHz operation

Although the 60-GHz band has significant advantages for obtaining cost-effective, very-high-data-rate wireless communications, it poses several challenges that previously made it unsuitable for use in CE devices.[2] Friis's equation shows that operation at higher frequencies requires higher gain (more directional transmission) to obtain the same range and data rate:

$$Power_{\mathrm{Rx}} = \frac{Power_{\mathrm{Tx}} \cdot Gain_{\mathrm{Tx}} \cdot Gain_{\mathrm{Rx}} \cdot c^2}{(4\pi \cdot Distance \cdot Frequency)^2}$$

Wireless systems can use high-gain horn antennas to focus in a fixed direction, but they require careful manual alignment to face each other. They also require line-of-sight operation without any intervening obstacles such as furniture or people. However, smart-antenna technology can electronically steer a focused directional beam to obtain the necessary beam focus while automatically adapting to the environment to find both direct line-of-sight (LOS), and indirect non-line-of-sight (NLOS) paths, which bounce off objects and walls. This directionality also reduces interference and improves link security. High-quality, low-latency, uncompressed HD A/V transmission requires a large number of antennas (more than 10) and very agile and dynamic beam steering (less than 1 ms).

Although this large number of antennas requires a large area when operating at lower frequencies such as 2.4 GHz, antennas only a few mm^2 in size can be effective with 60 GHz's shorter wavelengths. Optimized package modeling and design techniques allow the use of standard low-cost, high-volume IC packaging processes even at these high frequencies. Because 60-GHz antennas are small, they can be embedded in the same substrate as the radio IC.

The last hurdle is cost-effective manufacturing of 60-GHz radio circuits. Previously, operating frequencies in the 60-GHz range were obtained only with expensive III-V materials, such as GaAs and InP, which are suitable for high-frequency circuit design because of their high transition frequencies (f_t) and maximum oscillation frequencies (f_{max}). Over the past decade, however, major advances in ultrascaled silicon technologies, such as digital CMOS and SiGe HBT, have made transistors smaller and fast enough for millimeter-wave operation. CMOS promises the highest integration levels and the lowest cost, and SiGe performance is now comparable to, and in some cases better than, other compound semiconductor technologies. Taking advantage of these scaled silicon processes, the novel design and modeling of transistors and passive elements (microstrip or coplanar waveguide transmission lines, capacitors, and inductors) and new circuit design techniques have resulted in silicon circuit blocks operating at 60 GHz.[3,4]

Recently, the technology has progressed from individual circuit blocks (oscillators, LNAs, mixers) to increasing integration levels, culminating in fully integrated 60-GHz silicon radios.[5–7] Later in this article, we show an entire radio implemented in a standard digital CMOS process. Other applications include personal area networking (PAN) in the 60-GHz band,[8] as well as automotive radar in the 24- and 76- to 77-GHz bands.[9] The ability to design and manufacture fully integrated millimeter-wave radios in standard CMOS now makes 60-GHz radios inexpensive enough for consumer applications.

Wireless technology for uncompressed HD video distribution

Supporting streaming uncompressed audio and video at up to 1080p resolution in NLOS ranges of at least 10 meters for in-room applications requires careful system design at all levels. Such a system's PHY requirements include the ability to deliver up to 4-Gbps data rates in a beam-formed directional mode to stream high-speed A/V and data content. The system must also deliver communication at lower data rates omnidirectionally for device control and coordination. High-rate PHY modes support the 1 to 4 Gbps required for audio and uncompressed video up to 1080p at 60 frames per second using orthogonal frequency division multiplexing (OFDM) with quadrature phase shift keying (QPSK) and 16-phase quadrature amplitude modulation (16-QAM). The low-rate PHY modes support command, beacon, broadcast, acknowledgment (ACK), and audio traffic rates of 2.5 to 10 Mbps in omnidirectional modes, as well as 20 to 40 Mbps in beam-formed unidirectional modes, using OFDM with binary phase shift keying (BPSK) modulation.

The MAC layer also requires optimization to support high-quality streaming, HD, uncompressed content. A time-division multiple-access (TDMA) core scheduling mechanism enables high quality of service (QoS), which is more difficult to attain with the carrier-sense multiple-access with collision avoidance (CSMA/CA) scheme in 802.11/WiFi. A central coordinator schedules traffic for the WVAN. One of the devices present (typically a display in the network) automatically becomes the coordinator. All devices receive periodic beacons from the coordinator, indicating the access schedule that allows them to precisely time transmits and receives. This helps ensure that required bandwidth is available when needed and also eliminates the overhead of wireless collisions. Even though the coordinator schedules the traffic, all content is sent directly between devices, not via the coordinator. This results in greater network efficiency and relaxes coordinator requirements.

Data security and content protection are critical in wireless operation to prevent illicit access to users' data and duplication of commercial copyrighted content. Strong encryption techniques, such as Advanced Encryption Standard (AES) ciphers, thwart illegal or unintended use of data. Leveraging existing Hollywood-approved digital-transmission content protection (DTCP) mechanisms (http://www.dtcp.com) can facilitate the film industry's approval and buy-in process. Consumer content protection, also known as user data privacy, prevents unauthorized users from accessing authorized users' content as well as the devices themselves, so that unauthorized users cannot view recorded content and cannot control or query the devices inappropriately. Multi-Gbps transmission of uncompressed content has the inherent benefit of having a sufficiently high data rate to make capture of the data stream difficult. Additionally, the directional nature of high-speed 60-GHz communications makes it more difficult to capture signals if the device attempting to do so is not in the path between the sender and the intended recipient. Finally, additional proximity controls further ensure that communications are confined.

Uncompressed, 60-GHz, wireless HD chipset

SiBEAM expects its all-CMOS fully integrated chipset to enable the first WirelessHD-compliant systems in the market, fully supporting uncompressed and lossless wireless A/V streaming of up to 1080p/60 resolutions at 24 bits per pixel and frame rates with a wired equivalent robustness of less than a 10^{-10} bit error rate. The chipset supports deep color modes having greater than 8 bits per pixel component. It supports high-quality audio using up to eight channels at up to 192-kHz sample rates in both pulse code modulation (PCM) and compressed data formats.

Figure 3 shows the chipset's form factor in a typical implementation. The center chip is digital BB/MAC, and the chip on the right side is the RF chip with integrated antennas. Figure 4 diagrams the chipset's placement in source and sink systems. The two-chip set achieves complete antennas-to-A/V-bits integration, requiring minimal additional support hardware for integration into existing A/V sources (Blu-ray and HD DVD players and HD set-top boxes) and sinks (displays). Integrated device control features allow seamless single-remote-control operation and interdevice communication. The chipset supports DTCP content protection and security.

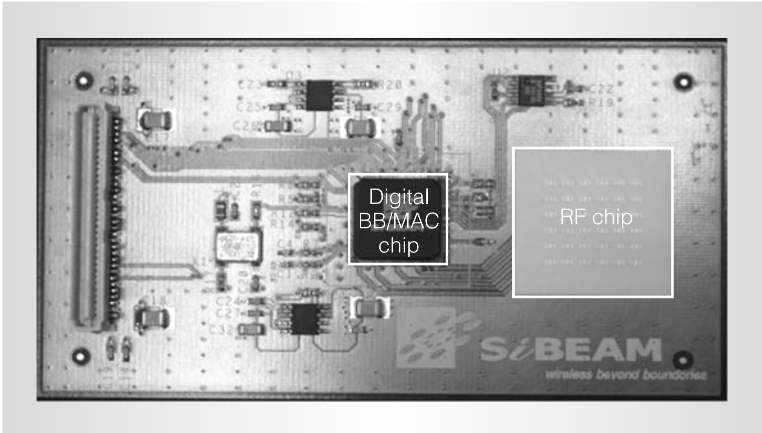

Figure 3. Form factor with two-chip antennas-to-bits integration. The center chip is digital BB/MAC, and the chip on the right side is the RF chip with integrated antennas. Other minor support circuitry includes voltage regulation and a frequency reference crystal.

Figure 5 shows the architecture of the RF chip containing the complete 60-GHz smart-antenna transmitter and receiver. It includes the 60-GHz low-noise amplifiers (LNAs), 60-GHz power amplifiers (PAs), mixers, and intermediate-frequency (IF) and baseband amplifiers. It includes beam formers to perform the smart-antenna functions. In addition, the integrated crystal oscillator and frequency synthesizer generate

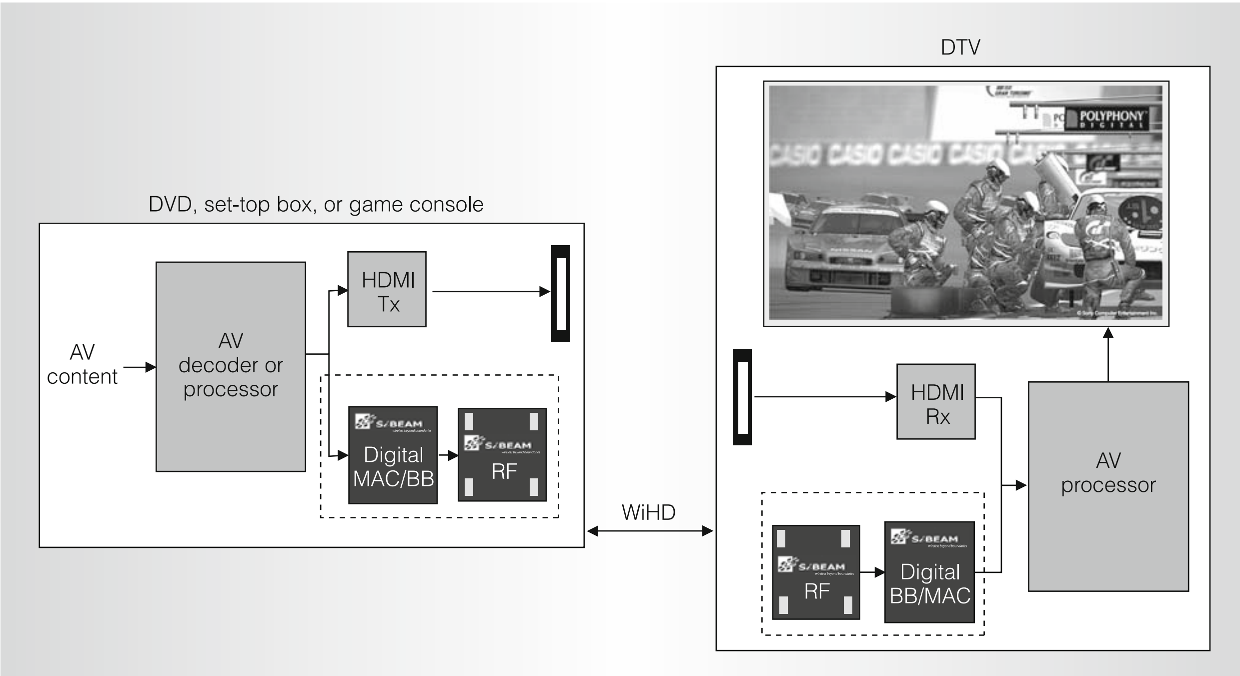

Figure 4. Placement of wireless chipsets in A/V source and sink systems. High integration and CE-friendly interfaces simplify overall system design. (HDMI: high-definition multimedia interface; BB: baseband.)

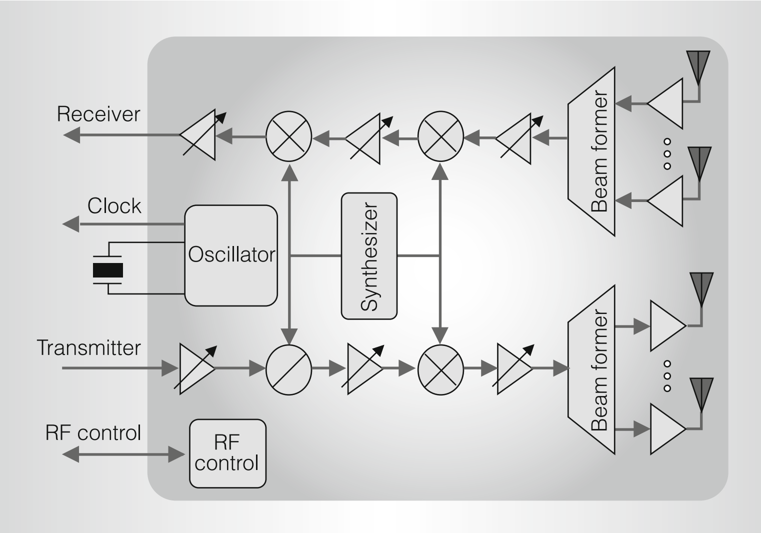

Figure 5. Radio architecture of integrated 60-GHz radio chip.

the required IF and RF local oscillator (LO) frequencies from a single external crystal. Figure 6 shows a die photograph of most of these components, fabricated in a standard 90-nm digital CMOS process.

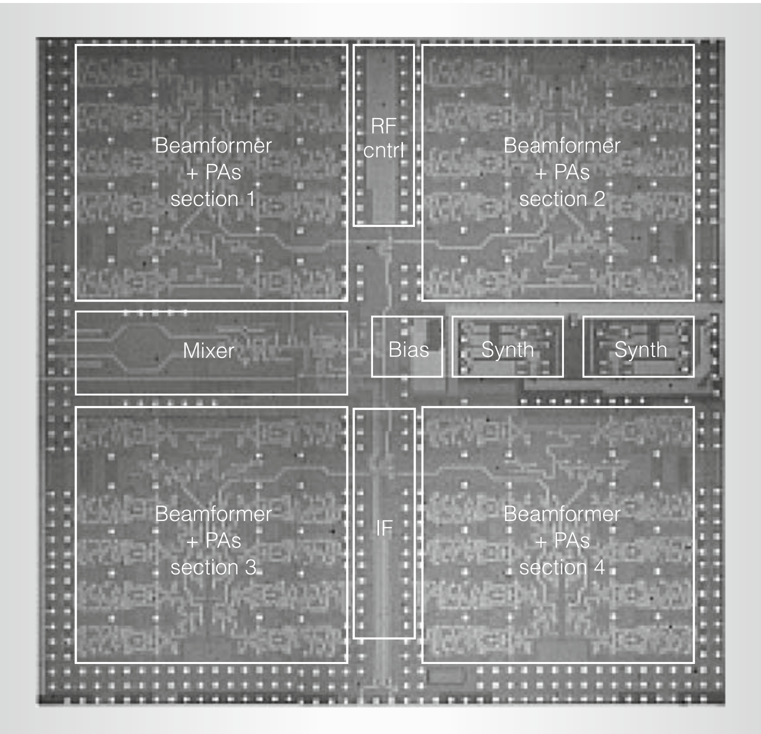

Figure 6. Die photograph of 60-GHz beam former and other radio components.

The radio chip's packaging includes integrated 60-GHz antennas that ease board and system design by containing all high-frequency routing within the CMOS die and chip package. As described earlier, achieving full 10-m NLOS coverage at the required data rates requires more than 10 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. This degree of parallelism requires careful design and implementation at many levels, including system architecture, DSP algorithms, circuit design, and packaging.

Figure 7 shows the digital BB/MAC chip, which contains mixed-signal components (A/D and D/A converters and phase-locked loops), digital PHY, digital MAC, audio and video interface unit, and embedded CPU. This chip manages all aspects of A/V and wireless-network operations, presenting direct digital A/V signals to the host device. The digital OFDM PHY encodes and decodes transmissions at data rates up to 4 Gbps and includes both inner and outer error-correcting codes for improved range and robustness. The PHY also controls several functions in the radio chip, including beam former settings for smart-antenna operation. The MAC architecture allows rapid response times for time-critical aspects of the MAC protocol and flexibility for more complex, less time-critical aspects. The MAC arbitrates access to the wireless medium and controls network operation. The security and content protection unit performs standards-based encryption and decryption. The A/V interface unit packs, unpacks, and processes raw A/V data from the digital A/V interface into packets suitable for transmission by the MAC. This unburdens the system design of additional A/V logic and allows the chipset to be inserted into the system in a similar manner to existing wired HDMI chipsets. The embedded CPU keeps the host system's load and complexity low by performing A/V network management. The system micro interface allows control information to pass

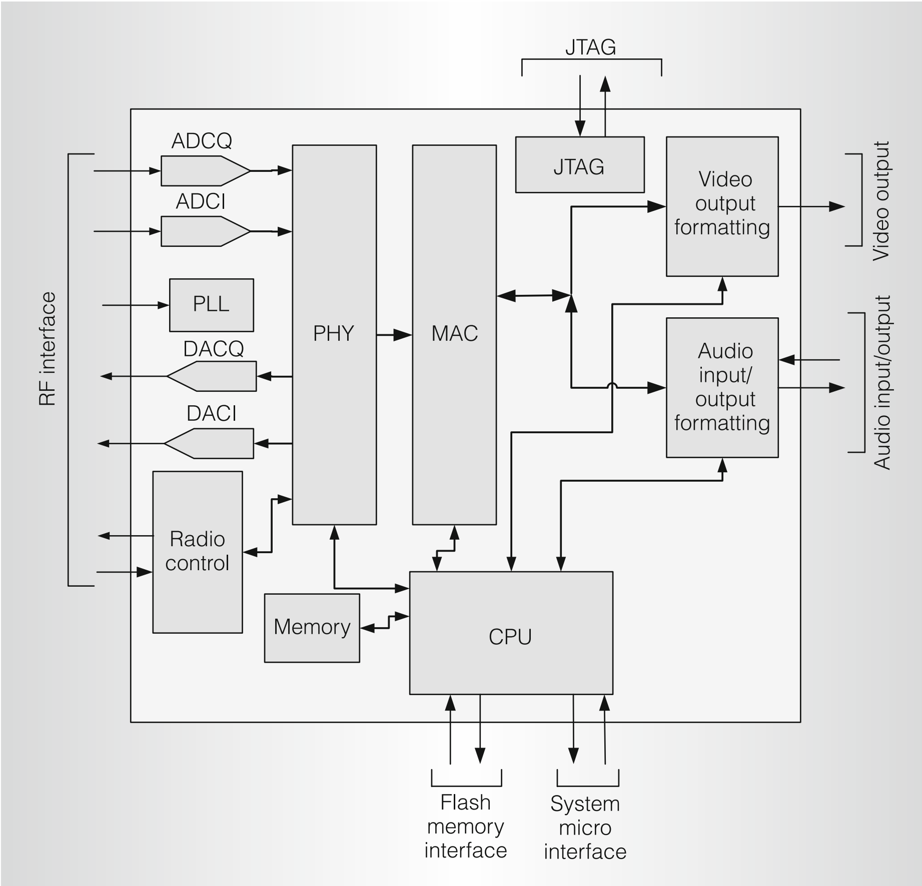

Figure 7. Receiver baseband chip architecture. Simple A/V and system micro interfaces ease integration and system design.

between the internal CPU and the host system.

Wireless data rates of 4 Gbps once seemed well beyond the reach of state-of-the-art technology, particularly for non-line-of-sight consumer applications. Now, thanks to the wide unlicensed 60-GHz band, advances in high-frequency CMOS circuit modeling and design, and highly scalable, quick-adapting smart-antenna technology, such data rates are now achievable in a cost-effective, robust manner. The WirelessHD specification, with its broad industry support, addresses the critical issue of multivendor interoperability. The SiBEAM chipset contains the full functionality necessary for integration into existing HD A/V systems. MICRO

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