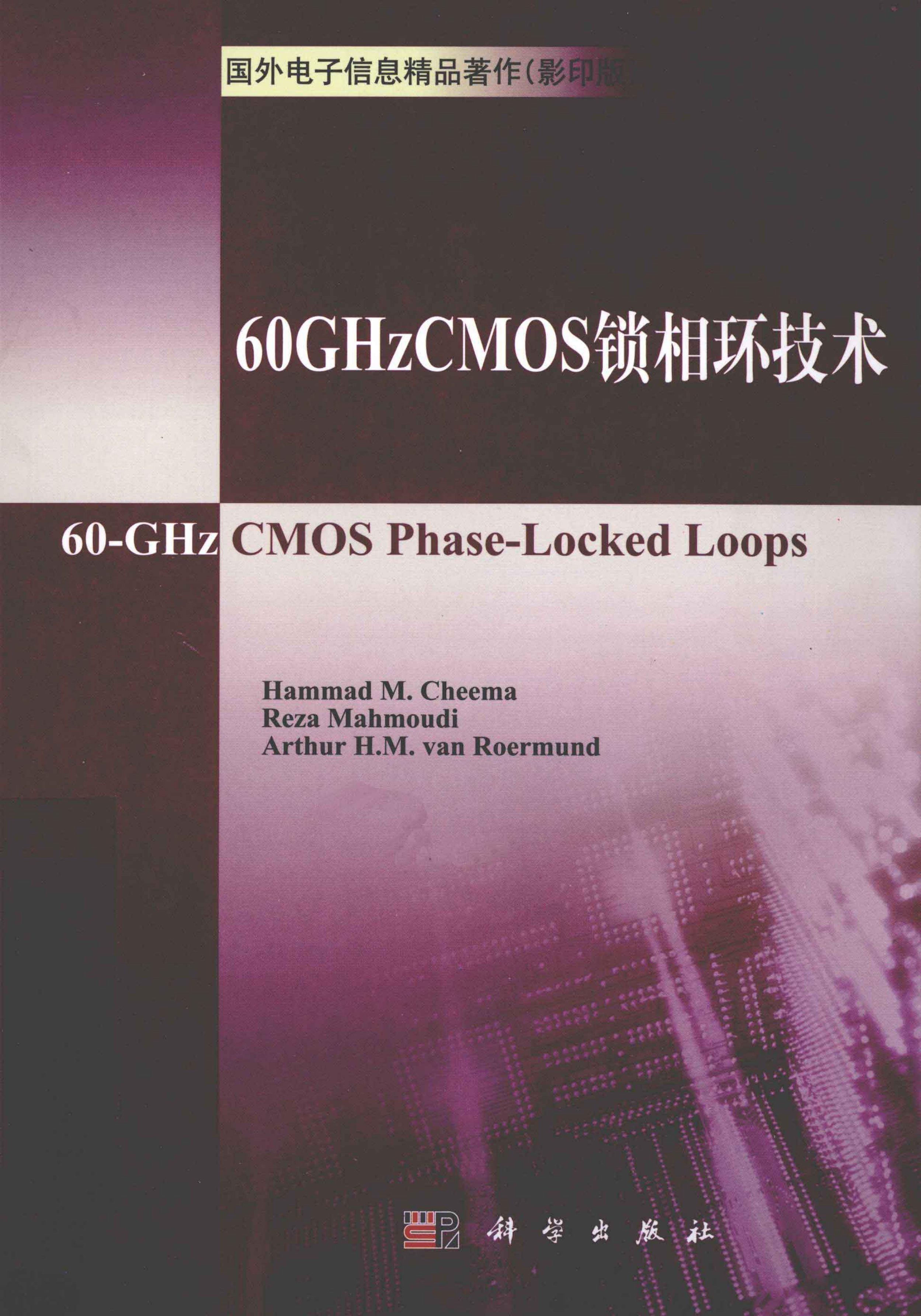

国外电子信息精品著作(影印版

60GHzCMOS锁相环技术

60-GHz CMOS Phase-Locked Loops

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北 京

图字：01-2012-3436

内容简介

近年来，毫米波尤其是60GHz频率段的高数据无线传输应用已经备受关注。而在毫米波CMOS电路设计时布线和测量所面临的问题需要科研人员认真解决。本书重点阐述了60GHz无线收发器技术面临的技术挑战，并提出了解决方案。

Reprint from English language edition:
60-GHz CMOS Phase-Locked Loops
by Hammad M. Cheema, Reza Mahmoudi and Arthur H. M. van Roermund

图书在版编目（CIP）数据

60GHzCMOS锁相环技术＝60-GHz CMOS Phase-Locked Loops：英文/（德）齐玛（Cheema，H. M.）等编著．—影印版．—北京：科学出版社，2012.6
（国外电子信息精品著作）
ISBN 978-7-03-034476-2
Ⅰ.①6…　Ⅱ.①齐…　Ⅲ.①CMOS电路－锁相环－电路设计－英文
Ⅳ. TN432
中国版本图书馆CIP数据核字（2012）第108172号

责任编辑：孙伯元／责任印制：张　倩／封面设计：陈　敬

科学出版社 出版
北京东黄城根北街16号
邮政编码：100717
http://www.sciencep.com
源海印刷有限责任公司印刷
科学出版社发行　各地新华书店经销
*
2012年6月第　一　版　开本：B5（720×1000）
2012年6月第一次印刷　印张：13
字数：276 000
定价：50.00元
（如有印装质量问题，我社负责调换）

《国外电子信息精品著作》序

20世纪90年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近30本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是2005年后出版的，力求" 层次高、内容新、参考性强"。在内容和形式上都体现

了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王越

中国科学院院士
中国工程院院士
2006年12月

Acronyms

AMOS	Accumulation metal oxide semiconductor
CMOS	Complementary metal oxide semiconductor
CP	Charge pump
DCM	Distributed capacitance model
DM-FD	Dual modulus frequency divider
DSP	Digital signal processing
DUT	Device under test
DVCO	Distributed voltage controlled oscillator
EMF	Electromotive force
FCC	Federal Communication Commission
FF	Flip-flop
FOM	Figure of merit
FSR	Frequency of self resonance
FTR	Frequency tuning range
GaAs	Galium arsenide
HBT	Heterojunction bipolar transistor
HDMI	High definition multimedia interface
HDTV	High definition television
IC	Integrated circuit
IF	Intermediate frequency
ILFD	Injection locked frequency divider
ISF	Impulse sensitivity function
ISS	Impedance standard substrates
LPF	Low pass filter
LO	Local oscillator
MC	Modulus control
MCML	MOS current mode logic
MIM	Metal–insulator–metal
PFD	Phase frequency detector
PDA	Personal digital assistant

PLL	Phase-locked loop
PM	Phase margin
PMP	Portable media player
PN	Phase noise
Q	Quality factor
RF	Radio frequency
RFD	Regenerative frequency divider
RFIC	Radio frequency integrated circuits
SA	Spectrum analyzer
SCL	Source coupled logic
SFD	Static frequency divider
SG	Signal generator
SiGe	Silicon germanium
SoA	Silicon on anything
SOI	Silicon on insulator
TSPC	True single phase clocking
TWD	Travelling wave divider
UWB	Ultra wide-band
VCO	Voltage controlled oscillator
VNA	Vector network analyzer
WLAN	Wireless local area networks
WPAN	Wireless personal area networks

Contents

Chapter 1
Introduction

Abstract This chapter lays the foundation for the work presented in latter chapters. The potential of 60 GHz frequency bands for high data rate wireless transfer is discussed and promising applications are enlisted. Furthermore, the challenges related to 60 GHz IC design are presented and the chapter concludes with an outline of the book.

Keywords Wireless communication · 60 GHz · Millimeter wave integrated circuit design · Phase-locked loop · CMOS

Communication technology has revolutionized our way of living over the last century. Since Marconi's transatlantic wireless experiment in 1901, there has been tremendous growth in wireless communication evolving from spark-gap telegraphy to today's mobile phones equipped with Internet access and multimedia capabilities. The omnipresence of wireless communication can be observed in widespread use of cellular telephony, short-range communication through wireless local area networks and personal area networks, wireless sensors and many others.

The frequency spectrum from 1 to 6 GHz accommodates the vast majority of current wireless standards and applications. Coupled with the availability of low cost radio frequency (RF) components and mature integrated circuit (IC) technologies, rapid expansion and implementation of these systems is witnessed. The downside of this expansion is the resulting scarcity of available bandwidth and allowable transmit powers. In addition, stringent limitations on spectrum and energy emissions have been enforced by regulatory bodies to avoid interference between different wireless systems.

At the same time, driven by customer demands, the last 2 decades have also experienced unprecedented progress in wireless portable devices capable of supporting multi-standard applications. The allure of "being connected" at anytime anywhere and desire for untethered access to information and entertainment "on the go" has set the ever increasing demand for higher data rates. As shown in Fig. 1.1, contemporary systems are capable of supporting light or moderate levels of

H.M. Cheema et al., *60-GHz CMOS Phase-Locked Loops*,
DOI 10.1007/978-90-481-9280-9_1,

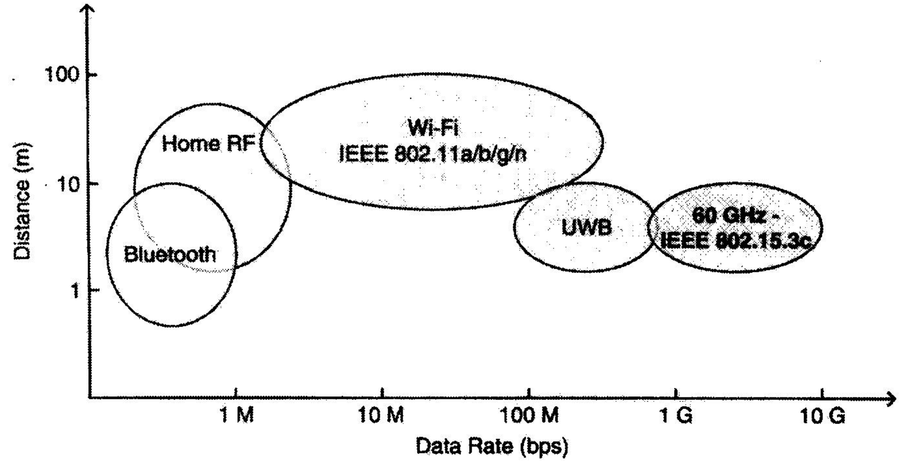

Fig. 1.1 Data rate and distance comparison for different WPAN and WLAN technologies

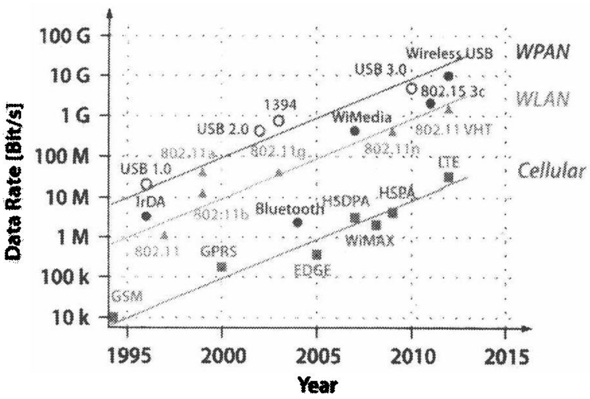

Fig. 1.2 Increasing data rate trend according to Edholm's law [2]

wireless data traffic, as in Bluetooth and wireless local area networks (WLANs). However, they are unable to deliver data rates comparable to wired standards like gigabit Ethernet and high-definition multimedia interface (HDMI) [1]. Furthermore, as predicted by Edholm's law [2], the required data rates (and associated bandwidths) have doubled every 18 months over the last decade. This trend is shown in Fig. 1.2 for cellular, wireless local area networks and wireless personal area networks for last 15 years.

The current standards and applications operating between 1 and 6 GHz have their market for long distance communication; however, in order to address the spectrum congestion and data rate issues mentioned above, new solutions have to be explored. As stated by Shannon [3], the maximum available capacity of a communication system increases linearly with channel bandwidth and logarithmically with the signal-to-noise ratio. Therefore, the obvious choice is to look upwards in the frequency spectrum where more bandwidth could be available.

An intermediate solution offered was the introduction of ultra-wide band (UWB) in 2002 by the Federal Communications Commission (FCC). It offers the frequency spectrum from 3.1 to 10.6 GHz and a minimum required bandwidth of 500 MHz for its applications. Although UWB partially solves the bandwidth issue and can potentially support high data rates, there are some limitations hindering its popularity. Firstly, international coordination is difficult to achieve among major countries and IEEE standards are not accepted worldwide. Secondly, as UWB is an overlay system over the existing 2.4 and 5 GHz unlicensed bands used for already deployed WLANs, the inter-system interference is a major concern. In order to safeguard the existing wireless systems in different regions, local regulatory bodies have defined their own requirements for UWB making world-wide harmonization of UWB almost impossible. Furthermore, to avoid interference, the allowed transmit power is low giving rise to reliability concerns. Thirdly, current multi-band orthogonal frequency division multiplexing (MB-OFDM) based UWB systems can provide data rates uptil 480 Mbps which can only support compressed video. Uncompressed high-definition television (HDTV) can easily require 2 Gbps or more data rate, which although possible by enhancing MB-OFDM UWB, increases the complexity, cost and power consumption many folds. Lastly, variation of the received signal strength over the entire UWB spectrum poses sensitivity problems for the receiver [4, 5].

The above constraints of interference, transmit power and low data rate motivated the exploration of completely unoccupied frequency band in the millimeter wave (mm-wave) regime and 60 GHz appeared as one of the promising candidates for the purpose.

In 2001, spurred by the increasing demand of high data rate applications and limitations of current wireless technologies, a 7 GHz contiguous bandwidth was allocated world-wide by the FCC. There was an immediate interest, both in academia and industry, to investigate the opportunities and possibilities using this large chunk of bandwidth. The fact that this band was unlicensed further helped in triggering the research effort. The regional regulatory bodies allocated local frequency bands with slight shift and defined the maximum effective isotropic radiated power (EIRP). Table 1.1 lists these two parameters for different regions.

The maximum allowed EIRP at 60 GHz is much higher than other existing WLANs and WPANs. This is essential to overcome the higher space path loss (according to classic Friis formula) and oxygen absorption of 10–15 dB/km as shown in Fig. 1.3 [6]. These two loss mechanisms dictate the use of 60 GHz for short range multi-gigabit per second transmission. The attenuation also means that

Table 1.1 Regional spectrum allocation and emission power requirements

Region	Frequency band (GHz)	Max. EIRP (dBm)
Europe	59–66	57
Canada/USA	57–64	43
Korea	57–64	43
Japan	59–66	57
Australia	59.4–62.9	51.8

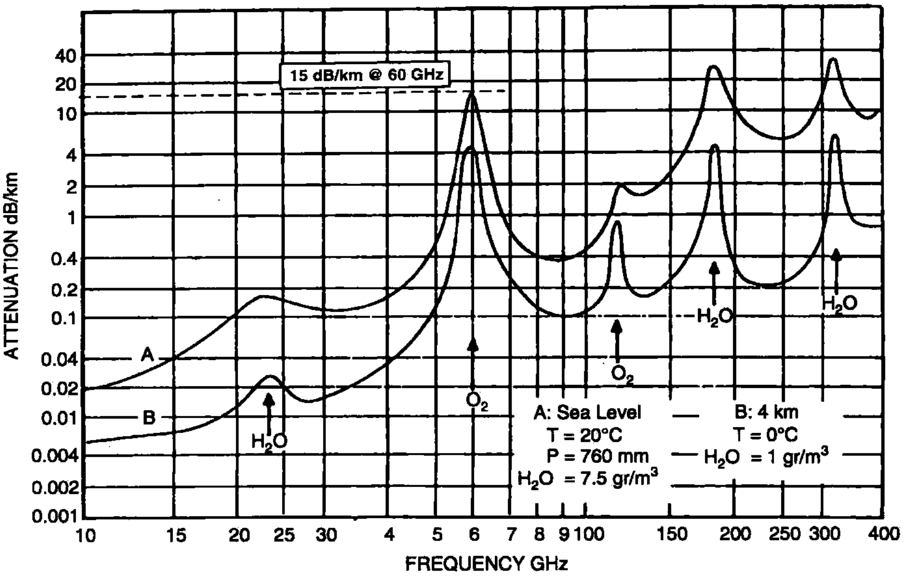

Fig. 1.3 Gaseous absorption at 60 GHz [6]

the system provides inherent security, as radiation from one particular 60 GHz radio link is quickly reduced to a level that does not interfere with other 60 GHz links operating in the same vicinity. Furthermore, this reduction enables the ability for more 60 GHz radio-enabled devices to successfully operate within one location.

Using the 60 GHz band for high data rate and indoor wireless transmission, a multitude of potential applications can be envisioned. The high definition multimedia interface (HDMI) cable could be replaced by a wireless system, transmitting uncompressed video streams from DVD players, set-top boxes, PC's to a TV or monitor. Current wireless HDMI products utilize the 2.5 and 5 GHz unlicensed spectrum where bandwidth is limited. As a result, these systems implement either lossy or lossless compression, significantly adding component and design cost, digital processing complexity and product size. Typical distance between these gadgets is 5–10 m and this communication can be point-to-point or point-to-multipoint. Depending on the resolution and pixels per line, the data rate required can vary from several hundred megabit per second (Mbps) to a few gigabit per second (Gbps). For instance, a typical high definition television (HDTV) offers a resolution of 1,920 × 1,080 with a refresh rate of 60 Hz. Assum-ing RGB video format with 8 b per channel per pixel, the required data rate is approximately 3 Gbps [1]. The future HDTV generation is expected to offer higher refresh rates as well as higher number of bits per channel scaling the required data rate beyond 5 Gbps. Therefore, transmitting HDTV transmission using 60 GHz remains an attractive test-case in the research field. Similarly, video and audio streams from personal digital assistant (PDA), portable media player (PMP) and laptops can also be transferred wirelessly to a display device.

In an office or home environment, 60 GHz radio links can essentially replace the clutter of cables of standards like USB, IEEE 1394, gigabit Ethernet and multimedia delivery. A PC can "talk" to all the external peripherals including printers, DVD writers, camcorders, digital cameras, external hard-disks and so forth. Wireless gigabit Ethernet and wireless ad hoc networks using 60 GHz are attractive applications for a conference room or library environment. A commercial application, particularly interesting for youth, is the so-called "Kiosk file downloading" in which users can download movies, games etc from a kiosk placed at locations like airports, railway-stations, market places and so on. These application examples are summarized in Fig. 1.4.

In addition to home and office, 60 GHz vehicular applications are also gaining much attention. They can be partitioned in three classes namely [4, 5]:

- Intra-vehicle wireless networks can be considered as a subset of WPANs that exist completely within a vehicle. The possibility of broadband communication within an automobile or aircraft by removing wired connections is desirable for manufacturers. The 60 GHz band is especially suited for intra-vehicle applications due to the containment within the vehicle and reduced ability to interfere with other vehicular networks.
- Inter-vehicle wireless networks are different from the intra-vehicle networks due to the outdoor propagation environment in the former. Applications like delivery of traffic information and range extension of mobile broadband networks are possible using inter-vehicle networks at 60 GHz.
- Vehicular radar, the last class of vehicular applications, has been deployed at millimeter-wave frequencies other than 60 GHz before; however, adaptive cruise control and automotive localization using the 60 GHz band have attracted interest in recent times.

Despite many advantages and attractive applications of short range gigabit per second wireless transmission at 60 GHz, a number of technical challenges related to design and performance need to be addressed. These can be broadly categorized into channel propagation issues, antenna technology, modulation schemes and integrated circuit technology and design.

In the last category, the choice of IC technology depends on the implementation aspects and system requirements. The former is related to the issues such as power consumption, efficiency, linearity and so on, while the latter is related to the transmission rate, cost and size, modulation etc. There are three competing IC technologies at mm-wave namely:

- Group III-V, such as Gallium Arsenide (GaAs) and Indium Phospide (InP). This technology offers fast, high gain and low noise circuits but suffers from poor integration and expensive implementation.
- Silicon germanium (SiGe) technology, such as heterojunction bipolar transistor (HBT) and BiCMOS are cheaper alternatives of GaAs and offer comparable performance.

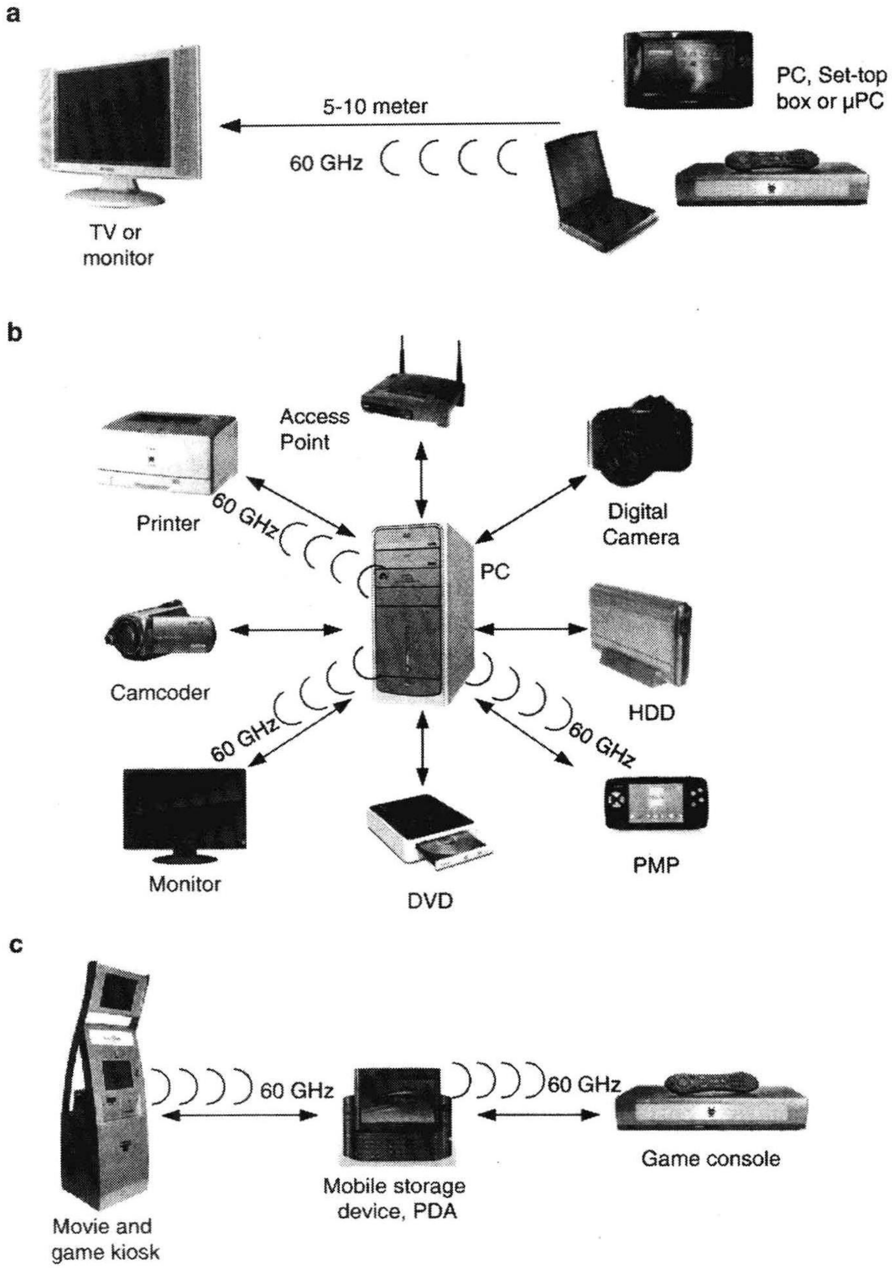

Fig. 1.4 Potential 60 GHz applications: point-to-point HDTV transmission (**a**), communication between a PC and different peripherals (**b**) and kiosk file downloading (**c**)

- Silicon technology, such as CMOS and BiCMOS. As size and cost are key factors for mass market production and deployment, CMOS technology appears to be the leading candidate as it offers high level of integration and is economical as compared to other alternatives. The downside of using CMOS is performance degradation due to low gain, linearity constraints, poor noise, low transition frequency (f_T) etc. However, the recent advances in CMOS technology, like silicon-on-insulator (SOI) and silicon-on-anything (SOA), coupled with continuous down-scaling to sub-nanometer technologies is facilitating the implementation of integrated circuits at 60 GHz. Furthermore, high speed digital signal processing (DSP) capabilities required for processing gigabit per second data is also possible using CMOS.

In order to circumvent the abovementioned performance limitations of CMOS, especially for phase-locked loops (PLLs), number of transceiver architectures have been proposed [7–18]. These methods generally aim to reduce the working frequency of the PLLs so that up-conversion or down-conversion of the signals is carried out at a lower frequency or in two steps. Furthermore, depending on the envisioned applications, one architecture might be preferred over another.

At circuit level design, the challenges are multi-fold. Low frequency circuits are not easily scalable to 60 GHz as the foundry transistor models are usually not characterized uptil this frequency. The parasitic elements of transistors also contribute to reduced high frequency performance. Consequently, considerable design margins have to be maintained resulting in power and silicon area penalty. Furthermore, few initial dry-runs are required to characterize the devices resulting in increased design times. Similarly, passives such as inductors and transformers etc., though become affordable in terms of silicon footprint, pose modeling related uncertainties and require meticulous electromagnetic (EM)-simulations. The quality factor (Q-factor) of varactors, which are invariably employed for capacitive tuning in voltage controlled oscillators (VCOs), frequency dividers etc, becomes very low. Low-ohmic substrate is also a hindrance in high-Q passive design. The technology scaling to sub-nanometer technologies reduces the supply and breakdown voltages, whereas the threshold voltage of transistors does not scale with the same order, resulting in a limited choice of reliable circuit topologies.

At layout level, as the wavelength of on-chip signals approach circuit dimensions, the interconnect between components becomes crucial part of design. These interconnects have to be simulated in EM solvers to incorporate the affect on circuit performance. Depending on the type of interconnect, this step is generally time consuming especially if multiple metal layers and vias are included. Furthermore, due to close proximity of components the overall layout also needs to be simulated for unwanted coupling and losses. Layout parasitics are also a major contributor for frequency shift and performance degradation and demand careful RLC extraction. Asymmetric layout of the RF paths at 60 GHz is a potential issue especially in circuits requiring phase accuracy. The typical layout approach of "smaller the better" at 60 GHz is sometimes contradictory to the symmetry requirement and some compromise has to be adopted.

The measurement of 60 GHz and millimeter wave circuits, pose a different set of challenges. Dedicated measurement equipment, components and setup is required for high frequency measurements. In some cases, when direct measurement of a parameter is not possible, in-direct methods are employed which are source of measurement errors. In order to shift the measurement plane to the device-under-test (DUT), accurate calibration and de-embedding is required. The losses and mismatch associated with cables, connectors, adapters have to be carefully accounted for. The stability and repeatability of accurate measurements is also an important challenge in high frequency measurements.

The challenges at 60 GHz related to circuit, layout, measurement and technology, mentioned in the preceding discussion, assist to select the set of problems which will be tackled in this book.

Firstly, due to the application dependence, there is no preferred transceiver architecture for 60 GHz. Thus, several different architectures can be expected in future. In order to cater for more than one application, a flexible synthesizer architecture will therefore be required. Moreover, such a multipurpose synthesizer will be expected to reuse some of its components to reduce design overhead. Secondly, a lack of design paradigm for 60 GHz is witnessed where the layout intricacies and measurement issues are understudied and lastly, the profound impact of parasitics necessitates the need of modification in the design flow of mm-wave integrated circuits. Adopting a top-down approach, this book addresses the above three problems by:

- System level analysis, design and realization of a flexible phase-locked loop suitable for a number of frequency up/down-conversion choices in a 60 GHz transceiver.
- Identifying the critical components of the synthesizer and characterizing them individually before complete system integration.
- Characterizing of passives, such as inductors, transformers and transmission lines that are extensively utilized in 60 GHz IC design.
- Revisiting the mm-wave IC design flow and incorporating the impact of parasitics (from circuit as well as layout) at an advanced stage of the design cycle.
- Identifying measurement issues for mm-wave circuits and providing possible solutions.

The structure of this book is illustrated in Fig. 1.5. In Chapter 2, after a brief overview of IEEE standardization for 60 GHz band and frequency conversion choices, a flexible PLL architecture is proposed. Based on theoretical analyses and system simulations of this architecture, target specifications are laid down for the PLL.

Chapter 3 discusses the layout and measurement techniques widely employed throughout this work. The circuit design of PLL components is divided in two chapters. The high frequency components, namely prescaler and voltage control oscillator (VCO) are discussed in Chapter 4. A variety of prescaler architectures are compared and two types are designed and measured. A number of VCOs are designed and measured with attention on improvement of tank quality factor,