60GHz Radios: Enabling Next-Generation Wireless Applications

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***Abstract*—Up to 7 GHz of continuous bandwidth centred around 60 GHz has been allocated worldwide for license free wireless communications. Highly attenuated due to oxygen absorption and small in wavelength, this band is ideal for extremely high data rate wireless data applications. These include numerous WPAN/WLAN applications such as home multimedia streaming. Traditional RF circuits used in this band are based on expensive compound semiconductor technologies. However for viable consumer applications, alternatives must be found. SiGe and CMOS based circuits are showing promise for enabling this technology at a price within reach of the consumer. This paper summarises a joint project aimed at developing high rate consumer level mm-wave wireless data systems. In particular, results to date in our RF design efforts are summarised.**

***Index Terms*—60 GHz, Millimeter-wave bipolar integrated circuits, Millimeter-wave integrated circuits, Millimeter-wave radio communication, MMIC transmitters, MMICs, SiGe, V-band.**

I. Introduction

Up to 7 GHz of bandwidth centred about 60 GHz is available for license-free wireless communication worldwide. It allows for an unprecedented capacity of information transfer as Table I shows [1][2].

Current products operating in this band utilise compound semiconductor technology such as GaAs and InP, resulting in large, power-hungry and expensive solutions. Such devices are acceptable for traditional uses such as broadband link radios where the cost per unit can be quite high. However, for the growing number of consumer applications targeted at this band such as Gigabit Wireless Local Area Networks (WLAN) and Personal Area Networks (WPAN), a much cheaper solution must be found.

To address this problem, Macquarie University, the University of South Australia and the University of Adelaide have joined NHEW R&D Pty Ltd (an early-stage technology company) in an ARC Linkage Grant that aims at building a prototype 1Gbps system at 60 GHz based on consumer level price expectations. The project is supported by Jazz Semiconductor, Cadence Design Systems, Peregrine Semiconductor and Intel Corporation.

TABLE I
INFORMATION TRANSFER CAPACITY

	802.11b	Bluetooth	802.11a	UWB	60 GHz
Cell Radius (m)	100	10	50	10	10
Information rate per channel (Mbps)	11	1	54	50	500
Number of channels	3	10	12	6	10
Capacity (Mbps/m^2)	0.001	0.03	0.1	1	16

II. Channel Characteristics

The 60GHz band has a number of interesting characteristics that enable unprecedented rates of wireless information transfer. The most prominent characteristic of the 60GHz band is that signals are highly absorbed by oxygen, with a peak value of 15 dB/km. The 60GHz band is also attenuated by precipitation. For example, in Europe where the maximum rain rate expected is about 50 mm/h [3], an additional specific attenuation of about 17 dB/km [4] is incurred in any link budget.

The severity of oxygen attenuation restricts link distances to a couple of kilometres. This fact, coupled with an inherently narrow beamwidth due to the high gain antennas used at

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TABLE II
ATTENUATION DUE TO HOUSEHOLD/OFFICE ITEMS (dB) [5]

	Thickness (cm)	60 GHz	2.5 GHz
Drywall	2.5	6.0	5.4
Office Whiteboard	1.9	9.6	0.5
Clear Glass	0.3	3.6	6.4
Mesh Glass	0.3	10.2	7.7
Clutter	-	1.2	2.5

this short wavelength (5 mm) makes the 60GHz band ideal for dense arrays of point-to-point links within a metropolitan environment.

The general indoor environment also affects 60 GHz propagation differently than it does devices using other bands. Table II above from [5] shows the average measured loss due to general household and office items that a 60GHz signal would encounter. Measurements at 2.5 GHz are also shown for comparison with current wireless standards such as 802.11b/g.

Due to the ray-like characteristics of 60GHz transmission, the signal is less susceptible to clutter than a 2.5GHz signal [5]. However, the diffraction effects with millimetre waves are only small, so any antenna misdirection or large obstacles will result in large losses at 60 GHz. Similarly, wall studs in the signal path can significantly attenuate signals at 60 GHz; e.g. in [6] the increase in loss was found to be over 27 dB. The significant loss encountered at walls, especially wall studs, effectively reduces a cell to the size of a room. This not only allows spectral re-use within buildings but also limits interference from neighbouring cells.

High oxygen absorption and narrow beamwidth result in signals in this band being inherently more secure than any in existing consumer wireless bands. Short transmission distances prevent signals travelling much further than their intended target, while narrow beamwidth means that any form of eavesdropping device would be required to be placed in the signal path, thus greatly increasing the rate of detection. Indoors, attenuation due to the surrounding walls effectively limits signals to the room intended. Using the 60GHz band, will greatly restrict access to corporate and home wireless networks outside their intended locations.

The high attenuation due to room partitions effectively limits multipath components to reflections inside the originating room [7]. This results in very low RMS delay spreads leading to the potential for extremely high data rates [5].

III. APPLICATIONS

Because of the unprecedented amount of contiguous bandwidth on offer and the special properties of the 60 GHz band, many applications are targeted for this band. Three of the most exciting applications are Gigabit WLAN, WPAN and unlicensed point-to-point links.

Current flavours of WLAN, i.e. 802.11a/b/g, are limited by small allocations of spectrum. The 60GHz band on the other hand has plenty of bandwidth for applications such as the streaming of multimedia. An obvious application is streaming video from a video source (usually at floor level) to a projector (at the rear and at ceiling level) in a home theatre situation. Routing the required cabling for multiple audio, video and control signals (e.g. DVI, component video, composite video, VGA and control) can frequently form a major part of the installation cost of a home theatre system. Such cabling would be obsolete when using 60GHz for this application.

WPAN's standard IEEE 802.15.3, commonly known as Bluetooth, is currently used to provide quick and easy low-data rate (1Mbps) connectivity for mobile devices such as mobile phones, headsets and handheld computing devices. A 60GHz solution would enable streaming of high-definition video to multiple devices simultaneously, enabling the most imaginative of home and personal multimedia applications.

Point-to-point links are also able to take advantage of the high spectral reuse due to the narrow beamwidth and short transmission distances. Wireless links of this type are currently used to bridge connections between office blocks in metropolitan environments augmenting or replacing the need to lay optical fibre. In providing low-cost solutions, this application area can be greatly expanded.

In a point-to-multi-point environment, 60GHz links could be used as a fixed last-kilometre solution for residential and commercial broadband. Similarly, such point-to-multi-point solutions could be used in disaster recovery, offering easy and immediate semi-permanent infrastructure to aid in the immediate coordination of support efforts.

IV. STANDARDISATION

There is currently one standard addressing the 60GHz band, the IEEE 802.16-2004 WirelessMAN-SC® Standard for Wireless Metropolitan Area Networks [8]; this standard addresses spectrum from 10 GHz to 66 GHz.

A task group addressing this band, the IEEE 802.15.3 Task Group 3c was formed in March 2005. This task group is developing a millimetre-wave based alternative physical layer for the existing 802.15.3 WPAN Standard - 802.15.3-2003.

V. SYSTEM DESIGN

This section provides an overview of some assumptions in relation to low-cost 60GHz systems. It should be emphasized that mm-wave high data rate systems abound in the commercial arena and have for many years. The innovation in this project is to provide these systems at a price point that is 100 times lower than present.

A. Constraints

The normal constraints of low cost, low power and high bandwidth are required for this application. A target unit power dissipation of under 250 mW for the complete system and under 200 mW for the analog section has been set (for a 0 dBm transmitter power level). A target cost for a single 1Gbps link has been set at $22.

B. Link Budget

For a system with 0dBm transmit (Tx) power, 3dBi receive (Rx) and transmit antennas, 10dB receive noise figure and 1GHz signal bandwidth, the range is predicted to be around 2.5 metres. Increasing the power to 10 dBm increases the range to around 5 m. Adding a 40dBi parabolic dish antenna to the receiver and transmitter extends this range to around 1.5 km. Reverting to 0 dBm of transmit power but using a 4×4 array of transceivers with 3dBi omni-directional antennas results in a range of around 10 m.

C. One Size Fits All

Based on the link budgets presented above, the notion of a "unit" mm-wave transceiver has been proposed. This comprises a single-chip 60GHz transceiver with 0-10 dBm transmit power, 3dBi omni Tx/Rx antennas and 10dB NF. This provides a single 1Gbps link.

Using the unit alone allows a WPAN style system. Placing this unit at the feed point of a 40dBi dish (~ 35cm diameter) yields a link radio. Arraying four by four units allows a beam steering system with a range of approximately 10 m.

To achieve this diversity of use, we require a stackable radio, capable of being phase locked while dissipating very low power, especially in the array case.

D. Modulation

In the WPAN application, the environment is subject to extreme multi-path interference. Therefore, a multi-path resistant modulation such as FDM (Frequency Division Multiplexed), UWB (Ultra Wide Band) or CDMA (Code Division Multiple Access) is required.

E. Packaging

One of the problems inherent with 60GHz chips is transitioning the signals on and off chip. Conventional bonding presents high stray inductance and capacitive loads that attenuate the mm-wave signal.

Our current approach to this is to use a two-chip sandwich. The substrate die is a Silicon-on-Sapphire die with integrated patch antennas (fabricated by Peregrine Semiconductor). The SiGe die (fabricated by Jazz Semiconductor) with the active circuitry, is attached to the substrate die via low inductance solder bumps.

VI. Radio Design

In the project to date we have made most progress in the design of SiGe Radio Frequency (RF) circuits, so in this paper we will concentrate on presenting those results in the context of the over-riding constraints that we have previously summarised.

Figure 1 shows the proposed receiver architecture that we have adopted. It is a "low-IF" or "moving IF" radio. This is similar to some of the radio architectures used at 2.4 and 5 GHz for WLANs. The transmitter is similar in architecture. In the Rx the incoming RF at 60 GHz is mixed with a 48GHz local oscillator (LO). This produces a 12GHz IF signal, which is passed through a variable-gain amplifier and then to an IQ mixer. This mixer uses a 12GHz quadrature signal derived from the first LO. A 0.5-1GHz low-pass filter follows the IQ mixer and a variable-gain baseband amplifier provides enough gain to drive dual analog-to-digital converters.

The next section summarises the approaches to design at mm-wave frequencies.

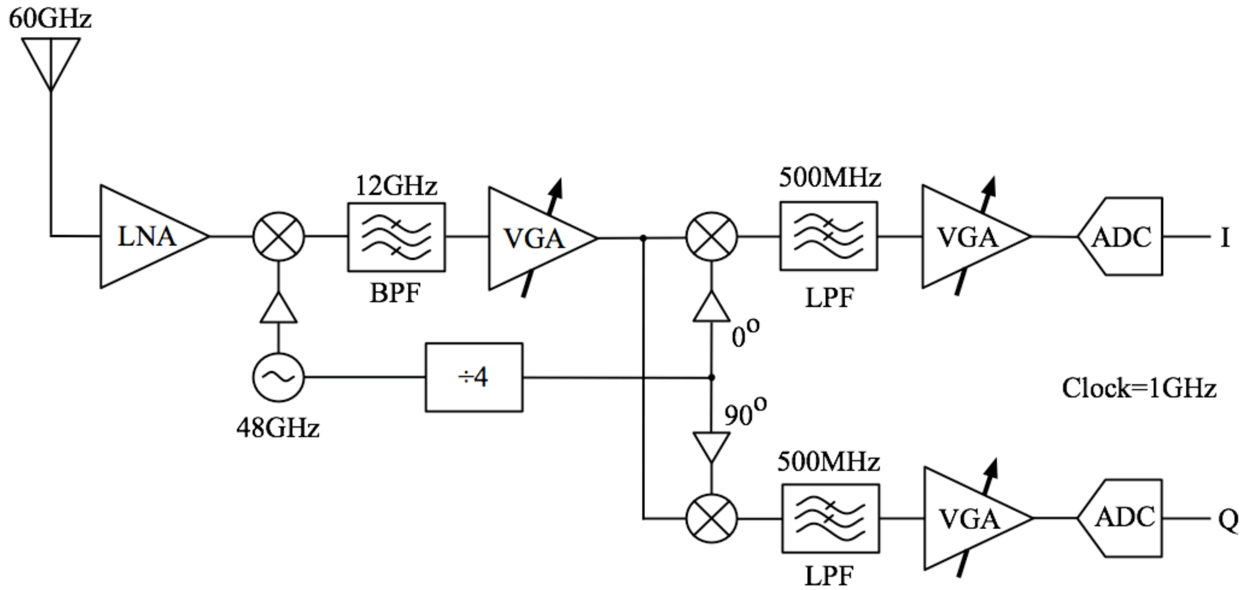

Fig. 1: Moving IF 60GHz Receiver

VII. 60 GHz Circuit Design

A. Active Devices

Traditionally, expensive compound semiconductor technologies such as GaAs and InP have been used to build circuits operating at 60 GHz. This was due to the inability of silicon-based technologies to achieve the required performance; e.g. [9]-[11]. However, recent silicon based technologies have shown an ability to perform at these high frequencies. Both CMOS [12] and SiGe [13]-[16] now have adequate performance at millimetre wave frequencies and additionally offer the ability for an entire system-on-chip (SOC) to be manufactured. This not only reduces size, power consumption and interconnect parasitics, but, most importantly for the many consumer applications slated for the 60GHz band, it can achieve aggressive price points.

Recent SiGe technology has overcome the reliability and manufacturability issues that plagued it for many years by using a conservatively graded Germanium profile in the base [17]. With the ability to simultaneously achieve f_T and f_{max} in excess of 250 GHz [18], high-gain and low noise figures, this technology is ideal for next-generation wireless applications. Other benefits including a thermal conductivity three times higher than that of GaAs and high voltage immunity, make SiGe an ideal process to design power amplifiers on [19].

Due to recent device scaling, CMOS has also reached the point where 60 GHz circuits can be achieved. Circuits for 60 GHz operation have been reported [12], however the performance at this stage cannot match that of the SiGe-based circuits [15].

Silicon-on-Insulator (SOI) with f_T and f_{max} of up to 208 GHz and 243 GHz respectively [20] is another technology possibility for 60 GHz radio design. Due to the insulating substrate, high-Q passives are realisable, making it very attractive for both matching networks and antennas.

B. Passives

Circuit design at 60 GHz requires the use of inductors and capacitors as well as transmission lines. One quarter wavelength at 60 GHz is approximately 650 μm on-chip. Circuits operating at 60 GHz have been demonstrated using both inductors and transmission lines [14], [12], [21] and [15] with Q of around 20 being achieved [22].

Inductors used for matching at 60 GHz are generally quite small. This poses a problem, because combined with process spread, they are hard to realise on-chip with a satisfactory repeatability. Transmission lines on the other hand offer structures that are much more resilient to process variations. Transmission lines also offer a variety of different configurations for circuit design such as inductive and capacitive stubs and inductors.

Another benefit of using transmission lines is that the parasitic resistances, inductances and capacitances are inherent in the distributed transmission line model, rather than being parasitics that would otherwise require compensation. Also relevant is the reduction of coupling to nearby structures due to a well-defined return path provided by the ground plane. Of course, this is well known from the GaAs/InP design approaches, but departs from the traditional lumped element CMOS design techniques used at 5 GHz and below.

Transmission lines used at this frequency are generally in either microstrip or coplanar configurations. Microstrip lines are generally realised by implementing a ground-plane in the bottom layer metal with the signal line in top layer metal. The characteristic impedance achieved by this structure depends on the width of the signal line and its height above the ground plane ($\propto h/w$). Common CMOS processes have only around 4 μm between the ground plane and signal line, thus severely limiting the characteristic impedance to around 65 Ω [15]. High impedance lines are desired for short-circuit inductive stubs as they have a higher inductive quality factor and therefore a higher Q [12]. These lines will also be shorter in length, resulting in less chip area being used.

Coplanar lines are generally implemented in the top layer metal and can offer higher characteristic impedances when process limitations impact the realisation of high impedance microstrip lines. In such cases the width of the signal line is selected to minimise loss while the distance of the ground plane away from the signal line is used to set the characteristic impedance.

VIII. Design Results

Using the basic architecture in Fig.1, a number of the key circuits have been designed and are summarised below. It is planned to fabricate these circuits later in 2005 and these results should be viewed as very preliminary but representative of what can be achieved in a state-of-the-art SiGe technology. A supply voltage of 1.8 volts is assumed.

A. Low Noise Amplifier (LNA)

A cascade of three cascode amplifiers was chosen for the LNA. Each stage is matched on input and output using transmission lines. The simulated performance is given in Table III (at 60 GHz).

Table III
Simulated LNA Performance

Gain	33 dB
Input IP3	-29 dBm
Power Dissipation	36 mW
Noise Figure	7.3 dB

B. Local Oscillator

A number of oscillators have been trialled. These include Colpitts oscillators [23] [24] and cross-coupled bipolar and CMOS designs at 48 GHz [25] [26]. The Colpitts oscillator, while showing reasonable phase noise performance, has poor output voltage swing and inadequate tuning range. The MOS cross-coupled oscillator provides the best phase noise (approaching –100 dBc/Hz @ 1 MHz offset) while the bipolar

TABLE IV
SIMULATED OSCILLATOR PERFORMANCE

Phase Noise	80 to –99 dBc/Hz @ 1 MHz offset (these figures are from simulations and must be viewed with conservatism)
Power Dissipation (LO alone)	5-15 mW

cross-coupled circuit is the only circuit capable of achieving the necessary tuning range 45-52 GHz with some margin. Simulated performance is shown in Table IV.

A regenerative divider has been designed to do the first division from 48 to 24GHz. Conventional digital dividers may be used after this stage to convert from 24 to 12 GHz.

C. Mixer

A Gilbert mixer is used for the down-conversion. It has the simulated performance shown in Table V.

TABLE V
SIMULATED PERFORMANCE OF A MIXER

Conversion gain	11 dB
Input IP3	-8 dBm
Noise Figure	16 dB
Power Dissipation	30 mW

D. Intermediate-Frequency (IF) Amplifier

The initial design for the 12GHz IF amplifier is a cascade of three resistively loaded, capacitively coupled, differential pairs which are each buffered by emitter followers. The simulated results are shown in Table VI.

TABLE VI
SIMULATED IF AMPLIFIER PERFORMANCE

Gain (at 12GHz)	27 dB
Power Dissipation	4 mW

E. Tx Power Amplifier (PA)

The power amplifier is comprised of a cascode stage followed by a common-emitter stage. Current simulation results are shown in Table VII.

TABLE VII
SIMULATED POWER AMPLIFIER PERFORMANCE

Gain	14 dB
P1dB	12.4 dBm
Power Dissipation	270 mW

The power can be considerably reduced for a transmitter at the 0dBm level. These results are included to show that the power amplifier can reach the 10 dBm level.

F. Rx Summary

For a 60GHz receiver, the total power dissipation can be estimated as shown in Table VIII.

TABLE VII
SUMMARY OF RECEIVE CHAIN POWER CONSUMPTION

LNA	36 mW
First Mixer	30 mW
First LO and Buffer	25 mW
PLL (est.)	30 mW
12GHz IF amplifier	4 mW
Baseband Amplifier (est.)	1 mW
ADCs (5 bits @ 1GHz est.)	60 mW
Total	186 mW

This indicates that at this early stage results are within the range of target power dissipation. Further tuning of the design and results of fabrication should improve the overall design. In addition, we are aiming for the die size of the receiver presented in Figure 1 to be approximately 9 mm^2. This would sit on a 25 mm^2 SOS die (1 mm on a side for radiating structures on the SOS die).

IX. CONCLUSION

An overview of the considerations for designing low-cost consumer devices for high-rate radio systems at 60GHz has been presented. In particular, it has been shown that, based on initial designs, single chip 60GHz radios can be implemented on SiGe technology with commensurate low power dissipations. With the complexity of the radio at a single chip level and accompanied by a single chip baseband section (or even a single system-on-chip), quite low costs can be predicted. Validation via fabrication remains, as does the detailed baseband modem design using the radio parameters that we can achieve monolithically.

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