Next-Generation RF Circuits and Systems

Behzad Razavi
Electrical Engineering Department
University of California, Los Angeles

Abstract

This paper describes developments foreseen to occur in the near future in the RF industry. Applications such as wireless local loops, wireless local area networks, RF identification devices, multi-standard transceivers, and cable modems are considered. The choice of IC technologies and CAD tools is also discussed.

I. INTRODUCTION

The RF and wireless market has suddenly grown to unimaginable dimensions. The annual worldwide sales of cellular phones exceeds $2.5 B. In the US, more than 20000 people join the cellular system every day. The global positioning system (GPS) market is expected to reach $5 B by the year 2000. The statistics are quite promising.

In addition to the market "push," the RF industry has also experienced a "pull" by the integrated circuits technology. Advances in silicon and GaAs devices continue to increase the level of integration and decrease the cost of RF circuits, allowing wireless products to compete with even their wired counterparts.

This paper describes current and near-future developments in the RF industry from the point of view of architectures, circuits, and IC technologies. Following a brief look at the past and present of RF design, we describe evolving applications such as wireless local loops, wireless local area netwroks, and RF identification tags. Next, we consider emerging applications, particularly trends in network and transceiver design, multi-standard systems, and cable modems. Finally, we discuss issues in the choice of IC technologies, devices, and design tools.

II. TRADITIONAL RF DESIGN

In contrast to other types of analog and mixed-signal circuits, RF systems demand a good understanding of many areas that are not directly related to circuit design. Communication and microwave theory, signal propagation and wireless standards, transceiver architectures, and CAD tools all play important roles in the design of an RF product. Most of these areas have been studied extensively for more than half a century, making it difficult for circuit designers to acquire the necessary knowledge in a reasonable amount of time. Even at present, the literature pertaining to RF design appears in more than thirty journals and conferences.

0-8186-7913-1/97 $10.00

Owing to this issue, traditional wireless system design was carried out at somewhat disjointed levels of abstraction: communication theorists created the modulation scheme and baseband signal processing; RF system experts planned the transceiver architecture; circuit designers developed each of the building blocks; and manufacturers "glued" the circuits and other components together. In fact, architectures were often planned according to the available off-the-shelf components, and circuits were designed to serve as many architectures as possible, leading to a great deal of redundancy at both system and device levels.

The need for "modularity" in traditional RF design introduced many limitations at circuit and architecture level. In fact, the prevailing design mentality was to *minimize* the number of active devices because of their cost, inevitably requiring many passive components in each block. Designed and optimized as a stand-alone circuit, each building block would need to operate with a standard interface impedance, usually 50 Ω, thus consuming substantial power.

Another attribute of traditional RF design was the use of trial and error rather than CAD tools. The lack of accurate device models and efficient simulation programs necessitated iterations at the board level to achieve an acceptable performance. Manual "tuning" used to be an integral part of RF systems, a practice inherited to some extent in today's RF power amplifier design.

III. Present Status of RF Design

Over the past two decades, RF systems have made remarkable progress, evolving from bulky, power-hungry boxes to miniature cellular phones and pager watches [1]. RF transceivers have gone from simple voice communications to supporting data, electronic mail, and facsimile.

A. *Applications*

In addition to familiar wireless products such as pagers and cellular phones, RF technology has created many other markets that display a great potential for rapid growth, each presenting its own set of challenges to RF designers.

WLANs. Communication among people or pieces of equipment in a crowded area can be realized through a wireless local area network (WLAN). Using frequency bands around 900 MHz and 2.4 GHz, WLAN transceivers can provide mobile connectivity in offices, hospitals, factories, etc., obviating the need for cumbersome wired networks. Portability and reconfigurability are prominent features of WLANs.

GPS. The use of GPS to determine one's location as well as obtain directions becomes attractive to the consumer market as the cost and power dissipation of GPS receivers drop. Operating in the 1.5-GHz range, such systems are under consideration by automobile

manufacturers, but they may be available as low-cost hand-held products sometime in the near future.

RF IDs. RF identification systems, simply called "RF IDs," are small, low-cost tags that can be attached to objects or persons so as to track their position. Applications range from luggage in airports to troops in military operations. Low power consumption is especially critical here as the tag's lifetime may be determined by that of a single small battery. RF ID products in the 900-MHz and 2.4-GHz range have recently appeared in the market.

Home Satellite Network. The programs and services available through satellite television have attracted many consumers to home satellite networks. Operating in the 10-GHz range, these networks require the addition of a dish antenna and a receiver to a television set and directly compete with cable TV.

B. Architectures and Circuits

Complexity, cost, power dissipation, and the number of external components have been the primary criteria in selecting transceiver architectures. As IC technologies and RF design techniques evolve, architectures that once seemed impractical may return as plausible solutions.

The most widely used receiver architecture is the heterodyne topology, shown in Fig. 1 in simplified form. The signal received by the antenna is amplified, filtered, and subsequently

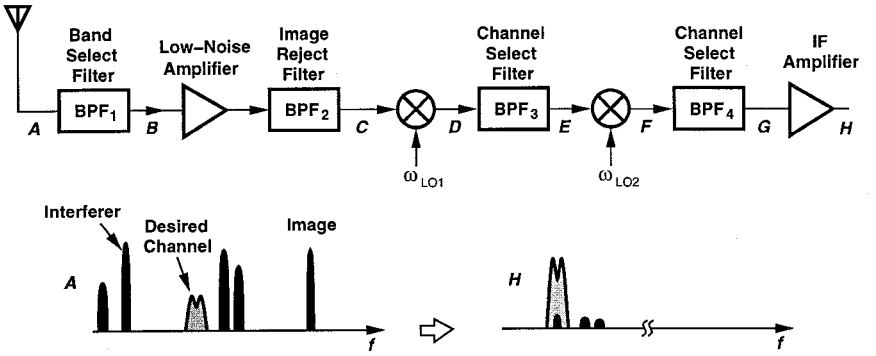

Fig. 1. Dual-conversion heterodyne receiver.

translated to lower center frequencies by two downconversion mixing stages. Since the image-reject and channel-select filters are typically passive, bulky devices that must be placed off-chip, this architecture does not easily lend itself to monolithic integration. Nevertheless, heterodyning has been considered the most reliable approach to receiver design because it can efficiently sense small signals in the presence of large interferers.

Fig. 2 depicts a common transmitter architecture. Similar to heterodyne receivers, this technique translates the center frequency in two steps such that the output frequency is far from the second oscillator frequency. This is necessary because coupling of the large signal

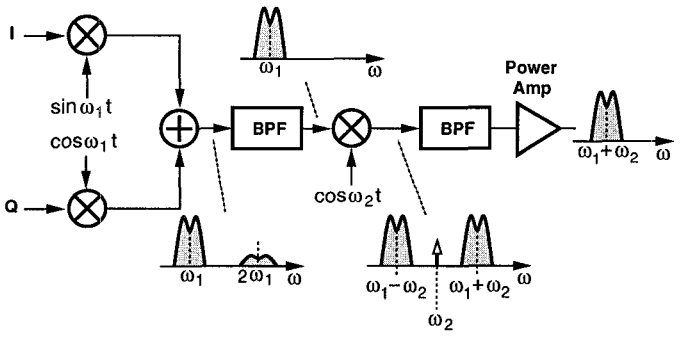

Fig. 2. Two-step transmitter.

generated by the power amplifier to the oscillator introduces substantial noise if the output spectrum is close to ω_1 [2].

An example of today's integrated transceivers is shown in Fig. 3 [3]. In addition to

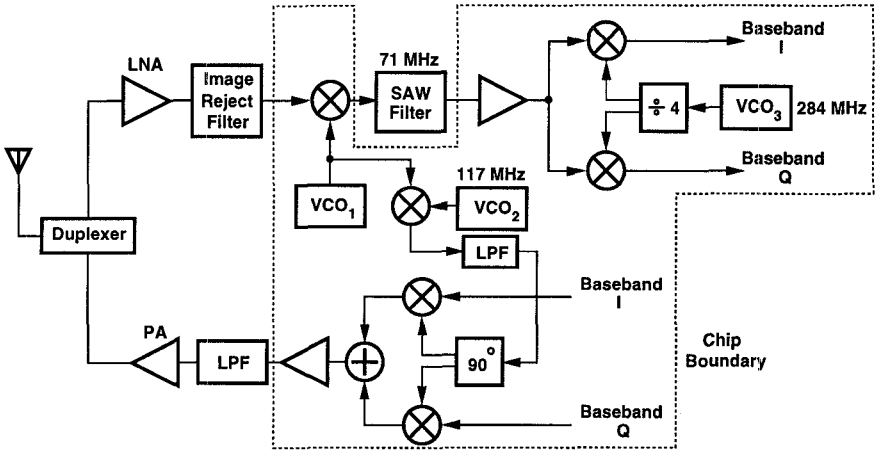

Fig. 3. Lucent Technologies' GSM transceiver.

receive and transmit paths, the circuit includes several frequency synthesizers that control various oscillators in the system. Designed in a 12-GHz silicon bipolar technology, the transceiver is used in the 900-MHz band for GSM applications.

Even with this level of integration, a large number of external components are necessary. A complete RF transceiver in the present technology consists of approximately five to ten integrated circuits and a few hundred discrete components.

C. *IC Technologies*

The viable IC technology for RF circuits continues to change. Performance, cost, and time to market are three critical factors influencing the choice of technologies in the competitive RF industry. In addition, issues such as level of integration, form factor, and prior (successful) experience play an important role in the decisions made by designers.

At present, GaAs and silicon bipolar and BiCMOS technologies constitute the major section of the RF market. Usually viewed as a low-yield, high-power, high-cost option, GaAs field-effect and heterojunction devices nonetheless have maintained a strong presence in RF products [4], especially in power amplifiers and front-end switches.

While GaAs processes offer useful features such as higher (breakdown voltage)(cut-off frequency) product, semi-insulating substrate, and high-quality inductors and capacitors, silicon devices in a VLSI technology can potentially provide both higher levels of integration and lower overall cost, as demonstrated in complex circuits such as frequency synthesizers. In fact, all building blocks of typical transceivers are available in silicon bipolar technologies from many manufacturers.

IV. Next-Generation RF Design

RF communication is experiencing what computing experienced one decade ago: evolving from limited applications to a wide presence in all facets of our lives. As the cost of RF design drops, the consumer market can afford increasingly more sophisticated RF communications in various products.

An example of such a development is the pager wristwatch introduced by Seiko, Inc. [1]. In addition to paging, the watch provides, in real time, traffic reports, weather forecasts, stock quotations, etc. Shown in Fig. 4 in simplified form, the receiver consists of a single-chip RF section, a digital signal processor, and a microcontroller. Operating in

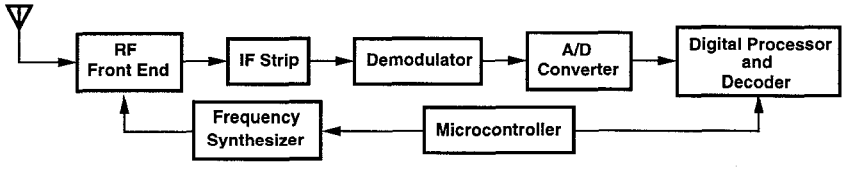

Fig. 4. Seiko's wristwatch pager.

the 88-108 MHz commercial FM broadcast band, the RF IC includes a heterodyne front end, a 10.7-MHz intermediate-frequency (IF) strip, a frequency synthesizer, and an FM demodulator. The DSP performs analog-to-digital conversion and baseband operations such as clock recovery and channel selection. The overall operation of the watch and the user interface is controlled by a 4-bit 50-kHz microcontroller.

With a data rate of 19 kb/s, the pager incorporates various software and hardware power management techniques to allow a battery life of 14 months while operating with a 3-V lithium cell [1].

We classify next-generation RF products under two categories: evolving applications and emerging applications.

A. *Evolving Applications*

Wireless Local Loop. Statistics indicate that approximately half of the world population has never used a telephone, suggesting that even ordinary phone service still has a large uncultivated market. Since many parts of developing countries do not even have a telephone network infrastructure, providing the service requires an enormous capital investment and a long deployment cycle. Thus, wireless phone service has been considered as a more reliable, flexible, and *economical* alternative to traditional wired networks, a possibility that exists because the cost of RF design has decreased significantly over the years.

One form of a wireless phone network is called the "wireless local loop" (WLL), also known as a "fixed cellular system" [5]. Shown in Fig. 5 is an example where each base station serves a large number of fixed users while providing connection to the central

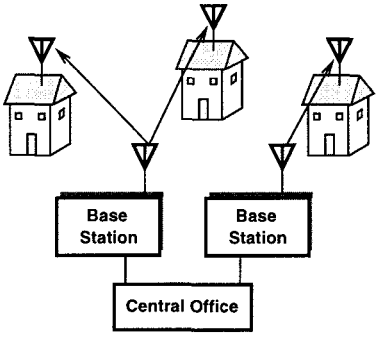

Fig. 5. Conceptual example of WLL.

office through wires [5]. The fixed nature of the transceivers in the WLL technology relaxes many of the requirements that would be quite stringent in a mobile communication environment. For example, directional antennas placed at high spots can enhance the signal power received by each user.

WLL applications mandate user transceiver sets with a low cost, comparable to that of cordless phones, and a relatively high performance, somewhat superior to that of cordless phones to allow communication over a distance of 500 m to 1 km. Modularity and programmability are also essential in such systems because of different requirements in different geographical areas.

WLANs. WLANs constitute a rapidly growing sector of the RF industry. At present, the unlicensed 2.4-GHz band is exploited for such applications [6] to provide data rates

around 2 Mb/s. However, the higher rates required in exchanging digitized video and eventually establishing a wireless multimedia environment make it desirable to employ wideband standards. One such standard is the High Performance Local Area Network (HIPERLAN), operating around 5.2 GHz and allocating a bandwidth of 23.5 MHz to each user [7]. Table 1 summarizes some of the HIPERLAN's specifications.

Carrier Frequency	5.15–5.3 GHz
Carrier Frequency Accuracy	10 ppm
Channel Bandwidth	23.5 MHz
Signaling Rate	23.5 Mb/s (High Rate) 1.47 Mb/s (Low Rate)
Modulation	GMSK, BT = 0.3 (High Rate) FSK, Δf = 368 kHz (Low Rate)
Output Power: Class A	+ 10 dBm
Class B	+ 20 dBm
Class C	+ 30 dBm
Transmitter Rise Time	< 1.5 us
Fall Time	< 3 us
Transmitter Unwanted Emissions	< –36 dBm in 100 kHz
TX–RX Switching Time	5 us
Receiver Sensitivity: (Packet Error Rate = 0.01)	
Class A	–50 dBm
Class B	–60 dBm
Class C	–70 dBm
Receiver Unwanted Emissions	< –57 dBm in 100 kHz

Table 1. Performance specifications of HIPERLAN.

HIPERLAN presents many challenges in the design of both the RF section and the baseband section of transceivers. The high carrier frequency makes it difficult to design RF amplifiers, mixers, and oscillators in mainstream VLSI technologies. Furthermore, for a 23.5-MHz bandwidth, functions such as channel selection filtering and A/D conversion with low noise and high linearity entail severe trade-offs.

Digital baseband processing for HIPERLAN involves its own challenges. Equalization at 23.5 Mb/s with reasonable power dissipation and silicon area demands a great deal of work in high-speed low-power digital design.

With a wavelength of 6 cm at 5 GHz, the use of "antenna diversity" becomes feasible. Shown in Fig. 6, the idea is to employ two antennas separated by roughly one-quarter of the wavelength so that if one antenna is located in a deep fade, the other is less likely to be. The principal issue is: how should the receivers be designed and at what point should the results be combined to minimize the overall power and hardware?

RF IDs. Low-cost RF ID tags can prove quite useful in asset tracking and management, automatic identification, security systems, toll collection, and control systems. An example of recent developments in the RF ID technology is the system introduced by Micron Communications [8]. Illustrated in Fig. 7, the tag integrates a 2.4-GHz RF transceiver with clock recovery and spread spectrum circuits, power management blocks, and an 8-bit

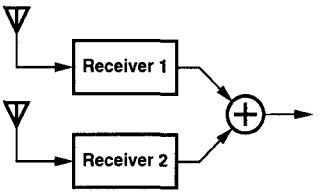

Fig. 6. Example of antenna diversity.

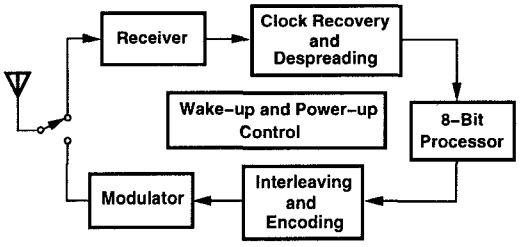

Fig. 7. Micron's RF ID.

processor including memory onto a 16-mm^2 CMOS chip. The system employs a direct-sequence spread spectrum technique. In a typical setup, the tag communicates with a host computer via an interrogator.

B. Emerging Applications

Microcell and Picocell Structures. Each cell in the present cellular system has a diameter of roughly 20 km. Thus, the portable phone must produce enough RF power to allow communication with the base station over a 10-km distance. Cost and efficiency issues of power amplifiers, especially as the supply voltage decreases to minimize the number of batteries, make it desirable to reduce the size of each cell. This applies particularly to the cases where most of the communication occurs within a small, but densely populated area. Reduction of cell size can lead to "microcell" (less than 1 km in radius) and even "picocell" (less than 100 m in radius) structures, with the required RF power going down to only a few tens of milliwatts.

The principal barrier in reducing the cell size is the need for additional base stations. Complexity, cost, and *real estate* issues make it difficult to divide a crowded metropolitan area into smaller cells, each of which must be served by a new base station. Nevertheless, the concept is particularly well-suited to communication within large buildings and is also actively pursued for a wider range of applications.

More Digital, Less Analog. The complexity of the typical heterodyne receiver in Fig. 1, especially the need for several off-chip, expensive, and bulky filters, has created a dream for RF system designers: discard all the analog signal processing, directly digitize

the signal received by the antenna, and perform all the operations in the digital domain (Fig. 8). Since the ADC would need a dynamic range of more than 100 dB and an

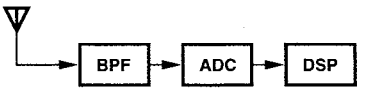

Fig. 8. Direct digitization of RF signal.

input bandwidth of greater than 1 GHz, this dream is not practical in today's technology. However, the idea of moving the A/D interface closer to the antenna seems promising.

A step toward this direction is the "digital-IF" topology, wherein the last mixer in the heterodyne chain is replaced by an A/D converter (Fig. 9). Since typical ADCs perform sampling before quantization, they can operate as downconversion mixers as

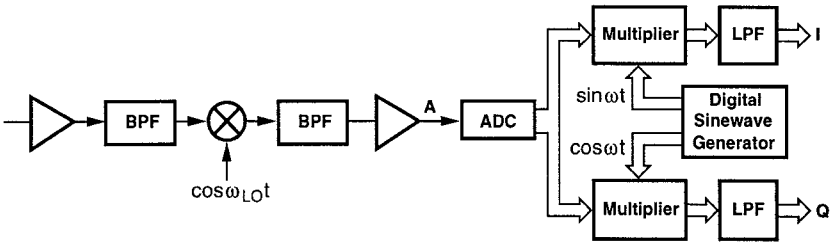

Fig. 9. Digital-IF receiver.

well. Another possibility is to simply digitize the signal and carry out the quadrature multiplication digitally.

As the A/D interface comes closer to the antenna, two of its parameters must simultaneously improve: the dynamic range and the input bandwidth. Increasing both the resolution and the input bandwidth requires substantial power dissipation penalty and is, in many cases, impractical due to device limitations. As a consequence, with present technology this interface may remain at the second IF in Fig. 1, but further advances in ADC design will bring it closer to the front end [9, 10].

Multi-Standard Transceivers. The existence of various wireless standards within the US and around the world has created a demand for transceivers that can operate in more than one mode. In the simplest case, two different receive and transmit frequency bands must be supported while other properties of the system remain unchanged. For example, the two European standards, GSM and DCS1800, differ by primarily their frequency bands. In a more sophisticated scenario, the transceiver can operate with two vastly different standards, e.g., IS-54 (TDMA) and IS-95 (CDMA).

Accommodating two or more standards in one transceiver generally requires substantial added complexity in both the RF section and the baseband section, leading to a high cost. Thus, the system must be designed so as to maximize the shared hardware. Fig. 10 illustrates

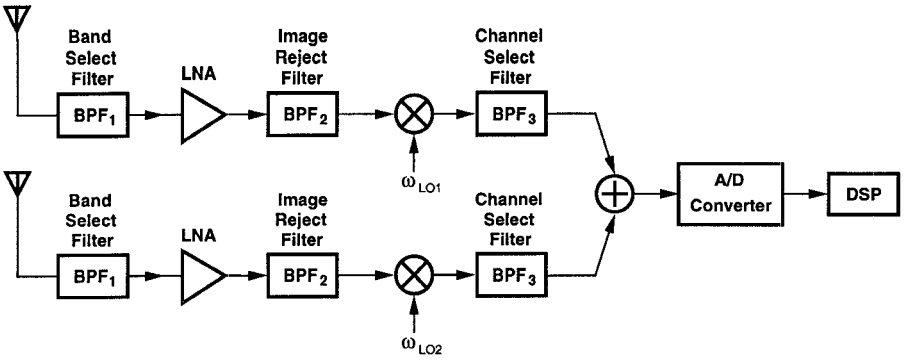

Fig. 10. Dual-standard receiver.

an example of a dual-standard receiver with two different input frequency bands. After downconversion to a single IF, the two signals are added and digitized. The remaining IF and baseband processing is subsequently performed in the digital domain. As mentioned above, the dynamic range and noise of the A/D converter are critical issues in such an environment.

Cable Modem. RF design finds application in *wired* systems as well. An important example is "cable modem," a standard that allows data communication over the cable TV network. Illustrated in Fig. 11 is a transceiver that can be used by a subscriber to

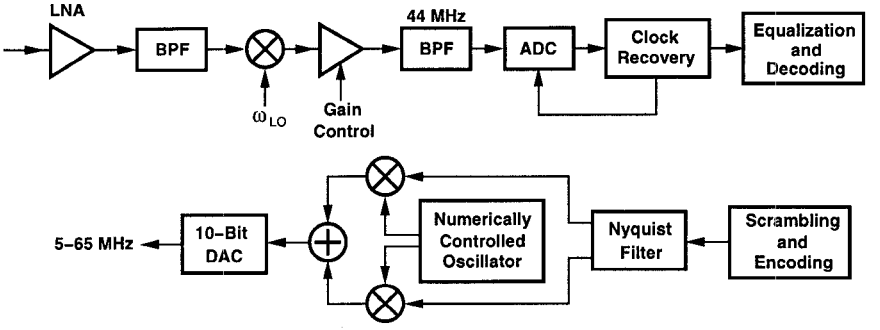

Fig. 11. A cable modem transceiver [11].

receive modulated data in the 50- to 750-MHz band ("downstream") and transmit in the 5- to 65-MHz band ("upstream") [11]. The receiver consists of a heterodyne front end, a 10-bit A/D converter, and a baseband processor performing operations such as clock recovery, equalization, and decoding. The transmitter carries out encoding, filtering, and upconversion modulation, all in the digital domain, converting the result to analog form at the end. In order to achieve downstream data rates as high as 30 Mb/s in a 6-MHz

bandwidth, the system incorporates quadrature amplitude modulation (QAM) with 16, 64, or 256 constellation points.

The principal challenge in cable modem RF design is that the system must interfere negligibly with the cable TV channels. Thus, unwanted noise, spurs, and harmonics, especially in the transmit path, must be predicted and controlled accurately. Furthermore, unlike typical wireless applications, cable modem operates across more than one decade of frequencies, requiring a wide range in some of the filters and oscillators.

C. *Devices and Technologies*

Market predictions indicate that GaAs and silicon bipolar and BiCMOS technologies will sustain their strong presence in the RF market for many years. However, a third contender is CMOS technology. Supported by the enormous momentum of the digital market, CMOS devices have achieved high transit frequencies, e.g., tens of gigahertz in the 0.35-μm generation, and "RF CMOS" has suddenly become the topic of active research. CMOS technology must nevertheless resolve a number of practical issues: substrate coupling of signals that differ in amplitude by 100 dB, parameter variation with temperature and process, and device modeling for RF operation.

A typical transceiver requires the following RF and mixed-signal building blocks: low-noise amplifiers and mixers, oscillators, frequency synthesizers, IF strips, filters, A/D and D/A converters, modulators, and power amplifiers. While CMOS realizations of many of these circuits have been reported [12, 13, 14], the ultimate figure of merit will be the performance of a complete CMOS system, especially when variations in a realistic environment are taken into account. Innovations at the architecture level may be required to alleviate design issues at the circuit level.

The trade-offs involved in the design of the above building blocks can be summarized in the "RF design hexagon" shown in Fig. 12, where almost any two of the six parameters trade with each other to some extent. The key point here is that, while digital circuits directly

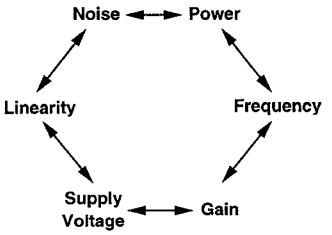

Fig. 12. RF design hexagon.

benefit from advances in IC technologies, RF circuits do not as much. In particular, simple figures of merit used for individual devices fail to predict the performance of circuits. Interestingly, the noise figure of a low-noise amplifier may be *lower* than that of a single transistor.

Since most RF building blocks are narrowband circuits, they can greatly benefit from resonances created by passive inductors. In fact, in some cases, e.g., oscillators, the use of inductors appears essential to achieving low phase noise. A critical shortcoming of integrated circuit technologies is the lack of high-quality inductors, more so in bulk CMOS technologies than in Si bipolar and GaAs processes. In this respect, the high-resistivity substrate in silicon-on-insulator (SOI) CMOS may be advantageous. Other properties of SOI, e.g., lower cross-talk through the substrate and smaller parasitic capacitances, make this technology attractive for RF design. Research on SOI continues [15].

D. Design Tools

Computer-aided analysis and synthesis tools for RF ICs are still in their infancy, forcing the designer to rely on experience, intuition, or inefficient simulation techniques to predict the performance. For example, nonlinearity, time-variance, and noise in RF circuits usually require studying the spectrum of signals, but the standard ac analysis available in SPICE uses only linear, time-invariant models. Thus, circuits are simulated in the time domain so as to include nonlinear or time-variant effects and the resulting waveforms are subsequently transformed to the frequency domain to obtain the spectrum. The difficulty is that the time-domain simulation must be run for a long period to resolve closely-spaced frequency components. In addition, spectral averaging techniques may be necessary if random noise is used in the time domain analysis.

Another issue in simulating RF circuits relates to external components that cannot be modeled by typical devices in SPICE. For example, surface acoustic wave (SAW) filters, used in both the receive and the transmit paths, exhibit input and output impedances that can be characterized only by scattering (S) parameters —essentially a table of numbers. Modeling such circuits with RLC networks provides a first-order approximation, but it may not predict effects such as instability and impedance mismatch.

CAD tool development for RF design is a topic of active research today [16, 17].

REFERENCES

[1] A. Kompolt and J. Brewer, "Designing a Wristwatch Pager Creates Its Own Special Challenges," *Wireless Systems Design,* pp. 37-41, March 1997.

[2] B. Razavi, *RF Microelectronics,* NJ: Prentice-Hall, 1997.

[3] T. D. Stetzler et al, "A 2.7-4.5 V Single Chip GSM Transceiver RF Integrated Circuit," *IEEE J. of Solid-State Circuits,* vol. 30, pp. 1421-1429, Dec. 1995.

[4] R. Schneiderman, "GaAs Continues to Gain in Wireless Applications," *Wireless Systems Design,* pp. 14-16, March 1997.

[5] V. K. Garg and E. L. Sneed, "Digital Wireless Local Loop System," *IEEE Communications Magazine,* pp. 112-115, Oct. 1996.

[6] R. O. LaMaire, et al, "Wireless LANs and Mobile Networking: Standards and Future Directions," *IEEE Communications Magazine,* pp. 86-94, Aug. 1996.

[7] ETSI TC-RES, "Radio Equipment and Systems (RES); High Performance Radio Local Area Network (HIPERLAN); Functional Specification," ETSI, 06921 Sophia Antiplois Cedex, France, July 1995.

[8] J. R. Tuttle and B. A. Pier, "New Technology Expands RFID Applications," *Wireless Systems Design,* pp. 24-27, Oct. 1996.

[9] A. Hairapetian, "An 81 MHz IF Receiver in CMOS," *ISSCC Dig. Tech. Papers,* pp. 56-57, Feb. 1996.

[10] J. E. Eklund and R. Arvidsson, "A 10 b 120 MS/s Multiple Sampling Single Conversion CMOS A/D Converter for I/Q Demodulation," *ISSCC Dig. Tech. Papers,* pp. 294-295, Feb. 1996.

[11] P. McGoldrick, "Super Chip Is the First to Get the Cable Modem Down to Size," *Electronic Design,* pp. 67-74, June 9, 1997.

[12] A. Rofougaran et al, "A 1-GHz CMOS RF Front-End IC for a Direct-Conversion Wireless Receiver," *IEEE J. of Solid-State Circuits,* vol. 31, pp. 880-889, July 1996.

[13] D. K. Shaeffer and T. H. Lee, "A 1.5-V 1.5-GHz CMOS Low-Noise Amplifier," *IEEE J. of Solid-State Circuits,* vol. 32, pp. 745-759, May 1997.

[14] J. Craninckx and M. Steyaert, "A 1.8-GHz Low Phase Noise CMOS VCO Using Optimized Hollow Spiral Inductors," *IEEE J. of Solid-State Circuits,* vol. 32, pp. 736-747, May 1997.

[15] W. M. Huang et al, "TFSOI Technology for Wireless Communication Systems," *Proc. CICC,* pp. 421-426, May 1997.

[16] K. Mayaram et al, "Overview of Computer-Aided Analog Tools for RF IC Simulation: Algorithms, Features, and Limitations," *Proc. CICC,* pp. 505-512, May 1997.

[17] J. Roychowdhury, D. Long, and P. Feldman, "Cyclostationary Noise Analysis of Large RF Circuits with Multi-Tone Excitation," *Proc. CICC,* pp. 383-386, May 1997.