60 GHz Wireless: Up Close and Personal

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The millimeter-wave band, especially the unlicensed spectrum at the 60 GHz carrier frequency, is at the spectral frontier of high-bandwidth commercial wireless communication systems. Compared with microwave band communication, spectrum at 60 GHz is plentiful (frequencies of 57–64 GHz are available in North America and Korea, 59–66 GHz in Europe and Japan [1], [2]), but attenuation is more severe (20 dB larger free space path loss due to the order of magnitude increase in carrier frequency, 5–30 dB/km due to atmospheric conditions [3], and higher loss in common building materials [4]). These characteristics make 60 GHz communication

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most suitable for close-range applications of gigabit wireless data transfer.

Several emerging 60 GHz standards, including WirelessHD [5], IEEE 802.15.3c [6], and ECMA 387 [7], are targeted toward short-range wireless personal area networking (WPAN) such as high definition streamed multimedia and high-speed kiosk data transfers. Currently, the two most popular 60 GHz standards, IEEE 802.15.3c and WirelessHD, will primarily deliver Gb/s streamed video and audio. Both standards are completed (WirelessHD finished a second revision for higher rates in May 2010) and WirelessHD-certified set top boxes for home multimedia streaming are already available in retail outlets.

Next-generation wireless local area networking (WLAN) will also exploit 60 GHz spectrum through the development of the IEEE 802.11ad and WiGig standards [8]–[11]. This is supported by WiFi companies who recognize that microwave band spectral resources are insufficient for next-generation applications, even with increased modulation efficiency and extended antenna resources (the approach taken by IEEE 802.11ac to increase data rates of IEEE 802.11n). Because WiGig is privately developed through an industry consortium, it has already published version 1.0 in May 2010, with consumer products expected to roll-out in late 2011, whereas IEEE 802.11ad is targeting final approval by December 2012. As a testament to the commitment of 60 GHz technology into WLAN markets, the WiFi and WiGig standards have recently announced interoperability agreements [12].

In addition to providing massive bandwidth for future WPANs and WLANs, adoption of wireless connectivity will soon be necessary, which is evident from the consideration of skin and proximity effects, substrate losses, and dispersion of wired interconnects at carrier frequencies of 60 GHz to hundreds of GHz. These impairments will make wired solutions extremely difficult and/or expensive for future massively broadband devices with data rates from tens to hundreds of gigabits per second [13], [14]. For example, on-chip and in-package antennas used in 60 GHz links may be the predecessors to wireless interconnects in personal computers. The maximum bit-rate of a wired interconnect of cross-sectional area A and length l is approximately $10^{16} A/l^2$ [13], indicating that the longest wired interconnect that can support 100 Gb/s without equalization is less than 5 mm in length. Ironically,

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massively broadband devices operating at 60 GHz and above are likely to have dimensions greater than 5 mm.

Current Challenges

Antennas

60 GHz chipsets exploit the short-carrier wavelength by incorporating antennas or antenna arrays directly on-chip or in-package. For the simplest and lowest-cost solutions, single antennas are attractive. Single-antenna solutions, however, must overcome the challenges of low on-chip efficiencies (typically 10% or less [14]) and in-package antennas must overcome lossy package interconnects (standard wire-bonds are limited to under 20 GHz [15]). For in-package antennas, package material with low dielectric constants will give the best gain-bandwidth products [16], but this must be weighed against other factors, including manufacturing precision and available interconnect technologies (for example, wire-bonding, flip-chip, or coupling connections) [17], [18]. Popular package technologies include low-temperature cofired ceramic (LTCC, $\epsilon_r = 5.9 - 7.7$ [19], [20]), fused silica ($\epsilon_r = 3.8$ [21]), liquid crystal polymer (LCP, $\epsilon_r = 3.1$ [22]), and Teflon ($\epsilon_r = 2.2$ [17], [23]).

High gain on-chip antennas (for example, 10 dBi gain, where dBi is the gain in decibles with respect to an isotropic radiator) offer the cheapest solution for 60 GHz communications. One approach is to develop

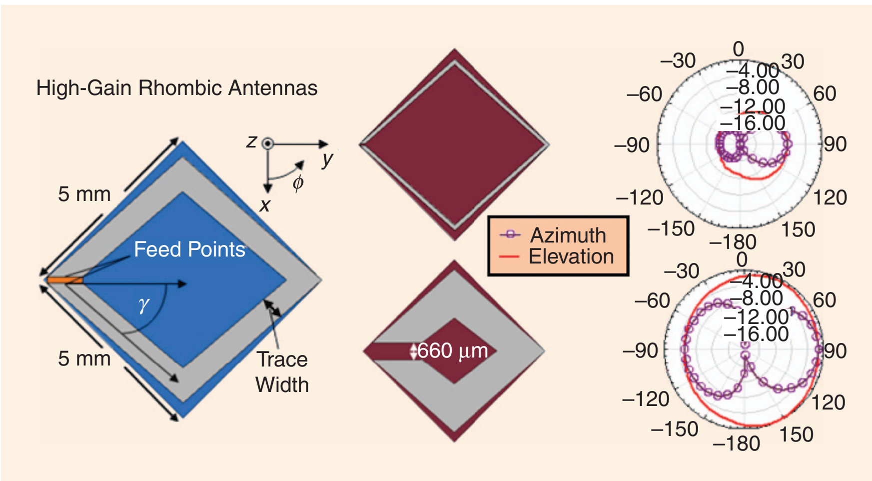

Figure 1. *Rhombic on-chip antennas and polar plots of their gains [14].*

Several emerging 60 GHz standards are targeted toward short-range wireless personal area networking such as high definition streamed multimedia and high-speed kiosk data transfers.

antenna topologies for operation over a lossy ground plane such as the rhombic antenna in Figure 1 [14]. This antenna achieves simulated gain of near 0 dBi without the use of compensating structures such as lenses that add to chip form factor (typical gains for single on-chip antennas without lenses are −20 to −10 dBi). Smaller antennas, such as the dipole and Yagi in Figure 2, are better for arrays. More research is needed to make on-chip antenna gains competitive with in-package antenna gains. Possible approaches include electromagnetic bandgap structures, frequency selective surfaces, and metamaterials [24], [25].

As an alternative to minimizing losses in a single 60 GHz antenna, phased antenna arrays or switched-beam antenna arrays can exploit transmit and receive beam steering to add link gain and reduce the observed impact of the inherent antenna losses. Phased arrays allow a continuous sweep of the array beam and are more powerful, flexible, and expensive than switched-beam arrays, in which the main beam selects one of a set of predefined orientations. Beam steering mitigates other 60 GHz design challenges, including packaging/interconnect effects [26], low-output-power amplifiers [27], and high-noise-figure components [28], [29]. Antenna arrays are promising, especially for non-line-of-sight channels where significant antenna gain is necessary to satisfy link budgets without sacrificing spectral efficiency, but arrays present several challenges. For example, phased-array beam steering requires generation and distribution of phased signals to array elements, and phased signal generation (for example, mixing with phased local oscillators [30] or phase-shifting at baseband with digital circuitry [29]), and distribution (for example, centrally or from multiple points) should be low loss and low space and have sufficient accuracy. Excessive space may result in antennas being too far apart to avoid grating lobes, hurting array directivity [26]. Furthermore, the trade-off between beam-steering accuracy versus steering algorithm complexity and control overhead should be optimized. To reduce algorithm complexity, codebook–based or switched-beam phased-arrays are often employed in place of optimal phased-array approaches, which feature bidirectional control signaling and larger computational complexity [29]. Heterogeneous networks can also cooperate to reduce the complexity burden on low-complexity nodes [31]. For example, nodes with high processing capabilities may determine the direction of arrival information by overhearing transmissions, providing for near-optimal performance with minimal complexity burden for most of the users [29].

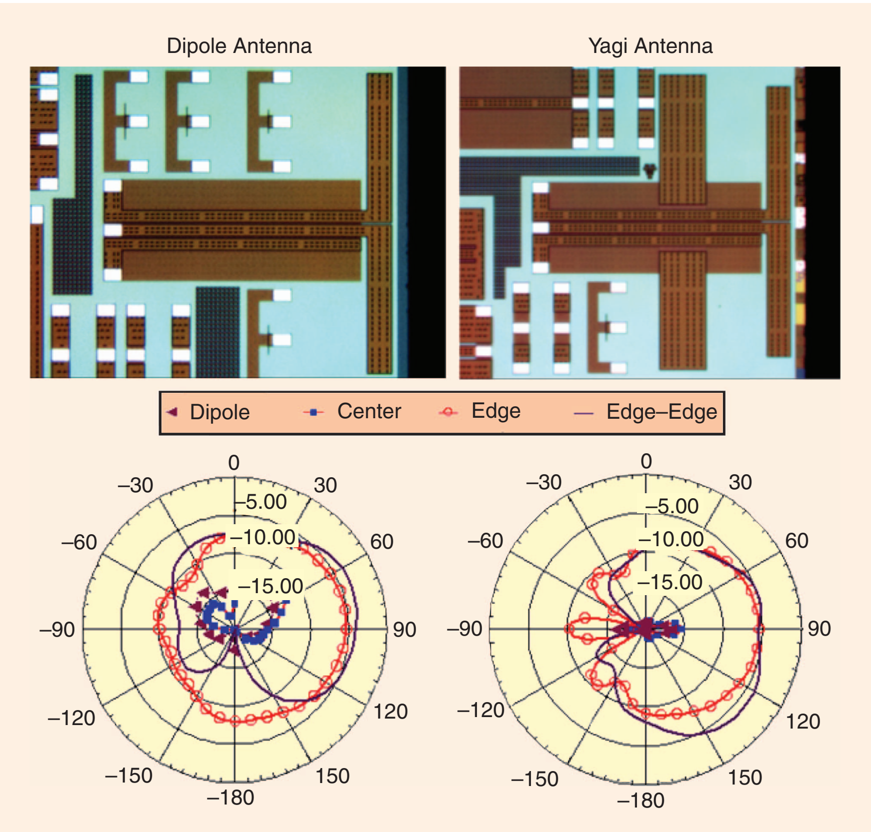

Figure 2. *Dipole and Yagi on-chip antennas and polar plots of their gains [14].*

Circuits

A key to low-cost 60 GHz circuits is the use of complementary metal oxide semiconductor (CMOS) or silicon-germanium (SiGe) technology rather than more expensive III-V processes, such as gallium-arsenide (GaAs), that traditionally characterize radio frequency circuit design [32]. Silicon-on-insulator (SOI) CMOS processes are also attractive for high-end applications as they allow for higher quality factors due to reduced values of parasitic capacitances and inductances for passive components

[33], but SOI processes, in which device channels and substrates are engineered separately, will not be as inexpensive as standard CMOS, in which the device channels and substrates are not separated. CMOS processes have now reached transit frequencies of hundreds of gigahertz [34]. Hence, single-chip 60 GHz systems, complete with a digital baseband and millimeter-wave analog front end, will provide cheap and low-power solutions [35]. This will also facilitate techniques like mixed-signal equalization [36], [37] that may improve the performance of complete systems versus multichip solutions. Unfortunately, foundries do not yet report relative permittivities or loss-tangents for process materials at millimeter-wave frequencies in process design kits (PDKs), forcing developers to measure these need-to-know parameters until they are provided. Test chips with structures including half-wave and quarter-wave transmission lines, as in Figure 3, are useful for this purpose. This structure was used to find loss tangent, approximately 0.13, and relative permittivity, approximately 4.22, of a 180 nm CMOS process substrate at 60 GHz [38].

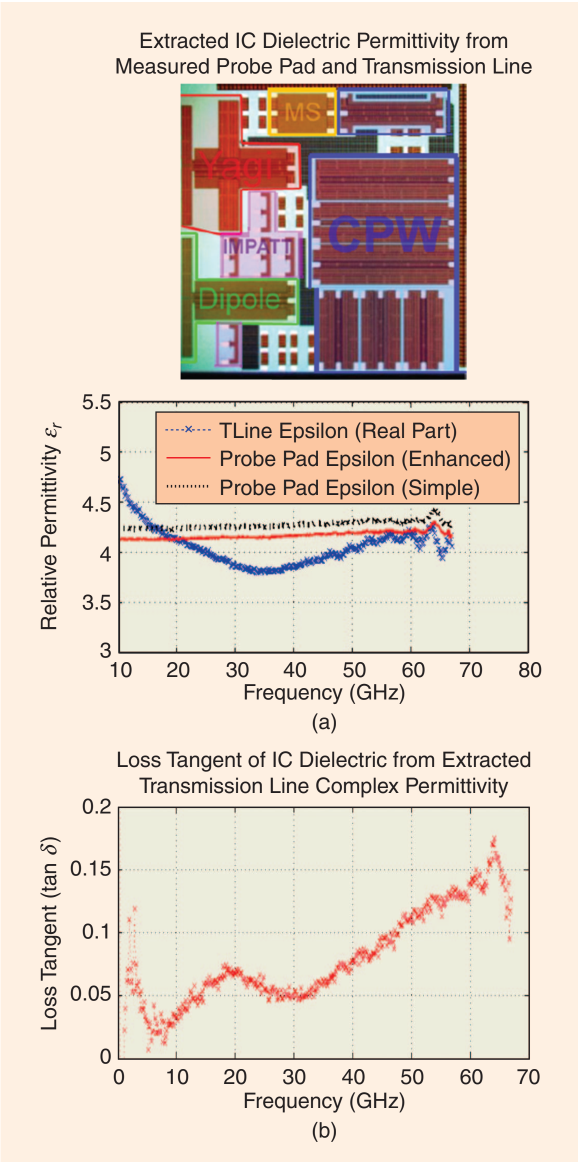

Figure 3. *Example of relative permittivity and loss tangent extraction [38].*

Digital communications at 60 GHz provides unique design trade-offs due to millimeter-wave hardware limitations and channel propagation characteristics.

Modulation and Equalization

Digital communications at 60 GHz provides unique design trade-offs due to millimeter-wave hardware limitations and channel propagation characteristics. The wide operating bandwidth results in tight digital processing constraints and severe frequency-selective signal distortion known as intersymbol interference (ISI). In typical indoor channel environments without beam steering or directional antennas, ISI can spread a single symbol over tens or hundreds of symbol periods. For example, the generated channel impulse response in Figure 4 from a popular open source channel modelling tool called *Simulation of Indoor Radio Channel Impulse Response Models with Impulse Noise* (SIRCIM) 6.0 for typical indoor environments shows a delay spread of 65.9 ns [39], which leads to approximately 120 symbols of ISI in the single carrier-physical layer (SC-PHY) of IEEE 802.15.3c.

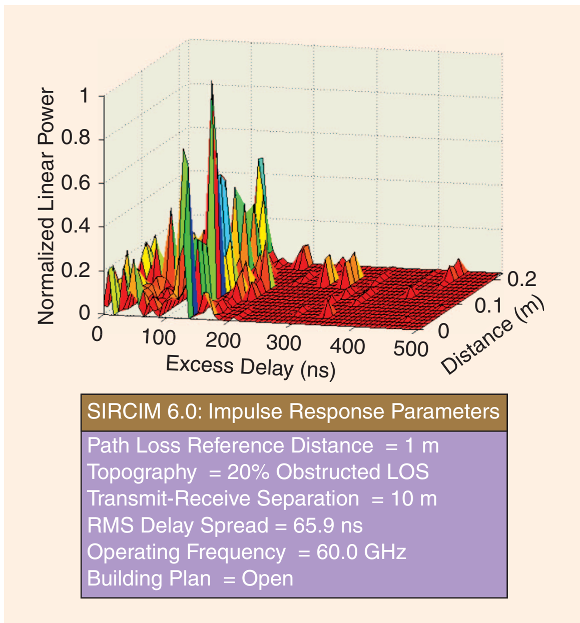

Figure 4. *Long delay spreads characterize wideband 60 GHz channels and may result in severe intersymbol interference. Plot generated with Simulation of Indoor Radio Channel Impulse Response Models with Impulse Noise (SIRCIM) 6.0 [39], available from The University of Texas at Austin.*

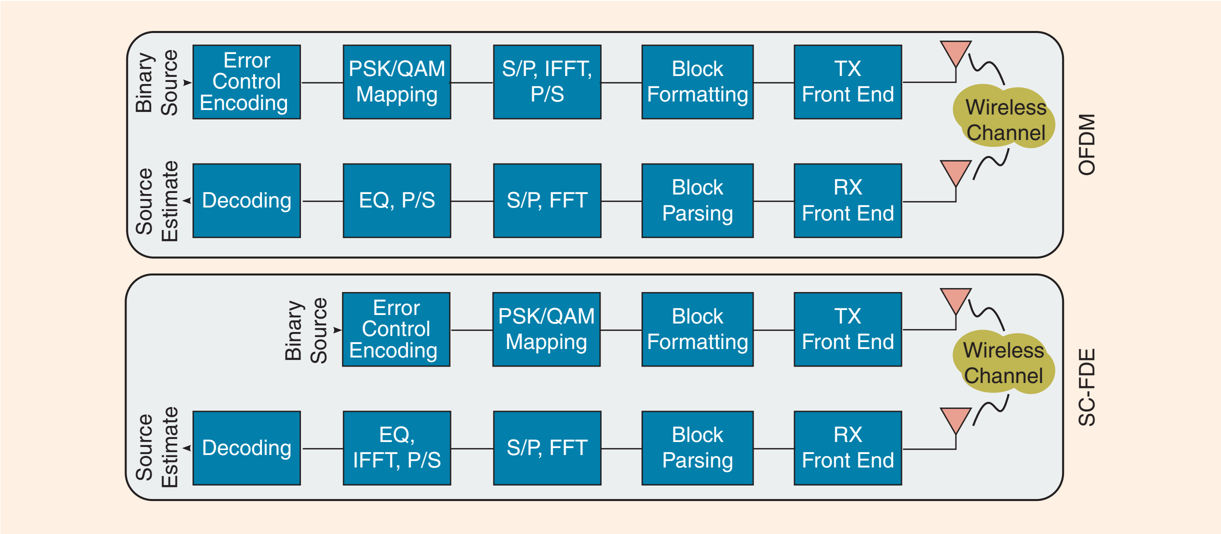

Figure 5. *Transceiver block diagrams for orthogonal frequency division multiplexing (OFDM) and single-carrier transmission with frequency domain equalization (SC-FDE). Serial-to-parallel (S/P) and parallel-to-serial (P/S) conversion is needed for fast Fourier transforms (FFTs) and inverse fast Fourier transforms (IFFTs). Block formatting is completed with a cyclic prefix to maintain cyclic convolution properties of transmitted symbols, resulting in the potential for low-complexity frequency-domain equalization (EQ). Note that the FFT and IFFT operations are separated between the transmitter and receiver for OFDM while SC-FDE processes both at the receiver.*

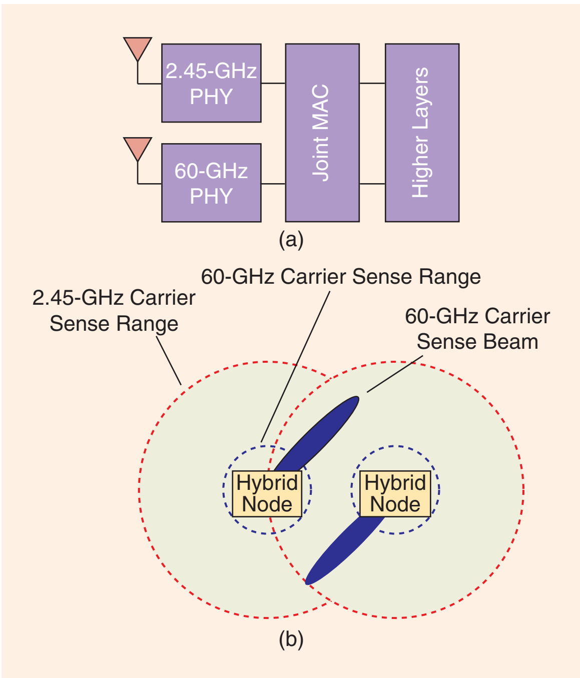

Figure 6. *(a) Block diagram of hybrid microwave/millimeter-wave wireless device and (b) illustration of 60 GHz network which exploits the microwave band to coordinate devices without beam alignment.*

Millimeter-wave modulation must also consider the increased presence of phase noise relative to microwave frequencies and limited output power, which makes nonlinear operation attractive.

The best modulation format for 60 GHz remains open for discussion. Since equalization in the frequency domain provides the lowest complexity to mitigate severe ISI, IEEE 802.15.3c features orthogonal frequency division multiplexing (OFDM) and single-carrier transmission with frequency domain equalization (SC-FDE). When low implementation complexity is desirable, links may also consider frequency-shift keying (FSK) [40], amplitude shift keying (ASK) [40], on-off keying (OOK) [41], or pulse position modulation (PPM) [42] where the carrier frequency, carrier amplitude, carrier presence, and carrier presence duration are modulated, respectively. These simple modulation strategies may lead to less complexity in the transmitter and receiver than OFDM or SC-FDE (where the amplitude and phase of the carrier are jointly modulated), however, they offer significantly less spectral efficiency. Hence, these simpler modulation techniques are less likely to find a permanent home at 60 GHz in the long term as digital capabilities scale.

Looking ahead, 60 GHz wireless systems would benefit from a universal modulation technique that combines the benefits of SC-FDE and OFDM, whose processing architectures are illustrated in Figure 5. OFDM is well established at microwave frequencies for its high efficiency mitigation of severe ISI, but it has increased sensitivity to phase noise from intersubcarrier interference (ICI) and requires large peak-to-average transmit power ratios (PAPRs). Like OFDM, SC-FDE provides low-complexity ISI equalization in frequency selective channels, but has lower PAPR and less sensitivity to phase noise. Furthermore, SC-FDE does not require high-redundancy error-control coding in frequency selective channels since data is not transmitted in the frequency domain. Moreover, SC-FDE requires lower resolution in analog-to-digital converters, which reduces cost [43]. OFDM may still provide better overall performance in highly frequency selective channels because data coding and interleaving in the frequency domain captures frequency diversity benefits more effectively, and linear equalization does not create colored additive noise [44]. Continuous phase modulation strategies have also been considered for their superior operation with nonlinear power amplifiers. For example, these strategies may use a phase matched cyclic prefix [45], with an efficient superimposed pilot training structure [46] for efficient frequency domain equalization.

MAC Protocols

Medium access control (MAC) protocols for millimeter-wave bands must support transmission and reception with highly directional and adaptive beams. This can complicate neighbor discovery and exacerbate the hidden node (that is, an interfering device is *not* prevented from transmission) and exposed node (that is, a device is prevented from communicating even when it will not interfere with other nodes in the network) problems. In addition, 60 GHz MAC protocols may need to support local-area, multihop operation for ad-hoc networking and signal routing in home and office deployments. A weakness of current 60 GHz MAC protocols, despite long consideration of directional MAC protocols in networking literature [47], is lack or poor support for omnidirectional transmission modes.

The design of efficient 60 GHz MAC protocols remains an important research topic. For example, [31] recently considered a hierarchical approach for sector-level and beam-level searching to link two devices with directional transmission and reception. Other work in [48] develops a pseudowired abstraction model for directional links and argues that distributed scheduling is key to avoiding deafness. There is also interest in alternative coordination mechanisms (the supercontroller in [49]), which could be implemented using a combination of microwave and millimeter-wave transmission frequencies as illustrated in Figure 6.

Conclusions and Outlook

To meet the needs of next-generation high-data-rate applications, 60 GHz wireless networks must deliver Gb/s data rates and reliability at a low cost. In this article, we surveyed several ongoing challenges, including the design of cost-efficient and low-loss on-chip and in-package antennas and antenna arrays, the characterization of CMOS processes at millimeter-wave frequencies, the discovery of efficient modulation techniques that are suitable for the unique hardware impairments and frequency selective channel characteristics at millimeter-wave frequencies, and the creation of MAC protocols that more effectively coordinate 60 GHz networks with directional antennas. Solving these problems not only provides for wireless video streaming and interconnect replacement, but also moves printed and magnetic media such as books and hard drives to a lower cost, higher reliability semiconductor form factor with wireless connectivity between and within devices.

Looking ahead, 60 GHz wireless systems would benefit from a universal modulation technique that combines the benefits of SC-FDE and OFDM.

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