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DynamicSilicon

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The Investor's Guide to Breakthrough Micro Devices

MEMS and the Cell Phone

Your cell phone is a radio. It uses different "modulation" schemes and different "bands" (ranges of frequencies) from common AM and FM radios, but it's still a radio. Microelectromechanical systems are invading cell phones to lower their size, cost, and energy consumption and to improve their quality and capabilities. To understand how this is happening, let's take a look at how radios work.

When you speak, your voice pressurizes air in a way that listeners interpret as sound. You are "modulating" the air—making it carry your voice. Radio stations modulate electromagnetic energy by varying its strength or its frequency—making it carry radio programs. Twenty-nine AM and fifty-seven FM radio stations broadcast in the San Francisco Bay Area. You don't hear any of them, but the radio in your car has no problem translating them into pressure waves your ears recognize as sound. AM stations broadcast in a radio frequency (RF) band from 540 kHz to 1650 kHz, with a 10 kHz spacing between stations. For example, KFRC in San Francisco broadcasts at 610 kHz. 610 kHz is called the "carrier wave." It carries the radio program. When you tune to 610 kHz, you are instructing your radio to: 1) find an electromagnetic signal whose voltage is changing 610,000 thousand times a second and 2) demodulate it—look at the changes in the strength of that signal and interpret those changes as KFRC. FM stations occupy the band from 88 MHz to 108 MHz with 200 kHz spacing between stations.

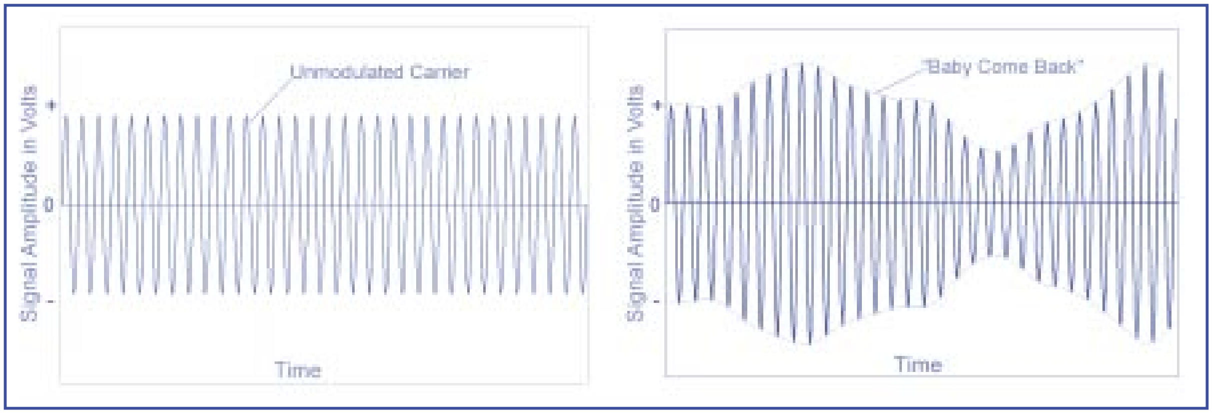

Fig. 1. One millisecond of unmodulated carrier and one millisecond of an amplitude-modulated signal.

Fig 1. is one millisecond of Bonnie Raitt's "Baby Come Back" (see *Dynamic Silicon*, Vol. 1, No. 3) modulating the amplitude (strength) of a carrier wave. If oldies station KFRC transmitted this millisecond of "Baby Come Back," there would be 610 of those spiky-looking cycles in fig. 1's carrier wave (I've drawn fewer cycles to make things easier to see).

Suppose I want to listen to KFRC as I'm driving around the Bay Area. My car's single radio antenna sees signals from eighty-six broadcast stations. I'm likely to be miles from KFRC's broadcast antenna. Since signal strength drops with the square of the distance, a 100,000-watt station transmits less than 3 *microwatts* through each square foot of space just 10 miles from the station's antenna. So the car's radio will need amplifiers.

As I tune the radio to 610 kHz for KFRC, I'm adjusting an electronic "filter" that discards signals from the other eighty-five broadcast stations. Simple filters use just a capacitor and an inductor. The inductor and capacitor in a filter exhibit a "resonant frequency" that depends on the values of the inductor and capacitor. Turning the

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station knob moves the plates of a parallel-plate capacitor, changing the capacitance and, therefore, changing the resonant frequency of the filter. Imagine a row of half pie-plates, in a dish rack, with every other plate attached through its center to the tuning knob. Rotating the knob moves half of the plates so there's less overlap between the two sets; that changes the capacitance. More sophisticated filters use transistors and have complex configurations, but they still use individual inductors and capacitors. Components in these original radios were three-dimensional. Tuning capacitors, for example, were large, really did look like collections of moving and flat plates in a dish rack, and were bolted inside the radio chassis with a tuning knob protruding through the faceplate. Inductor coils wound around a physical core in three dimensions. Vacuum tubes and diodes were the size of today's refrigerator light bulb.

In addition to blocking undesired signals, the radio's filters demodulate the signal—remove the carrier wave and see the modulating signal (i.e., "Baby Come Back"). Demodulation depends on the operating characteristics of the combined individual circuit components, particularly the capacitors and the inductors. It is difficult, however, to build a demodulator that gives good results over a range of frequencies such as the whole AM or FM band.

The Q, or "quality," of an inductor or capacitor is a measure of energy stored to energy lost in the component. Higher values of Q are better. Q depends on frequency. Q increases as frequency increases for both capacitors and inductors. Q also increases as capacitance or inductance increases. Because component Q varies with frequency, the behavior of a filter changes with frequency. The receiver works better for stations at one end of the band than for stations at the other end.

Heterodyne receiver

In 1932, Major Edwin Armstrong found a way around this difficulty by inventing the heterodyne (often called "superheterodyne") receiver. This receiver employs a variable-frequency local oscillator. ("Local" meaning that it is in the receiver and "oscillator" meaning a capacitor-inductor circuit that produces a resonant frequency.) The moving-plate tuning capacitor for the local oscillator is ganged together with the moving-plate tuning capacitor for the signal-selection filter. The filtered incoming signal and the signal from the local oscillator are subtracted to produce difference frequencies. Since the tuning capacitors are ganged together in a fixed relationship, the difference frequency remains constant over the tuning range. For the AM band (610 kHz to 1650 kHz), the local oscillator varies from 995 kHz to 2105 kHz—it's always 455 kHz higher than the input channel. The difference frequency is called the IF or intermediate frequency and is always 455 kHz. While it is difficult to build demodulators that work across a range of frequencies, it is possible to build excellent demodulators for a fixed frequency.

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The heterodyne receiver has three sections. The RF section amplifies incoming signals, filters them, and creates the IF, or intermediate frequency, signal. The IF section demodulates the signal. The "baseband" section interprets the demodulated signal. If the modulating signal was analog, the baseband function may be as simple as amplifying the demodulated signal to drive a speaker. If the modulating signal was digital, baseband functions may be complex enough to require a microprocessor, a digital signal processor, application-specific integrated circuits, and a few megabytes of software. The genius of the heterodyne receiver is gang-tuning signal selection and the local oscillator and mixing them to produce a constant intermediate frequency for the demodulator. Most of today's radios (including cell phones) use heterodyne receivers.

In the U.S., cell phones operate primarily in two frequency bands: cellular telephone and PCS (personal communication services). The cellular telephone band is 824 MHz to 849 MHz, for transmissions from handset to base station, and 869 MHz to 894 MHz, for transmissions from base station to handset. The base station allocates transmit-receive frequency pairs to the handset on each call. Transmit and receive frequencies are always separated by exactly 45 MHz. A handset transmitting on 830 MHz, for example, would receive on 875 MHz. The PCS band is 1850 MHz to 1910 MHz, for transmissions from handset to base station, and 1930 MHz to 1990 MHz, for transmissions from base station to handset.

Cell phone components

Andy Krumel and Brion Shimamoto let me dismantle their cell phones. Now fig. 2 shows one of the cell phones. The cell phone has three sections separated by metal strips. The RF section is on the left; it contains the transmit/receive switch, antenna, local oscillator (receive), channel selection filter, and mixer. The middle is the IF section. The IF section separates

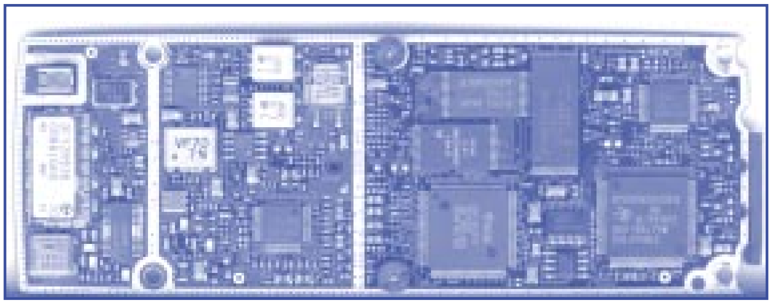

Fig. 2. The cell phone has too many discrete components.

the information content (bit stream) from the "carrier wave." The IF section contains amplifiers, filters, IF oscillator, IF mixer, and analog to digital converters. The RF and IF sections contain the transmitter's components: digital to analog converters, local oscillator (transmit), modulators, and the power amplifier. The right half of fig. 2 is the "baseband" section, which interprets the demodulated signal and thus includes the digital processing and the user interfaces. The baseband section contains the microprocessor, digital signal processor, application-specific integrated circuits, and memory.

I didn't count components in fig. 2, but there must be more than 200 in this circa 1998 cell phone. The integrated circuit (IC) has invaded the radio (including the cell phone), but it sure has not conquered it. The IC has been around for more than forty years; million-transistor ICs are common and cheap; why can't the cell phone be a couple of ICs? The IC process is "planar," meaning that ICs are two-dimensional. Inherently three-dimensional components don't flatten well. Inductors, for example, can be implemented in ICs as a flat spiral, but such inductors suffer due to losses coupled into the substrate. To make an inductor with a high Q rating, you have to work in three dimensions. The alternating fixed and moving plates of the tuning capacitor can't be duplicated in a flat semiconductor process.

The CMOS IC process uses primarily silicon, silicon dioxide, and aluminum, so components made of ceramics and crystals are foreign materials and do not integrate well. But ceramics are essential to certain filters and crystals are essential for precision oscillators. Switches are a problem too. Insertion loss and isolation measure switch quality. Insertion loss measures signal loss across a closed switch (the transistor is on) in a circuit. Isolation measures leakage through the switch when it is open (the transistor is off). Think of insertion loss as not being "on" enough. Think of isolation as not being "off" enough.

What? How can switches be a problem? Most of the millions of components in a modern microprocessor are transistor switches. But these millions of transistors are *logic* switches. Logic circuits tolerate huge variation in insertion loss and in isolation because they must distinguish only between a one and a zero. But the analog circuits of the RF and IF sections of a radio want ideal components—any loss or leakage degrades the signal.

It would be nice if the entire RF and IF sections of fig. 2 could be integrated into a single IC. Here's what's on and off the chip in typical RF and IF sections. In the RF section, the amplifiers, parts of the voltage-controlled oscillator, and the RF mixer are integrated into a single chip. The antenna, antenna switch, (ceramic) bandpass filter, transmit/receive switch, (ceramic) image rejection filter, the local oscillator's crystal, and the inductors and capacitors for the oscillators and filters are independent components. In the IF section, the amplifiers, the automatic gain control, and the IF mixer are integrated. The IF filter and the inductors and capacitors for the oscillator are independent components. In the transmitter, the modulator and the power amplifier are integrated. The oscillator crystal and the capacitors and inductors for the oscillator and amplifier are independent components.

Many components remain as 3D components because they don't flatten well for semiconductor implementation or because they require materials that don't mix well with standard semiconductor processes.

In 1995, the average cell phone contained about 500 individual components. By 2000, the number had shrunk to 100. There are economic and technical incentives to reduce the component count in the cell phone. Integrated components cost less to produce—making a single large component with integrated subsystems is cheaper than running individual production lines. Integrated components are smaller, save wiring and board space, and reduce assembly cost. Fewer components mean fewer reliability problems. Component variation is subtle but important. Suppose a circuit contains fifty individually produced components, each manufactured to a five- or ten-percent tolerance. Assembled circuits then exhibit a range of behavior that depends on the independent

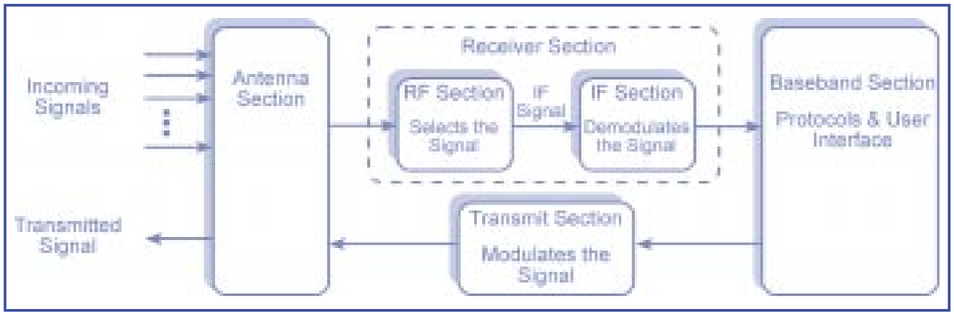

Fig. 3. Block diagram of a heterodyne radio (including the cell phone).

variation of constituent components. In building radio circuits, designers compromise circuit performance so the circuit can tolerate this variation of component values. If the components are integrated, tolerances may remain in the range of five to ten percent, but will vary in aggregate, favorably constraining variations in circuit behavior. Circuits become simpler to design and they perform better. These incentives create a "market pull" for technology that can reduce component counts. The trend to reduce component counts sounds good, but coming requirements in 3G, the desire for multi-band (e.g., 900 MHz, 1900 MHz), multi-protocol (e.g., CDMA, TDMA, GSM, AMPS) phones, and features such as GPS, inertial sensors, and biometric authentication buck the trend. And, there's still that problem of those pesky 3D components that don't flatten well for semiconductor processes.

MEMS—3D on chip

Microelectromechanical systems will come to the rescue. Microelectromechanical versions of relays, tunable capacitors, inductors, filters, microphones, reconfigurable antennas, local oscillators, resonators, switches, and programmable phase shifters (used with antennas) are either available today or will be in the near future. Component libraries and software development tools for designing and integrating many of these circuit elements are available from MEMSCAP, Coventor, Kymata, OnStream B.V., Standard MEMS, and IntelliSense. Cahners In-Stat Group estimates that sales of MEMS for consumer electronics will grow from $200 M in 2000 to $1.5 B by 2005.

Microelectromechanical systems offer a way to shrink the 3D components in a way that's compatible with standard semiconductor processes. Shrinking the components lowers cost, lowers power use, and reduces board space. Those pesky 3D inductors and capacitors that have resisted integration can now move onto the chip, reducing the cell phone's component count and lowering its cost and power consumption at the same time. As we've seen, there's substantial market pull to reduce the cell phone's component count. That market pull is driving research in RF MEMS and will soon support the MEMS invasion of the entire cell phone.

Switches. RF switches are perhaps the most critical MEMS components for improving the cell phone's performance. MEMS three-dimensional switches are similar to their ancient electromechanical equivalents; they offer low insertion loss and high isolation for critical cell phone applications such as the antenna switch and the transmit and receive switch. The competition is over what causes the switch to flip or "actuate." Candidate actuation mechanisms include: electrostatic, piezoelectric, thermal, magnetic, and shape-metal alloy. While there may be applications appropriate for each of these actuation mechanisms, the likely winner for the cell phone is electrostatic, because electrostatic actuation is most compatible with current semiconductor processes. MEMS switches show losses at 1 GHz that are about one tenth the losses of their 2D equivalents. And the MEMS switches offer substantially better isolation. The 3D MEMS switch is even five to ten times smaller than some 2D equivalents. The MEMS switch features small size, low insertion loss, high isolation, low control current, and adequate switching speed. Coventor, Hughes, Rockwell, Raytheon/TI, Motorola, Infineon, and others are developing MEMS switches.

Inductors. Flat spiral inductors possible in today's CMOS processes have low Q due to losses from series resistance in the spiral, parasitic capacitance between turns, and parasitic coupling into the substrate. The inductor improves if the substrate is etched away below the inductor's spiral. This "bulk micromachining" improves the inductor enough to make it useful for cell phone applications. "Surface micromachining," a process that builds three-dimensional structures above the substrate, can build inductors with coils perpendicular to the substrate, avoiding parasitic losses to the substrate. Surface micromachining also creates inductors good enough for cell phone applications. Both bulk micromachining and surface micromachining create MEMS. Lucent, Imec, Infineon, and others build MEMS inductors for RF applications.

Varactors—variable capacitors. There are at least three kinds of MEMS-based variable capacitors. The simplest scheme uses the MEMS switches mentioned above to switch binary-scale fixed capacitors into the circuit. Building a bank of capacitors with values C_1, $2C_1$, $4C_1$, and $8C_1$, enables sixteen discrete values of capacitance in a range from zero to $15C_1$. A second implementation, using surface micromachining, suspends one plate above the other and controls the distance between the plates with electrostatic forces. Capacitance varies with the distance between the plates. This translates to a "tuning range" around a resonant frequency. Professor Clark Nguyen of the University of Michigan's Center for Wireless

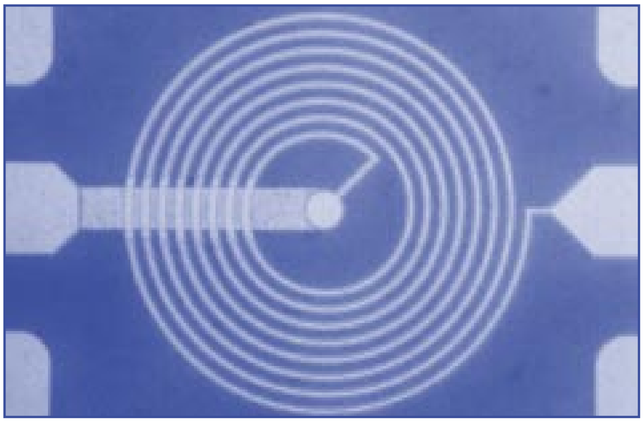

Fig. 4. Bulk micromachining removes the substrate (dark background) behind the inductor's coil, leaving free space below the coil.
(Photo by Peter Asbeck at UCSD)

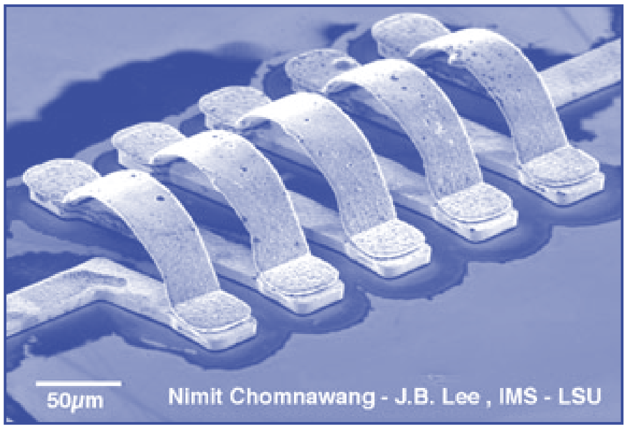

Fig. 5. Surface micromachining builds the inductor above the semiconductor's surface. *(Photo by J-B Lee at LSU)*

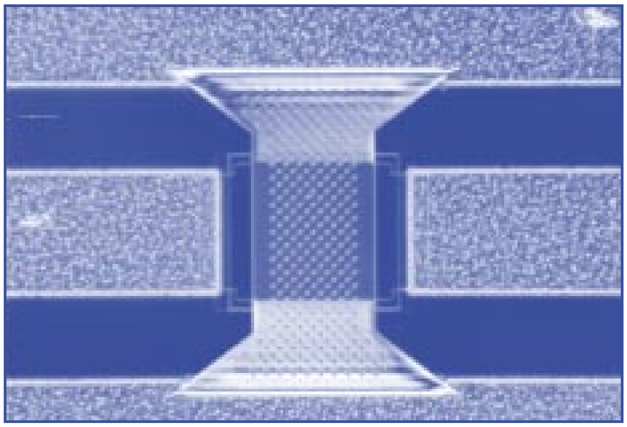

Fig. 6. A MEMS RF switch. *(Photo by Raytheon Company)*

Integrated Microsystems describes a varactor with a tuning range of 16%. Q for this example is 62 at 1 GHz, which is sufficient to displace off-chip varactor-diodes. The third variation electrostatically moves the fingers of a movable comb structure between the fingers of a fixed comb. This method yielded a Q of 34 and a tuning range of 200% in one example. These specs are good enough to displace off-chip alternatives.

New uses for MEMS in the cell phone

The MEMS switch is the leading enabler of innovative circuits for the cell phone. Prototype integrated MEMS switches show insertion loss of 0.1 dB (decibel) and isolation of 50 dB. This compares favorably with ancient electromechanical switches, which is the performance goal. A 10-dB isolation would leak a tenth of the power from input to output, 20-dB isolation leaks a hundredth, 30-dB isolation leaks a thousandth, and so on. A 0.1-dB insertion loss means that a 1-watt signal going into the switch becomes 0.977 watts coming out of the switch. The low loss and high isolation of these switches combined with their small size, zero standby power (no power to keep them on), and low control current enable circuit configurations that are not practical with discrete components or with integrated alternatives.

Power control. The cell phone conserves power if its output signal contains just enough power to reach the base station. By controlling its transmit power, the cell phone also reduces interference with other transmitters. The cell phone's MEMS switches could adjust transmit power levels by coupling different power amplifiers to the modulator's output depending on distance from the base station. External switches are too bulky to permit switching power amplifiers; semiconductor alternatives leak too much to isolate high-gain amplifiers and lose too much for low-gain amplifiers.

Switchable filters. MEMS-based switches and filters could be a thousand times or so smaller than their discrete-component equivalents. That so, it becomes possible to consider building a switched-filter front-end in lieu of the tunable filter used today. This circuit, proposed by Professor Nguyen, employs a bank of switches and filters—a pair of switches and a high-Q fixed filter for each desired input channel. In a similar scheme proposed by Professor L.E. Larson of U.C., San Diego, replaces the RF tunable local oscillator with a fixed oscillator and a bank of switches and IF MEMS filters. Both circuits reduce phase noise in the RF section and reduce dynamic-range requirements in the IF amplifier and mixer, enabling better performance with cheaper components.

Antennas

I've described how MEMS will invade the RF, IF, and transmit sections of fig. 3's cell phone, primarily by integrating components that have resisted flattening. MEMS will invade the antenna section too. (MEMS will invade them all, but I'll save the baseband section for another time.) Antennas are one of those mysterious "black art" specialties like waveguides, industrial power distribution, and radar. The industry seems to lie moribund for decades; no one gives antennas a second thought; and, suddenly, the world is awash with new ideas. That's what's happening in antennas.

The cell phone is creating the market pull for antenna development. In the old days, it was one radio, one antenna. Today's multi-band, multi-protocol cell phones need efficient antennas for transmission in each of two frequency bands. They want different, but equally efficient, antennas for reception in each of two frequency bands. They want an efficient antenna for GPS reception. There isn't room in the cell phone for arrays of independent antennas. No one wants a cell phone that looks like a porcupine. Is it possible to design an antenna that radiates and collects signals efficiently across a range of frequencies? Can MEMS help us build antennas that rearrange ("reconfigure") themselves to suit our needs? Market pull is driving extensive research in antenna design, reconfigurable antennas, phased-array antennas, and MEMS-based antennas. Before we talk about these antenna developments, I need to say how cell phones and base stations communicate.

The honeycomb of hexagonal base stations, commonly called "cells," provides efficient coverage for cell phones. The dot at the center of each hexagon is the base station, or cell, that is the bridge between cell phones and the landline network. Each base station can accommodate a number of cell phones—typically 20 to 25 simultaneous connections. As the cell phone crosses from one base station's area to another, the connection moves (transparently to the user) to the new base station.

The base station's antenna is generally omnidirectional, meaning that it transmits the signal uniformly in all directions. The transmit pattern will be a circle rather than a hexagon. Further, base stations cannot be located on a uniform grid in populated areas—base station locations depend on prevailing circumstances such as terrain, buildings, roads, and zoning restrictions. Coverage builds around high traffic areas and neglects remote areas, as in fig. 7.

Radius of the cell ranges from twenty-five kilometers to less than one kilometer, depending on how many active calls are expected in the area. The rising number of cellular users increases demand per unit area, especially in high-traffic areas. Fig. 8 shows smaller cell sizes clustering near high-traffic areas and larger base stations in less-crowded regions. Decreasing cell size means new equipment, new leases, higher maintenance costs, and new ties to the landline network. And mixing cell sizes complicates coverage planning and frequency planning.

An alternative to allowing the proliferation of smaller cells gives up the traditional omnidirectional antenna and uses directional antennas at the base station. Directional antennas split the cell's area into "sectors." Sector coverage increases frequency reuse and therefore supports a greater traffic load. In high-traffic areas the base station's directional antennas divide the area into six sixty-degree wedges. Each sector acts like an independent cell except that six cells share a common equipment location and connection to the landline network. Cell size does not change, so there's no need for new leases, new locations, and new connections to the landline network. In lighter-traffic areas, the base station continues to transmit with an omnidirectional antenna, so there's no need for coverage replanning.

ArrayComm. ArrayComm, an intellectual property company based in San Jose, California, has an even better idea called the IntelliCell. ArrayComm also calls it spatial division multiple access or SDMA (yet another wireless acronym). The IntelliCell is an adaptive array antenna system that takes us back to the configuration of fig. 7. Actually, it's mostly digital signal processing software that employs an array of antennas as sensors and actuators. Just as your brain uses your ears as sensors to determine direction for a signal source by discerning differences in sound arrival-times, the IntelliCell's software employs analysis of signal arrival-times *at an array of antennas* to pinpoint the location of a cell phone. Once the handset's location is determined, the base station tunes its listening to the vicinity and tracks the motion of the handset. It also notes the location of interferers and of multipath signals and adjusts its receive analysis to minimize their effects. The signal-processing software tracks the handset as it listens to the handset's transmissions; the software also computes the timing to focus transmissions, effectively beaming its transmissions directly to the handset.

The combination of signal-processing software and the adaptive antenna-array creates a two-way "spatial" channel between the handset and the base station. The base station can share the same channel with several handsets in its area—this channel sharing is in addition to the channel sharing already built into the protocol (e.g., CDMA, TDMA, GSM). Focusing the transmission and reception extends the range of coverage or reduces the power required by the transmitter and the receiver. Cells can then be spaced further apart or handsets built to require less power. An omnidirectional antenna is like a bright bulb radiating

Fig. 7. Base station coverage overlaps and clusters around high-traffic areas.

Fig. 8. Smaller cells accommodate more cell phones per unit area. Larger cells cover low traffic areas.

light in all directions. With ArrayComm, the base station's software focuses the adaptive antenna-array like a flashlight, shining it in the direction of the handset's calculated location. ArrayComm believes it can achieve capacity gains of six to twenty.

After a year of field trials in Japan, Kyocera began selling systems based on ArrayCom's IntelliCell in 1998. Today, there are more than 80,000 IntelliCell base stations in service in Japan, China, South Korea, Thailand, Taiwan, the Philippines, and the United Arab Emirates.

Antennova. If the base station can find the handset and focus reception and transmission in the handset's direction, there's no reason the handset couldn't reciprocate. Antennova, a pre-IPO startup in Cambridge, U.K., builds intelligent antennas for base stations and for mobile devices. Antennova's NovaCell is a tunable handset antenna capable of transmit and receive directional resolution of sixty degrees. About once a second the antenna sweeps the area to check whether the handset has moved and to assure that it is still locked onto the best channel. The antenna then electronically (no moving parts) beams its signal in a sixty-degree cone toward the base station. Antennova believes that focusing signal transmission will extend talk time by a factor of three. Antennova says its antennas both for the base station and for the handset are a tenth the size of conventional copper antenna designs but offer the same frequency and efficiency. In addition, the antenna is frequency independent, making it suitable for multi-band cell phones. The antenna for the mobile device is small enough to mount on the motherboard.

Researchers are working on MEMS-based reconfigurable antennas. One proposal is an array of antenna patches that looks like rows and columns of postage stamps with spaces between rows and columns that are about the same dimension as the patch. MEMS switches connect nearest neighbors vertically and horizontally. Activating switches builds antenna strips, or meandering lines, or whatever the application demands.

No need to integrate components that aren't there

MEMS are invading the cell phone to miniaturize and to integrate its 3D components. But there's another invasion coming as the cell phone's hardware softens. Software in the form of digital signal processing is invading the cell phone. Microprocessors and digital signal processors (DSPs) are cheap and they are powerful. They are already in the baseband section, where their signal-processing functions dominate the cell phone's development, cost, and operation. Next they will inch forward to eat the IF section.

A new type of receiver, the direct-conversion receiver, reduces component counts by eliminating the receiver's IF section. Direct-conversion receivers promise to drop the cell phone's parts count to fifty by replacing physical components with software running in the already-present microprocessor and DSP. The local oscillator and IF section were originally put there to avoid problems in tuning the demodulator's multiple filters to the desired frequency and to avoid variations in demodulation quality at opposite ends of the input frequency range. Problems arose because filtering and demodulation depended on characteristics of individual analog components whose quality varied with frequency. The direct-conversion receiver sidesteps these problems by not using filters and demodulators that require tuning. Instead, the direct-conversion receiver digitizes the IF signal and uses software for filtering and demodulation.

The heterodyne receiver supported analog information transfer. Direct-conversion receivers for digital information transfer don't require complex tuning of demodulator stages because analog components do not demodulate the signal. The direct-conversion receiver converts the incoming signal to digital for processing with digital circuits and software. The direct-conversion receiver removes the need for the IF section by converting the selected RF signal directly to digital samples. It shifts the demodulation burden from direct-acting analog components to less efficient digital components, but the tradeoff buys flexibility that will enable multi-mode and multi-band handsets. Hardware in the cell phone is getting softer. Softer hardware shifts the balance between direct-acting, tuned analog components and fixed, standard digital components with flexible software. Direct-conversion receivers make it easier to build flexible "software radios" that can adapt to new protocols and to regional differences in base station networks.

In February 2001, Texas Instruments announced the TRF6150 direct-conversion RF IC. The chip enables direct-conversion implementations of Universal Mobile Telecommunications System (UMTS, also known as 3G), General Packet Radio System (GPRS), and GSM handsets. It should reduce the component count by 30% over heterodyne implementations. The device also integrates the power amplifier controller, but it still requires two external filters and a single external voltage-controlled oscillator.

Also in February 2001, Analog Devices (ADI) and Conexant announced direct-conversion RF ICs. Analog Devices announced the OthelloOne direct-conversion receiver chip for GSM that is a follow-on to the two-chip Othello version announced two years ago.

Qualcomm's radioOne chip set for direct conversion for CDMA also contains the RF circuitry for GPS. Qualcomm says radioOne improves talk time by 20%, increases standby time by up to 400%, and reduces parts count by 50%. ParkerVision has announced Direct2Data direct-conversion receiver chip for CDMA and GSM.

Lessons from the cell phone

MEMS components offer advantages in cell phone implementation:

- Component integration and component count reduction
- Significantly smaller size
- Better performance than 2D alternatives
- Batch fabrication
- Reduced power consumption
- Zero power in standby or in dc operation
- Design options not available to discrete components or to integrated alternatives (e.g., hundreds of switched filters)

MEMS will improve the cell phone. Improvements will follow a well-worn path for electronic systems. MEMS-equivalent components will displace conventional components in legacy designs. MEMS switches will displace discrete miniature mechanical switches and inefficient integrated FET (field-effect transistor) switches. MEMS moving-plate capacitors will displace discrete miniature moving-plate capacitors and voltage-tunable varactor-diode capacitors. MEMS inductors will displace discrete-component inductors and integrated 2D-spiral inductors. And so on. Because they offer advantages in size, in performance, in mass production (and therefore in cost), and in integration, MEMS-based components will displace their legacy equivalents in *system* designs that remain principally unchanged from their precursors. Once MEMS components have proven themselves worthy to displace legacy components, system designers will begin to exploit intrinsic strengths of the components. That is, they will begin to incorporate design ideas suggested by researchers such as Professors Clark Nguyen and Gabriel Rebeiz (also at the Center for Wireless Integrated Microsystems).

Nick Tredennick and Brion Shimamoto
July 24, 2001

Dynamic Silicon Companies

The world will split into the tethered fibersphere (computing, access ports, data transport, and storage) and the mobile devices that collect and consume data. Dynamic logic and MEMS will emerge as important application enablers to mobile devices and to devices plugged into the power grid. We add to this list those companies whose products best position them for growth in the environment of our projections. We do not consider the financial position of the company in the market. Since dynamic logic and MEMS are just emerging, several companies on this list may be startups. We will have much to say about these companies in future issues.

Technology Leadership	Company (Symbol)	Reference Date	Reference Price	6/29/01 Price	52-Week Range	Market Cap.
General Programmable Logic Devices (PLDs)	Altera (ALTR)	12/29/00	26.31	29.00	18.81 - 67.12	11.5B
Dynamic Logic for Mobile Devices	QuickSilver Technology, Inc. (none*)	12/29/00				
MEMS Foundry, Dynamic Logic	Cypress (CY)	12/29/00	19.69	23.85	13.72 - 55.75	2.8B
RF Analog Devices, MEMS, DSPs	Analog Devices (ADI)	12/29/00	51.19	43.25	30.50 - 103.00	14.6B
Configurable Microprocessors	ARC Cores (ARK**)	12/29/00	£3.34	£0.98	£0.48 - 4.29	£499M
Field Programmable Gate Arrays (FPGAs)	Xilinx (XLNX)	2/28/01	38.88	41.24	29.80 - 97.50	12.9B
Configurable Microcontrollers (Peripherals)	Triscend (none*)	2/28/01				
Silicon for Wireless RF, GPS	SiRF (none*)	12/29/00				
Microprocessor Instruction Sets	Transmeta (TMTA)	12/29/00	23.50	5.58	3.6 - 50.88	528M
Photonic Switches	Calient (none*)	3/31/01				
DKI Development Suite	Celoxica (none*)	5/31/01				
Design Environment Licensing for Configurable Soft Core Processors	Tensilica (none*)	5/31/01				
CMOS Semiconductor Foundry	Taiwan Semiconductor (TSM[†])	5/31/01	19.86	15.59	11.52- 26.79	34.1B
CMOS Semiconductor Foundry	United Microelectronics (UMC[†])	5/31/01	10.16	8.90	6.14 - 13.21	16.1B

* Pre-IPO startup companies. ** ARK is currently traded on the London Stock Exchange [†] Also listed on the Taiwan Stock Exchange

NOTE: This list of Dynamic Silicon companies is not a model portfolio. It is a list of technologies in the Dynamic Silicon paradigm and of companies that lead in their application. Companies appear on this list only for their technology leadership, without consideration of their current share price or the appropriate timing of an investment decision. The presence of a company on the list is not a recommendation to buy shares at the current price. Reference Price is the company's closing share price on the Reference Date, the day the company was added to the table, typically the last trading day of the month prior to publication. The authors and other Gilder Publishing, LLC staff may hold positions in some or all of the companies listed or discussed in the issue.

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