# RF Semiconductors

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# Related Wireless Communications Activities In Canada

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**Industry Canada**

# RF Semiconductors and Related Wireless Communications Activities in Canada

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# Introduction

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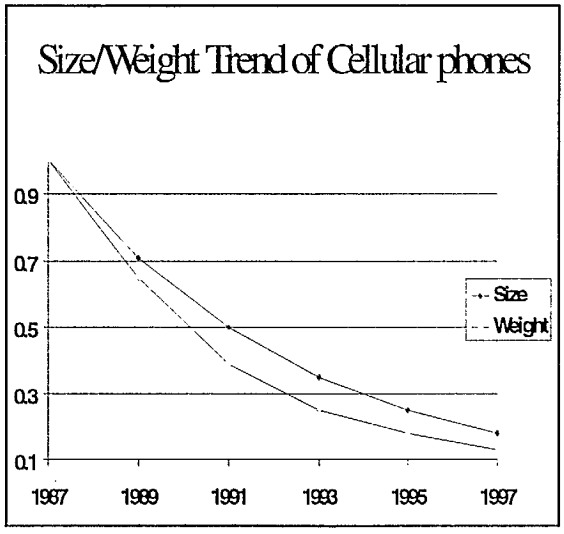
The world is undergoing a transformation to a next generation of communications systems. Wireless technology is a key enabler in these new technologies and devices which include PCS, mobile data, paging, wireless LANs, and a host of other devices and accessories which are emerging as the subscriber demands more mobility and ubiquity from their personal communications systems.

The wireless semiconductors that make this next generation of devices possible are divided into two categories. The first category is the basic RF components required for the wireless communication markets operating in the 800 MHZ to 2.5 GHz frequency range; these are used in the radio portion of wireless devices. The second category addresses baseband semiconductors which control the computing, logic functions, memory, power control and management, plus modulation and demodulation functions.

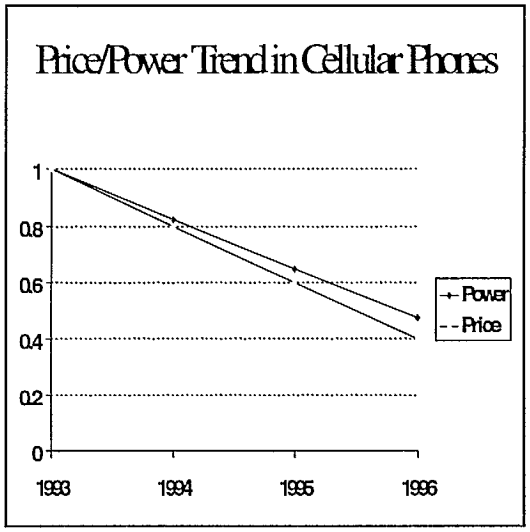
The trends and challenges for successful mobile communications products are parameters such as low power, reduced size and weight, and most importantly of all, high efficiency and high frequency ICs. The size/weight and price/power trends are depicted in Canada and abroad. This overview will address some of the key issues and strategic markets in RF semiconductors. This paper will also look at wireless semiconductors in the framework of the wireless personal communications industry in Canada with respect to the global market. A profile of some of the major PCS players is incorporated .

Figure 1.0




Source : Koichiro Mashiko, 1996

Figure 1.1




Source : Kochiro Mashiko, 1996

Wireless technology is becoming rapidly embraced as having a key role in both personal and business communications. Being more mobile is now necessary as work activities are often no longer being confined to a specific office or building. Teleworking which can be thought of as "location-independent" working is a recent phenomenon. In fact, the centralized workplace is a relatively recent mode of working. Not only are people working in less structured environments, they are increasingly demanding the ability to connect with and have access to the people and tools they are accustomed to using, in a reliable and effortless manner. At the same time, improvements in the microelectronics industry have made wireless products not only available, but affordable for many people. The fact that these two trends are strengthening over time makes it obvious that wireless technology has an integral role to play, both in the future of each of our lives, and in our economy. As people become increasingly on the move, they and their businesses and organizations will continue to broaden and move to wireless communications.

The wireless industry has established strengths in several areas which include mobile data communications products, paging networks, cellular phones, industrial radio controls, two-way radio products, CDPD modems, wireless local loop (WLL), wireless LANS, cellular network equipment, direct broadcast satellite (DBS), global positioning satellite (GPS), and PCS systems. In most cases the strengths of wireless come in three main areas. The first is in mobility, the second convenience, and the third is in cost savings. In many cases wireless products have been developed for use in situations where it is impractical or cost prohibitive to install new wires. Whether the location that the data is originating from is moving, or there are simply physical or cost barriers to running new wires, wireless networks become necessary. In Canada, due to our existing extensively wired infrastructure, we often find it cost-effective to utilize existing wires as part of our wireless system. These applications are considered to be part of the wireless category because no new wires are required for communications. The threshold is constantly being lowered for wireless products as new developments and cost reductions as depicted in the figures above, steadily make it more attractive to use wireless devices than adding additional wires. It is in this situation that we find ourselves today, one where we can be certain that further developments in the wireless field only add to the amount of wireless products demanded.

Developments in wireless have been occurring relatively quickly. While the industry continues to generate electronics with ever lower power requirements and circuits with perpetually greater integration, it is also in the middle of a change from analog to digital technology. Using digital systems allows not only voice, but other data forms to be

transmitted wirelessly. The combination of digital technology and small, low power electronics has allowed the production of handheld devices, like PCS, that are able to perform many functions. Not only does PCS allow voice communication like a traditional analogue cellular phone, it also has the capability to provide data transmission for applications such as e-mail and facsimile. If the ability to transfer information from one point to another has value, it is obvious that the ability to transfer that same information to a person rather than a point is more valuable. Whether PCS will displace much of the traditional cellular market remains to be seen. One thing that is for certain is that wireless communications are here, changing, and improving rapidly. This document attempts to look at the Canadian involvement in this field, and the changes occurring specifically within the semiconductor segment of this market.

# Canadian Companies and Contributing Researchers

# Key Companies and Contributing Researchers

Key players that will be referenced who are contributing to RF research and development in Canada are listed in the table below. We apologize for any omissions or errors that may occur because of the continuously evolving spectrum of activities in this vibrant technology sector in Canada

| Key Players In RF Research and Development | |
|---|---|
| Alberta Microelectronic Centre (AMC) | Micronet |
| Aprel Laboratories | Mitec |
| Cadence Design Systems | Mitel |
| Canadian Marconi | Mobility Canada |
| Canadian Institute for Telecommunications Research | Moli Energy Ltd. |
| Clearnet | MOSAID |
| Canadian Microelectronics Corporation (CMC) | Motorola |
| CML | Nortel |
| Com Dev | NRC |
| Communications Research Centre (CRC) | NSERC |
| Ericsson | Philsar |
| Focam | Quadrillion |
| Genesis Microchip | Research in Motion |
| Gennum | Rogers Cantel |
| Glenayre Technologies | SiGe Microsystems |
| Goal Electronics | Spar Aerospace |
| IBM | Syborg |
| Infomagnetics | TR Labs |
| Lucent Technologies | Wi-Lan |
| Microcell | Xilinx |

# Research, Results, and Applications

# Research, Results, and Applications

Much research is taking place in Canada with respect to RF communications, at both the university and corporate levels. The race is on to develop new and better ways to communicate and improve the existing hardware that is currently available. The scale of design effort and production varies from organization to organization, but the goal remains the same: reduce the cost, decrease the size, lessen the weight, and increase the battery life for the different lines of wireless products.

There are several universities in Canada with electrical engineering programs containing people working on RF related studies. The University of Waterloo, University of Toronto, University of Calgary, École Polytechnique, McGill University, Carleton University, and University of British Columbia all have ongoing research in the RF field. These universities have the following ratings as compiled by 1997 Gourman report. (See Appendix A)

At the *University of Waterloo*, a group of researchers has a goal to develop new methodologies and technologies within the field of microelectronics to improve on current economical and technological barriers limiting the processing and transmission of information. Towards this goal, the researchers have focussed on RF technology in the areas of high speed active and passive devices, development of RFIC/ MMIC receiver elements for low voltage and low power application, and the generation of very high frequencies (i.e. millimetre) waves on chip. This work is improving many areas of wireless communications, such as PCS, GPS, LAN, cordless, and cellular. Dr. Tajinder Manku, an Assistant Professor in the Electrical and Computer Engineering Department and his co-workers at the University of Waterloo says Waterloo have developed several novel devices for companies which are currently part of a product line. Companies with which the university has associations are RIM, Nortel, Mitel, ComDev, IBM, and Ericsson, among others.

*École Polytechnique* has research teams studying numerous topics, including device design, fabrication, and testing, GaAs, BiCMOS, and CMOS high performance circuit structures, heterojunction electrical devices, digital high performance microchip design, and high-speed mixed-signal design. The institute works closely with industry, illustrated by the close collaboration with firms such as Mitel and Design Workshop.

The *University of Calgary* has one of the larger research programs in Canada. With over forty researchers, the University of Calgary has extended its area of expertise into such areas as analog CMOS circuit design, signal processing electronics, high frequency circuit design, and GaAs UHF MMIC power amplifier design and fabrication. Another project of interest is that of a smart antennae. This project, supported by TRLabs, concentrates on the circuitry and the optimization procedures required to achieve an effective smart antenna.

*McGill University* established their Microelectronics and Computer Systems (MACS) Laboratory in 1982. Located in the Department of Electrical Engineering, MACS offers expertise and resources which are utilized by a number of research projects within the Federal Centres of Excellence Program, including MICRONET and the Canadian Institute for Telecommunications Research (CITR). One of the four major research thrusts within MACS is Analog and Digital Systems with Test, led by Professor Gordon Roberts. Within that initiative McGill University has a group of researchers working on integrated analog filter circuits for the VHF band, and are trying to extend this work into the RF band as well. Discussions are under way with Nortel that would provide McGill researchers access to an advanced SiGe process that will allow the construction of some very high-speed integrated circuits for the RF band. Over the past few years McGill has been developing on-chip test techniques that simplify the cost of production testing, in particular, RF type modulation systems and PLLs.

In Ottawa, *Carleton University* has been able to successfully integrate its electrical and electronic engineering programs with local company research initiatives. Working with Nortel, Carleton is actively involved in BiCMOS, advanced bipolar processes including bipolar RF front-end work, and Frequency Hopped Radio. Current IC research involves high-speed analog/digital conversion, adaptive analog filtering at radio frequencies, and high-speed digital-signal processing. Carleton has also been involved in the development of a methodology for the design of low-phase noise monolithic VCOs for digital radio applications. Other work at Carleton includes FPGA Baseband Processors, Low Power Speech Processors, Speech Coding Processors, CMOS Multimodulus Prescaler, and RF CMOS circuits. Companies and organizations that have been involved with Carleton include Nortel, Mitel, PMC-Sierra, SiGe, CITR, CRC, and Motorola. Several of these projects are being lead in large part by Professor Kwasniewski, who shared a CITO Innovation Award for Innovation Excellence with Martin Snelgrove and Miles Copeland, through his supervision of over 30 students working on RF projects.

*Laval university* is currently working in mobile and indoor wireless channel modelling, in microstrip antenna and antenna array design over the microwave range, within their Radiocommunication and Signal processing lab.

At the *University of British Columbia* there has been a large effort put forth studying the theoretical aspects of SiGe and III-V heterojunction Bipolar transistors (HBTs). The emphasis in this research has been on accurately modelling their high-speed performance in telecommunications circuits. Using high-speed laser-based techniques, known as electro-optic sampling, to determine the small and large signal electrical response of individual devices and simple circuits, comparisons are made with the predictions of Bipolar circuit models. Of particular interest to the researchers at UBC are the roles of self-heating, the dynamics of high-current effects, and the role of velocity overshoot in saturated and quasi-saturated operation. The theoretical work concerns physically-based modelling of HBT operation. The work is being led by Dr. Jackson on the experimental side, and Dr. Pulfrey on the leading work on modelling. UBC research into heterojunction bipolar transistors is supported directly by Nortel Technology, grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), and MICRONET.

In addition to long term projects with TRIUMF working on GaAs CCDs and transient digitizers, the *University of Victoria* has been working on amplifiers, comparators, and neural network circuits. The University of Victoria has also been working on mixed-mode IC design with fabrication through CMC. Another group is involved with design of antennas and modelling of their performance on handsets in the vicinity of the user. In connection with Industry Canada, the University of Victoria is evaluating the health impact and engineering evaluation of wireless technology. The university is also involved in advanced work on MMIC devices for communications systems.

The *University of Toronto* has made significant advances in Field Programmable Arrays, BiCMOS processes, Communications and Converters, and other circuits. Significant to the RF semiconductor market is research which has lead to improvements in low voltage analog CMOS/BiCMOS circuits, device design, modelling, fabrication, CMOS/BiCMOS compatible semiconductor memories, and high speed/low power mixed analog-digital circuits, in both silicon and GaAs.

*Aprel Laboratories* of Ottawa, is undertaking a major work project to model the effects of EMC/EMI on wireless communication devices such as the newest dual mode PCS

devices. The Cellular Industry Association has engaged this firm to do research for them in the area of evaluation of related impact.

# Marketing Opportunities and Potential Products

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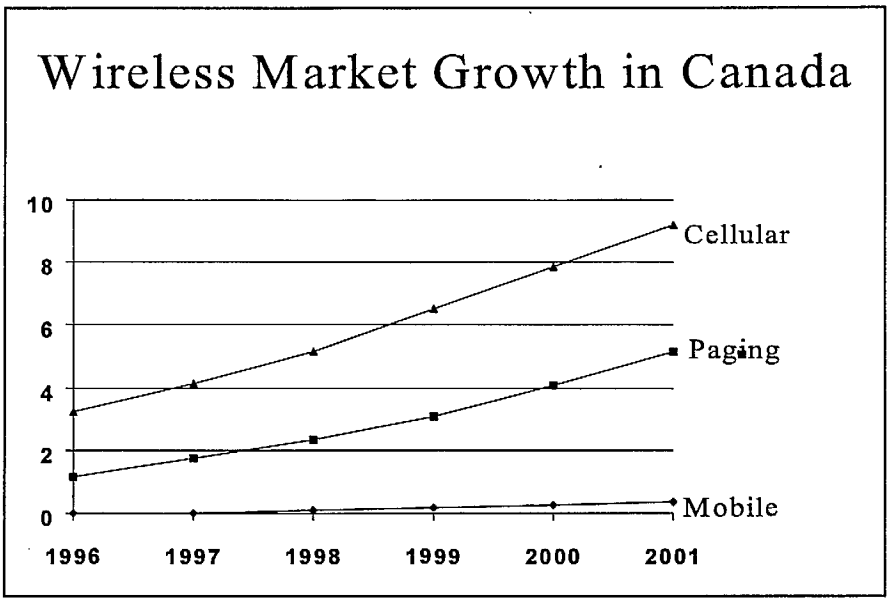
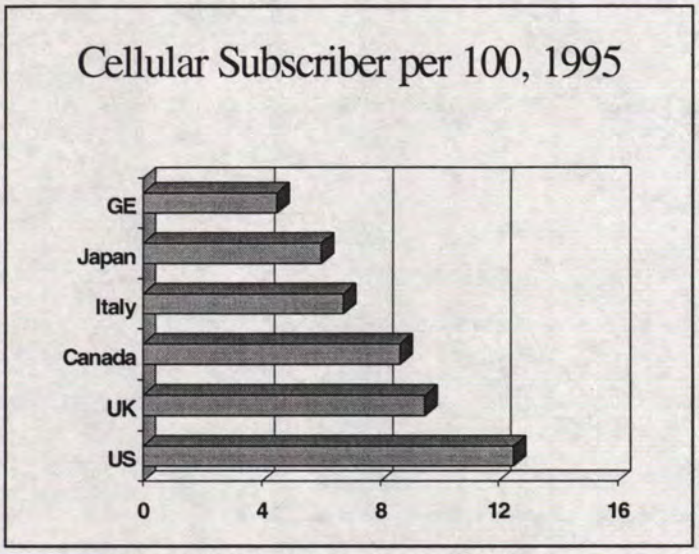



Source : The Yankee Group

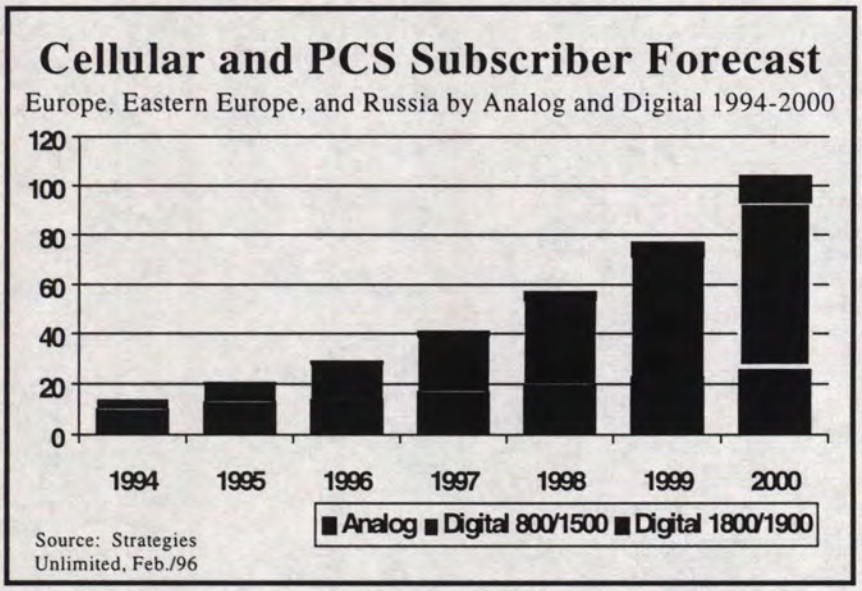
Cellular communications appears to be an area of ever increasing growth in wireless communications. This fact has not gone unnoticed within the companies servicing the market in Canada which can reach over 90% of the population. Microcell, Mobility Canada, Clearnet, and Rogers Cantel have all begun marketing digital cellular packages. Microcell, with their FIDO line, was first to market, in November of 1996. They have been followed by Rogers Cantel (Amigo) in May of 1997, as well as Clearnet (Mike) and Mobility Canada, both introducing their services in October of 1997. PCS is now the most talked about service, with lower costs and higher quality being the sales pitch of choice. Improved technology, allowing clearer voice transmission than traditional cellular, plus the numerous new services available with digital systems, makes PCS a more valuable service to subscribers eager for increased mobility and functionality.

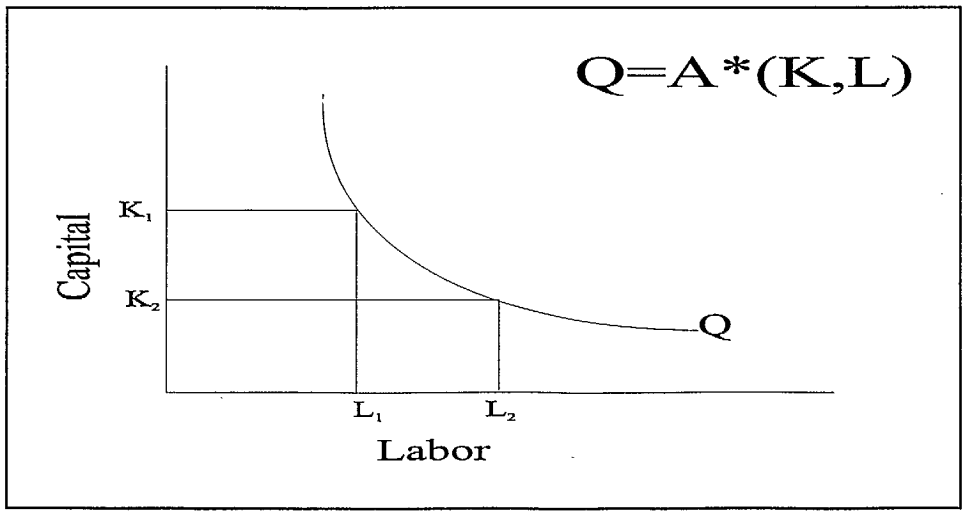
Links between the service providers and major telecommunications providers are fairly clear: Mobility Canada, led by Bell Mobility is partially supplied by Nortel; Rogers Cantel has links with AT&T Corp., has previously shown inclinations towards the purchase of equipment from Ericsson; Microcell which has links to, through partial ownership by, Sprint Canada,who purchase some of their equipment from Nortel; and Clearnet who is linked with Lucent Technologies.

Many analysts now think PCS has the opportunity to have a much larger market appeal and penetration than cellular has ever had. The estimation of PCS penetration in the forty percent area is good news to affiliated companies, as a bundling of services including PCS, cellular, paging, and Internet appears likely.




Source: World Telecommunications Indicators






The microeconomic viewpoint to support this market opportunity can be construed from a technical model as shown above which the firm combines capital and labor in a production function to produce a product of the amount "Q". The firm can freely substitute the capital for labor anywhere along the curve "Q". "A*" represents the technology parameters e.g. wireless communications, which can alter the output "Q" independent of capital and labor.

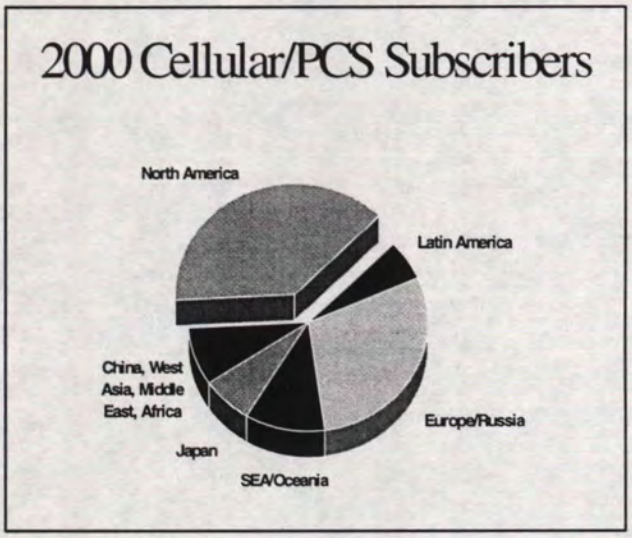
The global market for wireless handsets is exploding. The market currently produces 100 million units and is expected to jump to 200 million by the year 2000 and further increase to 300 million by the year 2002. Of these figures, digital technology maintains its high share of this at about 80% of total units sold. This 80% is expected to grow to 95% by the time year 2000 is over. The expected growth of the wireless market is expected to double by the year 2000 from its current value of $4 billion to at least $8 billion. Although the industry is widely scattered throughout the world it would be a misinterpretation to take this as meaning there is a complete and closed industry in each country. In fact the telecommunications business is not isolated inside countries or regions, but is heavily involved in global trade. As a nation, Canada is very active in the telecom trade arena, where we are both the largest importer from and exporter to the United States (see tables below).

Top 10 U.S. Export Markets
$millions US

| Country | YTD June 1997 |
|---|---|
| **Canada** | **1,339** |
| Japan | 901 |
| Mexico | 652 |
| Brazil | 621 |
| Hong Kong | 596 |
| United Kingdom | 562 |
| Korea | 452 |
| China (Mainland) | 317 |
| Israel | 293 |
| France | 257 |
| **Total Exports** | **9,580** |

Top 10 U.S. Import Markets
$millions US

| Country | YTD June 1997 |
|---|---|
| **Canada** | **1,343** |
| Japan | 1,161 |
| Mexico | 1,022 |
| China (Mainland) | 634 |
| China (Taiwan) | 437 |
| Malaysia | 343 |
| Philippines | 334 |
| Israel | 277 |
| Thailand | 148 |
| United Kingdom | 143 |
| **Total Imports** | **6,687** |



The PCS signal is also more penetrating than previous cellular signals, allowing the phones to be used virtually anywhere near a base station. As the previously analog system is supplanted by a substantially digital system, a bundling of services should become more apparent. PCS costs could even be lower than in cellular systems as new technologies allow more users per cell site as well as lower equipment costs per cell site.

In the past, telecommunications companies like Ericsson AB of Sweden and Nokia Oy of Finland have been trying to convince industry and consumers that cellular phones will be able to give personal computers the power to go on line. Ericsson AB a leader in Sweden is expected to get the go ahead with Nokia Oy to set the European standard for highspeed wireless transfer of data. They predict that in a few years it will actually be faster and cheaper to use wireless connections to the Internet. It is predicted by the year 2001, Internet users will quadruple to 400 million while the mobile phone consumers will rise to 300 million, about triple the current figures. They plan to see that their share of the 300 million cellular users have the ability to go online with speed and efficiency through their cellular phones. Nokia projects data traffic on mobile communications systems to increase to 30% of total traffic, from a current rate of just 5%. The major concern for phone companies may not be in attracting enough subscribers, but may be saturation of the radio spectrum in densely populated areas. The projections are based on "Metcalf's Law" which states "The value of a network - defined as its utility to a population is roughly proportional to the number of users squared." The scope and depth of the markets served thus influence the value of the services provided.

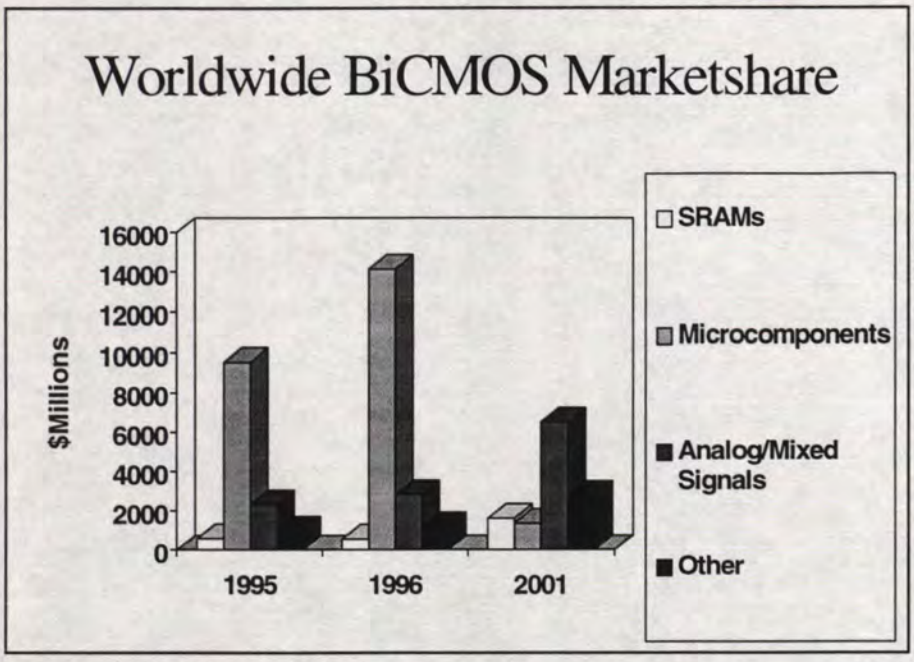
# Industry Forecast

# Industry Forecast

The wireless business has developed into a multilayered system of many companies combining to create high quality, complex products for the marketplace. Each step in the development of a product sees additional value added to the product until it can perform its desired service for the consumer. This is a major supposition supported by "Metcalf's Law" defined in the previous chapter. In this light, it can be seen that RF components are having increasing demand due to growth in the number of base stations and subsystems. Aggressive marketing by cellular service providers trying to increase their subscriber base has led to their subsidizing much of the handset cost for the end consumer. RF and wireless ICs also gain increased demand as the market for wireless data networks and WLANs are increasingly accepted and implemented. Another boost to the semiconductor market and IC demand is the emergence of cellular digital standards. Analog systems still offer a number of telecommunications services, but lesser voice quality and capacity constraints limit the functionality, and calls for either CDMA or TDMA digital standards. The PCS network in Canada appears to have favored Code Division Multiple Access (CDMA), rather than TDMA, or Time Domain Multiple Access. The attractiveness of CDMA is derived from several attributes such as low power consumption, high capacity, and the fact that it has become the default standard in the United States. Because of this, CDMA appears to enjoy support from some major cellular and PCS service providers and equipment suppliers, even though the chipset development is behind that of TDMA.

We will now discuss some of the major semiconductor technologies which are sustaining and promoting the wireless products we have discussed in previous chapters.

In RF, BiCMOS plays an integral role as it allows for high complexity, high data rates, and precise analog function to be self integrated. BiCMOS is slowly replacing a portion of the high-end market held by ECL and CMOS ICs as they are more advantageous than either bipolar digital and CMOS. BiCMOS is the new industry standard for high-speed as a replacement for CMOS alone as it combines CMOS with bipolar transistors to make a single chip. With the combination of both CMOS and bipolar technology, chips can be produced that offer high performance bipolar paths, higher density paths enhanced with the use of CMOS. This allows BiCMOS technology to be used efficiently in many devices currently such as MPU's, smart-power IC's, analog-to-digital converters, controllers for disk drives and memory, SRAMs, gate arrays, standard cells and more.

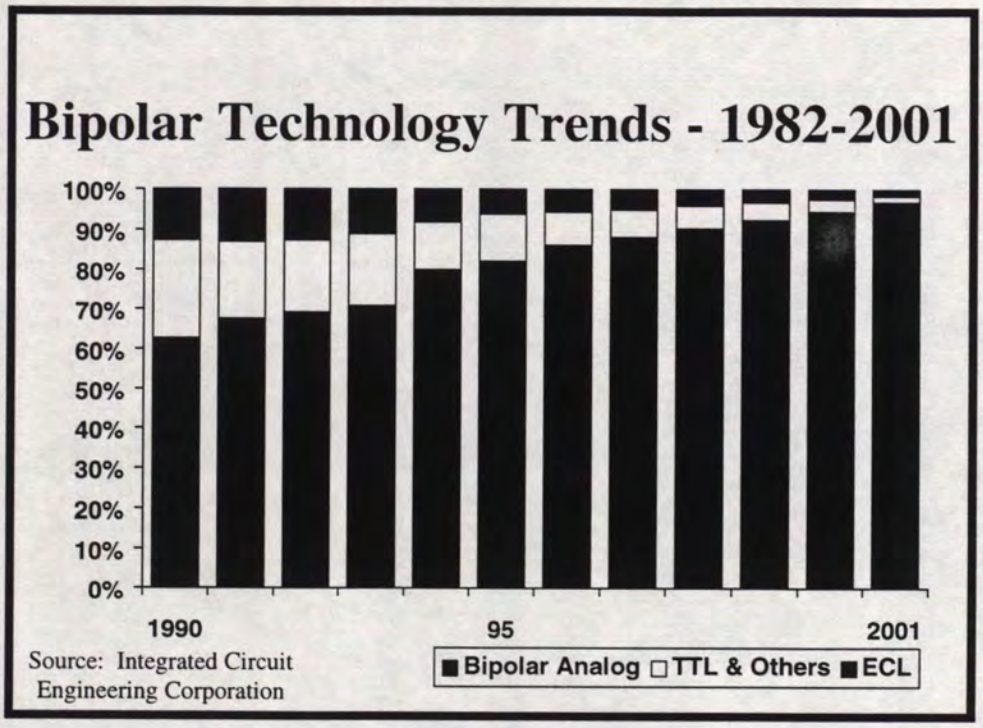



Source : ICE, "Status 1997"

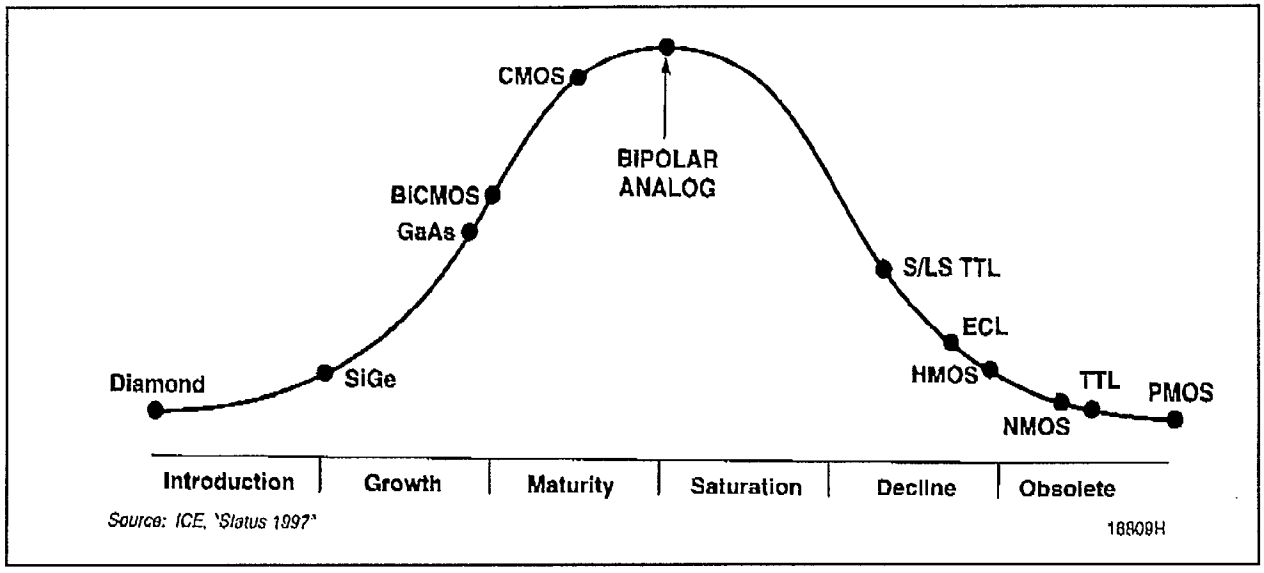
The future of BiCMOS will be based upon finding economically based technologies to produce specialized BiCMOS processes. Economics plays an important part of BiCMOS construction because of the cost created by the complicated processes used to combine both bipolar and MOS transistors into a single device. Due to this limitation, the market for BiCMOS ICs is expected to drop at about a nine percent annual rate on average. This technology is estimated to represent four percent of the total IC market at this time.

Bipolar technology is popular with analog ICs as Bipolar transistors allow for a better gain and more efficient power handling. Another point in favor of Bipolar transistors is they tend to being more rugged than the CMOS equivalents. Bipolar ICs are not necessarily more efficient than CMOS, because of the bipolars consumption of power per logic function. This means that CMOS is technically better than bipolar ICs except where bipolar ICs are able to perform at optimal speeds beyond CMOS equivalents. Therefore this makes Bipolar ICs the winner when it comes to high speed applications. These applications include communications for the telecom industry and mainframe computers which are able to use the bipolars speed to maximize power efficiency.

The heterojunction bipolar transistor (HBT) is another RF semiconductor device that is being impacted by the wireless phenomenon. HBTs are used in personal digital cellular systems.




The advances that have taken place in the development of silicon as a base in integrated circuits has come to a point where it is possible to see that there are physical restrictions associated with the exclusive use of silicon. Circuit speed is the sticky issue here since silicon physically cannot handle the high speeds in the GHz range. The use of germanium along with silicon allows for faster circuits and higher frequencies. SiGe device technology has improved cutoff frequencies to beyond 100 GHz.




As alluded to previously, some well known devices which allow high-speed performance such as ECL are showing declines in usage in favor of other performers such as GaAs and BiCMOS.

As RF communications applications move away from discrete devices, integration will be made possible by either or all of the following technology processes: GaAs, SiGe, and BiCMOS. According to Compound Semiconductor, the GaAs market is leading toward $2 billion in 2000, up from $1.3 billion in 1996. This corresponds to a CAGR of 15%. Most of this growth is attributed to the dramatic increase in the manufacturing of mobile phones. It is expected the communications market will be the source of 68% of GaAs applications in 2000. Of interest to Canadian firms is the fact that 90% of GaAs production is split almost evenly between the U.S. and Japan. The growth of GaAs has helped to create a booming market for communications equipment. The CMC licenses Canadian universities for GaAs technology and GaAs fabrication is being undertaken by Nortel. Considerable design effort on GaAs devices is being performed at Industry Canada's laboratories at CRC.

# Development and Technology Trends

# Development and Technology Trends

Wireless communications use radio waves to convey information over distance without wires. While the radio has become a basic technology all over the world, it was only just over one hundred years ago that Marconi invented the first device that could send Morse code signals over a short distance, in 1895. The first World War provided the first opportunity to seriously use radio communication, and was extensively used aboard military vessels. The first commercial broadcasting station started broadcasts in 1920 and the radio receiver soon became a standard household fixture. The first operational land mobile radio system came into use in 1928 using amplitude modulation (AM), which proved unsatisfactory since tall buildings and uneven landscape prevented successful transmission. The invention of frequency modulation (FM) in 1935 provided increased voice quality, required less power, used less bulky equipment, and was more resistant to propagation problems than AM. The advancements of the Second World War lead to the first mobile radio system connected to the public telephone network and in 1947 the concept of cellular telephony was conceived by AT&T engineers. The thought was that multiple low power transmitters could be placed throughout a city with calls being handed-off from one transmitter to another as a person moved throughout the city. Effective hand-off technology was not available though and wouldn't be for another couple of decades. In the United States, in 1977, the FCC approved two experimental licenses for mobile communications and in 1981 set aside 50 MHZ of spectrum in the 800 MHZ range for cellular use. As costs of expanding and running the cellular system decreased, airtime charges fell and the use of cellular spread rapidly throughout the world. In Europe at the same time the problems that were emerging due to the incompatibility of the cellular networks of different countries lead to the development of the Global System for Mobile Communications (GSM). The new standard chosen deviated from the then standard analog options of AMPS and TACS, and went with digital Time Division Multiple Access (TDMA). The commercial use of the GSM service began in mid 1991 and quickly spread around the world. On November 23, 1992, cellular subscriptions in the United States reached the 10 million mark. By mid 1996 this number reached 40 million. The GSM network now includes the original 25 MHZ of bandwidth, the Digital Cellular System, also called the Personal Communications Network (PCN), in the 1800 MHZ range, and the North American PCS network in the 1900 MHZ range. The high speech quality, low terminal and service costs, international roaming ability, spectral efficiency, ISDN compatibility, and the ability to support a host of new services of GSM has promised to displace analog cellular as the premier mobile communications system.

The electronic components that comprise the radio frequency portion of a wireless device are called RF electronic components (active and passive devices). RFIC technology is still in the emerging stage. The drivers will be low-cost, high performance and high

volume which will require new approaches in system and circuit design, semiconductor technology and packaging techniques. RFICs are the critical components of the terminal hardware section of wireless devices because they are responsible for processing the signal from the antenna and to deliver digitized signal intelligence to the data receiver.

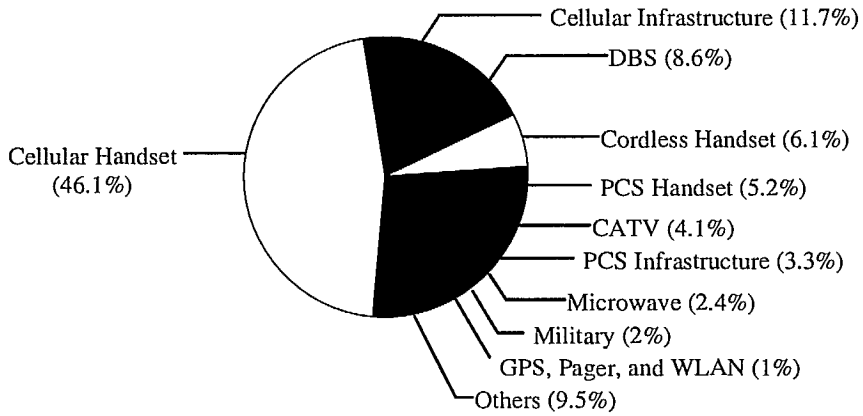
New products for digital mobile communications such as the PCS offerings provided by Mobility Canada, Clearnet, Microcell, and Rogers Cantel are being deployed at a rate which exceeds the deployment rate of any other consumer product ever introduced in Canada. The enhanced functionality in these and other related products in the 800 MHZ to 2 GHz frequency range is being largely delivered by the baseband and microprocessor circuitry within the device. RFIC technology enhancements are still in the early growth stage. Although the greatest efforts in silicon analog ICs have historically been aimed at baseband circuits which range in frequency of operation in the MHZ range, we are seeing some very sophisticated design occurring in radio receivers. Some of these are designs coming out of UCLA where RF amplifier transistors are integrated on these ICs, although they require discretes such as inductors for load on tuning circuits.

Mobile and handheld cellular phones are the first two large-scale applications of radio transceivers for commercial usage. Cordless phones were being developed about the same time. To support the large number of users in the allocated spectrum, cellular phones required a large amount of signal processing which required a high level of integration on the printed circuit board ICs. Conventional cellular telephones have typically employed GaAs ICs at the receiver and transceiver blocks. The new generation of PCS digital products are demanding a greater integration of RF and IF electronics. Miniaturization by the integration of ICs has been pioneered by semiconductor firms such as Siemens and Philips for GSM applications. With the proliferation of cellular users in the 900 MHZ spectrum, spread spectrum techniques will be the most prevalent modulation/demodulation scheme. UCLA has developed transceiver ICs which readily mix analog and digital circuits and employ CMOS and the IC technology of choice for the entire transceiver including the RF front end. Using CMOS voltages in the order of 3V and using a silicon substrate for discrete devices will ensure low power dissipation can be achieved since power consumed is directly proportional to voltage squared.

Paging receivers have been in continuous development since 1980, however it is only in the last two to three years that the binary frequency shift keyed (FSK) modulation has made possible data throughput of signals of over 1200 b/s. The demodulation circuitry has

allowed these throughputs to occur because of digital IC techniques but the RF sections of the wireless paging receiver have not evolved a great deal since the 80's. Even though the technology has not change rapidly, in the first half of 1997, paging alert devices and cordless telephones had year to date sales increases of 286% and 220%, respectively. The Yankee Group has forecast that the number of two-way paging customers in the U.S. will grow from under 400 thousand in 1997, to 77 million in 2005. Cordless phone designs are increasingly moving to the 900 MHZ spectrum incorporating the latest IC demodulation circuitry. Although the seemingly high rate of growth may partially be a reflection of the size of these two segments of the telecommunications equipment market, they are indicative of the overall strong growth in the telecommunications business. New test results have been achieved for a 900 MHZ paging receiver, a new development in the paging market. This development represents a step forward in the gradual evolution of the integrated radio.

**RF Semiconductors by Application Segment, 1996**




Source: Dataquest (August 1997)

The move to small modules and chipsets is spurring the inclusion of GPS receiver functions in a variety of products such as cellular phones and vehicles. The bundling of GPS with other services is being done to increase the value of the services being offered. The benefits of being wireless has not gone unnoticed by the cable industry. Within cable it has been the

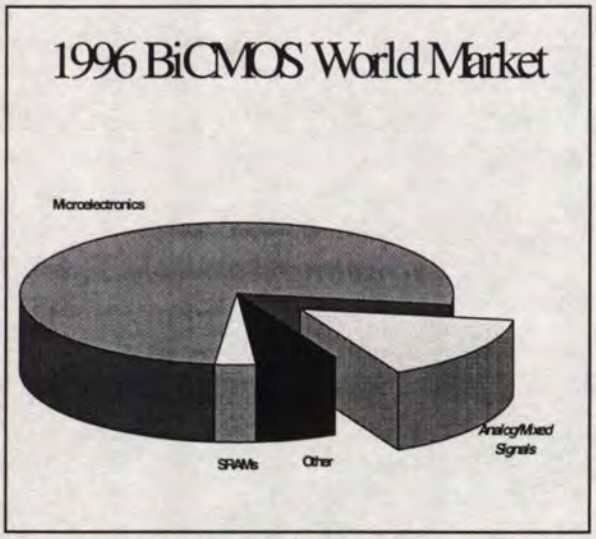
demand for two way service that has driven the development of wireless modems with two way capabilities and increased data capacity. Similar developments are also occurring in LMCS products.

The wireless LAN (WLAN) is a local area network without the cost or physical constraints of a wired connection. Besides the ease of installation and use, a wireless LAN has the characteristics of being isolated with short link ranges. These qualities allow for relatively small antenna sizes and the use of high frequency ranges. Frequency-hopping, spread-spectrum technology is usually considered more robust and less power intensive, but incapable of as high a rate of data throughput as direct-sequence radios.

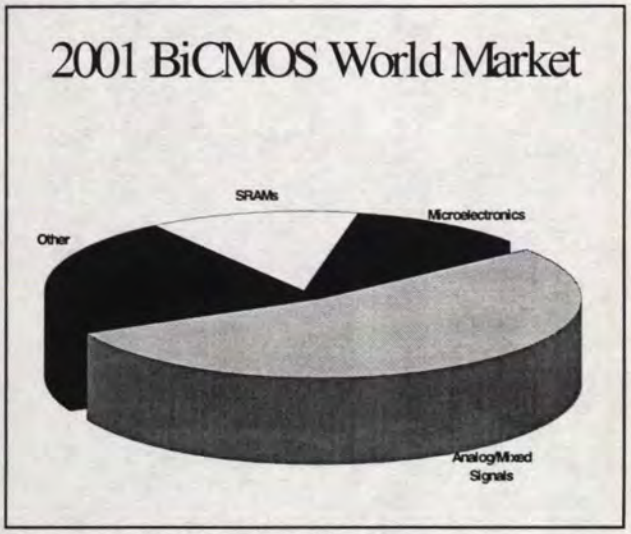
Another application segment which has seen tremendous change and growth is that of smartcards. The smartcard is an RF application with much time and resource saving potential. Whether used for security purposes, car tolls, or for financial transactions, the smartcard can be a product for not only every person, but every person several times over.

Discrete semiconductors are defined as components such as transistors, diodes, inductors, and capacitors. These devices are normally interconnected externally and they play a major role in the building of blocks such as amplifiers. Application driven markets for RF products are PCS and cellular handsets and their corresponding infrastructures. The infrastructure equipment usually involves different design, production, and marketing functions compared to the mobile phone portable device segment which includes product units such as cordless phones that do not roam amongst base stations like pagers, PDAs, and GPS. Microwave devices in the band beyond 2 GHz such as for LMCS applications require quite different design techniques and the active devices employed use primarily GaAs process technology at this point in time. The RF semiconductor market in 1996 experienced a sharp growth increase of 6% versus a decline of approximately 6% in the total semiconductor market. The most common RF semiconductor products were hybrid IC modules, monolithic ICs, and discrete components. According to Dataquest, the overall RF semiconductor market is 2.3% of the global semiconductor market with RF monolithic ICs the fastest growth area in this technology segment. The trend towards increasing integration has already begun as mentioned earlier in this chapter. No technology has the domination that CMOS does now, which estimates CMOS and its enhancements representing 90% of the total market in 2000. BiCMOS is on a growth curve as a high performance niche technology and will represent about 4% of the total IC market in 2000. The CMOS and BiCMOS combinations continue to advance and evolve to meet the majority of IC

performance demands. BiCMOS and SiGe are being considered as high speed replacements for pure CMOS because of their ability to implement CMOS and BiPolar functions on the same chip. According to ICE the BiCMOS IC market is forecast to grow at 11% CAGR in the period from 1994-2000 with the analog segment representing the strongest market sector for BiCMOS devices, particularly in communications systems.




Source : ICE, "Status 1997"




Source : ICE, "Status 1997"

ParkerVision, a Florida based American company had come out to announce a major breakthrough in RF technology. They say that this has the potential to completely revolutionalize the RF industry by making much of the current RF circuitry obsolete. It is promoting their innovation as the "Universal Direct Conversion Receiver", which could be used in many of today's RF products including telephone, pagers, security systems to name a few. This product's power consumption is less than 10mA, but can pass signal bandwidths up to 3MHz. It claims that it is an "excellent signal allowing for high gain / high sensitivity" for the fraction of the cost of current RF technology. A company official is quoted as saying "reads like a wish list of RF and wireless product designers" when talking about the capabilities of his Universal Direct Conversion Receiver.

In the U.S., Texas Instruments has started a drive in the wireless technology field with an eight product rollout. This will complete the company's strategy to produce all of the main silicon components for cellular phones. The new production TI is aiming at is for the digital cellular, digital cordless, and personal communications systems (PCS) telephone

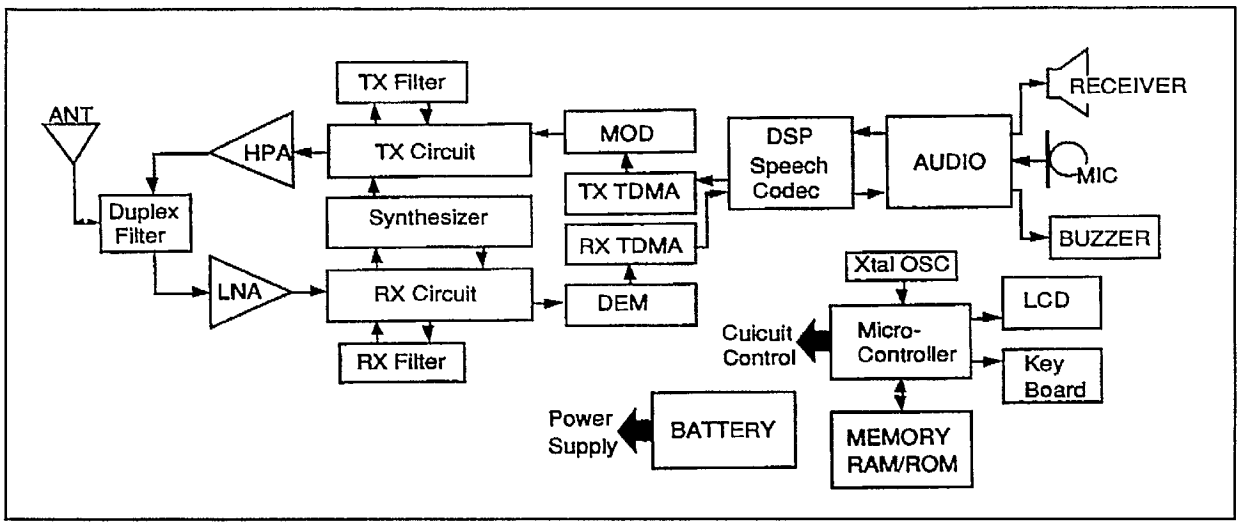
handsets market. In the third quarter of 97 after the introduction of this plan, Texas Instruments' profit increased dramatically on the back order for their new specialized computer chips. Their DSP's are being used currently in many products including cellular phones and high speed modems.

Corporations in order to maximize efficiency and compatibility, corporations tend to combine resources and make alliances to help further each other's research and development. One such alliance is the Universal Mobile Telecommunications System (UTMS) alliance which the Sony Corporation announce late 1997 that it was joining which is working towards a standard radio interface. This new radio interface standard will take many of the aspects of both time division multiple access (TDMA) and code division multiple access (CDMA). This alliance's members include some of the leading researchers in this area from corporations such as Nortel, Motorola, and others.

The combination of multiple standards and PCS and cellular frequencies, will see many subscribers using dual-mode/dual-band phones by the end of this decade. The most common current practice at the current time is unintegrated or ICs plus discrete and passive components. Suppliers are providing RF front ends of cellular phones by mixing and matching transceiver switches, LNAs, PAs and up/down converters. The goal of manufacturers and researchers such as those at the University of Toronto is to realize a single chip RF front-end for the mobile phone of the future.

Lucent Technologies have current released a new chip which they claim could significantly reduce the size and cost of many portable electronic devices such as pagers and cellular phones. Lucent Technologies is growing in this vibrant sector and has made many collaborations along the way. With Phillips, they were able to release a 1.9 GHz PCS phone that includes both analog and TDMA cellular technology. Their DSP designs are ones which theoretically are able to perform at triple the current level of speed that similar priced chips are running at today. Lucent research and development staff maintain they have the ability and expertise required to respond to the unique demands placed on them by the global wireless industry .

## Standard Digital Cellular Phone Design




Source : Koichiro Mashkio, 1996

In many cellular devices, the power source plays a major role in the choice of features and chips used. Without the advancement of batteries, many cellular devices would have a hard time evolving as they will require more power and power supplies will play a crucial role. The power consumption derivative is seen from analysis of the standard cellular phone design depicted above. The National Research Council of Canada's Institute for Chemical Process and Environmental Technology (ICPET) is currently working on the development of leading-edge batteries. Their pioneering research and development is focused on materials for energy storage. The main electrochemical materials being worked with are lithium. The Institute's research has led to many important and practical processing techniques involved in the testing, and fabrication of batteries. Results coming out of ICPET have contributed to a some patented inventions that have significant potential.

Rechargeable batteries are vital to the emerging mobile communications movement. The new lithium-ion rechargeable battery currently being researched at Dalhousie University is one of the most powerful rechargeable batteries being designed. It is expected to supply double the energy per mass unit than conventional batteries in use today. The requirement for increased power and energy density are driving this development effort. The

fundamentals behind this battery is a process known as intercalation, ie the reversible insertion of atoms into a solid. This means the insertion of lithium into the battery's electrode producing electricity and then being able to remove the lithium to restart over again. This new ratio of power to mass will allow batteries to have small geometries while maintaining the same power density.

# Canadian Activities

# Canadian Activities

Canada has been involved in RF studies ever since it became a recognized field after the second world war. Canadian involvement in RF spans all the realms of RFIC development and production, including R&D, semiconductor fabrication, electronic components, telecom, and servicing throughout. Through continuous expansion and growth the Canadian industry has become a leading proponent for the wireless industry and further RFIC development. Service providers have been responsible for developing many first-class alpha or beta sites for testing and implementation of these products.

The *Communications Research Centre (CRC)* is the major communications research facility of Industry Canada. With more than 200 engineers and scientists at CRC are involved in research of wireless, mobile and satellite communications, microwave and digital integrated circuits, new semiconductor materials, and wireless networks, among other areas. Their research can help access and evaluate technology opportunities both within Canada and around the world due to collaborative arrangements with over two dozen research organizations in North America, Europe, and Asia. The CRC actively participates in licensing agreements and collaborative ventures and currently has over 100 protected technologies ready for commercialization. Currently the CRC is carrying out R&D in hardware and software technologies applicable to the design of high performance ASIC and FPGA (Field Programmable Gate Array) based digital circuits and subsystems for communications applications. The pressing issues with the CRC are those of processing, power, and packaging for future applications that will require circuit integration of the order of subsystem or system on a chip. The memory, logic, and processor research focuses on the design methodology of generic cells and macrocells for communication DSP devices based on novel architectures and algebraic techniques for implementation on ASICs and FPGAs. The anticipation of future work in the area of MCMs has led to the investigation of subsystem and mixed technology integration issues. Collaborations with and provision of scientific consultation to Canadian industry and universities is also a major objective of CRC.

IRAP is one of the main programs run by the *National Research Council (NRC)*. By providing technology assistance to small and medium sized business, the NRC through IRAP has been very successful in providing support that produces invention, innovation, competitiveness, and business success for its clients. With 10 000 clients receiving advice each year from IRAP, of which 3500 have co-funded technical projects, it has become a centre of Canadian technology information growth and enhancement. Also at the NRC, the Canada Institute for Scientific and Technical Information (CISTI) is an information system designed to provide aid to CISTI clients around the world with medical, scientific, and technical information. This solution to a significant challenge in the product cycle of

targeted industries shows the commitment NRC has to stimulating the growth of technology intensive industries. One of the NRC's core competencies is with IT of which semiconductor process technologies is a major core element.

Another program initiated by Industry Canada, *Technology Partnerships Canada*, was created to help companies in specific industrial segments to ensure that pre-commercial products reach the marketplace.

The *Natural Sciences and Engineering Research Council of Canada (NSERC)* is a federally funded council which makes strategic investments in Canada's science and technology capability. Basic university research is supported through research grants to over 8000 Canadian researchers. Over $400 million annually has been invested in partnerships of universities with industry in fostering emerging and innovative technologies such as microelectronics.

The *Working Ventures Canada Fund* is one of Canada's leading Labour Sponsored Investment Funds. It has been established to provide a vital factor in the continued growth of Canada's economy by providing an investment source to SME's. The investment team for Working Ventures, invests in and contribute to some of Canada's promising growth companies in the wireless industry. Smaller Canadian companies have taken advantage of this group's investments to increment their company growth. Currently, over $65 million is invested in the computer and electronic sectors of Canadian business. These funds have help to support and encourage Canadian companies like Research in Motion and Mitec Telecom Inc which are established R&D manufacturing firms in the wireless business. Working Ventures Canada Fund is an investment firm looking into the future of technology as they support the rapidly growing sectors of our economy.

Another organization involved with both Canadian universities and industry is the *Canadian Microelectronics Corporation (CMC)*. Located in Kingston, Ontario the CMC provides services dealing with microelectronics and microsystems research and applications such as those using GaAs as building blocks. CMC has, for example, produced several products which allow companies to both extend the capabilities of existing products and to change the nature of, and allow for new uses of, existing products.

*Micronet* is a network of researchers from universities, industry, and government research organizations funded by the Government of Canada under its Networks of Centres

of Excellence (NCE) program. Working to develop new microelectronic systems, Micronet focuses on research dealing with the development of technologies for personal communications and information based systems. Through their Precompetitive Research Program, Micronet has developed focused research thrusts into several areas dealing with devices, circuits, and systems. The research work dealing with devices aims to investigate process technology, design, fabrication, modelling and characterization techniques for submicron semiconductor devices. Within the devices thrust, Micronet has addressed submicron devices, such as bipolar transistors, MOS transistors, SiGe heterojunction transistors, and device models for circuit design, as a major research area. The submicron devices initiative deals with the design, fabrication, characterization, and modelling of submicron MOS. This work is being done through a typical university, industry, and government organizations effort which includes Canadian Microelectronics Corporation, Gennum, National Research Council, Mitel, and Nortel Technology along with the University of Alberta, University of British Columbia, Carleton University , Simon Fraser University, University of Toronto, and the University of Waterloo. A primary component of the circuits is the high speed and low power analog and digital circuit design. The initiative development of CMOS, BiCMOS, and GaAs building blocks for high speed and low power signal processing applications is a major concern. Work in current mode circuits, mixed analog-digital circuits and data converters, wireless building blocks and ATM circuits is being carried out at universities across Canada in conjunction with Alberta Microelectronic Centre, Canadian Marconi, CMC, Gennum, Goal Electronics, Infomagnetics, Mitel, MOSAID, NRC, Nortel Technology, PMC-Sierra, Spar Aerospace, Wi-Lan, and Xilinx. The objective of the circuits work is to develop circuit design methodologies and implementation of cells and function blocks using both silicon CMOS and BiCMOS and GaAs technologies at the micron and submicron levels.

Research and development in Canadian companies and universities is not necessarily an isolated venture. Many collaborative efforts have been well received by industry with their academic counterparts. For instance, the *Telecommunications Research Institute of Ontario (TRIO),* one of Ontario's Centres of Excellence, which has become part of ITRC, matches the university research with the needs of Ontario industry. Using partnerships with industry and universities enables the researchers from both arenas to focus on shared research programs, producing precommercial results for both parties.

The above mentioned institutions of research and development which are partially government funded provide a locus for private companies to combine with the R&D

organizations thereby creating a broad base to support the growth in the Canadian activity.

With respect to the business sector, we have scoped out a partial list of contributors who are providing products and services in this technology domain.

*APREL Laboratories* located in Nepean, Ontario is an independent research and development firm specializing in the wireless communications industry. They work on electromagnetic interference and electromagnetic compatibility to name a few specific areas where APREL workers have focused in the past. Projects for clients include interference quantification for PCS; analysis, synthesis and development of technical positions on PCS interference; electromagnetic/health measurements methodology developments; and other complex topics on wireless EMC/EMI issues within this growing industry.

*Cadence Design Systems* opened it's Ottawa Design Centre in May, 1997. As a supplier of technology and services for Electronic Design Automation, Cadence provides characterization, testing, modification, and integration services for specific chip, board, and system design requirements. Being part of the Design Factory Network, the Ottawa Design Centre is developing specialization in the telecom sector with strengths in system design, as well as microelectronic chip and board design.

*FOCAM Technologies* is a microelectronics design engineering firm that specializes in analog, digital or mixed signal technologies. Focam has experience in telecommunications hardware design for data transmission and storage at the IC level as well as at the system level. This experience has come in the audio, video, graphics, and compression for data transmission and storage areas and has involved work with FPGAs, ASICs, and MCMs. The combination of Focam's state-of-the-art design software, and work stations give their design teams the ability to solve complex design problems in the design and manufacture of integrated circuits.

*Genesis Microchip* is a company specializing in graphics products. The image filtering technology and CMOS frequency synthesis circuits by Genesis are recognized as being some of the best in the industry. In November 1997, Genesis was awarded the title of "Outstanding Financial Performer" by the Fabless Semiconductor Association in the US.

*Gennum Corporation* of Burlington, Ontario designs and manufactures silicon integrated circuits and thick-film hybrid circuits. Gennum has in-house fabrication facilities

for wafer fabrication, hybrid manufacturing and packaging. While Gennum is a supplier of integrated circuit components for the professional video and broadcast markets, it also offers digital and analog products for a number of purposes, particularly for those markets that have unique performance and packaging requirements that can be applied to a range of products and telecommunications devices such as those highlighted in this document.

*Glenayre Technologies Inc.* recently acquired Wireless Access Inc. of Santa Clara, brings expertise in advanced pagers and IC design to Glenayre. This business development will allow Glenayre to expand on its R&D and manufacturing facilities in Vancouver where the company recently equipped Clearnet PCS Inc. with their MVP modular voice processing platform. Glenayre provides a custom solution for PCS networks. Glenayre won over several other manufacturers in part because of the depth of the services they were able to provide.

*Goal Electronics* specializes in mixed-signal circuits in CMOS processes in it's production of application specific integrated circuit design. Besides providing ASIC design services, Goal Electronics also provides prototyping services including circuit test and packaging to order. Through the company's wafer suppliers, limited production and full production runs can be accommodated.

*Nortel* based out of Brampton, Ontario is currently on the cutting edge of silicon germanium technology, the benchmark of the near future. Currently they are designing prototype chips for IBM which will be 30-50% cheaper than standard computer-chip designs using their SiGe technology. Nortel's staff of hundreds of IC designers are working on designing wireless components such as analog-to-digital converters and digital-to analog, embedded memories, high-speed interfaces and more. Nortel has complete lines of state-of-the-art Bipolar and CMOS devices available. Nortel Semiconductors' in-house capabilities, coupled with access to preferred external sources, provides solutions for a host of telecom semiconductor component. Nortel's DMS-100 switch which is used for wireless and wireline applications is a infrastructure sub-system. Nortel is an emerging North American wireless communications supplier and they are starting to become recognized as a primary supplier for some of the largest RBOC's and international PTTs

*Philsar* is an Ottawa based company specializing in custom integrated circuit design. Their engineers provide systems, RF design, and mixed signal semiconductor manufacturing expertise. Joint research projects at Carleton University has enabled Philsar to gain much

insight into low voltage/low power analog-digital circuit techniques and power optimization. Philsar chip design using this research techniques has attempted to combine completely integrated A/D converter, digital I&Q modulator, Digital FIR filters, along with dual DAC, interpolating FIR's and delta sigma techniques all on one chip. This has resulted in the creation of an Integrated GPS Receiver RF Front End ASIC using cutting edge bipolar technology.

*PMC-Sierra* of Burnaby, British Columbia, produces and services components for broadband transmission and networking systems. With a focus on high speed networking, PMC-Sierra makes high speed communications chips as well as custom mixed-signal and graphics chips.

The making of integrated circuits often includes a bit of guesswork. While making any batch of ICs, a given number of them will not be suitable for use after the manufacture and packaging process. *Quadrillion Corporation* in Kanata, Ontario has developed a product called Q-Yield that attempts to improve on this aspect of the IC industry. Using a process called 'data mining', Quadrillion can analyse and apply the data produced in a normal semiconductor fabrication process to the problems that reduce chip yields. The improvement in yields is another example of the commitment and initiative within the Canadian semiconductor industry to improve all aspects of the RFIC industry.

*Research in Motion (RIM)* has a strategic alliance with COM DEV, Intel, and Analog Devices for wireless teleworking products. RIM has design expertise in digital and analog ASICs. Four narrowband PCS carriers were chosen to operate new two-way paging services coast-to-coast which is requiring advanced RF technology (components, antennas, protocols) to enable technology for this market. RIM is a Canadian developer and manufacturer of two-way pagers, PC Card radios and OEM radios for the narrowband PCS wireless data industry, and wireless data modems for laptops and personal digital assistants. RIM claims that it is the Internet and the expansion of e-mail that is driving growth. Circuit-switched data, such as people talking on a cell phone, occupies a channel for the entire length of time that the call exists meaning it is more expensive and a less efficient use of spectrum than packet-switched data like the Internet and office LANs. RIM is concentrating on packet-switched messaging products to exploit this niche market.

Another company involved in silicon germanium is *SiGe Microsystems Inc.* This firm is attempting to capitalize on their strengths with silicon germanium processing technology

for use in high performance and low power digital wireless devices and related assemblies. The introduction of PCS in particular and GSM in general creates a potential market for their products.

TRLabs, a telecommunications research organization, was founded in 1986 is one of Canada's largest non-profit research consortiums. This consortium relies on industry, university and government collaboration. TRLabs employs a workforce of staff researchers, professors, university students, technical staff, and professionals. This organization focuses on many aspects of telecommunications including wireless communications. Currently in wireless technology, TRLabs is working on the following topics: reducing power requirements on indoor wireless communication devices for prolonged life of batteries; linearizing non-linear amplifiers in low power circuitry; providing wireless links to directly interface fibre optic systems; and other aspects or novel wireless technologies such as their wireless LAN using new technology to interface with fibre optic systems which has been demonstrated to be able to reach speeds of 150 Mb/s with a below average bit error rate commonly found in an equivalent fibre system.

*We have highlighted only a partial amount of the large amount of work being carried out in this technology sector and any omissions are completely unintentional.*

# Conclusion

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The RFIC industry is on the front end of a very large growth period in which Personal Communications Services is leading us. The growth in usage is changing the way people work and communicate and is providing many business opportunities for RF enterprises. Clearly, the Canadian involvement in the RFIC game indicates a strong and expanding presence in this emerging field. Currently a committed research and development effort and a receptive business community has provided Canada with the tools and products to maintain a lead in many areas of wireless communications. This overview on "RF Semiconductor and Related Wireless Activities in Canada" has attempted to provide a survey of some of the major activities occurring in Canada in the dynamic sector of wireless communications and semiconductors. Our conclusion is that as momentum increases in this vibrant sector, we will see that the most exciting times still lie ahead. We have the critical mass and skills to play a major role in this evolution.

# Glossary of Acronyms

| | |
|---|---|
| A/D | Analog to Digital |
| AMC | Alberta Microelectronic Centre |
| ASIC | Applied Specific Integrated Circuit |
| ATM | Asynchronous Transfer Module |
| BGA | Ball Grid Array |
| BiCMOS | Bipolar Complementary Metal Oxide Semiconductor |
| CAGR | Compound Annual Growth Rate |
| CDMA | Code Division Multiple Access |
| CDPD | Cellular Digital Packet Service |
| CISTI | Canada Institute for Scientific and Technical Information |
| CITR | Canadian Institute for Telecommunications Research |
| CMC | Canadian Microelectronics Corporation |
| CMOS | Complementary Metal Oxide Semiconductor |
| CSP | Chip Scale Package |
| DAC | Digital Analog Converter |
| DBS | Direct Broadcast Satellite |
| DSP | Digital Signal Processing |
| FCC | Federal Communications Commission |
| FET | Field-Effect Transistor |
| FIR | Finite Impulse Response |
| Flip Chip | An inverted silicon chip with no package |
| FPGA | Field Programmable Gate Array |
| GaAs | Gallium Arsenide |
| GHz | GigaHertz; billions of Hertz |
| GPS | Global Positioning System<br>Global Positioning Satellite |
| GSM | Global System for Mobile Communications<br>Globale Systemè Mondial (European) |
| HBT | Heterojunction Bipolar Transistor |
| IC | Integrated Circuit |
| IRAP | Industrial Research Assistance Plan |
| ITRC | Information Technology Research Centre |
| ISDN | Integrated Services Digital Network |
| KHz | KiloHertz; thousands of Hertz |
| LMCS | Local Multipoint Communication Systems |
| LMDS | Local Multipoint Distribution Systems |
| MACS | Microelectronics and Computer Systems |

| | |
|---|---|
| MCM | Multi Chip Module |
| MHZ | MegaHertz; millions of Hertz |
| MMIC | Microwave Monolithic Integrated Circuit |
| MVP | Modular Voice Processing |
| NCE | Network of Centres of Excellence |
| NRC | National Research Council Canada |
| NSERC | National Sciences and Engineering Research Council of Canada |
| PCN | Personal Communications Network (UK) |
| PCS | Personal Communications System |
| PDA | Personal Digital Assistant |
| RF | Radio Frequency |
| RIM | Research in Motion |
| SiGe | Silicon-Germanium |
| TDMA | Time Division Multiple Access |
| WACS | Wide Area Communications System |
| WLAN | Wireless Local Area Network |
| WLL | Wireless Local Loop |

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| Electrical Engineering Programs Ranking from the 1997 Gourman Report | | |
|---|---|---|
| **Institution** | **Score** | **U.S. Ranking** |
| Massachusetts Institute of Technology | 4.92 | 1 |
| Stanford University | 4.91 | 2 |
| University of California-Berkeley | 4.88 | 3 |
| University of Illinois, Urbana-Champaign | 4.86 | 4 |
| **University of Toronto (1)** | 4.86 | |
| University of California-Los Angeles | 4.82 | 5 |
| **McGill University (2)** | 4.82 | |
| Cornell University | 4.81 | 6 |
| **University of British Columbia (3)** | 4.81 | |
| **McMaster University (4)** | 4.80 | |
| Purdue University-West Lafayette | 4.79 | 7 |
| University of Southern California | 4.77 | 8 |
| Princeton University | 4.76 | 9 |
| University of Michigan-Ann Arbor | 4.75 | 10 |
| Carnegie Mellon University | 4.74 | 11 |
| Polytechnic University | 4.73 | 12 |
| **Queen's University (5)** | 4.72 | |
| **University of Alberta (6)** | 4.72 | |
| **University of Calgary (7)** | 4.71 | |
| University of Texas-Austin | 4.70 | 13 |
| **University of Manitoba (8)** | 4.70 | |
| **École Polytechnique (9)** | 4.70 | |
| **University of Saskatchewan (10)** | 4.70 | |

# U.S. Exports of Telecommunications Equipment

($millions US)

| | YTD June 1997 | YTD June 1996 | % change |
|---|---|---|---|
| Telephone Sets and Parts | 266 | 164 | 62% |
| Telephonic Apparatus and Parts | 2,098 | 1,903 | 10% |
| Telegraphic Apparatus and Parts | 716 | 570 | 26% |
| Radio Transmitters | 350 | 268 | 31% |
| Radio Receivers | 188 | 182 | 3% |
| Radio Trancievers | 917 | 787 | 17% |
| Telephone Answering Devices | 59 | 78 | -25% |
| Communications | 2,272 | 1,792 | 27% |
| Cellular Telephones | 903 | 1,021 | -11% |
| Facsimile Machines | 25 | 58 | -57% |
| Cordless Telephones | 546 | 171 | 220% |
| Modems | 558 | 512 | 9% |
| Paging Alert Devices | 4 | 1 | 286% |
| Fiber Optic Cable | 421 | 320 | 31% |
| Other Cable Parts | 256 | 214 | 20% |
| **Total** | **9,580** | **8,042** | **19%** |

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