Towards Integrated Transceivers in mm-Wave Applications

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Abstract — **In this paper, we discuss the trend towards higher frequencies in many consumer RF applications. This trend is, on the one hand, a consequence of an apparently endless demand for increased data rates and, on the other hand, being enabled by ongoing developments in IC technology and circuit design. After outlining some of the application trends that are defining the need for integrated transceivers operating in the mm-Wave region, the resulting technology and circuit challenges will be examined.**

I. Introduction

We live in a world in which wireless communication is virtually ubiquitous: a world in which the ever-increasing demand for bandwidth seems to be insatiable, and where this demand is pushing the RF frequencies at which consumer applications operate towards the mm-Wave region. This seemingly unstoppable trend is defining challenging requirements for both IC technologies and the associated circuit techniques that will be required to realise mm-Wave integrated transceivers for consumer applications. Of the possibilities currently under discussion, arguably the most well known is the use of spectrum near 60GHz for future wireless LAN and PAN applications. The possible worldwide availability of 3GHz of bandwidth for this purpose means that the prospect of multi-Gb/s RF transmission looks to be feasible. However, for such applications to be suitable for the consumer domain, low cost is a pre-requisite. This combination of low cost, high levels of integration and operation at mm-Wave frequencies will define what is required of technology and circuits operating in the 60GHz domain. This paper will highlight some of these requirements.

II. RF Consumer Applications

Ever since the emergence of AM radio (one of the very first examples of electronics in the home), the range of RF applications has steadily increased and, especially in recent years with development of the mobile telephone, the number of consumers using RF devices has exploded. Apart from the trend of increasing numbers of users, the other key trend is the increase of RF frequency over time [1], as shown in figure 1. The vast majority of RF applications currently in use operate at frequencies below 6GHz, and can be divided into three broad categories: broadcast systems, mobile phones, and wireless systems.

Although broadcast systems (radio and television) are the oldest consumer applications, innovation is still taking place in quite dramatic forms. Firstly, many of the systems have moved, or are moving, from analogue to digital modulation schemes: satellite TV was the first, followed by cable and, in the coming years, we will see a similar changeover in terrestrial TV. One advantage of the use of digital modulation schemes is that digital reception requires less signal-to-noise ratio (SNR) compared with its analogue counterpart. Secondly, most access schemes (terrestrial, cable and satellite) are moving towards bi-directional systems, which include a return path. Typically, these systems exploit the high bandwidth of broadcast systems for the downlink (6-8MHz for terrestrial and up to 40MHz for a satellite channel) and add a separate uplink channel.

Mobile telephony is *the* market that drives low power and miniaturisation of integrated transceivers. Initial systems, such as GSM, were defined to use the 900MHz band, but as the number of users rapidly increased, new bands at 1800MHz and 1900MHz were defined. There is also a clear desire to move to higher bandwidths, e.g. to support data transport for multimedia applications. 3G (UMTS and others) aims to be the solution for higher bandwidth, although there is much debate on whether this will provide sufficient bandwidth for future needs. Emerging standards such as 802.16x are set to challenge 3G as the route to higher mobile bandwidths. A key future trend will be the convergence of cellular and wireless applications.

Apart from mobile phones, the other main market for RF technology is wireless connectivity. Wireless Local Area Networking (WLAN) is the main application in this area, and has been driven from the PC market. These systems use un-licensed frequency bands and the dominant standards are IEEE 802.11b (11Mb/s) and

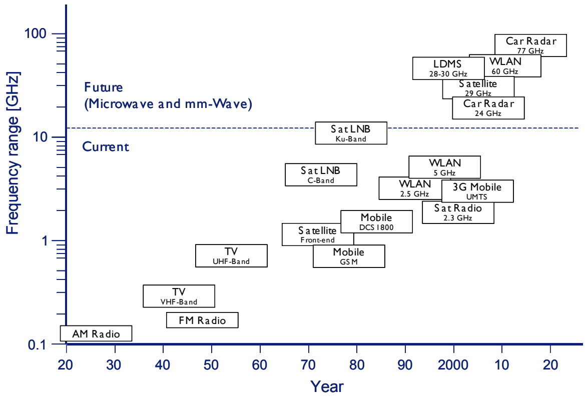

Fig. 1. Frequency trends in consumer RF applications

802.11g (22Mb/s) in the 2.4-25GHz band, and 802.11a (54Mb/s) in the 5.3-5.8GHz band. The use of un-licensed frequency bands means that a major consideration in the definition of the standard and design of the transceivers is handling of interference from other systems and users. As with all RF applications, there is a trend towards higher data rates: 17GHz was heralded as the next major frequency for next generation WLAN (but is fatally hampered by the lack of allocation in the USA), and much effort is directed towards the exploitation of MIMO techniques.

The other main component of wireless connectivity is Wireless Personal Area Networks (WPAN) – effectively a replacement for cables, typically operating over a 10m range. Bluetooth (2.4GHz, 700kb/s) is by far the most well-known standard, but other standards such as ZigBee (IEEE 802.15.4) are being developed for specific applications. Once again, we see a trend to higher data rates, and the current lead contender is Ultra Wideband (UWB). In contrast to other WLAN/WPAN systems, UWB transmits in a wide spectrum (several GHz), but at extremely low power density. In the USA, UWB transmissions are allowed between 3.1–10.6GHz. Expected data rates are in excess of 200Mb/s.

III. Towards Higher Frequencies

At this stage it should be clear that a major trend in RF consumer applications is that of ever increasing data rates. From the application perspective, this can be thought of as an inevitable consequence of Moore's Law: consumer devices are based on faster processors, growing amounts of storage and memory, higher resolution displays etc., and this, in turn, fuels the demand for high data rate connectivity between these devices both at home and on the move. From the wireless systems perspective, the question is – how can these higher data rates be supplied? Efforts to address this issue fall into two categories. Firstly, many systems are employing techniques to make more efficient use of the available spectrum – i.e. increasing bits/s/Hz. These include the use of advanced modulation schemes such as OFDM combined with QAM64. However, per today, there is a practical upper limit to the bandwidth efficiency of digital wireless transmission systems, which is around 2.5bits/s/Hz. This then leads us to the second alternative, which is to use more bandwidth, c.f. Shannon's Law in equation 1.

$$C = B\log_2\left(1+S/N\right) \tag{1}$$

Exploiting more bandwidth has the attractive property that the channel capacity rises in direct proportion with the bandwidth used. UWB does exactly this. However, with increasing levels of congestion at lower frequencies (e.g. < 6GHz) and future requirements for over air data rates of several Gb/s, there will be continued demand for additional bandwidth, and this can only be found at higher frequencies. This, then, is the driver that will take RF consumer applications from the microwave domain to the mm-Wave domain. Coupled to this, and of course a prerequisite for any new wireless system, is the allocation of frequency bands. In the mm-Wave region, several such bands are already allocated.

Of these, the 60GHz band is attracting most attention, primarily because, in the USA, the FCC has allocated 59-64GHz for unlicensed applications, and it is likely that 3GHz of this will be *globally* available for such applications. Both of these are essential conditions for promoting the future use of 60GHz for consumer applications. The characteristics of the 60GHz band are well known and have been reported previously. See, for example, [2].

The other pre-requisite for the take-up of 60GHz and other mm-Wave applications will be the availability of low-cost solutions. In order to achieve this, correct choices will have to be made in the areas of:

- Technology for the RF front-end;
- Transceiver implementation at the circuit level;
- System architecture.

Previous papers have discussed the issues concerned with the last of these points. For the remainder of this paper, we will concentrate on the first two points.

IV. Technology Choices

Until recently, the use of silicon technology for applications in the mm-Wave range was considered to be unfeasible. This is because of the comparatively low intrinsic speed of electrons in silicon, which is related to their effective mass and saturated drift velocity, was inferior to that of competing III-V technologies (GaAs and InP). Consequently, III-V technology was hitherto the default choice for mm-Wave applications.

The question is: can a silicon-based technology exhibit performance compatible with the demands of mm-Wave applications? In the following paragraphs, we examine aspects of this question, based on the use of two common figures-of-merit, f_T (the cutoff frequency) and f_{max} (maximum frequency of oscillation).

A. SiGe Technologies

Recent developments in bandgap engineering have produced SiGe HBTs with outstanding high-frequency performance, high current gains, large Early voltages and low-noise performance required for mm-Wave circuit design. The trend for SiGe HBTs and III-V devices is captured in fig.2, which shows increasing f_T as a function of reducing base thickness [3]. Although it is generally regarded as a useful intrinsic figure of merit, f_T can be somewhat misleading for mm-Wave applications because it ignores the small-signal power gain and the base intrinsic resistance r_B. The conventional expression employed for f_{max} is:

$$f_{\max} \cong \sqrt{\frac{f_T}{8\pi\, r_B\, C_{BC}}} \tag{2}$$

where C_{BC} represents the base-collector capacitance. This shows the importance of minimisation of r_B and C_{BC} to

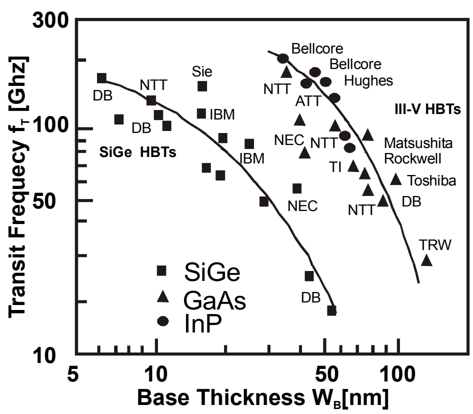

Fig. 2. The f_T trends for SiGe and III-V devices

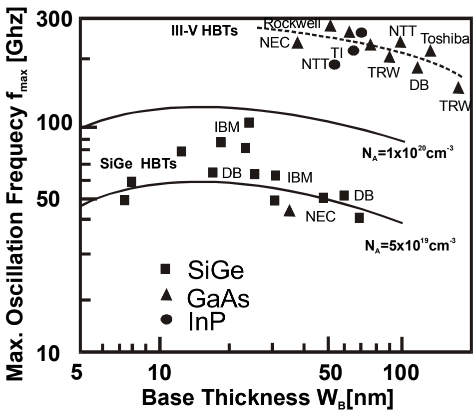

Fig. 3. The f_{max} trends for SiGe and III-V devices

allow a high f_{max}. A standard rule-of-thumb for μ-wave amplifiers is to design HBTs such that $f_{max}\approx 2f_T$. This implies that $f_T\approx[32\pi r_B C_{BC}]^{-1}$. The f_{max} trends shown in fig.3 are demonstrating again the increase of f_{max} in recent years. At large VCB or VCE, avalanche breakdown can occur. If a SiGe HBT is operated in the common-base mode, the breakdown BV_{CB0} occurs approximately when the peak electric field in the collector reaches E_B, the maximum electric field that can be supported by the collector material. A thick collector with low doping is required for a high breakdown voltage. The breakdown voltage BV_{CE0} in the common-emitter configuration when biased via a current source in the base is lower than BV_{CB0}. The Johnson figure of merit for breakdown is given by:

$$BV_{CE0} \times f_T \le \frac{E_B v_{sat}}{\pi} \quad (3)$$

The change of the collector thickness impacts the trade-off between BV and f_T: a thick, relatively lightly-doped collector increases the breakdown voltage at the expense of collector depletion transit time. This can degrade the f_T considerably, but the use of Ge in the base can recover some of the lost speed resulting in an increase in the Johnson limit. This dramatic increase in recent years has pushed the limit from 200GHzV to 600GHzV. In addition, the lightly doped collector minimises C_{BC}, further enhancing the f_{max} of the device. Although this trend will continue, we expect some hurdles in the near future. The insatiable need for speed will force technology houses to go below 2V breakdown, which implies that something has to be done at the circuit level. Two possible directions are: designing mm-Wave circuits at 1.8V (or even 1.2V), or finding topologies that can tolerate BV problems when large voltage swings are needed. Special topologies will be required for power amplifiers.

B. CMOS Technologies

Recent work in CMOS for RF applications [4] suggests that advanced CMOS processes will be able to deliver RF performance for use in the mm-Wave arena.

For a comparison between CMOS and SiGe, the most recently published results of production-ready technologies are presented in fig.4, which shows that CMOS is closely following SiGe HBT performance [4], [8]-[9]. The 90nm NMOS devices exhibit a record for MOS of 209GHz peak f_T and 248GHz peak f_{max}. The broadband noise performance shows 0.3dB Fmin at 2GHz and 0.6dB at 10GHz with maximum stable gains of about 16dB. Hurdles to be overcome by CMOS relate to the low device g_m per bias current, the large output capacitance present in the output bandwidth, and leakage currents which generate an extra noise component. As far as the trend to lower voltages is concerned, this is already present in CMOS, and the downscaling of the threshold voltages provides a possible solution for RF designs at or below 1.2V. Power generation and handling for power amplifiers will also be an issue.

Consequently, and also based on its lower cost structure, we believe that CMOS will gain its place in the mm-Wave applications provided a baseline process without extra process options is employed.

C. System in Package

Although not specifically covered in this review, an important technology development to mention is System-in-Package (SiP). One of the major challenges in the design of transceivers for mm-Wave applications will be RF signal handling: not only on-chip, but also where the antenna and RF passive components are concerned. SiP provides a potentially attractive solution, in that several dies and passives can be placed in single package using, for example, flip-chip techniques. In addition, the small size of an antenna (a few mm^2) at these frequencies, opens up the possibility of incorporating the antenna(s) into the package.

V. CIRCUIT DESIGN CHALLENGES

In the design of mm-Wave integrated transceivers, the main areas of concern are the low-noise amplifier (LNA), mixer, local oscillator (LO), dividers, frequency synthesizer and the RF power amplifier (PA).

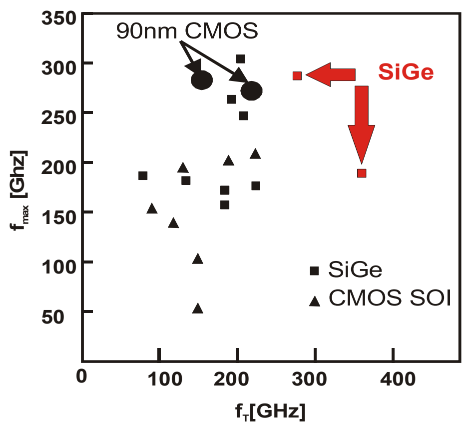

Fig. 4. The f_{max} trends for SiGe and III-V devices

Of these, the LNA and the PA are the critical building blocks. Appropriate architecture choices can ease the demands of the individual circuit blocks, and the use of a simple modulation format will simplify circuit design and reduce power consumption. A zero-IF architecture is a good choice for the reasons of large bandwidths required at the IF frequency and simplicity [5]. On the contrary, a low-IF architecture will pose extreme requirements for the A/D converters with deleterious consequences on power dissipation. Designing mm-Wave circuits at up to $f_T/4$ is possible, while progressing to $f_T/2$ is very challenging, but still feasible with new circuit topologies and exploitation of the combination of passive and active components. Given the rule-of-thumb, $f_{max}\approx 2f_T$, any process with an f_T above 120GHz and an f_{max} above 240GHz is a possible candidate for mm-Wave design at 60GHz.

In designs close to $f_T/2$, the low gain of the active elements is an issue, and the active elements will need to be coupled with passive matching networks. Such networks are realised with microwave components like transmission lines, stubs and capacitors. The size of the stubs and lines are in the order of ¼ of the wavelength λ, and at mm-Wave frequencies are suitable for on-chip integration. The slab inductor approach is possible by using coplanar wave-guides (CPW) and microstrip lines. The microstrip lines have low inductance and the ground plane shields the line from the substrate. Additionally, the CPW approach is less sensitive to process variations since the dimensions are determined by lithography and not by material thickness.

Finally, the design of a PA at mm-Wave frequencies will require particular attention. For example, in the 60GHz, FCC rules [6] permit 10W of equivalent isotropic radiated power. This means that 20dBm transmit power would be the maximum legal power limit with an antenna having 20dBi gain. Power combining is the major challenge of the PA design. The use of a distributed approach allows both power and efficiency control, while low-loss transmission lines enable the distributive active transformer (DAT) approach with 1:1 transformers. It should be noted that a choice of OFDM modulation formats will have consequences on the peak/average ratio of the PA and, in our view, should be avoided.

The design challenges in the frequency synthesizer are mostly related to the VCO and the frequency divider. Although 60GHz VCOs have been reported [7], the bottleneck is the design of the varactor or tuning element. Inductors have high quality factors at this frequency, but varactors with sufficient tuning range and high Q are difficult to manufacture. An alternative will need to be found. The prescaler is also on the critical path at mm-Wave frequencies but injection locking can, in principle provide a solution. An attractive alternative approach is the use of a lower frequency VCO and a frequency tripler [5]. Thereafter, a simple frequency divider can be employed.

To conclude, based on the above discussion, we believe that successful circuit design for mm-Wave integrated transceivers will require the development of improved circuit techniques that are the result of the innovative combination of both active and passive components.

VI. Conclusion

To us it is clear that, beyond microwave applications, mm-Wave applications will form the next major driver for the development of future integrated RF transceivers. This is the result of a combination of: (i) the insatiable demand for bandwidth, and (ii) regulatory decisions that are opening up mm-Wave bands for unlicensed use. In order to make these bands suitable for use in consumer applications, developments in IC technology and circuit design will be required to realise the combined goals of low-cost, small size and low-power consumption. Together, these will form the major thrust for RF research in the coming years.

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