WIRELESS SYSTEMS AND TECHNOLOGY OVERVIEW

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Wireless communication systems will be one of the biggest drivers of semiconductor products over the next decade. This paper provides an overview of current developments in this explosive market, looks at future product requirements and relates those needs with technology projections. Three key technologies are discussed: basic semiconductor processes, digital signal processing, and RF systems and circuits.

1. Introduction

The year is 2005. Wireless technology has become so pervasive that kindergarten children are tracked with Global Positioning System (GPS) receivers, businessmen work in virtual offices with high speed wireless connections to anywhere in the world, and telephone numbers are now assigned to individuals and support anytime, anyplace communications using subscriber units that are worn, not carried. Utopia or your worst nightmare—whatever your perspective, this is a future just over the horizon. It follows down a path which began with Hertz and Marconi experimenting with radio transmission through the "ether" in the late 19th century and continues today with an explosion of wireless communications products.

Twenty years ago, few would have predicted the revolution which resulted from the development of the personal computer in the late 1970s. It is hard to imagine, but the wireless revolution is an even more recent phenomenon. The first commercial cellular system was turned on in Chicago in 1983, and as recently as 1988, George Calhoun in *Digital Cellular Radio* talked about the reasons for the failure of cellular technology in the marketplace. The question now is what will take this industry to the next level—to make wireless products as pervasive for consumers as the telephone or the television. The answer is clearly technology—technology to expand functionality and technology to reduce costs. If the last five years has taught us anything—it is that the demand for wireless services is huge. The only thing which seems to be restraining growth is the high cost of using the service. Technology developments that have fueled this revolution and have the potential to move it to the mass market quickly center on four key areas:

1. Semiconductor technology (materials and processes): the drive to smaller, faster, cooler, etc., is certainly led by advances in integrated circuit technology. The question is: what materials and processes will be important in the future and where must this technology go from here?

2. Digital Signal Processing: DSP has been *the* primary enabler for digital communications. Previously, DSP has been driven by the simple need for more throughput. Wireless systems have a different set of needs including tailored instruction sets to provide more efficient MIPS, higher levels of integration and lower power consumption.

3. Linear/RF Electronics: Look inside a cellular telephone today. The parts count and volume are driven by the proliferation of parts in the RF subsystem—particularly its passive components. That must change.

4. System issues: Size and weight are key issues for portable electronics. Our ability to make progress on these issues is determined by system partitioning and component integration. There are also fundamental issues in human factors that may limit progress in this area. How small can a handset get? Technologies such as speech recognition may become important to overcome this limitation. Talk and standby times are another set of key careabouts.

Section 2 of this paper lays a foundation for discussing the future of wireless communications by reviewing the state of the art. It discusses the various categories of current wireless systems including systems supporting both voice and data applications. It also discusses the coming evolution of Personal Communications Services (PCS). Section 3 examines some of the key "careabouts" of the wireless industry and Section 4 reviews the technological basis for this industry and how some key technologies will both inhibit and enable future progress. Finally, given our technology projections, in Section 5 we will look into a crystal ball and try to imagine the world of 2005.

2. Wireless Systems Today

One way to look at wireless voice and data communication systems is by using categories which people generally just apply to data—distinguishing between local- and wide-area applications (See Table 1).

Wide-area systems are targeted at highly mobile users. The key careabout is the ability to access information anywhere at any time. It is particularly important that the system operate in high speed vehicles as well as while the user is on foot on the street or even in buildings such as airports, office towers, or shopping malls. Both analog and digital cellular systems fall into this category. Wide-area data applications are characterized by short, bursty traffic such as that required for messaging. Most digital cellular standards support wide-area data traffic using either circuit-switched or packet-switched protocols. Paging systems are another wide-area data service, and there are also a few dedicated wide-area packet networks, including ARDIS (developed by IBM and Motorola) and Mobitex (from Ericsson). The Cellular Digital Packet Data system (CDPD) supports a wide-area data capability using the AMPS analog cellular infrastructure. Finally, satellite-based networks constitute the ultimate wide-area systems and can serve both voice and data applications.

Local-area systems target an entirely different audience. In this case, the application is really a replacement for the local wireline network and the need for wireless is one of convenience. High-speed mobility is not a requirement, but support for handoffs at pedestrian speeds is desirable. Local-area systems must compete directly with their wireline counterparts in terms of features (such as call waiting and forwarding or data transfer speeds) and communications quality. Although local traffic may also be short and bursty, local data systems have much more of a need for high-speed, large-block transfers. Local-area systems include both voice-based analog and digital cordless systems, as well as data systems like wireless LANs.

It is no accident that the term *Personal Communications Services* (PCS) has been omitted from the previous discussion. Most articles in the popular press speak of PCS as if it were something unique. It is not. PCS will use the same set of technologies and will have no special cost advantages over any of the other systems that have already been discussed. There are as many different definitions of PCS as there are media and industry pundits. Just like the blind men's description of an elephant, it's all a matter of perspective. Cellular service providers argue that they are already providing personal communications services and that the recent spectrum auctions simply gave them a few extra MHz to expand their capacity and improve their geographic coverage. Others argue that PCS refers to an evolution of cordless telephones to allow anytime, anywhere communications. Some people would say that PCS simply refers to that set of services which will be supported in the recently auctioned 2-GHz band.

Early in 1994, auctions were held for narrowband PCS services (two-way paging, messaging or other low-data-rate applications). Early in 1995, the FCC completed the process of auctioning the first two 30-MHz bands of radio spectrum to support broadband PCS services (primarily voice and higher-rate data services). Table 2 and Table 3 give an overview of these PCS licenses [10].

Voice services will dominate the A and B wideband 30-Mhz PCS licenses that have been issued to cover the 51 Major Trading Areas (roughly equivalent to state-sized areas), as well as the C band 30-MHz PCS license for the 492 Basic Trading Areas. However, applications for the remaining PCS licenses (D-F), as well as the unlicensed PCS frequencies, will most likely represent a variety of disparate services ranging from standard wireless telephony (including both cellular and cordless applications), wide-area and local data services for portable computers and PDAs, paging services, and niche applications such as location finders, targeted information appliances, or biometric telemetry.

Wireless communications systems are very standards driven—largely because the manufacturer who builds infrastructure may not be the same one who delivers subscriber units. Standards can evolve from an international effort to standardize a communications infrastructure (such as GSM-ETSI), an industry consortium that is driven by mutual self-interest to develop standards (IS-54/136 or IS-95-TIA), or a *de facto* standard that is driven by one or a small number of companies (CDPD-McCaw, IBM, etc.). Table 4 summarizes some of the formal standards organizations that are driving the wireless industry.

Much of the standardization and regulation controlling these applications stems from the fact that the radio spectrum itself is highly regulated. Figure 1 provides another wireless systems taxonomy based on the usage of radio spectrum. This is by no means an exhaustive list of allocations, but it does serve to provide a flavor of the complexity of the problem, along with a general sense of the frequency bands that are associated with some of the services discussed in the rest of this paper.

	Wide Area (High Mobility)	**Local Area (Low Mobility)**
Voice Communications	Cellular telephones Satellite systems	Cordless telephones Wireless Local Loop systems Wireless PBXs
Data Communications	Cellular telephones Specialized packet data systems (RAM, ARDIS, CDPD) Satellite systems	Wireless LANs

Table 1. Categorizing Voice/Data Communications

	Number Available	License Area
50-kHz/50-kHz	5	Nationwide
50-kHz/12.5-kHz	3	Nationwide
50-kHz unpaired	3	Nationwide
50-kHz/50-kHz	2	Regional
50-kHz/12.5-kHz	4	Regional
50-kHz/50-kHz	2	Major Trading Area
50-kHz/12.5-kHz	3	Major Trading Area
50-kHz unpaired	2	Major Trading Area
50-kHz/12.5-kHz	2	Basic Trading Area

Licenses awarded in three 1-MHz bands: 901 to 902 MHz, 930 to 931 MHz, 940 to 941 MHz

Table 2. Narrowband PCS Licenses [10]

Frequency Block	Bandwidth	License Area	Frequency Range (MHz)
A	30 MHz	Major Trading Area	1850–1865 / 1930–1945
B	30 MHz	Major Trading Area	1870–1885 / 1950–1965
C	30 MHz	Basic Trading Area	1895–1910 / 1975–1990
Unlicensed	20 MHz	Nationwide	1910–1930
D	10 MHz	Basic Trading Area	1865–1870 / 1945–1950
E	10 MHz	Basic Trading Area	1885–1890 / 1965–1970
F	10 MHz	Basic Trading Area	1890–1895 / 1970–1975

Table 3. Wideband PCS Licenses [10]

Market Area	Standards Org	Technology	Standard
United States	Telecommunications Industry Association (TIA)	Cellular	• IS-54B; IS-136 • IS-95
United States	Joint Technical Committee (JTC) of Committee T1 and the TIA	PCS	• Omnipoint hybrid CDMAl/TDMA • IS-95 • PACS • IS-136 • PCS1900 • Wideband CDMA • DECT
Europe	European Telecommunications Standards Institute (ETSI)	Cellular PCS	• GSM • DCS1800
Japan	Research and Development Center for Radio Communications (RCR)	Cellular PCS	• PDC • PHS

Table 4. Cellular/PCS Standards Organizations [5]

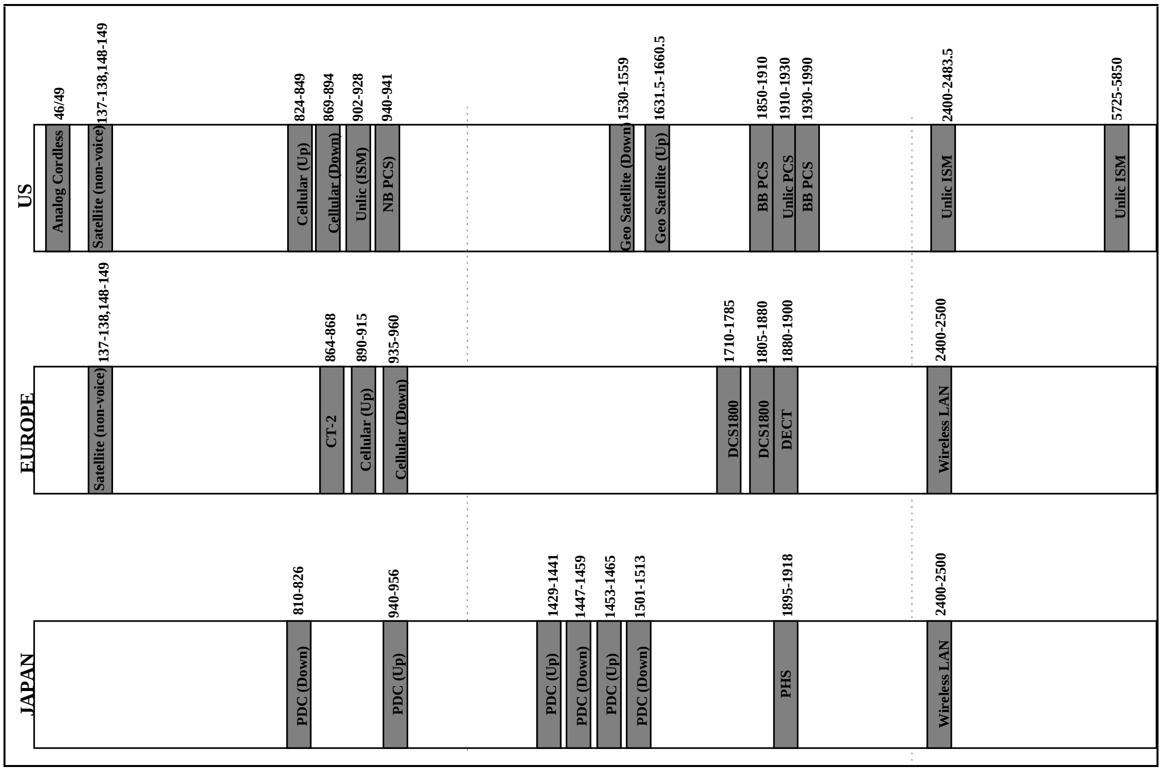


Figure 1. Worldwide Spectrum Allocations for Wireless Communications [6,10,11,15,23]

2.1 Wireless Voice

Cordless telephones and cellular telephones represent two classes of wireless voice systems. Although they share some striking similarities, the user requirements that drive design tradeoffs and technology choices can be diametrically opposed.

Cordless systems were invented to satisfy a need for tetherless communications in the home. Until recently, analog systems have dominated the market and continue to do so in the United States. These systems are usually based on proprietary air interfaces since the manufacturer owns both ends of the wireless link. They also tend to be larger and bulkier than their more complex cellular cousins since one doesn’t usually carry the handset around the house except when receiving or making a call. Recently, however, digital technologies have extended the concept of cordless to cover any low-mobility, pedestrian application in both private and public areas such as shopping malls and airports (this is especially true in Japan and Europe). These environments require standards since the infrastructure vendor may no longer have a monopoly on subscriber instruments.

Thus, while designers of home-based systems typically haven’t been terribly motivated to push the size/weight envelope, they will be for future low-mobility PCS systems. Because cell sizes in these applications will be on the order of a few tens or hundreds of meters, high cell capacities and high transmit powers are not a requirement. In fact, low transmit powers are an advantage, since they allow reuse of a frequency channel a short distance away. Battery life is a key issue for these systems. Remember that cordless systems are used in locations where there is generally a wireline alternative. Consequently they must compete directly in terms of service quality and convenience. Consumers will not stand for an instrument that requires frequent care and feeding. Standby and talk times must be measured in weeks and days—rather than hours and minutes. Voice quality must be comparable to what is easily obtainable in the instrument on the desk or the pay phone on the wall.

Cellular systems are very different. A key requirement is high mobility and the ability to hand off from one cell to the next while traveling in a high-speed vehicle. Coverage, spectral efficiency and system user capacity are additional keys. Consequently, cellular systems are driven to use complex modulation techniques to make more efficient use of available spectrum. They are forced to rely on voice coding and complex error correction techniques to reduce the number of bits required to reliably represent and transmit voice. Transmitter powers are measured in hundreds of milliwatts and even watts. Table 5 compares the key requirements driving cellular and cordless telephone designs.

Don Cox of Stanford, and formerly from Bell Labs and Bellcore, argues that system requirements naturally divide the market place into high-mobility (high-power cellular) and low-mobility systems (low-power cordless). He asserts that cellular systems are driven to emphasize system capacity and high-speed mobility. This drives equipment designers to build infrastructure and handsets using high-power transmitters and complex signal processing to increase spectrum efficiency. The result is a relatively high-cost instrument exhibiting marginal communication quality (because of the use of low-bit-rate vocoding) and using large, bulky batteries. Low-mobility systems, on the other hand, tend to try to minimize complexity and cost and maximize service quality. This leads to some diametrically opposed design choices. Cox’s conclusion is that everyone will carry one phone in their pocket and use a vehicle-mounted higher power instrument in their car. There is no single instrument which will suffice for all PCS applications [6].

While Cox’s conclusions may be valid in today’s technology environment, it is not clear that the marketplace will accept them. Moreover, as time and technology move on, the differences between the two classes of instruments will become less and less significant. The cost of digital signal processing is falling dramatically (See Table 6.), performance of the latest generation of moderate-bit-rate speech coders exhibit MOS scores which approach those of 32-kbps adaptive pulse-code modulation (ADPCM), and talk and standby times for cellular telephones are getting better and better as handset power supplies move down the voltage curve and systems/standards designers are producing more and more power-efficient systems. Ultimately, a user will be able to buy a single telephone instrument that can be used anywhere, anytime and will not force any significant compromise on service quality or battery life.

Feature	Cordless	Cellular	Comments
User Mobility	Pedestrian (low to no handoff requirement)	High Speed Vehicles; handoff required; GSM specs requirement up to 250 km/hr	Key parameter is allowable handoff speed.
Speech Coding	Low complexity: 32-Kbps ADPCM	Hi complexity: 3–13 Kbps	Quality versus bit rate tradeoff. Key issues are robustness in noise, algorithm latency (see System Latency), and tandem operation; importance of tandem operation will increase as mobile-to-mobile calls increase.
Transmit Power	10–250 mW	600–3000 mW	Cellular handsets incorporate complex power control to provide uniform reception at base stations across large cells.
Cell Size (radius) Cost (Cell site)	10–1000 m $3K	1000–50000 m $200K–$1M	Trade capacity versus coverage. Reduced cell size also reduces needed signal processing to combat effects of delay spread.
Access Technology	FDMA FDMA/ TDMA	FDMA FDMA/ TDMA FDMA/ CDMA	Cellular systems utilize more complex multiple access techniques to maximize capacity.
Duplex Technology	TDD	FDD	FDD required allocation of two frequency bands. Synchronization required for TDD not easy for large cellular network.
System Latency	<10 ms	~200 ms round trip	Large round trip delay in cellular caused by complex vocoder algorithms; echo cancellation required for >10 ms

Table 5. Cordless versus Cellular Feature Comparision [6]

Parameter	Typical 1982 DSP	Typical 2002 DSP	Improvement
Min chip dimension	3 μ	0.25 μ	12X
Transistors	50 K	5 M	100X
MIPS	5	500	100X
Clock	20 MHz	200 MHz	100X
Power	50 ma/MIP	0.1 ma/MIP	500X
Cost	$150	$1.50	100X

Table 6. Two Decades of DSP Evolution [8]

2.1.1 Digital Cordless Telephones [6,7,11-13,15]

Three major digital cordless telephone technologies are being promoted in different parts of the world. The Digital European Cordless Telephone (DECT) specification is the standard that has been adopted by the European community. The Personal Handi System (PHS) is being rolled out in Japan, and the Personal Access Communications System (PACS) is being promoted as a low-tier PCS standard in the U.S. (See Table 7).

The primary goal for these cordless standards is to supply service that maximizes service quality (minimizing voice distortion and delay) and handset battery life/talk and standby times while minimizing service costs. To accomplish these goals, cordless standards are forced to trade off system capacity and user mobility. It is interesting to compare the spectrum and bandwidth efficiency figures in Tables 7 and 8. Cordless systems exhibit spectrum efficiency numbers ranging from 0.67 to 1.28 bits/Hz, while the cellular figures are 1.36 bits/Hz to 1.68 bits/Hz. Even more telling is the effective bandwidth required to implement a single full duplex conversation. Cordless systems range from 75 to 144 kHz, while the equivalent figures for cellular are 16.7 to 50 kHz. Generally, cordless systems will utilize a very simple voice coder such as ADPCM to maximize voice quality, while at the same time minimizing the DSP power required to deliver service. Because ADPCM does not require the look-ahead processing that is inherant in more complex vocoder algorithms, system round trip delays are reduced and echo cancellation is not required. Another result of not requiring maximum voice compression and of restricting user mobility is the fact that cordless systems can avoid the use of complex error correction and bit interleaving schemes. These systems tend to rely on error detection and retransmission techniques. In addition, they will generally not require adaptive equalization or wide-area system synchronization.

DECT was originally developed and optimized for indoor applications such as wireless PBXs. Consequently, multicell business environments and data applications were a key consideration. This accounts for DECT’s high channel data rate and provision for the use of multiple time slots by a single user for high-rate data transfers. On the other hand, because of this high data rate, DECT systems are especially vulnerable to frequency selective fading and provision must be made for antenna diversity or the use of equalization.

PHS and PACS, on the other hand, seem to be targeted more at hybrid appliations for home/public cordless telephony. Generally, all three systems utilize dynamic channel allocation where the handset is responsible for finding a free channel and for handling any handoff when communications deteriorate.

PACS is a likely candidate for low-mobility PCS applications in the U.S. During the PCS standardization process, PACS evolved as a compromise between the characteristics of PHS and the WACS standard being promoted by Bellcore. PACS is a cordless standard which seems to be a cellular wannabe, since it retains some of the characteristics of the more complex cellular standards. For example, it uses frequency division duplexing rather than the time division duplexing used by PHS and DECT. In addition, PACS employs coherent detection to provide substantially better performance than the discriminator-based approaches employed by other cordless standards. As a result, PACS promises to support somewhat greater mobility than either DECT or PHS.

Feature	DECT	PHS	PACS
Frequency Band	1880–1900 MHz	1895–1918 MHz	1850–1910, 1930–1990 MHz
Carrier Spacing	1728 kHz	300 kHz	300 kHz
Access Method	FDMA/TDMA	FDMA/TDMA	FDMA/TDMA
Duplexing	TDD	TDD	FDD
Time Slots/Frame	12	4	8
Spectrum Efficiency (Bits/Hz)	0.67	1.28	1.28
BW/duplex channel (kHz)	144	75	75
Frame Duration	10 ms (both directions)	5 ms	2.5 ms
Channel Data Rate	1152 kbps	384 kbps	384 kbps
Modulation	GFSK (BT=0.5)	π/4 DQPSK	π/4 DQPSK
Speech Coder	32 kbps ADPCM	32 kbps ADPCM	32 kbps ADPCM
Handoff	Yes—pedestrian	Yes—pedestrian	Yes (handset controlled); <= 50 km/hr
Handset TX Power (average/peak)	10/250 mW	10/80 mW	25/200 mW

Table 7. Digital Cordless Telephone Standards

2.1.2 Digital Cellular Telephones [6,7,11,12,15,24,25]

There are four major digital cellular standards. Three of these use TDMA technology and have already been widely deployed. These include IS-54B (and its successor, IS-136) in the U.S., GSM in Europe and a number of countries around the world, and PDC in Japan. The fourth standard is IS-95 in the U.S. IS-95 is a CDMA standard that is still undergoing service trials in the U.S. Both GSM and PDC are all-digital standards, while IS-54B (and its IS-136 successor) and IS-95 are dual-mode systems that incorporate provisions to allow operation with both digital and analog base stations (See Table 8).

The standard answer to the question of “Why digital cellular?” is capacity. In the late 1980s the industry projected that in heavy use areas, analog cellular systems would begin to run out of capacity. In fact, what actually happened was that cellular calling patterns gradually changed (average call durations dropped) and the industry was able to reconfigure their infrastructure through the use of techniques such as sectorized antennas. Consequently, the urgency of the capacity issue has faded (the jury is still out on what will happen to calling patterns if and when air time costs begin to fall). The real motivation today is cost. The service provider is highly motivated to shift to digital because the cost of supporting a digital user is a small fraction of the cost of supporting the same user on an analog system. For IS-54B/136 that fraction is roughly 1/3. However, unless the carrier passes on those cost savings, the end user is not so motivated. Moreover, because of the quality of the current generation of speech vocoders, the promise of increased service quality has, to date, proved to be an illusion. The user's motivation could come through enhanced security (through the use of digital data encryption) and a wider range of services (such as short message services, which will effectively provide embedded alphanumeric paging capabilities).

It is interesting to compare the evolution of digital cellular systems in various parts of the world. Europe grew from a heritage of several incompatible national analog cellular standards. Consequently, Europe was highly motivated to move to a single digital standard to facilitate international roaming. The United States, on the other hand, already had a single, highly successful analog standard. AMPS users could easily roam and receive high-quality cellular service anywhere in the United States. There was little motivation to move to digital. Japan had a slightly different situation. Regulation and high costs limited the expansion of both digital and analog cellular service. As soon as the industry was deregulated in 1994, cellular service growth exploded. Now Japan has a capacity problem and the Japanese government has mandated a transition to digital. The situation today is that the European GSM standard is the most advanced and has been adopted by a number of countries around the world. The U.S. market is still confused. The TDMA technology of IS-54/136 is beginning to take off in the U.S., Canada, and some other countries—particularly in Israel and Latin America, but has been hampered by perceptions of poor service quality and by confusion over the TDMA/CDMA debate. PDC in Japan is growing rapidly, but is likely to remain a strictly Japanese national standard.

The three TDMA standards are very similar in their characteristics. IS-54/136 and PDC use a three-slot TDMA structure, while GSM has eight slots. GSM uses a substantially larger carrier bandwidth of 200 kHz, versus 30 kHz for IS-54/136 and 25 kHz for PDC. This makes GSM less susceptible to frequency-selective fading. PDC handsets employ antenna diversity to combat this issue. The GSM standard has provision to allow GSM handsets to hop the carrier frequency at the frame rate, further enhancing their resistance to fading. However, GSM’s shorter bit times make delay spread more of a problem—consequently, adaptive equalization is much more important. PDC does not even require an equalizer, and that requirement for IS-54/136 continues to be debated. Both IS-54/136 and PDC use derivatives of VSELP, a relatively modern voice coding algorithm compared to the RPE-LTP algorithm used by GSM, but because GSM allocates 13 kbps to the voice bit stream (versus 8 kbps for IS-54/136 and 6.7 kbps for PDC), the voice quality of GSM systems is relatively good. Both IS-54/136 and GSM are currently pursuing enhanced performance vocoders to combat user perceptions of poor service quality. All three of these standards include provisions for 1/2-rate vocoders that effectively double user capacity. Both GSM and PDC have already selected vocoders to support this capability, while IS-54/136 has delayed this move since no 1/2-rate vocoder candidate has been able to pass its quality metrics.

IS-95 is a completely different standard based on a narrowband spread spectrum technology developed by Qualcomm. IS-95 boasts a number of technical advantages over the three TDMA systems. Because of its use of a 1.25-MHz channel bandwidth, it is inherantly resistant to the effects of frequency selective fading. Multiple users within the same frequency channel are separated through the use of digital codes (thus the term Code Division Multiple Access). Users with different codes simply appear as white noise. This noise level gradually increases as the number of users on a specific channel increases. System design must limit that number to a level that allows users to communicate with a sufficiently small bit error rate. IS-95 trades the time synchronization complexity inherent in TDMA systems with power control complexity. Since multiple users operate on the same frequency channel, a mobile unit that transmits at too high a power level can drown out the transmissions of other mobiles. Consequently, the system must constantly work to maintain the same received power at the base station from all mobiles. This requires the mobile to incorporate sophisticated power control algorithms and to maintain closed loop power control with the base. A potential advantage for IS-95 is the fact that system handoffs in which a user stays in the same frequency band can occur without any break in communications like that required for either analog or TDMA digital systems, which must change frequencies for any handoff. This capability has been termed “soft handoff” by CDMA proponents. The downside of “soft handoffs” is the extra base station capcity required. The key attraction for CDMA is its potential capacity advantage over other air interfaces. Early theoretical estimates from Qualcomm proposed a potential 20:1 capacity advantage over AMPS, but recent field trials indicate that advantage will likely be closer to 6:1—-roughly in the same ballpark as the TDMA systems described above.

Feature	**IS-54/136**	**IS-95**	**GSM**	**PDC**
System Type	Dual-Mode (IS-136 can be implemented as all digital)	Dual-Mode (can be implemented as all digital)	All Digital	All Digital
Frequency Band (MHz) Forward/Reverse:	869-894 / 824-849	869-894 / 824-849	935-960 / 890-915	940-956 / 810-826 1447-1459 / 1429-1441 1501-1513 / 1453-1465
Carrier Spacing (kHz)	30	1250	200	25
Access Method	TDMA/FDMA	CDMA/FDMA	TDMA/FDMA	TDMA/FDMA
Duplexing	FDD	FDD	FDD	FDD
Time Slots/Frame	3	—	8	3
Spectrum Efficiency (Bits/Hz)	1.62	1.47 64 channels/1.25 MHz	1.36	1.68
BW/duplex channel (kHz)	20	19.5	50	16.7
Capacity (versus AMPS)	3X (full-rate) 6X (half-rate)	6X10X	2.1X (full-rate) 4.2X (half-rate)	3.6X (full-rate) 7.2X (half-rate)
Frame/slot/baud Duration (ms)	40 6.67 41 μs	20	4.6 0.577 3.7 μs	20 6.67 ?
Channel Data Rate (kbps)	48.6	28.8 per user	272	42
Modulation	π/4 DQPSK	BPSK/ODQPSK	GMSK	π/4 DQPSK
Speech Coder	VSELP (1)	QCELP (1)	RPE-LTP (2)	J-VSELP (3)
Speech Data Rate	7.95 kbps	800-8.55 kbps	13 kbps	6.7 kbps
Handset Tx Power (peak/average)	600mW/200mW	600mW/100mW	1000mW/125mW	
Freq Reuse	7	1	3–4	7

Table 8. Cellular Telephone Standards

(1) Enhanced performance full-rate vocoders in development. IS-136 will use G.729 standardized by the ITU. IS-95 considered several variable rate coders from 8 to 13 kbps.
(2) Enhanced performance full-rate vocoder in development; half-rate vocoder selected and will be deployed.
(3) Half-rate vocoder (PSI-CELP) selected and will be deployed.

2.1.3 Personal Communications Systems (PCS)

The definition of PCS depends on your geographical orientation. In Europe PCS generally means either DCS1800 for outdoor service or DECT for indoor installations. One interesting trend is the development of dual-mode handsets that support both standards. Japan seems to be focused on PHS for both home use and public pedestrian applications. The United States has really muddied the waters in PCS. The JTC has completed work on four different PCS air interface standards and three others are likely to follow. These standards will ultimately support a wide variety of services under the PCS label. Table 9 summarizes world-wide PCS standards.

Region	PCS Standards	Comments
Europe	DCS1800 DECT	• Upbanded GSM • Focused on indoor applications Expect to see dual-mode DCS/DECT handsets.
United States	• IS-136 • IS-95 • PCS1900 • PACS • Hybrid spread spectrum/ TDMA • Broadband CDMA • DECT	• Upbanded U.S. TDMA cellular • Upbanded U.S. CDMA cellular • US version of DCS1800 with different vocoder Expect to see all of above combined with AMPS in multi-mode phones to provide national roaming. • Cordless standard (merger of PHS/WACS from Bellcore) • From Omnipoint • Standard not final • Standard not final
Japan	PHS	Cordless standard with limited mobility/coverage

Table 9. PCS Standards

2.2 Wireless Data

The evolution of wireless data networks has taken two different paths. Some solutions have chosen to rely on existing infrastructure such as that provided by analog cellular networks. Simple cellular modems or the CDPD standard are examples of these systems. Cellular modems use the channel just like a normal cellular call. CDPD systems are designed to dynamically use idle channels in an existing AMPS network. Digital cellular systems will also support data applications as one of their standard service offerings. Unfortunately, digital wireless systems—whether they be cellular or cordless—have been slow to roll out any data capability. This has lead to the creation of a number of proprietary data solutions for both local- and wide-area applications.

2.2.1 Local-Area Networks [15-17]

In local-area networks, product vendors can generally control the equipment at both ends of the wireless link. This has led to the creation of a number of proprietary products. Most of these products have air interfaces that use low-power RF spread spectrum technology operating in the unlicensed ISM bands though there are some products which use licensed spectrum at 18 to 19 GHz.

There are three major standardization activities underway. In the United States, IEEE 802.11 and WINFORUM are both pursuing wireless LAN standards. IEEE 802.11 supports both direct-sequence and frequency-hopped spread spectrum technology for both peer-to-peer and centralized systems. Data rates of 1 and 2 Mbps are defined. WINFORUM is an industry consortium originally started by Apple. Its focus is the creation of rules for spectrum etiquette that will provide fair access to unlicensed spectrum in order to allow disparate PCS applications to coexist. ETSI in Europe is developing standards for wireless LANs operating in the 5.12 to 5.30 GHz and 17.1 to 17.3 GHz bands. This activity has been named HYPERLAN. They are chartered to develop a complete standard including modulation type, channel access technique and coding, and LAN protocols.

2.2.2 Wide-Area Networks [17]

Data networks come in two different flavors—circuit- and packet-switched. In circuit-switched applications, the user establishes an end-to-end connection and then proceeds to transfer data. The user pays based on the length of time the circuit is dedicated to his application—whether or not data is actually being transferred. A packet-switched system, on the other hand, simply provides an information channel that is shared by a number of users. No dedicated resource is provided, and each user is only charged for the amount of data transferred. Table 10 compares a number of the available wide-area packet data systems.

Feature	ARDIS	RAM	CDPD	Digital Cellular
Infrastructure	Proprietary	Proprietary	AMPS	IS-136, GSM, or PDC
Coverage	400 cities in US	216 cities in US Also Europe	Same as AMPS	Same as digital standards
Packet Size	256 B	512 B		Specified by application outside of cellular standard
Access Technique	DSMA	Slotted Aloha	DSMA	Specified by application outside of cellular standard
Frequency (MHz)	800	896–901 (Reverse) 935–940 (Forward)	Same as AMPS	Same as digital standards
Data Rates	19.2 kbps	8 kbps	19.2 kbps	9.6 kbps

Table 10. Wide-Area Packet Data Systems

2.3 Paging Systems [6]

Paging Systems represent a system category somewhat like analog cellular, whose demise has been predicted for some time yet it continues to prosper and grow. Paging systems can be defined as one-way, wide-area messaging networks. They have grown from a simple one-bit communication mechanism (you have a call) to include more sophisticated alphanumeric and, soon, voice messaging capabilities. They are based on asymmetric radio links that allow the use of very high-power transmitters and very low-cost, long-battery-life receivers. This combination allows the ubiquitous use of pagers anywhere—in both indoor and outdoor situations. [6]

The recent auctions for narrowband PCS spectrum (See Table 2) indicated the continuing enthusiasm and growth potential for this communications category. However, it is difficult to classify the coming generation of narrowband PCS systems as pagers. Note that most of the licenses include paired, bidirectional channels—support for so-called two-way pagers. This will open the way for a host of new data applications. One could imagine the use of this spectrum for telemetry to control vending machines or monitor biometric sensors. This may put this new generation of paging systems in direct competition with some of the other wireless data networks which have already been discussed. For example, one of the applications of CDPD is for vending machines to alert the network when their stock is running low. Digital cellular telephones will also support low-end data services embedded in the handset. In the digital cellular world these services are called Short Message Services. IS-136, for example, includes the capability to support alphanumeric messages of up to 256 characters.

2.4 Satellite Systems [23]

Despite the ubiquity of cellular systems in the United States, Europe, and Japan, there are large expanses of both the developed and developing nations of the world that are not covered by any kind of mobile telephone or data service. Satellites promise to fill that void. Traditional satellite communications have been based on geosynchronous satellites (GEOS) operating at an altitude of 35,786 km. A system based on this technique requires only three satellites to provide global coverage. However, this fixed-altitude system results in three basic problems for mobile voice communications:

1. The biggest problem is latency. A voice conversation over a GEOS will experience a one way latency of about 240 ms. When you add the return delay and other delays inherent in any communications system, the total lag can approach 600 ms. This is almost unusable for a normal telephone conversation. Such latency also restricts the use of selective retransmission to correct data errors.

2. Because of the fixed orbit of a GEOS, both the southern and northern polar regions above about 75° latitude will not have coverage.

3. Line-of-sight elevation angles above about 40° are required for consistent coverage. This means that coverage will be limited in urban and mountainous areas. This may also be a problem for other types of satellite systems.

Examples of GEOS-based mobile communications systems include London-based INMARSAT-M and the American Mobile Satellite Corporation (AMSC). The former supports mobile voice communications for both maritime and land mobile users. AMSC operates a GEOS system to provide communications to the United States, Canada, and the Caribbean.

Low-earth-orbit satellites (LEOS) use networks of satellites to provide communications with little latency and better coverage than their GEOS cousins. These advantages are gained by trading off the cost and complexity of running a multiple satellite network and of handling handoffs from one satellite to another as the satellites move across the sky and as users move from one satellite beam to another. LEOS systems are generally classified as either little or big. Little LEOS, generally physically smaller and less complex, are designed to provide narrowband data services. The big LEOS systems on the other hand are designed to have sufficent power and bandwidth to support high quality voice and higher bandwidth data services. The best known example of the latter type is the Iridium system. Table 11 contrasts systems from each category.

Feature	AMSC	ORBCOM	IRIDIUM
Schedule	Operating	1995	1998
System Type	GEOS	Little LEOS	Big LEOS
Number of Satellites	1 (+1 redundant satellite for backup)	2 in 4/95; all 36 launched by mid-1997	66
Satellite Altitude	35786 km	970 km	780 km
Coverage	U.S., Canada, Caribbean	U.S.	Global
Operating Freq (MHz):			
Up: mobiles	1631.5–1660.5	148-149	1616–1626.5 TDD
Down: mobiles	1530–1559	137-138	1616–1626.5 TDD
Up: ground stations	13000		29100–29300
Down: ground stations	11000		19400–19600
Sat to Sat			23180–23380
Services	Voice, data, fax	Non-voice, two-way messaging; positioning	Voice, data, fax, paging, RDSS

Table 11. Satellite System Examples

3. System-Level Careabouts and Issues

Figure 2 is a high-level generic block diagram of a cellular handset. It shows a typical functional and cost breakout for each of the four major subassemblies in the telephone: the package, baseband electronics, RF electronics, and the battery and associated power supply electronics.

3.1 Design Drivers

We will use this diagram to discuss the functions found in a typical handset and the design choices behind its construction. These choices are driven by three major criteria: cost, power and weight, and system performance.

3.1.1 Cost

Different market segments in the wireless industry tend to approach the cost equation differently. Cordless systems, for example, have generally been quite affordable for the average consumer. The model in this industry is to have the consumer purchase both a handset and base station and bear the burden of that total cost. Since users of most cordless systems are not charged for their air time, this makes sense, but it is likely that future cordless applications will incur air time charges when the phone is used outside of the home area. This may change the business model.

The cellular industry has an entirely different approach—they expect to make money on air time charges in order to recoup the cost of the handset, which is widely subsidized by the carrier. Subsidies vary depending on location, but amounts ranging from $200-$300 are common. The battle in the future will consist of the service providers competing by lowering air time charges while trying to wean the public from these expensive subsidies. Whatever happens, cost pressure on component and subsystem vendors will be sure to rise dramatically. Currently, the rate of cost erosion in this industry is about 20% per year (See Figure 3).

Figure 2 shows that the semiconductor content of a cellular phone consumes about 50% of the total cost. Of that 50%, 60% is used to implement the baseband function of the telephone and 40% for the RF components. The typical cost (to the service provider) of a digital phone in 1995 was about $400. If we assume a 50% markup, this leaves about $200 in cost or $100 in semiconductor content, $60 of which is used for baseband components (including the power supply) and $40 for the RF components (including all the passive and filters as well as the active elements).

3.1.2 Power and Weight

Since the weight of a wireless handset is dominated by the battery, these two factors reduce to a single careabout: power.

Today, the bulk of the power consumption in a cellular terminal is in the power amplifier in the radio. However, as we move toward an era of micro and pico cells, transmit power will drop dramatically from the current 1-watt area to perhaps a few tens of milliwatts. When that happens, the major power driver will become the DSP.

One of the most straightforward techniques for reducing power is to lower the voltage. The phones you can buy today generally operate at 5 V. Phones that are on the drawing board typically use 3 V. Sub-2-V systems are on the horizon. Since power varies as the square of voltage, this represents a dramatic reduction in power consumption. This trend results in two issues for component vendors:

1. Maintaining digital performance at lower voltages. We have an increasing need for DSP MIPS. Today's 5-V DSPs running at 40 MIPS will have to operate at less than 1/2 that voltage while increasing performance to more than 2X current rates.

2. Maintaining dynamic range and thus the ability to operate in poor RF conditions using analog circuits operating at historically low voltages. This may be the toughest issue and it is conceivable that RF components will lag digital parts in their ability to use much lower voltages. Expect to see phones that require multiple voltages: very low levels for the digital subsystems and somewhat higher voltages for baseband analog and RF sections to maintain adequate performance.

There are several other obvious techniques for reducing power consumption. At the system level, one should make partitioning choices so that as much circuitry as possible can be turned off when it is not needed. In addition, functions should be allocated where they can be executed with the minimum power. For example, tradeoffs can be made between functions executed by the MCU or by the DSP, or between the DSP and hardware data paths. Clock rates throughout the system should be minimized. Even the design of software can affect power consumption. Finally, at the component level, processor architectures, transistor designs and semiconductor processes all play into the power equation.

3.1.3 System performance

It is a given that any handset must at least meet the standard for which it was designed and interoperate with a variety of wireless infrastructures. Product differentiation will be on the basis of exceeding the standard in areas which matter to the consumer—areas such as voice quality, handoff reliability, or perhaps even the availability of features such as short message service. Flexibility will also become a big differentiator. Expect to see phones that can provide better coverage by supporting multiple standards or by accommodating multiple frequency bands.

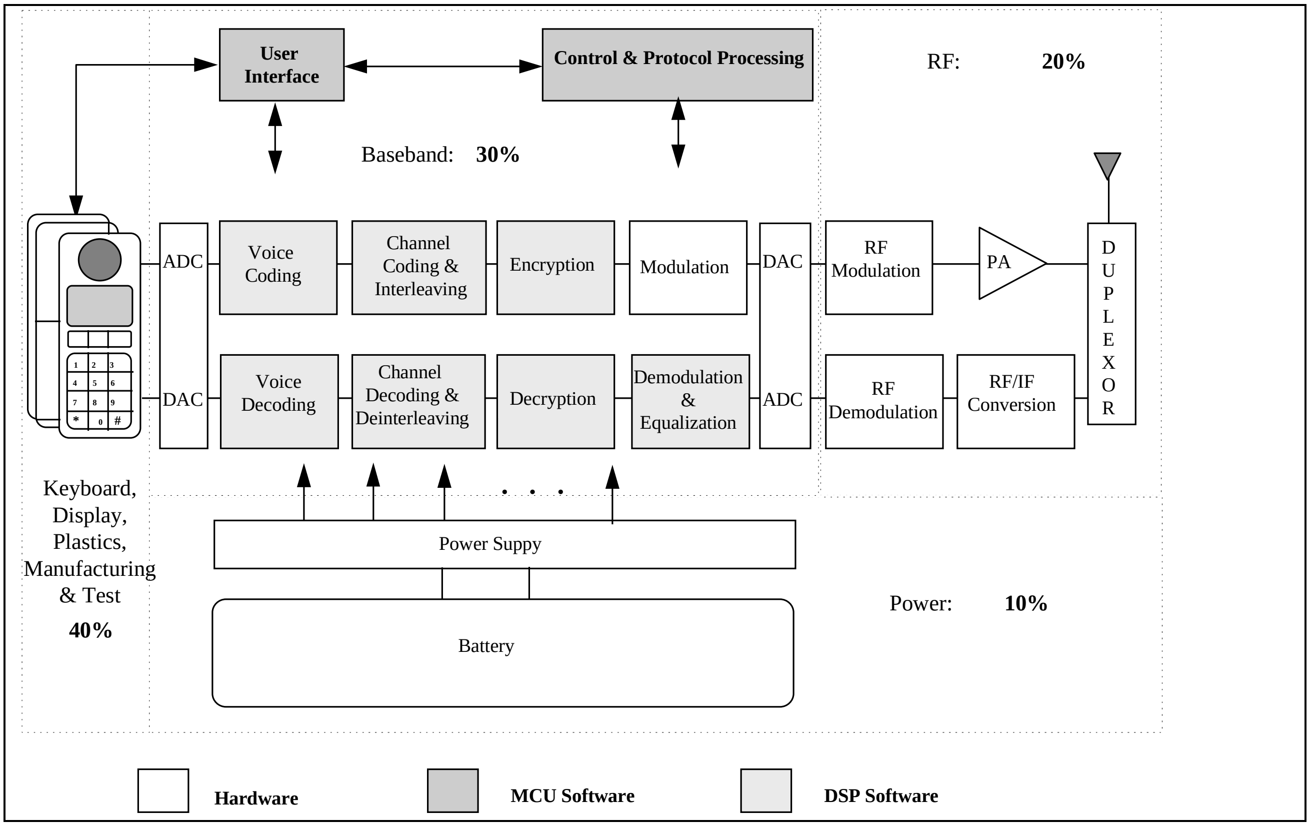


Figure 2. Generic Cellular Handset Block Diagram

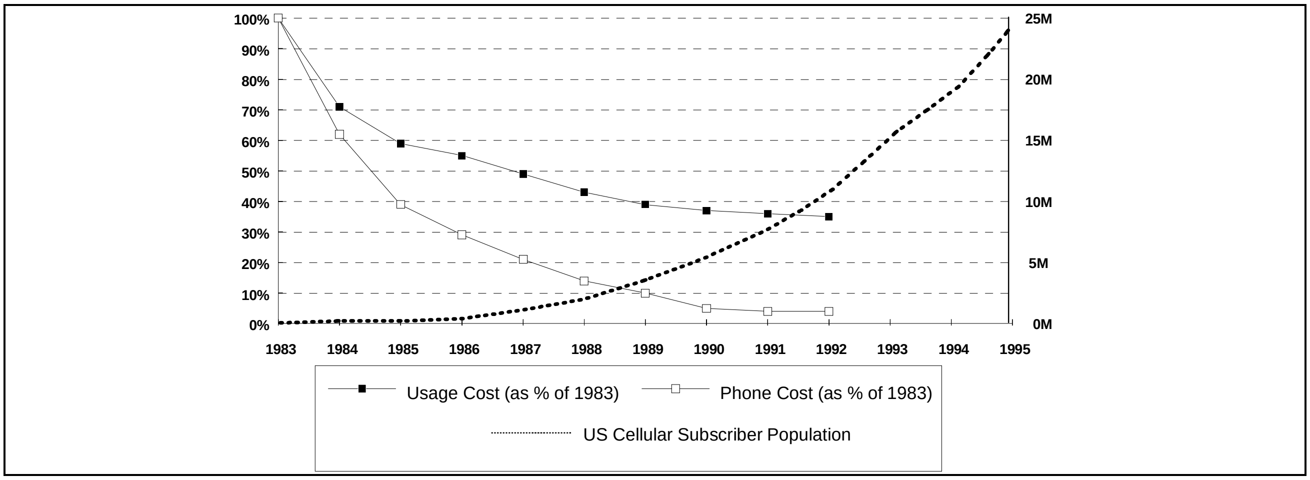


Figure 3. U.S. Cellular Cost Trends/Subscriber Growth

3.2 Handset Partitioning

A typical implementation of the handset in Figure 2 requires both audio and RF ADCs and DACs, hardware and/or software signal processing, some kind of control processor, and both active and passive RF components.

Most systems will tend to separate the baseband and RF subsystems. Integration tends to occur within of each of these modules.

3.2.1 Baseband

The baseband subsystem includes ADCs and DACs that support both the audio and RF interfaces. These devices may be integrated on one or more components. Typically, this part will also integrate a number of other functions required to support the designated standard. These will include auxiliary ADCs and DACs to provide automatic frequency and gain control in the radio, as well as a power ramp function for the transmitter power amplifier.

The signal processing functions will typically use a combination of a programmable DSP with some functions relegated to a digital ASIC. The bulk of signal processing in TDMA implementations will be done on a programmable device (in the range of 20 to 40 MIPS for current standards), while in CDMA systems the high bandwidth of the spread signal (about 1.22 Mbps for IS-95) requires the use of more hardware. For CDMA, a programmable DSP might only be used to implement the vocoder and some of the FEC functions.

A high-performance 8- or 16-bit microcontroller is generally used to implement both the protocol processing and user interface functions of the terminal. This software is generally quite complex (requires from 100 to 500 KB of code space) but is not very processing intensive—perhaps only 1 to 2 MIPS. It is generally written in C, so compiler efficiency is a key careabout for this component. Some manufacturers have implemented handsets that combine the controller and DSP functions in a single processor in order to reduce parts count and power consumption. This trend is likely to continue. However, there are significant barriers—particularly the small address space of most DSPs and their relatively poor compiler efficiency.

An advanced telephone purchased in today’s market will generally have separate audio and RF codecs, one or two programmable DSPs, one or more ASICs, and a separate MCU operating with up to 256KB of external program memory. Within the next two years, these phones will reduce that part count to a single integrated codec, a DSP and MCU integrated on an ASIC backplane, and external memory. Eventually, we can expect to see memory (probably up to 1 Mb of writable, non-volatile storage) also integrated on-chip, with the codec functions probably being absorbed by the RF transceiver.

3.2.2 RF

It is interesting to note that while tremendous progress has been made in reducing the parts count of the baseband functions of a wireless telephone, not much has happened in the RF arena. TI recently surveyed a number of telephones which came on the market over the last three to four years. Although there seemed to be a tendency to reduce the number of active components in the baseband section of the phones, there was no perceptible trend in the total bill of materials. The total parts count was relatively constant at about 300 to 400 over the last four years. Most of these parts are in the RF subsystem and most of those are passives—resistors, inductors, and capacitors. There are many integrated RF components on the market, but so far cellular manufacturers seem to be choosing tried-and-true, low-cost discrete component designs. This shows that integration is not the ultimate goal. We have already reached acceptable weight and volume levels for the traditional handset. The real goal is minimum cost, and unless integration provides minimum cost, we will continue to have phones with long bills of material. The other lesson is that active component integration will not solve the problem. The real problem is the integration of simple resistors, capacitors and inductors as well as more complex passives such as SAW filters. A challenge for component vendors will be to try to sell integration based on reduced total system cost (including cost savings resulting from a shorter bill of materials and reduced costs of manufacturing and maintenance) even if the actual cost of the bill of materials is higher.

3.3 System Operation

The following discussion reviews the operation of the cellular phone illustrated in Figure 2.

3.3.1 Transmit

In the first stage of the transmit chain, analog voice is digitized at 8 kbps and bandlimited to about 3.2 kHz (the bandwidth of a typical telephone channel). Generally, this conversion is done using either an 8-bit companded or a 13-bit linear ADC. This raw digitized speech at a rate of 64 to 104 kbps is then compressed to a data rate defined by the appropriate standard—generally somewhere between 6 and 32 kbps. See Spanias [20] for a detailed discussion of speech coding. The compression function is usually accomplished in software on a DSP. The only exception is that 32 kbps ADPCM for some of the digital cordless standards is sometimes implemented in hardware. When hardware is a viable option, the choice comes down to whether the desired function is fixed or is likely to change in future system implementations. As these various standards evolve, it is likely that more and more functions will move to hardware—particularly if that choice can provide a power consumption or cost advantage. Another consideration may be whether the DSP has sufficient processing power to implement the desired function. It may be advantageous to offload some functions to hardware to minimize the DSP MIPS load.

After the voice has been compressed, redundancy is added through the channel coding process. Simple parity, CRCs, and 1/2- or 1/3-rate convolutional codes are the most common coding techniques. The idea is to minimize the effects of transmission bit errors on the quality of speech produced at the other end. Generally, the more perceptually significant bits are coded most heavily. To guard against burst errors during transmission, the resulting bit stream is interleaved so that errors will be dispersed. GSM for example, adds 9.8 kbps of redundancy to the 13 kbps coded speech and interleaves the resulting 22.8 kbps data stream over 8 TDMA frames. Channel coding is a function that is implemented in either hardware or software. This was recently a point of contention during the development of a new vocoder and channel coding scheme for the upbanded GSM system (PCS1900) for the U.S. PCS market. Some vendors wanted to have the flexibility to modify the existing GSM channel coder in order to improve the performance of the new vocoder in low C/I (Carrier to interference) conditions. Other vendors objected. The problem was that the objecting vendors had implemented the channel coder in their base stations using ASICs. The opposing camp had implemented theirs in software. The decision was made to accept potentially lower performance and use the same channel coding standard so that no existing infrastructure hardware would have to be modified.

One of the biggest advantages of digital communications for the end user as well as the service provider is security. Fraud is a $1B problem for the analog cellular telephone industry. Thus the next step in the transmit chain of a digital cellular phone is the encrytion of the coded, interleaved bitstream. This function is generally required for the handset manufacturer, but is optionally implemented by the service provider. It is almost always implemented in software on a DSP.

The final compressed, error-protected, encrypted bit stream then must be modulated in the format defined by the appropriate standard. The IS-136 standard uses a technique call π/4 DQPSK (Differential Quarternary Phase Shift Keying). In this scheme each dibit is represented by a differential phase shift in the I/Q plane. This function could be accomplished in software, but most current system implementations have chosen a hardware approach in order to offload the DSP and minimize power consumption. In fact the modulation function is often integrated on the device that serves as the interface between baseband processing and the RF transmitter. The primary function of the “RF Codec” in the transmitter is to convert the modulated bit stream back to the analog domain. In the IS-136 system this conversion is at a rate of 24.3 Ksymbols/s (2 bits/symbol). This conversion is usually done by using a pair of DACs (one each for I and Q) operating at a rate of 48.6 Ksamples/s. The GSM standard, on the other hand, must support a much higher 271 kbps data rate for its GMSK modulator.

The final stages of the transmit chain include an RF modulator, which must convert the baseband I and Q signals up to the appropriate carrier frequency for cellular systems that will be on the order of 900 MHz, while PCS systems will target the 2-GHz band. This up-converted signal is then amplified by a power amplifier, passed through the antenna switch or duplexer and transmitted from the antenna. The choice of using a switch or duplexer at the antenna depends on whether a standard calls for simultaneous transmit/receive operation (like AMPS) or time multiplexed transmit and receive (like GSM). U.S. dual-mode phones have to be designed to support both. Consequently, a duplexer is chosen. See Section 4.3 for a more complete discussion of RF transmitters.

3.3.2 Receive

On the receive path, the signal is passed through the duplexer/switch and down-converted using one or more mixing stages before it is demodulated into baseband I and Q components. There are obviously architectural tradeoffs in how these functions are implemented. The I and Q separation technique is the most common, but some manufacturers use other approaches. For example, one major manufacturer uses R/θ notation—rather than I/Q. Other choices include the number of mixing stages or whether to use a standard heterodyne architecture or a homodyne approach (See Section 4.3).

Eventually the signal will be reduced to baseband and operated on by either hardware or software signal processing components. Unlike the modulator in the transmit path, the demodulator in the receiver is most commonly implemented in software on a programmable DSP. The output of this demodulator may then be passed through an adaptive equalizer to eliminate the effects of delay spread, which can cause intersymbol interference. The equalizer is also commonly implemented in software. The performance of the equalizer in the GSM standard is particularly critical since the symbol length is only about 3.7 μs, versus 41 μs for IS-136. There has been considerable debate in U.S. standards bodies about whether the IS-54/136 standard should even require an equalizer. The PDC standard, which is based on IS-54/136, has chosen to eliminate that requirement entirely.

The remainder of the receive path consists of relatively straightforward implementations of the reverse processes described for the transmitter including decryption, channel decoding and deinterleaving, voice decompression (or decoding), and digital-to-analog conversion to drive the handset speaker.

3.4 Industry Trends

As the wireless industry evolves it is possible to discern a number of disparate trends. Three of these are discussed below.

3.4.1 Higher Performance

There seems to be a substantial difference between user expectations of the communications quality of digital equipment and the reality of existing systems. This is driving a strong demand for higher performance in existing systems.

3.4.1.1 Voice Quality

Users expect digital systems to provide clear, higher-fidelity voice communications. The reality is that while digital systems utilizing compressed speech are somewhat quieter, the character of the noise background is unnatural and consequently distracting for some users.

There are several approaches to solving this problem. Existing algorithms can be modified to make them more robust in the presence of noise. Texas Instruments has taken this approach in its IS-54B chipset by modifying the VSELP vocoder to low-pass filter the vocal tract filter parameters that are computed. This smoothing tends to reduce the “swirling” effects in the noise background that were reported during the early rollout of IS-54B. A second approach is to try to add a separate noise reduction preprocessor; and finally, one could simply try to develop an enhanced vocoder with more robust operation. New vocoders are in development for at least four different standards: IS-136, GSM, IS-95, and PCS1900.

3.4.1.2 Latency

The latency introduced by a vocoder (or by naturally occurring delays, such as those in satellite links) can reduce communications efficiency and can make hands-free operation virtually impossible. One of the causes of latency is the fact that digital vocoders generally require a full frame of speech, plus some number of additional samples of look-ahead, before processing can begin. VSELP, for example, uses a 20-ms frame and requires 1/4 frame or 5 ms of additional delay for a total of 25 ms. G.729, the algorithm which is likely to adopted as the enhanced performance successor to VSELP, will reduce this processing delay to only 15 ms. As is the case with trying to improve vocoder robustness, reducing latency can be costly in terms of more complex processing requirements.

3.4.1.3 Graceful Degradation

A communication link based on analog technology tends to degrade gradually as signal-to-noise ratios decline. A digital system, on the other hand, operates at a relatively even level until error correction schemes totally break down and a call is dropped without warning. This can be very disconcerting to the caller. It is not clear how the industry will handle this problem. Since a handset knows when bit error rates approach unacceptable levels, it should be possible to warn a user when a dropped call is likely to occur. Another approach would simply be to reduce the occurrence of such situations by developing more sensitive, robust receivers or by adding base stations to improve system coverage.

3.4.2 More Functionality

In a standards-driven environment, service providers will try to differentiate their products by offering customized features to enhance customer capabilities, expand the customer base, or make their services easier to use.

3.4.2.1 Data Services and Personal Base Stations

Two examples of services that have the potential to expand the customer base are data services and personal base stations (PBS). Data services will be designed to attract the mobile computing user. Personal base stations are designed to expand the market from business users to true consumers. The biggest technology challenge in the former case is software—developing the applications and interfaces that will allow laptop computers and personal information appliances to communicate seamlessly using a digital cellular infrastructure. Success in the latter case will challenge our ability to deliver a quantum increase in functionality (versus a typical handset) for a cost that must compete at some level with a cordless phone. A PBS must include all of the functions of a cellular handset, plus it must support multiple channels and provide provisions for interface to standard telephone handsets. One published specification for a PBS for IS-136 would require about 80 MIPS of DSP processing, versus only about 40 MIPS for a standard handset.

3.4.2.2 Full Duplex Hands-Free Car Kits

User safety and convenience is driving cellular equipment vendors to offer high performance, full-duplex hands-free car kits. The problem is that the latencies that exist in current digital networks make hands-free operation very difficult. The solution, once again, is to add DSP power to eliminate the acoustic echos introduced by these delays and to reduce the effects of background noise. This can make full duplex hands-free operation possible for both digital and analog cellular systems. The additional processing can be located in the hands-free cradle in the car, or perhaps integrated with the DSP built into the telephone. The barrier to the latter approach is cost, power, and available throughput. The AEC and noise suppression functions can consume upwards of 30 MIPS by themselves.

Another feature that could be added to a hands-free kit is the ability to dial the phone using spoken commands. The issue here is the same safety issue which is served by the AEC and noise suppression functions described above. However, since the normal functions of a cellular telephone are not active during dialing, the problem with speech recognition in this application is not the MIPS required—those are free—but memory. Most reasonable performance speech recognizers will require the addition of a substantial amount of expensive RAM or some other writable memory technology.

3.4.3 Versatility

The industry can't seem to decide on a single standard and it certainly can't predict what products and services will be successful in the marketplace. The result is that the system vendors will have to build in versatility into their products. Three major trends stand out. First, the move to multi-mode, multi-band terminals. Second, a desire for base stations and terminals that can be dynamically reconfigured based on new software; and finally, a proliferation of the technology embodied by cellular telephones into other consumer devices which need communications. These devices will include laptop PCs, PCMCIA adaptors, PDAs, and personal organizers.

3.4.3.1 Multi-Mode, Multi-Band

The dominant trend is toward multi-mode, multi-band phones. In the U.S. this means that phones will service both cellular and PCS frequencies (900 MHz and 1.9 GHz) and also support whatever set of standards best provides a capability for seamless national roaming. Consequently, you can expect to find phones that support almost any PCS standard and AMPS. Omnipoint's hybrid CDMA/TDMA system will be combined with PCS1900. AT&T will require IS-136 operating in both the cellular and PCS bands, as well as AMPS at 900 MHz. In Europe you can expect to see DCS1800 combined with DECT. The number of permutations is enormous as are the implications. Protocols will have to be developed to allow phones to automatically determine which standard is appropriate. Handsets will have to include resident software for multiple standards. Systems will be required to seek out the lowest cost communications infrastructure. Radios must be designed to handle multiple bands and even multiple modulation schemes. All of this must be accomplished in a cost environment which will not allow much of a premium for all of this increased functionality. One service provider has commented that such phones should have no more than a 25% cost adder.

3.4.3.2 Downloadable Functionality

One way to add flexibility is by allowing software to be dynamically loaded when new functionality is required.

This is common with base stations. In fact, an important requirement for DSPs that serve the base station market is a large internal RAM. Downloadable software has been considered for handsets, but it has not yet been deemed practical either from a cost or technical standpoint. However, it is clear that some kind of downloadable reconfiguration is likely to be necessary in the future. This will drive the need for integrated, writable, non-volatile memories such as FLASH.

3.4.3.3 Spin-Off Products

Many typically wired or standalone products will eventually have a wireless modality. Wireless telephone functionality will be delivered in totally new form factors. The most obvious will be PCMCIA cards for PCs. The normal telephone handset could be handled using the standard PC keyboard and display with a built-in speaker phone. A natural extension would be to include video phone support.

Other more innovative products can also be conceived. When you begin to move into new product domains, the human factors constraints of a telephone handset begin to fall by the wayside. The size/weight issue which has been largely solved in the telephone handset arena will put increased pressure on the semiconductor industry to reach more aggressive levels of integration. If the size limitations of a keyboard and display are separated from the electronics, the guts of a telephone can be integrated into heretofore unimaginable packages—perhaps contained within a piece of jewelry.

4. Key Technologies and Critical Challenges

Given the requirements and future trends of wireless systems discussed in the preceeding sections, four technology drivers emerge as the basis on which future progress will be determined.

1. Semiconductor Technology: will determine the levels of integration, power consumption and system performance that will be achievable.

2. DSP Technology: will continue to be the key baseband technology on which digital wireless systems are built. It will grow in importance as the partition between the radio and the baseband subsystem gradually moves to drive more and more functionality into the signal processor.

3. RF Components and Architectures: will drive much of future system cost and volume reductions. A key issue will be where the system is partitioned between the RF and baseband subsystems.

4. Batteries: size, weight, and life will ultimately determine how far the wireless revolution can go.

4.1 Semiconductor Technology

4.1.1 Component technologies and trends

Typical cellular or cordless telephones consist of several hundred components—concentrated in the RF subsystem—distributed over a few PC boards. These include VLSI integrated circuits, discrete GaAs components, a range of resistors, capacitors, inductors and filters along with RF switches, power supply and other I/O-related components. To achieve the lower power, cost, and volume with increased functionality described in earlier sections, the industry has challenged semiconductor technology to integrate these hundreds of components into a low-cost "single-chip wireless engine." Another view of a handset architecture is shown in Figure 4. This figure illustrates the types of components and the semiconductor technology required. Critical considerations for integration, in view of the single-chip goal, are:

1. Higher-performance active elements such as bipolar transistors, with higher f_T, linearity, and lower noise figures for RF and analog functions.

2. Higher-speed power product and higher-circuit-density CMOS for digital signal processing, control and memory functions.

3. Lower intrinsic device and interconnect parasitics (junction capacitances and resistances).

4. Monolithic high frequency (RF) integrable passive elements such as inductors, capacitors, RF and IF filters, along with accurate passive elements for mixed-signal applications.

5. Low noise and good isolation between on-chip digital and analog/RF functions.

6. Process simplicity and compatibility between digital and analog functions, as well as low speed and RF for manufacturability and lower cost.

7. Lower total system power and complexity dictating optimum digital/analog, RF/BB partitioning and power supply voltages.

Figure 4 shows f_T and gate delay (T) trends of conventional BiCMOS, CMOS, GaAS and some emerging semiconductor technologies such as Si-Ge. These are plotted as function of major technology nodes and their approximate relation to the year of technology availability.

For small-signal RF applications, we are presently seeing a transition from single-poly 8- to 10-GHz bipolar/BiCMOS technology to 15- to 25-GHz BJT/BiCMOS with lower parasitics and improved intrinsic noise figures. With f_T requirements estimated to be 5X to 10X the operating RF frequency, these two technologies are expected to provide adequate performance at current 800 to 900 MHz frequencies, as well as the next generation of 1.8 to 1.9 GHz PCS and 2 to 2.5 GHz ISM band applications.

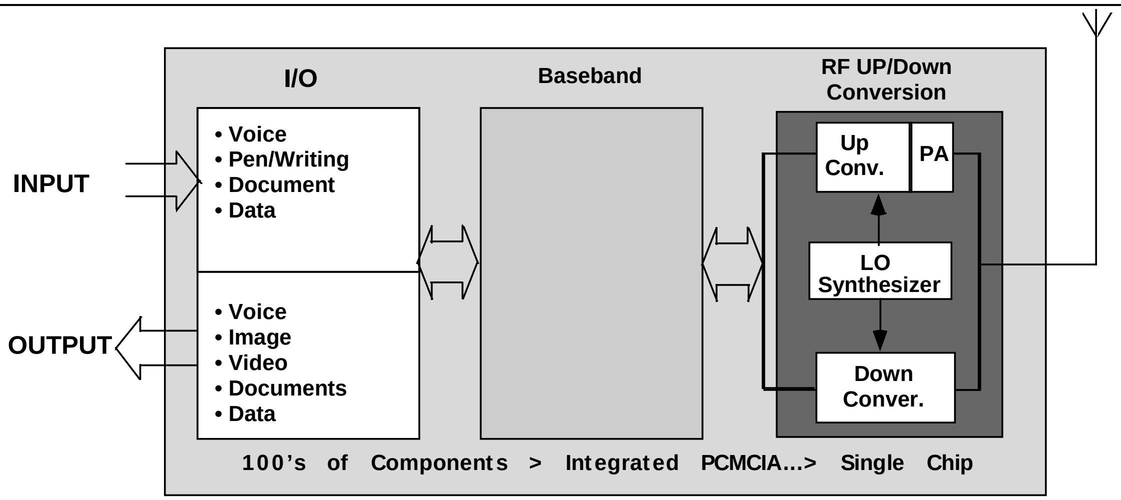
Many of today's systems use GaAs low-noise amplifiers, power amplifiers and RF switches to meet the stringent RF TX/RX front-end needs. High-performance BJT and MOSFETs are beginning to compete to replace these in future integrated, lower-cost single-chip transceiver solutions.

CMOS, a traditional digital logic and memory VLSI workhorse, continues to scale through the current 0.5-micron node down to sub-0.2-micron by the year 2000. This will provide continued improvements in MIPS/mW in traditional digital and signal processing applications. Added functionality using mixed-signal, analog elements, and on-chip high-density volatile and nonvolatile memory will allow increased integration of the baseband and I/O functions. Submicron CMOS is also being investigated as an option for realizing some of the traditional high-frequency conversion and filtering operations.

For applications in higher frequency bands, as well as for further improvement in performance and level of integration in current bands, device structures such as Si-Ge with higher f_T's (40 to 60 GHz) and substrates with isolation and passive element integration superior to conventional silicon (e.g., SOI) are being proposed.

4.1.2 Passive Element Integration

Passive elements constitute more than 50% of the components and a significant portion of the actual and related costs in today's discrete implementation of wireless terminals. These range from simple resistors, capacitors, and inductors critical in biasing and matching circuits, high-frequency elements for RF and IF filtering, antenna switches, duplexers, SAW filters and resonators. Elements such as high Q inductors have been successfully integrated on insulating substrates such as GaAs; however, to realize the needed Q and self-resonance for monolithic inductors beyond the 2-GHz range in Si is a significant challenge. Antenna switches and SAW filters are critical for spectral selectivity and sensitivity in narrowband applications. Building these monolithically in processes and materials compatible with traditional Si IC technologies is also a significant challenge, yet essential to reaching the goal of a single-chip, low-cost wireless engine.



Technology:	Now • CMOS Future • BiCMOS	• CMOS (BiCMOS)	• GaAs • BiCMOS
Components:	• A/D ,D/A • M ixed Signal • Codecs • I/O interface • Battery/Power Management	• DSP,BBprocessing • Memory • Compression/ Decompression • Voice/channelCoding Decoding • Equalization	• PA • LNA • LO/Synthesizer • Filter • Mixers • Antenna switches • Modulation/Demodulation

Figure 4. Component Technology Used in Wireless Handsets

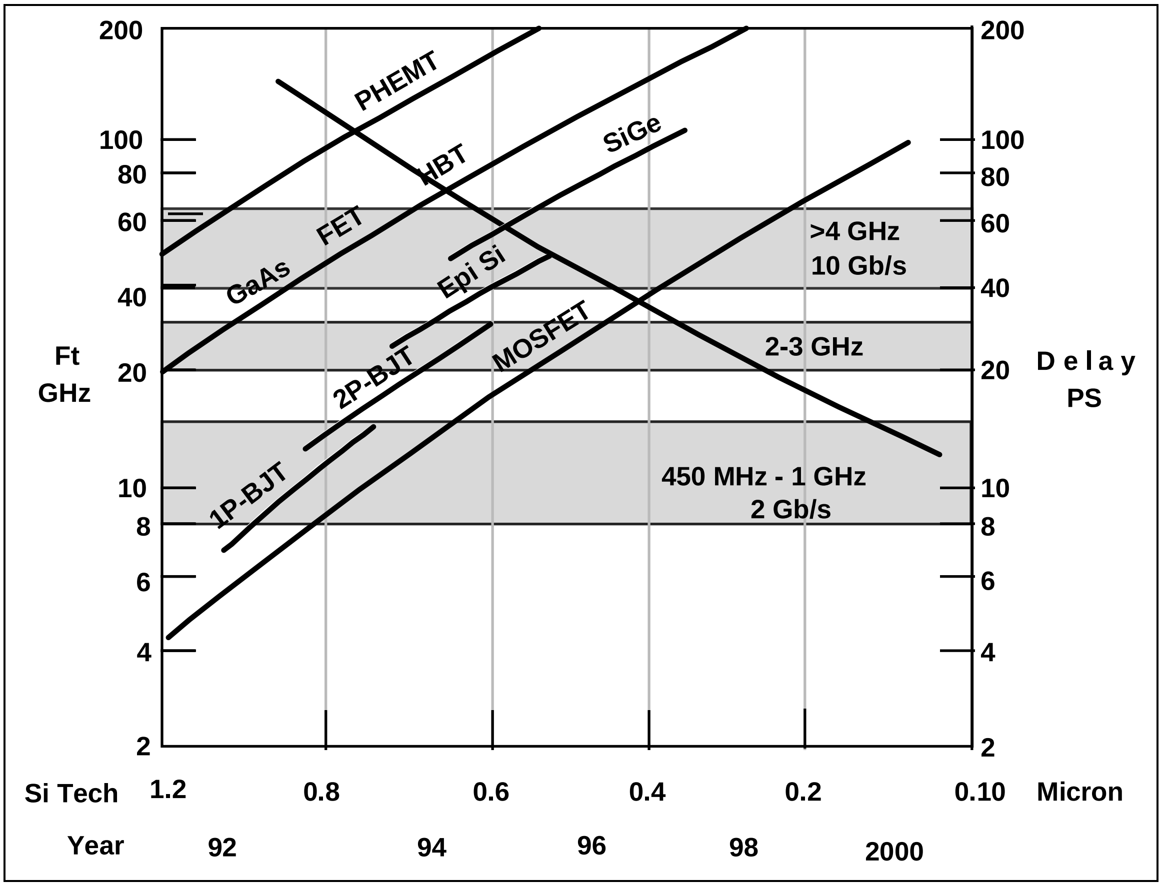


Figure 5. F_T/Gate Delay Trends

	Si-CMOS	Si-BiCMOS	Si-BJT	GaAs	SiGe-BiCMOS	SOI-CMOS
Cost	lowest	medium	low	highest	high	high
RF Functions	medium	good	good	best	better	medium
Mixed Signal	good	best	good	poor	good	good
Digital speed/pwr; density	best	medium	medium	poor	good	good
Integration	good	best	poor	poor	good	good
Total Power (analog + digital)	good	good	medium	poor	medium	best
Passives integration	poor	poor	poor	best	poor	better
Maturity (manufacturability)	best	good	good	medium	new	low

Table 12. Semiconductor Technology Assessment Matrix

4.2 Digital Signal Processors

Now let’s look at the DSP and determine how it will have to evolve to support wireless applications over the next decade. First, we are interested in the basic capacity of the DSP to perform the task. This translates to MIPS and memory. Second, we must address the wireless trends that we have already discussed: digital connectivity, handset size, power, and cost.

4.2.1 More MIPS/Memory

Today's digital cellular handsets require anywhere from 20 to 50 DSP MIPS, depending on the specific processor and specific standard which is to be implemented. Table 13 shows how this MIPS requirement has evolved from AMPS to GSM to the current version of IS-54B. The biggest driver is the particular vocoder which is chosen. AMPS is an analog system and does not require a vocoder. GSM used an algorithm that requires less than 5 MIPS to implement, while the VSELP algorithm implemented in IS-54B requires between 12 and 18 MIPS. Most current digital standards are in the process of selecting new vocoder algorithms to either improve voice quality or lower the channel data rate. These new algorithms require more memory and more MIPS than their lower-performing predecessors. This trend will be accelerated as manufacturers add more and more features to differentiate their products. Echo cancellation and noise suppression are good examples. These features are needed to enhance audio quality—particularly for hands-free operation. These simple features could easily consume 10 to 30 MIPS. It would not be unreasonable to expect that in the future we could expect that a DSP implementation of a digital cellular system would have to support as much as 80 to 100 MIPS.

The trend toward increased functionality and performance is also pushing memory requirements. A typical IS-54B DSP implementation will require about 16 Kwords of program memory and about 4 Kwords of RAM. The requirement for the next generation of the same standard increases the ROM requirement by about 50%. The target in two to three years will be a DSP with a program memory capacity of about 48 Kwords, with a corresponding increase in RAM.

Standard	**DSP MIPS Required**
AMPS	10
GSM	20
IS-54B	40

Table 13. DSP MIPS Required by Cellular Handsets

4.2.2 Low Power, Small Size, Low Cost

Configuring a DSP for a real-time task consists of selecting the minimum speed clock that can execute the task within the time window allowed. This will minimize power consumption by minimizing the time the CPU spends in idle mode doing no useful work. Once a clock rate is chosen, DSP power consumption can be calculated directly from the number of MIPS consumed by simply multiplying the number of MIPS by an appropriate value of current consumption per MIP. It is obviously advantageous to select a DSP whose instruction set is tailored to wireless applications so that the average MIPS load is minimized. Remember also that the real battery drain is based on the average number of MIPS required—not the peak MIPS, which must be used to size the DSP. Secondly, the software should be architected to minimize the differential between the peak and average MIPS load. This will allow the system designer to reduce the speed of the base clock since it must be chosen based on peak load.

One of the most straightforward ways to reduce power consumption by a DSP is to reduce its operating voltage. Remember that power consumption can be expressed as:

$$\text{Power} = \text{Capacitance} * \text{Voltage}^2 * \text{Freq}$$

If we reduce operating voltage by a factor of 2, with everything else being equal, power consumption will drop by a factor of 4. The current generation of handheld cellular phones generally uses DSPs operating at a voltage of 5 V. The next generation (those phones which are currently in design) will use only 3 V, and lower voltages will not be far behind. Besides lower power consumption, this trend has a second important effect: it reduces the number of battery cells and thus reduces system volume and weight.

However, the DSP itself is not the only story. Many functions can be accomplished more efficiently with customized hardware solutions. The tradeoff is flexibility for cost and power, since those hardware solutions may prove more efficient. The designer has to decide which functions are likely to remain constant and which need to be able to accommodate future changes.

DSPs need to be delivered in a form that supports the integration of a variety of relatively disparate technologies. As a first step, DSP cores must be integrated with high-speed, power-efficient ASIC backplanes. This will allow the development of custom hardware that can be efficiently and closely coupled with the DSP. This includes custom ROM/RAM spins as well as custom hardware for specific wireless standards, such as a timer circuit for TDMA standards such as GSM or IS-136 or the modem for a CDMA terminal.

We also need to consider either using the DSP to support the controller functions that typically reside in a general-purpose microprocessor, or we need to support the integration of a microprocessor core on the same ASIC backplane as the DSP. If we choose the former course, the problem is not MIPS, because the control function probably only requires 1 to 2 MIPS. The problem is code space. Some of the more sophisticated controllers could require as much as 500 Kbytes of code. Applications for PDAs will even be more memory-intensive. Today's fixed-point DSPs don't support that kind of address range.

At the same time, we need to be able to support the integration of both baseband analog and small-signal RF functions. If we examine the inside of a cellular telephone today, it is these functions that dominate the parts count, and it is the passive components such as filters and duplexers that dominate the physical volume required to support all the electronics in an instrument. Ultimately, we will need to figure out a way to integrate all of these analog functions with the digital baseband processor.

4.3 RF Technology

Wireless communication systems transmit information by modulating a electromagnetic wave. Wireless communication systems utilize only a minute fraction of the spectrum. Examples of such systems are:

1. Radio frequency (RF) systems (VLF, LF, HF, VHF, UHF, L-band, S-band)
2. Microwave systems (3 to 30 GHz)
3. Millimeter-wave systems (30 to 110 GHz)
4. Infrared (IR) systems (3- to 10-µm wave-length)

Wireless systems fall into two categories: coherent and incoherent. In coherent systems, the frequency and/or phase of the carrier are locked to a stable reference source. Both can carry information. In an incoherent system, the phase of the carrier is random and information can only be coded into the amplitude. Most common RF communications systems such as cellular telephones are coherent. IR wireless systems are incoherent due to the lack of tunable frequency sources (IR tunable lasers are feasible but impractical). They employ LEDs for sources and IR photo-sensors as amplitude detectors.

The type of wireless system used is determined by several factors, among which are: range, omni-directional versus line-of-sight, capacity (number of simultaneous users), data rate, noise and interference immunity, availability of component technology, and of foremost importance, cost. The range of wireless systems generally decreases with increasing frequency, due to increased atmospheric attenuation. At certain frequencies, such as 60 GHz, this attenuation increases dramatically, resulting in a very limited range of communication. Note that a limited range may be desirable for some applications, such as local-area networks (LANs). On the other hand, the capacity and data rate of coherent wireless systems increase with increasing frequency, due to the corresponding increase in system bandwidth. Microwave and millimeter-wave systems have advantages in capacity and data-rate over RF systems. IR systems have intrinsically low capacity due to their incoherent nature. On the other hand, microwave and millimeter-wave systems tend to be directional, due to the large size of radiating elements relative to the wavelength. They are primarily used for line-of-sight communication. RF systems can be made omnidirectional for mobile terminals.

RF systems also have a significant advantage in terms of cost per user due to the availability of low-cost active, passive, and antenna technologies. Today, low-cost silicon technology can meet RF system requirements up to 2 to 3 GHz. Also, the availability of low-cost surface-acoustic wave (SAW) and ceramic filters, discrete components (capacitors, inductors, resistors) and dielectric substrates (thick-film) make low-cost wireless transceivers possible. Microwave and millimeter systems have substantially higher cost due to technology requirements.

In short, RF technology offers the best combination of range, capacity, data rate, coverage, and cost, for wide-area mobile communication systems. Microwave and millimeter-wave systems, are more suitable for high data-rate, line-of-sight applications such as digital microwave radio links for telephony and video, links between cellular base-stations, and ground terminal to satellite communication.

4.4 RF Transceivers

RF transceivers perform the bidirectional transfer of information between the baseband processor and the antenna. There are two types of RF transceivers: full-duplex and half-duplex. In a full-duplex transceiver, the transmitter and receiver operate simultaneously. An AMPS analog cellular phone is a good example. In a half-duplex system, such as GSM, either the transmitter or the receiver may be on in a time slot. This has significant bearing on the architecture and design of the transceiver. Isolation between the transmitter and receiver is a major issue in full-duplex phones. It impedes integration of several functions in a small package or on a single chip. Half-duplex transceivers, on the other hand, can achieve higher levels of integration and simplicity in architecture.

Figure 6 shows a generic block diagram of an RF transceiver that has three major blocks: receiver, transmitter, and frequency source. In this section, various approaches to the receiver, transmitter and sources are described. Each approach has implications on the technology used to implement that function.

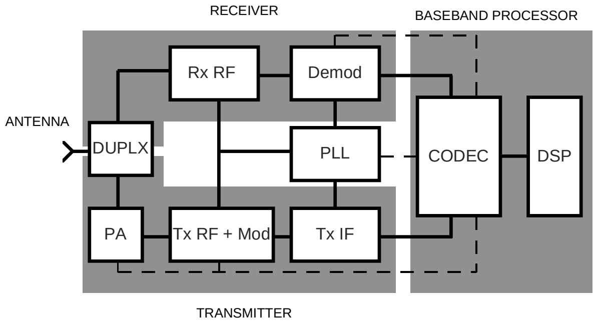


Figure 6. RF Transceiver Block Diagram

4.4.1 Receiver

The RF receiver extracts the baseband signal from the RF carrier. This process involves a frequency translation from the RF carrier to the baseband frequency. There are two types of receivers depending on the manner this frequency translation takes place: heterodyne receivers and homodyne receivers. In heterodyne receivers the carrier is generated independently in the transceiver via a frequency synthesizer. *A priori* knowledge of the received signal frequency (channel frequency) is needed. The channel assignment is handled by the base station and communicated to the mobile terminal at a predefined frequency. This allows dynamic allocation of the channels to mobile terminals. Heterodyne receivers require a stable reference source to be synchronous with the transmitter. Temperature compensated crystal oscillators with 1 ppm stability provide excellent reference source for mobile and base units.

In homodyne receivers, the carrier is extracted from the received RF signal and thus on-board stable reference sources are theoretically not needed. Homodyne receivers are used in ATM (asynchronous transfer mode) transceivers. In such systems, frequency-division multiplexing is difficult to implement since the receiver cannot distinguish different transmitter signals. Time-division multiplexing is used in homodyne systems in conjunction with amplitude modulation. In cellular and PCS systems, bandwidth efficiency is of paramount importance since the available spectrum is limited. Therefore, heterodyne systems offer significant advantages. The discussion in the remainder of this section will focus on heterodyne receivers.

Heterodyne receivers offer excellent sensitivity and dynamic range. The frequency translation from RF to baseband can take place in one (direct conversion), two (single down-conversion), three (dual down-conversion), or several steps. The last step of the frequency translation is generally known as RF demodulation. Direct conversion receivers are sometimes mistakenly referred to as homodyne receivers but in fact they are heterodyne because of the need for independent carrier generation. Figures 7 through 9 show the block diagrams of direct, single-conversion, and dual-conversion receivers. In each frequency translation, the baseband signal is transferred down to the next intermediate frequency (IF). This is generally done through mixing of the RF signal with an on-board-generated local oscillator (LO) in a nonlinear semiconductor device (known as the mixer). The LO signal is generated using frequency synthesizers and stable reference sources. The IF generated in this process is the difference between the RF and LO frequencies. The following sections discuss the key components of the heterodyne receiver.

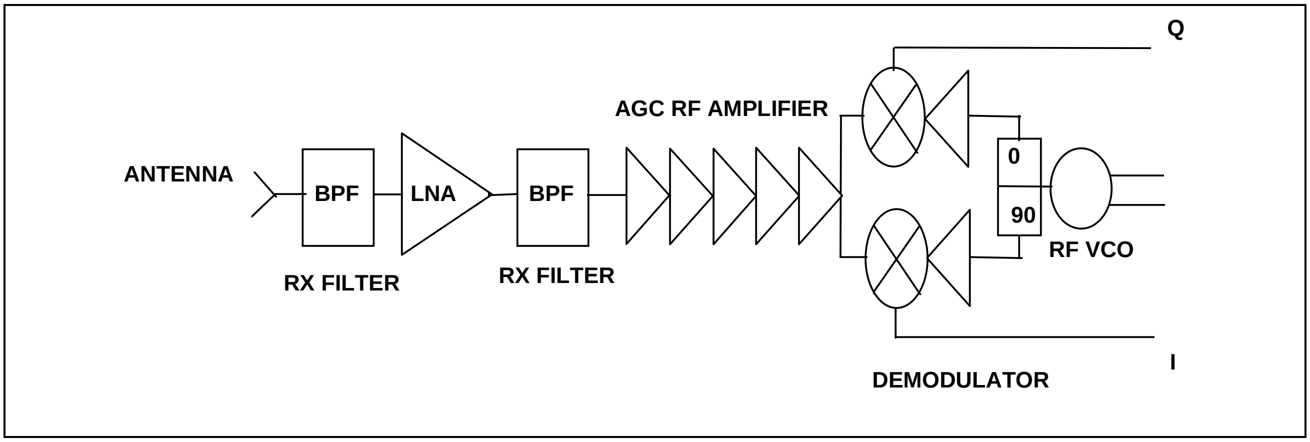


Figure 7. Direct-Conversion Receiver

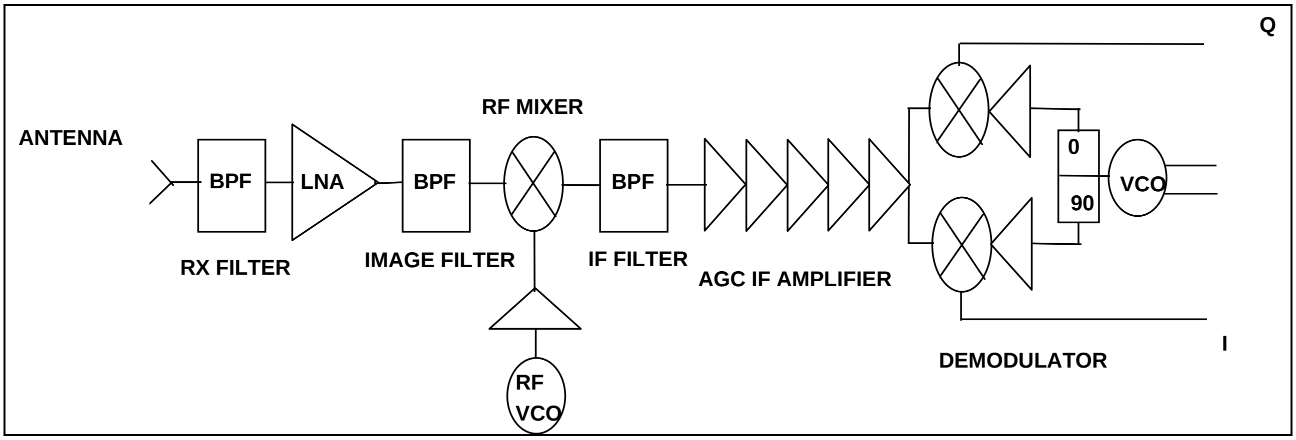


Figure 8. Single-Conversion Receiver

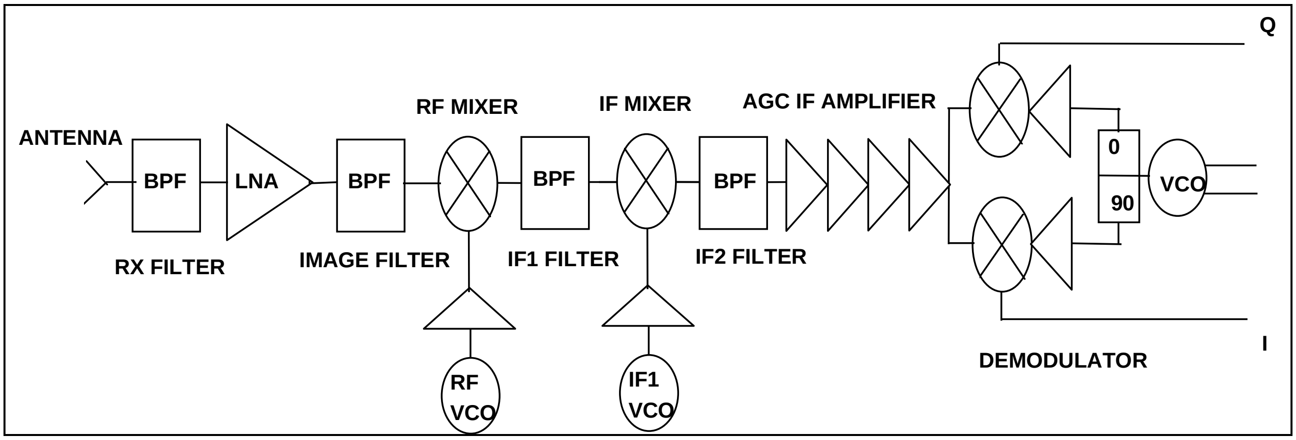


Figure 9. Dual-Conversion Receiver

4.4.1.1 Receiver Filter

The receive front-end band-pass filter (BPF) serves to protect the receiver from saturation by interfering signals at the antenna. RF antennas are generally broadband and do not provide selectivity. The RF BPF is typically combined with a transmit filter in the form of a diplex filter (also known as diplexer or duplexer). The duplexer connects the antenna to the transmitter (Tx) and receiver (Rx) and provides isolation between the Rx and Tx blocks. Ceramic coupled-resonator filters are commonly used for front-end receiver filters or duplexers. Lower-cost discrete inductor/capacitor filters are also used, especially in half-duplex transceivers where strong interference from the system's own transmitter is not an issue, and thus lower out-of-band rejection is acceptable.

4.4.1.2 Low Noise Amplifier

The low noise amplifier (LNA), to a large extent, sets the noise figure (NF) of the receiver and thus its minimum detectable signal level. Other factors such as front-end filter losses also directly affect the NF of the receiver. The noise contributions of each block in the receiver to the overall NF is reduced by the total gain of the preceding blocks. Therefore, for minimum receiver NF, the gain of the LNA should be maximized and its NF minimized. However, higher LNA gain results in higher signal level into the RF mixer and thus higher spurious products. There is a distinct trade-off between the receiver NF and its spurious performance. Figure 10 shows the qualitative variation of the bit-error rate (BER) for a digital receiver as a function of received signal power. At low signal levels, the BER increases due to poor S/N (signal-to-noise) ratio at the baseband A/D converter. At high signal levels, the BER increases again due to in-band spurious products of the mixer, which increase the S/I (signal-to-interference) ratio at baseband. In PCS or cellular applications, the receiver has to have good sensitivity as well as immunity to interference resulting from proximity to other terminals or base units. Also the effective antenna temperature (a measure of the ambient noise the antenna sees) at the 800- to 2000-MHz range is generally high due to large utilization of this spectrum for a number of industrial and commercial RF systems. This implies that below a certain NF level, the receiver sensitivity is no longer limited by its NF. This is in contrast to satellite communication ground terminals where the received signals are always low-level and the antenna temperature is also low (space background radiation is very small). In this case, receivers are designed for minimum NF to yield the best sensitivity. An example is the Direct Broadcast Satellite (DBS) receiver.

For PCS and cellular terminals, a total receiver NF of about 6 to 9 dB is generally needed to meet system specifications. This corresponds to an S/N ratio of about 6 to 10 dB at the baseband A/D converter input. In order to achieve such total NF, the LNA NF is in the range of 1.5 to 2.5 dB, with associated gain of 12 to 14 dB. Such performance levels can be attained with high-speed Si bipolar or BiCMOS processes. In some cases low-noise GaAs FETs are also used to improve the front-end performance.

Another careabout for the LNA is its power consumption since the receiver is generally on during the standby mode. Si bipolar or GaAs FET LNAs can meet PCS and cellular requirements with about 3 to 6 mA of current. In full-duplex systems, the LNA has to withstand the transmitter signal which leaks through the front-end duplexer and appears at the input of the LNA. For AMPS terminals, the level of Tx interferer at the LNA input is about -20 dBm. Therefore, the 1-dB gain compression level of the LNA must be at least -10 to -5 dBm (10 to 15 above the interferer).

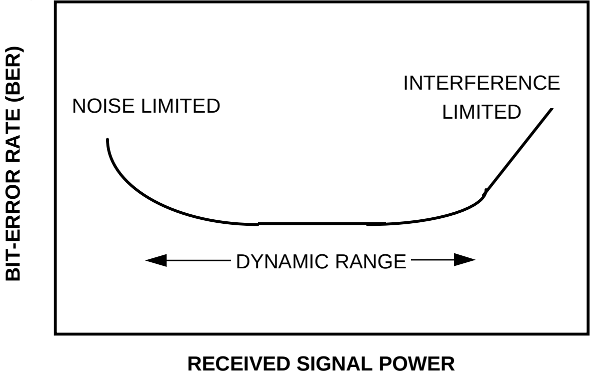


Figure 10. Variation of BER versus Received Signal Power

4.4.1.3 Image Reject RF Bandpass Filter

The image-reject RF bandpass filter serves two functions. First it protects the RF mixer from out-of-band interferer signals. Second it suppresses the undesired spurious signals generated by the RF mixer. Specifically, the image signal (which has the frequency of $f_{image} = f_{LO} + f_{IF}$, where f_{LO} and f_{IF} are the LO and IF frequencies), needs to be suppressed because when mixed with the LO signal it generates an undesirable signal at the IF frequency and cancels the desired IF signal. The image frequency has to be suppressed by at least 10 dB in order to meet the system NF. To meet spurious requirements, RF receivers generally need about 65 dB of image rejection. This is achieved in the front-end duplexer and the image filter combined. The image-reject filter also provides isolation between the LO source (VCO) and the LNA input. SAW filters are typically used to provide image rejection. Low-cost L/C filters can also be used at the expense of lower rejection levels.

4.4.1.4 The RF Mixer

The RF mixer is a key component in the overall receiver. It transfers the modulation from the RF signal to the IF via the non-linear mixing process. The same nonlinearity, however, generates spurious products that are undesirable. While some of the mixer spurious products can be suppressed by using high-selectivity filters, others fall in the receive band and can*not* be filtered out. These products tend to limit the BER performance at high signal levels. A good receiver designer must consider *all* possible mixing combinations of the signals present in the system and ensure that the in-band products are of sufficiently low level to result in good S/I ratios. The key careabouts for the mixer are low spurious response, low NF, conversion gain, low LO drive level, and low dc power consumption. Isolation between the LO, RF, and IF ports are also important. An important in-band spurious response for the mixer is the Third-Order Intermodulation Product (IP3). This occurs when two closely spaced signals (say f1 and f2 in adjacent channels) appear at the input of the mixer and the resulting interaction yields spurious responses at 2*f2-f1 and 2*f1-f2 frequencies. These spurs fall in channels adjacent to the two signals and create interference. To minimize such products, the mixer has to have maximum input at the third-order intercept point (IIP3). The mixer IIP3 is proportional to the total power consumption in the mixer. Therefore, high IIP3 implies high power consumption. For battery-operated mobile terminals, a trade-off between mixer IIP3 and power consumption is reached. A typical mixer IIP3 level for an AMPS terminal is about -4 dBm, assuming 10 dB combined gain in front of the mixer (LNA gain - duplexer loss - image filter loss). This can be achieved with active mixers such as single-balanced or double-balanced bipolar Gilbert mixers using 6 to 10 mA of current consumption. Active mixers also provide conversion gain, which reduces the need for additional IF gain stages.

Passive diode mixers have better IIP3 than active mixers. They do require higher LO drive level, which translates into higher power consumption. These mixers are common in base stations, where much higher IIP3 levels are needed due to the large number of signals present in the system. Passive mixers with IIP3 levels of +30 dBm are available.

Other types of spurious products can also be a problem, such as the (2*f2 - 2*f1), known as the 2-2 spur. The 3-3 spur can also be a problem if the total receiver bandwidth is wide enough to allow for that to be in-band. For example, in AMPS and IS-54 systems, the 2-2 spur falls in-band for IF frequencies of less than 50 MHz (total receive bandwidth is 25 MHz). In the IS-136 PCS system, the 3-3 spur can also occur in-band, since the receive bandwidth is about 60 MHz.

Typical single-sideband NF is achieved with RF bipolar Gilbert mixers in the 7 to 10dB range, which is adequate for cellular receivers. GaAs FET mixers have about 10 dB NF in the same frequency range.

Image rejection can be obtained using two double balanced mixers and quadrature phase shifters. This eliminates the need for image-reject filters at the expense of higher power consumption in the receiver. Image reject mixers also cannot sustain out-of-band interference. Image reject mixers can more readily be implemented in half-duplex terminals such as GSM, where transmitter interference is less of an issue.

4.4.1.5 Voltage-Controlled Oscillator (VCO)

The RF VCO is also an important part of the overall receiver. It supplies the LO signal for the mixers to down-convert the RF-modulated signal to IF. It also provides the channel selection for the receiver via the phase-lock loop synthesizer. The careabouts of the VCO are: phase-noise, thermal noise floor, tuning range, RF power, dc power consumption and pulling/pushing factors. For most communication applications, the close-in phase noise of the VCO is a limiting factor. The IF signal generally assumes the phase noise characteristics of the VCO. While the phase-lock loop (PLL) suppresses the phase noise within the loop bandwidth, for most terminals the loop bandwidth is small (a few kHz at most). Outside the loop bandwidth, the LO will have the VCO free-running phase-noise. This noise generally falls in the modulation band (in voice channel) and in the adjacent channels. For AMPS and IS-54 terminals, the channel spacing is 30 kHz, and the phase noise requirements at 60 kHz offset from the 1-GHz LO signal is about -118 dBc/Hz. To attain this level of phase noise, two conditions must be met: (1) the white and 1/f noise of the transistor must be low, and (2) the loaded-Q of the resonator must be high. 1/f noise corner frequencies of less than 10 kHz are needed for the active device in the VCO. This can be met with Si bipolar transistors and JFETs. GaAs FETs have excessive 1/f noise (corner frequency > 1 MHz) and are not suitable for VCO applications. Unloaded resonator Qs of 200 to 300 are needed for AMPS and IS-54 phones to meet phase noise requirements. This corresponds to loaded Qs of about 20 to 50. Ceramic resonators using high-dielectric materials offer a low-cost and compact solution to the resonator problem. For GSM application, the phase noise requirement is about -120 dBc at 600 kHz offset. This can be achieved with lower Q resonators made of discrete or printed inductors and chip capacitors. It is difficult to integrate the resonator on Si due to the high Q level required. Research and development efforts are under way to build high-Q piezoelectric thin-film resonators on Si.

The thermal noise floor of the VCO is also an important parameter. Since the front-end gain of wireless communication terminals is generally low, due to spurious requirements, the noise floor of the RF signal present at the input of the mixer is only 15 dB or so above the absolute thermal noise floor (-174 dBm/Hz at room temperature). At the IF port of the mixer, this level could be 10 dB higher, due to the gain and NF of the mixer itself. This puts the noise floor of the desired signal at the IF port at about -150 dBm/Hz. The VCO thermal noise appears directly at the IF port and can affect the overall S/N ratio and thus the total NF of the receiver. In order to prevent the VCO from affecting the receiver NF, a maximum noise floor of -160 dBm/Hz (10 dB below the desired signal noise floor) is needed from the VCO. Since the VCO signal at the LO port of the mixer is about -5 dBm for an active mixer, this corresponds to -155 dBc/Hz noise floor for the VCO. The VCO noise floor is affected by the NF of the active transistor used in the VCO. Si bipolar VCOs in discrete module form are popular in cellular phone applications. Integrated VCOs are also being developed which do not include the resonant circuit on chip.

In order to meet the tuning range for the receiver, while maintaining low phase noise, high-Q varactors (variable capacitor diodes) are needed. Discrete Si varactor diodes offer a good combination of cost, Q-factor, capacitance ratio and breakdown voltage. Si varactors have special doping profiles that are not common in typical IC processes and therefore are difficult to integrate on chip. The diodes present in Si IC processes cannot meet the Q-factors required for this applications. Discrete GaAs varactors are also available for higher-Q applications at higher cost. Capacitance ratios of 5 are common for Si and GaAs varactors. Varactors with hyper-abrupt doping profiles can provide capacitance ratios as high as 10 or more. To achieve good phase noise, the resonator element needs to be lightly coupled to the varactor and the overall tank needs to be lightly coupled to the VCO cell (negative resistance cell). Tight coupling will result in low loaded-Q for the resonator and poor phase noise.

4.4.1.6 IF Channel Filter

The IF filter sets the noise bandwidth for the receiver and provides some degree of isolation to the adjacent channels. All RF channels are down-converted to the same IF frequency via the RF mixer. This scheme allows for narrow channel spacing while maintaining reasonable tuning bandwidth. SAW filters are the component of choice for most IF filter applications. They provide the best out-of-band rejection at reasonable size and cost. Crystal and L/C filters can also be used at the expense of lower performance.

4.4.1.7 IF AGC Amplifier and RF Demodulator

In order to maintain wide dynamic range for the receiver, automatic gain control (AGC) has to be implemented in the receiver. This is done to maintain a constant signal into the baseband A/D converter for a wide range of RF signal levels at the antenna. Typical AGC requirements for cellular phone applications range between 65 and 80 dB. For digital cellular phones, the AGC has to be done in such a way as to not distort the amplitude of the desired signal. The advantage of implementing the AGC function in the IF amplifier as opposed to the front-end LNA is that the overall NF can be maintained constant as the total gain of the receiver is varied. This is an important consideration. The gain of the IF AGC amplifier is set by the baseband processor based on Received Signal Strength Indicator (RSSI) and BER measurements on a predetermined sequence. There are two approaches for the IF AGC amplifier: continuously varying AGC (or analog AGC), and use of a digital AGC. In the later case, a series of fixed gain amplifiers are cascaded and switched in and out of the main chain to provide quantized gain control. This approach has advantages in terms of control of the gain steps versus the analog approach.

The RF demodulator extracts the baseband signal(s) from the last IF signal. Implementation of the RF demodulator depends on the type of modulation scheme used. In AMPS phones, FM demodulation is performed using a limiting amplifier and a Gilbert cell multiplier in quadrature (used as phase/frequency detector). In IS-54 and IS-136 systems, DQPSK demodulation is done using two double-balanced mixers and a quadrature (0/90) phase-shift network. In this case, the accuracy of the phase-shifter is very important to obtain low BER.

Double- and single-conversion heterodyne architectures are typically found in cellular, cordless and PCS terminals. The choice of double versus single conversion depends on a number of factors, such as channel spacing, frequency plan, spurious response and total gain. The smaller the channel spacing, the more difficult it is to implement a single-conversion receiver. It is also more difficult to implement the total gain of the receiver at one frequency due to limited isolation in the phone. By down-converting in two or more steps, the total gain can be broken up among the various RF and IF stages and isolation is improved.

Direct conversion receivers have been studied for cellular phone applications for some time. They offer reduction in parts count for the receiver. However, there are tremendous hurdles to implementing a direct conversion receiver at RF. The biggest problem is that in a direct conversion receiver, the LO frequency is the same as the RF frequency. This requires extreme isolation between the LO and LNA input, which is often not feasible. Consider that a typical RF signal at the input of the receiver may be at -116 dBm while the LO signal in the phone is of the order of -5 dBm. This means that the isolation between the LO signal and the LNA input has to be of the order of 120 dB to keep the LO signal from overriding the desired signal. This is physically impossible at RF frequencies in the small volume of a portable terminal. The other limitation is that the close-in noise of the VCO is down-converted into the baseband and thus affects the S/N ratio (or the overall NF). In the AMPS and IS-54 phones, information bandwidth is of the order of 30 kHz and thus the VCO phase noise must be kept below 155 dBc/Hz at such offset.

4.4.2 Transmitter

The RF transmitter also has trade-offs in terms of performance, complexity and cost. The simplest approach to a transmitter consists of an RF VCO at the transmit frequency that is locked to a programmable PLL and can be modulated via an RF modulator. The signal can then be amplified with a power amplifier to the appropriate signal level and fed to the antenna. The transmitter has to perform this function with minimal distortion to the baseband signal. Since the transmitted signal levels are of the order of 1 W or more for portable RF terminals, power consumption in the transmitter is substantially higher than the receiver and thus is the limiting factor in the talk time of the terminal.

The key careabouts of the transmitter are: power consumption (efficiency), modulation accuracy and linearity, output spurious products, the S/N ratio of the transmitted signal, and power control. The simple approach described above (direct RF Tx modulation) has many drawbacks. The most important one is that the isolation between the PA output and modulated RF Tx source is limited. Since the PA output signal is of the order of +30 dBm, it can feed back to the modulated VCO via its resonant tank circuit and cause remodulation. This results in undesirable spectrum broadening and adjacent channel interference. In order to solve this problem, an offset Tx signal at some intermediate frequency can be used. This signal is then up-converted to the RF Tx band using the receiver LO signal. Figure 11 shows the architecture of an RF transmitter for IS-54. The key components of the transmitter are discussed below

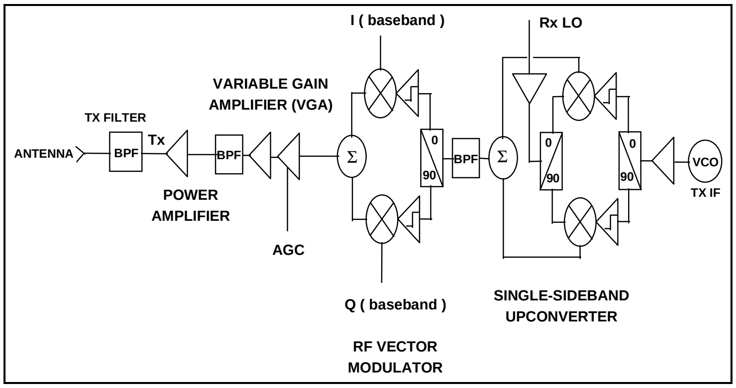


Figure 11. Digital RF Transmitter Architecture

4.4.2.1 Transmit IF VCO

The observations made about the receiver RF VCO generally apply to the Tx IF VCO as well. The close-in phase noise of the Tx IF VCO does not have to be as low as the receiver LO, since the Tx baseband signal is at much higher levels than the RF received signals. Tunability is also not a factor since the transmit VCO is at a fixed frequency.

4.4.2.2 Up-converter

The up-converter translates the Tx IF frequency to the RF Tx band using the receiver LO signal. The key parameters of the up-converter are: LO suppression, sideband suppression, power consumption, and noise floor. In case the TX IF source is modulated, linearity is also a big factor in the up-converter. The up-conversion takes place in a mixer and thus produces several spurious products. Good sideband and carrier rejection minimized the need for costly external transmit filters. Single-side-band up-converters provide carrier suppression of about 30dB or more. They also suppress the image frequency significantly. Odd order products (3rd and 5th) do appear at the output of the up-converter and require some filtering to meet spurious output requirements of the transmitter.

4.4.2.3 Modulator

The modulator is a critical block in the transmitter chain. It must transfer the baseband signal to the RF transmit carrier with minimal distortion. The type of modulator used depends on the modulation scheme. In analog FM phones (AMPS), the VCO can be FM-modulated by using the PLL in a narrow bandwidth mode as the modulator. For QPSK systems (IS-54/136) and sometimes for GMSK systems (GSM, DSC1800, PCS1900), vector modulators are commonly used. The vector modulator is similar to the up-converter in that it uses two double-balanced mixers and a quadrature phase-shift network for the RF signal. The modulation signal is generally supplied in-phase (I) and quadrature (Q) by the baseband processor. The accuracy of the phase-shift network in terms of amplitude and phase balance at RF frequency is of paramount importance to the accuracy of the transmitted signal. Any amplitude or phase imbalance can result in unacceptable spurious sidebands that fall in the transmit band and can*not* be filtered out. Typical amplitude and phase accuracy requirement for RF vector modulators are 0.1 dB and 0.5°, respectively for an IS-54 transmitter. There are different approaches to the quadrature phase shift network. The simplest approach is using passive R-C network to obtain the 0/90° phase shift. This approach suffers from inherent amplitude imbalance and requires good resistor and capacitor matching in the process.

A more accurate implementation of the quadrature phase shifter is to multiply the RF signal by four and use a digital divide-by-four network, which produces quadrature signals with excellent amplitude and phase balance. In practice, however, divide-by-four networks at 3.5 to 4.0 GHz would require very high-speed processes that may not be cost-effective. An alternative approach uses a divide-by-two circuit to provide the quadrature signals. In this approach the duty cycle of the RF signal must be maintained at 50%. This approach offers a practical implementation of accurate RF vector modulators using existing high-speed bipolar or BiCMOS processes. The key parameters of the modulator are: side-band suppression (related to amplitude and phase balance), power consumption and S/N ratio.

4.4.2.4 Variable Gain Amplifier (VGA)

The VGA allows for transmit signal level adjustment into the PA. The VGA has to accomplish this with minimum distortion and added noise figure. Typical VGA gain control requirements are about 40 dB for most cellular terminals. In order to maintain linearity at all gain settings, the VGA has to consume sufficient DC power. Both continuously varying and stepped VGA approaches are applied to RF transmitters. Continuous VGAs generally have higher NFs and are more difficult to control over temperature and parametric variations. Si bipolar technology offers the best choice for this portion of the transmitter.

4.4.2.5 Power Amplifier

Power amplifiers are critical components of any wireless transmitter. They have the difficult task of amplifying the modulated signal by orders of magnitude without distortion and at minimum dc power consumption. Low distortion and high efficiency are contradicting requirements for a PA. For low distortion, class-A linear PAs, which have low efficiency, are needed. For best efficiency, class-B (or class-C) PAs, which have unacceptable distortion characteristics, are needed. In systems where amplitude distortion is not a factor, such as in an FM transmitter (for AMPS), class-B power amplifiers are common. PA modules with 60% dc-to-RF conversion efficiency are common today in AMPS phones. The technology of choice is generally GaAs FET modules or ICs. Si MOSFET PAs are also used in AMPS phones at slightly lower efficiency but at lower cost as well. For IS-54 and IS-136 phones in the digital mode, QPSK modulation is employed and thus any amplitude or phase distortion can be detrimental to the BER. Phase distortion has to be kept to less than 2° and amplitude distortion to less than 0.5 dB over the envelope of the QPSK signal (or about 5 dB range). This requires linear class-A or class-AB power amplifiers, which have lower efficiency. The lower efficiency is offset by the fact that the transmitter is pulsed with about 1/3 duty cycle. Today's IS-54 PAs run at about 45% efficiency. Lower-cost Si bipolar modules can also be used with lower efficiency (30 to 35%). For GSM application, the modulation (GMSK) is constant envelope, and theoretically class-B amplifiers can be used. However, there are restrictions on adjacent channel interference and maximum phase change in the GMSK envelope (20° max.), which would require back-off from class-B/C conditions. GSM power amplifiers have efficiencies in the 45 to 50% range. Si MOSFET power amp modules are common in today's GSM phones due to the lower cost of achieving the required power level (3 to 4 W) for GSM Class IV applications. GaAs power amps are also being developed for this market, but it remains to be seen whether they can replace Si MOSFET modules.

Other careabouts of the power amplifier are cost, output noise floor, stability and spurious response, high-voltage (battery charge-up), handling and ruggedness. Low-cost packaging is also a major issue due to large thermal dissipation. It is also very desirable to have a single polarity supply voltage in the PA to simplify system design. This is an advantage for Si MOSFET and bipolar compared to GaAs FETs. The other advantage of Si MOSFET and bipolar power amplifiers are low standby (leakage) current. GaAs FETs have high leakage current and thus require external PMOS switches to disconnect them from the battery in the standby mode. On the other hand, GaAs FET processes can integrate moderate-Q inductors and high-Q capacitors, which allow for the power amplifier matching circuit to be integrated on the chip. This allows for smaller package compared to hybrid modules. Both GaAs and Si PA solutions will exist in the market for the foreseeable future, with GaAs PAs being used for higher-performance, higher-cost products and the Si PA for low-end, low-cost products.

4.4.2.6 Transmit Filters

Transmit filters are needed to meet the output noise and spurious requirements of the transmitter. In full-duplex systems, the transmitter noise can leak into the receiver via the duplexer and destroy the receiver sensitivity. Therefore, the noise output of the PA in the receive band must be kept to a minimum (generally -90 dBm in a 30 kHz bandwidth in the receive band are needed for AMPS phones). This requires the use of transmit band-pass filters between the modulator and the power amplifier. The duplexer by itself cannot provide adequate isolation between the transmitter and the receiver. In half-duplex systems, theoretically, a duplexer is not needed and can be replaced with a transmit-receive switch. However, T/R switches alone do not offer adequate protection for the receiver and duplexers are currently used in GSM phones. The technology of choice for transmit filters preceding the PA is SAW. For output duplexers, ceramic band-pass or notch filters are used. Ceramic filters have lower insertion loss and thus have less detrimental effect on the transmitter efficiency.

4.4.3 Frequency Source

Digital phase-lock loop (PLL) synthesizers are commonly used in analog and digital RF transceivers. Digital PLLs combined with RF VCOs provide for fast and accurate synthesis of RF LO signals for the system. Typically, the RF LO signal and Reference signal are divided down to one channel and then compared using a phase detector. The error signal is fed back to the VCO varactor through a low-pass filter. By changing the division ratio, the PLL can set the VCO at different frequencies separated by one channel spacing. Digital RF PLLs can operate at very low power consumption. This is important since the PLL as well as the receiver has to be on during the standby mode and thus its power consumption affects standby time. Digital RF PLLs at 1 GHz can operate at about 5 to 10 mA and 3 V. The key parameters of the PLL are: acquisition time, lock-up time, spectral purity (noise and spurs), programmability, and power consumption.

The key components of a digital PLL are discussed below.

4.4.3.1 RF Prescaler

Since programmable dividers cannot operate at RF frequencies due to long logic gate delays, RF prescalars are used to step down the frequency of the RF signal. They are synchronous and normally provide fixed division ratios (such as 1/4, 1/16, or 1/64). Dual modulus or triple modulus prescalers are also implemented using pulse swallow techniques. Typical dual-modulus prescalars are 4/5, 8/9, 32/33, 64/65, 128/129, etc. The choice of the prescalar depends on the frequency plan of the transceiver. The output of the prescaler is at a frequency where programmable dividers can operate. The technology of choice for the RF prescalers is high-speed bipolar. Submicron CMOS will also be applied to the prescalar in the near future.

4.4.3.2 Main and Reference Dividers

The main and reference dividers are asynchronous dividers made of programmable counters. They are generally composed of flip-flops with feedback loops to set the divide ratio. The divide ratio can vary from one to a maximum number set by the number of bits in the programming register. 11 to 13 bit dividers are common in digital PLLs. CMOS offers the best technology for the implementation of the dividers due to low power consumption.

4.4.3.3 Digital Phase Detector

The digital phase detector provides a pulsed output in response to a phase difference between the main and reference signals. Tristate digital phase detectors are often used to provide bipolar error pulses as well as large linear ranges. Tristate detectors are also phase-frequency detectors in that they respond to both phase and frequency difference. This is important for acquisition of the signal in the initial state. Higher-order phase detectors are also possible but increase the complexity of the PLL. The output of the phase detector drives the charge pumps, which provide the analog error signal for the VCO.

4.4.3.4 Charge Pump

The charge pump converts the digital output voltage of the phase detector to error currents that can be adjusted in magnitude. The accuracy of the charge pump is very critical to the overall performance of the PLL. Slight variation in the charge pump currents will show up as sidebands in the VCO output. The error currents are fed to a low-pass filter to generate an analog tuning voltage for the VCO. The closed loop operation of the VCO has complex dynamics and is a strong function of the VCO, PLL, and loop filter design.

Si BiCMOS processes offer the best trade-offs in terms of speed and power consumption for RF PLL applications. The prescaler is usually implemented in bipolar, whereas the main dividers, phase detector and charge pumps are implemented in CMOS. RF PLLs with 2 GHz bandwidth are available today. Variations of the basic PLL circuit are also used for faster lock-up time. The digital PLL is programmed by the main processor via a three-wire serial bus, allowing for a small pin count.

4.5 Batteries [1,9,19]

Batteries may represent the one technology discussed in this paper which is slowing down development in the wireless industry. Compared with semiconductor technology, battery technology advances at a glacial pace.

The issues which determine the type of battery technology to be selected for portable applications like wireless terminals include:

1. Cost: this is a major factor for every component of a wireless device.

2. Energy Density: this factor determines how much power a battery can deliver as a function of its weight or volume.

3. Cell Voltage: the cells from different materials exhibit different operating voltages. This factor can have a strong influence on the operating voltage of the telephone.

4. Cycle Life: how many times can the battery be recharged before performance deteriorates.

5. Shelf Life: how well does the battery retain its charge while idle.

6. Environment: some materials are toxic and damage the environment when disgarded.

There are a large number of battery technologies being used in or considered for wireless applications. These include:

1. Lead Acid: used in large capacity applications such as car batteries; too heavy for portable systems.

2. Alkaline: common for many portable consumer products—only recently available in rechargeable form. Good shelf life but poor cycle life.

3. Zinc Air: new technology promoted by AER Energy Resources.

4. Nickel Cadmium: NiCd-most common in cellular telephones; memory effect and environmental concerns causing manufacturers to shift to NiMH or lithium-based technologies.

5. Nickel Metal Hydride: NiMH-similar in performance to NiCd without environmental concerns; used in many of today’s phones.

6. Lithium Metal/Lithium Ion: recent technologies with greater energy densities; attracting attention for future designs.

Table 14 describes the relative merits of three of the battery technologies listed above.

Feature	NiCd	NiMH	Li Ion
Cost	Lowest; in volume production for years	Now in volume production	Highest; just beginning to ramp up production
Energy Density	15–35 Wh/kg	50–60 Wh/kg	55–90 Wh/kg
Cell Voltage	1.2 V	1.2 V	3.6 V (other Li-based technologies can support 1.5 V or 3.0 V)
Cycle Life	2 > 1000 cycles	3	1
Shelf Life	70% after 1 month	70% after 1 month	88% after 1 month
Environment	3	1	1

1 = Best; 3 = Worst

Table 14. Battery Technology Comparison

5. Wireless Systems in the 21st Century

Two issues must be overcome before wireless products will really become pervasive in the 21st century. First, we must overcome the technical challenges described in this paper. When that happens and wireless service is available at prices that are comparable to current wireline systems, we could see an explosion of demand. The second problem, however, may be trickier—instituting the cultural change which will influence people to want to be “in touch anywhere, anytime.”

The technical side is relatively easy. If we can reach or even approach the dream of a single-chip wireless engine, it will be possible to integrate the working electronics of a wireless instrument into almost any form factor imaginable—though antennas might prove to be a challenge. We can assume that device will contain large memories so that data or voice can be buffered. Thus we should be able to produce wireless real-time communicators or store-and-forward devices that can be worn or carried unobtrusively—perhaps as jewelry.

The key issue will be interfacing that form factor with a human to perform real-time voice communication or with a computer to transfer data. The latter modality could be accommodated via another wireless link—perhaps with line-of-sight IR. The same must be true in the former case, since the microphone and speaker may have to be separated from the guts of the instrument. Once again, a low-power RF or IR link seems appropriate. In order to maximize the quality of the signal appearing at the input to the microphone, it is likely that it will be placed in the vicinity of the head. The same is true for the speaker, since it will be desirable to keep oral communications as private as possible.

A tricky problem will be how to interface to the instrument to enter data—such as dialing instructions. The most obvious solution is to incorporate speech recognition.

The vision then is of a wireless future where the guts of a subscriber instrument can be housed in a package as small as a ring, with the microphone and speaker in a separate package—probably worn around the head—perhaps in an earring or worn like a small hearing aid inside the ear.

If you believe in technology, you must believe that the technical challenges outlined in this paper will be surmounted. The biggest challenge will probably be to institute the cultural change necessary to make people want to be “in touch anywhere, anytime” (and wearing that earring speaker may be a tough one too).

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