Advanced Millimeter-wave Technologies

Antennas, Packaging and Circuits

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Preface

This book is intended for a wide range of researchers, engineers, managers and the wireless industry at large who are interested to learn and influence the future direction of wireless. Its focus is on millimeter-wave (mmWave) antennas and packaging, but context and relevance is provided by including a systems perspective to give the reader an understanding of the importance of each element and the hidden depths beyond the seemingly simple topics. The goal of this book is not to showcase problems solved, but to educate everyone in this new and exciting area of research that holds the promise further to invigorate and fuel the wireless industry and pull together the brightest minds to solve some of the toughest technical challenges we have ever faced as a wireless industry. What the reader will find between these covers is the work of a small subset of people who have begun to scratch the surface enough for others to see the few brilliant gems hidden in the depths of granite-hard challenges.

At the time of writing, there were no books available on the subject of mmWave chip, antenna and packaging co-design. In order to fill this void, the authors decided to leverage some of the most recent efforts and pull them together into a coherent story that builds from a bottoms-up approach into useful and interesting systems.

Acknowledgements

The authors would like to acknowledge the many people and organizations that made this work possible, especially seed funding from programs including NASA, under contract NAS3-03070, and DARPA, contracts N66001-02-C-8014 and N66001-05-C-8013. As in every field, there are pioneers who began in this area years ago. There is no clear delineation of by whom and when work in the mmWave field began, but there was a defining demonstration of its potential as early as 1895 with J.C. Bose, and the field has been rich with many contributors since. Likewise, Japan stands out as the first country to promote strongly the use of mmWaves, beginning decades ago. Therefore, it only seems fitting to mention from a very long list a few key people who helped to inspire this work: J.C. Bose [1], Johann-Friedrich Luy [2], Keiichi Ohata [3, 4], Peter F.M. Smulders [5], Herbert Zirath [6], Peter Russer [7], Hiroyo Ogowa [8, 9], Ted Rappaport [10], Larry Larson [11], John Cressler [12]. Also, fundamental to the success of any new technical area is university involvement. A few of the key researchers and their universities who took up this challenge early on and helped to make great strides, as seen in recent ISSCC and other symposia, journals and conferences, are: Professor Ali Hajimiri of California Institute of Technology; Professors Robert Broderson and Ali Niknejad of UC Berkeley; Professors John Cressler and Joy Laskar of Georgia Institute of Technology; Professor Charles Sodini of the Massachusetts Institute of Technology (MIT); Professors Behzad Razavi, Frank Chang [8] and Tatsuo Itoh of UCLA; Professors Larry Larson, Gabriel Rabiz and Larry Milstein of UCSD; Professor John Long of Delft University; Professors Ken O of the University of Florida; Dr Efstratios Skafidas of Melbourne/NICT Australia; Professors Linda Katehi and Jennifer T. Bernhard of the University of Illinois; Professor John Volakis of Ohio State University; Professor Koichi Ito of Chiba University, Japan; Professor Yue Ping Zhang of Nanyang Technological University, Singapore; and Professor Jri Lee of Taiwan National University.

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1

Introduction

Brian Gaucher

There is an unusual confluence of three major disruptive and threshold events taking place that are fundamentally reshaping the wireless industry. First, wireless has become a critical, accepted and necessary part of everyday life, e.g. the number of mobile phone users growing at approximately one billion per year and younger generations and countries skipping the PC in favor of handheld wireless devices [1]. The second threshold event is the now rapidly growing high-definition video, automotive radar and high-resolution imaging markets, which have created a sudden need for extremely broadband gigabits per second (Gbps), highly integrated, low-cost and low-power wireless devices in the millimeter-wave (mmWave) frequency bands, which previously only the military could afford. The third threshold event occurring is silicon technology and tools have been developed with suitable performance characteristics to enable radio design, integration and operation at mmWave frequencies; here we specifically discuss the range 60–194 GHz, although the literature is now showing silicon working at hundreds of gigahertz [2].

The enormous reliance of consumers and enterprises on wireless and the evolving mobile Internet is having a disruptive influence on the telco industry, e.g. wireless subscriptions now outnumber landline phone subscriptions and Apple's iPhone™ or Google's GPhone™ [3, 4] are forcing mobile carriers into 'openness', effectively reinventing wireless networks and the way they operate and make money. This reliance and evolution speaks to the convenience factor as well as perceived new utility that this technology is providing consumers and enterprise users.

Likewise in the automotive industry, radar units are now options for high-end vehicles and may become mandatory under Intelligent Highway programs around the world, owing to the potential increased safety they can provide. This means a new market for tens of millions of mmWave systems per year.

The growing high-definition multimedia revolution will also require a significant portion of devices to be wireless. This is creating demand for high-speed bandwidth that goes well

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beyond what wireless systems of today can handle. If one looks at the lowest bandwidth requirement for uncompressed high definition television (HDTV), it is about 1.5 Gbps and with some minor coding to make it more robust to multi-path and fading, it easily tops 2 Gbps as discussed within the IEEE 802.15.3c [5]. Today's conventional WiFi delivers unprecedented performance for both office and home use, but tops out at 54 Mbps, with some proprietary systems going as high as 108 Mbps. There is hope that 802.11n and ultra wide band (UWB) systems will get as high as 480 Mbps. UWB systems that utilize limited spectrum between 3.1 and 10.6 GHz have met with marginal success so far, but also promise up to 960 Mbps over a meter or two. At the time of writing, such systems have met with only marginal success in both data rate and distance. Thus, wireless is exploding in use and rapidly evolving from convenience to need across multiple industries and will continue to grow in this direction. In order to satisfy these future WiFi, HDTV, radar and other system needs of speed, capacity, security and robust performance over distance, completely new mmWave (60–194 GHz) solutions will be required.

1.1 Challenges

There is a growing need to solve the huge technical hurdles to cost-effectively leverage the vast unlicensed bandwidth available at mmWave frequencies and satisfy these growing demands. Wireless HDTV is a good example of this and worthy of further exploration here. This application is demanding dramatically higher data rates on the order of 10–100 times current rates. Indeed, they are increasing much faster than current wireless systems can handle and an alternative solution is needed. Given the data rate, capacity and quality of service (QoS) requirements, this can only reasonably happen in a spectrum location where there is suitable worldwide bandwidth on the order of gigahertz with rules that allow one to close a reasonable link budget. These issues have been the fuel and motivation for looking upward in spectrum. As one climbs the spectrum ladder, the first frequency allocation where all of this has the possibility of working well across the varied application space is the 60 GHz band. At 60 GHz there is 3–7 GHz of worldwide bandwidth available depending upon the country; see Figure 1.1 for a sample of countries. In terms of available bandwidth and allowable rules such as transmit power, lack of incumbent users, simple flexible transmission rules, etc. 60 GHz is a boon but it also comes with significant challenges, e.g. ability to do this in a low-cost, physically suitable and robust manner; likewise, the 77 GHz band is the direction the automotive industry is taking, especially in Europe, for automotive radar systems, also called adaptive cruise control (ACC) and Collision Avoidance Systems. There is also increased development activity in the 94, 120 and 194 GHz bands which are being utilized for homeland security applications such as radar, imaging systems, remote sensing, active denial and many others.

Given this set of events, opportunities and constraints, wireless designers have begun developing mmWave system architectures, circuits, antennas and packages; but as expected, they face enormous challenges of simulation, design, integration, physical realization, packaging and test of complete systems that are literally orders of magnitude more difficult than 2.4 and 5 GHz WiFi systems of today; yet to be successful they have to be nearly the same cost.

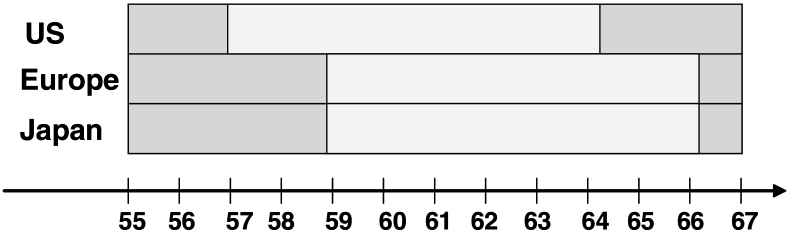

Figure 1.1: The 60 GHz spectrum chart.

If designers can find ways around these challenges, then there are significant benefits that are well worth the effort. The bandwidth and flexible open rules are the most obvious, but there are other less obvious ones also, depending upon if the glass is viewed as half full or half empty. At 60 GHz the wavelength in free space is approximately 5 mm, so circuit designers have the option to use transmission line structures as matching elements and resonant structures, in ways impossible to think about at 2.4 or 5 GHz. Similarly, on-chip filtering becomes possible and on-chip or in-package antennas are now a choice. Traditional microwave board elements such as Lange couplers, 90° hybrids, rat-race structures and many others are now small enough for on-chip consideration. Antenna beam-forming, steering and spatial-power combining become viable system design considerations even in consumer-level solutions, something previously only enjoyed by high-end military systems. Owing to this wavelength consideration, levels of integration go beyond what is achievable at 2.4 and 5 GHz, e.g. including filters and antennas on chip or in the chip package. Indeed, the whole area of packaging is flipped on its head when considering including antennas within the package itself. One's packaging mindset shifts from containing radiofrequency (RF) radiation to intentionally radiating specific frequencies, while attenuating others. This will be one of the themes for this book.

Then there is the glass half empty point of view. At mmWave frequencies, the world of consumer level systems, circuit, antenna and packaging design, is largely unknown. For example, at 2.4 and 5 GHz, a designer takes the dielectric constant of PC boards for granted, something that is known and can be relied upon; but this is not the case at e.g. 60 GHz and higher. At such frequency extremes, each material has to be characterized and relevant data extracted from samples. There are also new metamaterials and devices that might prove invaluable, e.g. electronic band gap (EBG), anisotropic approaches, new polarization techniques, etc., but as yet they remain largely untried and untested at mmWave frequencies. Simple interconnects that work well at 5 GHz may have untenable loss at 60 GHz, where each and every interface outside the chip has to be considered in the link budget. As designers pull the antenna design into the chip or chip package, there are many new and important considerations and design options that need to be taken into account and traded off, which affect the whole system. Then there are the circuit design challenges too. At 60 GHz basic transistors, as good as they have become recently, run out of gas in this frequency range, e.g. gain is considerably lower than 5 GHz, isolation decreases, power generation is much more challenging and losses are much higher [6]. On top of all of this, today's design tools have not been tested in any significant way at 60 GHz and even the smallest variation or error may have a significant impact on the end product's performance. Although time will help, today even relatively simple 60 GHz circuits require hours to simulate and it is not unusual to wait days for more complex circuits. Simulation times of digital systems that include analog front ends running at 60 GHz are currently un-simulateable due to both convergence and time required. And where do designers get valid active and passive models and macros they can trust for use in silicon level chip design that yield the correct designs at the first attempt? Even basic RF switches and switch elements need special consideration for device selection, design, use and simulation.

Thus, the challenges and benefits are many, making this an incredibly rich and deep area of research in the coming years, with streams of patents emerging around all of the above, virtually reinventing the wireless industry. As all of this takes shape, we will begin to benefit as consumers of this technology; we will find 60 GHz will enable 1–10 Gbps wireless solutions in a wide range of products such as next-generation WiFi, wireless HDTV, MP3 players and cell phones. These latter devices will be used as electronic wallets that can nearly instantly download, pay for and store a HD-movie for transport to the home and wirelessly upload it to home theater systems. There will be kiosks that act as displays for the hard drives and systems that reside in your cell phone and so much more.

As we master the design idiosyncrasies of 60 GHz, the wireless industry will move up to 77 GHz to develop cost-effective ACC for cars and Intelligent Highway Systems, where there exist a whole new set of packaging and antenna challenges on top of extreme environmental conditions. As next-generation silicon-based terahertz (THz) imagers evolve, inspectors will more easily be able to detect non-metallic weapons and explosives from a safe distance using THz imaging techniques and high-performance computing. This will make airports and critical entry points safer for everyone. However, to achieve all or any of the above in any cost-effective manner requires designers to solve a myriad of extremely challenging problems.

1.2 Discussion Framework

With a reasonable motivation of why the mmWave frequency is important and useful and the basics of what the challenges are, the next step is to establish a simple consistent framework that can be used throughout the book that addresses the system architecture, antennas, circuits and packaging in a holistic manner. Rather than highlight the multitude of architectural solutions for all wireless architectures and applications, e.g. direct conversion, low-intermediate frequency (IF), heterodyne, super-heterodyne, etc., and performance targets, we choose a single commonly applied approach of the super-heterodyne architecture [7, 8]. We use this as our reference point for discussion purposes. It is not the simplest architecture, but is general purpose and contains all the elements of virtually any wireless system one can imagine. Based on that architectural approach, we call out circuits, antennas and packaging options that reference this and which then be addressed in the remainder of the book.

1.3 Circuits

The super-heterodyne architecture is one of the more complex and therefore more encompassing architectures, making it a good choice to frame the larger circuit, antenna and packaging challenges. Although not optimal for all, it could be used for any of the

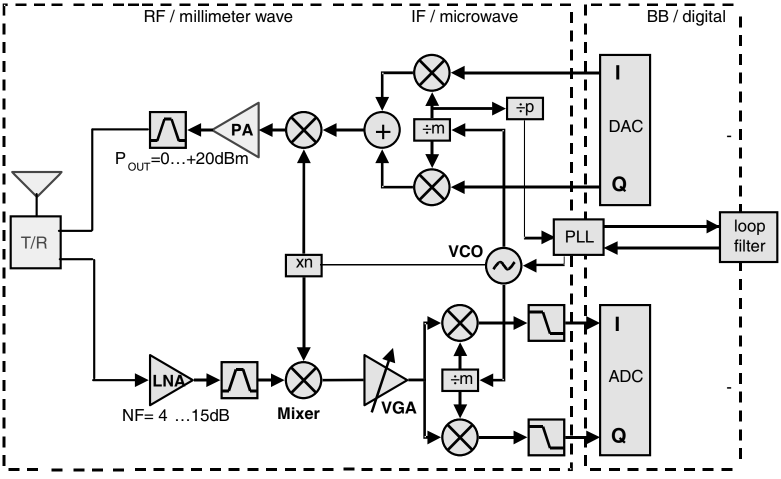

Figure 1.2: Generalized 60 GHz super-heterodyne block diagram.

aforementioned applications; Gbps wireless, radar, imaging etc. A simplified block diagram of a 60 GHz radio architecture is shown in Figure 1.2. It is based on a single-voltage controlled oscillator (VCO) super-heterodyne (multiple mixing stages) time-division duplex (switches from transmit to receive (T/R) rather than simultaneous transmit and receive) design with variable-IF frequency (byproduct of a single local oscillator (LO)). The high-frequency 60 GHz signals connect directly from integrated antennas to the T/R switch and to the low noise amplifier (LNA) input or the power amplifier (PA) output to avoid the need for external packaging and waveguide structures with their associated size, weight and power losses.

1.4 Antenna

For reasons to be discussed in detail throughout the book, mmWave antennas will nearly always be integrated with the chip or chip package. The integrated antenna has two major functions: the first is an efficient radiator or collector and the second as a bandpass filtering function. The natural bandpass filtering provided by the antenna helps both to limit the noise bandwidth prior to the LNA and to provide some image rejection. It is critical to any wireless system, but at mmWave frequencies the antenna becomes even more so because of the potential detrimental effects of interconnection losses, distance to RF electronics, match and proximity effects of nearby materials, receiver noise figure and transmit power. At mmWave frequencies power generation is extremely difficult and ‘expensive’ DC power wise, making antenna efficiency paramount. Designers cannot afford to waste hard-fought-for RF power only to lose it to ‘simple’ but lossy interconnects. For consumer level (cost-sensitive) products, performance needs and ease of use, it is a virtual requirement that the antenna be an integral part of the chip package from start to finish. This places new constraints across the whole antenna/package simulation, design and test space.

1.5 RF Electronics

The RF electronics make up the body of any wireless device and consist of a receiver and transmitter where each place critical and sometimes conflicting requirements on both the antenna and the package. For example, loss between the antenna and the RF electronics decreases transmit output power and increases system noise figure directly; thus, each RF subsystem needs to be located close to the antenna. Since there are physical limitations and both cannot be minimized, tradeoffs must be made as to which should be the closest. To establish a common vocabulary for the rest of the book, it is worth reviewing both receive and transmit chains.

1.5.1 Receiver

As shown in Figure 1.2, the signal at the output of the receive antenna is amplified by an LNA with enough gain ($>$10–15 dB) to establish the system noise figure ($<$6 dB). The LNA drives an integrated bandpass image filter, which is designed to eliminate received noise power amplified by the LNA at the IF image frequency to minimize the noise. The output of the LNA drives a mixer that translates the mmWave signal to an IF frequency in the range of 9.2 GHz. This IF frequency is chosen to provide easy image rejection at the RF and to support very high data rates. The mixer then drives a variable-gain IF amplifier, which increases the dynamic range of the receiver.

A single VCO operating in the band around 17.6 GHz is multiplied by three to generate the LO for the up and down mixers. The VCO is also divided by two to generate the 8.8 GHz LO signals for the IF quadrature mixers, which translate the received signal to baseband frequency I and Q channels. The baseband I and Q channels are band limited by variable bandwidth low-pass filters. From here the signals are either A/D (Analog to Digital) converted or detected directly depending upon the chosen modulation. The only cost effective, power efficient and performance friendly design approach at mmWave frequencies is to implement fully integrated solutions in silicon; going off chip for any mmWave frequency element could prove disastrous.

1.5.2 Transmitter

The transmit path uses the same variable-IF technique as the receive path to minimize the complexity of the system design. The band limited IQ signals are combined to a real IF signal by the quadrature up mixer. The IF signal is amplified if necessary and translated to the 60 GHz carrier frequency by a second mixer. The 60 GHz signal is increased to the desired transmit power required to close the link budget by the power amplifier (PA). The output of the PA drives an integrated bandpass filter, which suppresses the out-of-band image and carrier feed-through products, as well as broadband noise from the PA. The image filter connects to a tuned antenna designed to pass the minimum amount of spectrum necessary for operation at the desired data rate. As mentioned above, full integration of receiver, transmitter and synthesizer/LO subsystem should be done and thought of as a system. The antenna also needs to be considered closely in the design since single-ended or differential approaches can dramatically impact realizability and performance.