CHAPTER 5

HARDWARE FOR RF FRONT-END OF WIRELESS COMMUNICATION

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INTRODUCTION

Hardware provides the building blocks for the specified requirements and functions of wireless communication systems. In many defense and satellite systems, devices and circuit designs are aimed at the best performance, although the choice of hardware is often conservative. In the case of wireless communication systems, this conservative approach is somewhat true because of the rapid turnaround in commercial products. In fact, manufacturability and marketability become the drivers for many high volume short-cycle commercial products as many industrial participants in this study like Dr. J. Golio of Rockwell emphasized. However, in looking at the future beyond the G3 and even G4 environment, research concerning hardware needs to be advanced in a steady and accelerated pace. This includes not only devices and circuits, but also enabling process technology and design methodologies. This is because the performance of future wireless systems critically depends on hardware capability. Dr. Golio mentioned that the faster, smaller, lighter and cheaper philosophy still holds. It is also true that research methodologies for hardware may need to be modified.

One of the factors influencing hardware research is the frequency of operation, which affects bandwidth and signal processing speed. Although much industrial effort is aiming at frequencies up to 2.4 GHz (at most 5.7 GHz) for mobile wireless and 28 GHz for fixed wireless such as LMDS, several industrial research centers are looking at much higher frequencies beyond 60 GHz. Although the need for bandwidth far exceeding the G3 requirement is often questioned, research on higher frequency devices and circuits has at least two benefits. One is to enable a potential system that takes advantage of the wider bandwidth such as 5 GHz around a carrier frequency of 60 GHz, as envisioned by Sony for ultra-wideband wireless connections. Another is to make low frequency design more flexible and device and circuit performance superior through the availability of higher frequency devices used lightly.

Since hardware research is motivated by system requirements, listing some of the desired features for the future systems and the potential technologies necessary to achieve these goals is a good place to begin. The list is not intended to be exhaustive, but it includes features envisioned by some industrial participants in the WTEC study. Dr. Walid Ali-Ahmad of Maxim, who is engaged primarily in silicon based wireless systems, provided the following list of targets for future circuits and devices:

- complete wireless system on chip including radio frequency (RF), analog baseband, digital baseband, digital logic, digital signal processing (DSP), microprocessor and power supply

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1 At the recent Workshop on Single Chip Radio during the 1999 IEEE International Microwave Symposium, most panelists expressed the desirability (but extreme difficulty) in achieving this in the foreseeable future.
- low cost system solution with minimum off-chip component count, high yield process
- small size system solution and portability
- very low power consumption and extended battery life

Dr. Ali-Ahmad provided the following list of device and circuit technologies needed:

- MEMS devices and micromachined components including the high-Q on-chip filters
- advanced IF circuits for software radio
- advanced process technology
- optimized RF silicon transistors for high efficiency linear power amplifiers
- continued scaling of complementary metal oxide semiconductor (CMOS) technology
- advanced packaging
- battery technology
- CAD for system-on-chip design

In regard to the device technology, a number of other study participants from the United States and abroad emphasized the importance of III-V devices for high frequency applications such as 5.7 and 60 GHz (Mr. Kawasaki of Sony, Dr. K. Honjo of NEC, Dr. Kagiwada of TRW). In fact, TRW can deliver a 190 GHz amplifier based on III-V technology. On the other hand, many people considered SiGe as a promising device with potential low cost, high frequency applications.

**CMOS TECHNOLOGIES AND SILICON BIPOLAR TRANSISTORS**

CMOS and silicon bipolar devices and circuits currently are responsible for the majority of wireless communication hardware. Silicon technology has a long history for digital signal processing, VLSI, A/D and D/A converters. CMOS based radio has been steadily progressing toward higher frequencies. State-of-the-art CMOS uses the 0.18 \( \mu \text{m} \) process. CMOS is currently the workhorse for wireless up to 800 MHz. Substantial effort is being expended worldwide to extend the frequency to 1.9 GHz, 2.5 GHz and 5 GHz ranges. One of the major drawbacks for silicon devices used for RF applications is the low resistivity of silicon, causing substrate loss. This problem causes low Q of passive circuits, particularly for inductors. Much effort is spent to enhance the capability of silicon circuits by, e.g., elevating the inductor from the chip to increase Q and by introducing SOI (silicon on insulator) technology for power and speed.

Philips Research Laboratories have been working on “silicon-on-anything” devices based on the bipolar process with the circuits transferred to a range of insulating substrates such as glass (Fig. 5.1). In this way the parasitic capacitance is reduced, and high-quality RF passive components can be integrated on the chip. They have manufactured RF devices, including a bipolar transistor with an active emitter of only 0.05 square micrometers and with proportionately smaller junction capacitances. This resulted in low power consumption with only 15 \( \mu \text{A} \) at the cut-off frequency of 10 GHz. One example of the chips is a fully integrated LC-type VCO including a phase-locked-loop frequency synthesizer and divider chain for local area networks (LANs).

Much effort has been expended to improve performance by changing the device fabrication process. For example, Philips has proposed a double-poly-transistor with SiGe in-situ grown base (Fig. 5.2). The traditional base contacts are eliminated. Instead, the base contacts are poly-silicon strips on a thick oxide layer. The base layer is grown into the narrow opening in the oxide and automatically contacts the poly-silicon strips. Finally, heavily n-doped poly-silicon is deposited to form the emitter. Adding 10 to 20\% Ge to the base layer offers new possibilities to adjust device parameters.
Although it has not used CMOS, NEC has utilized Si nMOSFETs (field-effect transistors) for both a low frequency (900 MHz) amplifier for GSM and high frequency (Ku band) amplifier (Fig. 5.3). Since the substrate is lossy, the amplifier design for 900 MHz makes use of the loss matching technique to obtain an unconditional stability from a conditionally stable design to obtain a power added efficiency (PAE) of 62% with the power output $P_{out}$ of 27 dBm. The device uses two-generation old 0.6 $\mu$m technology. For the Ku band amplifier based on 0.18 $\mu$m nMOS (with $f_t$ of 50 GHz and $f_{max}$ of 45 GHz), the substrate loss is too significant to use the same approach. Therefore, the transmission line structures for the circuit are modified (Fig. 5.4). For “Type A” modification, microstrip lines are placed on a polyimide layer that is in turn placed on Si substrate via SiO$_2$ and SiON isolation layer. In “Type B,” a thin-film microstrip line that has an Al layer inserted in the SiON and SiO$_2$ layers is used. The insertion loss is about 1 dB/cm. The amplifier gain is 10 dB with a noise figure of 4 ~ 5 dB in Ku band.

One technology that has drawn recent attention is SOI (silicon on insulator). Recently IBM announced that it plans to use SOI technology to manufacture a range of logic integrated circuits (ICs). IBM’s first 0.22 micron SOI devices were scheduled to be used in Apple Computer Inc.’s Macintosh systems and in IBM servers, perhaps by early in the year 2000. IBM is also developing 0.18 and 0.13 micron processes for 1 GHz microprocessors. Along with up to 30 percent performance gains, SOI could improve power consumption by 30 to 50 percent. Because SOI’s advantage is more pronounced at low-voltage operation, the technology is suitable for mobile applications, with reasonable RF performance at single-volt supply voltages well above a few GHz. Similarly, Motorola is preparing an SOI BiCMOS process for RF/IF circuits for cellular phone applications.
Many modern wireless communication systems use digitally modulated signals. Therefore, at some point this digital information needs to be extracted so that DSP can take over. Much work has been carried out for the direct conversion receiver. Central to this scheme are AD and DA converters. Although there is a need to place this A to D conversion scheme as close to the antenna as possible, the performance of the AD and DA converters set the limit (Fig. 5.5). The bit rate and the frequency are in a trade-off relationship. Analog to digital conversion improves 1 bit/3 years according to Philips, and CMOS AD conversion may slow down due to low V_{dd}. In fact, a good rule of thumb to describe a figure-of-merit of the AD converter is given by

\[ F = \log_2(\text{Sampling Speed}) + \text{Resolution} \text{ (given as Effective No. of bits)} \]

For the state of the art, this \( F \) value ranges from 38 to 40 at the moment. For example, for 1 GHz speed with 10 bits of resolution, \( F \) becomes 40.
III-V DEVICES AND CIRCUITS

Although the market is much smaller than that for silicon based devices, III-V devices have been developed for high performance, high frequency applications from UHF to millimeter-wave frequencies. In addition to the discrete devices, the past several years have seen significant advances in MMIC based on III-V materials. The most common baseline materials are GaAs and InP. GaAs metal Schottky FETs (MESFETs) are quite mature and are available off the shelf up to X and Ku band applications. More advanced high electron mobility transistor (HEMT) devices are the preferred choice for higher frequency and higher performance applications with lower noise figures for low noise amplifiers. InP HEMT provides better performance for higher millimeter wave frequencies as demonstrated by Daimler-Chrysler in Fig. 5.6.

TRW recently demonstrated the world’s first 190 GHz InP HEMT low noise amplifier (LNA), which exhibited a gain of more than 7 dB from 160 – 190 GHz, with a peak of 9.6 dB, while the noise figure is 6 dB at 170 GHz (see Fig. 5.7). This device has a 70 nm e-beam defined T-gate on a 2-mil substrate with a 25 μm backside via. TRW also has demonstrated an InP HEMT MMIC power amplifier with an output power of 427 mW with PAE of 19% and an associated gain of 8.2 dB (see Fig. 5.8). The state of the art devices exhibit $f_t > 300$ GHz and $f_{max} > 500$ GHz. The expected future performance would be $f_t > 500$ GHz, $f_{max} > 1$ THz, and an LNA with a gain of 10 dB at 260 GHz, as well as a PA with an output power of 0.25 W at 260 GHz.
For applications at somewhat lower frequencies, GaAs HEMT (PHEMT or pseudomorphic HEMT) is a very practical and readily available device. In fact, Dr. Honjo of NEC believes that wireless applications up to 100 GHz do not require the use of InP devices. For future mobile wireless communications for multimedia, a high speed (> 20 GHz) and low power phase lock loop (PLL) is required. NEC has developed a CPW-based MMIC using a 0.1 μm GaAs E/D-HEMT. The salient feature of this device is the use of a two stage mushroom gate (see Fig. 5.9).
A new type of microwave device that has drawn a considerable research attention is III-V heterojunction bipolar transistor (HBT). This device tends to have a lower phase noise than FET type devices. At the moment, the usable frequency range is lower, however. NEC uses selective regrowth to reduce the base resistance to one fourth (see Fig. 5.10). At the same time, pseudomorphic InGaAs graded base was used so that the regrowth-performed GaAs-based HBT achieved low R_C, leading to an f_max comparable to those of high-performance InP-based HBT that has a higher f_T. Some of their devices include (1) a 26 GHz power amplifier module made of two device power combined with 3.63 W and PAE of 21%, (2) a 1W 35 GHz HBT power amplifier with PAE of 29% and a 60 GHz dynamic frequency divider, and (3) a low phase noise 38 GHz HBT MMIC VCO.

**SiGe DEVICES AND CIRCUITS**

To achieve high integration and multifunction capability, industry is pursuing the development of SiGe for range sensors, speed control, etc. In addition to integration and performance, this technology is likely to be utilized in customer products for wireless applications including communications and sensing/navigation. Comparisons made between InP-, GaN- and SiGe-based products show superior cost potential in the SiGe technology (see Fig. 5.11) and indicate device superiority due to very low 1/f noise and low phase noise. SiGe transit-time diodes in self-oscillating mixers have demonstrated frequency stability with subharmonic
locking. Free running has demonstrated about -60 dBc/Hz at 100 kHz from the carrier, and with phase locking about -90 dBc/Hz at 100 kHz from the carrier. In this circuit technology, CPW has been chosen as the interconnect medium due to its superiorit to thin film microstrip and its associated need of a via hole technology. CPW solves a number of problems but requires an air-bridge technology, which in terms of fabricating is easier to establish due to its requirements for wafer-surface and not wafer-bulk fabrication. Daimler-Chrysler is a leader in SiGe technology and has demonstrated performance records in SiGe HBT, as shown in Fig. 5.12. A number of SiGe applications include Ka-Band CPW oscillator HBTs, a 77 GHz near-field sensor with SiGe Schottky diodes, a 77 GHz closing velocity sensor, etc. While SiGe technology is progressing fast, a number of processing issues still need to be resolved. To alleviate some of these issues, passivation of the device by Si$_3$N$_4$ has been adopted. Low temperature, low-power cpw-based HBT structures are routinely demonstrated (20 mW at 47 GHz) (6 emitter figure device). Presently research is focused on the development of phase resonant devices with $f_{\text{max}}=300$GHz achieved by quantum-well injection.

**SiGe SIMMWC: Motivation**

<table>
<thead>
<tr>
<th>Material</th>
<th>SiGe</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permittivity</td>
<td>11.67</td>
<td>12.7</td>
</tr>
<tr>
<td>Electron mobility</td>
<td>1300 cm$^2$/Vs</td>
<td>1500 cm$^2$/Vs</td>
</tr>
<tr>
<td>Breakdown field</td>
<td>3 x 10$^5$ V/cm</td>
<td>4 x 10$^5$ V/cm</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.5 W/cmK</td>
<td>0.6 W/cmK</td>
</tr>
<tr>
<td>Mechanical stability</td>
<td>low</td>
<td>DM 200 - 3&quot; (semis)</td>
</tr>
<tr>
<td>Substrate cost</td>
<td>DM 30 - 4&quot; (high resistivity)</td>
<td>DM 200 - 3&quot; (semis)</td>
</tr>
<tr>
<td>Good RF performance data of GaAs</td>
<td>Cost advantage (1 order of magnitude) of silicon</td>
<td></td>
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</tbody>
</table>

Fig. 5.11. Comparison of GaAs and SiGe (Daimler-Chrysler).

**SiGe SIMMWC: (Modules)**

Fig. 5.12. World record performance of SiGe HBTs (Daimler-Chrysler).

Daimler-Chrysler is inserting this technology into customer products via an extensive product development effort performed in the “Microwave Factory” owned by DASA. Sensors have been produced such as SatCom, MobilCom, Cruise control at 77 GHz and LMDS at 28 GHz, in addition to 24 GHz radar designed
to measure material properties for application in steel production. Other products include a 58 GHz point-to-point link in hybrid configuration with GaAs MMICs using bonding wires for connection to MMIC chips.

**GaN DEVICES AND CIRCUITS**

Devices based on a wide bandgap semiconductors also have received considerable attention. In particular, GaN based devices are considered more appropriate for higher frequency operations than SiC based ones. Although GaN has been successfully applied for blue laser development, its microwave application has encountered a number of challenging research issues, two of which are material purity and substrate material. Daimler-Chrysler, for example, uses material from Cree and silicon carbide substrate for X band high power application (10 W/mm at 50 V bias) (see Fig. 5.13). NEC has attained $f_{max}$ of 90 GHz with an SiC substrate. This device, when matured, is promising for the base station applications.

![Fig. 5.13. Daimler-Chrysler GaN FET.](image)

**MILLIMETER-WAVE CPW MMIC**

At UHF to lower microwave frequencies, RF front-end circuits are primarily made by monolithic microwave integrated circuits (MMIC). The typical MMIC makes use of microstrip line technologies for which sufficiently accurate and fast CAD software is available, and industry all over the world has sufficient design experience. At higher microwave frequencies to millimeter wave frequencies beyond 60 GHz, a microstrip line is not necessarily the best choice, while coplanar waveguide (CPW) technology has received considerable attention. At this time, CAD tools for CPW are not completely satisfactory. CPW has much smaller dispersion in phase velocity and has a more tightly coupled electromagnetic guided field than microstrips and many other guided wave structures. In addition, its uniplanar nature does not require a via-hole process due to lack of the backside ground plane while air-bridges are required. IMST in Germany has spent considerable effort in establishing design techniques for CPW, primarily based on lumped element approximations. A number of corporations visited by the WTEC panel, including Daimler-Chrysler and NEC (see Fig. 5.14), now make use of CPW for millimeter-wave MMIC development.
Use of CPW and slot line in MMIC have been core research items at NTT Wireless Systems Laboratory. Its Uniplanar MMIC can reduce the chip size to 1/1.5 to 1/5 in comparison with the microstrip line based MMIC. NTT has further advanced research toward 3D MMIC, which is discussed later in this chapter.

**HIGH Q COMPONENTS AND FILTERS**

Murata holds a very strong position in the manufacture of high-Q components and filters through the development of novel ceramic materials and devices. Its success is based largely on the ability to develop unique designs of ceramics materials, employ a low-cost manufacturing process, and design useful devices incorporating these materials better and cheaper than probably anyone else. Murata's technology policy leads to the integration of material, processing, design and production processes. This approach is followed in all component and element design. About 10 billion capacitors are produced per month. Murata has extensive tools for design and analysis and has developed its own manufacturing equipment. Material characterization is performed via resonator measurements using HP equipment. Murata's method will become an IC standard next year.

Most of the high-Q components and filters are based on the company's ceramic material formulations combining high dielectric constant with high Q (low dielectric loss), and good thermal stability in both dielectric constant and temperature coefficient of expansion. Murata ceramics are known as the best in the world. Dielectric constants range from 20 to 13,000. A value of 3000 is most popular. Ceramic dielectric constants are notoriously temperature sensitive, but one material changed only 10 percent from -45°C to +85°C.

Filters are developed via use of piezoelectric materials (PZT) and multilayer technology for very low frequency applications from the 400 kHz region up to 10 MHz. In addition, ferrite materials are used to develop transformers and noise suppression filters. Pyroelectricity is a material property explored for sensor development. Furthermore, semiconductor materials are used for the development of thermistors. The kind of device used for filtering depends *inter alia* on frequency and power levels. Thus SAW filters are good at lower power levels and better at the lower frequencies. Piezoelectric filters have been used up to 450 kHz with an unloaded Q of 400 and only about 1/2 mm on the side.
Murata has a good capability to design microwave combline and stepped-impedance filters and duplexers to specified performance. These dielectric filters are constructed in a neat miniaturized monoblock construction out of a block of high-dielectric-constant material (under the trade name GIGAFIL). Murata has written its own proprietary CAD programs to aid in various designs. It has demonstrated progress in miniaturization by showing successive versions of two 900 MHz GIGAFIL duplexers: the mobile version came down from 66 cc in volume and 154 g in mass in 1983 to 3.9 cc and 20 g, respectively, in 1996. The handheld version went from 9.5 cc and 30 g in 1986 to 0.9 cc and 3 g in 1995 (and 0.5 cc in 1997). Murata’s work on both dielectric block filters and on multilayer functional substrates is particularly impressive, both leading to miniaturized high-performance components. The latter starts out with thin strips of green ceramic piled in layers. One such device consisted of 21 layers; as many as 600 layers have been contemplated, but not made. The fabrication steps are briefly stated as follows: Mix materials, de-air, make sheets, cut sheets, punch via holes, fill via holes, add dielectric material + solvent + binder, print inner electrode, punch cavity, stack, press, form grooves (for later breaking into separate modules), cofire, inspect, plate Au/Ni electrode, print solder paste, mount components, solder, break where grooved, package and mark, inspect, pack and ship. Filter technology goes to 2 micron thickness, which is expected to be reduced further to reach the 1 GHz mark. The transverse dimension may be as high as a few millimeters.

A major trend in filter technology is the constant push toward three-dimensional (3D) micro-miniaturization, as evidenced here by the multilayer construction currently attempted in filter design. The driver is smaller size, lower mass, lower cost, and sometimes better performance (afforded by integration and the avoidance of connectors and connecting 50-ohm cables). Research into better ways to accomplish this miniaturization might have good payoff though this is perhaps several years away.

PACKAGING AND INTEGRATION

Packaging and integration of the entire radio including the RF front end is one of the most expensive portions of wireless hardware. The ultimate goal could be the so-called system-on-the-chip in which all the constituent elements of wireless communication hardware are in a single chip including the baseband DSP, RF-front end, and even antennas. In practice, however, the approach is to combine several different chips or functional elements and connect them together to form a functional block. The so-called multi-chip module (MCM) of this type. In many attempts, the techniques developed at lower frequencies can be modified for high frequency applications. Flip-chip mounting of the MMIC on a motherboard is one such example (see Fig. 5.15).

![Flip-chip MMIC Structure](image)

**MAIN CONCERNS**
- Proximity effect on transmission lines
- Discontinuity at bump interconnects

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**Fig. 5.15.** A typical flip-chip MMIC structure by NEC.
Matsushita Research Institute Tokyo has been engaged in flip chip technology with micro-bump for quite some time with very successful results. More recently, it has demonstrated a 3D hybrid IC as a future PC-card-type radio terminal for millimeter-wave frequencies. This structure consists of a dual-mode filter in a dry-etching micromachined cavity, multilayered thin films, and flip-chip bonding of GaAs devices (see Fig. 5.16).

On the other hand, NTT has for some time proposed 3D MMIC with 6 metal layers and polyamide for insulation (see Fig. 5.17). This has resulted in a comparable microstrip-line-based MMIC 1/3 to 1/20 in size, for applications up to 65 GHz. NTT has built a U-band single-chip down converter based on this technology with a conversion gain of $0 \text{ dB} \pm 1.5 \text{ dB}$ and an image rejection ratio greater than 15 dB in a chip size of $1.78 \text{ mm} \times 1.28 \text{ mm}$ (see Fig. 5.18). The K-band Si 3D MMIC has an $0.70 \text{ mm} \times 0.46 \text{ mm}$ amplifier together with an $0.46 \text{ mm} \times 0.42 \text{ mm}$ mixer (see Fig. 5.19).
Fig. 5.17. NTT’s concept on 3D MMIC.

Fig. 5.18. NTT U-band single-chip down converter.
The millimeter wave band is expected to be a frequency resource for the next generation’s mobile communication system and is aimed at achieving a high-frequency PC-card-type radio terminal. To realize all the wireless functions including the antenna and the filter on a chip, a 3D hybrid IC structure is one of the most effective solutions. Matsushita has recently developed a 3D millimeter-wave IC that uses silicon micromachining. For the development of this IC, several technologies were used, including a dual mode resonant filter, multi-layer thin-films on silicon, and flip-chip bonding for the GaAs devices. This circuit has been utilized in a 25 GHz receiver down-converter and has an area of 11 mm$^2$ including the built-in micromachined filter.

With the progress of technology and the invention of the transistor, it became apparent that very small transmission lines compatible with the planar technology of the newly discovered two- and three-terminal devices are needed to effectively couple the power of microscopic devices and macroscopic systems. Circuit miniaturization can be achieved by use of 3D integration where circuits are laid in all dimensions of the space. This approach has been effectively used in designing microprocessors and has resulted in a dramatic reduction of size and an unbelievable increase of speed. The next leap beyond the current state of the art multichip modules (MCMs) is the development of a technology that can integrate high-frequency Si-based active circuits, advanced micro-electromechanical (MEMS) devices, and micromachined components (e.g., filter/multiplexers) into one wafer. By employing 3D integration, significant reduction in mass (by a factor of 10) in physical volume and in cost can be achieved easily.

New concepts in integrated conformal packaging have been introduced, leading the way for micromachining to impact planar microwave circuits beyond the component level and into the system integration area. Micromachining has the potential to revolutionize microwave devices by offering new techniques that can be used to integrate entire systems onto a single IC. One scenario for total system integration calls for the use of multiple layers to accomplish various system functions such as amplification, signal reception, down conversion, and filtering. Micromachining offers the possibility of connecting these multiple layers together vertically to achieve new levels of high density integration. This concept has already been applied to the
The amplifier is the key element in wireless hardware, be it a receiver or a transmitter. In the receiver, a low noise receiver is needed to “screen” the desired signal out of background noise before the signal reaches the down-converter. Although a futuristic direct conversion receiver is supposed to eliminate the conventional heterodyne system, the increasing operating RF frequency makes it difficult for direct conversion to be adopted. Good low noise reception can be accomplished routinely by the microwave industry with HEMT technology.

The high-power final-stage (or output) amplifier is the key element in the transmitter. Since this amplifier is the most power consuming, high efficiency amplifiers have drawn considerable research attention in the past several years. On the other hand, for the spectrally efficient modulation scheme used in CDMA, amplifiers will need to deal with a modulated RF carrier with a non-constant envelope, hence, amplifier linearity is important. In order to obtain higher power-added efficiency, a higher class of amplifiers such as Class AB, Class B or even Class C or switched mode Class E or F is often used. However, due to the V-I curves of devices operated in these classes, the amplifier becomes nonlinear. Therefore, often high efficiency and high linearity are contradictory objectives. There are several techniques to combat this problem.

One method tried at NEC is the use of adaptively controlled bias with a DC-DC converter for W-CDMA applications (see Fig. 5.20). A similar approach has been demonstrated at the University of California at San Diego to increase the average PAE while the amplifier is kept in Class A operation. Since the PAE is extremely low in most instances of normal operation, the DC supply voltage is reduced in such instances to reduce the DC power consumption.

Fig. 5.20. PAE improvement with DC-DC converter by NEC.

Somewhat more routine approaches are first to design a high PAE amplifier with a nonlinear mode and then to provide a linearity-improvement scheme, such as feedback, feed-forward and predistortion. These approaches tend to make the overall circuit configuration complex and the PAE lower. Matsushita Research
Institute Tokyo reported a new approach called the Hybrid Adaptive Predistortion method shown in Fig. 5.21.

Fig. 5.21. Hybrid adaptive predistortion method by Matsushita.

A recent trend is to cope with the linearity-PAE issue from the point of “transmitter unit” rather than a single amplifier. The above examples include a control or signal processing circuit in the configuration.

ANTENNAS

The antenna is a constant subject of discussion, but as yet no perfect solution has been found for wireless applications. There are many varied antennas from one-dimensional (dipole or monopole), two-dimensional (inverted F and microstrip patches), and 3D (dielectric antennas). In addition, dishes and phased arrays are used for base stations and satellite based communication. In this section, only the hardware aspect will be reported while the software aspects, such as the smart antenna or software antenna, will be discussed in Chapter 6 of this report. Also, as many efforts on the antennas are quite similar, the reports are intended to provide the descriptions below only as typical examples.

NTT’s multisector monopole Yagi-Uda (MS-MPYA) consists of two very low profile 12- and 6-sector units for operation at 19 GHz. The 12-sector unit has a gain of 14 dB, and the 6-sector unit has a 10 dB gain. These units are used for beam forming, as Fig. 5.22 shows.
NTT has developed rod-type small-sized antennas for 25 GHz applications. Microstrip antennas are printed on panels within the rod, the beam radiating out from a cylindrical disk-like radome on top of it (Fig. 5.23).

At IMST, the effect of the human head on the antennas has been investigated extensively. It was found that 8 ~ 10 dB loss is caused by the human head in an experiment at 450 MHz. IMST tested the efficiency of several antennas. IMST’s helix antenna has 38% efficiency while its end-inductance antenna provided 84%. A ¼ wavelength patch has proven to be twice as efficient as the helix structure. IMST has also tried a ceramic antenna for 0.9 and 1.9 GHz and have found that the bandwidth is too narrow.

Parabolic dishes still play an important role for wireless communication, especially for satellite-based communication. NTT has developed several deployable on-board antennas (constructed of solid, wire-mesh) that are inflatable. NTT’s current non-inflatable mesh model consists of 7 modules, 10 meters in diameter, and weighing about 80 kg. The target is 14-modules 14 to 15 meters in diameter and 120 kg in weight. This technology was successfully transferred to NASDA (Japanese counterpart of NASA).

CONCLUDING REMARKS

Throughout this study and visits to selected sites in Europe and Japan and interactions with selected U.S. industries, the WTEC panel recognized that hardware technologies for future wireless applications provide substantial research opportunities on a worldwide scale. The following technological areas are either emerging or evolving and are considered important for the future health of wireless technologies:

- devices and materials
  - new materials and components (GaN, SiGe, MEMS, substrate materials, etc.)
- higher $f_t$ and $f_{max}$ as well as higher linearity for active devices
- new 3D oriented process technologies
- higher performance passive components
- broadband antennas, higher gain antennas, low cost phased arrays

- front-end architecture
  - amplifier linearization and efficiency
  - interconnects and packaging
  - mixed signal IC (baseband/RF)
  - front-end architecture for software oriented radio
  - RF aspects of smart antennas
  - multifunction/reconfigurable devices/circuits/antennas
  - MEMS RF components

- frequency of operation
  - 10, 35, 60, 77, and 95 GHz

- CAD
  - global CAD (circuits, electromagnetics, devices, antennas, thermal, mechanical, packaging all inclusive and interactive)

Some specific additional features are as follows:

Amplifier efficiency and linearity are contradictory requirements. The typical approach is to design an amplifier operated in a nonlinear mode and then provide schemes to improve linearity. The latter can be a simple output power back-off or a more sophisticated feed-forward or predistortion technique. In any case, not only good devices but also synergistic approaches are essential. It is important to optimize the amplifier block or transmitter containing an amplifier and output circuits including antenna, or to make use of digital technology for “signal processing” for the amplifier. Modulation format often dictates the choice of control. For instance, a spectrally inefficient constant-envelope modulation is very resistive to nonlinear effects. Combining digital techniques with an amplifier may lead to a form of “software” oriented radio.

A mixed signal IC may be a good ingredient for a futuristic one-chip radio or system-on-a-chip. But both good devices and also low loss and high isolation interconnects are needed.

Software oriented radio has drawn much attention. However, often software issues and digital circuits issues are emphasized while the RF front end is sometimes neglected. Therefore, front-end architecture should be included in the studies for software radio.

Smart antennas are another example where the software and hardware collaborate well. Integrated antennas alleviate some of the hardware difficulties associated with smart antennas. Also, reconfigurable circuits and antennas should play important roles in developing the smart antenna.

Three-dimensional integration schemes are required to provide communication systems that are very small, very low in weight and very low in cost without compromising performance. The use of heterogeneous materials for the circuits and devices incorporated in the system may lead to unique solutions in integration and packaging.

High-Q, low-loss passive devices are also needed for high performance. The development of RF MEMS also provides new directions with the possibility of new functions and system architectures.
The above are some of the possible future directions of research. What should be emphasized is that future research must require interdisciplinary approaches not only in terms of different hardware components but also hardware and software.

TECHNOLOGY ASSESSMENT

It is always difficult to make a comparable assessment of the technical advances of several countries and regions. The hardware technologies for wireless communication are no exception. In fact, due to the very broad technical topics involved in this chapter, the challenge is even greater. Therefore, Table 5.1 provided below is based on the quite subjective judgment of the authors of this chapter. The WTEC panel as a whole does not disagree with this table.

<table>
<thead>
<tr>
<th>Table 5.1</th>
<th>Wireless Technology Assessment for Hardware</th>
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<tbody>
<tr>
<td></td>
<td>U.S.</td>
</tr>
<tr>
<td>Millimeter Wave Circuits and Systems</td>
<td>**</td>
</tr>
<tr>
<td>Packaging/Interconnect</td>
<td>*****</td>
</tr>
<tr>
<td>CAD</td>
<td>*****</td>
</tr>
</tbody>
</table>
| SiGe/Si | **** | *** | *****
| III-V | **** | ***** | **** |
| GaN | **** | **** | *** |
| Antennas | *** | **** | *** |
| Passive Components | **** | **** | **** |
| Amplifier Technique | ***** | **** | **** |
| MEMS/Micromachining | **** | *** | ** |

1 Germany only; 2 UK activities

The following six points pertain to the entries in Table 5.1:

1. Millimeter Waves. Here, it is very clear that in terms of devices and MMICs, the United States is ahead of others, largely because of DARPA’s successful MIMIC and MAFET projects. However, the U.S. entry here reflects expertise in millimeter wave circuits for non-military wireless applications. In Japan, government-led programs on 60 GHz wireless technology have been implemented, while in Europe a substantial effort has been expended mainly for automotive applications centered around 77 GHz.

2. The United States has dominated CAD development and commercialization and it maintains an unchallenged position.

3. In the area of SiGe, IBM is the leader. However, its circuit applications have lagged behind Daimler’s effort, particularly in millimeter wave areas. In an effort to make the process technology available to others, IBM and Daimler process technologies are expected to benefit circuit design efforts funded by other organizations.

4. GaN is still in its infancy in industrial applications. Most high performance devices devices are still at the research stage. It is interesting to note that the United States is leading in the RF (microwave) area, i.e., transistor development, while Japan’s effort has mainly been in the area of optical devices. Cree in the United States and Nichiya in Japan have made excellent materials available.

5. Antenna research has left much to be desired. In wireless communications, antenna research is meant to be different from the traditional in terms of the analysis, design, and characterization of antenna
elements and/or phased arrays, from an electromagnetic point of view. What is needed is the development of an interdisciplinary research field useful for future wireless technologies. Examples are the integration of antennas with the RF front end, such as passive filters, MEMS devices, amplifiers, and even DSPs.

6. In the area of passive components, the Japanese are slightly ahead due to their effort in high Q components led by Murata.

In closing, it should be emphasized that future research on wireless oriented hardware requires interdisciplinary approaches not only between hardware and hardware but also between hardware and software.