A STUDY OF THE VIABILITY OF RF MEMS FOR THE IMPLEMENTATION OF A SINGLE-CHIP PROGRAMMABLE RF FRONT END FOR SOFTWARE DEFINED RADIO FEMTO CELLS

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RADIO FEMTO CELLS

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DISSERTATION ABSTRACT

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The RF front end circuitry makes up over 60% of the cost of a base transceiver station (BTS, also referred as Node B in 3G networks). Included in this cost is that of the Power Amplifier unit, RF filters, and the GPS unit for clock recovery and synchronization. Because of the evolving mobile wireless communications standards (2G/2.5G/3G/LTE/4G and their various implementation standards including CDMA2000, WCDMA, TD-SCDMA, WiMAX, etc), the BTS original equipment manufacturer (OEM) is faced with the monumental task of designing a BTS RF Front End for each mobile network standard that they wish to support. Moreover, the OEMs are forced to manufacture and maintain in the field all of these BTS variants.

One way to address the frequency re-use and power range limitations of today's base stations is to have more base stations covering smaller geographical areas by implementing what is called a femtocell, which also implies a significant cost reduction of the RF front end. Thus the RF front end represents the single biggest opportunity for cost reduction and logistics simplification for the base station of the future: the software-defined radio based cellular femtocell. The problem is that today's BTS RF front end implementations are not programmable but fixed to work with a specific RF frequency (e.g., 1,900 MHz) for a specific mobile network standard (e.g., CDM2000 or W-CDMA). To band-aid this problem, the OEMs typically implement multiple RF front ends to give the illusion of a "multi-band" programmable system at twice, triple or quadruple the cost of a single-band system.

RF MEMS (micro-electro-mechanical systems) is a technology that has the potential to not only help solve the BTS cost and logistic issues, but also to complement SDR architectures by providing a true low cost, high performance, programmable RF front end. Because of its potential in the implementation of low cost, high performance, programmable RF front end filters and antennas, the author is investigating the possibility of implementing a single-chip programmable RF MEMS front end for SDR-based cellular pico and femto base stations for commercialization by 2015 or earlier. This dissertation summarizes the author's findings, conclusions, and future work recommendations.

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Computer software used: Microsoft© Office Word 2003.

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Chapter 1 The State of the Mobile Wireless Communications Industry

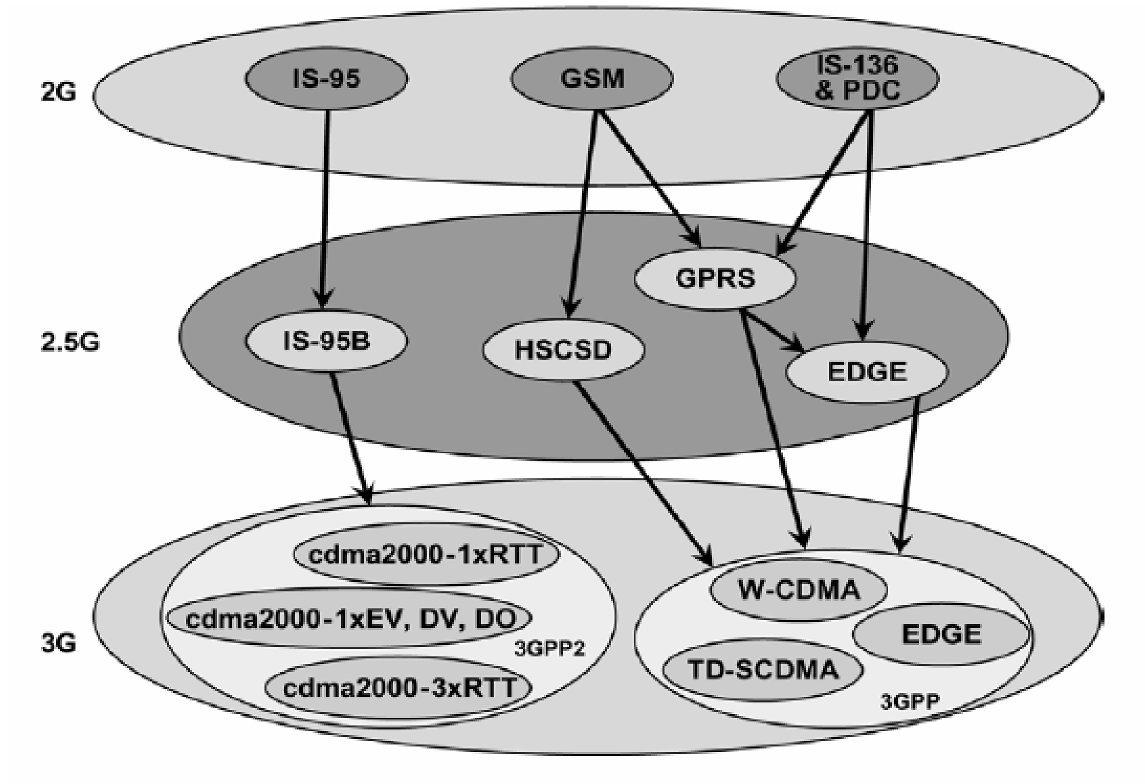
1.1 General Overview

The wireless mobile communication industry is the fastest growing segment of the telecommunications market. At the same time the wireless mobile industry is in a state of transition from the legacy analog network, 2G, to the new 3G network. Japan has been leading the way in the implementation of new 3G services, including EVDO and HSDPA for data access. A series of new standards have emerged over the past few years for mobile wireless, including WCDMA, CDMA-2000, TD-SCDMA, EVDO, and HSDPA. Fig. 1.1 shows the migration paths across the various generations of wireless mobile technologies.

The 3rd Generation Partnership Project (3GPP) is a collaboration initiative between groups of telecommunications associations, to make a globally applicable third generation (3G) mobile phone system specification within the scope of the International Mobile Telecommunications-2000 project of the International Telecommunication Union (ITU). 3GPP specifications, also known as UMTS, are based on evolved Global System for Mobile Communications (GSM) specifications. 3GPP standardization encompasses Radio, Core Network and Service architecture.

3GPP2 (not to be confused with 3GPP) is the standardization group for CDMA2000, the set of 3G standards based on earlier 2G CDMA technology [1]. Not shown in Fig. 1.1 is the migration from 3G to 4G yet to come in the next three to five years (see also Chapter 6**).**

In today's market, the subscriber / end user is at the center of everything, and the



Source: [2]

Figure 1.1 Various Upgrade Paths for 2G to 3G Technologies

services are driven by user demands. Initially more focused on short message service (SMS), multimedia message service (MMS), and content downloading, the 3G market has moved rapidly toward video sharing, mobile video, and IPTV, all of which require very high data throughput and highly efficient radio.

The latest UMTS evolution brings improved spectral efficiency at lower latency and higher data speeds with almost 100 times improvement from 3G, which is the promise of 4G services. In addition, because of the increasing popularity of broadband access services like xDSL and cable for graphics and video streaming, a new broadband wireless access (BWA) competing and complementary technology has recently emerged: WiMax (Worldwide Interoperability for Microwave Access). This technology has the potential to compete not only with 3G mobile wireless networks primarily in data applications, but also in voice applications thanks to voice-over-IP standards (VoIP). Fig. 1.2 shows a typical WiMax 802.16 network which also requires base stations connected to 802.11 "hot spots" to reach the end users.

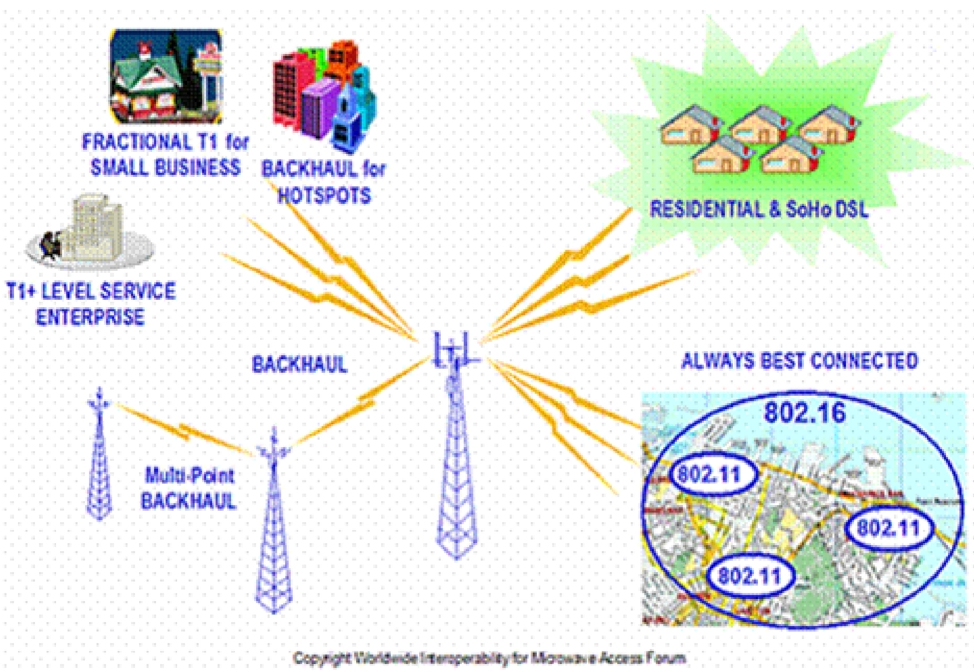
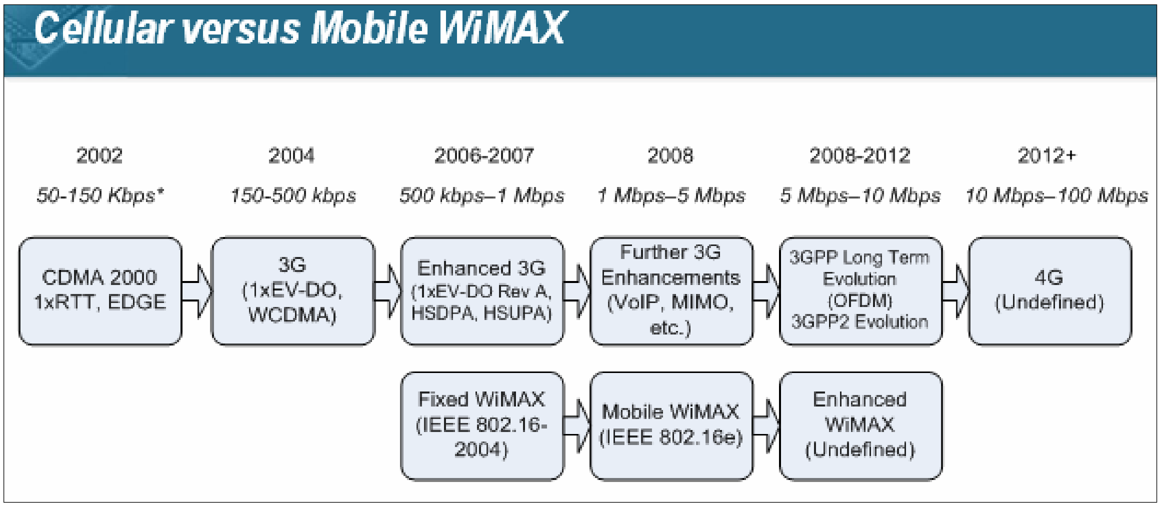


Figure 1.2 WiMax Network

Fig. 1.3 shows a more complete view of the various competing wireless standards and highlights that the trend for the co-existence of multiple wireless standards will continue for many years ahead.



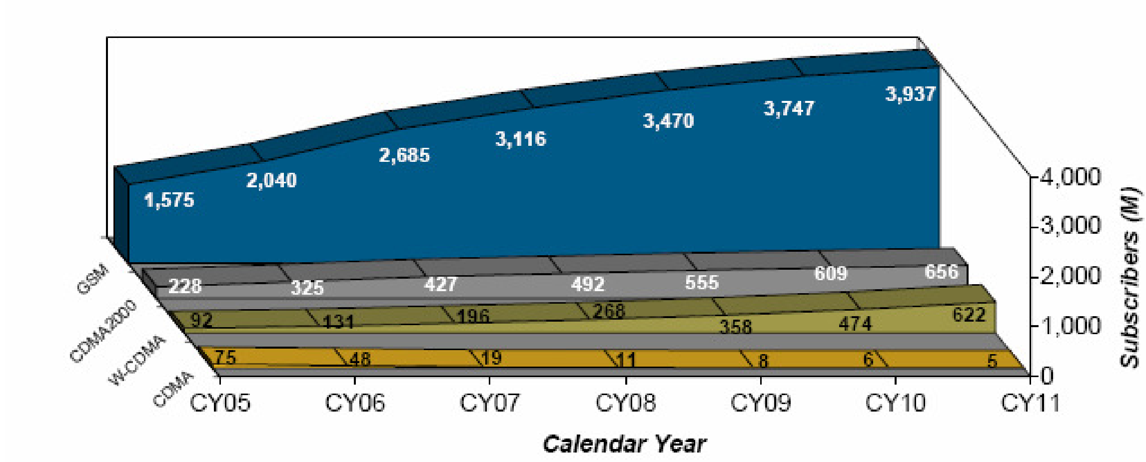
Source: Dr. Hossam Hmimy, Ericsson, 2006

Figure 1.3 Cellular versus Mobile WiMAX

Fig. 1.4 not only shows that the predominant technology for subscribers continues to be GSM but also that the 3G technologies are starting to increase in volume and will become more predominant in the next decade.

Fig. 1.5 shows the top mobile operators around the world. Of particular interest is the fact that the Chinese operators have the most subscribers followed by Latin America. In terms of operator's market share, China Mobile ranks at the top with Vodafone in second place. However, China Mobile is a domestic operator only while Vodafone, a UK company, is worldwide.

Of particular interest are the wireless telecommunication trends that are



Source: Infonetics Research, September 25, 2008

Figure 1.4 Worldwide Mobile Subscribers by Technology

Top Mobile Operators

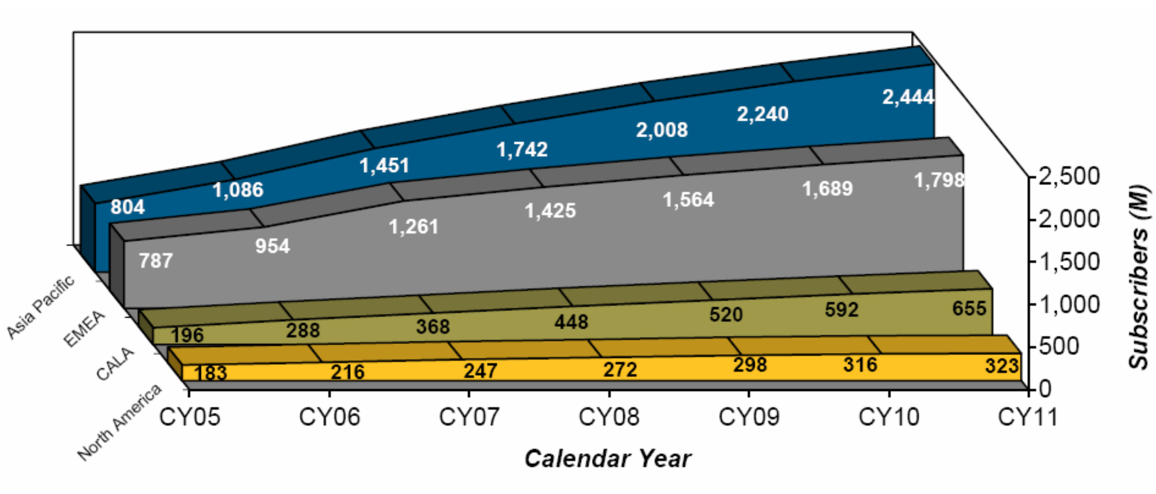
Service Provider	Service Provider Type	Region	Country	Q2 2008 Subscribers (in millions)
China Mobile	Wireless	Asia Pacific	China	414.6
Vodafone	Wireless	CALA, NA, EMEA, Asia Pacific	Worldwide	234.4
China Unicom	Wireless	Asia Pacific	China	170.8
America Movil	Wireless	CALA	Pan-Latin America, Jamaica, Puerto Rico, US	165.3
France Telecom	Incumbent	EMEA, NA, CALA	Pan-Europe, Pan-Africa, Dominican Republic	113.8
Telefonica Latin America	Competitive	CALA	Pan- Latin America	113.5
Deutsche Telekom	Incumbent	EMEA, NA	US, Pan-Europe	93.5
Orascom	Wireless	EMEA, Asia Pacific	Pan-Middle East, Zimbabwe, Pakistan, Bangladesh	74.1*
AT&T	Incumbent	NA	US	72.9
Bharti Airtel	Wireless	Asia Pacific	India	69.4
Verizon	Incumbent	NA	US	68.7
MTN	Wireless	EMEA	Pan-EMEA	61.4*
NTT Group	Incumbent	Asia Pacific	Japan	53.4
Sprint Nextel	Wireless	NA	US	52.6
PT Telkom	Incumbent	Asia Pacific	Indonesia	51.3

**Subscribers as of 1Q 2008*

SOURCE: Infonetics Research Service Provider Capex, Opex, ARPU, and Subscribers: Worldwide, Monthly Update: 09/05/08

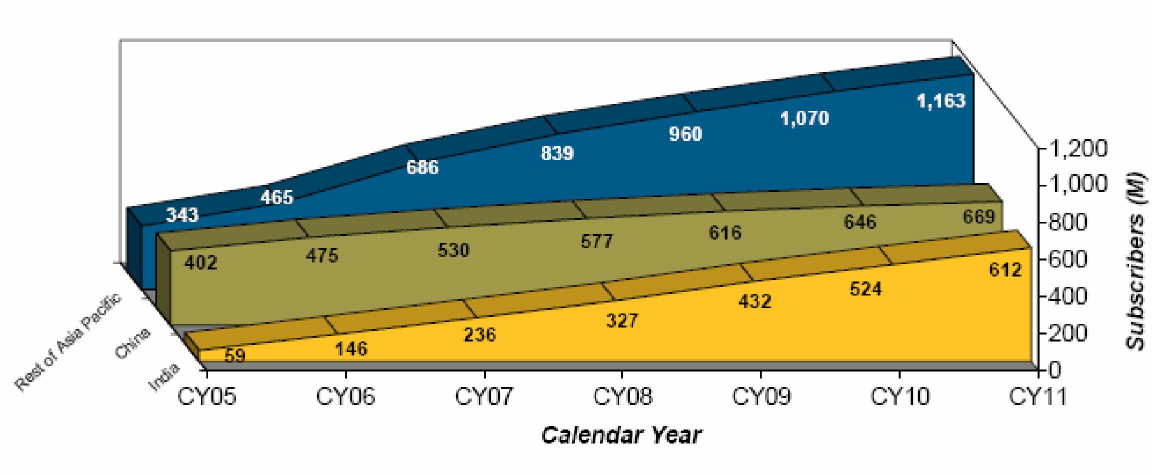
Figure 1.5 Top Mobile Operators around the World happening in China, Japan, South Korea, India, Europe and the United States. The author spent several months at each of these regions of the world, in particular China and Japan, researching such market trends and published his findings in various papers at Auburn University [3].

Fig. 1.6 shows the number of mobile subscribers by geographical region between 2005 and 2011. It can be seen that Asia Pacific leads the world in terms of subscribers with EMEA ranking in second place. Asia Pacific is also the fastest growing market and is expected to add over 200 million subscribers per year between 2009 and 2011. India will have the highest subscriber growth adding about 100 million subscribers per year as shown in Fig. 1.7Figure 1., followed by other countries in Asia Pacific (primarily South East Asia).



Source: Infonetics Research, September 25, 2008

Figure 1.6 Mobile Subscribers by Geographical Region



Source: Infonetics Research, September 25, 2008

Figure 1.7 Mobile Subscribers by Asia Pacific Sub Region

1.2 China

As of 2006, China had been conducting standardized on-location tests on all three internationally recognized 3G technologies. The three technologies are: TD-SCDMA standard jointly developed by China's Datang Mobile Communications Equipment Corporation and Siemens from Germany [See Appendix B]; W-CDMA standard based on the global mobile communication network system, a system commonly used in Europe; and CDMA2000 standard, popular in USA using CDMA standards. Among the three, China owns the intellectual property of TD-SCDMA.

On May 23, 2008, China, the most populous nation in the world, announced a historical re-structuring of their telecommunications carriers. The announcement called for the six major Chinese carriers (China Mobile, China Telecom, China Netcom, China Unicom, China Railcom, and China Satcom) to re-structure into three New carriers: New China Mobile, New China Telecom, and New China Unicom. Each of these New carriers would be focused on different 3G standards: New China Mobile would promote TD-SCDMA (China's own 3G standard), New China Telecom would focus on W-CDMA, and New China Unicom on CDMA2000. Interestingly, this re-structuring came as no surprise to the author. On May 18, 2006, the author interviewed a high-level official at Huawei Technologies who speculated that, while China was working on its own 3G standard (TD-SCDMA), the most like scenario would be that the Chinese government would end up supporting all three 3G standards concurrently.

Fig. 1.8 shows the trend on the number of wireless subscribers in China from 1999 to 2008. The total number of wireless subscribers in 2007 was estimated between 510 to 540 million, which would amount to a penetration of just over 40% considering that China had a population of 1.33 billion as of mid-2008. Moreover, another industry estimate predicts that by 2010 the number of subscribers will increase to 738 million, or roughly 55% of the population [4]. As of 2008 over 75% of the subscribers in China were for 2G GSM services and the rest for 2G CDMA services. China is in the very early stages of 3G technology deployment but it is expected that after 2009 subscribers will rapidly move to 3G services.

The recent China telecommunications re-structuring and wireless mobile market trends support the belief that multiple wireless standards will co-exist in China for many years to come. The adoption of the three 3G standards in early 2008 also indicates that a vast volume of 3G base stations and handsets will be deployed in China during the next five years at cost targets which will be much lower than most Western countries.

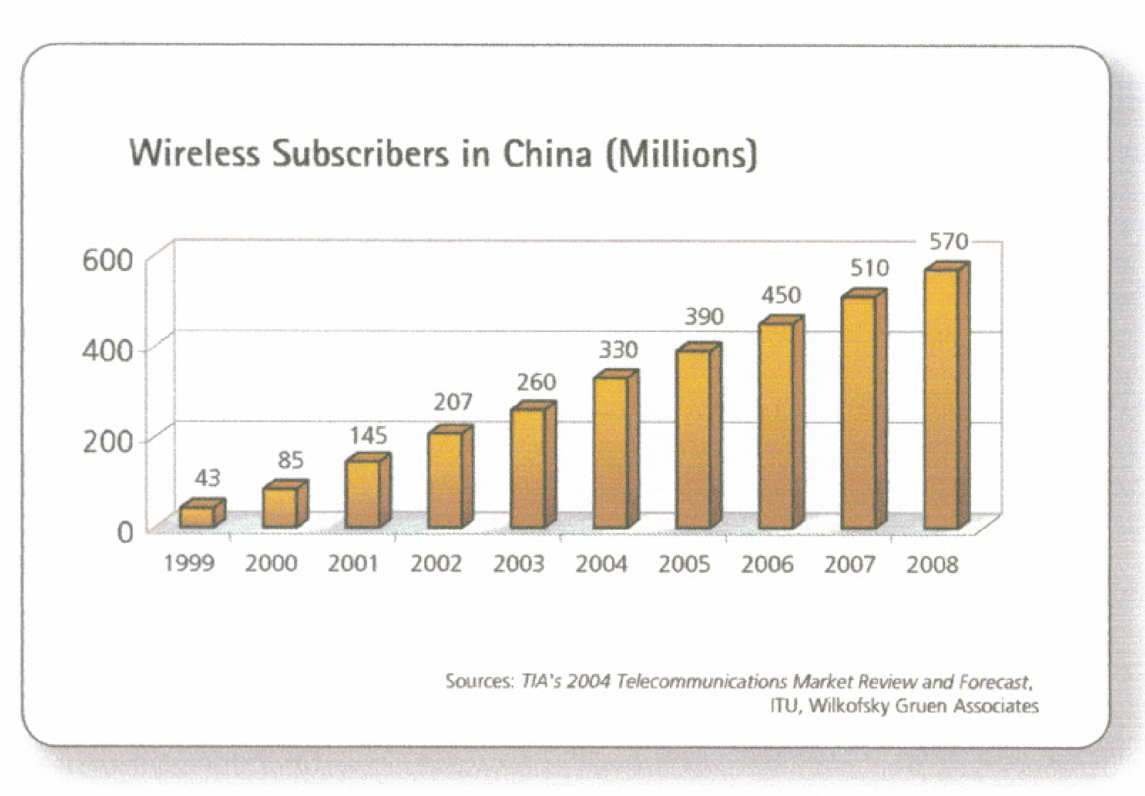


Figure 1.8 Wireless Subscribers in China

1.3 Japan

As of August 31, 2008, Japan had just over 104 million subscribers of mobile wireless phones [5], representing a penetration rate of 81% for a population of 128 million as of mid 2008. About 89% of the 104 million are for 3G services using either W-CDMA or CDMA2000 technologies. What is most interesting about Japan's 3G subscribers is that 100% have access to the Internet via their mobile phones. The data access rates vary according to which technology is used as shown in Fig. 1.9. Japan's leadership in the adoption of the latest wireless mobile technologies was further validated by DoCoMo's announcement in June of 2005 that it was already testing 4G wireless networks, which would provide down link data speeds of about 1 Gbps [6].

> What is important about 3G upgrade technologies is that it allows for the evolution to faster and faster mobile data communications, from the old 2G speeds of 9,600 bits per second (bps) to maximum peak data rates of (depending on its implementation):
>
> - 160 kbps (theoretical limit) for GPRS (General Packet Radio Service), a 2.5G GSM technology
> - 384 to 480 Kbps for EDGE (Enhanced Data Rates for GSM Evolution), a 2.75G W-CDMA technology
> - 2.4 to 3.1 Mbps for EVDO (Evolution Data Optimized), a 3G cdma2000 technology
> - 1 to 14 Mbps based on different modulation and error-correcting methods for HSDPA (High Speed Downlink Packet Access), a 3.5G W-CDMA technology.
>
> In reality, the actual data rates that can be achieved today are less than the advertised "maximum peak" rates indicated above.

Source:
www.mobilein.com/Perspectives/eJapan_Article_062206.pdf by Jeorge S. Hurtarte

Figure 1.9 3G Data Access Speeds

On January 22, 2001, The Prime Minister and His Cabinet released the following statement to the Japanese people:

> "Japan must take revolutionary yet realistic actions promptly in order to create a "knowledge-emergent society," where everyone can actively utilize IT and fully enjoy its benefits. We will strive to establish an environment where the private sector, based on market forces, can exert its full potential and make Japan the world's most advanced IT nation within five years." [7]

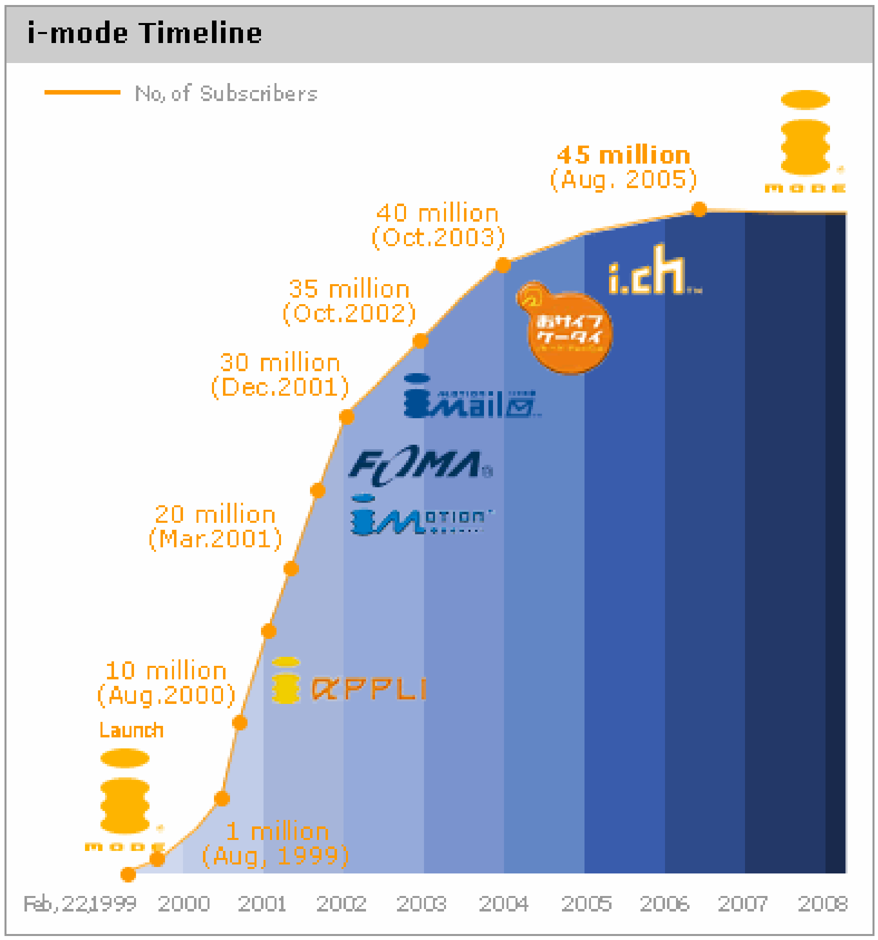
The e-Japan initiative had as one of its goals to "establish one of the world's most advanced Internet networks within five years, and enable all the people who need it to have ultra high-speed access networks" using fixed-line and wireless networks. In the wireless mobile industry, Japan was the first country in the world to install the latest third generation (3G) wireless network infrastructure.

During the five-year e-Japan project of 2001-2006, three were the wireless carriers that took the lead in its implementation:

- NTT DoCoMo with a W-CDMA 3G wireless network infrastructure launched in October 2001. NTT DoCoMo was the first wireless carrier to introduce the "always-on" data services capability with its i-mode feature, and the first one to introduce financial services to the mobile phone with its FeliCa technology. NTT DoCoMo's market share in 3G services by was 49% by August 31, 2008.
- KDDI AU with a CDMA 2000 3G wireless network infrastructure launched in April 2002. KDDI AU was the first one to introduce the high speed data service in Japan in November 2003 using EVDO technology at 2.4 Mbps peak rates (the effective data rate is about 500 kbps). KDDI AU's market share in 3G services was 32% by August 31, 2008.
- Vodafone (J-Phone before being acquired by Vodafone) with a W-CDMA 3G wireless network infrastructure which was launched in December 2002. Vodafone was later acquired by Softbank in early 2006. Softbank's 3G market share was 17% by August 31, 2008.

Fig. 1.10 shows the evolution of i-mode related services as introduced by NTT DoCoMo. The number of i-mode services stood at 46 million subscribers as of August 31, 2008.

Thanks to their 3G wireless infrastructure all newer phones are "always-on" in the sense that as long as they are powered up, they are always connected to the high speed Internet. Thus, email messages can be received instantaneously and there is no need to log in to any e-mail service provider account. Just a quick look at NTT DoCoMo's phone line-up can provide a good insight of the various feature trends in Japanese phones, which include larger LCD displays, IR information exchange, bar code readers, built-in FM radios, Moji icons, etc. NTT DoCoMo's phone line up even includes some models for children aimed at promoting the use of mobile communications at an early age [8].



Source: www.nttdocomo.co.jp

Figure 1.10 NTT DoCoMo's i-mode Services Evolution

Japanese people have access to a wide variety of 3G services which include: 1) e-mail, 2) internet access, 3) location-based services which enable the user to check the weather forecast, traffic and store information, and other convenient information for local areas as well as the map information to the user's current location, 4) dynamic video content, 5) financial services that enable to phone to act like a "credit card" and many other 3G-enabled services [9].

Japan's leadership in the adoption of 3G technology has led the way to a wide variety of data-intensive services and features which in turn has given way to a lot of innovation in the phones. Japan's top-down initiative by its government will continue to drive the Japanese people towards even more advanced wireless mobile technologies like 4G ahead of any other nation in the world. It can also be inferred from such market trends that the amount of features that will be added to Japan's 4G-enabled phones will tax the amount of the printed circuit-board space available and will also drive down the cost budgets for the electronics related to the RF front end of such phones. See also [10] for an article written by the author on Japan's world leadership in the implementation of 3G infrastructure and its related phones.

1.4 South Korea

South Korea's mobile phone penetration was roughly 88% in early 2008 for a population of 49 million people, and the mobile phone penetration is expected to grow to 95% by 2010. After Japan, South Korea launched the second 3G network to go commercially live by SK Telecom in South Korea on the CDMA2000 1xEVDO technology in January 2002. By May 2002 the second South Korean 3G network was launched by KTF on EVDO, and thus the Koreans were the first to see competition among 3G operators.

South Korea has long led the way in the rapid adoption of wire-line high speed broadband access and took a world leadership position with the adoption of xDSL broadband access technologies. Non-surprisingly, such leadership on broadband access prompted South Korea to also lead the way on yet another broadband access technology: WiBro, which stands for Wireless Broadband. WiBro is the South Korean service name for the IEEE 802.16e (mobile WiMAX) international standard.

WiBro was devised to overcome the data rate limitation of mobile phones (for example CDMA 1x) and to add mobility to broadband internet access (for example ADSL or Wireless LAN). In February 2002, the Korean government allocated 100 MHz of electromagnetic spectrum in the 2.3 - 2.4 GHz band, and in late 2004 WiBro Phase 1 was standardized by the TTA of Korea. In late 2005 the ITU incorporated the elements of WiBro in the IEEE 802.16e standard. Two South Korean Telcos (KT, SKT) launched commercial service in June 2006.

In November 2004, Intel and LG Electronics executives agreed to ensure compatibility between WiBro and WiMAX technologies. This agreement signaled a major step towards the adoption of both WiBro and WiMAX as viable competing technologies versus 3G mobile technologies. This fact was further accentuated when in September 2005, Samsung Electronics signed a deal with Sprint Nextel Corporation of the United States of America to provide equipment for a WiBro trial.

WiBro base stations will offer an aggregate data throughput of between 30 to 50 Mbps and will cover a radius of 1-5 km allowing for the use of portable internet usage. WiBro will provide mobility for moving devices up to 120 km/h (74.5 miles/h) compared to Wireless LAN having mobility up to walking speed and Mobile Phone having mobility up to 250 km/h. The technology will also offer improved Quality of Service (QoS; see also Chapter 4). The inclusion of QoS allows for WiBro to stream video content and other loss-sensitive data in a reliable manner. These all appear to be (and may be) strong advantages over the fixed WiMAX standard (802.16a).

Wireless broadband access is set up like a cellular system; using base stations that service a radius of several miles/kilometers (see Fig. 1.2). Base stations do not necessarily have to reside on a tower. More often than not, the base station antenna will be located on a rooftop of a tall building or other elevated structure such as a grain silo or water tower. A customer premise unit, similar to a satellite TV setup, is all it takes to connect the base station to a customer. The signal is then routed via standard Ethernet cable either directly to a single computer, or to an 802.11 hot spot or a wired Ethernet LAN.

South Korea's leadership in the adoption of broadband access technologies has established WiBro/WiMAX as yet another wireless mobile technology that has potential as a viable competing technology against 3G mobile wireless (see also Fig. 1.3). This fact further validates the fact that the base stations and handsets of the future will continue to support multiple wireless standards.

1.5 India

The mobile market in India continued its strong growth through 2007 and looked to be carrying a 50 percent annual growth rate into 2008. While the market was initially totally a GSM domain, CDMA technology was introduced as a Wireless Local Loop (WLL) service, which after a long battle with the regulator was eventually accepted as a legal mobile service. The subscriber base has developed into a fairly stable mix of GSM subscribers, (74 percent market share at end-2007) and CDMA subscribers (24 percent).

India had almost 350 million mobile subscribers (including GSM & CDMA) in early 2008, representing a penetration rate of only 30%. However, the number of subscribers surpassed by far all estimates of 2004 as shown in Fig. 1.11.

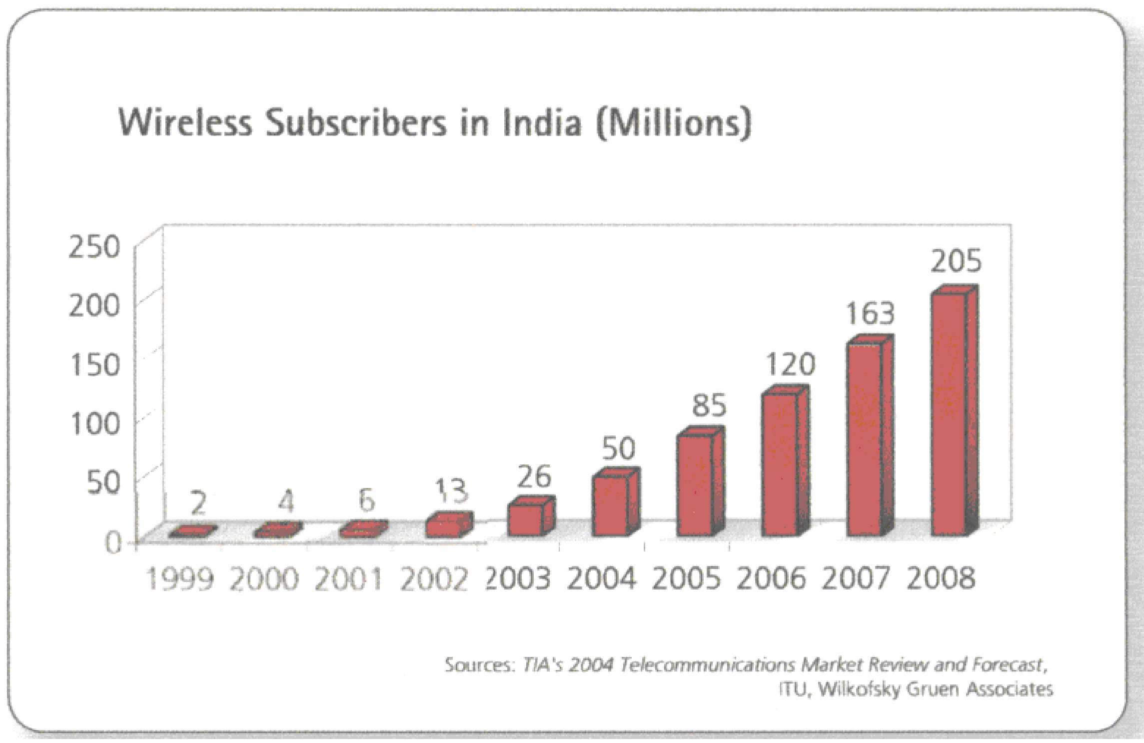


Figure 1.11 India's Wireless Subscribers

The huge potential of the mobile wireless market in India was attracting foreign investment. Vodafone arrived on the scene with a considerable impact, having successfully acquired Hutchison Telecom's 67% stake in Hutchison Essar for US$11.1 billion, one of the largest ever single foreign investments in India. UK incumbent BT also boosted its presence in India in 2007, expanding the footprint of its managed network services and IT operations in the country through its acquisition of i2i Enterprise.

As of mid 2008, there was a capacity crunch in India primarily paced by capacity limitations at the State-owned Bharat Sanchar Nigam Ltd (BSNL). In August 1, 2008, India's government announced its plans to hold an international auction for 3G and WiMAX telecoms services in the world's second-largest mobile phone market, with the minimum price for a pan-India license set at Rs20bn ($472M) [11]. Wireless licenses would be auctioned, and the process was expected to be completed within several months. Up to five operators would be selected to provide wireless services in each coverage area. As of March 2009, the 3G action was still pending.

Government-owned service providers, Bharat Sanchar Nigam Ltd (BSNL) and Mahanagar Telephone Nigam Ltd. (MTNL), would each receive a license, gaining a head start of several months over competitors in rolling out 3G services. At least two CDMA operators would be allowed to offer 3G services in each license area.

Indian spectrum in the 2.1-GHz band was designated for 3G services, with as many as 10 blocks available for auction in each region. Spectrum for EVDO data services would be auctioned in the 450- and 800-MHz bands, and eventually in the 1,900-MHz band. Some pockets in the country are expected to have WiMax earlier than 3G as private operators such as Reliance, Tata and Bharti have been aggressive on this technology front.

Clearly, India is still at the early stage of mobile phone penetration and the growth of 2G services will continue to be phenomenal. 3G services will be next with W-CDMA, CDMA-2000 and WiMAX co-existing for the many years ahead.

1.6 Europe

In general the EU countries have completed the transition to UMTS W-CDMA 3G networks and are quickly becoming at par with Japan, which has led the implementation of 3G in the world. With mobile penetration at or nearing saturation across Western Europe, the deployment of new technologies and services such as HSDPA and broadcast mobile TV is providing operators with the opportunity to enhance their product portfolios and increase the average-revenue-per-user (ARPU) levels. The country with the highest penetration rate in the world is Luxembourg with 157.3 mobile subscribers for every 100 people.

The total mobile subscription in Europe reached 753.5 Million by the end of December 2007 at a CAGR of nearly 17.6% during the period 2002-2007. In terms of subscriber base, the largest market in Europe is Russia with a share of 22%. In comparison, Ireland forms the smallest market with approx 0.7% share in 2006. Total mobile subscribers in the European region are expected to increase at a CAGR of around 2.35% during 2008-2012. Eighty percent of Europeans will use 3G by the end of 2013. Mobile Internet usage will triple from 2007 to 2013 to 125 Million Users. [34]

The following are some mobile market trends to watch in the EU:

- Mobile Broadband. Internet access via the mobile phone at broadband data rates in excess of 500kbps.
- Data networking. The use of shared applications such as Microsoft NetMeeting, as well as access to corporate intranets and to corporate database applications such as customer relationship management (CRM) and enterprise resource planning (ERP) applications or mobile workforce management applications.
- Browsing. Content that is made available over cellular networks without charge, other than those charges that apply for standard network access,

including mobile-specific content (free-to-air information) and general Web access (Web browsing).

- Paid information. Push or pull electronic content, delivered over cellular networks, for which a premium is paid over and above standard network access charges.
- Entertainment services. Downloading or accessing games, cartoons, music, video clips and other forms of entertainment over a cellular network. Messaging based on third-party content and interaction with other media (such as TV programs) is included in this service category.
- M-commerce. Transaction-oriented services, including e-pay facilities, mobile shopping portals, mobile banking and share trading, and bookings and ticketing, but excluding games and other forms of content.
- Video-telephony. Real-time, audio-visual, person-to-person communications.
- Fixed-Mobile Substitution (FMS). While voice telephony generates by far the greatest proportion of mobile operator revenue in Western Europe, mobile voice telephony will strongly influence mobile operators' revenue prospects for at least the next three years. Fixed–Mobile Substitution (FMS) encompasses traffic substitution, as voice calls migrate from fixed to mobile services, and line substitution, as households and businesses dispense with their fixed-line voice services. FMS continues to represent a critical threat to fixed operators. Fixed-line substitution is particularly damaging because it removes fixed operators' opportunity to generate revenue from either voice or broadband services.
- HSUPA. High-Speed Uplink Packet Access (HSUPA) is a 3G mobile telephony protocol in the HSPA family with up-link speeds up to 5.76 Mbit/s. The specifications for HSUPA are included in Universal Mobile Telecommunications System Release 6 standard published by 3GPP. Vodafone, T-Mobile, 3, Telecom Italia and all other major European carriers introduced HSUPA service in late 2007. Vodafone was the first network operator in Germany to launch in 2007 a notebook data card that delivers online content downloads at speeds of up to 7.2 megabits per second plus extremely fast uploads. It supports upload rates of up to 1.45 megabits per second using the new HSUPA technology, which is four times faster than ever before. It can be used to send very large image and video files or PowerPoint presentations with a notebook - at faster rates than standard wired broadband connection - while on the move.

2G digital GSM technology started in Europe and has since evolved into various technologies. Europe is now leading the way in the adoption of the most recent 3G High-Speed Uplink Packet Access (HSUPA) is mobile telephony protocol, which requires that the base stations and mobile phones be upgraded for forward compatibility with new protocols such as HSUPA. As later described in this dissertation, the constant need for network and phone handset upgrades only highlights the need for a programmable RF front end architecture which can complement a software configurable/defined radio bases band architecture.

1.7 North America

1.7.1 Overview

The total number of mobile subscribers in North America rose to 278 million at the end of Q1 2008, from 257 million a year earlier. The penetration rate saw a 5.3 percentage-points gain to 82.5%. Obviously this figure is close to the 84.9% penetration rate in the USA, the region's largest market by some distance with 92.7% of North America's mobile customers, although it is dragged down by the low Canadian rate of just 60.5%.

By far the fastest growing technology in North America is W-CDMA, which saw a 336.7% gain in customers in the 12 months ending on March 31, 2008. The total number of W-CDMA subscribers surpassed the 10 million mark during Q1 2008 to finish the quarter at 11 million. This is still below the number of iDEN customers, which stood at 16.6M at the end of Q1, but with iDEN losing 5.1M customers year on year and W-CDMA gaining 8.6M, it seems likely that iDEN will lose its status as North America's third most important technology before the end of 2008.

CDMA remains the dominant standard with 52.7% of the total North American customer base, or 146M subscribers, up from 130M (50.7% of the total) a year earlier.

The number of GSM subscribers broke through the 100M barrier to reach 104M at the end of Q1, but growth more than halved from 15.0% in the 12 months ending Q1 2007, to 7.0% in the subsequent 12 months, as a consequence of the success of W-CDMA. Annual CDMA customer growth was also down compared to the prior twelve months with a 4.4 percentage-points fall in the rate, although it remained in double digits with a 12.2% yearly gain [34].

1.7.2 Femtocells

Home base station solutions, also called femtocells have recently attracted a lot of attention. The idea is to give the mobile user a small box similar to a wireless router that provides mobile cellular coverage at home. Femtocells are a relatively recent trend in the United States. The Femto cellular device (being smaller than pico, the term used by mobile operators that refers to smaller cell sites) has a cellular antenna to boost the available signal as well as an Internet connection. The device uses the user's Internet connection to connect to the mobile provider's network and route the phone calls.

The 3G femtocell is a tiny, consumer-friendly 3G base station optimized for the home. It is a low-cost, high-performance W-CDMA (or any other 3G standard) femtocell delivering voice and HSxPA services to the home while improving capacity in the entire cell. The physical box is a standalone unit with an Ethernet interface to the user's broadband connection and can also be embedded into other residential gateway products (e.g. ADSL or Cable/WiFi routers). Some of the most recent femtocells being announced are based on a software-intensive parallel DSP core and as such are software upgradeable in the field to be compatible with the latest W-CDMA and IP network features.

Fixed line carriers and DSL service providers are seriously threatening the mobile business by offering new products centered around Fixed Mobile Convergence, which in essence utilizes wireless access technology (like WiMAX) to capture mobile users when at home, and divert their mobile originated voice and data calls to the fixed line network.

Mobile operators thus have found themselves in a predicament: the traditional macro cellular networks are not able to compete with what DSL service providers can offer, neither from a cost structure point of view, nor in terms of access speeds. A home base station or femtocell can help mobile operators in many ways. First they can compete directly with other home access solutions which rely on other types of access technology such as WiFi or WiMax. This is because low cost mobile handsets are widely available, whereas dual mode handsets with WiFi capabilities are pricey and still limited in variety.

The femtocell will also enable the operator to cater to subscribers where the service is most needed. Compare this with traditional macro deployment where the infrastructure is first built in places where subscribers are "likely" to appear and even before subscribers start using the network. A femtocell also circumvents the issue of outdoor-to-indoor propagation which typically kills the capacity of 3G and 3.5G systems.

The deployment costs associated with a femtocell are marginal in comparison with Macro cell deployment. This is because the customer is providing the "real estate" to keep the box, the power, as well as the backhaul (e.g., DSL subscription).

1.8 Chapter 1 Summary

One key conclusion that can be derived from this wireless market analysis is that industry standards are changing dynamically, which in turns forces the telecommunications carriers to frequently change or upgrade their networks with the latest technology equipment. In turn, the original equipment manufacturers need to also design new equipment with the new standards to stay in business.

Another key conclusion is that the market size for mobile wireless service still has a long way to go especially in China, India and Latin America, and that these regions will require lower equipment price points as compared to Western Countries.

As data-intensive services become available due to the higher data rates possible with 4G and WiMAX/WiBro technologies, the base stations and hand sets will require a smaller footprint and lower cost RF front end electronics.

The competition for customers between fixed line and wireless mobile operators has also brought about the advent of the femtocell or "personal base stations" which will also have to adopt the various 3G/4G standards. Femtocells will also face a new price point in the market as compared to pico base station thus putting more pressure on the cost reduction of the RF front end of the femtocells.

The combination of above wireless mobile industry trends dictates the need for a flexible, low cost, small size, programmable RF front end that can quickly adapt to the changing wireless standards, protocols, and feature sets of the future.

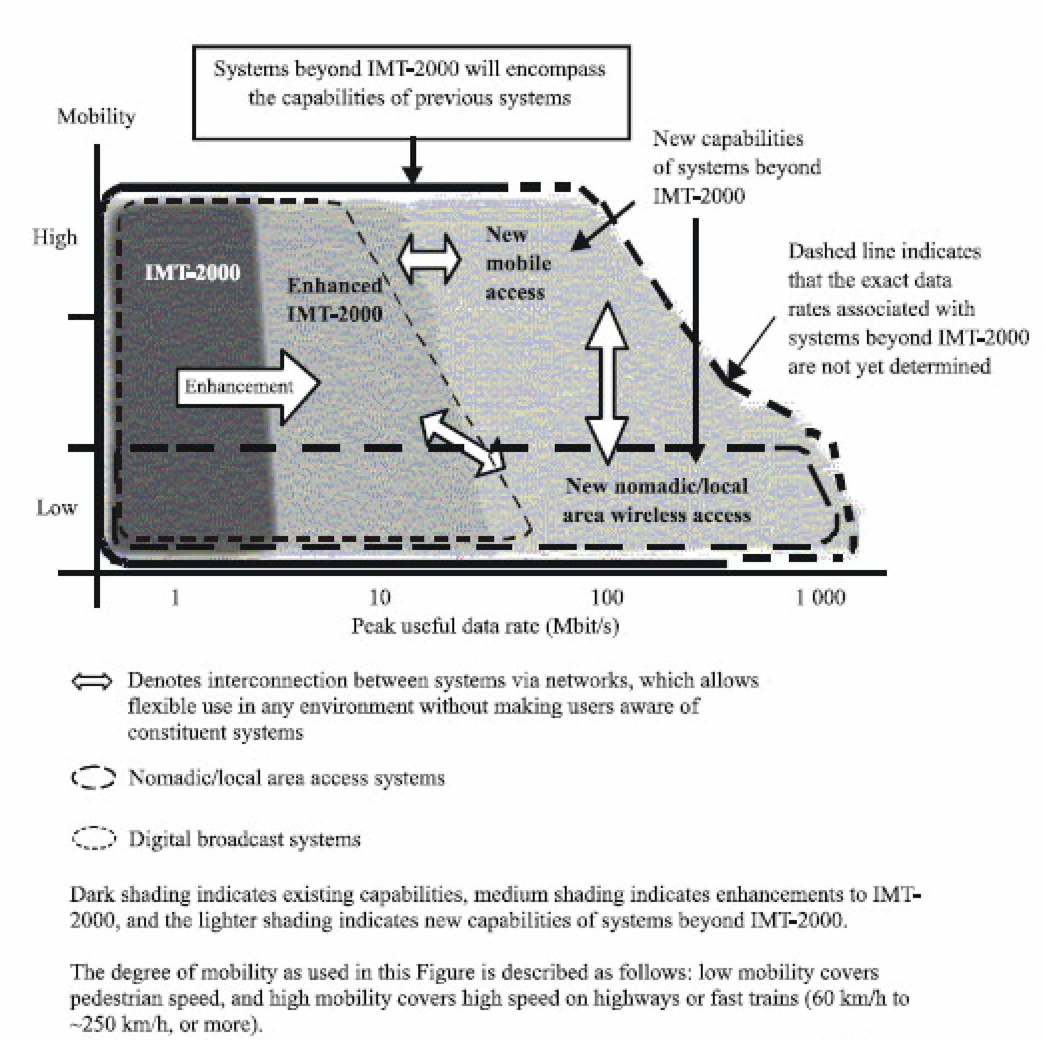
Chapter 2 The Mobile Wireless RF Spectrum Allocation

2.1 Introduction

The ITU-R Working Party 8F is responsible for the overall system aspects of IMT-2000 and beyond. The ITU-R believes that systems "beyond IMT-2000" (e.g., 4G) should support a steady and continuous evolution of new applications, products and services through improvements in data rates and enhancements to the existing IMT-2000 radio interfaces. In addition, it further states that a framework for systems beyond IMT-2000 should be realized by the functional fusion of existing (legacy), enhanced, and newly developed elements of new mobile access, nomadic local wireless, and so forth, with high commonality and seamless inter-working.

2.2 Data Rate Requirements

The new capabilities of systems beyond IMT-2000, for example, 4G systems, will include much higher data rates than the current 3G systems. For example, the capabilities of some of the IMT-2000 terrestrial radio interfaces are already being extended up to 10Mbps and it is expected that these will be expanded even further. For systems beyond IMT-2000, there may be a requirement for a new wireless access technology for the terrestrial component and the ITU predicts that the data rates for such new systems will be in the range of 100 Mbps for high mobility such as mobile access, and up to approximately 1 Gbps for low mobility such as nomadic/local wireless access (see Fig. 2.1). In fact, as early as 2005, NTT DoCoMo announced that it was already testing systems capable of 1Gbps (see Fig. 2.2).



Source: ITU-R, M.1645, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000."

Figure 2.1 Capabilities of IMT-2000 and systems beyond IMT-2000

These data rate figures and their associated mobility should be seen as the targets for research and investigation of the basic technologies necessary to implement the framework. Note that 100 Mbps and 1 Gbps refer to the overall cell throughput in wide and local access, respectively.

Press Release Article

NTT DoCoMo Achieves 1Gbps Packet Transmission in 4G Field Experiment

TOKYO, JAPAN, June 23, 2005 --- NTT DoCoMo, Inc. announced today that it achieved 1Gbps real-time packet transmission in the downlink at the moving speed of about 20km/h in a field experiment on fourth-generation (4G) radio access. The experiment took place in Yokosuka, Kanagawa Prefecture on May 9, 2005.

This is the latest achievement in DoCoMo's ongoing development of key radio access technology for 4G mobile communications.

The 1Gbps real-time packet transmission was realized through Variable Spreading Factor-Spread Orthogonal Frequency Division Multiplexing (VSF-Spread OFDM) radio access and 4-by-4 Multiple-Input-Multiple-Output (MIMO) multiplexing using "adaptive selection of surviving symbol replica candidate" (ASESS) based on Maximum Likelihood Detection with QR decomposition and the M-algorithm (QRM-MLD), which was developed by DoCoMo. By using the new algorithm, DoCoMo was able to reduce the

Source: *www.nttdocomo.com.jp*

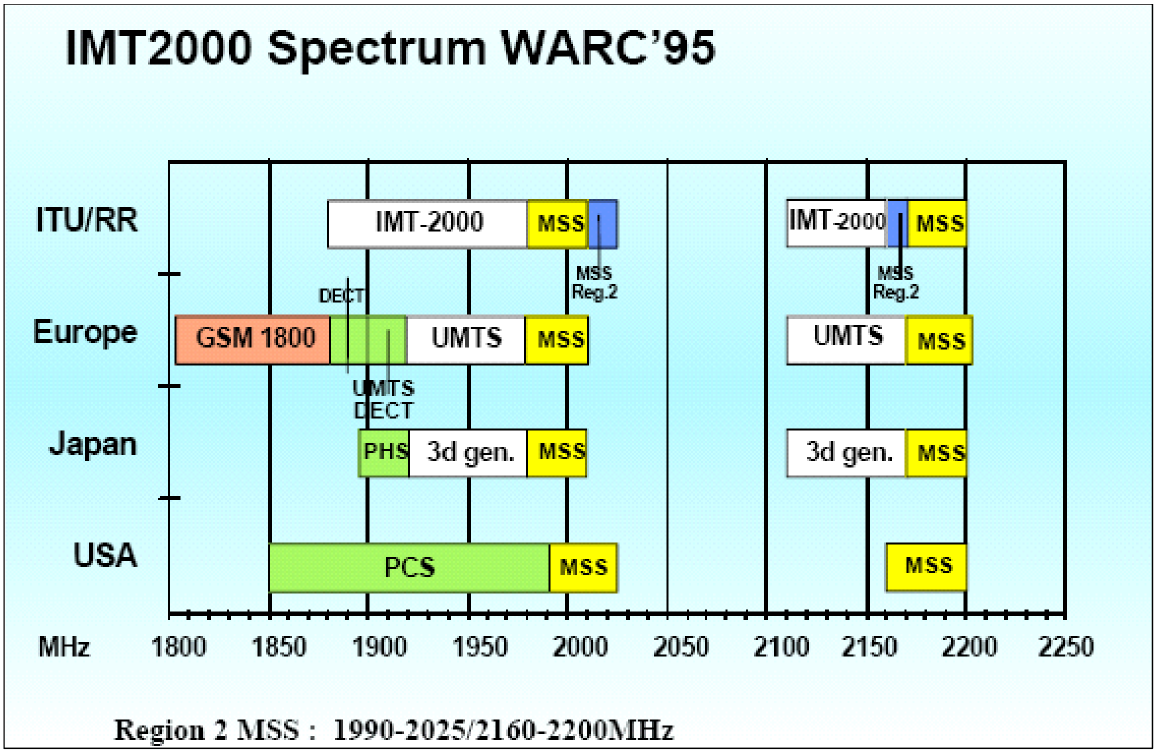
Figure 2.2 NTT DoCoMo Achieves 1 Gbps Packet Transmission

Due to the predicted data rate requirements, additional RF spectrum will be needed in order to deliver the new capabilities of systems beyond IMT-2000. It also possible that upstream (uplink) and downstream (downlink) may have different maximum transmission speeds. In addition to IMT-2000 and "beyond IMT-2000" systems, other different radio access and communications systems will continue to co-exist, for example, WLANs, WPAN, WMANs, digital broadcast, and fixed wireless access (FWA) like WiMax.

2.3 Spectrum Issues

Spectrum is a crucial issue in the design and manufacture of wireless systems and devices. The characteristics of propagation and technical parameters of the frequency bands may influence or determine requirements of devices for systems operating in the frequency bands and service characteristics such as mobility requirements and coverage. In addition, spectrum is a scarce resource and, therefore, it should be utilized efficiently. Thus, suitable and affordable frequency bands should be allocated to each wireless system for the purpose of efficient use of spectrum.

The ITU-R plays an important role in the allocation/identification of wireless services and the WRC, supported by the ITU-R, is the only entity that can make decision on the global use of spectrum. To meet the technical and service objectives of systems beyond ITM-2000, more spectrum is required than that already identified for IMT-2000 (see Fig. 2.3) and pre-IMT-2000. Therefore, the ITU-R allocates new spectrum in terms of bandwidth (spectrum amounts), affordable frequency bands, and associated sharing or compatibility problem.



Source: 1995 World Radio Communication Conference

Figure 2.3 IMT-2000 Spectrum Allocation WARC '95

The working methods of the ITU-R WP8F (Working Party 8F) pursuing new 4G systems spectrum allocation are as follows:

- Identify potential future services for 4G and calculate associated traffic demands.
- Develop methodology for calculating spectrum requirements for 4G and estimate required spectrum amounts (bandwidth) for 4G that reflect future traffic demands.
- Identify candidate frequency bands for 4G mobile and nomadic systems, respectively, and conduct sharing and compatibility research in the identified bands.
- Develop technical and regulatory framework/requirements for 4G with regard to sharing/compatibility studies.
- Derive frequency bands for 4G and the required bandwidth in each frequency band.

2.4 New Spectrum

New frequency bands for the new mobile systems beyond IMT-2000 concentrate on frequency bands below 6 GHz. Several technical and regulatory aspects support these frequencies bands. On the technical front, mobile systems usually suffer from larger Doppler shift as the operating frequencies are increased. Moreover, path-loss in the transmission also influences system performance and coverage, and hence, system deployment costs. Path-loss has an explicit and direct relationship with the frequency bands. To obtain bandwidth sufficient enough to support services with very high data rates, frequency bands for future mobile networks need to be above frequency bands allocated for IMT-2000, that is, above 2.7GHz. While at this point there is no conclusive technical evidence on what the upper frequency limit for the band should be, 6 GHz appears to enjoy support among the active members of ITU working on spectrum identification and planning. Thus, frequency in the band from 2.7 to 6 GHz could be regarded as the most promising frequency bands for future mobile communications systems.

Report ITU-R M.2078 calculated that for a single network deployment per country the overall spectrum requirements for the future development of IMT-2000 and for IMTAdvanced to be around 1280 MHz in a low market setting and 1720 MHz in higher market settings for the year 2020. This results in an additional spectrum demand of around 500 MHz and 1 GHz respectively in all ITU Regions as shown in Fig. 2.4.

The total traffic volume (voice and data) in mobile networks is expected to grow significantly. For example, Report ITU-R M.2078 expresses growth factors of about 2 to 3 by 2010 for Europe compared to today. The traffic increase originates from both voice and non-voice traffic. Fixed voice substitution, broadband Internet access and mobile TV will be major contributors along this way. Therefore, sufficient network capacity is a must to satisfy the end-user expectations in terms of service quality, namely throughput and latency.

		Region 1		Region 2		Region 3	
Market Setting	Predicted total (MHz)	Identified (MHz)	Net additional (MHz)	Identified (MHz)	Net additional (MHz)	Identified (MHz)	Net additional (MHz)
Low	1 280	693	587	723	557	749	531
High	1 720	693	1 027	723	997	749	971

Region 1: Europe; Region 2: Americas; Region 3: Asia.

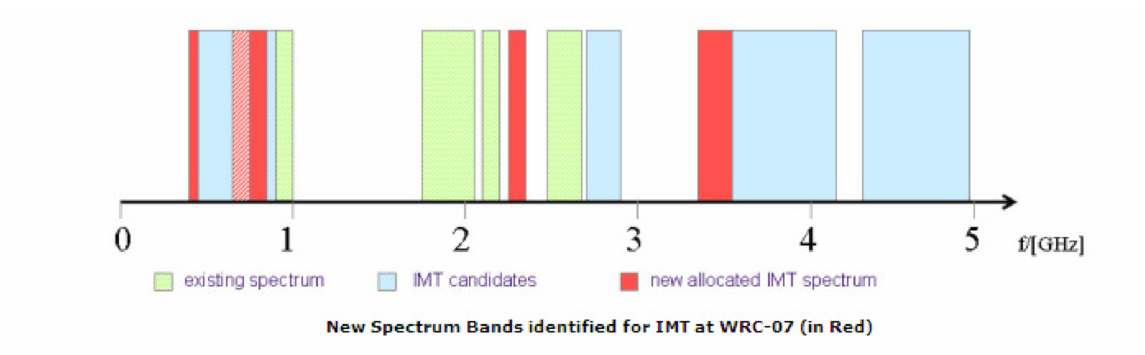
Source: ITU-R M.2078

Figure 2.4 Spectrum requirements for IMT-2000 and for IMT-Advanced

In November 2007, the WRC-07 identified globally harmonized spectrum for use by International Mobile Telecommunications (IMT-2000 and IMT-Advanced). Additional spectrum was allocated for IMT systems in various new bands, resulting in 392 MHz of new spectrum in total in Europe and 428 MHz in the Americas [12] (see also Fig. 2.5):

- 20 MHz in the band 450–470 MHz (globally)
- 72 MHz in the band 790–862 MHz for Region 1 (Europe) and parts of Region 3 (Asia)
- 108 MHz in the band 698–806 MHz for Region 2 (Americas) and some countries of Region 3 (Asia)
- 100 MHz in the band 2.3–2.4 GHz (globally)
- 200 MHz in the band 3.4–3.6 GHz (no global allocation, but identified in 82 countries)

Note: These bands will not be available immediately for next generation mobile networks (NGMN) usage, but opened to the market following transition periods of up to several years. Additionally, the allocations regarding the bands 790-862 MHz and 3.4 - 3.6 GHz in Region 1 will only come into full effect in 2015 and 2010 respectively.



Source: IMT at WRC-07

Figure 2.5 New Spectrum Bands Identified for IMT at WRC-07

Current global allocation of the 3- to 6- GHz band is shown in Fig. 2.6, while the global allocation of the UFH band is shown in Fig. 2.7.

Frequency Bands	ITU-R Allocations	Current Operating Mobile Systems
3,100-3,300 MHz	Radio location Earth exploration satellite (Active) Space research (active)	Airborne Warning and Control Systems (AWACS) Synthetic aperture radars (SARs)
3,300-3,400 MHz	Radio location	AWACS SARs
3,400-3,600 MHz	Fixed, mobile, fixed satellite, radio location	Broadband wireless access (BWA) such as WiMAX , 802.16 European countries: electronic news gathering (ENG) / Outside broadcasting (OB)
3,600-4,200 MHz	Fixed, mobile, fixed satellite	Fixed Satellite Services (FSS), FWA, including microwave link
4,200-4,400 MHz	Aeronautical radionavigation	
4,400-4,500 MHz	Fixed, mobile	Point-to-point microwave link
4,500-4,800 MHz	Fixed, fixed satellite, mobile	Global geostationary Earth orgit (GEO) satellite bands, point-to-point microwave link
4,800-4,990 MHz	Fixed, mobile, radio astronomy	Point-to-point microwave link
5,000-5,150 MHz	Aeronautical radionavigation	
5,150-5,350 MHz	Aeornautical radionavigation, fixed satellite (Earth-to-space), mobile	5-GHz wireless LAN
5,350-5,470 MHz	Earth exploration, radiolocation, space research, mobile	5-GHz wireless LAN
5,470-5,650 MHz	Maritime radionavigation	
5,650-5,725 MHz	Radio location, space research, mobile	5-GHz wireless LAN
5,725-5,825 MHz	Radio location, amature	5-GHz wireless LAN, dedicated short-range communications (DSRC)
5,825-6,000 MHz	Fixed, fixed satellite (Earth-to-space), mobile	Broadcasting relay

Source: [15]

Figure 2.6 Global Allocation in the 3- to 6- GHz Band

Frequency Bands	ITU-R Allocations	Operating Mobile Systems (Current and Future)
406-430 MHz	Mobile, fixed. Europe: PMR U.S.: PMRS	TRS including TETRA, iDEN
440-470 MHz	Mobile, fixed Radio location (440-450 MHz) Radio sonade (460-470 MHz)	Cellular (NMT 450), TRS inlcuding TETRA, iDEN
740-806 MHz	Mobile, broadcasting	No current mobile services
806-960 MHz	Mobile (IMT-2000 additional bands)	Cellular including CDMA (IS-95, 1x), GSM TRS including TETRA, iDEN
1,710-2,025 MHz 2,110-2,200 MHz	Mobile (IMT-2000 additional bands) IMT-2000 core bands (1,885-2,025 MHz and 2,110-2,200 MHz)	PCS1900, GSM 1800, IMT-2000 including FDD, TDD and satellite component DECT (Europe, 1,880-1,900 MHz)
2,300-2,400 MHz	Mobile, fixed	WiBro (Korea), TDS-CDMA (China)
2,400-2,500 MHz	Mobile (ISM bands)	IEEE 802.11b/g, Bluetooth
2,500-2,690 MHz	Mobile, fixed, satellite (BSS: 2,605-2,655 MHz, MSS: 2,500-2,520 and 2,670-2,690 MHz)	IMT-2000

Source: [15]

Figure 2.7 Global Allocations for Mobile Services in the UHF Band

2.5 Chapter 2 Summary

Wireless systems frequency spectrum utilization for pre-IMT-2000, IMT-2000, and "beyond IMT-2000" will continue to co-exist for many years to come. The ITU's envisioning of a backward compatibility of services as new systems are deployed will also dictate that the new systems and devices become network agnostic and thus should be able to operate with as many as possible of the existing networks. The RF front end of the radio interfaces of the future should be able to be "plug and play" and be agnostic to any spectrum frequency domain while capable of operating at frequency bands in the 1 to 6 GHz domain for backward and forward compatibility with pre- and post-IMT-2000 systems. Moreover, the radio RF front-end should be capable of allowing data rates of up 1 Gbps for low mobility and 100Mbps for high mobility systems.

Chapter 3 The Mobile Wireless Channel Multiple Access Techniques

3.1 Introduction

The understanding of the various multiple access techniques for mobile wireless communications is relevant to this dissertation because it also validates the thesis that a variety of multiple access techniques will continue to co-exist in systems beyond IMT-2000. Thus, the platform for the implementation of future base stations and handsets will have to be flexible enough to accommodate a variety of multiple access techniques.

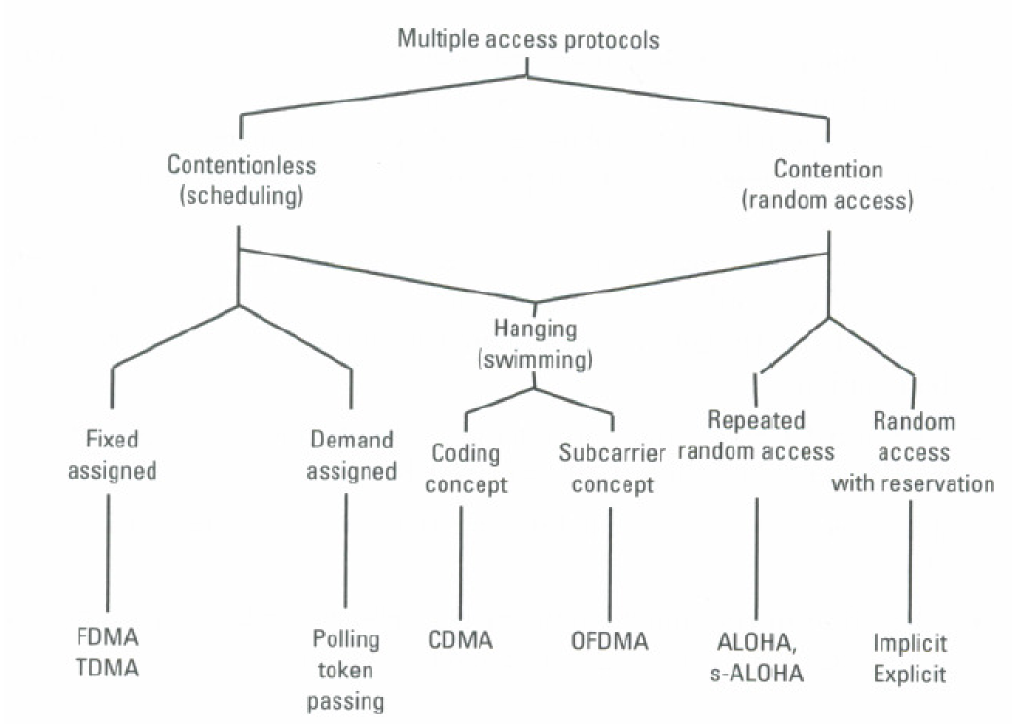
Software Define Radio (SDR) technology addresses the multiple access techniques in that it provides for configurability of the protocol via DSP techniques. However, the author believes that a "smart programmable RF front end" (SP-RFFE) will also be needed to complement the functions being implemented by SDR techniques. Thus, before elaborating on the functions that the SP-RFFE will implement, it is critical that an overview of the various multiple access techniques is provided to understand how the SP-RFFE might be able to assist in addressing any implementation issues regarding the various multiple access techniques.

3.2 Overview of Multiple Access Protocols

Agreement among users on the means of communication is known as protocol. When users use a common medium for communications, it is called multiple access.

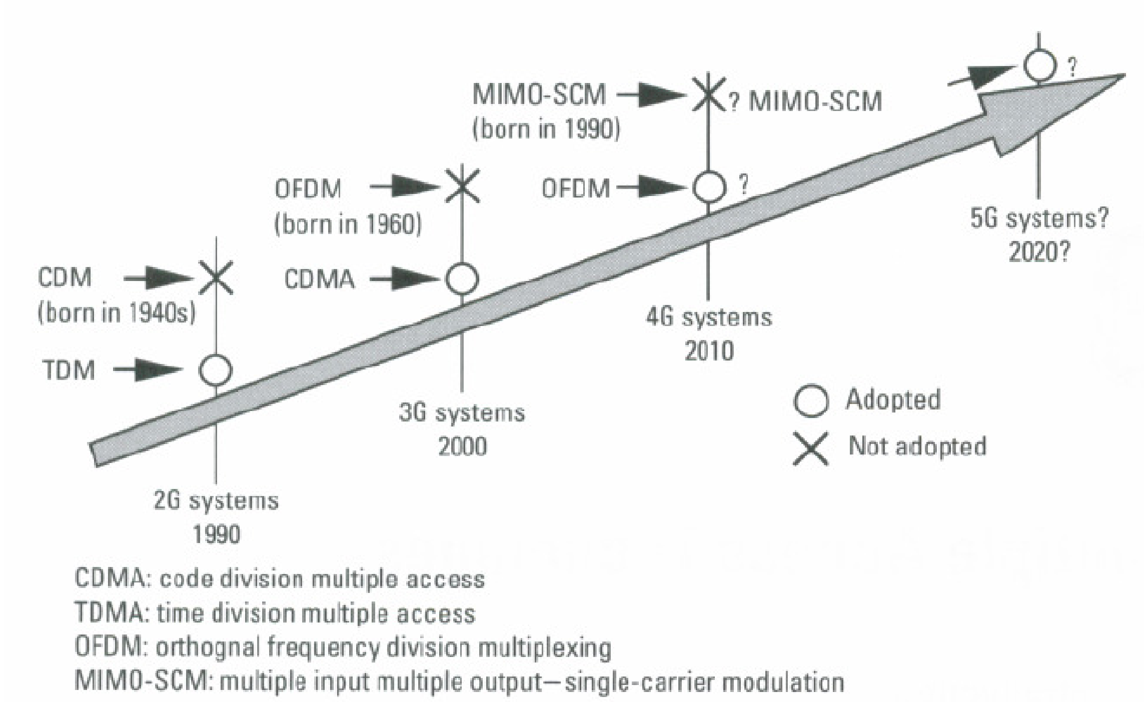
Thus, the multiple access protocol is defined as the agreement and set of rules among users for successful transmission of information using a common medium. Whenever some resource is used and thus accessed by more than one independent user, the need for a multiple access protocol arises. In the absence of such a protocol, conflicts occur if more than one user tries to access the resource at the same time. Therefore, a multiple access protocol should avoid or at least resolve these conflicts. Thus, a *multiple access technique is defined as a function sharing a (limited) common transmission resource among (distributed) terminals in a network* [15].

Starting in 1970 with the ALOHA protocol, a number of multiple access protocols have been developed. One classification breaks these various protocols in three categories: the contention-less protocols, the contention protocols, and the hanging (or swimming) protocols. Fig. 3.1 shows the various protocols under each of these three classifications and Fig. 3.2 shows the history of mobile communications generations in terms of adopted access technique.



Source: [15]

Figure 3.1 Classification of the Multiple Access Protocols



Source: [15]

Figure 3.2 History of Mobile Communications Adopted Access Techniques.

3.3 OFDM-based Hybrid Protocols

Of all of the multiple access protocols, OFDM-based techniques look the most promising for systems beyond IMT-2000 (e.g., 4G). OFDM stands for Orthogonal Frequency Division Multiplexing. The reasons for the high potential of OFDM are as follows:

- Multi-carrier techniques can combat hostile frequency selective fading encountered in mobile communications. The robustness against frequency selective fading is very attractive especially for high-date transmission.
- The OFDM scheme is a mature technology due to much research and development for high rate wireless LANs and terrestrial digital video broadcasting. A great deal of know-how has been developed on OFDM.
- By combining OFDM with CDMA, we can have synergistic effects, such as enhancement of robustness against frequency selective fading and high scalability in possible data transmission rate.

OFDM, which is a form of multi-carrier modulation, is used as a multiple access scheme in wireless communications. In OFDM, densely spaced sub carriers with overlapping spectra are generated using fast the Fourier transform (FFT). Signal waveforms are selected in such a way that the sub carriers maintain their orthogonality despite their spectral overlap. Usually, CDMA or TDMA is used with OFDM to achieve multiple access capability.

Basically, orthogonal frequency resources (i.e., orthogonal sub carriers) can be shared among users, which is the simplest multiple access technique based on OFDM modulation. Besides, there are a number of hybrid multiple access techniques that can be found in the literature. Hybrid means an amalgamation of OFDM and multiple access techniques (with the main accent on spread spectrum) to provide an efficient multi-user scenario with very high data rate. Some of the most popular techniques are:

- MC-CDMA (multi-carrier code division multiple access)
- OFDMA (orthogonal frequency division multiple access)
- OFDM-CDMA-SFH (OFDM-CDMA slow frequency hopping)
- VSF-OFCDMA (variable spreading factor-orthogonal frequency and code division multiplexing) - proposed by NTT DoCoMo (see also Fig. 2.2)

The hybrid approach of above techniques solve a variety of issues that cannot be addressed by CDMA or OFDM techniques alone. Fig. 3.3 summarizes some of the problems and solutions using the various hybrid techniques.

Problem	Solution
1. OFDM system only supports one user	Use OFDM/CDMA, which supports multiple users
2. CDMA does not permit very high data rates, owing to frequency selective fading at high data rates	OFDM counters this by S/P conversion, allowing flat fading at subcarrier level.
3. CDMA systems suffer from near-far effect in the uplink	This is solved in the hybrid system using SFH
4. CDMA systems use DS-SFH to control the near-far effect. But DS-SFH mostly supports noncoherent modulation owing to hopping at bit level. However, coherent modulation is possible, but maintaining phase coherence between hops is difficult.	The OFDM-FH system hops on frame basis allowing coherent modulation
5. CDMA systems cannot indefinetely support multiple users due to MAI and SI problems caused by too many users.	The hybrid system allows any number of users by increasing the number of hops. Hence, Number of Users - Number per CDMA System Number of Hops. Bandwidth should, however, be available.
6. CDMA poses synchronization problems at very high chip rates	OFDM systems have an easier synchronization problem due to using cyclic prefixes.

Source: [15]

Figure 3.3 Hybrid System Overall Aspects

Each of the presented protocols has its own merits but each of them should strive to solve the following issues related to the wireless mobile communications environment:

- The hidden terminal problem: two terminals are out of range of each other, hidden by a hill, a building, or some physical obstacle opaque to UHF signals, but both are within the range of the central or base station;
- The near-far effect: transmissions from distant users are more attenuated than transmissions from users close by;
- The effects of multi-path fading and shadowing experienced in radio channels;
- The effects of co-channel interference in cellular wireless systems caused by the use of the same frequency band in different cells.

Many of the protocol properties mentioned above are conflicting, and a trade-off has to be made during the protocol design. The trade-off depends on the environment and the specific use for the protocol one has in mind.

3.4 Chapter 3 Summary

The various multiple access techniques for mobile wireless communications will continue to co-exist as the migration to systems beyond IMT-2000 occurs. Because of the various ODFM hybrid approaches being proposed, it is clear that a flexible and programmable platform would have to be used for the implementation of the various multiple access schemes. SDR-based platforms have the potential to address such flexibility and programmability requirements. SDR systems use DSP techniques and there is plenty of research and industry work being done in this area. The author of this dissertation believes that some of the SDR-DSP functions may be able to be assisted via a smart programmable RF front end (SP-RFFE), which in essence, complements the SDR platform. Future chapters examine possible functions that can be moved from the SDR-DSP section of the radio to the SP-RFFE. The idea behind the SP-RFFE is that it has the potential of becoming some sort of a *"wireless channel sniffer"* whose specific features and functions will be later defined by the future work being proposed in this dissertation.

Chapter 4 Quality of Service Requirements

4.1 Quality of Service (QoS) Attributes

In addition to understanding the various spectrum and data access techniques which impact the architecture of the radio, it is critical to gain a good understanding of the QoS (quality of service) requirements for the next generation mobile systems beyond IMT-2000.

Usually, the QoS attributes for a particular application or service are: required throughput, maximum acceptable delay, maximum acceptable delay jitter, and maximum acceptable bit error rate. Any change in radio architecture must take into account these QoS parameters so as to optimize their performance.

The following issues must be taken into account as viewed from the end user's point of view:

- The end user only cares about the degree of QoS, and not about how it is provided;
- It is the user that decides whether he is satisfied with the provided QoS or not;
- The number of "user defined/user controlled" parameters has to be kept at a minimum;
- A derivation/definition of QoS attribute from the application requirements has to be simple enough;
- End-to-end QoS has to be provided.

4.2 QoS Classes

In UMTS standardization the following four service classes are defined: background class, interactive class, streaming class, and conversational class. The primary difference between these four classes is the delay sensitivity of the traffic. For example, the conversational class is most delay sensitive since the users would not tolerate any appreciable time of silence by the far end party. The background class is the most delay tolerant. Fig. 4.1 summarizes the UMTS QoS classes and their main characteristics. The table also shows some typical applications for each class of service.

• **Traffic class**	**Conversational class** **Real Time**	**Streaming class** **Real Time**	**Interactive class** **Best Effort**	**Background class** **Best Effort**
Fundamental characteristics	- Preserve time relation (variation) between information entities of the stream - Conversational pattern (stringent and low delay)	- Preserve time relation (variation) between information entities of the stream	- Request response pattern -Preserve payload content	-Destination is not expecting the data within a certain time -Preserve payload content
Example of the application	Voice, video games, voice telephony	Streaming video	Web browsing, network games	Telemetry, background download of emails

Source: 3GPP 23.107

Figure 4.1 UMTS QoS Classes

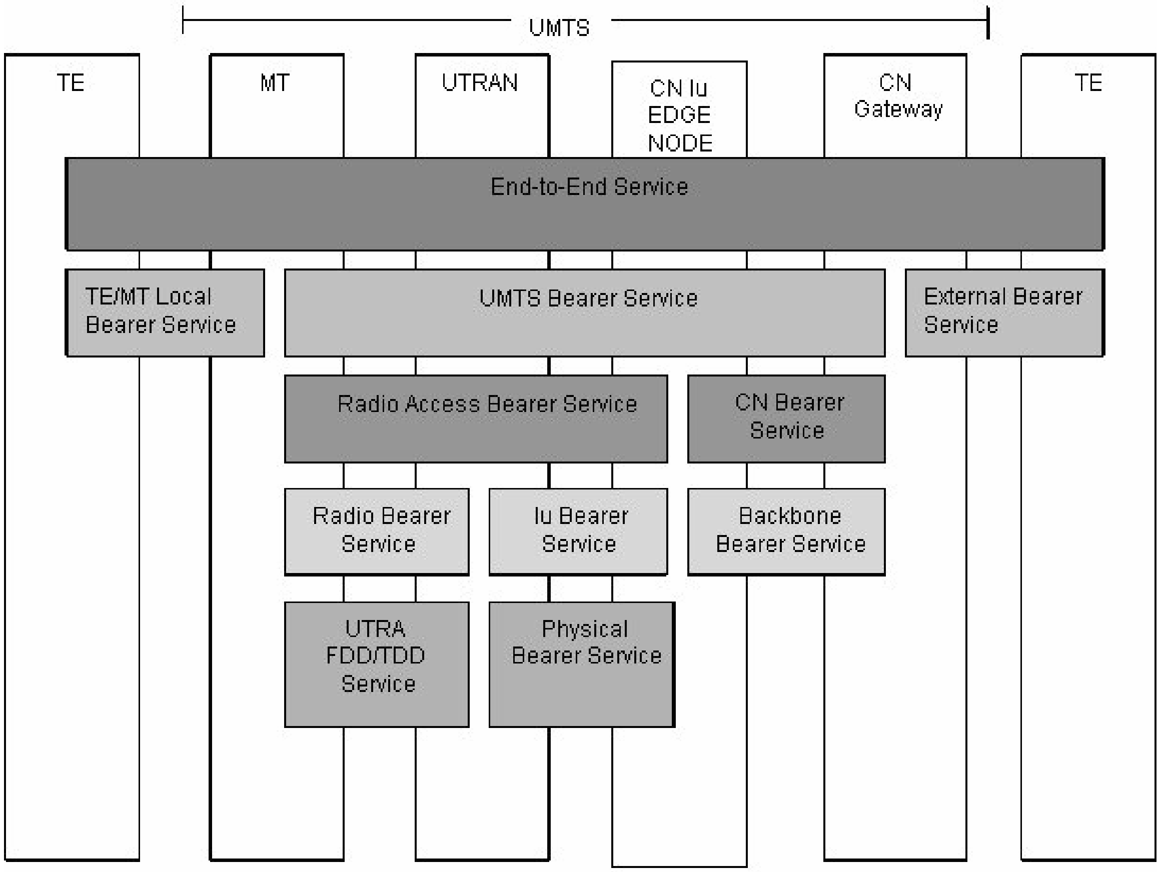
4.3 QoS Architecture

Network Services are considered end-to-end [13], this means from one Terminal Equipment (TE) to another TE. An End-to-End Service may have a certain Quality of Service (QoS) which is provided for the user of a network service. As indicated above, it is the user that decides whether he is satisfied with the provided QoS or not.

To realize a certain network QoS a Bearer Service with clearly defined characteristics and functionality needs to be set up from the source to the destination of a service. A bearer service includes all aspects to enable the provision of a contracted QoS. These aspects are among others the control signaling, user plane transport, and QoS management functionality. A UMTS bearer service layered architecture is depicted below in Fig. 4.2. Each bearer service on a specific layer offers its individual services using services provided by the layers below.

The UMTS Bearer attributes are:

Traffic class (conversational, streaming, interactive, background)
Maximum bit rate (kbps)
Guaranteed bit rate (kbps)
Delivery order (y/n)
Maximum SDU size (octets)
SDU format information (bits)
SDU error ratio
Residual bit error ratio
Delivery of erroneous SDUs (y/n/-)
Transfer delay (ms)
Traffic handling priority
Allocation/Retention Priority
Source statistics descriptor (speech/unknown)



Source: 3GPP 23.107

Figure 4.2 QoS Architecture

The Radio Access Bearer (RAB) shown in Fig. 4.2 is the entity responsible for transporting radio frames of an application over the access network in UMTS. The parameters of a RAB, namely the maximum bandwidth and the allowed frame sizes, can be configured according to the requirements of the application using it. The understanding of the RAB is of most interest to this dissertation as it has direct implications in the radio design.

3GPP has defined the concept of Radio Access Bearer (RAB) as a user plane connection provided by the UMTS Terrestrial Radio Access Network (UTRAN) between a User Equipment (UE) and the Core Network. The general characteristics of a RAB (data rates, QoS, etc) are normally set by the Core Network (CN) based on subscription and/or requirements of the media or set of medias using the RAB. The actual configuration for a RAB is decided by UTRAN based on the RAB information received from the CN.

The RAB configuration has a direct impact on network resource usage. The more suited the RAB configuration is to the actual pattern of the data being transferred, the more efficient the RAB is in terms of usage of network resources. Choosing proper RAB configurations is key to UTRAN, given the high cost of last-mile transport (Iub interface) and the rather limited radio resources [14]. The RAB bandwidth determines the QoS received by the application, and the set of allowed frame sizes for the RAB determines the amount of bandwidth wasted for padding. Given a certain application, it is crucial to define its RAB well adjusted to its requirements; too small bandwidth will result in a bad quality, while too large bandwidth or improper frame sizes will result in a waste of resources. From the above it follows that a RAB design optimized for the various applications (VoIP, streaming video, web browsing, etc) is an important issue in UMTS networks.

The application may specify its QoS requirements to the network by requesting the radio access bearer (RAB) with any of the specified traffic type (conversational, streaming, interactive, background), maximum transfer delay, delay variation, bit error rates, and data rates. In practice, it should be possible to define the main RAB characteristics from the service quality requirements:

- The *transmission rate* of RAB should be determined by the bandwidth requirement of the information source.
- The choice of dedicated or shared RAB should be based on the requirement for the maximum delay and delay jitter.
- The SNIR requirement, channel coding, and interleaving for the RAB shold be based on the BER requirements.

4.4 Chapter 4 Summary

The QoS problem involves integrating delay-sensitive applications such as voice, audio, and video onto a single network with delay-insensitive applications, such as e-mail, fax, and static file transfer. 3GPP has defined the concept of Radio Access Bearer as a user plane connection provided by the UMTS Terrestrial Radio Access Network between a User Equipment and the Core Network. The RAB parameters must be optimized for each type of traffic and QoS requirements.

The radio architecture for next generation mobile networks needs to consider the optimum way to implement the RAB function. Should it be handled by SDR or should it be handled by a “co-processor” co-located next to the radio interface, namely, the RF Front End? As explained in the next chapter, SDR technology may be prohibitive for certain applications where ASICs may be most suited for cost reasons. Yet, the possibility of having some “SDR” functions embedded closer to the RF front end may prove advantageous for a wide variety of applications without adding too much cost to the architecture.

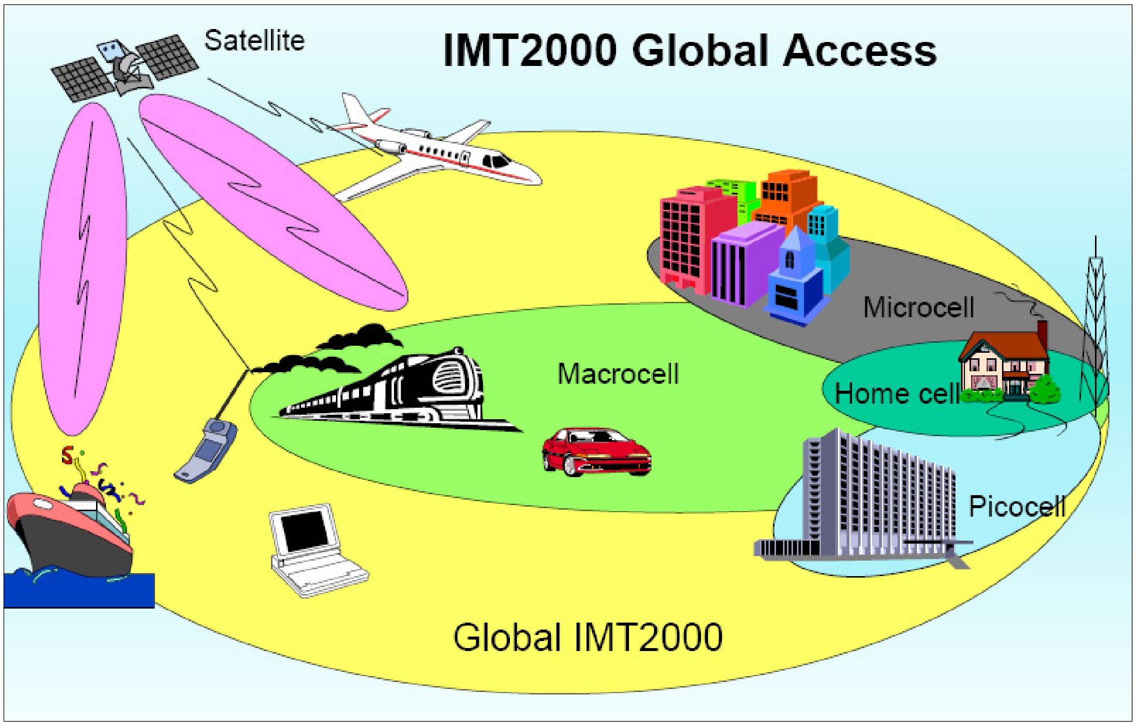
Chapter 5 Trends in Base Station Architectures

5.1 Introduction

This chapter provides an overview of recent trends in the architecture and design characteristics of base stations and what technology challenges most be overcome in the design of next generation base stations. This overview is presented here to stress the fact that the radio front end of the future (c. 2012) will have to be that of a programmable, smart RF front end which is flexible enough to work with all the various spectrum allocations, data access methods, and QoS requirements for various applications while being small in size and very low cost.

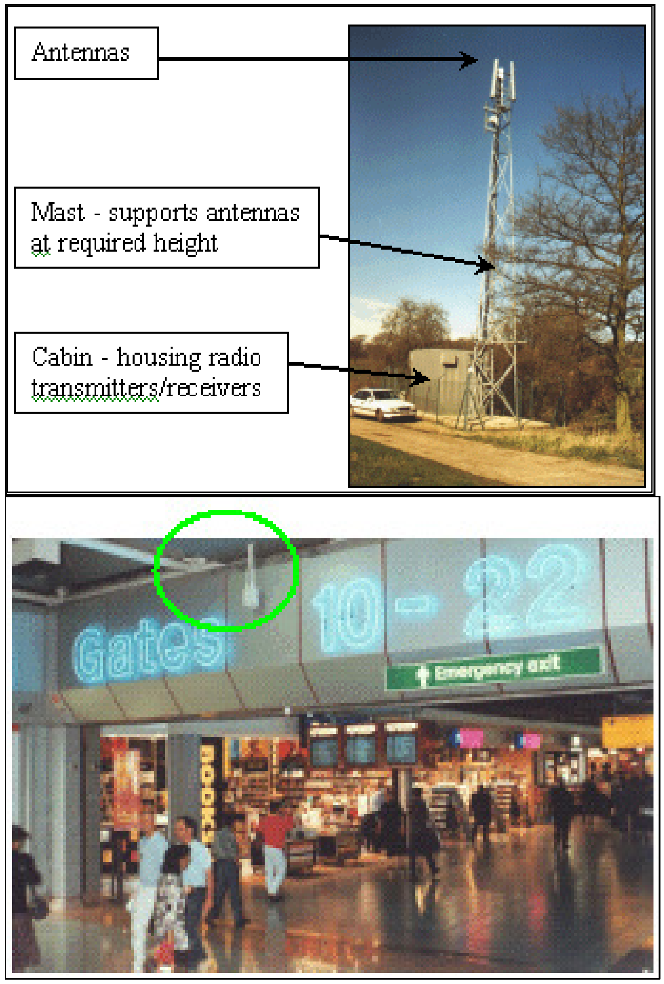
The first generation of W-CDMA base stations were launched in 2000. Since then, the increasing size of W-CDMA networks has led to greater challenges in terms of network deployment, and 3G base stations are now required to balance high performance with low cost, possess flexible deployment capabilities and be future-oriented. To meet these demands, new generation base stations featuring digital power amplification, multi-carrier technology, HS D/U PA support and open architecture have come into being.

Additionally, increased diversity in base station form is being witnessed. Traditional base stations provide macro and micro base station services. Large-sized, high capacity and powerful macro base stations are suitable in most cases, while smaller, less powerful micro (and pico) base stations are applicable for densely-populated areas and indoor coverage (see Fig. 5.1 and Fig. 5.2).



Source: Advanced Topics in Wireless Communications, SMU

Figure 5.1 Various Forms of Base Stations



Source: *http://en.wikipedia.org/wiki/Base_station*

Figure 5.2 Macro and Pico Cell Base Stations

5.2 Distributed Base Stations

Distributed base stations are becoming increasingly prevalent given their great power capability and high capacity. For small areas such as a cluster of households, concept base station Pico cells are proving highly suitable. While an increasing number of base station types are emerging that boast an array of features, it is distributed base stations which no doubt represent "next-generation base station" development. This is of interest for this dissertation as it validates the view that the RF front end will have to evolve on its merits towards a much more flexible, smaller size, and lower cost form factor platform as explained below.

5.2.1 CPRI and OBSAI Architectures

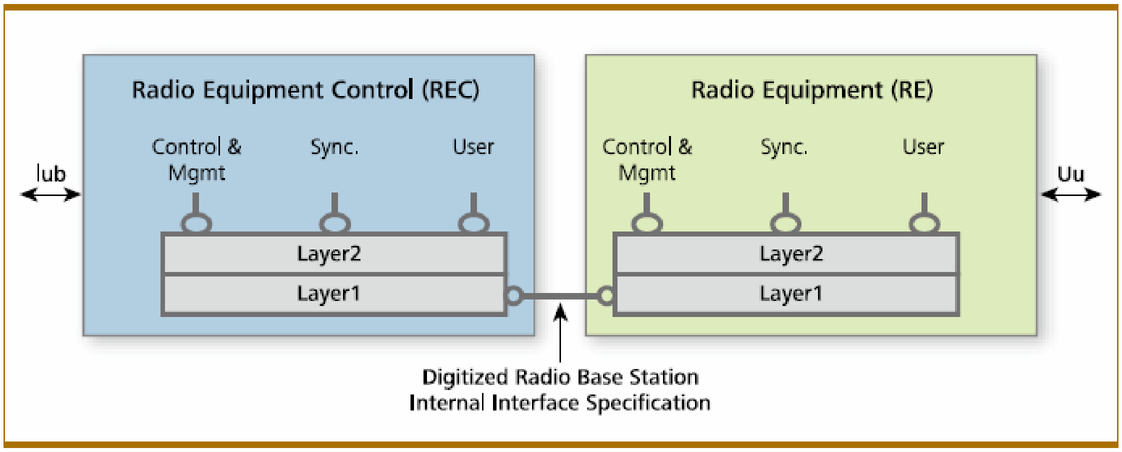
RRH (Remote Radio Head) and baseband pool technologies are popularized in recent products, and this in turn greatly promotes the development of distributed base stations. Previously, base station manufacturers were accustomed to making their products in isolation. This resulted in an increased variety of modules and specifications for connecting them, and module suppliers had to make different processors or radio frequency devices to adapt to different base station products. Costs, therefore, rose. Not surprisingly, it was logical to move toward standardized base stations interfaces that allow inter working between a large number of third-party module manufacturers and digital interfaces, with possibilities for multiplexing modules. This gave rise to two organizations spontaneously formed by industry vendors.

Nokia, NEC, LG and Samsung established OBSAI (Open Base Station Architecture Initiative) in October 2002. The organization's objective was to standardize wireless base stations' architecture, internal interfaces, control modules, transport, baseband and radio frequencies. However, OBSAI was disadvantaged by possessing only one strong base station vendor - Nokia.

In June 2003, Ericsson, Huawei, NEC, Nortel Network and Siemens jointly set up an organization called CPRI (Common Public Radio Interface), which also aimed to identify a universal standard of key internal interfaces; specifically interfaces between baseband and RF modules. The organization's strength was increased by the fact that the five CPRI members were all large-scale base station vendors. NEC – a founding member of OBSAI – turned to support CPRI less than a year after its inception. Numerous manufacturers have continued to join the organization, which now has over 100 members.

5.2.1.1 CPRI

According to CPRI, a base station can be divided into two units: BBU (Baseband Unit), which is also called as REC (Radio Equipment Control) and RRU (Radio Frequency Unit), which is also called RE (Radio Equipment). CPRI's interface mainly features baseband and radio frequency separation. Small in size, easy to install and offering all-round function provision with low power consumption, the BBU can coexist with current sites and support expansion in the cascade mode. RRU is small, light, simple and can be directly mounted on a pole or a wall near the antenna thus maximizing its convenience. CPRI defines interfacing between BBU and RRU, thus making it possible for different manufacturers' BBU and RRU modules to be interconnected**.** Fig. 5.3 shows the partitioning of the CPRI architecture.

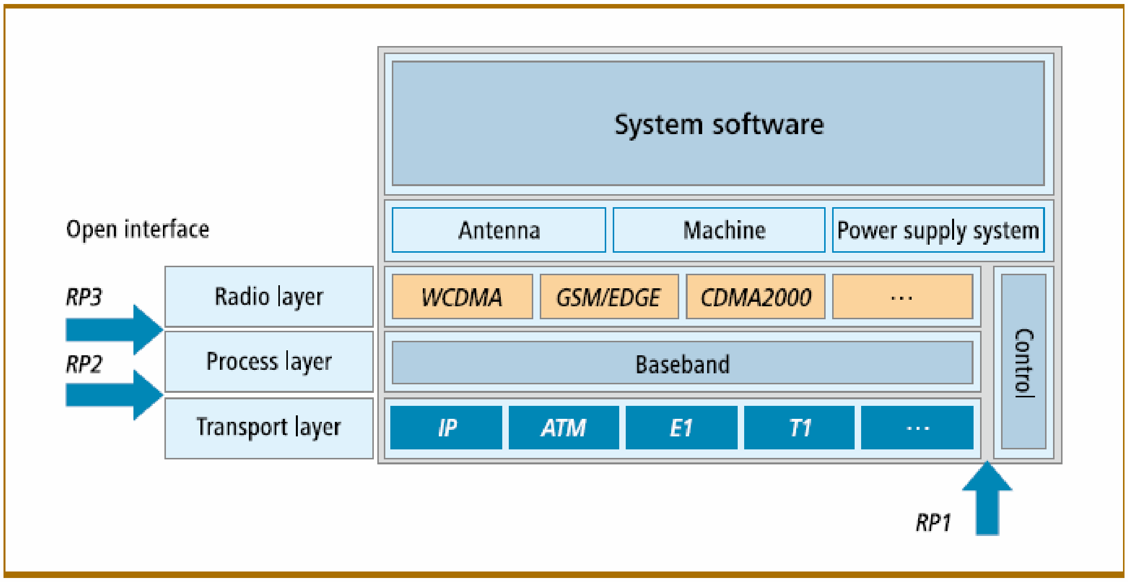


Source: http://www.cpri.info/spec.html

Figure 5.3 Partitioning and Interfaces defined by CPRI

5.2.1.2 OBSAI

OBSAI divides a base station into four functional modules: transport, processing, radio and control. The transport module provides base stations with standard external network interfaces including IP and ATM. The processing module is used to process baseband signals. The radio module receives, transmits and amplifies RF signals, and converts them from digital baseband signals to analog RF signals. The control module provides a system clock for timing, manages and configures base station devices, monitors the operational status of the other base station modules and submits a report to the network equipment management system. Fig. 5.4 illustrates the OBSAI-defined open interfaces.



Source: http://www.obsai.org/obsai/obsai/

Figure 5.4 Open interfaces defined by OBSAI

The superiority of a distributed base station is easily apparent. Equipment networking is more flexible due to the distributed base station's smaller size, and the equipment involved enhances the value of site resources given their current short supply. The construction of equipment rooms and their daily maintenance requires numerous personnel and a high level of financial investment from operators. Apart from cost savings, RF module and baseband transport separation grants greater capacity allocation flexibility and base station expansion potential. Transport via optical fibers can be realized between different base stations or management modules, which will greatly improve an entire network's performance. These reasons underpin the trend for equipment manufacturers to produce this type of base station.

However, given that the CPRI and OBSAI standards were created by manufacturers, they remain non-mandatory. In terms of the standards themselves, CPRI only defines layer-1 and layer-2 of the CPRI interfaces between BBU and RRU, with nothing defined for layer-3. In layer-2, manufacturer-defined fields exist, but there is no definition for O&M. From a practical perspective, there is still a long way to go before inter working between RF and base band modules and the openness of current repeater equipment can be achieved.

5.3 Chapter 5 Summary

Two trends in the design of base stations are clearly happening and both are challenging the architecture of the radio. One trend is related to size reduction of the radio and the other is related to the separation of the radio from the base band module. Two industry initiatives are addressing these trends: the CPRI and OBSAI initiatives. The fact that the radio is being separated from the base band also validates the view that the radio will in fact become "smarter" and more flexible so that it can communicate with different base station implementations as well as with the various air interface standards.

Chapter 6 4G Requirements

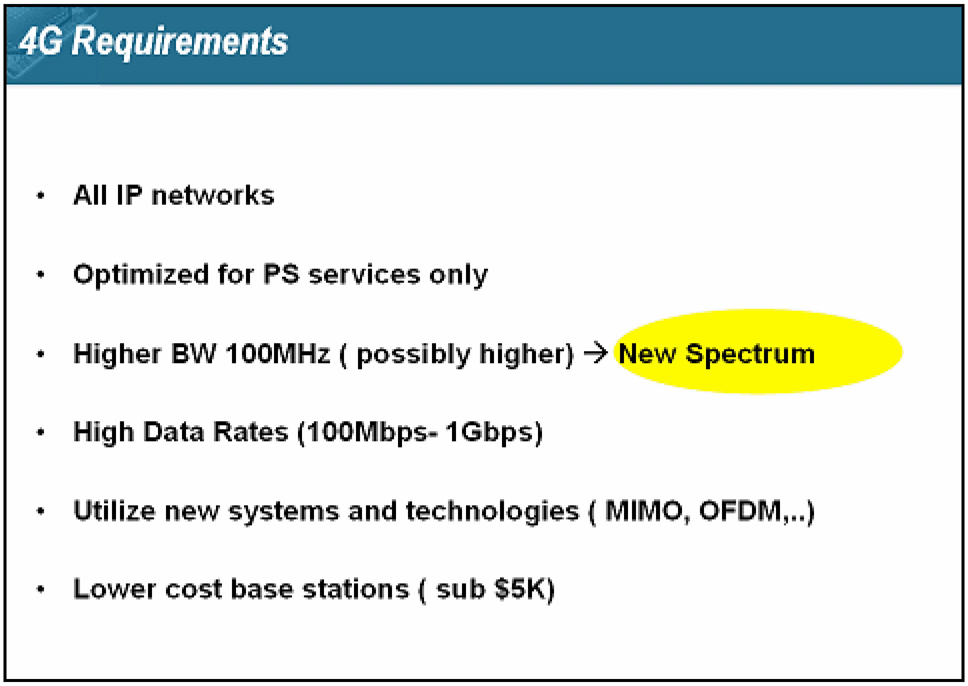
6.1 4G Definition

Reference [15] attempts to define 4G as "a fully IP-based integrated *system of systems* and *network of networks* achieved after the convergence of wired and wireless networks as well as computer, consumer electronics, communication technology, and several other convergences that will be capable of providing 100 Mbps and 1 Gbps, respectively, in outdoor and indoor environments with end-to-end QoS and high security, offering any kind of services anytime, anywhere, at affordable cost and one billing." This definition matches well the characteristics of 4G as summarized by Dr. Hossam Hmimy, from Ericsson, in a lecture at TranSwitch Corporation, Shelton, CT, as shown in Fig. 6.1.

6.2 4G Requirements

4G (also known as "beyond IMT-2000") handsets and base station architectures will have to satisfy the following requirements:

- Adaptive and scalable air interfaces;
- Reconfigurable ambient networks;
- Highly available backbone technologies (e.g., fiber ring, MPLS);
- User friendly multimedia interfaces and context-aware technologies;
- Flexible platforms



Source: Dr. Hossam Hmimy, Ericsson, 2006

Figure 6.1 4G Requirements

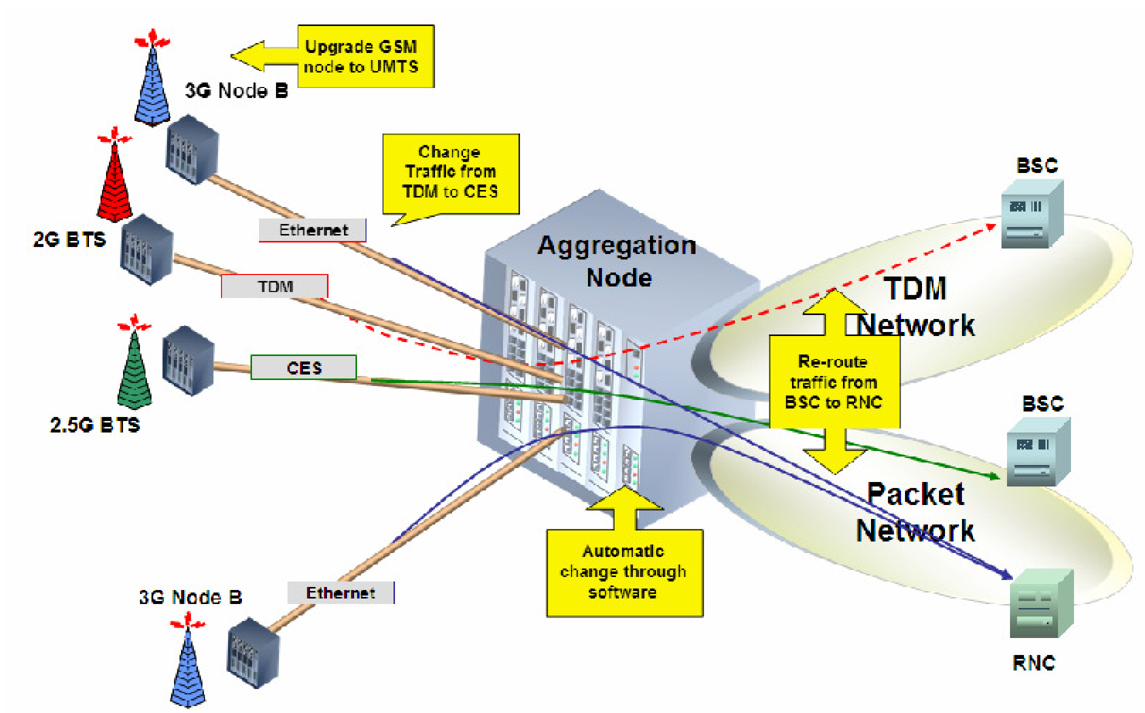
As explained earlier, 4G requires data rates of 100 Mbps for full mobility and 1 Gbps for low mobility indoor coverage. To satisfy this requirement, a highly reliable wireless access technology is needed (e.g., OFDM, MC-CDMA) as well as efficient coding schemes, reconfigurable radio, multiple antennas, and adaptive power control. In addition, to enable adaptability to various network conditions and scalability (in terms of data rate and QoS), new air interfaces (like HSDPA+, ultra-wideband, optical wireless, etc) will have to be investigated in terms of coexistence with other radio systems, multiple access capability, resistance to interferers, low cost, low power, and other implementation issues.

Reconfigurable networks imply the design of new communications mechanisms at different layers. The reconfiguration actions have an impact on various levels of mobile systems architecture and introduce high complexity that has to be handled by some reconfigurability management intelligence, which could be distributed. This reconfigurability requirement mandates compatibility to legacy networks and that compatibility into future IP-based networks and future network topologies (such as ad hoc networks) also be embedded in them. One possible scenario of these reconfigurable ambient networks is that more and more algorithms and concepts will have to be implemented at higher layers (that is, above the physical layer) in an efficient manner as variations in topology increase as well as user requirements and resource and power constraints persist. Such migration of functions into higher the higher layers (2 and 3) will continue to put a strain to the processing power of DSPs which are at the heart of SDR architectures. Thus, the issue of distributed reconfigurable management intelligence becomes more relevant.

6.3 Backhaul Interworking

Wireless systems need to be interconnected with each other via the backhaul wire line network (See Fig. 6.2). While most of today's existing backhaul technologies include legacy T1/E1 interfaces, the future all-IP-network will require backhaul technologies that are IP-compatible (e.g., Ethernet-over-PDH, Ethernet-over-SDH, etc). This trend is already happening as the backbone network migrates to IP.

The network concepts are also moving from network-centered towards person-centered solutions (wireless personal area networks, or WPAN). WPANs will enable a person to establish connectivity from his or her personal wireless devices to the outer world. Since the WPAN personal networks may utilize various wireless technologies, mechanisms for the provision of interoperability between existing and forthcoming wireless infrastructures become mandatory. Thus, the coexistence of the various wireless devices will require further research of the impact of this requirement at the physical layer, medium access control layer, radio frequency channel models, and data traffic models.



Source: Courtesy of TranSwitch Corporation, 2008

Figure 6.2 Core Network Backhaul Access Technologies

6.4 Flexible Platforms Requirement

The above 4G requirements, that is, adaptive and scalable air interfaces, reconfigurable ambient networks, and interoperability and access of the WPANs to the backbone network, dictate *a fundamental need for flexible (programmable, reconfigurable, adaptable) platforms as a key requirement for 4G networks*.

Flexible platforms will be necessary to cope with the broad range of end user requirements in a context-aware environment. A flexible platform will require a flexible architecture. A flexible architecture implies a high degree of re-configurability achieved both in hardware and software. Beyond the current FPGA and NPU (network processing units) technology, newer and more advance solutions will have to be developed and optimized for packet-based traffic. Mixed architectures utilizing DSPs and ASICs will also be utilized for some solutions but the increased functionality that will be required of these components will most likely necessitate more innovative (and possibly distributed) solutions. For example, 3G terminals already require some 100 MIPS (million of instructions per second) as compared to 10 MIPS for a 2G terminal, and the requirements for a 4G terminals, as explained below, will be much greater. Thus, a key area for further research is how much of the layer 1 and 2 processing can be pushed back as close to the RF front end module as compared to the base band module so as to offload the various DSP, FPGA, or ASICs in the base band module to process other layer 3 functions.

In addition, the introduction of "multi system" flexible architecture platforms will require highly reconfigurable antennas and RF subsystems given the variety of spectrum frequencies the *network of networks* vision in the 4G requirement. Thus, new RF architectures will be needed (for example, zero-IF, tunable MEMS filters for optimum cost and performance, etc).

In summary, a flexible platform for 4G systems will have to meet the following requirements:

- A flexible service platform
- Co-existence with other wireless systems
- Co-existence (access to) various core network backhaul access technologies
- Automatic service discovery
- End-to-end QoS and security
- Compatibility with wireless legacy networks
- Upgradability to newer or enhanced wireless networks
- Scalable connectivity
- Capacity enhancements-ready
- Spectrum efficiency enhancements

6.5 4G Handsets

The analysis of 4G requirements would not be complete without an overview of the requirements for 4G terminals (that is, the handsets). Per [15], the critical success factors for future 4G terminals are *service convergence*, *user-centric interface*, and *portable intelligence.* Of these, the most relevant to the subject of this dissertation is that of service convergence. Service convergence is important not only in the sense of a terminal's ability to support multiple services, some of them concurrently, but also from the standpoint that many services from different providers will have to be compatible with a large variety of terminals with different capabilities. This implies that both the base station and the terminals will have to be capable of automatic service and capability discovery.

Two clear market trends are seen in the realm of terminals: single-mode versus multi-mode (multiple functions) terminals. Based on current market trends, it appears that both of these terminal options will continue to co-exist in the future. However, the promise of 4G is more data-centric applications like video, audio, GPS, email (and other applications) to the handset. Thus, below are the expected basic requirements of hardware and software technologies for the 4G terminals (the trends relevant to this dissertation paper appear in bolded fonts):

6.5.1 Hardware

- Multimedia;
- Modem, processor: enhanced processing power, embedded applications processor;
- Display, camera, storage, battery: all requiring high-quality and high-performance because of the rich-media services;
- Flexibility to various environments;
- **RF, antenna: support of multiband and multimode, support of advanced technologies (e.g., SDR, MIMI, smart antennas);**
- **Modem, system-on-chip (SOC) (i.e., modem and RF integrated onto one chip)**
- **Multiple connectivity: supporting several communication standards (e.g., W-CDMA, CDMA-2000, Wireless LAN, Bluetooth, WiBro, etc);**
- Active development of alternative technologies;
- Display, keypad: maximize portability and performance (e.g., flexible display, virtual keypad, virtual display);
- Storage, battery: overcome the limitations of current technology (e.g., small DHH, MRAM, FRAM, fuel cell);
- Convergence;
- Camera: auto-focusing, several mega pixel resolution, and optical zoom;
- Various technologies and services converged into the mobile terminal such as media, biometric, health, leisure, and fashion.

6.5.2 Software

- **General purpose, flexible;**
- **Connectivity protocol: seamless connectivity among W-CDMA, CDMA, WLAN, Bluetooth, and WiBro;**
- Middleware: wider acceptance of middleware platform, such as Java and Brew;
- Operating system (OS), codec; open OS (Symbian, WinCE, Palm) and general purpose Codec (H.264);
- Standardization is very competitive;

- Middleware: Java versus Brew;
- OS, Codec: Symbian verus MS, H.264 versus MPEG4, MP3 versus AAC/WMA

At present, terminals are only capable of accessing one network at a time and a terminal is capable of switching a radio network among some standards, like GSM, UMTS, CDMA, WLAN, and WiMAX. Parallel radio or multiple simultaneous access technologies will allow access to different radio networks at the same time. For example, the user could be connected to the cellular network engaged in a voice service while simultaneously retrieving information from a WLAN. Antenna evolution promises increased throughput and more optimal utilization of bandwidth using MIMO-capable base stations and mobile terminals. Terminals will be able to communicate with a large number of other devices using different techniques (e.g., radio and optical interfaces) [16]. Also, many types of sensors will be embedded in future devices to allow control of applications and to sense the current user context.

6.6 Chapter 6 Summary

The various 4G requirements discussed in this chapter show the *fundamental need for flexible (programmable, reconfigurable, adaptable) platforms as a key requirement for 4G networks*. This need will also propagate into the RF front end section of both the base stations and terminals because it will need to support multiple bands and air interfaces for seamless connectivity among W-CDMA, CDMA, WLAN, Bluetooth, WiBro, and other standards.

Chapter 7 Technologies and Research Aimed at Addressing the 4G Requirements

The Mobile IT Forum [17] has identified the following techniques and technologies aimed at addressing the future 4G requirements. A few of the relevant technologies for this dissertation are later discussed in more detail.

7.1 Wireless Transmission Techniques.

The following are several technologies and research areas aimed at improving the high speed and large-capacity wireless transmission techniques.

- *Frequency re-farming:* Re-arrangement of allocated frequency bands to allow more efficient spectrum utilization and study of new bands
- *Advanced adaptive techniques to increase spectral efficiency:* Adaptive modulation and coding, adaptive control for automatic repeat request (ARQ), adaptive antennas
- *MIMO techniques for exploiting spatial multiplexing:* Fundamental for attaining very high data throughput
- *Multi-carrier techniques:* Frequency orthogonal techniques (e.g., OFDM) as the baseline modulation technique for 4G systems used in general in combination with CDMA and TDMA techniques give more design flexibility and interference protection
- *Interference and fading mitigating techniques:* These two major impairments in typical wireless scenarios may cause serious degradation to systems performance. Interference cancellation, equalization, and multi-antenna techniques, among others, are key approaches to be investigated
- *Error control techniques:* Advance FEC and ARQ schemes need to be incorporated to 4G systems to guarantee a desired signal quality regardless of the channel conditions
- *High-speed packet radio:* Important techniques are needed to improve the utilization of radio resources, allowing higher systems capacity and higher data rates

- *Handover techniques:* As seamless communications is one of the most distinctive features of future systems, fast and reliable handover techniques for a large number of scenarios should be investigated

7.2 Network Technologies

The following are several technologies and research areas aimed at improving the network for 4G.

- *Radio access network technologies:* These techniques will enable the dynamic establishment of multiple continuous or isolated access cells.
- *Robust networks:* Variable-capacity networks able to adapt to the variable traffic demand conditions while keeping performance unchanged is a challenging area for research. Multiple antennas, congestion control, and multihop communications have been identified as promising techniques for this purpose.
- *Ad hoc networks:* Rather than the centralized approach of conventional wireless communications where communications use a central node (base station) to access the network, an ad hoc network can be seen as a distributed approach where the signal can hop through several nodes (terminals) to reach the destination. Routing protocols, user and service discovery procedures, and security issues are the main research items.
- *Seamless networking techniques:* Allows seamless interconnection of a packet-based backbone network with radio access or other networks.
- *Approach link techniques:* A number of techniques used to connect base stations or remote stations to control stations by using optical means (fiber, free-space optics), microwaves, and so forth.
- *High-speed transport technology:* Techniques to transport and switch efficiently very high-speed packet data.

7.3 Mobile Terminal Techniques

The following are several technologies and research areas aimed at improving the mobile terminals for 4G.

- *Circuit and component technology:* Faster processing circuits, denser integration capabilities, smaller batteries, and display technologies with better image quality are identified an important goals to be fulfilled to fully comply with 4G system requirements and user expectations.
- *Battery technology:* Enhancement of battery capacity, efficiency, operational time, and size is crucial to succeed in producing future handheld terminals.

Low-cost batteries and environmentally friendly materials are also very important facts to consider.

- *Human interface:* This is recognized to be a very important research area, where natural ways of interaction between user and machine are of the utmost importance in order to make future 4G systems attractive. Terminal form factor, wearable terminals, visual and voice interfaces, and the use of biometric information are among the most important research issues.
- *Terminal security techniques:* Techniques aiming to provide levels of security at least similar to those found in networks using public key-based infrastructure should be developed. User authentication and data protection are also highly relevant research topics.
- *Terminal software:* Common operating systems, software platforms, and applications compatible with SDR should be developed.
- *Multi-system wireless terminal technologies:* It is envisaged that future terminals will be able to handle seamlessly short-range, wide-area, and broadcast communications using different technologies implemented in the terminal. There is a series of technical challenges that need to be solved, including multi-system radio for multiple modulations, protocols and frequencies, multi-band antennas, practical realization of SDR and seamless operation between the systems.
- *Software defined radio:* Fundamental technology applicable in both base stations and mobile terminals permitting the use of multiple access technologies in a very efficient fashion. Issues to be studied include transceiver architecture, basic implementation technologies, and basic transmitter and receiver technologies realizable in software, e.g., multimode modulation and demodulation techniques, multi-band transmit and received techniques, and so forth.

7.4 Mobile Systems Technologies.

The following are several technologies and research areas aimed at improving the mobile systems for 4G.

- *Quality of service:* These techniques encompass different methods to control and ensure fundamental communications parameters, like desired transmission speed, bandwidth, delay, and packet loss rate.
- *Mobility control:* Techniques aiming to provide and maintain QoS in environments characterized by mobility. These include handovers and mobile Internet protocols.
- *Mobile multicast techniques:* Broadband transmission techniques for real-time and non real-time broadcasting of information.
- *Location determination and navigation:* Reliable techniques for providing user coordinates, speed, and other navigation information in outdoor and

indoor scenarios. A large number of applications could potentially exploit this kind of information.

- *Security, encryption, and authentication:* Techniques aiming to secure mobile communications by preventing any type of illegal use of the wireless resources.

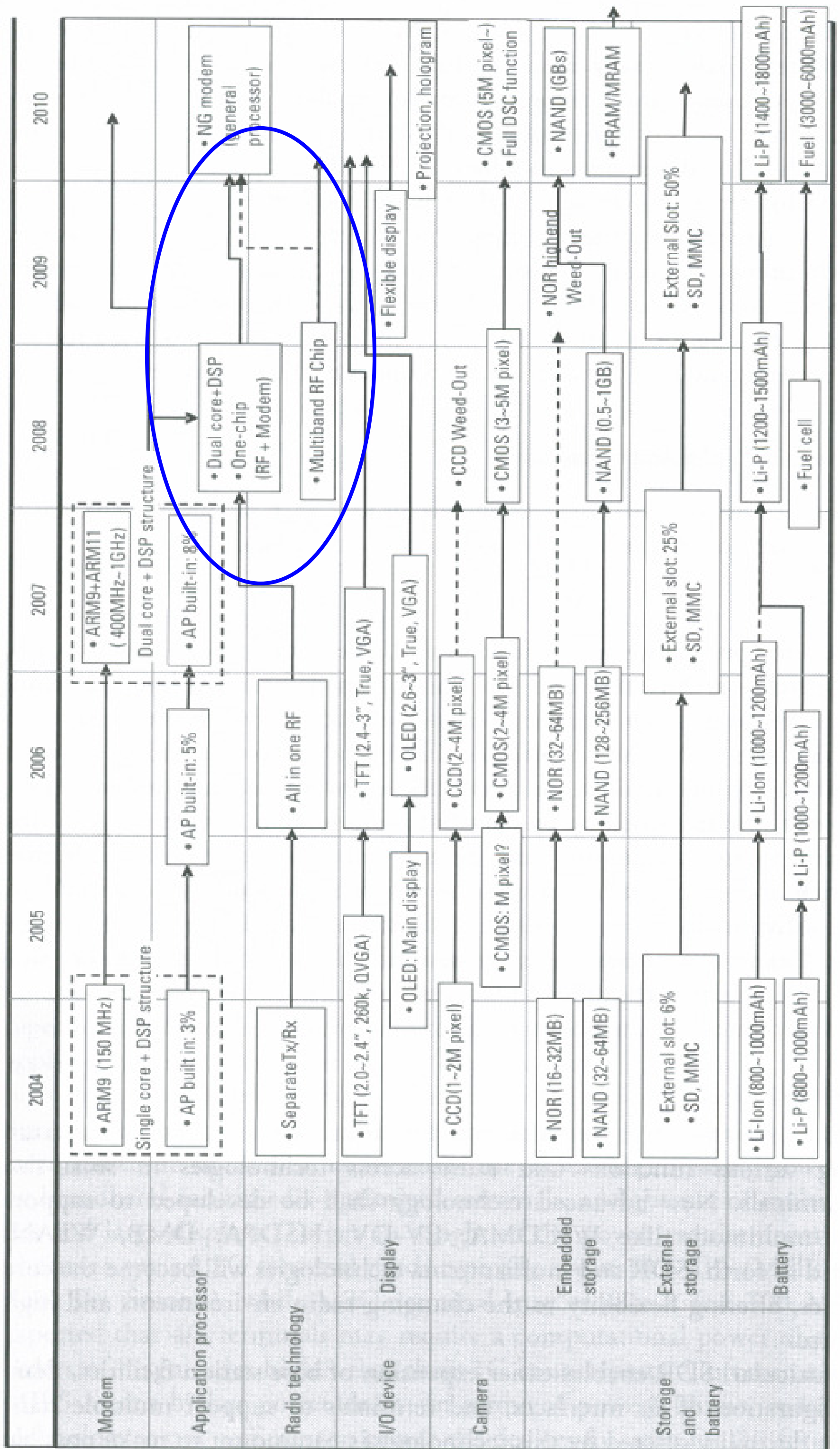
Of the above list, two technologies are most relevant to the topic of this dissertation paper: multi-system wireless terminal technologies and software defined radios. As indicated above, there is still a series of technical challenges that need to be solved, including multi-system radio for multiple modulations, protocols and frequencies, multi-band antennas, practical realization of SDR and seamless operation between the systems.

7.5 Hardware Technology Roadmap

Fig. 7.1 shows a Hardware Technology roadmap that shows several key hardware related components and technologies that are relevant to this dissertation as follows.

7.5.1 Modems

As the need for processing power is increased, the competition between integrated single-chip architecture and functionally divided multi-chip architecture will become more pronounced. Single-chip architecture has the advantages of requiring less size and, in some situations, lower power consumption. On the other hand, a multi-chip architecture is powerful in processing multimedia applications. The need of fixed (e.g., ASIC) or flexible (e.g., reconfigurable) structures has to be assessed carefully when



Source: [15]

Figure 7.1 Hardware Technology Roadmap

designing the platforms for implementing the modem. Cost and space limitations also need to be taken into account when considering single and multi-chip architectures.

7.5.2 Radio Technology

It is anticipated that new advanced technology will be developed to support multi-band/multimode applications like W-CDMA, CDMA2000, EV-DV, HSDPA, DMB, WLAN, WiBro, Bluetooth, etc. SDR and multi antenna technologies will become the core technologies, offering flexibility to the changing radio environment and higher performance. In particular, SDR enables easier expansion of base station facilities, flexible reconfiguration of air interfaces, and terminals to support multiple standards. The flexibility offered by this technology is paramount to make possible truly seamless networks, and to support multiple communications schemes. It also provides an effective means for expanding functions for multimode operations, as terminals and base stations can be reconfigured in the field. In addition, multiple antennas at both ends of the wireless channel can be used to increase the data rate via spatial multiplexing and to improve the link quality through diversity.

Thus, future terminals and base stations could become extremely complex, particularly if the trend of developing multipurpose terminals capable of providing various types of connectivity (e.g., multi-standard) and supporting diverse services persists. A number of challenges for the design of such terminals have been identified and among these is RF integration and the issue of centralized versus distributed architectures as highlighted above.

7.6 Chapter 7 Summary

As discussed in this chapter and as also shown in the hardware roadmap of Fig. 7.1, it is anticipated that the modem processor and the DSPs required for SDR should eventually converged into a single piece of silicon. It also shows that the radio technology will evolve into a multi-band RF chip. Another possible scenario shown in the roadmap is the integration of both RF and DSP into a single chip. However, the exact definition and implementation of the future radio architecture is not yet clear as more research and industry products in this area are developed.

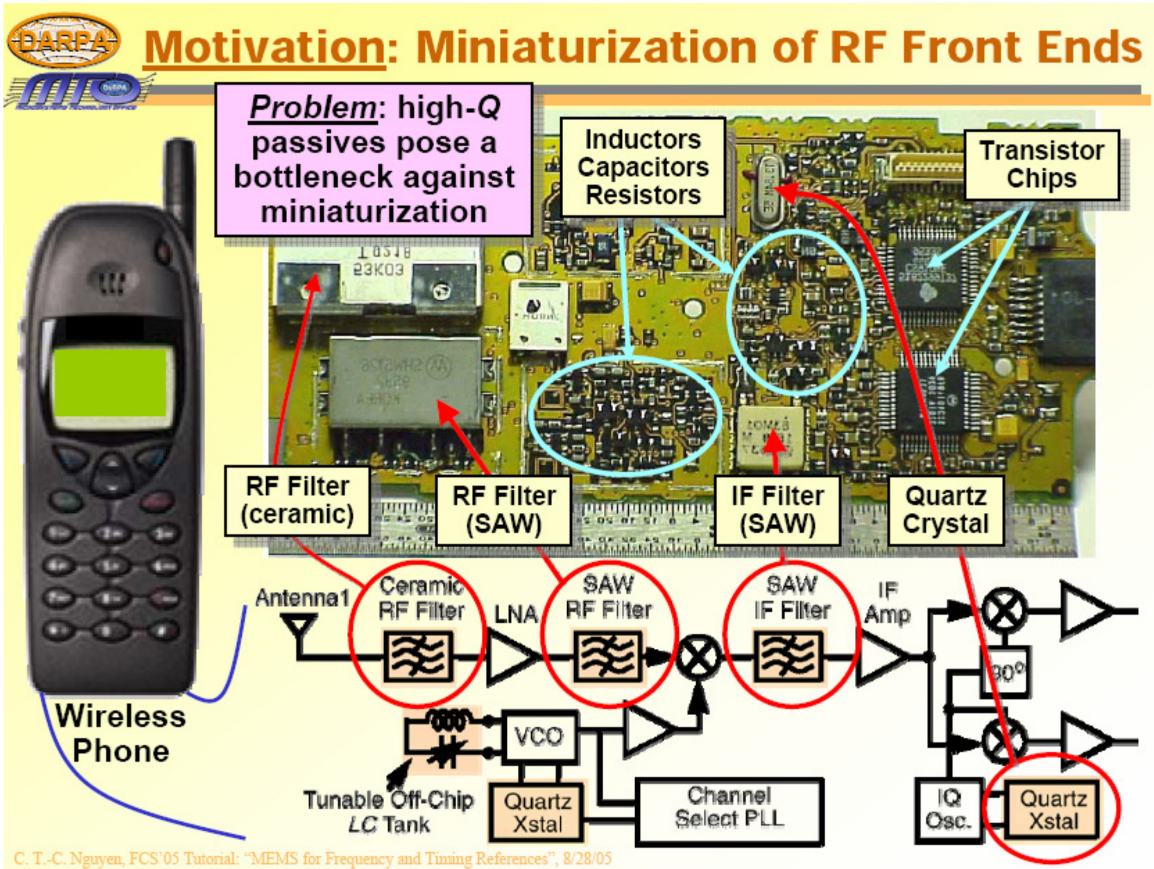
Chapter 8 RF Front End Technology Requirements and Challenges

8.1 The Vision for the RF Front End of the Future

In order to provide wide coverage, mobility, and roaming, the base stations and terminals of the future (4G and beyond) will have to include cellular 2G (e.g., GSM) and 3G (e.g., UMTS) transceivers working in the 900 to 1,800 MHz bands. High-speed local access could be provided by an 802.11 (Wi-Fi) transceiver in the 2.4/5 GHz bands. Basic short-range communications capabilities could be additionally carried out with a Bluetooth transceiver operating at 2.4GHz. RFID is already being integrated in some handsets and allows very short-range instant connections for several purposes (e.g., payments, identification, and information retrieval). RFID operates typically in the 13-MHz band, though low and high-frequency versions are available (100 KHz, 1 GHz, 2 GHz, 5 GHz).

In addition to the above functions, and following the trend of designing terminals with as many features as possible, one can also see the integration of a conventional FM radio receiver (already a trend in many mobile phones), a terrestrial or satellite broadcast TV receiver (100-MHz to 1-GHz band), and a GPS/Galileo receiver (1.1- to 1.6 GHz band). Though all of these devices will not be used simultaneously, several could be switched on in certain applications. Terminal design could become the bottle-neck for the development of multi-standard, multi-featured terminals, as radio frequency interference between different transceivers could have detrimental effects on the performance, in particular taking into account the physical limitation of having receivers and transmitters enclosed in a very small space. Methods of interference management and control should be carefully applied at the design stage. The situation becomes critical if one considers the fact that the transceivers (e.g., for communications) and /or receivers (e.g., radio, TV, GPS) may need to use different antennas.

Moreover, in order to attain the expected level of performance, particularly high data throughputs, cellular and local area systems have to resort to the use of multiple antennas. At high frequency bands (e.g., 5-GHz or higher) it is feasible to place several antennas on a small (handheld) terminal – for example, an array of four or even eight antenna elements. Typically, these antennas have to be distributed to cover virtually all the available main plane (largest surface) of the terminal, in order to maximize antenna element separation. Obviously, future designers will face a very difficult task trying to efficiently integrate multiple receiving and transmitting elements into small form factors. This could even be impossible for certain combinations of multi-standard and desired form factors. Fig. 8.1 shows the challenges already being faced by designers in integrating the various discrete components associated with the RF front end part of a mobile phone.



Source: Dr. C. Nguyen, FCS 2005 Tutorial: "MEMS for Frequency and Tuning References"

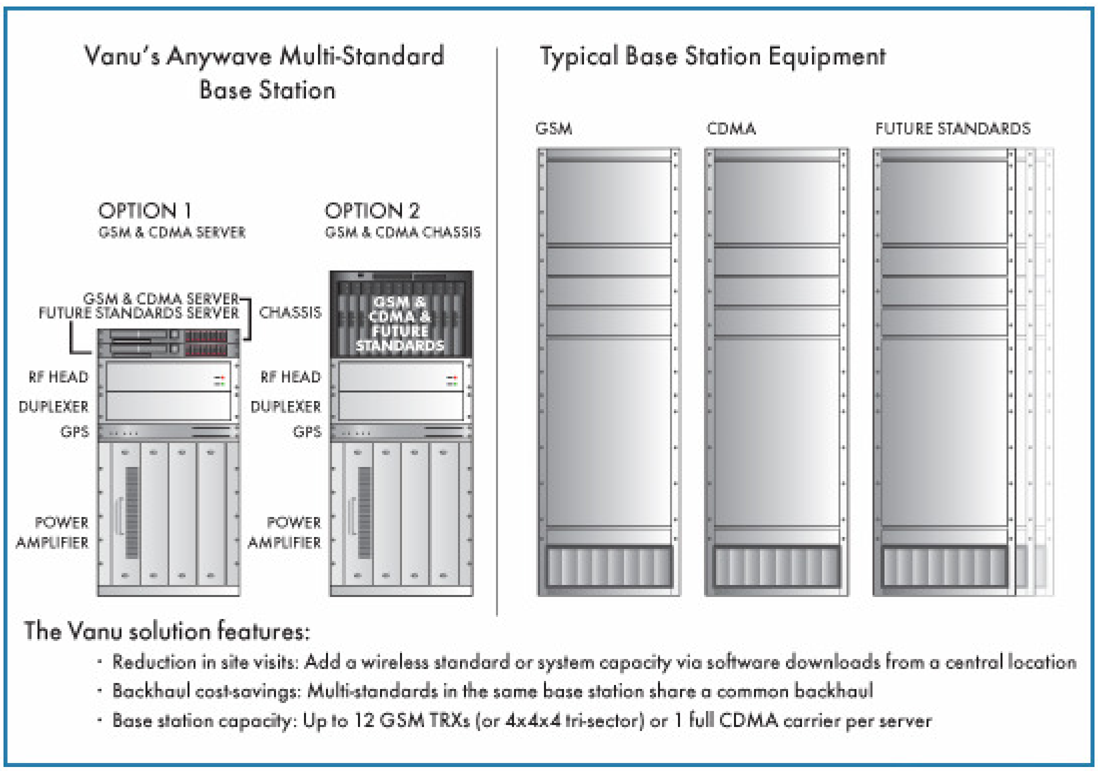
Figure 8.1 Miniaturization Challenge in Mobile Phones

8.2 Cost Considerations

There is another important factor against implementing several transceivers on one terminal: cost. Even in the case where multiple-integration is technologically feasible, the relatively high cost associated with having several standards implemented remains one of the central issues to be solved. However, there exists a different approach that has been extensively studied in recent years, and in the view of their proponents it could be, cost- and technology-wise, the most efficient way to go towards making complex terminals a reality. This solution is known as Software Defined Radio.

Ideally, in the *broadest sense*, SDR allows on-the-fly modification of the RF front ends, base band processing, and even the MAC layer of the terminal, aiming to realize a given air interface by reconfiguring the system. The degree of flexibility brought by real-time re-configurability opens up a new world of possibilities for users, operators, services providers, and terminal manufacturers. Users can establish a connection in any network, allowing simple local and global roaming. Users could also benefit from the low-cost terminals that this technology would eventually bring. As new advanced services are introduced, software modifications can catch up with the new requirements. Hardware and software updates could be easily and wirelessly carried out by the user or by the operators. Manufactures can also take advantage of SDR since large volumes of terminals (or base stations) with identical hardware (and fewer number of components) would have to be produced. Even upgrades or changes in the terminals could be carried out simply. Also operators and service providers could exploit this flexibility to better match their operation and services to use demand. Vanu Inc., [18] has already made significant advances towards the implementation of SDR-based architectures for base stations, and the benefits of such architecture are clearly shown in Fig. 8.2.

From the above synopsis of the challenges that terminal and base stations designers face, it can be seen that the RF Front End represents one of the biggest opportunities for cost reduction and logistics simplification for the base station and terminals of the future. While there is a lot of academic and industry research focused on software-defined radio architectures, SDR still does not solve the RF Front End cost issue. In fact, for SDR architectures to achieve their promised "programmability" mantra, they need a true "programmable" RF Front End. The problem is that today's RF front end implementations are not programmable but fixed to work with a specific RF frequency (e.g., 1,900 MHZ) for a specific mobile network standard (e.g., CDM2000 or W-CDMA). To band-aid this issue, OEMs typically implement multiple RF Front Ends to give the illusion of a "multi-mode" programmable system at twice, triple or quadruple the cost of a single-mode system.

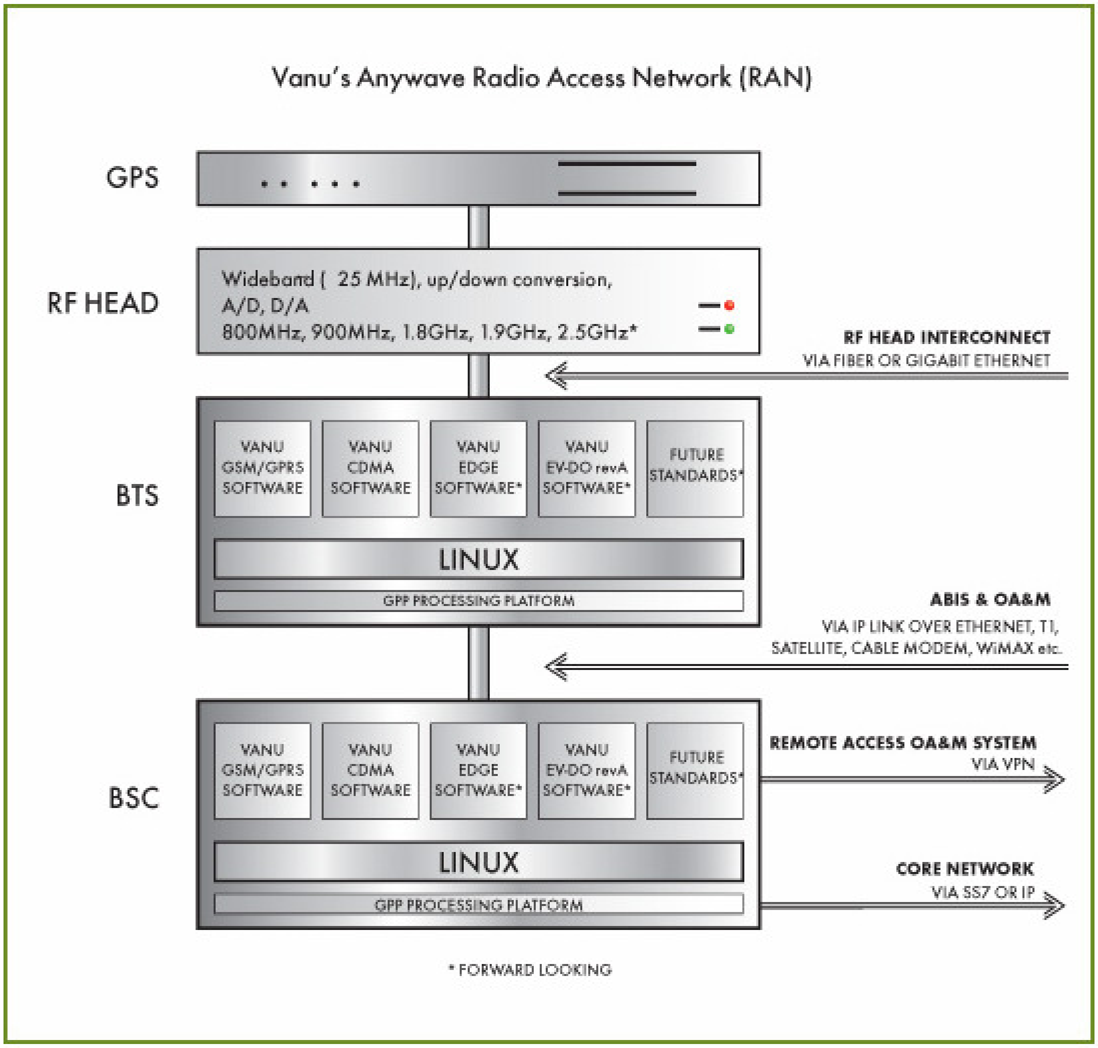


Source: www.vanu.com

Figure 8.2 Vanu's *Anywave* Multi-Standard Base Station

8.3 Vanu, Inc.

Even industry-ready software defined radio architectures have not yet solved the requirement to have multiple RF front end "heads" for each of the bands supported. Vanu Inc., [18] has developed a very innovative software configurable architecture for base stations still requires multiple RF front end "heads" for its software-based architecture as shown in Fig. 8.3.



Source: www.vanu.com

Figure 8.3 Vanu's System Level Base Station Architecture

Vanu's story is best summarized by extracting it from their website [18]:

"Traditionally, wireless infrastructure manufacturers have developed single-standard, high-power, high-capacity networks to address cellular coverage needs. These dedicated networks required extraordinary financial investments that took a long time to generate positive returns. And as new technologies emerged, so did the need for another large dollar investment to build a new network to support an additional standard. Each technology, or wireless standard, required its own dedicated hardware platform and network build-out.

Vanu, Inc. has developed the first commercially available software radio access network (RAN) that lets wireless carriers operate multiple standards simultaneously on a single platform. That means GSM, CDMA, iDEN and more… all operating simultaneously from a single base station. Vanu was founded in 1998 to enable wireless operators to operate and expand their networks with the ease, flexibility and cost-effectiveness of modern computing practices, using its innovative software radio technology, the Vanu *Anywave*® solution.

The number of wireless standards and licensed frequency bands in use are multiplying, and the pace of innovation is accelerating. Carriers can't afford to implement a dedicated network for each standard they wish to deploy, and the faster rate of change makes it harder to earn a return on investment within a reasonable period of time. Yet competitive pressures and consumer trends are requiring operators to support multiple standards, creating bigger financial challenges in the process.

Additionally, the traditional high-power, high-capacity networks do not provide cost effective solutions for in-building enterprise and home coverage, the fastest growing wireless environments today. Carriers need a way to cost-effectively adopt – and profitably operate – multiple standards using their existing spectrum, tower, antenna, shelter, etc. And this needs to be accomplished while successfully delivering RF coverage solutions for outdoor and indoor settings. Vanu has addressed these needs with its *Anywave* software radio technology.

Vanu's Anywave is the wireless industry's first software radio access network (RAN) to obtain FCC certification and commercial deployment. Rather than processing wireless standards in single-purpose components – the traditional method that requires costly, specialized signal processing hardware – Vanu Anywave defines and processes each technology entirely in software.

As a result, expanding an *Anywave* network with a new wireless standard is a fast and cost-effective, remote software download from a central location. Leveraging a common software platform that sits on IT grade or NEBS-compliant commercial off-the-shelf (COTS) computing servers, the Vanu *Anywave* solution enables carriers to operate multiple standards simultaneously on a single platform. Furthermore, because the *Anywave* solution is hardware agnostic, scalable up and down and highly portable, the solution can be packaged to fit the broadest range of coverage needs, including:

- Outdoor, large-cell coverage that accommodates both urban and rural environments

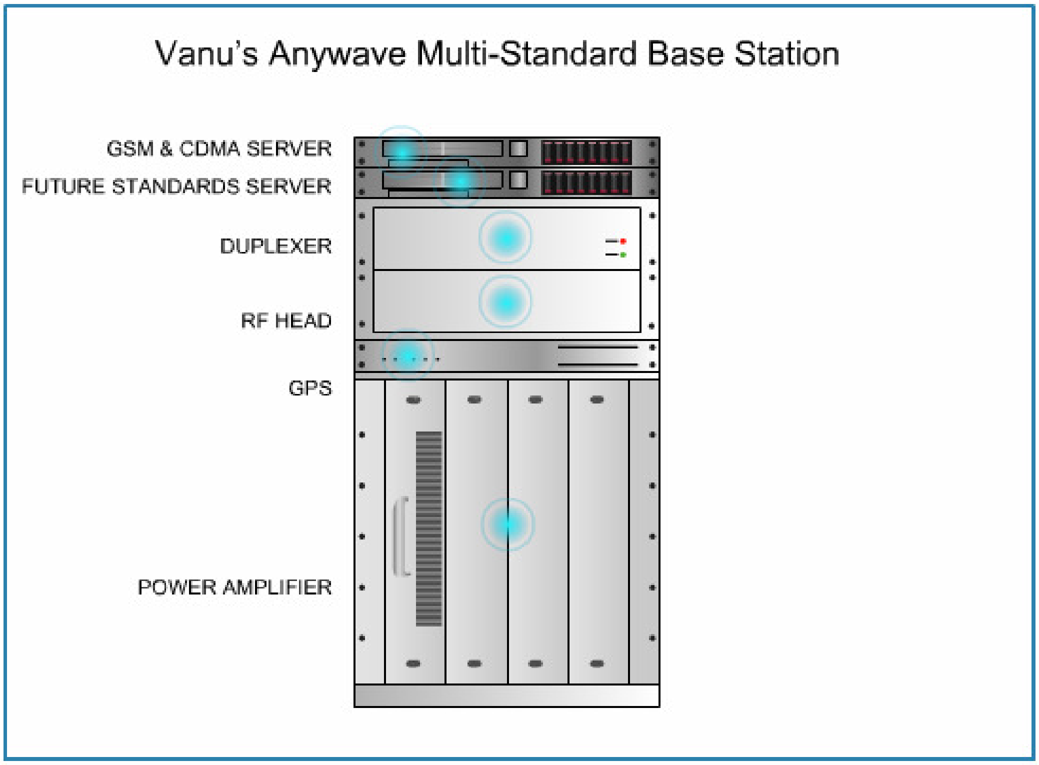
- Outdoor pico cell filler coverage to selectively increase capacity in high-density traffic locations
- Pico cells with or without a distributed antenna system (DAS) for enterprise applications
- Femto cells with broadband IP backhaul for home use
- Mobile cell sites for temporary venues or disaster recovery applications

New standards, new frequency bands, new competitors and demand for new services will continue to escalate. The Vanu *Anywave* solution enables operators to "future-proof" their networks. If additional wireless standards are acquired or desired, they can easily be accommodated on the same network infrastructure through a remote, software download without the time-consuming expense associated with costly site visits. The same is true when the operator wants to add system capacity. Additionally, because the software-based Vanu *Anywave* RAN runs on COTS hardware, it's able to ride the coattails of Moore's Law where computing capacity doubles every 18 months—that's price performance that only gets better over time.

The Vanu *Anywave* system can help operators expand their offerings and reduce costs, which will help them to compete more effectively in a constantly changing marketplace. It's what carriers have hoped for in the past, and what will enable them to succeed – today and in the future."

Fig. 8.4 shows Vanu's *Anywave* system architecture in more detail. A typical Vanu *Anywave* RF head supports up to 16 carriers, depending on the cellular standards being used. This design can, in many cases, provide significant heat dissipation and power loss savings compared to the power-inefficient combining networks used in legacy line card BTS architectures.

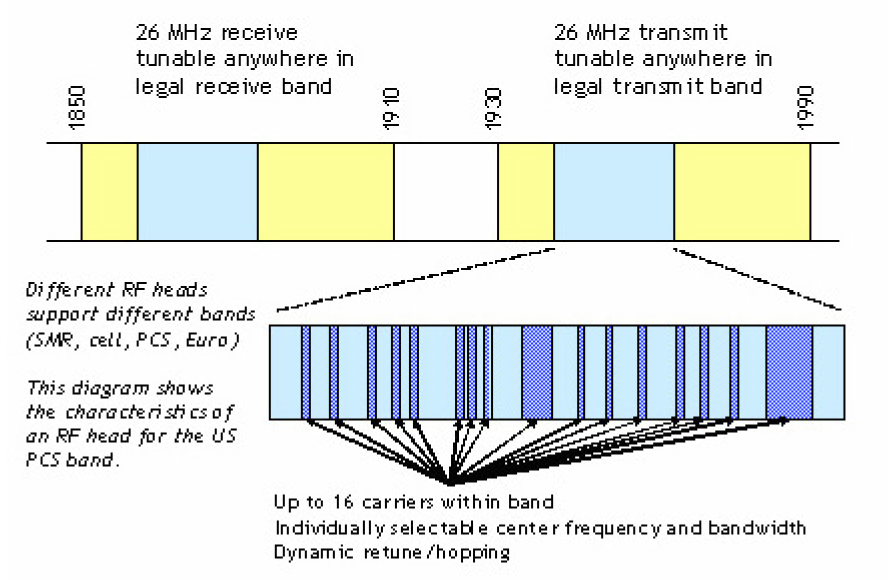
The analog electronics in the RF head offers sufficient linearity and spurious free dynamic range (SFDR) to support any of a variety of cellular standards. Selectable carrier frequency and bandwidth allows multiple carriers in different wireless standards to operate simultaneously (Fig. 8.5), for example, the transmission and reception of GSM and CDMA channels at the same time through the same RF head. The carriers in use can even be changed dynamically, for instance to match the capacity of each standard to the number of customers currently in the coverage area of the BTS. The transceiver in the RF head performs digital channelization and down-conversion on receive and digital up-conversion and summing on transmit to reduce the bandwidth requirements on the RF sample interconnect.



- **The RF head** performs RF up/down conversion, digitization, and digital channel filtering to provide multiple digital baseband sample streams to the processing platform. It can simultaneously operate on GSM, CDMA, and other technologies.
- **The RF duplexer** is a filter that takes in the antenna signal and separates the high-power transmit signal from the receive signal. The duplexer may also include a receive filter for the diversity receive antenna.
- **The multi-carrier power amplifier** (MCPA) takes in the low-power RF transmit signal from the RF head and boosts it by as much as 60 dB. The MCPA is designed to support simultaneous amplification of multiple waveforms within a 25 MHz bandwidth.
- **The GPS** provides a highly accurate timing reference to the RF head. Both 10 MHz and 1 pulse-per-second references are used by the base station to achieve the required frequency accuracy and synchronize itself with other base stations.
- **The processing platform** runs the software waveforms on top of a standard operating system like Linux. The processing platform is made up of one or more processing units, either embedded, rackmount or blade.

Source: www.vanu.com

Figure 8.4 Vanu's Anywave Multi-Standard Base Station



Source: www.vanu.com

Figure 8.5 Vanu’s Selectable Carrier Frequency Architecture

8.4 Chapter 8 Summary

Vanu’s architecture clearly illustrates the advances being made as of 2008 in base station architecture using SDR techniques. It also highlights the importance of RF “heads” with “selectable carrier frequency and bandwidth” which allows multiple carriers in different wireless standards to operate simultaneously. The challenge that both industry and academia research now face is how to both reduce the cost and size of these RF “heads” and scale these down so that the same architecture can be implemented in the much smaller-sized femtocells and mobile handheld terminals of the future.

Chapter 9 Current Technology Limitations of Software Defined Radios

9.1 SDR Defined

Software defined radio (SDR) is the term adopted by the SDR Forum [19] which is an international body looking at the standards aspects of software radios. The term software radio has become associated with a large number of different technologies. The term is usually used to refer to a radio transceiver in which the key parameters are defined in software and in which fundamental aspects of the radio's operation can be reconfigured by the modification of that software.

A multi-standard terminal (MST) refers to a terminal which is capable of operation on a number of differing air interface standards, and it may also be implemented using SDR techniques. The benefits of a reconfigurable multi-standard terminal include economies of scale, global roaming, service upgradeability and adaptive modulation and coding to cope with the prevailing channel or traffic conditions. The operational characteristics of an ideal multi-standard terminal include the following operations:

- Software-Definable Operation. This is a key requirement to achieve above stated benefits as the terminal must have the ability to be reconfigured either: during manufacture, prior to purchase, following purchase (e.g., after-market software), in operation (e.g., adaptation of coding or modulation), or preferably all four. This impacts primarily the digital and base band section of the terminal and will required the use of reprogrammable hardware as well as programmable digital signal processors in a power and cost-effective manner.

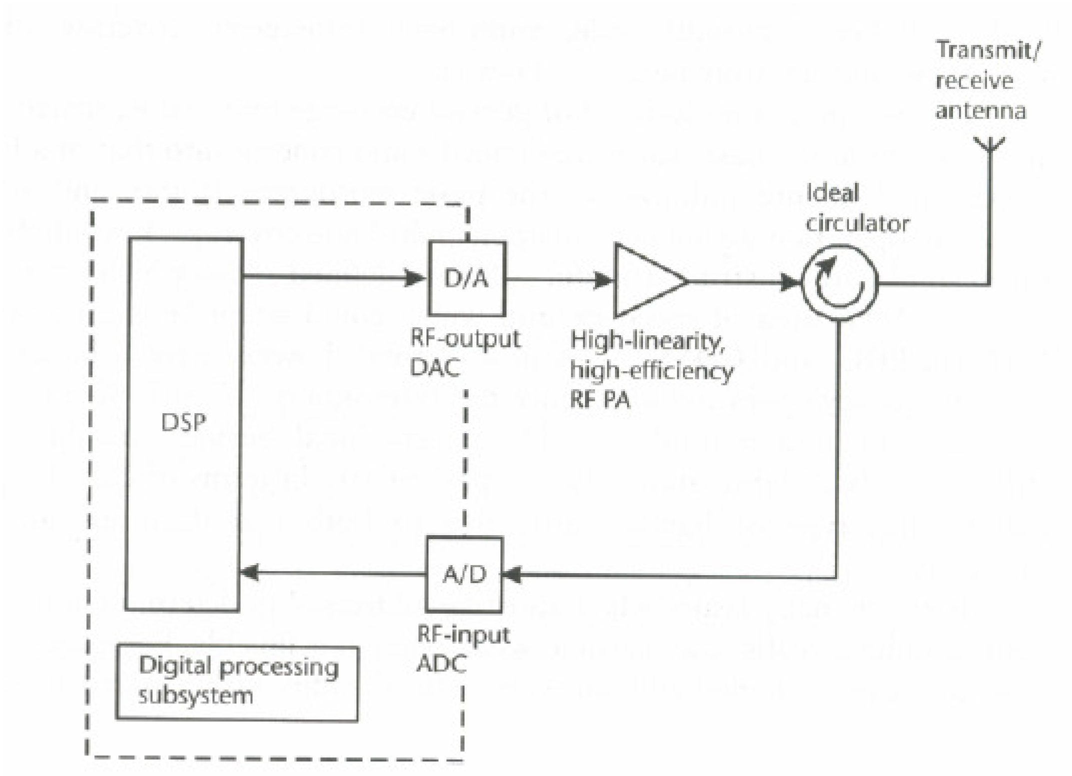
- Multi-band operation. The ability to process signals corresponding to a wide range of frequency bands and channel bandwidths is a critical feature of a MST. This will impact heavily on the radio frequency segments of the terminal, and *it is this area which is arguably the main technology limitation on software defined radio implementation at present* (although processor power consumption and cost are still both major issues for SDR
- Multi-Mode Operation. This is the ability to change mode and, consequently, modulation, coding, burst structure, compression algorithms, and signaling protocols.

The concept of a multi-band or general coverage terminal is really an extension of the basic software defined radio concept into that of a broadband flexible architecture radio, since the basic re-programmability and adaptability aspects of operation do not depend upon multi-band coverage. It would be possible for example, to construct a useful SDR-based radio which operated in the 800-/900-MHz area of spectrum and which could adapt between AMPS, GSM, DAMPS, PDC, and CDMA.

9.2 Current SDR Limitations

There are many issues that must be addressed in determining if a software defined radio is realistic and also to what extent it is flexible. For example, it is possible to create a single-band software defined radio with a narrowband channel restriction relatively easily [20]. Coping with a wider channel bandwidth and operating in multiple bands in different parts of the spectrum is much more difficult, but nevertheless essential, for a combined GSM/PCS/WCDMA/TD-SCDMA/WiBRO/WiFI/Bluetooth handset, for example.

Fig. 9.1 will used next to discuss the issues and current limitation of software defined radio architectures. Note that the A/D converter in Fig. 9.1 is assumed to have a built-in anti-alias filter and that the D/A is assumed to have a built-in reconstruction filter.



Source: [21]

Figure 9.1 Ideal Software Defined Radio Architecture

The ideal software defined radio has the following features:

- The modulation scheme, channelization, protocols, and equalization for transmit and receive are all determined in software within the digital processing subsystem. A DSP appears in Fig. 9.1, but there exists a variety of applicable signal processing hardware solutions for this element.
- The ideal circulator is used to separate the transmit and receive path signals, without the usual frequency restrictions placed upon this function when using filter-based solutions (e.g., a conventional diplexer). This component relies on ideal (perfect) matching between itself and the antenna and power amplifier impedances and so is unrealistic in practice, based upon typical transmit/receive isolation requirements. Since the primary alternative (a diplexer) is very much a fixed-frequency component within a radio, its elimination (or "transparency') is a key element in a multi-band or even multi-

standard radio. Note also that the circulator would have to be very broadband, which most current designs are not.

- The linear (or linearized) power amplifier ensures an ideal transfer of the RF modulation from the DAC to a high-power signal suitable for transmission with low (ideally no) adjacent channel emissions. Note that this function could also be provided by an RF synthesis technique, in which case the DAC and power amplifier functions would effectively be combined into a single high-power RF synthesis block.
- Anti-aliasing and reconstruction filtering is clearly required in this architecture (but is not shown in Fig. 9.1). It should, however, be relatively straightforward to implement, assuming that the ADC and DAC have sampling rates of many gigahertz. Current transmit, receive, and duplex filtering can achieve excellent roll-off rate in both hand portable and (especially) base-station designs. The main change would be in transforming them from a band-pass (where relevant) to low-pass designs.

To better analyze the difficulties in achieving the ideal software defined radio, the set of specifications in Fig. 9.2 can be used as an example. Those specifications can also be used as representative for a software defined radio femtocell. The current difficulties and limitations preventing the realization of the specifications in Fig. 9.2 will be summarized next.

9.2.1 Antenna.

A frequency range of almost 5 octaves is required, together with a realistic gain/loss figure of around 0 dBi. Combine this with the usual (handset) requirements of small size, near-omnidirectional coverage pattern (typically, excluding the users head), and low cost, and the physical realization of this component becomes extremely challenging.

Parameter	Value	Notes
Frequency Coverage	100 MHz - 2.2 GHz	This would cover most PMR, cellular, PCN/PCS, mobile satellite, and UMTS bands worldwide
Receiver dynamic range	0 dBm to -120 dBm (based on a 25-kHz equivalent channel bandwidth)	This must not only cope with fading and in-band interferers, but any signals in the above frequency range
Transmit power output	1W	This is reducing as time progresses and health fears increase, but most systems stillrequire this power level (many PMR systems require more).
Transmit adjacent channel power	-75 dBc	This figure is slighly in excess of most known specifications in this area (e.g., TETRA)
Transmit power control range	70 dB	Most CDMA systems, for example, require a large power control range
Transmit power ramping range	75 dB	DECT requires 68 dB and is probably the toughest requirement in this area
Channel bandwidth	5 MHz	Based on the 3GPP WCDMA standard for UMTS
Receiver image rejection	60 dB	Based on an interpretation of the TETRA specification

Source: [21]

Figure 9.2 Basic Specifications for a Handportable Software Defined Radio

9.2.2 Circulator or Duplexer.

This is discussed in more detail in the next chapter of this dissertation. However, it needs high isolation and broadband coverage range. In the case of a conventional, filter-based duplexer, this latter requirement (that is, broadband coverage range) is essentially impossible to achieve with current technologies.

9.2.3 A/D Converter.

The sampling rate of this converter, if it is to Nyquist sample directly at RF, would need to be at least 4.4 GHz and, in reality, much more (to allow for a realistic anti-alias filter roll-off and real-world converter performance). For a 4G spectrum with frequencies in the 3- to 6-GHz, the sampling rate is much higher. If, however, the converter is permitted to under sample, the required sampling rate drops dramatically. The required sampling rate could fall to 20 MSPS (based on two-times Nyquist band-pass sampling), assuming that the RF filtering and ADC analog input were up to the task.

This would lead to an input bandwidth requirement extending to 2.2 GHz and a resolution of around 20 bits (from the receiver dynamic range requirement. Note that if a synthesizer and conventional down conversion are employed (in place of band-pass sampling), this resolution is available at very low cost in the form of digital audio converters. Up to 200 kHz of channel bandwidth can be accommodated in this way, relatively easily and cheaply (based on I/Q down conversion prior to the A/D converters).

9.2.4 D/A Converter.

This component is currently realizable, although with a relatively high-power consumption, again assuming that conventional up conversion is employed and that power control is employed either prior to or within the linear power amplifier. A resolution of 12 to 14 bits at 20 MSPS would be required. IF output devices are also now increasingly common, and the available IFs are increasing as technology improves. Current devices are capable of operation at an IF in the hundreds of megahertz region; however, this will improve over the coming few years to the point where RF output frequencies (e.g., 800/900 MHz and 1.9/2.1 GHz) will become a reality, at a realistic cost.

9.2.5 Receiver Anti-alias Filtering.

Based on the two times Nyquist sampling converters discussed above, an attenuation of 60 dB is required around 18 MHz from the channel edge. This would be extremely difficult, if not impossible, to achieve in a bandpass filter capable of tuning from 100 MHz to 2.2 GHz. With the architecture of Fig. 9.1, this component presents a serious challenge and strongly indicates that a synthesizer-based down-conversion mechanism would almost certainly need to be employed in a software defined radio for the foreseeable future. Improvement in sampling rates (for a give converter resolution) will, however, allow this requirement to be relaxed and may enable some limited forms of SDR to be realized without such high-performance filtering needing to be included.

9.2.6 DSPs and Equivalent Technologies

Technology in this area is progressing very rapidly and the primary issue at present is that of power consumption (for handset operation). Combination of reconfigurable hardware (e.g., FPGAs) and fully software programmable processors are likely to yield the best performance in terms of power consumption, although other, newer architectures are also strong challengers in this area (e.g., massive parallel arrays).

9.2.7 RF Power Amplifiers

Considerable research has been directed at the linearization of power amplifiers in recent years, and a number of candidate techniques exist. Many narrow band systems have employed the Cartesian loop technique, achieving up to -70 dBc inter-modulation product levels [20]. For broader bandwidth systems, RF pre-distortion, digital pre-distortion and feed-forward techniques have also been used. At present, digital pre-distortion is a realizable solution and fits well with the architecture of a software defined radio.

9.3 Chapter 9 Summary

The specification outline in Fig. 9.2 and the components required to realize it are clearly not all available with current technology and may not be achievable, in many cases, for a considerable period (if ever). It is therefore necessary to examine other architectures and/or restrictions in the specifications contained in Fig. 9.2, in order for a software-defined radio to become a reality in the short or medium term. In the next chapter of this dissertation, the author proceeds to examines in more detail the various architectures for the implementation of SDR-based multi-band flexible transceivers, with particular attention to the RF front end issue highlighted above.

Chapter 10 Multi-Band Flexible (MBF) Transceiver Architectures

10.1 Introduction

The preceding chapters have explained the compelling reasons for flexible radio architecture. It has been shown that future 4G systems will require the co-existence of multiple modes and multiple radio frequencies and that this requirement will be needed at both ends of the network: both at the base station and the handset. It has also been shown that while software defined radio (SDR) technology is very promising for the implementation of flexible radios, there are other radio design issues that are not being addressed by DSP-based SDR techniques and thus require further research.

This chapter now focuses on a very specific research area that must be solved within the next three to five years in order to address the specific issue of multi-frequency filter technology required for a true multi-band flexible (MBF) transceiver. This chapter starts by presenting at a high level several possible MBF architectures at both the receiver and transmitter and concludes by showing that the requirement for a single-package multi-band tunable filter must be addressed as an alternative for MBF transceivers.

The concept of flexibility in a receiver breaks down into two main areas: that of the flexibility in the modulation format, coding, and framing, and that of flexibility in terms of RF frequency (that is, the ability to cover multiple bands, or provide general coverage, which is defined as covering all bands between a declared minimum and maximum frequency). This latter area, frequency flexibility, is certainly the more challenging of the two and is a concept which is the subject of much research. The former area has been much more widely addressed and most commercial communications receiver designs employ many of its basic principles, even if they do not yet aim to provide a wide choice of modulation formats.

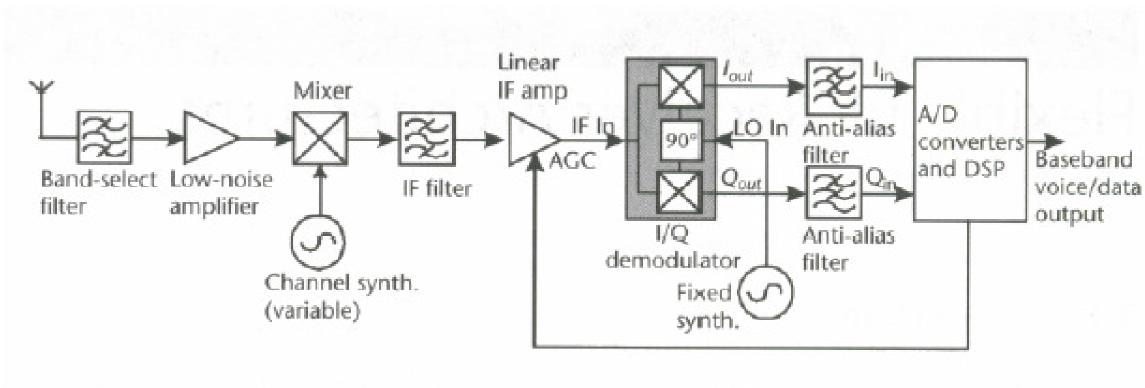
10.2 Receiver Single-Carrier Designs

Receiver single-carrier designs have been available for some time and are widely explained in the literature (see for example [22]). They are briefly reviewed here for completeness of the study as such single-carrier designs do not address the requirements of future generation RF front ends as explained in the preceding chapters.

10.2.1 Analog Quadrature Receiver Design

A simplified, single-band flexible receiver architecture is shown in Fig. 10.1. Its flexibility stems from the use of a DSP as the base band demodulation function; it can thereby demodulate any modulation format within its processing and data conversion bandwidth. Note that if a variety of different modulation formats are to be received by the same radio architecture, then the desired channel bandwidths must be carefully considered. For example, if the receiver is to handle both GSM (9200-kHz bandwidth) and PDC (40-kHz bandwidth), then the IF Filter, anti-alias filters, and A/D input bandwidth (and hence sampling rate) must be chosen based on the wider of the two bandwidths (more than 200 kHz for the IF filter and more than 100 kHz each for the anti-alias filters and A/D converter input bandwidths).

If this is done, then it is possible for the IF chain and A/D converters to experience a wide dynamic range of signals when in PDC mode, since at least six PDC channels could appear in the IF bandwidth. This would lead to a requirement for a greater instantaneous dynamic range in the IF and A/D converters than might otherwise be necessary. This problem may be overcome by the use of flexible base band filtering employing, for example, switched-capacitor techniques using MEMS technology, although such techniques have other inherent problems (to be discussed in the next chapter).



Source: [21]

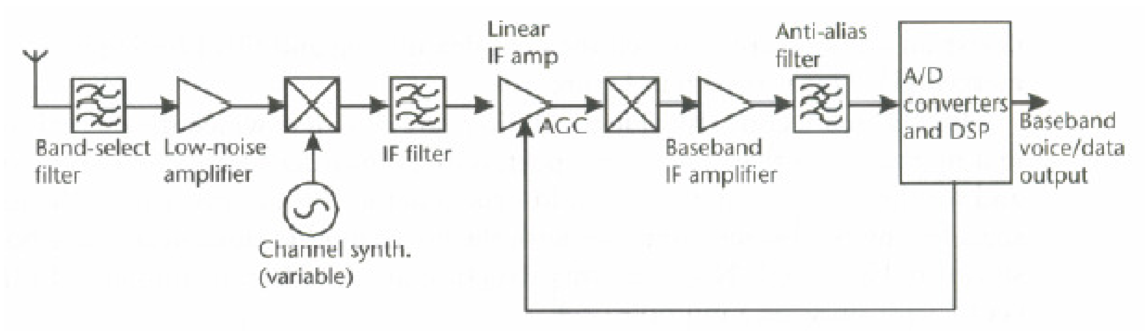
Figure 10.1 Simplified Linear Receiver Architecture

Note that the flexibility of the processing of the DSP allows many of the conventional receiver functions to be implemented in that part of the system. Some examples included:

- Detection/demodulation;
- Fast AGC (e.g., by feed-forward techniques);
- AFC, either by the use of internal (to the DSP) oscillators for frequency translation, or by pulling of the external frequency standard (not shown in Fig. 10.1);
- Companding for analog voice;
- De-interleaving and decoding/error correction of data.

10.2.2 Digital IF Receiver Architecture

An alternative, single-band flexible receiver architecture is shown in Fig. 10.2**.**



Source: [21]

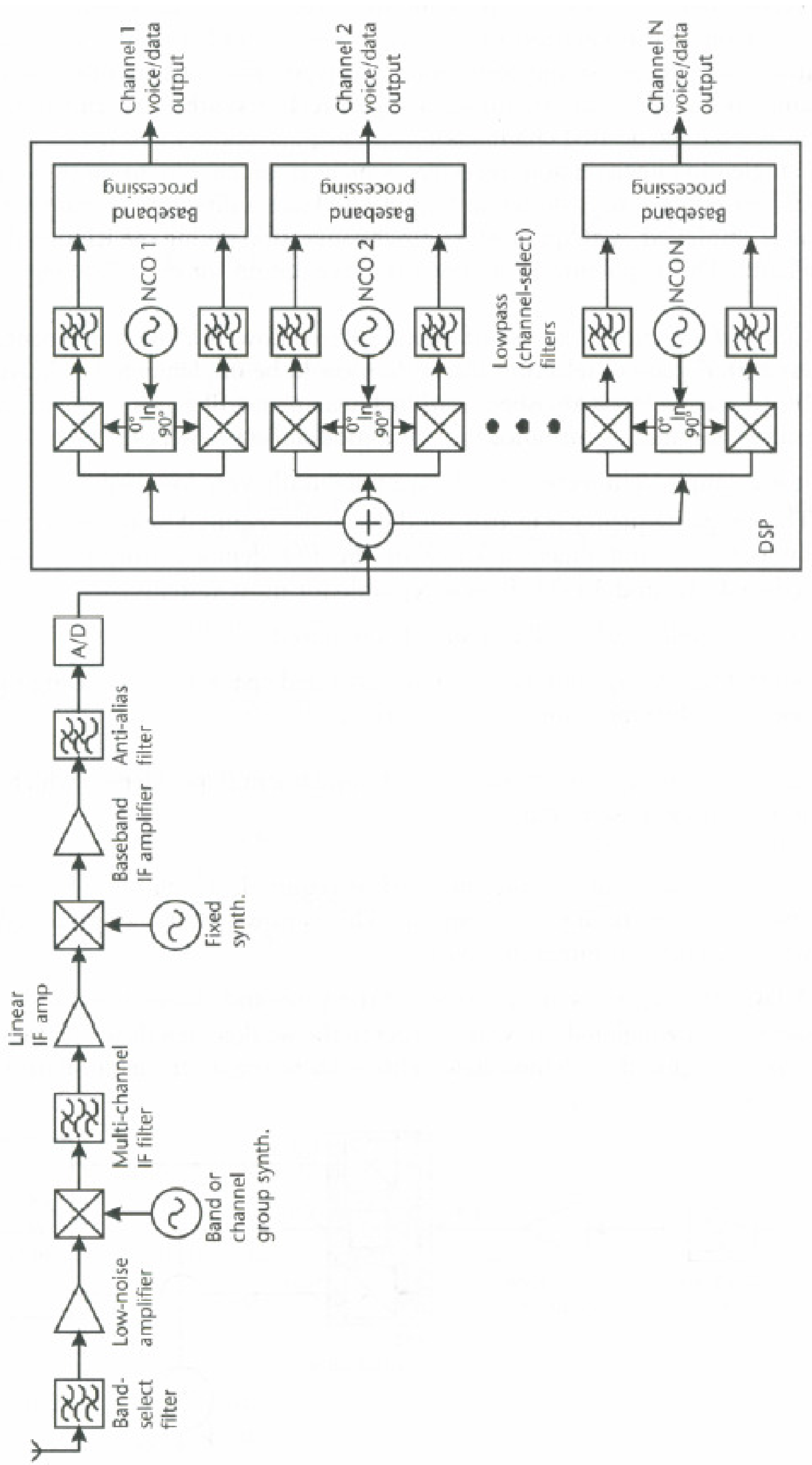
Figure 10.2 Digital IF-based Linear Receiver Architecture

Here the quadrature down conversion function is contained within the DSP, and this has the advantage that perfect quadrature accuracy can be obtained, without the presence of DC offsets. This is usually performed by ensuring that the final IF (labeled baseband IF in Fig. 10.2) is at a frequency sufficiently high that some channel selection can be performed, but sufficiently low that a sensible A/D and DSP processing bandwidth results. This compromise is around 10-50MHz [21] but continues to increase as A/D technology advances. The minimum frequency is determined by the requirement that at least a single channel must be capable of being Nyquist sampled at the A/D converter (10 MHz being the minimum requirement, approximately, for 3GPP W-CDMA). Some allowance should be made for frequency drift of the receiver local oscillator in selecting this frequency, if frequency correction is to be performed within the DSP. For wideband systems (e.g., CDMA), this is generally negligible. Allowance must also be made for the roll-off of the IF filter and hence the potential for adjacent-channel energy to enter the front-end. This will also force the base-band IF higher in frequency.

It should be noted, however, that while the digital IF receiver architecture shown in Fig. 10.2 is simpler than that shown in Fig. 10.1 due to the down conversion being implemented in the DSP, both architectures still require the use of band-select, IF, and anti-alias filters tuned to the bandwidth of interest.

10.3 Multi-Carrier (Multi-band) Receiver Design

The multi-carrier receiver concept can be an extension of either architecture shown in Fig. 10.1 or Fig. 10.2. The architecture shown in Fig. 10.1 would be less preferred versus the digital IF radio architecture of Fig. 10.2 as it would require too many components to implement, and its cost may be prohibitive for hand held applications. Thus, the architecture of Fig. 10.2 can be extended to multiple quadrature down conversions as shown in Fig. 10.3. In this case, the multiple quadrature down conversions are performed in the digital domain using separate numerically controlled oscillators (NCOs). Channel selectivity is provided using digital low-pass filtering on the resulting I and Q base band signals; as a consequence, the selectivity achieved can be very good. This approach to a multi-carrier receiver problem, such as a cellular BTS, has the significant advantage of a considerable savings in RF hardware over an approach involving a number of separate receivers (as shown in Fig. 10.1). In the case of surveillance receivers, it allows a larger number of channels to be monitored simultaneously at a relatively modest cost and with a small device. A multiple-receiver design would quickly become unwieldy in this case.

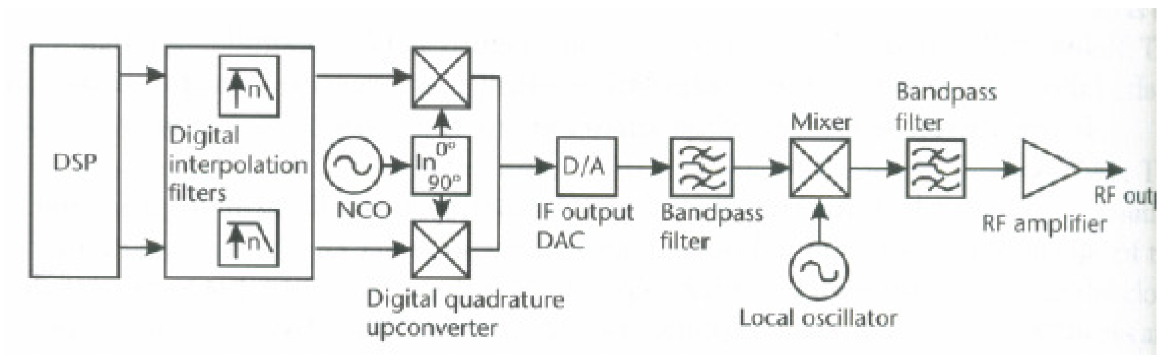


Source: [21]

Figure 10.3 Multi-carrier Receiver Architecture Based on Digital IF

10.4 Flexible Transmitter Architectures

It is now possible, with modern DACs, to obtain an output at a useable IF frequency (i.e., many tens of megahertz). This brings with it the option of performing the required quadrature up conversion processing in the digital domain as done for the receivers. This has the advantage of achieving near perfect image rejection and local oscillator suppression. The transmitter architecture required to accomplish this is shown in Fig. 10.4.



Source: [21]

Figure 10.4 Transmitter Architecture Employing a Digital IF Output

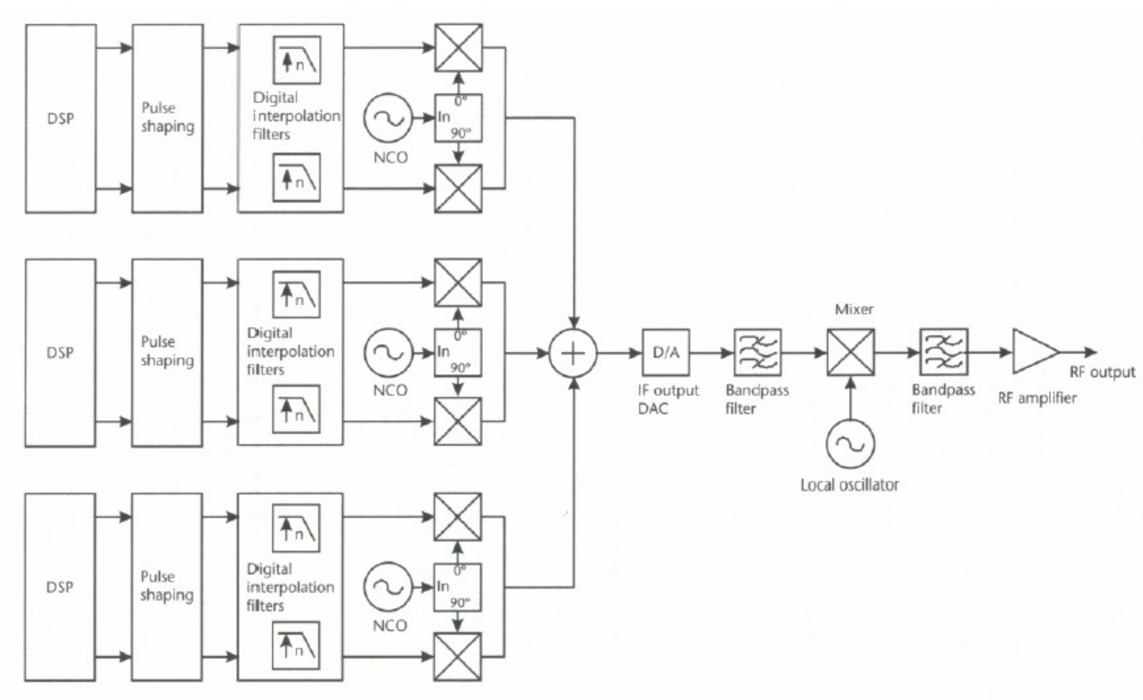
The implementation shown in Fig. 10.4 employs interpolation filtering and provides similar benefits as provided by an analog up conversion technique. The outputs of the interpolation processes feed a digital quadrature up converter, which utilizes a numerically controlled oscillator (NCO) as the local oscillator signal.

The use of an NCO permits frequency-hopping to take place digitally, if desired, and this can typically provide a much shorter hop time than with an analog PLL. If this approach is chosen, however, it is important to note that the analog IF filter must now be widened to cover the whole bandwidth over which hopping may occur (typically the whole frequency allocation). It is therefore no longer able to remove close-in DAC spurs, and these must be sufficiently low to meet the required system specification.

The output of the digital up-converter feeds an IF output DAC, which, if over-sampled, may be operating at a rate of many hundreds of megahertz. The output of this DAC contains the wanted band, plus a range of harmonic and alias products. These are typically removed using a band-pass filter (e.g., a SAW filter); however, some simple analog low-pass filtering to eliminate some of the higher harmonics may also be beneficial (the higher-frequency stop band attenuation of some filters can be poor). Once the wanted IF band has been selected by this first IF filter, one or more stages of conventional frequency up-conversion may then be employed to translate the signal to its final RF allocation.

This architecture has the advantage that only a single DAC is needed; although the requirements for one or more IF filters (with typically a tight specification) will frequently more than offset the cost saving of a second DAC. In addition, the performance of most DACs with an IF output will be poorer than with a base-band output, thus making a given specification more difficult to achieve. Comparing the performance of a typical DAC, when utilizing a 5-MHz base-band signal and a 20-MHz IF signal, indicates that a 5 to 10dB reduction in spurious-free dynamic range can result. This assumes that the DAC is designed to operate at a suitable sample rate, such that the 20-MHz IF can be accommodated with a reasonable, but not an excessive, margin.

Fig. 10.5 shows a logical extension of the digital IF transmitter architecture detailed above. In this case, multiple carriers (three are shown) are separately upconverted, each by its own NCO. There are then summed digitally, prior to digital-to-analog conversion. Since this is now a multi-carrier signal, the peak-to-mean ratio of the signal is likely to have increased, unless steps are taken to counteract this effect. The DAC must posses a sufficient dynamic range to cope with this and hence this architecture is generally the most demanding in terms of DAC performance.



Three-carrier version shown

Source: [21]

Figure 10.5 Multi-carrier transmitter architecture employing a digital IF output

The circuitry following the DAC is similar to that described earlier for a digital IF based transmitter. The main differences in this case are:

- The filtering must now be sufficiently wide to cope with a number of not necessarily adjacent carriers, but while still having a similar roll-off (typically) to that of the single carrier system. This therefore places greater demands upon the filter design.
- The dynamic range of the active circuitry (mixers, amplifier, and so forth) must be greater in order to cope with the greater peak-to-mean ration of the multi-carrier signal.

The NCOs may be used for frequency hopping, as outlined earlier for the digital IF architecture. In this case, however, there is no disadvantage in terms of the analog IF filter, as this must already cover the whole band of interest and hence the DAC spurs must be low enough to meet the system requirement (or this architecture cannot be used).

10.5 The Problem of the Diplexer

The diplexer filter in a mobile radio transceiver has, for many years, been the sole method of achieving the necessary removal of the transmitter output signal from the receiver input, in a full-duplex radio. This component is normally essential in order to realize the benefits of a standard telephone conversation in a FDD system (i.e., to be able to speak and listen simultaneously). In addition, it has been a feature of many TDD and TDMA systems, due to the requirement for the transmit and receive frames to overlap, when a long turnaround time for the transmit/receive signals is present (e.g., when the user is close to the edge of a cell).

The use of a diplexer (or duplexer) filter has a number of significant disadvantages that must either be tolerated or circumscribed in order to enjoy its benefits. These can be summarized as follows:

- *Size*: Their physical construction is such that they are often bulky, and even in hand portables they can consume a relatively significant amount of space.
- *Construction*: Their function, and hence their required form of construction means that it is unlikely that they will be successfully integrated along with the silicon components within a transceiver (at least in the foreseeable short or medium term). They are therefore a barrier to achieving a single-chip, full-duplex radio.
- *Spectrum inefficiency*: The use of a diplexer requires a frequency *split* between transmit and receive bands. A proposed technique to eliminate the diplexer should mean that his split *could* be eliminated, thus allowing both transmission paths to operate on the same frequency (know as *on-frequency duplex*). This in turn could lead to a doubling of the number of channels available in a given bandwidth. Note that the required performance from the technique increases markedly when attempting to achieve on-frequency duplex, as the performance requirement changes from one of eliminating overload in the receiver path to one of suppressing the transmit signal to a level below the minimum required receive sensitivity, by more than the co-channel protection ratio of the modulation formant in question. This is an extremely tough requirement in most systems.

10.5.1 The Isolation Issue

One example of a problem in the transmit-receive frequency split occurs in the 220-MHz SMR band in the United States. The issue is that of a small split between transmit and receive bands within the 220-MHz allocation; a given pair of transmit and receive channels is only separated by 1 MHz and this is a very small percentage of the frequency of operation. By contrast, the 1,800-MHz DCS band has a split of 90 MHz which is around 5% of the operating frequency, compared to only 0.45% for the SMR band. *It is this small percentage, which dictates the specification required of the diplexer filters in order to allow full duplex operation.* Creating a filter with a suitable high rejection over such a narrow frequency band, at say VHF, would result in a very large and expensive item if indeed it is realizable at all. Such filters would be nonsense in hand portable and prohibitively expensive and unacceptably large in a mobile handset. Thus, a radically new approach to this problem is therefore required, via advances in miniaturization technologies (like RF MEMS) or the aforementioned on-frequency duplex concept.

If it is assumed that a 2.5-W output power (+34 dBm) is required from the mobile and that the receiver is well designed and hence has a dynamic range of 80 dB, then the maximum level of transmit signal permitted in the receiver front end is -40 dBm (for an overall receiver sensitivity of -120 dBm). The rejection required therefore is +34-(-40) dB = 74 dB. This level of rejection must mainly be provided by some form of cancellation without sapping significantly additional power from the supply or adding unreasonable levels of complexity.

There are a number of issues which arise when considering a multi-band flexible (MBF) architecture radio. In particular, the requirement for flexibility, in a multi-mode radio capable of operating with a number of radio systems (even in the same area of spectrum), introduces new duplexer issues which must be addressed. The problems occur since the different systems may use different multiple access schemes [e.g., frequency-division duplex (FDD), time-division duplex (TDD), time-division multiple access (TDMA), or code-division multiple access (CDMA)] and may have different transmit/receive splits (or none at all in the of TDD systems).

The required transmit/receive isolation for continuous-time, full duplex transmission (i.e., not TDD and not TDMA with non-simultaneous transmit/receive timeslots) is based on the transmit power level and required receive sensitivity, along with the receive A/D dynamic range and the selectivity of the receiver (digital) filtering.

Consider the example of a handset full-duplex transceiver, with a 1-W (+30 dBm) maximum output power capability and a minimum receive sensitivity of -110 dBm (for a given modulation bandwidth). If it is assumed that a 10-dB C/I (carrier to interference ratio) is the minimum for adequate demodulation of the chosen modulation scheme, then the minimum isolation which must be provided by the duplexer, for *on-frequency duplex*, is [21]:

$$
\begin{aligned}
Z_{I,OFD} &= P_{Tx} - (P_{min} - D_{C/I}) \\
&= +30 - (-110 - 10) \\
&= 150 \text{ dB}
\end{aligned}
$$

This is an extremely stringent requirement and would prove almost impossible to meet by any currently known and economic technique.

If however, a duplex frequency split is now introduced, the situation becomes more realistic. Consider the example above, but now with a duplex frequency-split introduced, such that the receiver IF digital filtering can reduce the unwanted residual transmitter signal appearing in the front-end received signal, to a negligible level. This makes no assumption about any analog IF filtering, which may well ease the burden on, for example, ADC dynamic range, as the general case of fully flexible receiver architecture is assumed here. There are now two isolation considerations which must both be met, however each is potentially much less stringent that that considered above.

The first consideration is overload of the receiver's front-end and receiver strong signal handling capability. This breaks down into the analog part (LNA, mixers, and so forth) and its IMD performance and the A/D converter and its dynamic range. In this case (split-frequency duplex), the required isolation may be derived as follows. In this case, the IMD power generated by the receiver non-linearity (or clipping) must not exceed the specified minimum sensitivity plus the required C/I for the modulation format in question. In practice a margin of at least 3 dB would be desirable; however, the simplified analysis below assumes no margin, hence [21]:

$$P_{IMD} = P_{min} - D_{C/I}$$

The IMD power resulting from the front-end non-linearity, based upon the simple assumption of a two-tone and purely third-order non-linearity, is given by:

$$P_{IMD} = 2 (P_{Tone} - P_{IP\,3})$$

The tone power in this case is provided by the unwanted leakage of the transmit signal into the receive signal path, hence:

$$P_{Tone} = P_{Tx} - Z_{I,\,SFD1}$$

Combining above equations gives:

$$Z_{I,\,SFD1} = P_{Tx} - [(P_{min} - D_{C/I} / 2] - P_{IP\,3}$$

Here P_{Tx} is the transmitter output power, P_{min} is the minimum specified signal power, $D_{C/I}$ is the minimum carrier-to-interference ratio for the modulation format in question, and $P_{IP\,3}$ is the third-order intercept point of the receiver front-end analog components. If this example is used and a receiver input intercept point of +30 dBm is assumed (a reasonable upper limit for a linearized receiver front-end in a handset), the required isolation reduces to 60 dB. This is still a very high value, but may not be completely beyond the bounds of possibility for a future isolation technology.

Note that above analysis also assumes an adequate A/D converter dynamic range is available, where this dynamic range is given by the difference between the unwanted (residual) transmitter output signal impinging upon the receiver and the maximum permitted interference level. Strictly speaking, this is the required spurious-free dynamic range (SFDR) rather than the signal-to-noise ratio (although this may also be important, depending upon the degree of averaging and/or filtering which can be employed in the digital domain, to extract the wanted signal). It is given by:

$$D_{A/D} = (P_{Tx} - Z_{I,SFD1}) - (P_{min} - D_{C/I})$$
$$= 90 \text{ dB}$$

This is again high, but not out of the question, particularly in a narrowband system. As ADC technology improves in the future, it will become increasingly realistic, even in broadband (and hence high sample-rate) systems.

The second requirement is that the transmitter noise floor must not mask the received signal. This results in the following isolation requirement:

$$Z_{I,SFD2} = N_{Tx} - (P_{min} - D_{C/I})$$

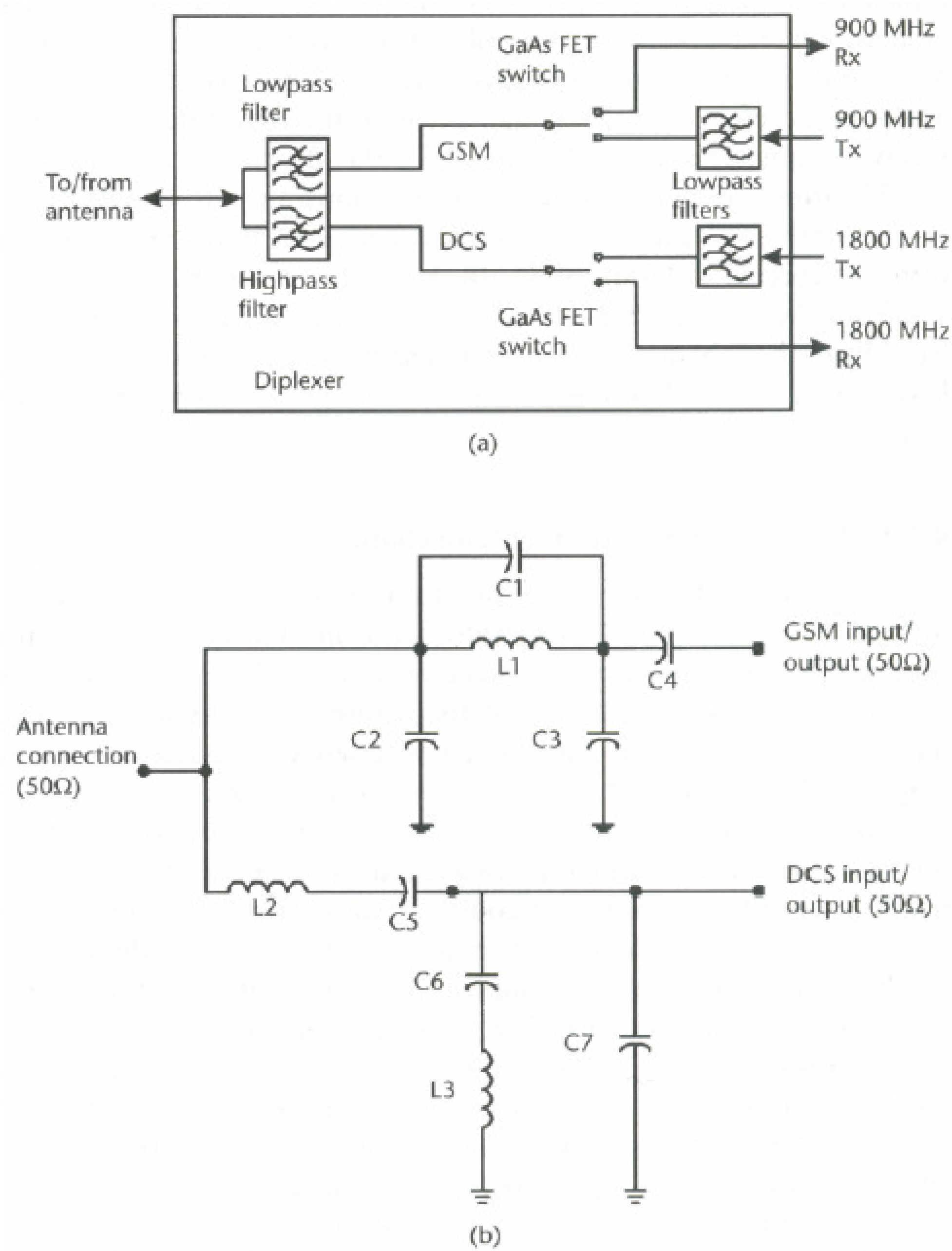
Here N_{Tx} is the transmitter output noise power (in the receiver bandwidth). A typical figure for this noise power is around – 75 dBm, based upon the minimum received power levels used above (and hence channel bandwidths). With this figure, the required isolation is 45 dB, making the first consideration (on receiver linearity) dominant in this case.

10.5.2 Potential Solutions to the Isolation Issue

There are a number of partial or complete solutions to the isolation problem:

- *Tx / Rx Switch*. It is possible to implement a purely switch-based duplexer facility, and this has many advantages. First, it can be made very broadband (multi-octave, if necessary) since filtering is not necessary. Second, it places no restriction on the system duplex frequency split, since no frequency-selective components need to be involved. Finally, it will allow on-frequency duplex (i.e., TDD) for the same reason. It may be implemented using simple PIN-diode switch technology and is therefore low cost, although transmit-receive isolation is an issue and it may be necessary to disable the transmitter while in receive mode to ensure that the transmitter noise floor does not de-sense the receiver.

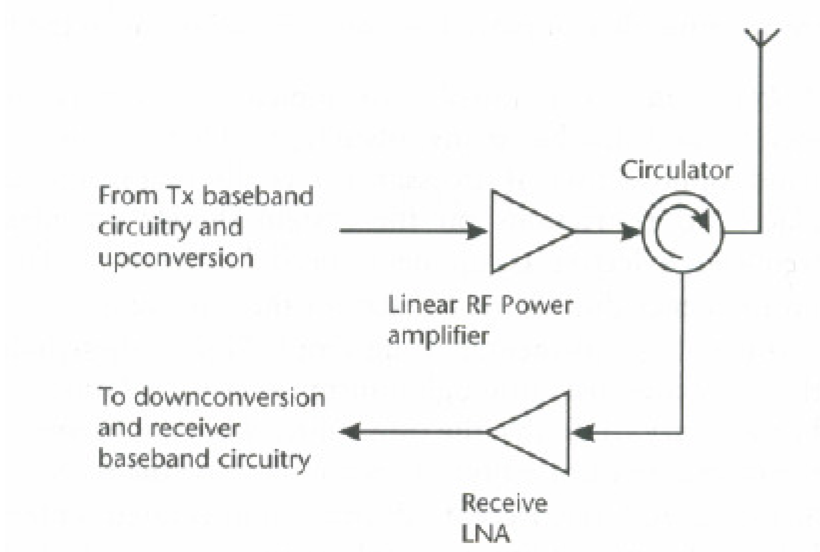
- *Switched Diplexer.* Recent advances in integrated diplexer techniques have led to the possibility of implementing a switched diplexer, in which the transmit and receive paths can be switched between two (or more) paths. This type of system is shown in Fig. 10.6. A two-way or multi-way change-over switch is employed, to select the required filter pair for a five transmit and received band allocation. The example shown in Fig. 10.6 utilizes GaAs PHEMP switches, as these were reported to have a number of advantages over PIN diodes at the required frequencies of operation. These advantages included: low current/low voltage and single supply operation together with having no requirement to resonate out parasitics. The switches provided more than 20 dB of isolation (excluding filter isolation), together with an insertion loss of less than 1 dB for the overall diplexer circuit. This system, however, has a number of disadvantages, including band limiting (i.e., it is not commensurate with an ideal general-coverage SDR), relatively high loss (typically) due to losses in the switches, and limited power handling (again due to switch-related issues, such as saturation and IMD).
- *Circulator.* A second solution is to use a circulator, as shown in Fig. 10.7. The main drawbacks of this approach lie in the frequency range limitation of most high-isolation parts and the achievable isolation from low-cost, small-sized components, suitable for handset applications. Typical isolation values for these parts, even band-specific items, are in the range of 10 to 25 dB. This is adequate for their current, primary application in protection of the transmitter from the wide range of antenna VSWR conditions. However, even the higher value is not adequate for the duplex function under consideration here.
- *Duplexer elimination schemes.* This includes some new methods of achieving transmit/receive isolation. It is possible for example, to use cancellation-based techniques in order to remove the transmit signal from the receive signal path, although these techniques themselves have a number of disadvantages. They are complex and have difficulties, coping with external reflections, They also generally require complex antenna arrangements, which are not currently compatible with small handset designs. Research is, however, being performed in this area and a solution may be developed in the future.



(a) Block diagram of the diplexer module; (b) Diplexer circuit schematic

Source: [21]

Figure 10.6 Switched Antenna Diplexer



Source: [21]

Figure 10.7 Use of a Circulator to Provide Transmit/Receive Isolation

10.6 Chapter 10 Summary

Current radio receiver designs are, in general, inherently narrowband and can only achieve general (or broadband) coverage by the switching or alteration of narrowband elements. Certain designs, such as those used in many scanning receivers, do not attempt to overcome some of the fundamental receiver problems, such as blocking and image rejection, but rely on the user being able to eliminate interference by positioning of the set, or some other mechanism such as the use of a directional antenna. Where this is not possible, the user most tolerate the problem and the restriction in frequency usage which results, as the price of achieving wideband coverage.

While SDR technologies using DSP have made significant inroads into the utopia wideband flexible radio, there are still two basic problems to be solved:

- The diplexer filter required in a full-duplex transceiver must be specifically and carefully designed for its intended frequency band of operation. This filter is usually either a helical component or formed from a dielectric (such as ceramic) and hence is almost impossible to tune in any sensible fashion over a reasonable range of frequencies. A multiple-band transceiver would therefore require a number of diplexer filters and this would be very quickly become prohibitive, both in terms of cost and size.
- The front-end *pre-select* filter (also known as *band-select* or *cover* filter), utilized to reflect the image signal and other particularly strong out-of-band signals, must also be either tunable or eliminated in order to allow multi-band coverage. Electronic tuning of this filter is a more realistic proposition than that of the diplexer filter mentioned above; however, the change in technologies (from, perhaps, lumped-element to dielectric-based) across, say, 100 MHz to 2 GHz, would make this very difficult. The alternative to the use of such a filter would require the front-end amplifier [or low-noise amplifier (LNA)] to be able to handle the full dynamic range of signals within the broad coverage range. This may include TV transmissions of many kilowatts and microcellular transmissions of a few milliwatts, and hence a very high dynamic range amplifier is required. Such an amplifier could be created by backing off a high-power linear amplifier (of say, 10 W), but this is unrealistic in a hand portable radio. It is therefore necessary to utilize a more conventional low-noise amplifier and eliminate its distortion when dealing with high input signal strengths.

As discussed in this and preceding chapters, the addition of wide channel bandwidth and, in particular, multiple operating bands significantly increases the difficulty of producing a flexible receiver design. The widening of the channel bandwidth has the following consequences:

- The number of narrowband carriers which can enter the IF and base band chains is significantly increased, thus increasing the potential dynamic range required in these parts of the system. In going from an IF of, say, 200 kHz (for GSM) to 4 or 5 MHz (for UMTS in Europe), the number of 25 kHz channels (e.g., for TETRA) that could enter the IF increases from 8 to 200.

In going from a single-band to multiple bands, the receiver faces a number of further problems:

- RF pre-selection filtering becomes difficult or impossible, since the filter must now be tuned to each band of interest. Alternatively, a bank of switched filters may be employed, but this can be quickly become unwieldy for a truly flexible system. This latter technique has been used in a number of scanning systems in the past. RF MEMS is a technology that has recently gained more interest as a way to realize smaller economical tunable filters, and it is discussed in more detail in the next chapter.

- The channel synthesizer must tune over a far wider range than for a single-band system.
- The diplexer in a full-duplex transceiver must have a variable frequency of operation and a variable transmit/receive frequency split. Since the diplexer is currently realized in ceramic, SAW, or helical resonators in most portable systems, this is clearly impossible with current techniques and thus represents another R&D opportunity for RF MEMS. Again, the main obvious alternative is the use of multiple units, with switching to determine which is in use at a given point in time. As before, this can quickly becomes unwieldy.

One last point to make, which emphasizes the ongoing need for tunable front-end pre-select and diplexer filters, is related to the consequences of eliminating them, namely:

- All image rejection from the filter is lost, thus leaving the receiver prone to signals appearing at its image frequency,
- All radio signals within the bandwidth capability of the antenna will impinge upon the front-end low-noise amplifier in the receiver. This amplifier will therefore require a very high dynamic range to prevent overload from strong, unwanted signals (e.g., broadcast TV transmissions in a hand portable communications receiver).
- Without a diplexer, the full power of the transmitter output signals may impinge upon the receiver input (depending upon what is used to replace the diplexer). The receiver must therefore be able to cope with these signals, or else utilize an alternative method of eliminating them.

Thus, it can be safely concluded that tunable pre-select and diplexer filters (in addition to IF anti-alias filters) will continue to be required for multi-band flexible, SDR-based radio architectures for a long time to come as newer 4G and beyond technologies get developed and deployed. Therefore, both research and development opportunities exist now and in the future for achieving lower cost, smaller size, tunable filter banks for MBF transceivers.

Chapter 11 The Current State of RF MEMS Technology

11.1 Introduction

This chapter provides an update on the current state of RF MEMS technology and attempts to derive some conclusions as to the viability of such technology for the commercial realization of RF tunable filters for multi-band flexible SDR-based architectures for applications in both base stations and handsets.

RF MEMS stands for Radio Frequency Micro-Electro-Mechanical Systems, and refers to components of which freestanding or moving sub-millimeter-sized parts provide RF functionality. RF functionality can be implemented using a variety of passive and active RF technologies. Besides RF MEMS (passive) technology, ferrite (passive), ferroelectric (passive), GaAs (active), GaN (active), InP (active), RF CMOS (active), and SiGe (active) technology are available to the RF designer. Each of the RF technologies offers a distinct trade-off between cost, frequency, gain, scale of integration, linearity, noise figure, packaging, power handling, reliability, and supply voltage.

RF MEMS components, such as inductors, resonators, switches, switched capacitors, and varactors, offer low loss, high linearity power handling, and high-Q factor, but require a high supply voltage and wafer-level, liquid crystal polymer (LCP) or low temperature co-fired ceramic (LTCC) packaging. RF MEMS components can be fabricated in class 100 clean rooms using 6 to 8 lithography steps, whereas state-of-the-art MMIC and RFIC fabrication processes require 13 to 25 lithography steps

11.2 “More than Moore”

“More than Moore” [24], or the combination of sensors/actuators, radio, power and interfaces with signal processing and storage, is recognized as one of the most significant trends in the microelectronics industry. Strong drivers for the More-than-Moore domain are automotive applications, ambient intelligence (including bio-medical), and wireless applications (including environment monitoring and security). In this framework, RF-MEMS appear as a key enabling technology for dramatically improving miniaturization, low-power, low-cost and system performance of wireless systems.

11.3 The State of RF MEMS Technology

The status and trends in RF MEMS components, systems and services can be summarized as follows.

RF MEMS switches and variable capacitors have reached maturity and are ready for industrial applications. Applications range from reconfigurable front-ends, cognitive radios, antenna switches, matching networks to delay lines and others. Research will however continue to explore new switching technologies, applicable to power management and low power RF switching. Among the interesting candidates, the NEM-FET appears to be very attractive with a high on/off ratio.

Resonators and oscillators are the next candidates for industrial application where they could replace bulky ceramic filters, quartz oscillators and others. Full maturity is not reached yet, but interesting breakthroughs are appearing in terms of precision, temperature stability and frequency range. The next breakthrough is expected from nano electro-mechanical FET (NEM-FET) resonators and oscillators. Tune-ability, reliability and long-term stability remain challenging.

Smart antennas are attracting a large interest, due to their wide field of applications in automotive and avionics. Besides the use of "classical" MEMS for generating the variable phase shift, very innovative solutions appear that are based on liquid crystal or meta-material phase-shifters. These new approaches are promising and should be carefully monitored.

Some challenges, however, remain in multi-physics modeling, MEMS-IC co-design and system modeling. Several initiatives exist for providing access to technology platforms, support for design, testing and packaging, and others.

The focus of this chapter is on the viability of RF MEMS for the realization of RF tunable filters for multi-band flexible SDR-based radio architectures. Thus, the primary areas of interest related to RF MEMS are switches, varactors, and inductors and the subsystems that can be commercially realized with these RF MEMS components.

11.4 Switches

There are two distinct parts to an RF MEMS switch: the actuation (mechanical) section and the electrical section (see Fig. 11.1). The forces required for the mechanical movement can be obtained using electrostatic, magnetostatic, piezoelectric, or thermal designs. The switches can also move vertically or laterally, depending on their layout. Electrostatic-type thermal switches and magnetostatic switches have been demonstrated at 0.1 – 100 GHz with high reliability (100 million to 60 billion cycles) and wafer-scale manufacturing techniques. As for the electrical part, a MEMS switch can be placed in either series or shunt configurations and can be a metal-to-metal contact or a capacitive-contact switch. This means that one can build at least 32 (2 x 2 x 2 x 4) different type of

MEMS switches using different actuation mechanisms, contact, and circuit implementations.

Actuation Mechanism						
	Voltage (V)	Current (mA)	Power (mW)	Size	Switching Time (μs)	Contact Force (μN)
Electrostatic	20–80[a]	0	0	Small	1–200	50–1000
Thermal	3–5	5–100	0–200[b]	Large[c]	300–10,000	500–4000
Magnetostatic	3–5	20–150	0–100[b]	Medium	300–1,000	50–200
Piezoelectric	3–20	0	0	Medium	50–500	50–200

Movement	
Vertical	Typically results in small size devices
Lateral	Typically results in large size devices

Contact Type (Switches only)	
Metal-to-Metal	DC-60 GHz
Capacitive[d]	10–120 GHz

Circuit Configuration	
Series	DC-50 GHz with metal-to-metal contact and low up-state capacitance. 10–50 GHz with capacitive contact[d] and low up-state capacitance.
Shunt	DC-60 GHz with metal-to-metal contact and low inductance to ground. 10–200 GHz with capacitive contact[d] and low inductance to ground.

[a] Voltage can be reduced to 5 V using low spring constant designs, but at the expense of stiction and reliability.

[b] Power is virtually zero with an electrostatic or permanent magnetic field hold.

[c] Size can be made quite small with the use of a vertical design.

[d] Can be extended to 2 GHz using high-ε_r dielectrics.

Source: [25]

Figure 11.1 Different Configurations of MEMS Devices

Electrostatic actuation is the most prevalent technique in use today due to its virtually zero power consumption, small electrode size, thin layers used, relatively short switching time, 50-200 uN of achievable contact forces, and the possibility of biasing the switching using high-resistance bias lines. However, in many cases, it requires an actuation voltage of 30-80 V, and this necessitates the use of CMOS up converters to raise the input 3-5V control voltage to the actuation voltage. In many designs, a thermal actuation is coupled with an electrostatic (voltage) hold, or a magnetostatic actuation (current in a coil) is coupled with a permanent magnetic field. Both result in virtually zero power consumption once the switch is actuated. Still, they require a substantial amount of current for the switching cycle and, therefore, must be biased using low-resistance (gold or Al) lines. The low-resistance lines couple to the microwave transmission lines; therefore, careful design must be done for complicated switching networks requiring a large number of switches and bias lines.

Fig. 11.2 shows a comparison between electrostatic MEMS switches and GaAs PIN diode and transistor switches. It is hard to make an accurate comparison over a wide range of RF power levels since the size of diode and transistor switches can be easily increased for high power applications. This, in turn, has a substantial effect on the switch isolation, insertion loss, switching speed, and power consumption. Still, it is evident that MEMS switches, with their extremely low up-state capacitance (series switches) and their very high capacitance ratio (capacitance contact switches), offer a far superior performance compared to solid-state switches for low to medium power applications.

Fig. 11.2 also summarizes some of the key advantages of RF MEMS switches over the conventional GaAs PIN and FETs, namely: no DC power consumption, much higher cutoff frequency, very high isolation, lower insertion loss, and higher third-order intercept point. These superior parameters can replace the GaAs switches in cellular telephones resulting in much lower DC-power consumption and longer battery life. RF MEMS switches can be used in phase shifters and low-loss tunable circuits (like matching networks and filters), and in high-performance instrumentation systems.

Parameter	RF MEMS	PIN	FET
Voltage (V)	20–80	±3–5	3–5
Current (mA)	0	3–20	0
Power consumption[a] (mW)	0.05–0.1	5–100	0.05–0.1
Switching time	1–300 μs	1–100 ns	1–100 ns
C_{up} (series) (fF)	1–6	40–80	70–140
R_s (series) (Ω)	0.5–2	2–4	4–6
Capacitance ratio[b]	40–500[b]	10	n/a
Cutoff frequency (THz)	20–80	1–4	0.5–2
Isolation (1–10 GHz)	Very high	High	Medium
Isolation (10–40 GHz)	Very high	Medium	Low
Isolation (60–100 GHz)	High	Medium	None
Loss (1–100 GHz) (dB)	0.05–0.2	0.3–1.2	0.4–2.5
Power handling (W)	<1	<10	<10
Third-order intercept point (dBm)	+66–80	+27–45	+27–45

[a] Includes voltage upconverter or drive circuitry.

[b] Capacitive switch only. A ratio of 500 is achieved with high-ϵ_r dielectrics.

Source: [25]

Figure 11.2 Performance Comparison of FETs, PIN Diode, & RF MEMS Switches

11.5 Applications

Fig. 11.3 summarizes the application areas of RF MEMS devices and the lifetime and number of cycles required. The same figure also shows some of the subsystems and circuits that can benefit from this technology.

Fig. 11.4 shows a multi-band RF front end and the specific circuitry where RF MEMS technology has very promising applications in implementing tunable matching networks, tunable and switchable RF filters (Filter Bank), diplexers and multi-band antennas.

RF MEMS switches are extremely linear devices since they do not contain a semiconductor junction and therefore do not have a nonlinear current versus voltage relationship. MEMS switches and varactors can be designed to be mechanically stiff (large spring-constant design) and can tolerate large RF voltage swings without generating any significant levels of inter-modulation products. They are thus near-ideal elements for tunable filters and matching networks.

The third-order intercept point of MEMS switches was measured independently by Rockwell Scientific and HRL (metal contact) and Raytheon (capacitive contact) and was found to be at least +66 dBm (capacitive contact) to +80 dBm (metal contact). These numbers are 25-35 dB higher than what can be obtained with PIN diode and FET switches. There is no doubt that the high linearity of MEMS devices will allow the design of complex communications and radar systems that are currently not possible with standard GaAs devices.

Area	System	Number of Cycles (Billions)	Years
Phased arrays	Communication systems (ground)	1–10	2–10
	(space)	10–100	2–10
	(airborne)	10–100	2–10
Phased arrays	Radar systems (ground)	10–100	5–10
	(space)	10–100	5–10
	(missile)	0.2–10	1–5
	(airborne)	1–100	5–10
	(automotive)	1–10	5–10
Switching and reconfigurable networks	Wireless communication (portable)	0.01–4	2–3
	(base station)	0.1–100	5–10
	Satellite (communication and radar)	0.1–1	2–10
	Airborne (communication and radar)	0.1–10	2–10
	Instrumentation	10–100	10
Low-power oscillators and amplifiers (varactors, inductors)	Wireless communication (portable)	0.1	2–3
	Satellite (communication and radar)	0.1–1	2–10
	Airborne (communication and radar)	0.1–10	2–10

RF MEMS Elements:	Switch, Varactor, Inductor
Subsystems:	Switching networks[a]
	Transmit/receive switches
	Very high isolation switches (instrumentation)
	Programmable attenuators
	Phase shifters (digital and analog)
	Reconfigurable antennas
	Reconfigurable matching (or impedance) networks
	Reconfigurable Butler matrices for multibeam systems
	Tunable filters
	Switched filter banks
	Miniature microwave filters
	Switched diversity antennas, oscillators, amplifiers
	Low phase-noise oscillators (fixed and tunable)
	High-efficiency networks (low-power systems)

[a] SPST, SPDT, DPDT, SPNT, $N \times N$, absorptive and reflective designs

Source: [25]

Figure 11.3 Application Areas of MEMS Switches, Varactors, and Hi-Q Inductors

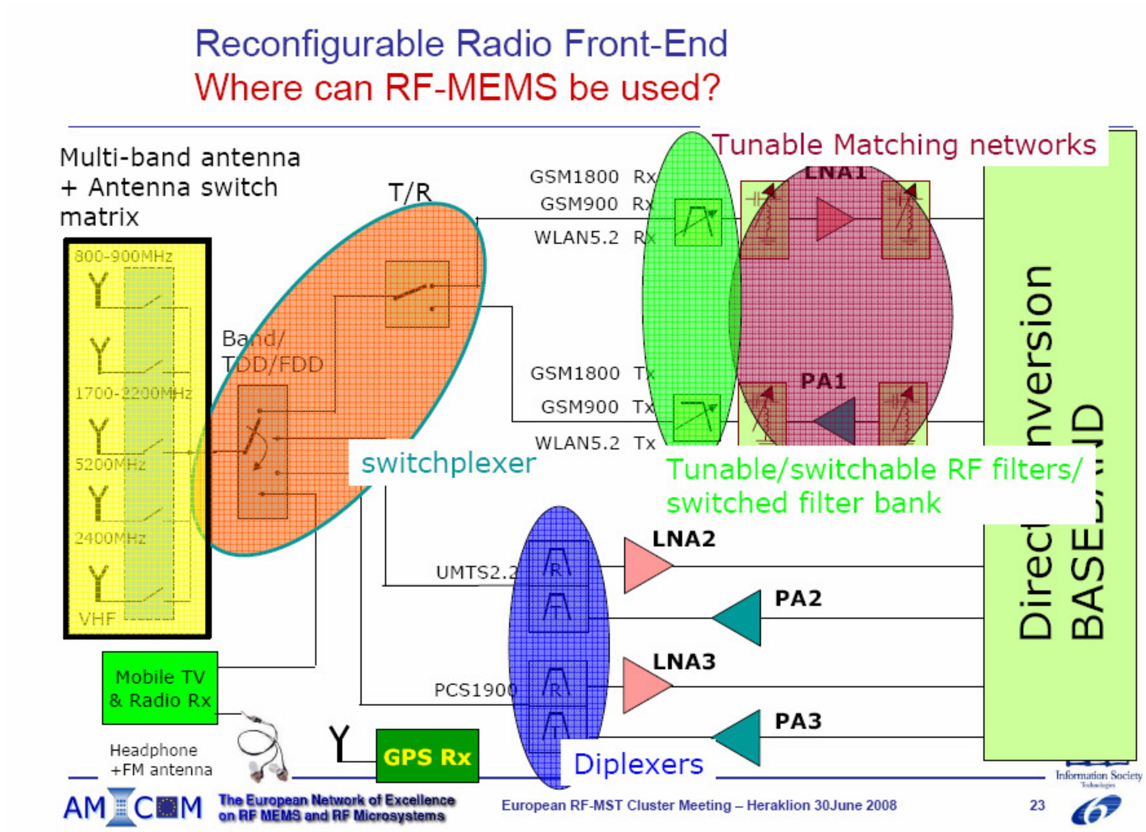


Figure 11.4 RF MEMS Applications in Multi-band RF Front Ends

11.6 Reliability

As of 2008, many metal-to-metal (DC) contact and capacitive switches have achieved > 60 billion cycles under low power conditions (0.5 to 5 mW). All tests are done in nitrogen atmospheres and under clean-room conditions. The failure mechanisms are complex and are different for capacitive or DC-contact switches. Also, the failure mechanisms depend on the RF power used and can be due to thermal issues, dielectric breakdown, self-actuation, or critical current density problems. It is believed that once a switch crosses over 10 billion cycles, then it can be easily taken to 100 billion cycles since the failure mechanisms (dielectric charging, pitting, hardening, dielectric formation, etc) typically present themselves in the first billion cycles.

Capacitive switches with their large contact area can handle more RF power than metal-to-metal switches and are therefore the preferred switch for applications requiring 30-300mW. However, most capacitive switches operate at 8 GHz and above due to their relatively small down-state capacitance (2-5pF), and DC-contact switches are the only switch of choice at 0.1-8GHz. The lifetime of metal-to-metal contact switches is highly dependent on the RF power used, and most electrostatic switches result in only 10-1000 million cycles at an RF power of 10-100 mW. This is due to the relatively small contact forces (50-200 uN) and small contact areas that can be achieved using electrostatic actuation. On the other hand, thermal MEMS switches with their large contact forces (2-3 mN) have been proven to reliably switch to > 50 million cycles under an RF current of 350 mA (which is equivalent to an RF power of 6 W in a 50-Ω system). However, thermal actuation consumes a large amount of DC power (50-200 mW) and is not suitable for most applications.

It is believed that both capacitive and DC-contact switches can be taken to > 100 billion cycles under low power conditions, and to billions of cycles under medium to high-power conditions. This will be done with advances in contact metallurgy, thermal analysis, high-quality dielectric materials, stress control, and mechanical design.

The operation of RF MEMS devices can be severely affected by the presence of water vapor, oxygen, contaminants, and other hydrocarbons. The reason is that the contact or pull-up forces are quite small (950-500 uN in most cases), and there is simply not enough force to either (a) puncture through any contaminants or dielectrics that deposit or form on the metal contract surfaces or (b) overcome the adhesive forces of water molecules on the capacitive contact. It is for these reasons that metal-to-metal contact MEMS switches typically fail as open circuits, and capacitive switches fail in the down-state position (stiction).

11.7 Packaging

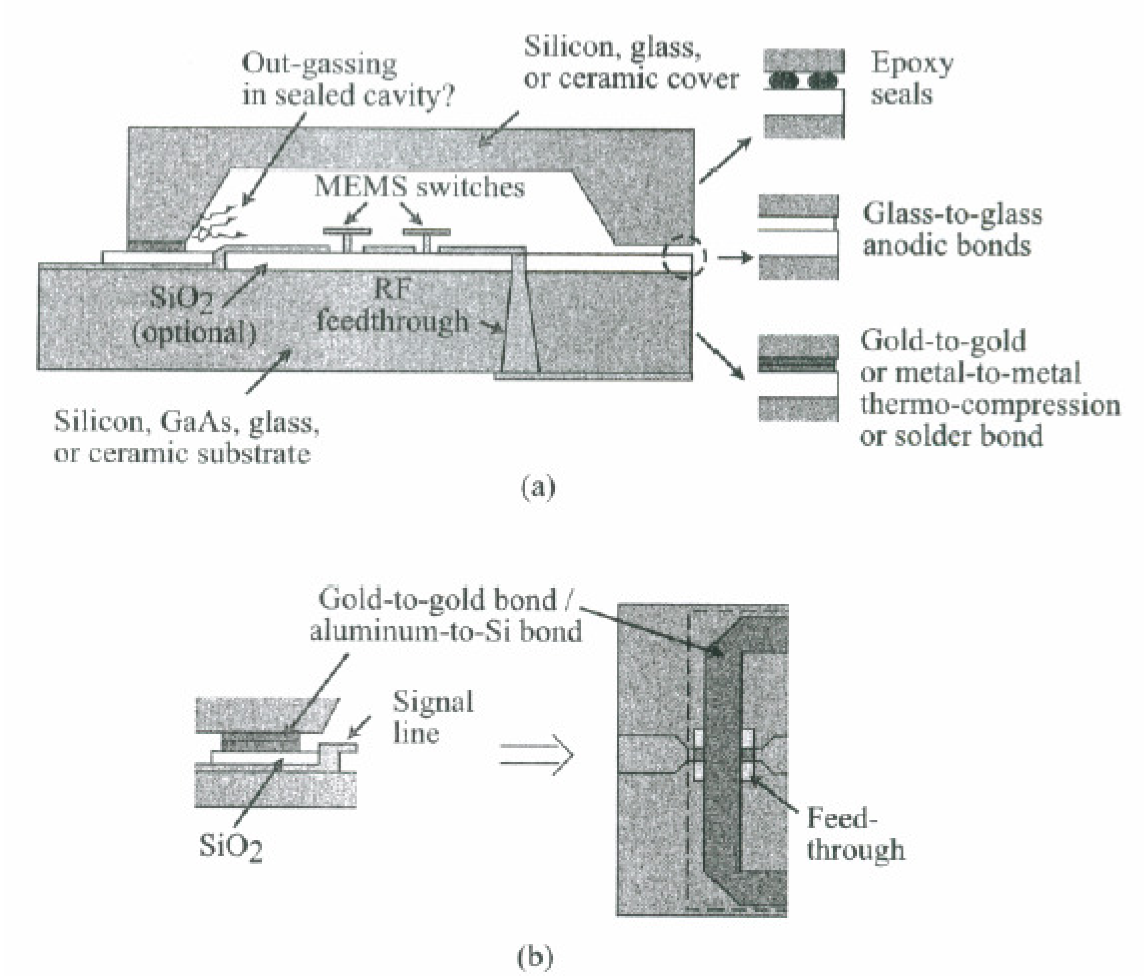
RF MEMS devices are tested in nitrogen atmospheres and under clean-room conditions. While this is acceptable in the laboratory, careful attention must be placed on the packaging of RF MEMS device for commercial applications. An important question is the long-term viability of non-hermetic packages for RF MEMS. This is critical because a non-hermetic package is inexpensive (about $0.2-0.5 per unit), while hermetic packages require high temperatures and very smooth surfaces and are, in general, quite expensive (about 42-50 per unit). The answer to this question will eventually determine the cost and the application areas of RF MEMS devices.

The only other way to reduce the cost of RF MEMS switches is to use wafer-scale packaging solutions. Fig. 11.5 shows some of the different wafer-scale packaging and inter-connect schemes for MEMS. In this case, the MEMS switches are first released, packaged on-wafer, and then scribed into individual units. Several different technologies are available for packaging MEMS devices as follows:

- Epoxy Seals
- Metal-to-metal solder bonding
- Glass-to-glass anodic bonding
- Glass frit bonding
- Gold-to-gold thermo-compression bonding

It is important to note that many conventional MEMS devices are packaged at low pressures (1-50 mtorr), while RF MEMS device should be packaged at standard pressures and in nitrogen or non-reactive gases (argon, etc). This results in a low mechanical-Q structure due to gas damping, and it increases the reliability of the switch. Also, MEMS switches and varactors are built using at least one metal layer (Au or Al) and therefore cannot be subsequently placed in high-temperature LPCVD or thermal oxidation furnaces for packaging purposes.

High-temperature glass-to-glass anodic and frit bonding have been the most commonly used techniques in hermetically packaged MEMS sensors [26]. Anodic bonding also requires a large voltage between the glass wafers (600-1200 V). The reason why these methods are successful with MEMS accelerometers, gyros, pressure and temperature sensors, and so on, is that these devices are generally fabricated using thick polysilicon layers and can withstand higher post process temperatures, do not have surfaces that touch each other, are not sensitive to release of organic gases during the packaging process, and are calibrated every time one turns on the device. There options do not exist for RF MEMS switches.



(a) Different wafer-scale packaging and interconnect schemes for MEMS switches
(b) Top view of a possible RF transition. Feed-through or via technologies are needed to pass the RF signal through the sealed package

Source: [25]

Figure 11.5 MEMS Packaging

There are several problems with these techniques when applied to RF MEMS. Most bonding techniques outgas organic materials inside (and outside) the MEMS cavity during the bonding process due to wetting compounds in the glass, gold, or epoxy layers. This has a serious detrimental effect on the reliability of the MEMS switches, both DC-contact and capacitive switches. Hermetic bonding processes also require a temperature of 250-500 ^{o}C to achieve a good seal. This is not compatible with a release structure that may be thin (0.5-2um) and quite long (250-350 um). The high temperature may bow the membrane by ± 1-5 um, making the switch unusable. Also, many bonding techniques such as glass-to-glass anodic bonding or gold-to-gold thermo compression bonding are sensitive to the planarity and cleanliness of the wafer (glass case) or to the surface roughness and exact height of the plated gold rings on the wafer (gold case).

While there are many packaging techniques, the packaging of MEMS switches provides a larger challenge than standard MEMS devices due to hermeticity, temperature, and out gassing constraints. Also, MEMS devices must be packaged in nitrogen or dry-air atmosphere for high reliability. Thus, the question remains as to whether it is possible to produce a reliable switch using a low-cost near-hermetic package and more research is needed to determine what leakage rate is permissible and what gases have detrimental effect of the reliability of RF MEMS devices.

11.8 Varactors

The development of MEMS varactors has not progressed at the pace of MEMS switches. This can be explained by the abundance of discrete high-Q silicon and GaAs varactors usable up to 30 GHz. Planar silicon varactors, even at 0.5-5 GHz, result in a Q of 30-60 using the latest SiGe and high-f_T silicon technologies. In fact, the performance of planar oscillators is not limited by the silicon varactor, but by the loss of the planar inductor. Another reason for the limited development of MEMS varactors is their capacitance ratio of 1.2-2.5, while standard solid-state varactors have a capacitance ratio of 4-6. Also, it is hard to build MEMS varactors with capacitance values of 5-50 pF, which are needed for 30 to 600 MHz applications. MEMS varactors suffer from Brownian, acceleration, acoustic, and bias noise effects, especially for low-spring-constant designs that are necessary for 3 to 5 V applications.

There is still, however, a pressing need for MEMS varactors. First, they have the potential of very high-Q (100-400) operation, especially at mm-wave frequencies. Also, they can be designed to withstand large RF voltage swings and therefore result in very high IIP3 tunable networks. MEMS varactors do not contain PN junctions and therefore do not pass current under high-power operation. They can be inexpensively produced on glass, ceramic or high-resistivity silicon substrates with applications in low-cost 3 to 60 GHz tunable networks and filters. Still, MEMS varactors may take a long time before they replace (in high volume handset applications, for example) silicon and GaAs varactors, especially below 5 GHz, since solid-state devices result in excellent performance and do not have any special packaging requirements.

Currently, there are three different technologies for building MEMS variable capacitors. The first one is based on the parallel-plate approach (vertical design), and a variable capacitance is achieved by changing the gap between the capacitor plates. The second approach is based on an inter-digitated (horizontal) design; again, the gap is changed to achieve a variable capacitance. The third approach consists of building a fixed capacitance bank and using MEMS switches to select the required total capacitance.

These different techniques have yielded MEMS variable capacitors for applications in the range of 0.1 to 100 GHz

The reliability of analog MEMS varactors (non-switched) is much better than standard capacitive and series switches. In the analog mode, the contact areas do not touch and one can easily obtain billions of cycles. The mechanical reliability of thin gold or Al membranes and cantilevers has been shown to exceed 10^{10} cycles for small deflections (1-2 um). The main problem is charging of the dielectric layer (if used), which can create a progressive increase in the applied voltage. This can be solved by eliminating the dielectric layer between the capacitor plates and by limiting the applied voltage so as to ensure that a pull-down condition is never achieved. Analog MEMS varactors do not need to be hermetically sealed since they do not suffer much from charging or surface-contact problems resulting from humidity. However, if long-term operation and billions of cycles are needed, then it is best to hermetically seal the varactor. Still MEMS varactors must be handled and packaged in clean-room environments since contaminant particles may cause failure if they come in contact with the inter-digitated fingers, or if they settle on or around the capacitor plates. The reliability of switched capacitors (or any design where a metal layer contacts a dielectric layer) is identical to that of MEMS capacitive switches. The switched capacitors must be hermetically sealed in clean-room environments for long-term reliable operation.

Analog parallel-plate and cantilever MEMS varactor designs result in very high-Q operation at mm-wave frequencies, but with a limited capacitance ratio of 1.3-1.9:1. The inter-digitated and switched capacitors have shown impressive performance and versatility with a Q of 50-70 at microwave frequencies (0.3-4 GHz). Both switched capacitor and interdigital designs can be scaled to higher frequencies using a compact low-inductance approach. Low-loss MEMS varactors are an essential component in tunable networks and filters, and very high-Q designs with capacitance ratios of 3-4 are being developed already. Fig. 11.6 shows a summary of various analog varactor and switched capacitors development around the world.

11.9 Inductors

As indicated earlier, RF MEMS high-Q inductors are also key components for tunable LC filters in multi-band communications systems. RF MEMS can be two dimensional (planar) or three-dimensional. The work differs from the RF MEMS switch and varactors effort because micromachining techniques are used to create high-performance *static fixed-value* inductors. To date, there has not been a practical implementation of a tunable high-Q inductor (as in the case of RF MEMS varactors), and such inductors are currently synthesized using RF MEMS switches and a set of fixed-value inductors.

High-Q inductors are essential for many different passive and active circuits and can substantially reduce the phase noise or power consumption of oscillators and amplifiers. Also, they result in low-loss matching networks and filters as the loss is inversely proportional to the Q. Micro-machined inductors are based on three different technologies depending on the frequency range:

- Three-dimensional solenoid-type inductors result in large-value designs suitable for 0.2- 6 GHz
- Substrate etching underneath the inductor reduces the parasitic capacitance to the substrate (suitable for 1-100 GHz).
- Self-assembly of the inductor away from the substrate to reduce the parasitic capacitance to the substrate (suitable for 1-100 GHz).

Varactors and Switched Capacitors (Mostly Electrostatic)					
Company/University	Voltage (V)	Zero-Bias Capacitance (pF)	Type	Capacitance Ratio	Q (for C at f)
Rockwell Scientific	5–20	0.5–1	Interdigital	4–8	100 (1 pF at 1 GHz)
University of Michigan	10	1.15	Interdigital	1.4	>100 (1.2 pF at 2 GHz)
University of Michigan	20	0.1–0.3	Parallel plate	1.3, 1.9	>150 (0.1 pF at 35 GHz)
University of Illinois	5	0.04	Parallel plate	1.6	N/A
Columbia University	6	1.5, 4	Parallel plate	1.35, 1.9	20 (1.5 pF at 1 GHz)
Berkeley	5	2	Parallel plate	1.3	60 (2 pF at 1 GHz)
Seoul National University	60	0.1	Cantilever	1.25	>150 (0.1 pF at 30 GHz)
LG	5	0.1	PZT/parallel plate	3	N/A
Raytheon	45	0.4–3	Switched capacitor	0.3–24	60 (2.4 pF at 2 GHz)
University of Michigan	20	0.1	Switched capacitor	3–25	>100 (2.2 pF at 1 GHz)
University of Michigan	20	0.1	Switched capacitor	2–3	>100 (0.1 pF at 34 GHz)
University of Colorado	35	1	Switched capacitor	3.5	140 (2 pF at 0.7 GHz)

Source: [25]

Figure 11.6 Varactor and Switched Capacitor Development Around the World

Recently, standard inductor designs on CMOS and SiGe substrates have resulted in a Q of 12-18 at 2 GHz and 16-22 at 6 GHz. The reasons are many: modern electromagnetic simulation software allows the user to optimize the inductor geometry for the highest inductance and lowest associated series resistance. Also, the substrates used today have a relatively high resistivity (10-2000 Ω-cm), thereby reducing eddy current losses underneath the inductor. The inductors are integrated on the top metal layer using a 3-μm-thick gold layer and are separated from the silicon substrate using 3-6-μm thick oxide layers. The oxide layers reduce the parasitic capacitance to the substrate, and they allow the integration of large value inductors without having problems with the inductor resonant frequency. Micro-machined inductors will therefore be only used for high-Q applications (Q >30) in low-noise oscillators, high-gain amplifiers, on-chip matching networks, and integrated LC filters. Still, thick-metal electroplating or substrate etching is an additional step in the fabrication process and results in an increased cost.

The substrate etching technique is useful for high-frequency applications or for large-value inductors, and the thick copper electroplating technique is ideal for low-frequency applications (0.2-5 GHz). The elevated copper inductor technique results in small size inductors and outstanding Q from 1 GHz to 10 GHz [27]. The main limitations of high-Q inductors are their increased fabrication cost and special handling in the case of substrate etching. However, it is expected that RF MEMS inductors will eventually be integrated with CMOS and SiGe transistors for low phase-noise oscillators, high-efficiency power amplifiers, and tunable LC filters for MBF SDR-based transceiver architectures.

11.10 RF MEMS and CMOS Integration

Because RF MEMS are typically fabricated using low-temperature processes, they are therefore compatible with post-CMOS, SiGe, or GaAs integration. In fact, since most of the MEMS switches, varactors, and inductors are surface micro-machined, they can even be integrated on glass, quartz, or polished ceramic substrates. The integration of RF MEMS with GaAs was demonstrated by Rockwell Scientific as far back as 2001 [28].

In conclusion, RF MEMS can be integrated with CMOS or SiGe electronics for low-power wireless front-end systems. Also, CMOS is ideal for the development of voltage up-converter circuits next to a MEMS switch (thus allowing for a low supply voltage operation), or to integrate an intelligent controller next to a MEMS varactor for improved tuning range and temperature stability.

11.11 Chapter 11 Summary

In the near term (1-3 years), the requirement for hermitically sealed packages (with its related higher cost) may restrict the use of RF MEMS to the lesser cost-sensitive RF front ends (macro, micro, and pico), with applications for low cost femtocells and handsets only following after significant advances in reliable on-wafer hermetic packaging techniques are commercially available. Also, a hybrid approach, that is, combining already-reliable RF MEMs devices with SiGe or GaAs devices may accelerate the deployment of RF MEMS into such lower cost applications.

Chapter 12 A MBF Transceiver Architecture with RF MEMS

12.1 The Ultimate Goal

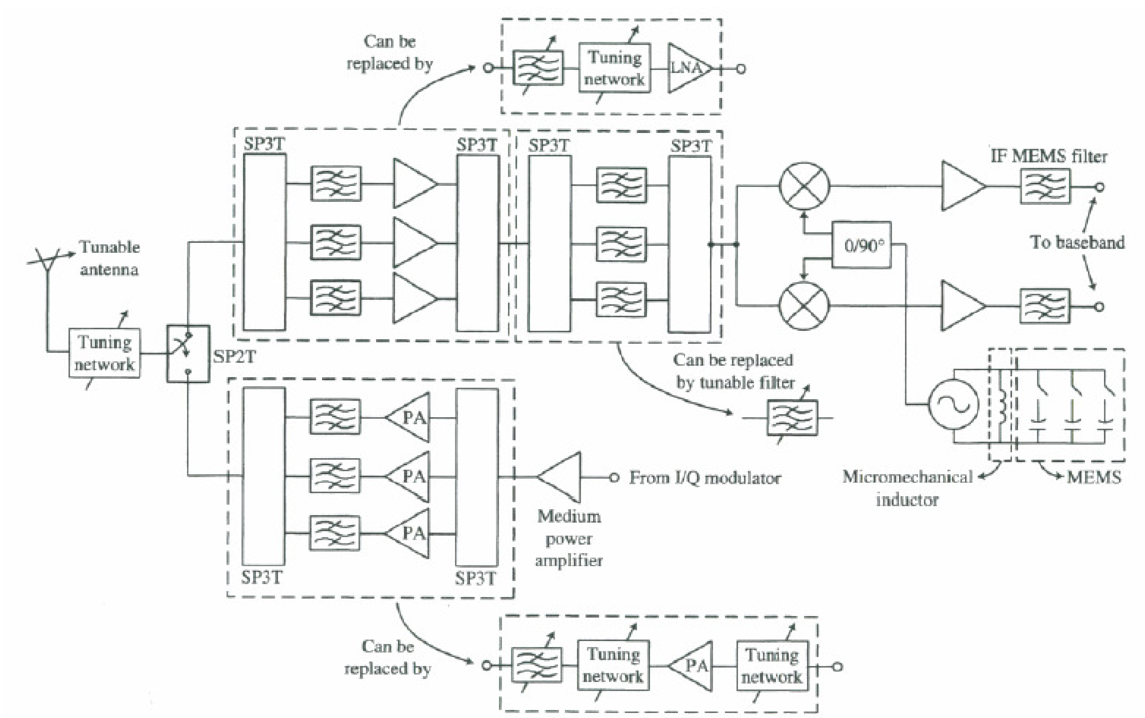
In this chapter the author presents a system level architecture for a single chip RF front end for a 4G multi-band flexible (MBF) transceiver radio using RF MEMS technology. The required feature set for the single chip is outlined and the necessary technology, processes, packaging, and other R&D issues to achieve it are discussed.

The proposed architecture is unique in that it offers a single chip "front-haul processor" (with built-in RF MEMS-based wireless interfaces) capable of processing either 1) the base band of one or more high-usage frequencies and 2) passing through the IF of any air interface standard into the base-band processing unit via a wireless or wire link.

Fig. 12.1 shows a block diagram of an RF front end for a three-band wireless telephone system. As indicated in the previous chapters, RF MEMS may be used to allow the development low-power systems based on tunable antennas, low-noise tunable oscillators, tunable filters, and tunable matching networks for wideband and multi-band transceiver radios. The ultimate goal is to integrate the entire front end into a single chip.

12.2 A Single Chip Front-Haul Processor Architecture

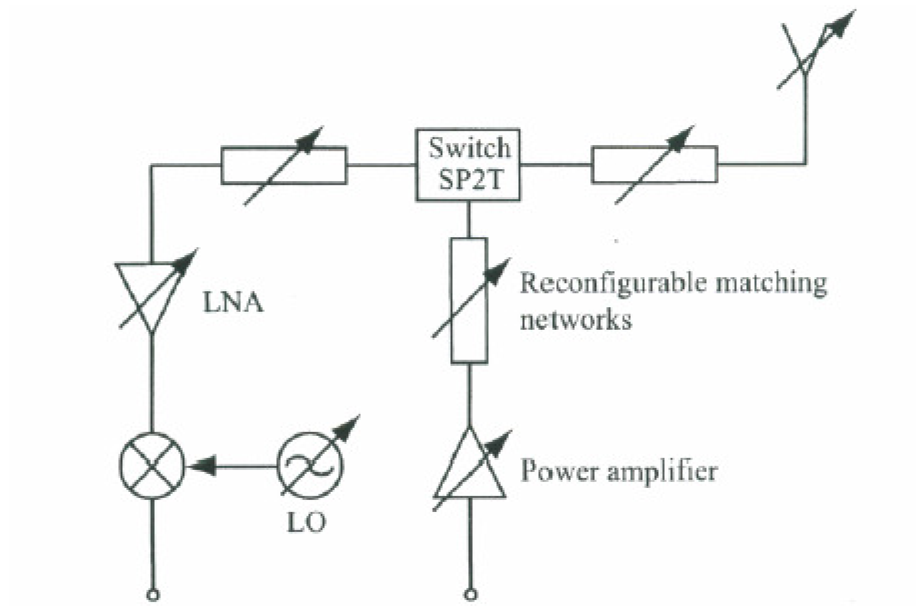
The primary requirement for a 4G MBF transceiver RF front end is that it is fully tunable to all the required RF frequencies of interest (see Chapter 2 and Chapter 6). As



Source: [21]

Figure 12.1 RF Front-End Design of a 3-band MEMS Wireless Telephone System shown in the simplified circuit diagram of Fig. 12.2 **,** changing the frequency of operation means that the antenna resonant frequency must be reconfigured, together with the band pass filter center frequency, the local oscillator frequency, and the matching networks for the LNAs (low noise amplifiers) and the power amplifiers. In certain cases the frequency of operation remains fixed, but the power amplifier output impedance changes with time and one must retune the output matching network to result in the highest system efficiency. In many portable applications, the antenna input impedance is strongly dependent on the position of the portable device, and a low-loss reconfigurable matching network at the input of the antenna would result in a substantial performance improvement. Also, some systems require a very wideband but non instantaneous frequency coverage, such as 2-18 GHz or 0.1-6 GHz, and this can be done efficiently with the use of reconfigurable antennas, matching networks, and filters. Reconfigurable MEMS circuits can also be used to generate a large range of impedance loci which are necessary for transistor and diode characterization (gain, noise, conversion loss, etc).

As indicated above, the author is hereby proposing an architecture which utilizes the various concepts and blocks outlined in the various chapters of this dissertation. As can be seen in Fig. 12.3, the proposed architecture is unique in that it offers a single chip “front-haul processor” (with built-in RF MEMS-based wireless interfaces) capable of processing either 1) the base band of one or more high-usage frequencies and 2) passing through the IF of any air interface standard into the base-band processing unit via a wireless or wire link.



Source: [21]

Figure 12.2 A Reconfigurable RF Front End Block Diagram

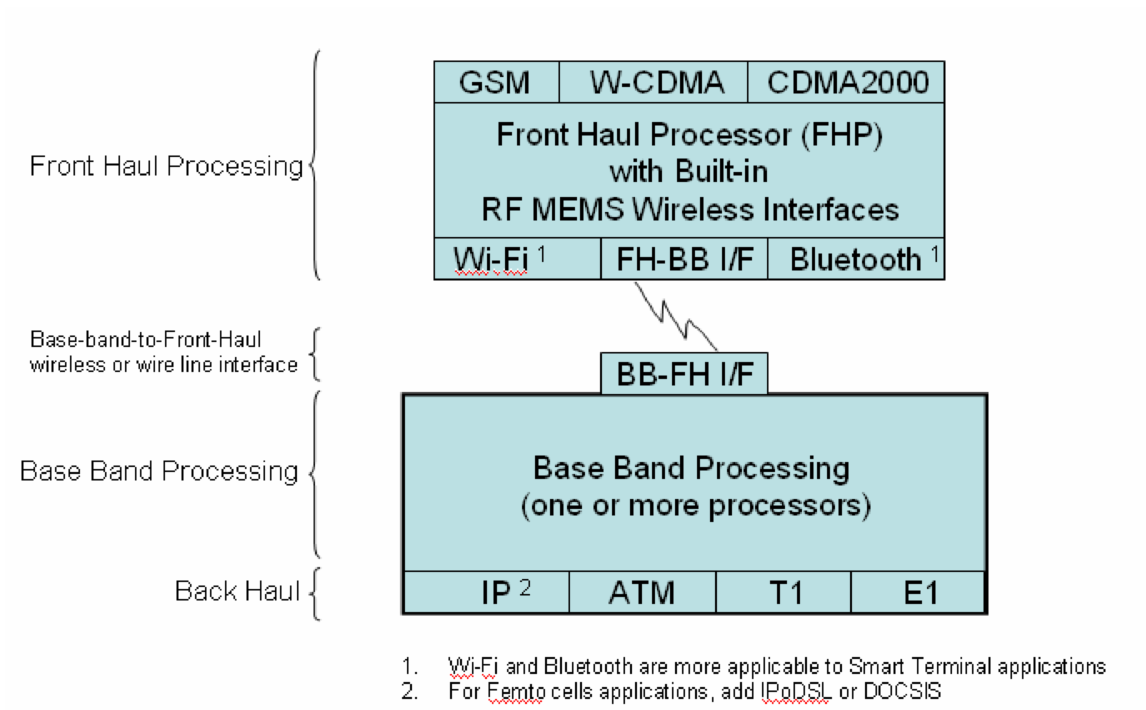


Figure 12.3 Multi-band Flexible Base Station Architecture

At the heart of this architecture is the "front-haul processor" (FHP or SM-RFFE, smart programmable RF front end) with built-in RF MEMS wireless interfaces as shown in Fig. 12.3. The FHP is a relatively smaller processing unit (as compared to the base-band processors) which contains the necessary SDR software to either 1) handle the base-band processing of *one* or more high volume air interface standards like GSM and W-CDMA, or 2) pass through the intermediate frequency (IF) of *any* air interface standard (e.g., UMTS, WiMax, 4G, etc) to the base-band processing unit via a wireless (Wi-Fi or TBD) or wireline interface (for example, CPRI or OBSAI interface standards).

The advantages of this architecture are:

1. Off loading of the main base-band processing unit when handling the high volume air interface base band processing. In this configuration, the FHP in essence becomes a base station on its own merit. The back haul connection of the FHP becomes either the Wi-Fi or wire line interface to a nearby Base Station Controller. In this configuration, the FHP is well suited for a Femtocell application supporting a single air interface standard.
2. Providing flexible FHP-to-BB wireless or wire line interfaces which are easily configurable in the FHP's SDR software and built-in programmable RF MEMS circuitry.
3. Achieving economies of scale due to the single chip programmable flexibility as described in the various chapters of this dissertation.

In order to achieve the commercial implementation of the proposed FHP for MBF SDR-based transceiver architectures the following technological challenges need to be addressed and it is believed that all are within commercial realization within the next three to five years:

1. Integration of RF MEMS on top of standard CMOS or SiGe semiconductor processes. This is critical to achieve the lowest possible cost.
2. A full set of RF MEMS libraries for the implementation of switches, capacitors, inductors and oscillators for the implementation of filters and antennas using standard CMOS or SiGe processes as indicated in 1 above.

3. Reliable packaging solutions for RF MEMS suitable for industrial temperature range at medium power applications such as those required by pico or femto cells, and smart terminals.
4. Base Station Controller application software modifications required to treat the “dual personality” front-haul processing unit, which can behave as a) standalone base station and b) as IF-pass-through processing unit for multiple frequency bands.

12.3 A Five-Year Horizon Possibility

In regard to the integration of RF MEMS on top of standard CMOS or SiGe semiconductor processes, the author believes that significant advances have already been made in this area and that, while the high volume fabs like TSMC or UMC are not yet offering the required solutions, there are other “specialty fabs” already offering viable alternatives [29]. Also, the International Technology Roadmap for Semiconductors (ITRS) has provided a technology roadmap update [30] shows that the integration of RF MEMS components, including resonators, is expected to be a reality starting in 2011 (see Fig. 12.4).

Mr. Volker Herbig, Product marketing manager at X-FAB Semiconductor Foundries AG said [31]:

> “The MEMS foundry market is certainly growing, but more slowly than expected. From a technology standpoint, integration of CMOS and MEMS is hot.”

A partial list of fabs already in the MEMS processing business follows. Also including are various quotes from their CEOs published in [31] on December 22, 2008 regarding their business trends.

Micralyne, Edmonton, Alberta, Canada

http://www.micralyne.com/?gclid=CIXKpLGZ1ZcCFQgRFQod1UzLDg

"Micralyne has experienced very significant growth recently - 40 percent to 50 percent revenue growth - and the pipeline of new opportunities looks very strong. VCs are investing more and the failures associated with the optical bust are now a distant memory. Furthermore, the VCs are not investing in MEMS fabrication capacity. Therefore, most new start-ups that incorporate MEMS are going fabless. Mainly captive fabs are not able to deviate much from their internal processes or might not have the flexibility to address issues that arise during the early, less defined stages. There's also a concern that external customers will be treated as second class citizens compared to internal product lines. While we can't ignore these companies, we believe we can compete with them very effectively. "

Innovative Micro Technolgoy, Santa Barbara, CA http://www.imtmems.com/

"We are also in high volume production for a switching application for telecom and shipping on the order of two million working MEMS switches each week for that customer. Other areas showing strong potential are IR imaging, RF and MM-wave, and biomedical applications. Our customers range from those with a spec to those with a design, to those that have prototyped or even produced working devices. In all cases, we collaborate closely on both process transfer/development and design for manufacturability. Our skills and experience in these areas enable smooth startup or transfer to our facility of processes even where the tool sets do not match up. Tight collaboration is key and several of our customers have personnel permanently or periodically assigned at our facility. We believe in strong and open partnering as the solution."

Semefab, Fife, Scotland http://www.semefab.co.uk/

"Semefab is a provider of MEMS foundry services and therefore is open to all companies seeking silicon processing for MEMS applications. The key application fields where Semefab is seeing growth are in microfluidics, RF MEMS (albeit still in R&D), biomedicine, accelerometers and thin film applications such as pressure sensors. The defense industry is slowly waking up to the possible applications of MEMS in security applications and is seen as a major contributor to business by 2010."

Table RFAMS8 RF and A‌ll RFMEMS

Year of Production	2008	2009	2010	2011	2012	2013
Design Tools						
BAW	(1) IRFM, (2) CM	(3) DF		DF + MEMS TCAD		
Resonator	(1) IRFM, (2) CM	(3) DF				
Switch—capacitive contact	) CM	(1) IRFM	(3) DF			
Switch—metal contact	) CM	(1) IRFM	(3) DF			
All MEMS devices	(4) MEMS TCAD	(4) MEMS TCAD				
Packaging						
BAW	Wafer level package. Micro cavity package (CVS).			Above IC integration and TFS		
Resonator	Stacked die		Integration into IC and TFS			
Switch—capacitive contact	Above IC integration with CVS			Embedded integration into IC and TFS		
Switch—metal contact	Above IC integration with CVS			Embedded integration into IC and TFS		
Performance Driver						
BAW	F= 900MHz to 5GHz. Testability improved. TCF= -5ppm; K2*Q=150		Coupled Resonator Filter (CRF) ≥ increase functionality (e.g., impedance match).		F= 900MHz to 10GHz. Built In Self Test (BIST) structure. Tunable filter? TCF= -1ppm; K2*Q=200	
Resonator	ock (32 kHz)	Clock oscillator (10-100MHz) multi-frequency per die.		Nano resonator for filter function (800MHz–2.5GHz)		
Switch—capacitive contact t	Cellular Frontend (Tuning): 20:1 tuning ratio, 40V actuation			Cellular Frontend (Tuning): 30:1 tuning ratio, low-voltage actuation		
Switch—metal contact	Cellular Frontend (Tuning, T/R): Insertion loss <0.3dB, lifetime >1e10 cycles			Cellular Frontend (Tuning, T/R): Insertion loss <0.2dB, lifetime >1e11 cycles		
Cost Driver						
BAW	Die size / package			Integration with semiconductor die		
Resonator	essing cost	Packaging	Integration with semiconductor die			
Switch—capacitive contact	Processing cost. Die size / microcavity package. Test.			Integration with semiconductor die		
Switch—metal contact	Process cost. Reliability / size / microcavity package. Test.			Integration with semiconductor die		

Source: [30]

Figure 12.4 ITRS Roadmap for RF MEMS

X-FAB Semiconductor Foundries AG, Erfurt, Germany http://www.xfab.com/

> "The MEMS foundry market is certainly growing, but more slowly than expected. From a technology standpoint, integration of CMOS and MEMS is hot. Companies need to offer a wide variety of process options. X-FAB is continually expanding its portfolio, and is investigating or implementing several new modules, including DRI etching for bulk micromachining, electroplating, and wafer-level packaging/encapsulation. X-FAB aims to develop batch processing for MEMS, and looks for synergies between CMOS operation and MEMS operation, such as doing MEMS wafer batch processing instead of single wafer processing. We use a KOH batch etch instead of a DRI single wafer etch whenever possible. X-FAB also reduces packaging costs by providing wafer-level packaging. "

In addition, captive fabs are expanding their MEMS capabilities and capacity as highlighted in [32]:

> "In 2006, only the two companies in the top 30 MEMS manufacturers, TI and HP, were manufacturing MEMS at 200 mm diameters. By 2011, there should be at least 12 players: ST's and Freescale's 8-inch lines are already operational: Bosch, Omron and Canon should follow in the next 18 months. And WTC (Wicht Technologie Consulting) knows of a further six companies among the top 30 who expect to, but have not yet publicized their plans to move to this diameter.
>
> The foundry offer also currently expands in 200 mm. Dalsa, tMt, DNP and Jazz Semiconductor have started to offer services, while APM, Omron, TSMC Silex come on line by 2009.
>
> RFMD is currently building an 8-inch facility dedicated to RF MEMS and NXP will also probably start at this diameter. WiSpry will partner with Jazz Semiconductor."

12.4 Chapter 12 Summary

The author believes that the proposed single chip front-haul processor (FHP) architecture of Fig. 12.3 using RF MEMS or a hybrid approach combining RF MEMS and traditional SiGe or GaAs devices is achievable within five years.

The proposed FHP is a relatively smaller processing unit (as compared to the base band processors) which contains the necessary SDR software to either 1) handle the base band processing of *one* or more high volume air interface standards like GSM and W-

CDMA, or 2) pass through the intermediate frequency (IF) of *any* air interface standard (e.g., UMTS, WiMax, 4G, etc) to the base-band processing unit via a wireless (Wi-Fi or TBD) or wireline interface (for example, CPRI or OBSAI interface standards).

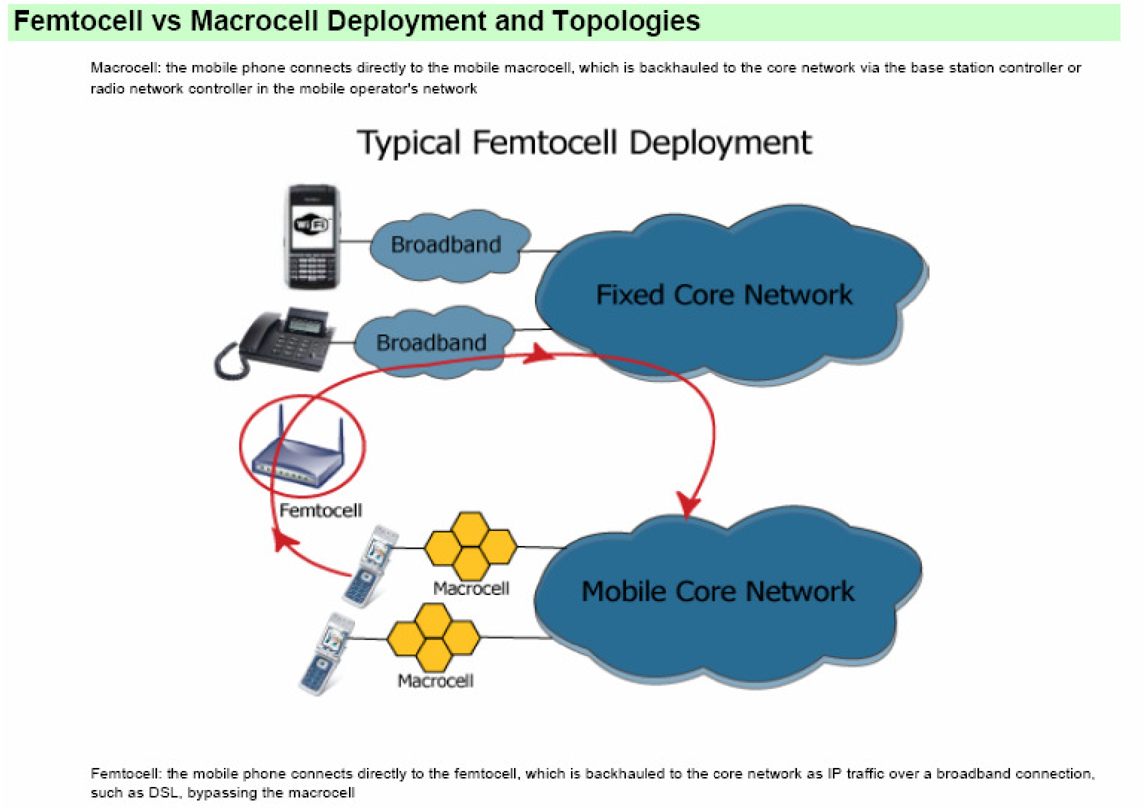
The business potential of such device is explored in the next chapter as it relates to the femtocell market which is in its infancy stage.

Chapter 13 Femtocell Market Overview

13.1 Femtocell Market Trends

As shown in Fig. 13.1 and Fig. 13.2, femtocells will enable mobile operators to push IP out to the edge of the mobile network and generate opportunities for value-add services, preserve 3G macro cellular capacity for voice services, and reduce operational costs by running backhaul over DSL lines. However, the business model is not yet proven and the benefits to consumers are not universally compelling; mobile operators will have to develop sophisticated bundles covering phones, data cards/devices, femtocells, and voice, data (and likely video) services to attract subscribers.

The lack of a femtocell standard will inhibit adoption in the next 12 months; any such standard would have to incorporate existing standards including 3GPP, 3GPP2, and possibly WiMAX for radio access, plus SIP and IMS for IP services, and could also include WiFi for local area wireless Ethernet, TR069 for CPE device management and IPSec for security. Although the Femto Forum now has 40 members, including major integrated vendors, it is not a standards body and creating a coherent set of accepted practices from all the technologies which need to be integrated - not to mention the agendas of vendors with competing intellectual property - means that the market will still be in a very early phase of adoption through CY 2009.

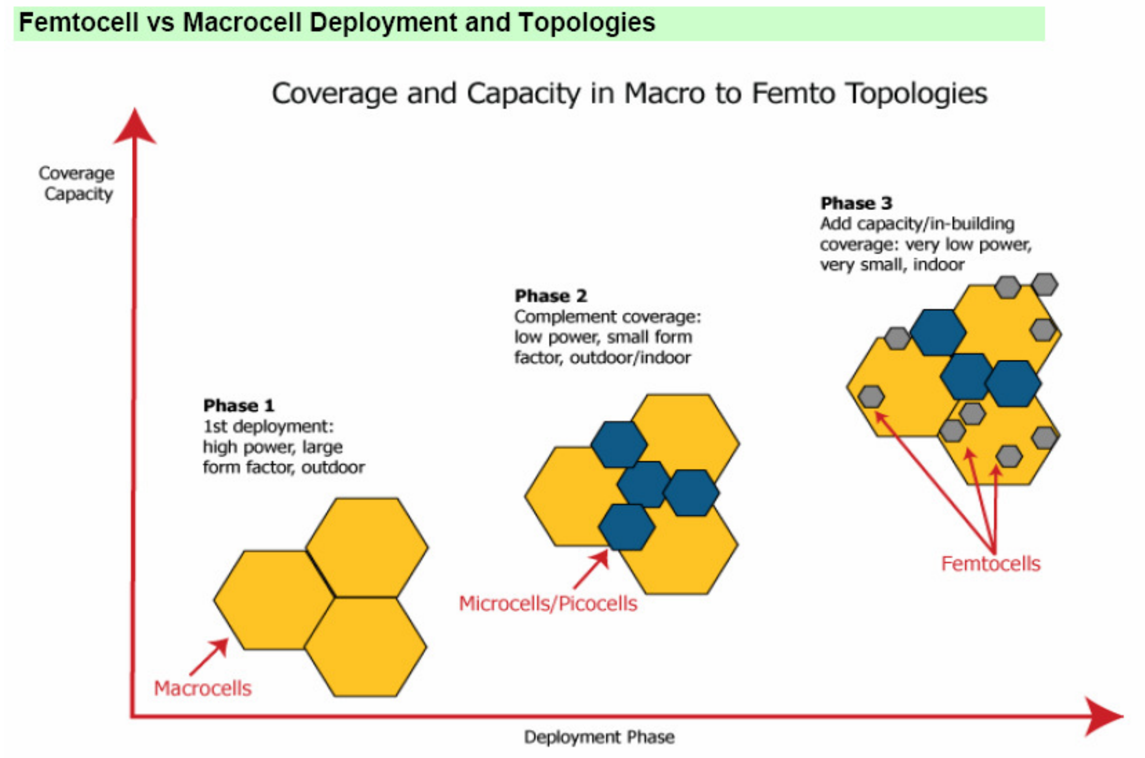


Source: Infonetics Research, September 25, 2008

Figure 13.1 Femtocell vs Macrocells Deployment and Topologies

The more widespread availability of HSDPA (and, within the next 12-18 months, HSUPA) is driving adoption of mobile broadband; this in turn, is a driver for femtocell adoption: once users are hooked on high speed mobile data services, subscribing to a femtocell service could follow to ensure coverage and capacity consistency for those services in the home or office.

Not all mobile operators will be able to leverage the potential business benefits of 3G femtocells; for operators in low-ARPU markets their customer demographics will not support the investment required by the end-user to purchase a femtocell and use value-added mobile data services, in addition to having a DSL line.



Source: Infonetics Research, September 25, 2008.

Figure 13.2 Femtocell vs Macrocell Deployment and Topologies

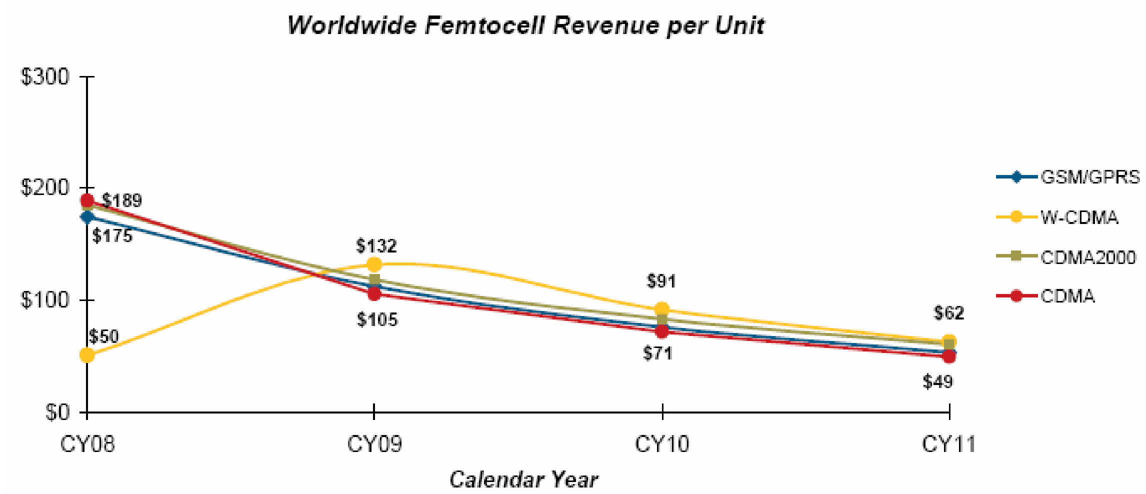
In these countries, typically in developing countries, there may be opportunity for 2G femtocells, driven by cheaper mobile voice calls within the home, but this is not likely to be a booming market as 2G coverage does not generally suffer from the in-building penetration issues that can beset 3G networks.

3G femtocells could have far-reaching consequences for the telecommunications industry; mobile operators have invested heavily in macrocell network construction, but, in this scenario, will increasingly divert investment towards indoor femtocell base stations, which will have profound implications for cellular network infrastructure vendors; potentially, femtocells could allow mobile network operators to make dramatic reductions in investment in conventional 3G macrocellular networks and dedicated broadcasting networks (such as DVB-H).

Femtocells still have a number of technology challenges to overcome: it is not proven that they will not interfere with signals on the macro cellular network when mass deployed, network management, and troubleshooting is not clear-cut as femtocells connect directly to fixed broadband lines, which may be operated by another service provider, and the efficient scaling up and remote operation of femtocells remains a potential challenge.

The unit price pressures that femtocells will face in the coming years are shown in Fig. 13.3. There it can be seen that the price range will be between \$50 to \$100 depending on technology and feature set. This, however, does not necessarily mean that the fabrication cost of the femtocell will be this low as the price to the end user can be subsidized by the service subscription as currently done with the handsets. However, it clearly shows that significant pressures will be put in the cost of the components required to implement the femtocell function.

As most adoption is expected to come from consumers, the fall in average revenue per unit for femtocells is critical to stimulate mass market adoption; only when it falls below \$100 in late CY 2009 or early CY 2010 do shipments ramp up into the millions.



Source: Infonetics Research, September 25, 2008

Figure 13.3 Worldwide Femtocell Revenue per Unit

13.2 Market Size and Forecast

13.2.1 Overview

The worldwide femtocell market is expected to reach $1.5B in revenue and 24.7M units by CY 2011. In 2Q08 55% of total revenue came from femtocell gateways and 45% from femtocells; by CY 2011 it is forecasted this split will shift to 6% and 94% respectively; the ratio of femtocell gateways to femtocells in CY 2008 was approximately 1:1,000 and by CY 2011 this will grow to approximately 1:10,000.

Operators will likely only launch femtocell services in focused areas of high population density in the early years of service; if they were to launch over a geographic area which was too widely dispersed, subscriber adoption would be patchier, and the proportion of femtocell gateways required to support these users would not be cost-effective; operators will instead use a build-and-grow model, migrating this template to new areas with a focused Capex expectation based on number of gateways required to support adoption within that area.

13.2.2 GSM / GPRS Femtocells.

In CY 2008, the worldwide GSM / GPRS femtocell revenue is expected to hit $605K and units are expected to reach 3.5K, based on predicted service launches in Western Europe and possibly in Asia Pacific; by CY 2011 revenue will hit $195.5M, a 2008-2011 CAGR of 586%; units are expected to reach 3.7M, a 2008-2011 CAGR of 920%; femtocells based on 2G/2.5G technology have a limited appeal, as they support predominantly voice centric services, and voice coverage is typically satisfactory over 2G/2.5G networks; the main adoption drivers for users are home-based cellular call tariffs, a valid driver in developing countries with low household income. In such countries, the necessity of a broadband line for backhauling femtocell traffic could also be cost-prohibitive.

13.2.3 CDMA Femtocells.

In CY 2008, the worldwide CDMA femtocell revenue is expected to hit $1.9M and units are expected to reach 10.2K; by CY 2011 revenue will hit $4.6M, a 2008-2011 CAGR of 33%; units are expected to reach 92.7K, a 2008-2011 CAGR of 108%; with most of the world's CDMA user base migrating to EVDO over this period, the long-term opportunity for CDMAone femtocells is limited and will quickly diminish despite being the earliest market to ship units.

13.2.4 W-CDMA Femtocells.

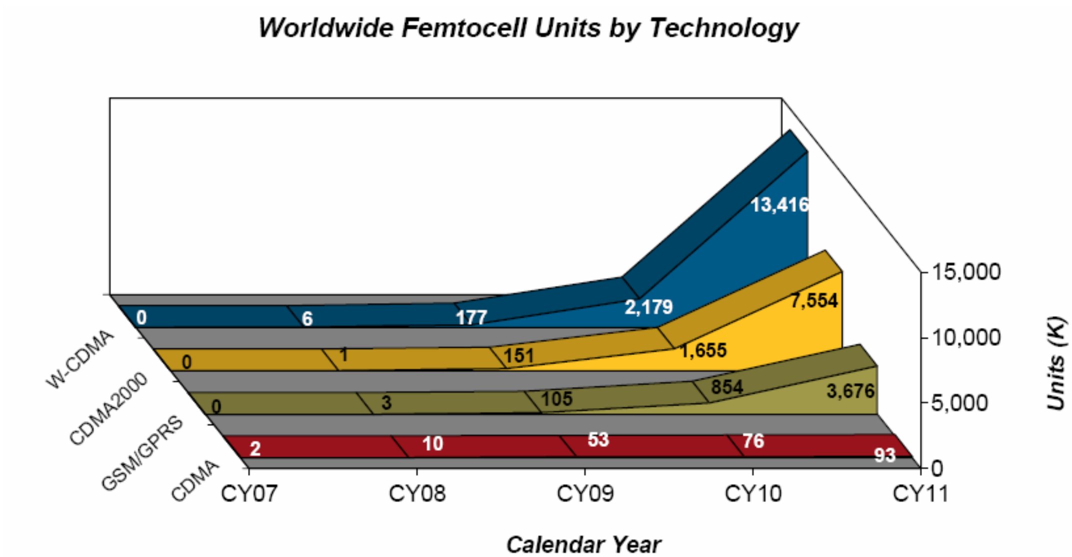
In CY 2008, the worldwide W-CDMA femtocell revenue is expected to hit $291.9K and units are expected to reach 5.8K; by CY 2011 revenue will hit $836.9M, a 2008-2011 CAGR of 1321%; units are expected to reach 13.4M, a 2008-2011 CAGR of 1222%; this will be driven by Western European mobile operators: for example, Vodafone, Orange, T-Mobile, TeliaSonera, and O2 have all announced femtocells trials, and some of these operators are expected to launch limited services before the end of this year.

13.2.5 CDMA2000 Femtocells.

In CY 2008, the worldwide CDMA2000 revenue is expected to hit $207.8K and units are expected to reach 1.2K; by CY 2011 revenue will hit $454.1M, a 2008-2011 CAGR of 1198%; units are expected to reach 7.6M, a 2008-2011 CAGR of 1788%; Sprint has already launched a service in North America, and Verizon is likely to follow suit, driving early market growth. Over the mid to long term of the forecast period, more Asian mobile operators will also enter this market, with at least one service expected to go live in late 2008 to early 2009.

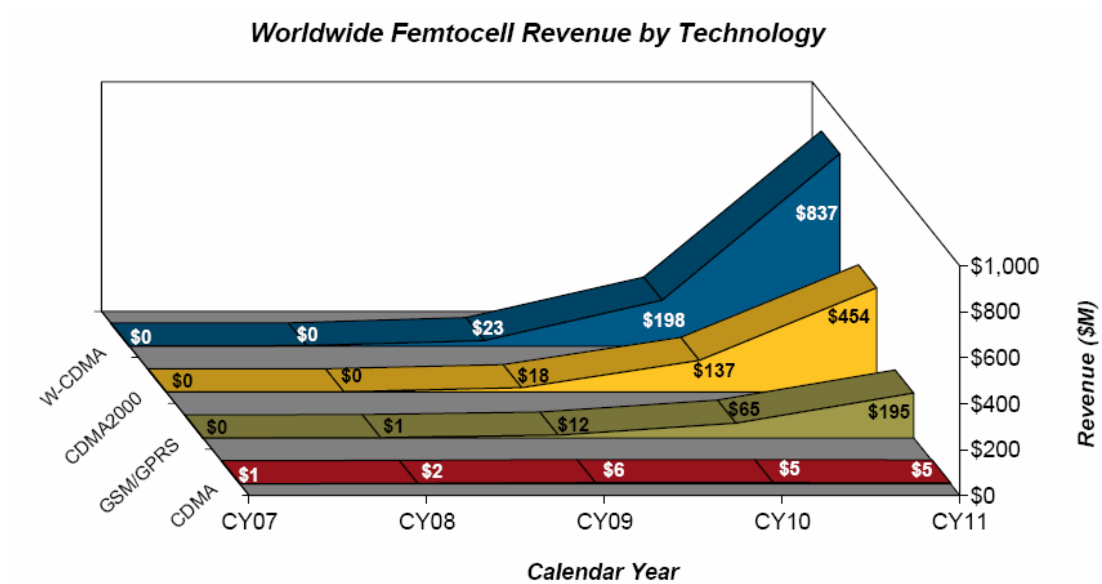
13.3 Market Growth Potential

The femtocell market is just starting to take off. The growth will be exponential starting in CY 2010 as shown in Fig. 13.4 and Fig. 13.5. Unit volumes are expected to grow from 4.7 million units in CY 2010 to over 24 million in CY 2011 with 3G technologies (W-CDMA and CDMA2000) being predominant. Revenue should thus reach about $1.5 billion in CY 2010, or almost quadruple that of CY 2009. While there are no forecast projections in [34] beyond CY 2011, it can be inferred from this analysis and other literature that the growth will continue to be exponential at least through CY 2014.



Source: Infonetics Research, September 25, 2008

Figure 13.4 Worldwide Femtocell Units by Technology



Source: Infonetics Research, September 25, 2008

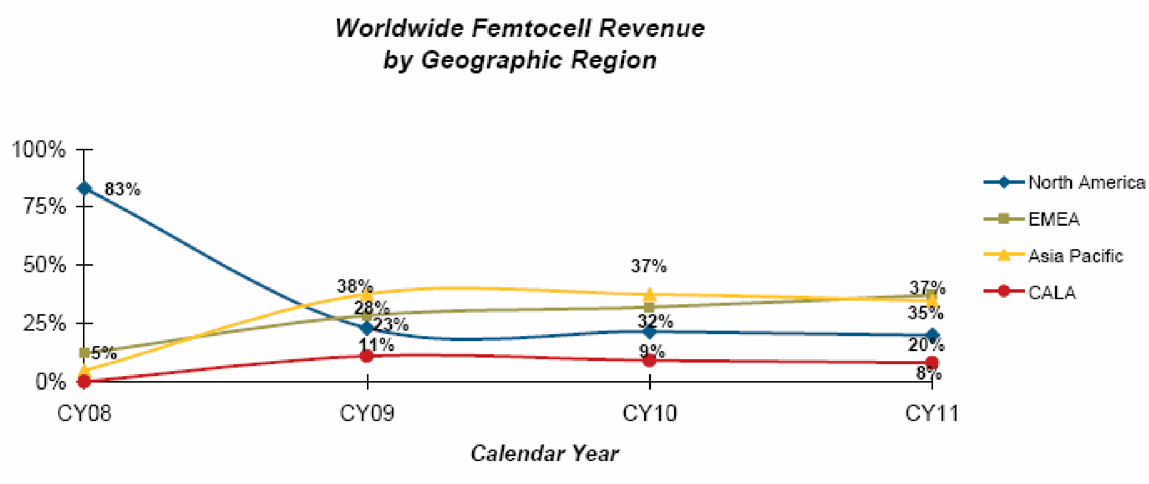
Figure 13.5 Worldwide Femtocell Revenue by Technology

13.4 Market Size by Geographies of the World

The strongest early market for femtocells are in developed countries, as 3G rollout is more pervasive and it is believed that 3G femtocells have stronger adoption benefits for consumers, because 3G suffers from poorer in-building penetration than 2G. Also, 3G femtocells will provide more consistent coverage and capacity for mobile data, which will be more rapidly adopted by consumers in developed countries with higher average household income.

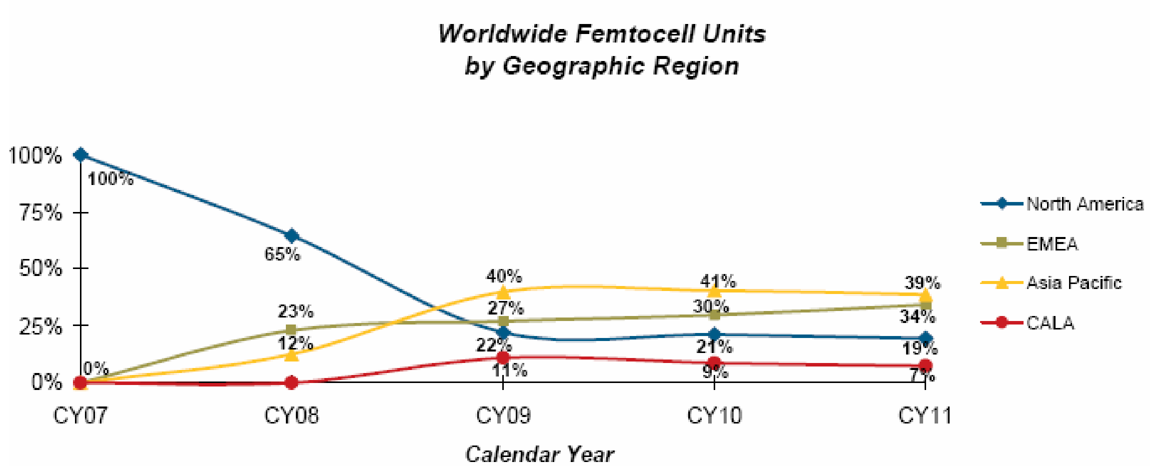
The large potential of developed countries in both Asia Pacific and Western Europe will drive adoption and equipment revenue growth through the forecast term provided in reference [34] and beyond; femtocell adoption will be much later in developing countries in MEA, Asia Pacific, and CALA.

In 2Q08, all revenue came from North America. In CY 2008 it was expected to breakdown as: 83% from NA, based on the early femtocell initiative from Sprint in North America, with 12% from EMEA and 5% from APAC as services just start to go live, and 0% from CALA; by CY 2011 (see Fig. 13.6), this shifts with 20% of femtocell revenue being from NA, 37% from EMEA, 35% from APAC, and 8% from CALA driven by the multitude of mobile operators in Western Europe and developed markets in Asia Pacific (e.g., Japan, South Korea, Taiwan, Singapore, Australia, New Zealand) launching services. Fig. 13.7 shows the unit volume projections by geographic region through CY 2011.



Source: Infonetics Research, September 25, 2008

Figure 13.6 Worldwide Femtocell Revenue by Geographic Region



Source: Infonetics Research, September 25, 2008

Figure 13.7 Worldwide Femtocell Units Percentage by Geographic Region

13.5 Femtocell Equipment Manufacturers

Shown in Fig. 13.8 is a list of equipment manufacturers that have either introduced or announced the introduction of femtocell equipment as of late 2008. It can be seen that design activity is on going for all femtocell technologies, including 2G and 3G. It is also important to note that both Tier 1 manufacturers (like Alcatel Lucent, Huawei, Ericsson, and others) as well as Tier 2 and Tier 3 manufacturers are pursuing this new market.

2G Femtocells

GSM/GPRS	
Ericsson Femto Cell*	RadioFrame H-Series
Hay Systems HSL 2.75G Femtocell	Ubiquisys ZoneGate*
ip.access nanoGSM	

CDMA	
Airvana HubBud CDMA Femtocell	Samsung CDMA UbiCell
Airwalk EdgePoint	ZTE Femto Cell Home Access Station

3G Femtocells

W-CDMA/HSDPA	
2Wire HomePortal BaseStation**	
Airvana UMTS Home Base Station	NETGEAR Femtocell Voice Gateway
Alcatel-Lucent Base Station Router (BSR) Femto - W-CDMA/HSDPA	Nokia-Siemens Networks 3G Femto Home Access Point
Ericsson Femto Cell	RadioFrame S-series
Huawei Home Node B UAP3801 Femtocell	Ubiquisys ZoneGate
ip. Access Oyster 3G	Samsung HSPA UbiCell
Juni JU-100 Femtocell	Thomson TG870 Integrated Femtocell Gateway
Motorola 8000, 8100	ZTE Home NodeB ZXWR H8901
NEC Femtocell Access Point	

CDMA2000/EV-DO	
2Wire HomePortal BaseStation**	Alcatel-Lucent Base Station Router (BSR) Femto - CDMA/EV-DO
Airvana HubBud CDMA Femtocell	Samsung EV-DO UbiCell
Airwalk EdgePoint	ZTE Femto Cell Home Access Station

Source: Infonetics Research, September 25, 2008

Figure 13.8 Femtocell Equipment Manufacturers

13.6 Femtocell Adoption Roadmap

Femtocell adoption has already started as shown in Fig. 13.9. However, mass deployment will only start in 2013 and beyond when the operators see the Capex and Opex benefits of femtocells. By then, femtocell will become a significant element in the 4G deployment strategy aimed at dense urban environment and less intensive macro cellular rollout.

2006	2007 2008	2009 2010 2011	2012 2013 and beyond
Femtocell concept emerges	**Femtocell ecosystem evolves**	**Femtocell market accelerates**	**Mass market femtocell adoption**
• First femtocell prototypes, based on improving indoor coverage • Business model is uncertain	• Commercial launch of femtocells by specialists • Gateways launched, much variance in architecture • Femto chip evolution driven by picoChip and others • 1H08: Sprint launches service in US; numerous trials worldwide, but few live services	• Numerous femtocell service go live; technical and marketing challenges remain • Mini-RAN approach using femtocell gateway becomes popular • Femtocells increasingly integrated into consumer broadband CPE (e.g., home gateways) • Sub $100 retail price point reached, stimulating market acceleration	• Femtocells are a proven technology, and adoption is driven by pricing, coverage and growth in demand for mobile broadband • Operators see opex benefits of femtocells • LTE femtocells available • Femtocells become a significant element in 4G deployment strategy, aimed at dense urban coverage and less intensive macrocellular rollout

Source: Infonetics Research, September 25, 2008

Figure 13.9 Femtocell Adoption Roadmap

13.7 Chapter 13 Summary

The femtocell market concept is a relatively new event which started in 2006. While initial adoption has commenced as of early 2009, mass market adoption in the tens of millions of units is not expected to occur until 2013, when it will be come a significant element in the 4G deployment strategy aimed at the dense urban environment and less intensive macro cellular rollout.

Because femtocells are aimed to be collocated at the user's home, price points will be much lower than picocells and have already reached the sub $100 level. As a result, there will be significant pressure on the cost of the components needed to implement femtocells.

Additionally, it should be noted that femtocell RF front ends will require low transmission power and will be powered by a wall-mounted supply source. Both of these elements are necessary for RF MEMS as discussed in Chapter 11**.**

It is precisely because of the above market and product characteristics that the author has selected this new market as a case study for a financial and revenue analysis for the proposed “front-haul processor” (FHP) discussed in Chapter 12**.** This financial and revenue analysis can be further utilized as the starting point for the new venture proposed in Chapter 14.

Chapter 14 Summary and Future Work

14.1 Summary

The RF front end circuitry makes up over 60% of the cost of a base transceiver station (BTS, also referred as Node B in 3G networks). Included in this cost is that of the Power Amplifier unit, RF filters, and the GPS unit for clock recovery and synchronization. Depending on the architecture complexity, number of supported sectors, power range specification, and wireless network standards supported, a base transceiver station can cost between USD $10,000 to $40,000.

In addition, because of the evolving mobile wireless communications standards (2G/2.5G/3G/LTE/4G and their various implementation standards including CDMA2000, WCDMA, TD-SCDMA, WiMAX, etc), a BTS original equipment manufacturer (OEM) is faced with the monumental task of designing a BTS RF Front End for each mobile network standard that they wish to support. Moreover, the OEMs are forced to manufacture and maintain in the field all of these BTS variants.

The cost issue and logistics complexity of supporting a multitude of BTS variants is further accentuated when looking ahead into future in the next 5-10 years. One way to address the frequency re-use and power range limitations of today's base stations is to have more base stations covering smaller geographical areas (that is, add more cell clusters) by implementing what is called a Pico BTS. The very concept of a Pico BTS again implies a significant cost reduction of the BTS to below $5,000 and a Femto base station will have to meet a cost target in the range of USD $200.

Thus the RF Front End represents the single biggest opportunity for cost reduction and logistics simplification for the base station of the future: the SDR-based Cellular Femto BTS. While there is a lot of academic and industry research focused on software-defined radio architectures, SDR still does not solve the RF Front End cost issue. In fact, for SDR architectures to achieve their promised "programmability" mantra, they need a true "programmable" RF Front End. The problem is that today's BTS RF Front End implementations are not programmable but fixed to work with a specific RF frequency (e.g., 1,900 MHz) for a specific mobile network standard (e.g., CDM2000 or W-CDMA). To band-aid this issue, OEMs typically implement multiple RF Front Ends to give the illusion of a "multi-band" programmable system at twice, triple or quadruple the cost of a single-band system.

RF MEMS (micro electro-mechanical systems) is a technology that has the potential to not only help solving the BTS cost and logistic issues, but also to complement SDR architectures by providing a true low cost, high performance, programmable RF Front End. Some of the advantages of RF MEMS include: very good isolation and insertion loss, virtually no control circuit power dissipation in ON or OFF state, with proper design it is capable of broadband and high power switching, switching speed is sufficient for RF control circuit applications, and relatively low cost as it is manufactured by standard semiconductor manufacturing techniques.

Because of its potential in the implementation of low cost, high performance, programmable RF Front End filters and antennas, the author has shown in his research via this dissertation work that the possibility of implementing a Single-Chip Programmable RF MEMS FRONT END for SDR Cellular Pico BTS for commercialization by 2011 is a true possibility.

14.2 Future Work

The author thus recommends to take the findings of his industry and technical research to the next R&D step, which is the formation of a new business venture as follows.

14.2.1 A New Venture

This is a new business venture expected to be founded in the second half of 2009. The venture addresses the wireless telecommunications industry, which is undergoing migration changes from 2G/2.5G to 3G (third generation) and next to 4G and beyond. In addition, new services are being added like high speed web browsing from mobile handsets, multi-media messages, IPTV, video conferencing with mobile handsets, etc.

The FHP ("front haul processor") product is currently in the concept stage and requires additional detailed feature specification. The product specification details will be done as part of the first phase of the new venture during calendar Q3 of 2009. A final specification will be available in Q4 2009.

It is expected that it will take approximately 24 calendar months, and 120 man-months to develop and prototype this product. The first product customer samples are expected to be available in Q4 2011 and initial production is expected to commence in mid 2012.

14.2.1.1 Market

The wireless telecommunications infrastructure is a global market, with very high growth rates in underdeveloped regions like China, India and Latin America. The targeted market is Femtocels for the wireless mobile communications market. See Chapter 13 for the femtocell market overview.

14.2.1.2 Financing

The venture will first seek “angel” investors and then will be followed with VC investors. Also, it is possible that financing can be obtained from the OEM system integrator. This last financing has the additional benefit in that it provides a first customer to the venture since the founding of the company. It is expected that “angel” financing will be enough to produce the first full functional requirements specification by Q4 2009. VC funding will be sought after a solid partnership with an OEM integrator and RF MEMS and NPU suppliers. It may also be possible to obtain investment from the suppliers as well.

14.2.1.3 Management Team

Jorge S. Hurtarte (Founder)

Jorge "Jeorge" S. Hurtarte, P.E., has more than 20 years of semiconductor industry experience in design engineering and manufacturing operations. His responsibilities at TranSwitch have encompassed worldwide VLSI chip design, software and technology development; EDA and manufacturing supplier selection; supply chain management and manufacturing logistics; and worldwide Sales. Prior to joining TranSwitch in January 1999, Mr. Hurtarte spent 15 years at Rockwell Semiconductor

Systems, now Conexant Systems. During his tenure there, his responsibilities ranged from semiconductor product engineer to director of an engineering group, ultimately becoming a vice president of the company. Mr. Hurtarte holds a BS degree in electrical engineering from the University of California, Irvine, and a MBA from Auburn University. He is a graduate of Harvard Business School's Advanced Management Program, and is a Registered Professional Engineer in the State of California. He served on the Board of Directors of the Fabless Semiconductor Association during 2002-2005.

TBD 1 (Co-Founder): NPU Architect / Specialist

This individual should have a proven track record in NPU architecture and NPU-based designs in telecommunications applications.

TBD 2 (Co-Founder): RF MEMS / Analog Designer / Specialist

This individual should have a proven track record in RF MEMS and analog circuit design for RF front ends for wireless mobile systems.

TBD 3 (Co-Founder): VLSI Designer / VLSI Technology Specialist

This individual should have extensive VLSI SoC design experience preferably in the telecommunications and wireless base stations industry.

14.2.1.4 Product

Purpose of the product

The FHP is a base transceiver station (BTS) line card semiconductor device with embedded RF MEMS wireless interface integrated with a real time processing unit and the necessary software to automatically configure itself to operate with any 2G/3G /4G wireless communications systems.

The FHP is a relatively smaller processing unit (as compared to the base band processors) which contains the necessary SDR software to either 1) handle the base band processing of *one* or more high volume air interface standards like GSM and W-CDMA, or 2) pass through the intermediate frequency (IF) of *any* air interface standard (e.g., UMTS, WiMax, 4G, etc) to the base-band processing unit via a wireless (Wi-Fi or TBD) or wireline interface (for example, CPRI or OBSAI interface standards).

The advantages of this innovative architecture are:

1. Off loading of the main base-band processing unit when handling the high volume air interface base-band processing. In this configuration, the FHP in essence becomes a base station on its own merit. The back haul connection of the FHP becomes either the Wi-Fi or wire line interface to a nearby Base Station Controller. In this configuration, the FHP is well suited for a Femto cell application supporting a single air interface standard.
2. Providing flexible FHP-to-BB wireless or wire line interfaces which are easily configurable in the FHP's SDR software and built-in programmable RF MEMS circuitry
3. No need to carry multiple part numbers in production inventory as one device does it all with software programmability
4. Ability to download new software updates as wireless systems standards change or evolve

To facilitate the design in of the FHP device, a reference design will be available as well as a full set of software application programming interfaces (APIs) and technical documentation.

14.2.1.5 Unique features

The unique features of the FHP product are:

Real time automatic adaptation to any 2G /3G/4G wireless network standard.

- On chip base-band processing for femtocell application
- Off loading of the main base-band processing unit when handling the high volume air interface base-band processing. In this configuration, the FHP in essence becomes a base station on its own merit. The back haul connection

of the FHP becomes either the Wi-Fi or wire line interface to a nearby Base Station Controller. In this configuration, the FHP is well suited for a Femto cell application supporting a single air interface standard.

- Providing flexible FHP-to-BB wireless or wire line interfaces which are easily configurable in the FHP's SDR software and built-in programmable RF MEMS circuitry
- No need to carry multiple part numbers in production inventory as one device does it all with software programmability
- Ability to download new software updates as wireless systems standards change or evolve.

14.2.1.6 Trademarks, Patents, Copyrights, Licenses, and Royalties

No patents, trademarks, service marks, or copyrights have been obtained yet. However, the unique concept of a "dual personality" of the front haul processor deserves a trademark filing to begin with.

No license or royalty agreements are in place yet. It expected that license agreements will be need for the NPU of choice. All other circuits will be designed by the venture.

It is expected that several patents, trademarks, and license agreements will be pursued as the definition and development of the product proceeds.

14.2.1.7 Governmental approvals

No governmental approvals are required to ship the product. However, the customers using the product may need some form of type approvals will be needed and provided by the telephone carriers where their products will be sold.

14.2.1.8 Production

The company will be a fabless company. All manufacturing will be subcontracted out.

14.2.1.9 Suppliers

The primary suppliers are EDA (engineering design automation) tool providers like Cadence, Synopsys, Magma, Verisity, etc, and IP (intellectual property) providers like ARM, Tensilica, etc. Also, since the company is fabless, fab and packaging suppliers will be contracted to perform all manufacturing and test operations.

14.2.2 Future Research and Development

The following are the primary R&D milestones and completion timeframe. The dates shown are subject to change if funding is delayed beyond Q4 2009.

Product Outline Specification	Q3 2009
Functional Requirements Specification	Q4 2009
RF MEMS Technology Fab partner selection	Q3 2009
RF MEMS front end design	Q2 2010
NPU IP core selection	Q3 2009
SDR OEM partner selection for system software integration	Q4 2009
VLSI design and verification	Q2 2010
RF MEMS and NPU integration	Q3 2010
FHP system verification	Q4 2010
Tape Out	Q1 2011
Silicon-level verification	Q2 2011
Initial Samples	Q3 2011
Reference Design Specification	Q4 2009
Reference Design Development	Q1 2010

14.3 Business Case

A full business case should be developed to include a Financial Plan with Sales Projections, Income Projections, Cash Requirements, Sources of Financing, competitive analysis, financing and exit strategies, etc. A preliminary Financial Plan with Sales Projections is shown in Appendix D.

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Appendix A Wireless Communications Technologies

2G

TDMA: One of the original digital standards, TDMA divides call spectrum into different time slots to transmit multiple calls simultaneously. Most TDMA networks in the U.S. have been overlaid with GSM and upgraded to support GPRS and EDGE; some in Latin America, however, remain on the legacy standard.

iDEN: A TDMA-based technology that also supports data, short messaging and dispatch radio (two-way radio). Nextel in the U.S. uses the iDEN standard, though with its acquisition by Sprint, Nextel's subscribers are likely to migrate to CDMA-based technologies.

GSM: A TDMA-based technology that uses SIM cards to identify individual subscribers. GSM is the predominant 2G standard in use throughout Europe, Asia and the Middle East and Africa, though most GSM carriers have added 2.5G GPRS across the network and most handsets are GPRS capable as well. These networks will eventually migrate to W-CDMA/UMTS, and many carriers are well underway with their network upgrades.

PDC: A TDMA-based technology that is widely used in Japan. Most carriers in Japan have already upgraded their PDC networks to W-CDMA and are actively migrating their subscriber bases, skipping the 2.5G node entirely.

CDMA: Pioneered by Qualcomm, CDMA uses a spread spectrum technique to overlap every transmission on the same carrier frequency, assigning a unique code to each signal. This requires fewer cell sites for the same number of calls. 2G CDMA networks (sometimes referred to as "CDMAone") have already moved to 2.5G CDMA2000 1xRTT and are already starting to roll out 3G CDMA2000 1xEV-DO.

2.5G

GPRS: GPRS is an update to GSM that supports data packets. Most GSM carriers are now fully GPRS-capable, with GPRS handset shipments now far outpacing 2G GSM shipments.

EDGE: EDGE is a 2.5G enhancement that increases data throughput to 384 Kbps.

CDMA2000 1xRTT: 2.5G standard that has replaced 2G CDMA, adding enhanced data capabilities and throughput.

3G

W-CDMA/UMTS: 3G standard that is beginning to replace GSM, TDMA and PDC. W-CDMA, as the name implies, brings CDMA technology to the GSM world, and thus, it requires new network hardware in addition to different handsets (whereas GPRS was a mostly a software upgrade in the network). Note that Japanese carriers have already rolled out W-CDMA and are actively migrating their subscriber bases from PDC; carriers in Europe and the U.S. are implementing W-CDMA/UMTS now.

CDMA2000 1xEVDO: 3G CDMA standard that boosts throughput for the data side of the handset. The EVDO build out has accelerated in recent quarters, and EVDO services are now available from carriers in the U.S. and Asia.

CDMA2000 1xEVDV: 3G CDMA standard that boosts throughput for both the voice and data sides of the handset. Qualcomm (and therefore its handset customers) have shelved plans for EVDV chipsets and is instead focusing on EV-DO.

TD-SCDMA: 3G standard being developed from the ground up for China. The Chinese Ministry of Information Industry is spearheading the effort to drive this standard along with Chinese carriers, networking OEMs, and handset vendors.

Appendix B TD-SCDMA Standard

TD-SCDMA (Time Division - Synchronous Code Division Multiple Access), proposed by Datang Telecom Technology and Industry Group on behalf of the Chinese government, was approved by the International Telecommunication Union (ITU) in May 2000, and by 3rd Generation Partnership Project (3GPP) in March 2001 as one of the 3G mobile communications standards.

TD-SCDMA adopts high-edged technologies such as Smart Antenna, Software Radio, Joint Detection, Banton Handover, High-speed Transmission technology for Downlink Packet Data. Compared with other mobile systems, TD-SCDMA boasts outstanding technological benefits:

High Spectrum Efficiency: TD-SCDMA, with the highest spectrum efficiency, better supports dense services in populated areas. It is capable of making full use of fragmented spectrum, and effectively alleviates spectrum resource shortage and limitations at carriers' side.

High Capacity: Adoption of high-edged technologies dramatically lowers interference and increases system capacities.

Highly Suitable for Operators Asymmetrical Data Services: As TD-SCDMA is competent for dynamically adjusting data transmission rates with uplink and downlink, it specially suits to handing asymmetrical IP data services.

Low Costs: Adoption of Smart Antenna technology decreases transmission Power in TD-SCDMA system and dramatically lowers the cost of the system products.

Source: [33]

Appendix C Glossary of Terms

2G: Second generation (Analog) wireless infrastructure

3G: The third generation of wireless networks. These networks should be able to support peak data rates of 144 Kbps at mobile user speeds, 384 Kbps at pedestrian user speeds and 2 Mbps in fixed locations (peak speeds), although some initial deployments were configured to support just 64Kbps. ITU coordinates 3G standards through its IMT-2000 project and incorporates the key standards bodies, 3GPP and 3GPP2.

ADSL: Asymmetrical digital subscriber lines, a method of transmitting data over traditional copper telephone lines. Data can be downloaded at speeds of up to 1.547 Mbps and uploaded at speeds of 128 Kbps.

ASON: Automatic switching optical network, the functions of the control interface of which allow it to develop an optical communication channel customized to users' needs according to their requests on an unmanned basis and support multi-channel development, capacity expansion, configurability and network intelligence development.

CAPEX: Capital expenditures

CDMA: Code division multiple access, one of the standards for 2G mobile communications. It is a spread spectrum technology standard that assigns a pseudo-noise (PN) code to all speech and data bits, sends a scrambled transmission of the encoded speech over the air and reassembles the speech in its original format. By assigning a unique correlating code to each transmitter, several simultaneous conversations can share the same frequency allocations.

CDMA2000: A technical specification for the provision of enhanced capacity for voice under the CDMAOne standard with a maximum data rate of 2Mbps, comprising particular specifications such as 1xRTT (radio transmission technology), 1xEVDO (data only version) and 1xEVDV (voice and data version).

DSP: Digital Signal Processor (or Processing)

DWDM: Dense wavelength division multiplexing, a technology that enables a single optical fiber to carry multiple data channels (or wavelengths). Commercial DWDM systems now exceed 100 channels.

DSL: Digital subscriber lines, the collective name given to a number of techniques used for transmitting digital data over the local loop or subscriber line. These are also known as xDSL. Examples are ADSL, HDSL, VDSL, MDSL and RDSL.

EDGE: Enhanced data for GSM evolution

EVDO: Evolution Data Only

FCC: Federal Communications Commission

FRE: Radio Frequency Front End circuit

GSM: A global system for mobile communications, a digital cellular phone system standard that originated in Europe. It is deployed in more than 170 countries and uses a TDMA radio propagation scheme.

IP: Internet protocol, as more specifically defined in RFC 791, the primary purpose of which is to define packet architecture and address format.

HSDPA: High-Speed Downlink Packet Access. Third-Generation Partnership Project's high-speed downlink packet-access

NGN: Next generation network, a data packet-based network capable of providing a variety of services by using multiple broadband transmission technology to support unlimited access to different service providers and of supporting ordinary mobile communication to provide uninterrupted services to users.

PHS: Personal handy phone system, a digital mobile telephone system using technology developed according to Japanese standards and operating on the 1900Mhz frequency.

SNR: Signal-to-noise ratio

Softswitch: Abbreviation for software switch, softswitch is an application protocol interface which is used to link a traditional PSTN to IP networks and manage traffic containing a mixture of voice, fax, data and video.

TD-SCDMA: Time division synchronous code division multiple access, a 3G technology developed in China to support voice and data transmission.

WCDMA: Wideband CDMA, a UMTS standard for 3G digital mobile networks adopting CDMA technologies to provide enhanced capacity for voice with a theoretical maximum data rate of 3Mbps.

WiMax: Worldwide interoperability for microwave access

WTO: World Trade Organization

Appendix D Preliminary Financial Plan and Sales Projections

This appendix summarizes the rough Sales and Financial Plan estimates for the start-up company explained in section 14.2.1 (A New Venture). The numbers will be to be verified and fine tuned as part of the Future Work recommended in the same referenced section.

D.1 General Assumptions:

- It will take 18 months of start up work before Year 1 Sales start.
- The new venture will be funded with venture capital equity
- The company's addressed market and R&D development is a explained in section 14.2.1.

D.2 Specific Assumptions

The following tables show the specific assumptions related to Years 1, 2, and 3 related to:

- Units (from Fig. 13.4),
- Company's market share projections
- ASP and COGS projections
- Sales projections
- Headcount and Salaries assumptions

Annual Unit Growth % Projections

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA		200%	400%
FHP-CDMA2000		200%	200%
FHP-GSM/GPRS		200%	300%
FHP-4G			500%

Annual Units Projections

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	15,000,000	30,000,000	120,000,000
FHP-CDMA2000	8,000,000	16,000,000	32,000,000
FHP-GSM/GPRS	5,000,000	10,000,000	30,000,000
FHP-4G	-	1,000	5,000
Total	28,000,000	56,001,000	182,005,000

ASP Projections ($)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	$ 20.0	$ 15.0	$ 10.0
FHP-CDMA2000	$ 18.0	$ 13.0	$ 8.0
FHP-GSM/GPRS	$ 15.0	$ 10.0	$ 7.0
FHP-4G	$ -	$ 30.0	$ 25.0

Gross Margin Projections (%)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	50%	40%	30%
FHP-CDMA2000	40%	30%	25%
FHP-GSM/GPRS	30%	25%	20%
FHP-4G		80%	70%

Unit Cost Projections ($)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	$ 10.0	$ 9.0	$ 7.0
FHP-CDMA2000	$ 10.8	$ 9.1	$ 6.0
FHP-GSM/GPRS	$ 10.5	$ 7.5	$ 5.6
FHP-4G	$ -	$ 6.0	$ 7.5

Market Share Projections (%)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	10%	20%	30%
FHP-CDMA2000	15%	25%	30%
FHP-GSM/GPRS	5%	10%	15%
FHP-4G	0%	50%	60%

Market Share Unit Projections

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	1,500,000	6,000,000	36,000,000
FHP-CDMA2000	1,200,000	4,000,000	9,600,000
FHP-GSM/GPRS	250,000	1,000,000	4,500,000
FHP-4G	-	500	3,000
Total	2,950,000	11,000,500	50,103,000

Sales Projections ($K)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	$ 30,000,000	$ 90,000,000	$ 360,000,000
FHP-CDMA2000	$ 21,600,000	$ 52,000,000	$ 76,800,000
FHP-GSM/GPRS	$ 3,750,000	$ 10,000,000	$ 31,500,000
FHP-4G	$ -	$ 15,000	$ 75,000
Total	$ 55,350,000	$ 152,015,000	$ 468,375,000

COGS Projections ($K)

Product Category	Year 1	Year 2	Year 3
FHP-WCDMA	$ 15,000,000	$ 54,000,000	$ 252,000,000
FHP-CDMA2000	$ 12,960,000	$ 36,400,000	$ 57,600,000
FHP-GSM/GPRS	$ 2,625,000	$ 7,500,000	$ 25,200,000
FHP-4G	$ -	$ 3,000	$ 22,500
Total	$ 30,585,000	$ 97,903,000	$ 334,822,500

Average Gross Margin %	45%	36%	29%
Average COGS %	55%	64%	71%

D.3 Financial Tables

Based on above general and specific assumptions, the author used the methodology taught and the Excel software provided by New Venture Creation [35] and produced the following financial tables. Again, these tables are very rough and for illustration purposes. The tables will need to be updated as the New Venture's concept matures and the team founders agree to the numbers together with possible investors.

START-UP FUNDING & EXPENDITURES
Auburn Semiconductor Systems

Assume 18 months of start-up work before the start of Year 1 Sales.

Start-up Cash	$
Equity Investments	6,000,000
Loan Proceeds	-
Real-Estate Loans	-
Total Start-up Cash	6,000,000
Start-up Expenditures	
Security Deposits	
Rent (last month's)	5,000
Telephone Deposit	1,000
Utilities Deposit	1,000
Other Deposits	2,000
Total Security Deposits	9,000
Start-up Expenses	
Accounting Fees	9,000
Activation Fee	-
Corporate Fees & Taxes	-
Federal Tax ID	18,000
Fictitious Name Costs	18,000
Insurance	9,000
Legal & Consulting Fees	9,000
Meals & Entertainment	9,000
Office Supplies	9,000
Payroll Expenses (training/setup)	
Salaries & Wages	3,067,500
Payroll Taxes	920,250
Benefits	613,500
Pre-opening advertising	9,000
Printing (cards, stationery, brochures)	1,800
Sales Tax Permit	1,800
Rent	90,000
Total Start-up Expenses	4,784,850
Other Costs	
Opening Inventory	-
Capital Expenditures	
Computer Equipment	250,000
Equipment/Machinery	-
Furniture & Fixtures	40,000
Vehicles	-
Leasehold Improvements	-
Buildings	-
Land	-
Total Start-up Capital Expenditures	290,000
Total Start-up Expenditures	5,083,850

Auburn Semiconductor Systems
Year-End
Income Statement (Projected)

	2011	2012	2013
Net Sales (less returns & allowances)	54,796,500	150,494,850	463,691,250
Cost of Goods Sold	30,279,150	96,923,970	331,474,275
Gross Income	**$ 24,517,350**	**$ 53,570,880**	**$ 132,216,975**
Operating Expenses			
Advertising	12,000	3,000	3,000
Bad Debt Expense	2,739,825	7,524,743	23,184,563
Bank Charges	300	300	300
Depreciation & Amortization	89,048	89,048	89,048
Dues & Subscriptions	1,200	1,200	1,200
Insurance	21,000	12,000	12,000
Licenses & Fees	37,800	-	-
Marketing & Promotion	61,800	60,000	60,000
Meals & Entertainment	27,000	18,000	18,000
Miscellaneous	-	-	-
Office Expense	1,800	1,800	1,800
Office Supplies	12,600	3,600	3,600
Outside Services	12,000	12,000	12,000
Payroll Expenses			
Salaries & Wages	5,112,500	2,882,000	3,013,000
Payroll Taxes	1,533,750	864,600	903,900
Benefits	1,022,500	576,400	602,600
Professional Fees	18,000	-	-
Property Taxes	-	-	-
Rent	120,000	120,000	120,000
Repairs & Maintenance	12,000	12,000	12,000
Shipping & Delivery	6,000	6,000	6,000
Telephone	36,000	36,000	36,000
Training & Development	-	-	-
Travel	120,000	120,000	120,000
Utilities	24,000	24,000	24,000
Vehicle	12,000	12,000	12,000
Other	-	-	-
Other	-	-	-
Other	90,000	-	-
Total Operating Expenses	**$ 11,123,123**	**$ 12,378,690**	**$ 28,235,010**
Operating Income	**$ 13,394,227**	**$ 41,192,190**	**$ 103,981,965**
Interest Expense	-	-	-
Other Income (interest, royalties, etc.)	-	-	-
Income Before Taxes	**$ 13,394,227**	**$ 41,192,190**	**$ 103,981,965**
Income Taxes (if C Corp)	-	-	-
Net Income	**$ 13,394,227**	**$ 41,192,190**	**$ 103,981,965**

Auburn Semiconductor Systems
Year-End
Balance Sheet (Projected)

	2011	2012	2013
Assets			
Current Assets			
Cash & Equivalents	14,371,782	72,915,235	202,233,459
Accounts Receivable	4,566,375	17,557,733	61,825,500
Inventory	305,850	(38,654,958)	(112,779,674)
Security Deposits	9,000	9,000	9,000
Other Current Assets	-	-	-
Total Current Assets	**$ 19,253,007**	**$ 51,827,009**	**$ 151,288,285**
Fixed Assets			
Property, Plant & Equipment	290,000	290,000	290,000
Less: Accumulated Depreciation	(89,048)	(178,095)	(267,143)
Other Non-Current Assets	-	-	-
Total Non-Current Assets	**$ 200,952**	**$ 111,905**	**$ 22,857**
Total Assets	**$ 19,453,959**	**$ 51,938,914**	**$ 151,311,142**
Liabilities			
Current Liabilities			
Accounts Payable	4,078,000	7,728,422	34,313,275
Line of Credit	-	-	-
Other Current Liabilities	-	-	-
Total Current Liabilities	**$ 4,078,000**	**$ 7,728,422**	**$ 34,313,275**
Long-term Liabilities			
Loans	-	-	-
Mortgages	-	-	-
Other Non-Current Liabilities	-	-	-
Total Non-Current Liabilities	**$ -**	**$ -**	**$ -**
Total Liabilities	**$ 4,078,000**	**$ 7,728,422**	**$ 34,313,275**
Equity			
Equity Investments	6,000,000	6,000,000	6,000,000
Retained Earnings	13,394,227	54,586,417	158,568,382
Less: Owner's & Investor's Draws	(4,018,268)	(16,375,925)	(47,570,515)
Total Equity	**$ 15,375,959**	**$ 44,210,492**	**$ 116,997,868**
Total Liabilities and Equity	**$ 19,453,959**	**$ 51,938,914**	**$ 151,311,142**