Device and Technology Requirements for Next Generation Communications Systems (Invited Paper)

Lawrence E. Larson*

IBM Research Division, San Diego, CA

Abstract

The rapid deployment of next generation communications systems – both wired and wireless – on a worldwide basis creates a unique opportunity for the semiconductor industry. High-speed networks require massive computing power and analog and radio frequency devices with wide dynamic range and bandwidth. The semiconductor technologies required to implement these systems will be highlighted, with particular emphasis on the technologies required to meet the demands of mobile computing applications.

Introduction

The explosion of worldwide demand for communication systems - both wireless and "wired" - has created an enormous and entirely new market for semiconductor devices of all types. As an example, well over 100 million wireless handsets are sold annually today, and the annual worldwide market could approach an astonishing 500 million telephones by the middle of the decade [1].

This boom has provided an unprecedented opportunity for a variety of new semiconductor device technologies; devices previously deemed too "exotic" for high-volume production are now finding themselves inserted into the most inexpensive portable devices. At the same time, scaled digital CMOS technology is finding increasing use for analog and RF communications applications.

This paper will summarize the semiconductor technological requirements for next generation communications systems, and highlight some trends and challenges for the future. Table I highlights a very "top level" view of the role of differing technologies in future telecommunications applications.

Table I: Overview of Integrated Circuit Requirements for Next-Generation Communications Systems

System	Dynamic Range	Level of Integration	Speed	DC Power	Cost
3G Wireless	Very High	Medium/ High	1-2 GHz	Very Low	Low
Ad-Hoc Wireless	High	High	2-5 GHz	Very Low	Very Low
Fiber	High	Medium /High	10-40+ GHz	Medium	Medium
ADSL/ Cable	Very High	High	0.5-2 GHz	Medium	Low

Architectures and Systems

An electronic communications system has to contend with a channel that is essentially hostile; its loss is large and time varying, and it often supports multiple users (resulting in interference). These aspects of the environment typically result in a great diversity in the amplitude and bandwidth of the received and transmitted signals. How does this fundamental aspect of the medium affect the system design and device requirements? I will examine three typical examples of the requirements of next-generation communications systems: a cable modem transceiver system, a 3G cellular WCDMA system and a Bluetooth wireless system. These examples will illustrate some of the unique technology requirements of future communications systems.

A. Cable Modem Design

As shown in Figure 1, the "downstream" portion of a typical cable-modem system consists of a set of shared 64 QAM channels - each roughly 5 MHz wide - from 54 MHz to 860 MHz. The receiver - at each cable modem - is required to tune over this entire range, digitize the resulting signal, perform equalization, demodulation and symbol and timing recovery, along with standard Media Access Control functions [2]. Another feature of this example - which is common to most communications systems - is that due to highly variable cable losses, the receiver must operate close to the thermodynamic limit of sensitivity,

* Currently on leave from the University of California, San Diego

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with a Noise Figure of 10 dB or less. The receiver is a complex mixture of radio frequency, analog, and digital functions; in this case, it is currently implemented with several CMOS ASICs and a SAW filter for channel selection purposes.

Scaled CMOS technology enables the high-level of integration to be compatible with a consumer application, and the surface acoustic wave (SAW) filter performs the crucial role of channel selection. In fact, the SAW filter is one of the key unheralded technologies that has made the communications revolution possible, and at present remains stubbornly beyond the range of replacement by integrated circuit techniques due to its outstanding dynamic range and group delay properties. The rest of the system is expected to be implemented with CMOS technology for the foreseeable future.

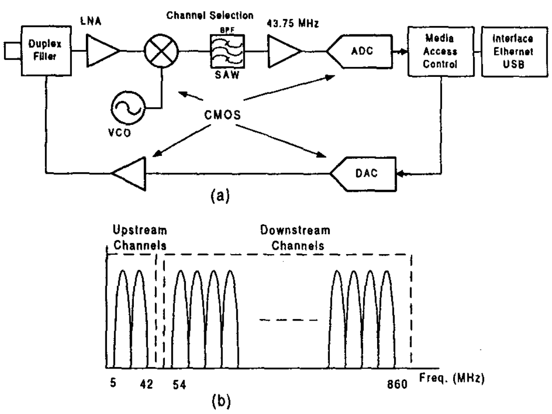

Figure 1: (a) Simplified block diagram of cable modem transceiver. (b) Frequency plan.

B. Wideband CDMA Wireless

The proposed Third Cellular standard known as Wideband CDMA is a wireless cellular standard, to be placed into service in Japan in 2001, and implemented on a worldwide basis over the next decade. The goal of third-generation (3G) communications is to provide high-speed data over the cellular infrastructure while providing for improved multipath resolution and diversity compared to existing 2G solutions. The target data rates are 144 kbps for wide-range usage and full mobility, and up to 2Mbps for virtual home service and low mobility. The carrier frequency of the transmit and receive waveforms is approximately 2 GHz. A block diagram of a generic WCDMA handset transceiver is shown in Figure 2.

In this case, the performance challenges require a more complex range of semiconductor device technologies, since minimum dc power consumption is an absolute necessity. The handset transmitter power amplifier must transmit a roughly one watt microwave signal with near audio fidelity levels, and dc-rf efficiency as close to 100% as possible. Existing CDMA power amplifiers mostly employ GaAs HBT technology, although GaAs PHEMT technology has also become more popular recently, exhibiting even greater efficiency and linearity [3]. Linearity is an extremely important consideration for 3G power amplifiers, since multiple channels are expected to be transmitted simultaneously through the device, resulting in a very wide dynamic range of the transmitted waveform.

The low-noise amplifier/down-converter and frequency synthesizer sections are typically implemented in a BiCMOS technology for high-gain and dynamic range in the microwave region [4]. The frequency synthesizers can be implemented in BiCMOS or all-CMOS technology. BiCMOS technology is often used for its low-phase noise characteristics, but recent CMOS frequency synthesizers have also demonstrated excellent performance. The digital baseband ASIC is naturally implemented in CMOS. As with the cable modem design, surface acoustic wave (SAW) filters performs the crucial role of channel selection and interference suppression. Once again, one of the key goals of next generation implementations is the elimination of these bulky and relatively costly devices.

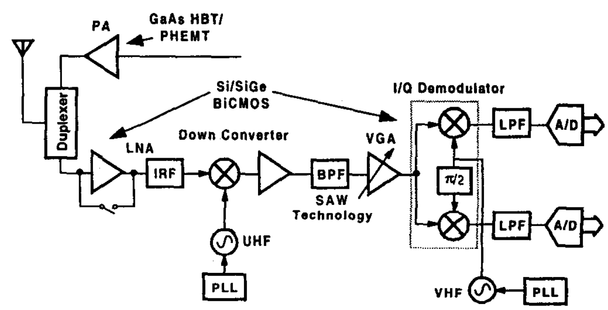

Figure 2: Block diagram of 3G wireless transceiver. A variety of technologies will be required for a complete implementation.

C. Bluetooth Wireless

The Bluetooth wireless standard was proposed in an attempt to provide ubiquitous short range (<10m) wireless interconnection (at speeds up to 2 MB/s) between a myriad of devices [5]. These Personal Area Networks (PANs) represent a tremendous opportunity to extend the range of applications of wireless technologies. These devices must have a *very* low power consumption to be embedded in portable applications, be *very very* inexpensive so they can be inserted into every conceivable consumer device. This is indeed a difficult goal, given the fact that the physical layer characteristics of the system are in fact quite challenging.

The Bluetooth standard uses the 2.4-2.5 GHz band, which is available in much of the world for unlicensed operation. The transceiver uses a slow Frequency Hopped Spread Spectrum (FHSS) access method with a nominal rate of 1600 hops/second. The modulation is constant amplitude Gaussian Frequency Shift Keyed (GFSK), with a frequency deviation of up to ±175 kHz and a transmit power of up to 100mW. As an unlicensed transmitter, all Bluetooth devices in the United States must operate under Part 15 regulations of the FCC – they must not cause interference to other licensed systems, and they must accept interference from all other systems, including microwave ovens!

The key challenge with the proposed Bluetooth device is the implementation of the entire transceiver on a single low-cost integrated circuit die. So, the transmitter, receiver, and frequency synthesizer must all be "co-located" on a single CMOS or BiCMOS substrate. The cost and form factor requirements probably prohibit the use of SAW filters for channel selection, so a Direct Conversion - or zero-IF - downconversion architecture is commonly proposed, as shown in Figure 3. In this case, all of the filtering can be done at low frequencies, easing the monolithic implementation. This architecture has numerous historical problems, despite its attractiveness for monolithic implementation, so a variety of alternatives have been proposed, including very-low IF, low-If and high-IF [6].

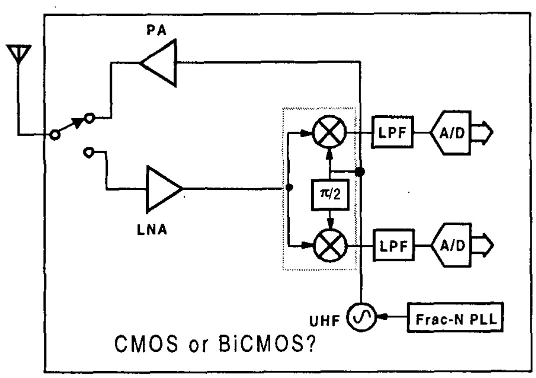

Figure 3: Simplified block diagram of Bluetooth transceiver. The goal in this case is a single-chip implementation of the complete function, for the lowest possible cost.

Semiconductor Technologies for Next Generation Communications Systems

In most cases, next generation communications systems will follow the evolutionary path of traditional silicon and III-V technologies. However, within each of these, improved device technologies will create new opportunities for system insertions previously dominated by more exotic approaches. The next sections will briefly summarize the status of these technologies, with particular emphasis on where changes make come in key implementation strategies as we move into next generation systems.

A. Silicon and SiGe Semiconductor Devices

Digital CMOS is the "tsunami," that created the technological impetus for the communication revolution. Traditional scaling of CMOS technology continues unabated, with production gate lengths now less than 0.15um [7]. The digital VLSI portions of the communications system can "ride" the CMOS scaling wave for the foreseeable future, and the analog and RF portions of the communications system are also increasingly being implemented in CMOS. The Bluetooth and cable modem systems are two examples of applications where CMOS can probably implement all of the required semiconductor functions in the future.

The major issue here is the ultimate limit on scaling and the reduction in dynamic range of MOS devices, since many of the newer systems are actually increasing their dynamic range requirements – 3G wireless is a good example [8]. So the challenge will be to maintain the dynamic range of scaled CMOS technology while exploiting its digital capabilities. In addition, digital CMOS foundries have made considerable progress recently in the addition of key passive component technologies - inductors, MIM capacitors, varactor diodes - for RF and mixed-signal applications.

There are applications where power dissipation, high-speed, and dynamic range are crucial in the RF and analog portions of the device – once again in 3G wireless and fiber-based circuits - and in these cases, there is a clear role for a Si/SiGe HBT BiCMOS technology. The high transconductance per current and high f_T at low collector voltages [9] makes the bipolar device in a BiCMOS process an ideal candidate for low-power high-performance applications, if its associated CMOS technology is close to the state-of-the-art performance. Most state-of-the-art BiCMOS foundries have recently announced Si/SiGe HBTs as their baseline bipolar technology, and there seems to be no fundamental reason to prevent the technology from scaling to the 150 GHz f_T region in the next few years.

B. III-V Devices

After suffering a "near death" experience in the early 1990s, GaAs technology has found a large and profitable niche serving as key antenna interface circuits (low-noise amplifiers, switches, and power amplifiers) for cellular handsets, and, to a lesser extent, as a key technology for fiber-based circuits. The GaAs HBT demonstrated a real knack for linear, efficient, power amplifiers for 2G CDMA wireless applications, and it expected that this will continue for the foreseeable future. This is partly due to the high linearity, gain and breakdown voltage of the device - due to the well-known Johnson limit [10] - and partly due to its intrinsic advantages of single power supply operation compared to a GaAs MESFET. However, GaAs PHEMTs have recently demonstrated even better performance, and may prove to be an important power amplifier technology in the future. Silicon HBT power amplifiers have also demonstrated comparable performance to GaAs HBTs in some of these applications [11]. The advantage of III-V technology for high-volume applications other than power amplifiers is less clear, and it is expected that silicon technology - both CMOS and BiCMOS – will gradually encroach on the GaAs applications in the lower microwave frequency region (below 5 GHz).

New Devices for Communications Applications

A common problem highlighted in the previous sections is the persistence of the use of SAW filters for communications applications, primarily for channel selection purposes. These devices continue to be relatively expensive and bulky and have stubbornly thwarted architectural and technological attempts at their elimination. There are fundamental limitations on the use of *active filter* circuit techniques for their replacement, so there are a number of ongoing efforts to eliminate the SAW device that are more grounded in semiconductor device technologies.

One of the most promising new developments in this area is MEMs technology. These devices promise to solve some of the most vexing long-standing problems in communications, including optical switching and low-loss microwave switching in addition to low-loss monolithic filters [12]. In most cases, these devices can be fabricated using silicon VLSI fabrication techniques, and the improvement in performance over traditional approaches can be substantial. However, a variety of fundamental material issues - primarily reliability and yield - need to be solved before these devices find widespread acceptance.

Another very promising semiconductor device technology is GaN-based heterojunction FETs. GaN has a much higher breakdown field than GaAs or InP, and its electron velocity is comparable to those other compound semiconductors. As a result, it may be a nearly ideal device for high power microwave and millimeterwave applications – like base stations. Recently, a 9.1W amplifier was demonstrated in this technology at 7 GHz [13].

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