A Technological Rationale to Use Higher Wireless Frequencies

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EXECUTIVE SUMMARY

Spectrum applications are driven by the consumer market's appetite for products and services, the unchanging laws of nature as applied to radio wave propagation, the state of electronics manufacturing technology (which is continually extending the upper frequency limits of practical spectrum use), and regulatory policy. A maximum frequency of 3 GHz is often stated to be the limit for practical low-cost applications. Although true in the past, this is clearly not so today. Even a casual review of commercially available electronic components and consumer systems shows much activity at frequencies greatly in excess of 3 GHz. Despite the constancy of the physical laws of nature, developers and policymakers will find continually higher frequencies suitable to support emerging technologies and services.

The free-space path loss (the signal loss between transmitter and receiver) increases rapidly with increasing frequency. This factor is often cited as the reason that higher frequencies (frequencies above 3 GHz) are not suitable for mobile radio systems. However, properly designed systems can take advantage of higher antenna gains and shorter communication distances to compensate for the higher path loss while enabling the system to serve more customers.

The semiconductor industry is building complex monolithic microwave integrated circuits (MMIC's) that can operate at frequencies as high as 20 - 30 GHz. Although the gallium-arsenide (GaAs) MMIC's are considerably more expensive than integrated circuits made from silicon, it is often possible to put all critical high frequency circuits on a single MMIC, while using lower cost silicon to build everything else. The rapidly growing use of small-dish satellite TV receivers operating at 12 GHz shows the practicality of consumer systems operating far above 3 GHz.

So-called "smart systems" (systems that depend on complex computer technology) are also a key to efficient use of higher frequencies, because "smartness" makes it easier and cheaper to build dense infrastructures with many short-range base stations. In addition to making small-cell systems practical, smart systems are expected to stimulate the capacity and bandwidth demands needed to justify the dense infrastructure.

The frequencies used by newly introduced broadcasting systems have increased by a factor of about 2.5 every 10 years. Today's practical upper limit for various terrestrial- and satellite-based consumer broadcasting systems is about 12 GHz, with systems at 28 GHz expected to be available soon. Similarly, historical trend information shows that maximum frequencies for new mobile applications have increased by a factor of about 1.8 every 10 years.

Altogether, various physical, technological, and application trends suggest that a growing number of consumer wireless applications will very successfully use frequencies above 3 GHz . Moreover, the higher frequencies offer unique opportunities not available at low frequencies, and consumers should expect to see totally new types of services developed using these higher frequencies.

A TECHNOLOGICAL RATIONALE TO USE HIGHER WIRELESS FREQUENCIES

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Trends within the wireless and mobile communications industry are examined and extrapolated into the near future. The paper examines the relationships between propagation loss and antenna gain at higher frequencies, shows how dense intelligent infrastructure affects cell size and system capacity, and describes the improving high frequency capabilities of RF electronics technology. The authors conclude that frequencies above 3 GHz may be uniquely suited to many wireless applications, but that non-traditional system architectures and technologies will need to be used.

Key Words: mobile communications; wireless communications; radio spectrum; microwave radio; MMIC; propagation; antennas; system capacity; technology trends.

1. INTRODUCTION

Government and industry recognize that additional radio spectrum will be needed for new fixed and mobile wireless services. NTIA's 1995 publication *U.S. National Spectrum Requirements: Projections and Trends* predicts a shortfall of 204 MHz of spectrum for land mobile radio through the year 2005 [1]. Overall, the NTIA report found increased demand for spectrum coming primarily from the cellular/personal communications services (PCS), mobile satellite, and intelligent transportation system sectors.

Radio frequencies up to 3 GHz are currently considered to be particularly suitable for low-cost consumer services. Radio wave propagation characteristics (higher path loss) and the higher cost of electronics have been perceived to be major disadvantages for frequencies above 3 GHz. Recent legislation directed NTIA and the Federal Communications Commission (FCC) to release additional spectrum to be auctioned for new services, with the stipulation that the spectrum must be below 3 GHz [2].

Successful wireless consumer applications are always a combination of the market's desire for products and services, the natural laws of radio wave propagation, the state of manufacturing technology (which is continually extending the upper range of usable radio frequencies), and regulatory policy. Technology has historically been the most important factor limiting the use of higher frequencies; every successive decade of the twentieth century has faced a new and higher limit. This does not mean that the differences in propagation factors at higher frequencies can be ignored.

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Systems using higher frequencies will need to adapt new architectures and technologies, appropriate to the frequency and the application, as has every past innovative radio application.

This report summarizes the challenges and opportunities of building systems at higher frequencies. It describes the chief features of radio wave propagation, as well as state-of-the-art wireless technologies that will be available to implement the new systems.

2. RADIO SYSTEM FUNDAMENTALS

A typical radio communications system consists of several components, as shown in Figure 1.

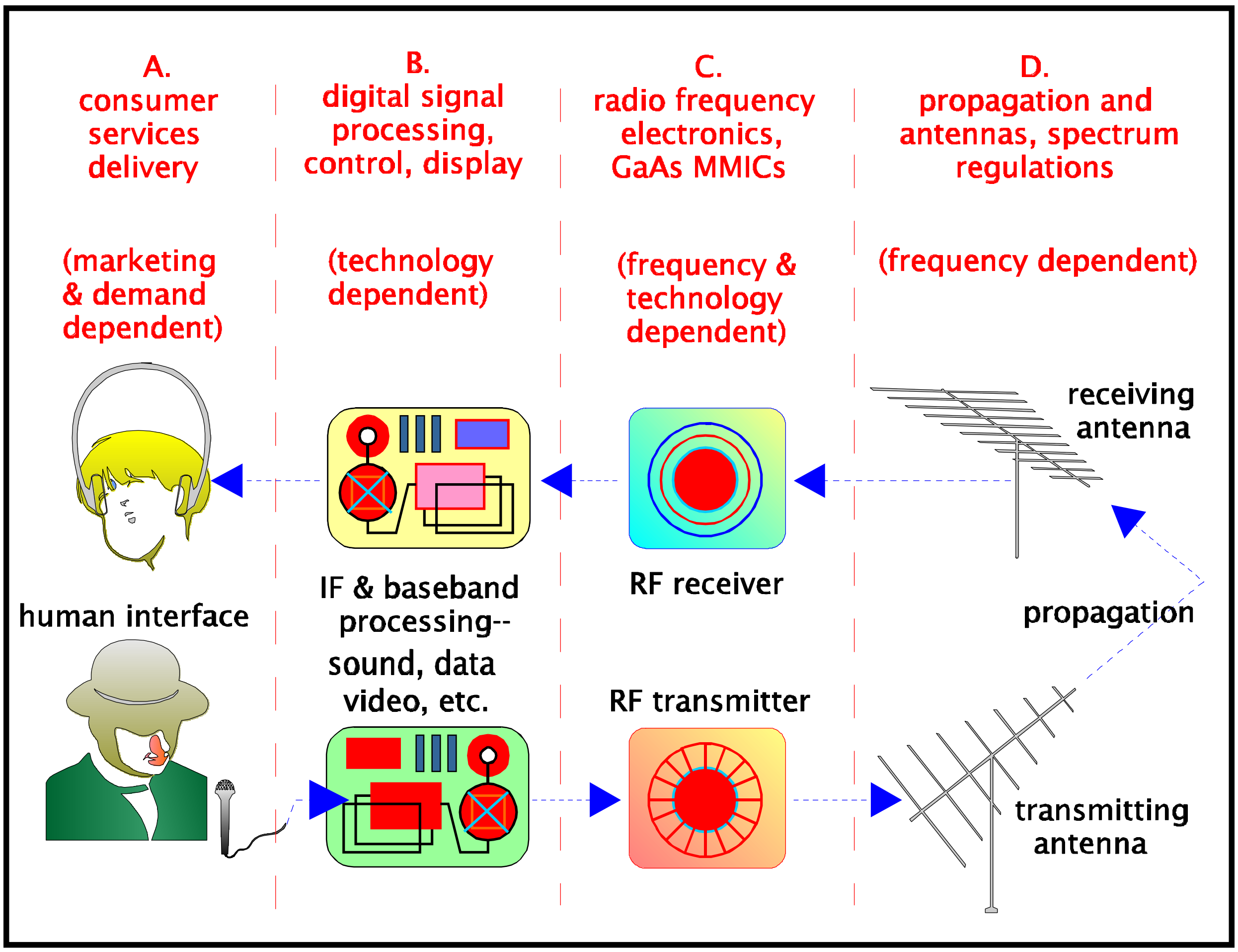

Figure 1. Radio system fundamentals.

A. Consumer services. Market opportunities and consumer demand drive the creation of wireless services. From the consumer's viewpoint, it makes little difference what frequencies or technologies are used to provide these services–as long as they are sufficiently reliable, economical, and capable.

B. Signal processing. Though the consumer will typically interface with these services through sound, video, or text media, many modern services encode all these media as digital data for transmission and convert them back to the original media in the receiver. Whether or not digital encoding is used in a system, the majority of the electronics in most wireless systems is used to control the receiver and process and display the signal. This processing often occurs at some convenient "intermediate frequency" or at baseband, and this part of the circuitry can be essentially identical for all systems providing similar services–regardless of the frequency band used to transmit the signal. Therefore, the processing circuits are considered to be highly dependent on technologies for implementation, but relatively independent of the frequency of transmission.

C. Radio frequencies. The final act of processing a signal in a transmitter is to "convert" the signal inside the transmitter from an intermediate frequency (IF) to a (usually) much higher radio frequency (RF) used to transmit the signal through the air. In many newer systems, the RF is so high that conventional silicon electronics cannot process it very well. In these cases, special circuits made from gallium arsenide (GaAs) are used. Although GaAs circuits are more expensive than silicon circuits, they work better at high frequencies (and fortunately are needed only for the RF circuits). A reverse process occurs in the receiver. The RF signal enters the receiver via the antenna and is converted to an IF signal, which undergoes further processing.

D. Radio wave propagation. The radio wave path begins with the RF signal being launched into the air by a transmitting antenna and ends with a tiny portion of the transmitted RF signal being picked up by a receiving antenna. The movement of the signal from the transmitting antenna to the receiving antenna is called "propagation." Since all radio signals share the "airspace," two signals being transmitted on the same frequency might interfere with each other inside a receiver. For this reason, the Government regulates the use of radio waves, and it licenses only selected users to transmit on given radio frequencies.

These concepts are described in more detail in the following sections. They are covered in the reverse of the order listed above, beginning with radio wave propagation.

3. ANTENNAS AND PROPAGATION

3.1 Radio wave Propagation

The propagation of radio waves is influenced by many physical mechanisms, including free space loss, terrain blocking and reflection, foliage absorption, ionospheric reflection and absorption, rain loss and reflection, clear air absorption, Doppler shift, and multipath fading. Individual effects are stronger in certain frequency bands, and communication systems are usually designed to take advantage of these effects–or at least to tolerate them. For example, in the frequency range below 30 MHz (the so-called "shortwave" bands), radio signals reflect off the ionosphere, enabling communication ranges of several thousand miles. The downside of this ultra-long-distance communications mode is that the ionosphere is constantly changing and interfering signals and noise are very major problems.

Radio waves at higher frequencies–above 10 GHz–are increasingly reflected and absorbed by rain and atmospheric gases. The maximum usable range of such signals is partly dependent on the tolerable degree of interruption by inclement weather–the further the range, the greater the chance of interruption by rainstorms. Still higher in frequency, radio signals are absorbed by gases in the atmosphere. For example, water vapor lightly absorbs radio waves near 20 GHz, and oxygen very strongly absorbs signals near 60 GHz. Though atmospheric absorption would be considered a disadvantage for many radio systems, some systems have been proposed that use this phenomenon to prevent unauthorized interception of signals, to strongly limit interfering signals, and to substantially increase frequency reuse in these bands.

Propagation at higher frequencies is different from propagation at lower frequencies in several major respects. While all radio waves tend to move in straight lines, higher frequencies are blocked more sharply by terrain or buildings, and they can be focused more easily by high-gain antennas. Because wavelengths are shorter at higher frequencies, higher frequencies can move more easily through small openings (like windows and hallways in buildings, or into tunnels). On the other hand, higher frequencies suffer more loss between omnidirectional antennas. Free space path loss is proportional to $1/F^2$, where F = frequency. For example, the use of a frequency that is twice as high will result in only 25% as much energy being available at the receiver (assuming the use of omnidirectional antennas, with other factors kept the same). The increased path loss at higher frequencies can also be described as a “20-dB/decade” loss: the path loss increases 20 dB (a factor of 100) for a decade (a factor of 10) increase in frequency.

A communications system can interfere with itself when multiple copies of the transmitted signal arrive at the receiver via different paths. These “multipath” signals with different directions-of-arrival, amplitudes, and propagation delays arise from the reflection of radio signals off various objects, such as mountains and buildings. Depending on the relative amplitudes and time delays between them, the signals can constructively add or destructively subtract from each other. Multipath is one primary limitation in wave propagation, with destructive cancellation causing occasional unexpected signal loss (called frequency-selective fading.) Multipath can also cause data errors (intersymbol interference) when the time delay differences are on the order of the time duration of a transmitted symbol. Intersymbol interference tends to become a greater problem when data rates are higher, when higher-order efficient modulations are used, or when the terminal is in motion.

These propagation phenomena are the driving factors that determine radio coverage zones. A number of computer simulation tools consider these propagation phenomena and are used to design radio systems. Figure 2 shows example outputs of transmission path losses for a hypothetical station in Washington, DC, using the Communications System Performance Model (CSPM) which is based on NTIA’s Irregular Terrain Model [3]. Inputs to the program include transmitter latitude and longitude (CSPM uses digital terrain databases), transmitter frequency, antenna height, polarization, mobile station antenna height, and other factors. In these examples we assumed a transmitting antenna

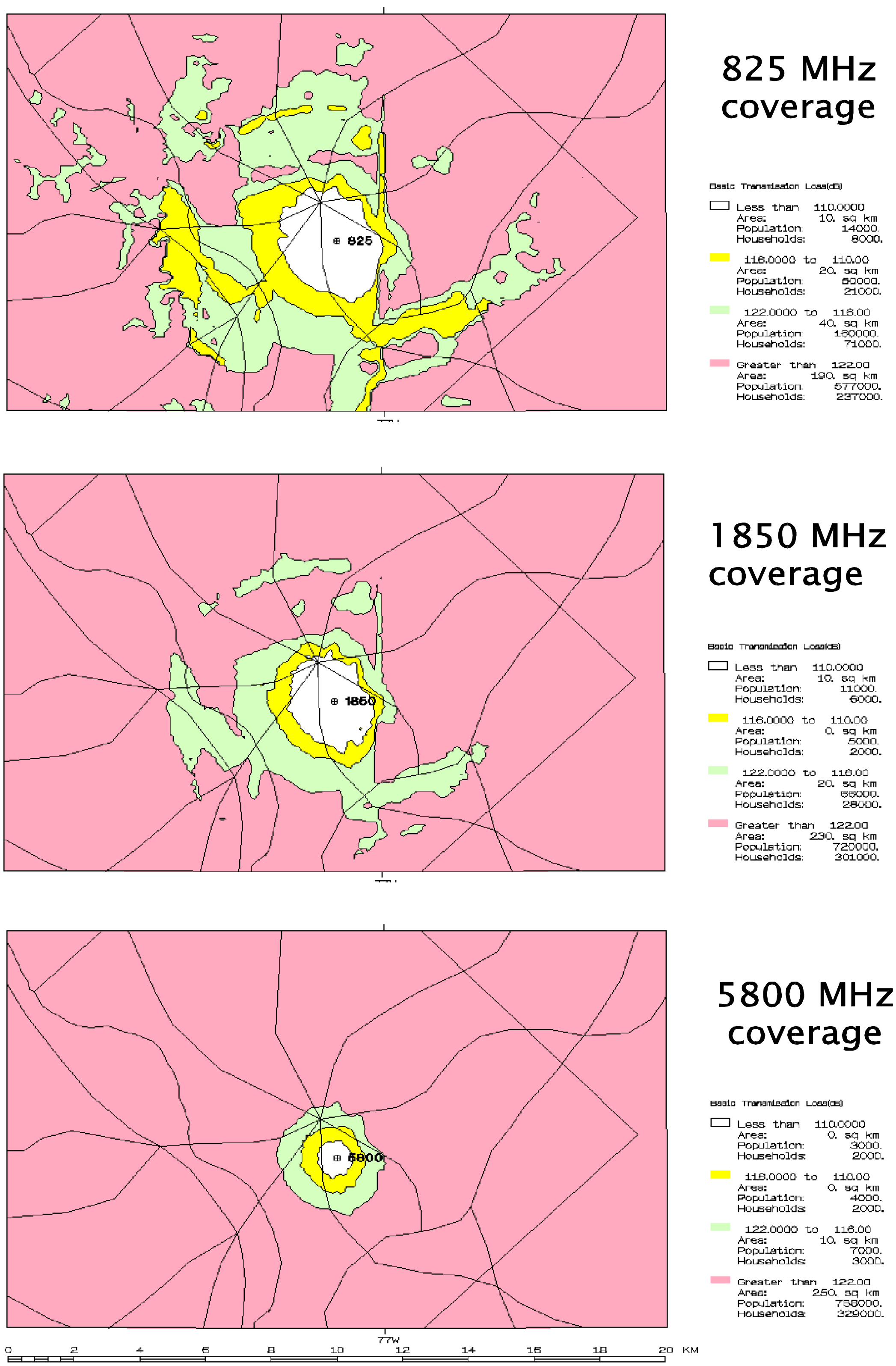

Figure 2. Basic radio path loss at three frequencies

height of 9 m, a mobile receiving antenna height of 1.5 m and frequencies of 825 MHz, 1850 MHz, and 5800 MHz, respectively.

It is clear from these examples that as frequency increases, radio coverage decreases (assuming fixed antenna gain and other factors held constant). What should ***not*** be assumed, however, is that this decreased coverage is necessarily detrimental to the operation of a radio system that is properly designed to accommodate these losses. Various engineering solutions are available to compensate for increased transmission losses, if required. In addition, many modern radio systems depend on smaller coverage zones (cells) to increase frequency reuse (which enables more clients to be served simultaneously).

3.2 Antenna Gain and Path Loss

Antenna gain is the ability of an antenna to focus the electromagnetic energy it radiates in some preferential direction (or, conversely, to favor one direction in receiving energy, while tending to reject energy from other directions). Increasing antenna gain at higher frequencies can help counter the increased path loss at those frequencies. In particular, the gain of a dish antenna of fixed dimensions will increase proportional to F^2. A two times increase in frequency will increase dish antenna gain by a factor of four (6 dB more gain).

The signal power available at the output of a distant receiving antenna is a function of transmitting antenna gain, path loss, and receiving antenna gain. Figure 3 shows the relative received signal power, including the effects of transmitting and receiving antenna gains, compared to the received signal power at 1 GHz. To simplify the issue, many factors were omitted, such as terrain blocking, rainfall absorption, and multipath reflections. "Case 1" shows the relative received signal power when the transmitter and receiver both use omni-directional antennas (or any antennas with constant gain). The graph shows a 20-dB/decade signal loss. A system operating at 10 GHz would require 20 dB more transmitter power (100 times more power), compared with an identical system operating at 1 GHz, in order to deliver the same power to the receiver.

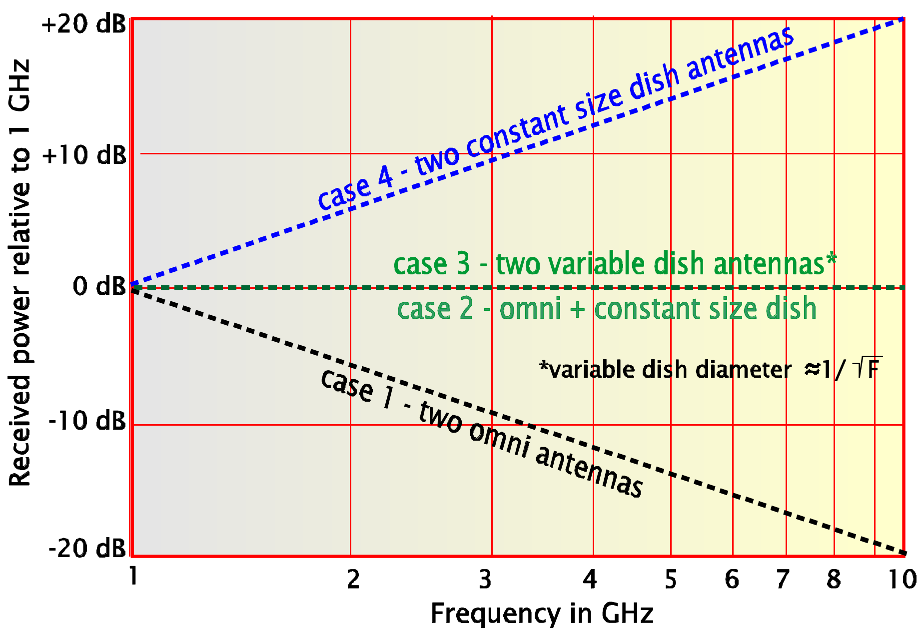

Figure 3. Received signal power (including antenna gains) relative to power received at 1 GHz.

This 20-dB/decade effect is the major factor that is operative in the three coverage plots in Figure 2, and it is the major reason that some people have declared that mobile communication systems cannot operate efficiently above 3 GHz (or some other similar frequency limit).

Although case 1 might be construed to show that frequencies higher than "X" GHz are not practical for mobile systems, a more general conclusion might be that it would be foolish to attempt to build a wireless system at 10 GHz in the same way that it would be built at 1 GHz.

Consider "case 4" as an alternative way to build systems. Instead of the omnidirectional antennas of case 1, case 4 uses dish antennas of a fixed physical size at the transmitting and receiving terminals. Since energy can be focused more effectively at high frequencies than at low frequencies, the gain of the dish antennas increases with frequency and more than cancels the increased path loss. The 20-dB/decade path loss is combined with a 40-dB/decade antenna gain (20 dB/dec-ade for the transmitting antenna and 20 dB/decade for the receiving antenna) to give a net gain of 20 dB/decade for the system. At 10 GHz, for example, the received signal power would actually be 100 times (20 dB) more than at 1 GHz.

With the higher antenna gain of the dish antennas come narrower antenna beamwidths. This means that the transmitting and receiving antennas will need to be (and remain) precisely aimed at each other. This can be a major nuisance if either terminal is mobile, but the narrow beamwidth can also be used to discriminate against unwanted signals and to increase system capacity. Case 4 is typical of fixed point-to-point microwave applications, which often have advantages at higher frequencies. (In fact, substantial growth is currently underway in the 39-GHz microwave band, where the small antenna size offer substantial siting advantages.)

The equal-but-opposite signal powers illustrated by case 1 and case 4 can be balanced against each other in various ways, illustrated by case 2 and case 3, giving received power that is independent of frequency. "Case 2" antenna systems use a constant size, high-gain base station dish antenna (whose gain increases with increasing operating frequency at the same rate as path loss increases) and a fixed gain (e.g., omnidirectional) subscriber antenna. "Case 3" antenna systems use directional transmitting and receiving dish antennas, whose physical areas (effective apertures) decrease as 1/F, giving improvements in antenna gain that exactly offset the increased path loss. Cases 2 and 3 describe no specific systems, but rather a family of systems that have particular types of transmitting/receiving antenna geometries.

Examples of generic systems incorporating "case 2" antennas:

1. Fixed size directional transmitting antenna, omnidirectional receiving antenna.
    - PCS satellite spot beam antennas transmitting to omnidirectional antennas of PCS subscriber units;
    - high-gain, highly segmented terrestrial PCS base station antennas transmitting to omnidirectional personal receivers;
    - active-tracking PCS base station transmitting antennas; and

- high-gain standoff transmitters providing remote wireless coverage of a relatively distant site.

2. Omnidirectional transmitting antenna, fixed size directional receiving antenna.
   - the reverse paths of the examples in #1 above;
   - multiband multipoint distribution systems (MMDS) and local multipoint distribution systems (LMDS);
   - wireless local loops with directional home antennas aimed towards an omnidirectional street corner transmitter;
   - and DBS (direct broadcast satellite) TV dish receiving antennas aimed at DBS low-gain satellite transmitting antenna.

Examples of generic systems incorporating "case 3" antennas include:

- all point-to-point fixed systems supporting wireless local area networks, spot-beam coverage to LMDS subscribers, and PCS backhaul systems; and
- systems where mobile and base stations both employ active antenna tracking.

The point of these generic examples is to show that there are many potential wireless applications where directional antennas or active tracking on either end or both ends of the path can be effective in compensating for the higher path loss.

To illustrate the feasibility of using higher frequencies for consumer applications, consider the recent success of DBS TV receivers. Although the technology that was needed to support inexpensive 12-GHz receivers became available only recently, DBS systems are growing rapidly and displacing earlier 4-GHz satellite TVRO (TV receive only) systems. Digital clarity, many channels, and low cost contributed to the success of the new DBS systems. However, the rapid market penetration (especially among urban cable customers) was enabled by the small antennas– which were made possible by the use of 12-GHz broadcast frequencies. DBS TV systems arguably could never have been so successful if they had operated at 4 GHz, because of the larger antennas required at 4 GHz. Similar comments may someday be appropriate in describing the future successes of 24-GHz wireless local loop, 28-GHz LMDS, and 39-GHz fixed microwave systems.

3.3 Antenna Requirements For Mobile and Base Stations

For mobile use, antennas must be omnidirectional in azimuth because the vehicle (and antenna) orientation, relative to the base station, cannot be controlled. For all practical purposes, this constrains the antenna on the mobile unit to omnidirectional whip antenna designs, similar to the common fender-mounted AM/FM car radio antennas.

Mobile Radio Technology [4] gives a history of the evolution of mobile antennas. At 25- to 50- MHz frequencies, mobile antennas were essentially constrained to quarter-wavelength whip designs. Higher gain mobile antennas were impractical at these frequencies because of their larger physical size;

quarter-wavelength antennas for this band are on the order of 2 m (6 ft) in length. Smaller antennas at these frequencies do not radiate power as efficiently and are more narrowband in frequency.

When operating frequencies increased to 150 MHz, antennas could be made smaller (because of the inverse frequency/wavelength relationship). Higher gain antennas, on the order of 3 dB more gain, that retained omnidirectional coverage were possible because 1/2- and 5/8-wavelength designs are only about 1 m (3 ft) long.

When mobile radios began operating at 500 MHz, smaller, more complex whip antenna designs became practical. One example is the 5/8-wavelength collinear whip antenna, consisting of two 5/8-wavelength sections with a phasing coil between them. The 5/8-wavelength collinear whip has about 5 dB of gain over the quarter-wave whip and retains the desired omnidirectional radiation characteristics in azimuth.

Mobile antenna designs at 800-940 MHz, 1850-1900 MHz, and 2200-2900 MHz have retained the 5/8-wavelength collinear design, incorporating improvements such as glass-mounted capacitive feedthroughs to eliminate the requirement of drilling holes in vehicle roofs or trunk decks. The use of higher frequencies has allowed the size and structural wind-loading installation requirements of the mobile antenna to be reduced proportionally, but antenna gain has reached a plateau.

Base stations utilize dipole antennas to provide omnidirectional coverage over a large geographic area. Stacked dipole arrays, using several vertically collinear dipole antennas, can provide up to 18-dB gain with omnidirectional coverage [5]. The higher gain offered by the base-station receiving antenna arrays allows lower power mobile and portable transmitters to be used.

As frequencies of operation move higher, base-station antennas having comparable performance can be made smaller, reducing structural wind-loading requirements and making the antennas less visually objectionable. Alternatively, higher frequency antenna arrays having the same approximate physical size would have improved gain and directivity. The increased antenna gain would cancel the increased high-frequency path loss (i.e., the “case 2” antenna system approach described in Section 3.2), providing similar coverage ranges for higher and lower frequencies.

3.4 System Capacity

System capacity can be defined as the maximum number of users that can be adequately served by a communications system. Cellular telephone systems deliberately limit the operational range of the individual base stations so that base-station frequencies can be reused by other base stations in a metropolitan area; this increases the cumulative capacity of the whole system. When this technique was first adopted, it violated the traditional mobile system design principles that preferred to maximize the range of each transmitter. Figure 4 shows how the numbers of cellular and PCS base stations and customers have grown since 1984 [6]. Although most of the earlier base-station sites were added to increase the total area of coverage, much of the more recent growth (before 1996, which began to reflect massive PCS construction) has been directed toward increasing the total capacity of the cellular system. The data shows that the average cellular site currently supports 1400-1500 users, a number that has gradually increased while the number of sites continues to increase rapidly. This suggests that future increases in system capacity will continue to be made by adding sites (down-sizing existing cells).

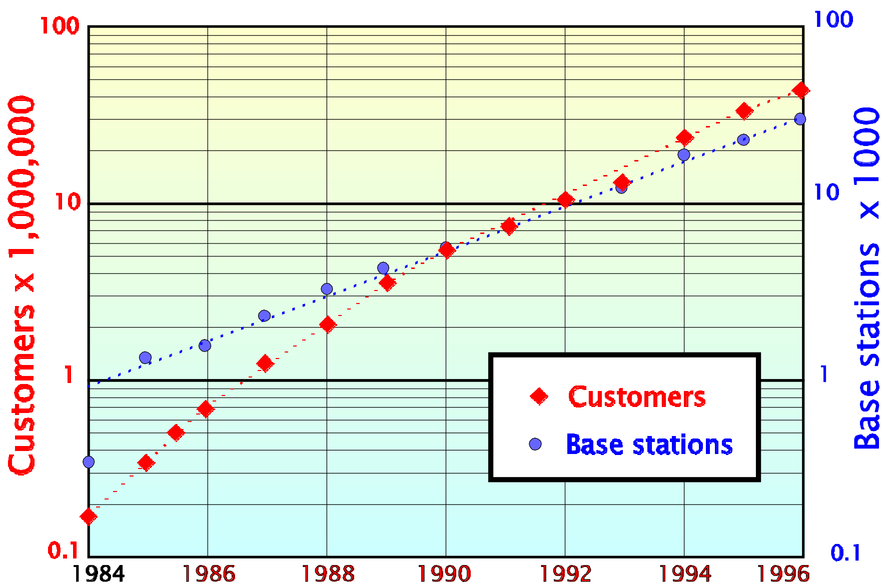

Figure 4. Growth in number of cellular base stations and users.

The capacity of a cellular system can be increased by "cell splitting," which divides existing cells into multiple smaller cells, thus increasing the number of cells and base stations serving a region. A smaller cell implies reduced communications range for mobile and base-station transmitters. The base-station range is engineered by adjusting transmitter power and antennas. The mobile transmitter power is automatically adjusted by control signals from the base station. This allows any mobile transmitter to automatically use higher power to work efficiently with large rural cells and lower power for small cells in densely populated urban areas. Since a given frequency can typically be reused every 7-12 cells, a larger number of cells allows more frequency reuse, making it possible to simultaneously serve more users.

Another way to increase system capacity is by "sectorizing" existing base stations, i.e., by using directional antennas to generate several independ-ent cells from each base station. Typically, sector-ized base stations employ three directional antennas whose individual patterns each cover 120° of azimuth. One obvious advantage of sectorization vs cell splitting is cost; new base stations cost about $1million each. Future radio systems operating at higher frequencies will probably exploit these techniques even more fully. Some PCS systems have explored the use of 16-sector antennas, and an MMDS system has been proposed that uses 20-sector antennas [7]. These systems can more easily exploit complex antenna arrays because they operate at higher frequencies, where antennas are proportionately smaller (and therefore cheaper, less visually objectionable, lighter, and cause less wind loading on towers).

Cellular systems have already made extensive use of small cells and sectorization to gain additional capacity. Wireless technology companies are developing even more powerful directional antenna techniques to further increase system capacity [8]. Adaptive beam-steering techniques use highly directional antenna beams to track individual mobile users as they travel through the cell. The narrow beams reduce co-channel interference by rejecting most co-channel energy from unwanted directions. Furthermore, independent users can share the same frequency within the same cell, as long as the mobile users do not lie along the same bearing from the base station. This is accomplished by techniques that electronically adjust the phase of each user's signal that is sent to every antenna array element, thereby synthesizing an antenna beam that points in the appropriate direction. For maximum system capacity, multiple independent users' signals can be transmitted on the same frequency. The appropriate phases for each user's signal are determined, added together, and sent to each antenna array element. This directs multiple antenna beams, each independently steerable relative to the other antenna beams, along the appropriate bearing. Figure 5 illustrates the basic concept.

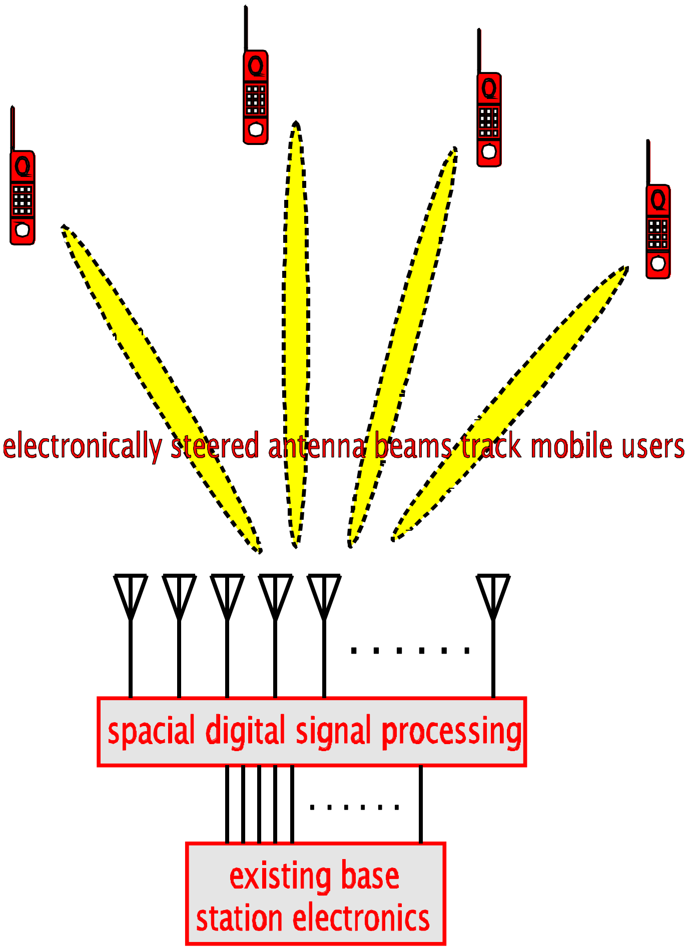

Figure 5. Adaptive antenna concepts.

In Section 3.4 we mentioned that adaptive antenna arrays become increasingly effective and practical as the operating frequency increases. This is because the realizable performance gains, in terms of beamwidth and antenna gain, are obtainable with smaller, less costly, and less visually objectionable antennas. In order to synthesize antenna beams that are "narrow" in azimuth, the antenna array must be large, in terms of wavelengths, in horizontal extent. Since wavelength is inversely proportional to frequency, the "real estate" required to implement equivalent antenna arrays decreases with increasing frequency. Hence, higher frequencies are more desirable to implement antenna systems of this complexity.

3.6 Summary of Propagation and Antenna Technologies

Current cellular systems have used small cells and sectorization mainly to gain additional capacity. Future antenna systems may gain even more capacity through the use of a larger number of fixed-azimuth sectors or adaptive antenna systems that actively track individual users. However, all of these techniques give an important extra advantage: they allow the mobile stations to use less transmitter power. The use of more-directional antennas provides higher gain for the desired signal, as well as increased rejection of undesired signals. Both the small cell size and the higher-gain directional antennas contribute to lower transmitter power requirements, which can be used to compensate for higher path loses at higher frequencies. Therefore, the improved antenna system required to expand system capacity is simultaneously facilitated by the use of higher frequencies and also permits the use of weaker signals, or higher frequencies, or a combination of both.

One might object that the benefits outlined in the previous paragraph are predicated on having a market for services that is large enough to sustain a robust and expensive infrastructure. Although that is true, the need for additional frequencies is also predicated on a large potential market. The requirement to start with an extensive and costly infrastructure (rather than starting with a much sparser infrastructure and growing with demand) is a problem that entrepreneurs and regulators will have to consider carefully.

Finally, note that shorter radio paths and the directional antennas also tend to discriminate against multipath signals (which are a limitation on signal bandwidth). Thus, the same infrastructure/an-tenna configurations that support higher capacity, lower power, and higher frequencies also will tend to support higher bandwidths and data rates. This factor may be of growing importance for future wide-band mobile data or Internet access.

4. RADIO FREQUENCY ELECTRONIC DEVICES

As shown in Figure 1, a portion of any wireless equipment (block C) must operate at the frequency used to transmit the RF signal. The RF electronics have often represented the most difficult part of an electronic system, because it is generally more difficult to make electronic circuits that operate efficiently at higher frequencies. Hundreds of megahertz of UHF TV frequencies remained almost unused for many years after they were allocated, partly because the consumer electronics industry had great difficulty producing a high-performance, low-cost UHF TV tuner. These are the same frequencies that are now used for cellular telephones and pagers–arguably the most valuable spectrum in existence today. The difference between then and now is that electronic technology eventually became proficient at manufacturing excellent inexpensive RF devices for that frequency range.

The highest frequency at which RF devices can operate has been increasing continuously. Five years ago manufacturers were concerned about being able to produce devices for the newly announced PCS bands near 2 GHz. The current upper limit for widely used consumer devices is 12 GHz, used in small direct broadcast satellite TV dishes.

Two of the most important technical factors contributing to maximum operating frequency for electronic circuits are “channel length” and “carrier mobility.” Channel length refers to the size of the features of the microscopic transistors that can be etched into an RF integrated circuit (IC). The shorter the channel length, the less time it takes for electrical charges to move through the channel, and the less time required to turn the channel on and off. The time required to turn the channel on and off is approximately the limitation on the maximum frequency of operation. Typical consumer RF IC’s use feature sizes of 0.5-1 micron today.

Although it might be a simple conceptual exercise to reduce the channel length in RF integrated circuits, it is not so easy in practice. These circuits are typically manufactured using photographic lithography techniques to make thousands of copies of the circuits on semiconductor wafers. The features are already extremely small (Figure 6) [9], and extraordinary precision is required in aligning new lithographic features with the ones already produced on the wafer. Even more challenging is the fact that current features are already smaller than a wavelength of light (about 1 micron in length) and ordinary visible light cannot be used in the photographic processing. The technology development needed to further reduce feature size is extremely expensive. Fortunately, this development is mostly paid for by the computer industry, which is investing tens of billions of dollars in advanced IC manufacturing facilities. The computer industry is building facilities with a 30% reduction in feature sizes every 3 years to support ever more complex CPU and memory chips. Thus, the computer IC industry is expected to produce a progression of new manufacturing technologies that will help to decrease channel length and increase the maximum operating frequency of RF semiconductor devices.

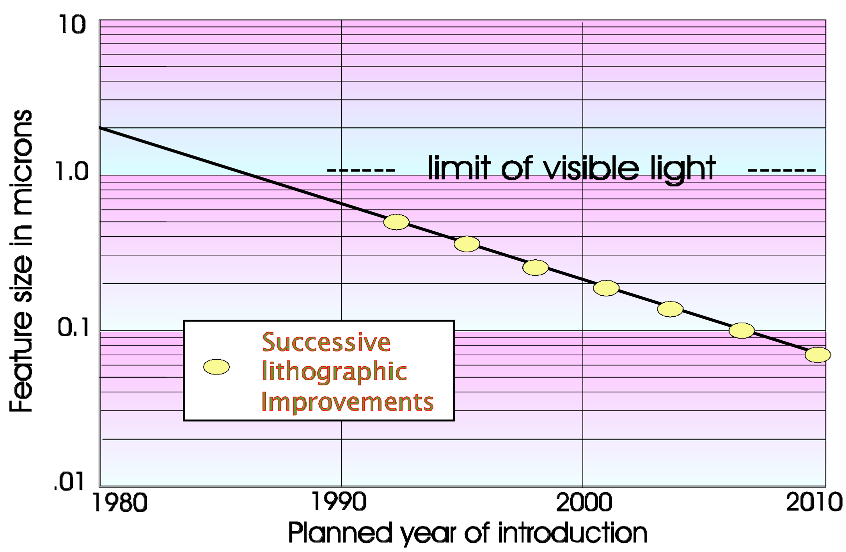

Figure 6. Semiconductor lithographic feature size vs planned year of introduction

The other major factor in the maximum frequency of RF devices is carrier mobility. While channel length is important, so is the speed at which electrical charges (carriers) move through that channel. Different materials have different carrier mobilities. Building RF devices from materials with a high carrier mobility can substantially affect the maximum frequency of operation. Table 1 shows the carrier mobilities for several semiconductor materials. Note that semiconductors use both electrons (“-” charges) and holes (“+” charges) for conduction. The electron carrier mobility of gallium arsenide (GaAs) is several times higher than silicon (Si).

Therefore, GaAs is used for the production of many higher-frequency RF devices, even though GaAs is considerably more expensive than silicon. Silicon-germanium is an experimental new material that is claimed to equal the performance of GaAs with the potential of Si costs [10].

Table 1. Carrier Mobilities and Cost of Fabricated Semiconducting Materials [11]

Material	Electron mobility	Hole mobility	Cost per mm^2
Silicon	1500 cm^2/V-s	450 cm^2/V-s	$.10-.40
Gallium-arsenide	8500 cm^2/V-s	400 cm^2/V-s	$1.00-4.00

The use of improved fabrication techniques (e.g., shorter channels) can increase the maximum operating frequency of any semiconductor material. Therefore, it is expected that silicon will eventually become suitable for some frequencies now requiring GaAs, at the same time that the maximum frequency of GaAs is increased.

Finally, the maximum frequency where a device can be practicably used is not a sharp line. Instead, RF devices generally work less well at higher frequencies. At higher frequencies, the gain of an amplifier decreases, the noise figure increases, the efficiency and maximum power output decreases, etc. As the maximum device operating frequency is approached, a certain amplifier gain that required a single gain stage at lower frequencies might require three cascaded gain stages, along with a considerable increase in power consumption and cost. Therefore, there will usually be substantial advantages in using devices whose maximum frequency capability is well above the actual system operating frequency; process improvements that increase device frequency capabilities are also likely to produce benefits for systems operating at lower frequencies.

Typical high-end consumer RF IC’s are manufactured with GaAs and a 0.5-micron process. This technology yields devices with a maximum frequency of operation near 40 GHz. Laboratory devices manufactured with 0.18-micron features include Si devices capable of operation near 50 MHz and GaAs devices in the 90- to 100-GHz range. It is anticipated that these performance parameters will continue to be improved.

4.2 The State-of-the-Industry for RF Devices

Multiple RF devices are often combined on a single chip into complex receiver front ends, power amplifiers, etc. These complex RF IC chips are also called microwave monolithic integrated circuits (MMIC’s). The state-of-the-art for MMIC’s has continued to produce improved packaging (size reduction), integration (consolidation of many circuit functions into a single integrated circuit), efficiency (lower power supply requirements), refinement of processing/fabri-cation techniques (improvement in manufacturing yields), and maximum operating frequency. These improvements reduce the cost vs. performance of MMIC electronics. The following key questions remain: At what frequencies does MMIC performance make it too difficult to design practical systems, and at what frequency do the costs of MMIC's and other RF devices begin to escalate and become impractical for the consumer marketplace?

There are three factors that lead to the "price breakpoint" effect where MMIC or discrete device fabrication costs escalate. One is economics: current high-volume applications tend to be at lower frequencies; there are many suppliers producing a variety of commodity parts and there is considerable market competition. Policy (regulations) plays a significant role; manufacturers are not producing communications electronics for mass market applications in frequency bands that have not been allocated for those applications. And finally, at higher frequencies, the performance of Si is inferior to GaAs and so more-expensive GaAs must be used instead.

This is not meant to infer that GaAs is not used for lower-frequency applications; 850-MHz portable cellular telephones routinely use GaAs components where the extra cost is warranted by the improved performance. GaAs in cellular receivers can provide improved noise figures (giving better reception of weak signals) and GaAs used in portable cellular transmitter stages provides more output power with less battery drain.

MMIC and IC costs are decreasing. International Data Corporation reports that semiconductor costs in typical cellular handsets will decrease from $75 in 1995 to $57 in the year 2000 because of continued integration of functions into IC's and because of improved manufacturing techniques [12]. Recent GaAs IC packaging techniques use low-cost solutions such as plastic encapsulation and standard integrated circuit pin-out designs with no degradation in performance [13]. Higher power IC's capable of 2- to 3-W RF power levels have been manufactured in ceramic packages, and the more stringent grounding requirements for RF IC's have been met by bridging neighboring pins protruding from the standard IC package into a single wide pin, thus acting as a heat sink while concurrently providing a lower impedance to ground. GaAs RF IC's containing entire receiver front ends are advertised in trade journals at costs as low as $4 each in quantity for 8 GHz and higher frequencies. Simpler amplifier blocks can be obtained at costs of about $1 each in quantity purchases.

The GaAs market continues to grow. Two years ago, Strategies Unlimited reported that the GaAs, GaP (gallium phosphide) and InP (indium phosphide) wafer manufacturing market would grow from a $250 million market in 1994 to a $360 million market in 2000 [14]. Blumm reports the GaAs wafer manufacturing market at $300 million as of 1997 (Figure 7).[2]

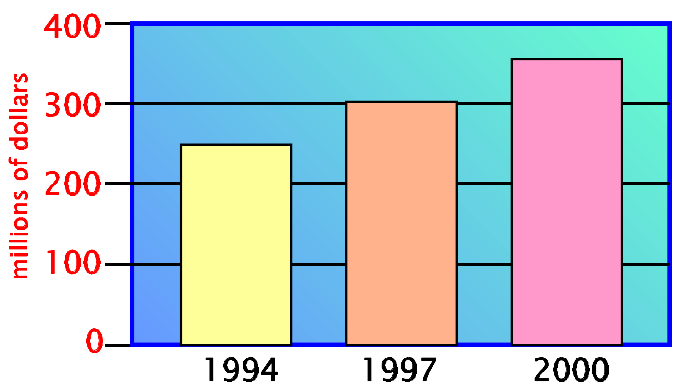

Figure 7. U.S. GaAs wafer manufacturing market.

ITT GTC, a U.S.-based semiconductor foun-

[2] Personal communication, F Blumm, Sequel Corp., 1997.

dry, announced in late 1995 that their GaAs wafer fabrication had grown into a 24-hr/day, 7-day/week operation [15]. Kenneth W. Taylor and Associates, a consultant firm, estimates that the North American digital wireless IC market is expected to skyrocket from $974 million in 1994 to $2.2 billion in North America by the year 2000 [16]. Anadigics supplies finished RF IC products for cellular and PCS applications in excess of 1.5 million IC's per month and expects the industry to grow to $2 billion by the year 2000 [14], Figure 8. Even at lower frequencies, where GaAs is not actually required, GaAs can offer significant performance advantages over Si [17], [18]. Some of these advantages include:

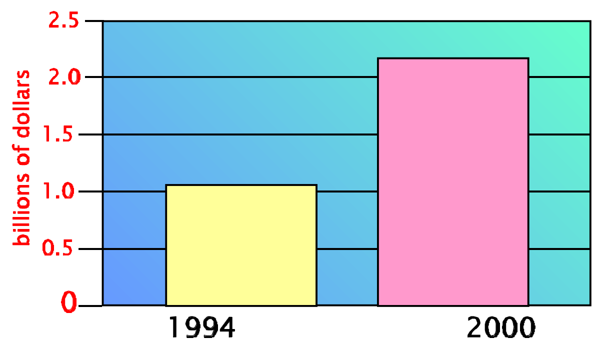

Figure 8. U.S, digital wireless market

- lower noise figure (better sensitivity);
- higher gain per stage (fewer stages needed);
- greater efficiency in power amplifiers (longer battery life); and
- ease of circuit integration.

MMICs play an important role in communications hardware miniaturization. There are a significant number of foundries in the U.S. that manufacture and market a wide variety of commercially available MMIC devices. A number of participants in the MMIC industry are listed in Table 2 [19].

Table 2. Principal MMIC Foundries in the United States

Alpha Industries
Anadigics
Celeritek
Hughes
ITT GCC
Litton
Lockeed-Martin-Sanders
M/A-Com
Northrop-Grumman
Raytheon
Rockwell
Texas Instruments
TriQuint
TRW

Table 2 demonstrates that there are a significant number of MMIC foundries in the United States, indicating that the GaAs MMIC industry has matured well beyond an industry in its infancy. Various sources report the GaAs industry as a $1 billion industry, and growing at 20-30% annually. This corresponds with a Frost & Sullivan Associates report that states the U.S. mobile communications market is growing annually at a 20% rate [20].

Figure 9 illustrates the performance characteristics of a variety of GaAs RF MMIC transmitter devices, compiled from various manufacturers' data sheets. Some operate as high as 42 GHz; some have output power as high as 2-3 W (33-35 dBm). The devices shown are representative of the marketplace. Some of these MMICs are proprietary designs; others are "commodity" MMIC's, where similar functions are available through many other manufacturers. Other functions, such as receiver front ends, mixers, and RF switches, are available in MMIC packages as well.

MMIC devices permit complex circuits and functions to be packaged into a single integrated circuit, such as mixers, amplifiers, and receiver front ends. Circuit integration fosters miniaturization and allows consumer products as complex as cellular telephones and GPS receivers to be constructed in lightweight, small-size packages. Circuit integration leads to lower costs, especially after nonrecurring engineering costs have been recovered in high-volume manufacturing. Discrete amplifiers that use GaAs FET's are useful for final amplifier power stages where 2- to 3-W MMIC transmitter powers are not sufficient for the intended application.

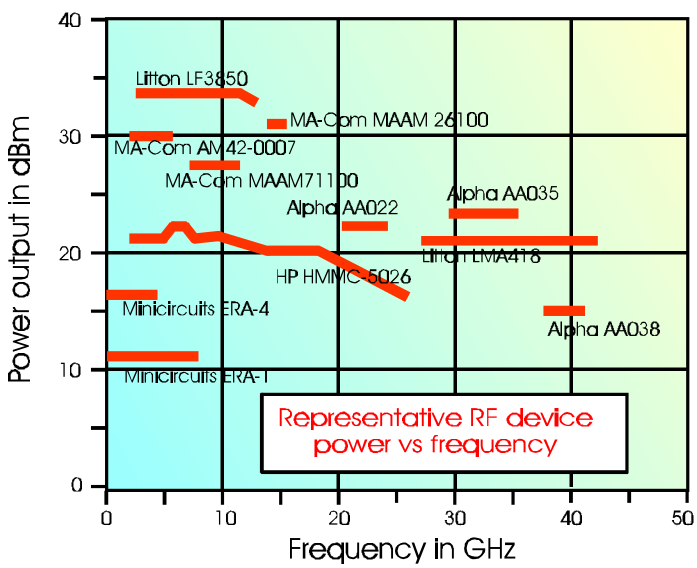

Figure 9. Output power of various MMIC devices.

The small receiving dish antenna system for DBS TV is a good example of high-frequency consumer applications. This system receives satellite signals at 12 GHz. It uses a single GaAs MMIC chip that contains the whole satellite receiver front end, including the later stages of a low- noise preamplifier, a block downconverter, local oscillator, and IF gain stages. Special ultra-low-noise PHEMT discrete transistors are used ahead of the MMIC to provide an overall system noise figure of 1.1 dB. The remainder of the receiver operates at frequencies below 1.5 GHz, where Si parts give adequate performance. About 3 million DBS receiver systems have been sold; the entire front end assembly (including the MMIC) currently costs less than $30.

4.3 Summary of RF Devices

The availability of suitable RF devices should not constitute a major limitation on the use of higher frequencies. The current high-frequency state-of-the-art for MMIC's used in consumer systems is the 12-GHz MMIC used in small dish satellite TV receivers, but considerable improvement is expected through continued advances in MMIC feature sizes and other processing developments.

5. SMART SYSTEMS

The term "smart" applies mainly to the non-RF electronics in a wireless system (part B in Figure 1). We define "smart" to mean systems that use computer-based intelligence to execute complex algorithms for system control and data processing/display. It applies equally to the consumer terminal and to the overall system architecture. The development of inexpensive miniaturized computer electronics has been crucial to the development of smart systems.

"Smart" is crucial in the planning of modern wireless systems, particularly those that operate at higher frequencies. Smart systems implement complex functions, such as network management, frequency, and power control, down to the individual subscriber level. Management of system access, channel assignments, power control, cell hand-off, and similar functions are performed transparently to the user. Cellular telephone and GPS receivers are prime examples of economical systems that have benefitted by packaging many complex functions into integrated circuits. Cellular telephones, available for less than $100 each, are capable of sequentially scanning multiple control channels, switching frequencies under direction of base-station control, providing link quality assessment in conjunction with automated power control, and performing cell hand-off (seamless reassignment of the subscriber to a different base station). GPS receivers, which can be purchased for less than $100 each, compute the user's geographic location by acquiring, tracking, and processing several spread spectrum signals from multiple GPS satellites.

5.1 A Description of Smart Systems

One of the most noticeable features of the traditional long-range mobile radio system was its simplicity. In the past, a long-range radio link was the only practical solution to the problem of obtaining a large operating area, because multisite networks linked by intelligent infrastructure were beyond the technology of the time. Today, however, because of very cheap computing power, it is possible to design practical systems that are much more complex than traditional wireless systems. This complexity has been used to increase system capacity, decrease cost, provide a wider range of services, and operate in higher frequency bands. Moreover, as described in the well-known Moore's law [21], Figure 10, the power of intelligent systems–whether part of the infrastructure or the personal terminal–will continue to increase in capability and to drop in cost.

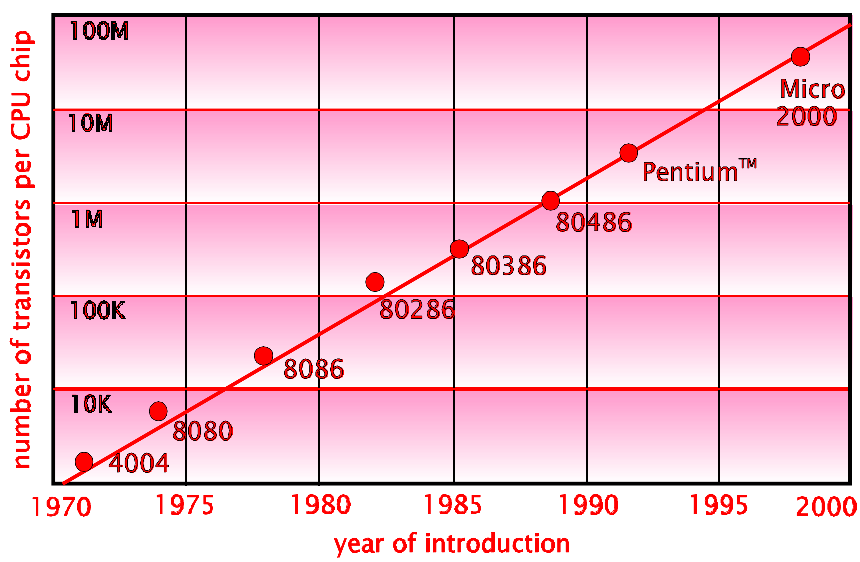

Figure 10. Moore's law of increasing CPU complexity.

At the most trivial level, smart consumer devices substitute computer processing for electronic hardware. So-called "software receivers" digitize the received signal and process it mathematically to recover data, speech, etc. For example, what was done in the past by a bandpass filter is now done by a computer chip executing FFT algorithms and windowing functions. Because software processes the information, multiple system protocols, data modulations, and information formats can be handled in the same terminal by simply recognizing the signal and running the appropriate software. The software receiver might be considered a trivial application–not because of trivial technology and software (indeed not!), but because the intelligence is merely used as a substitute for hardware. There would be little functional difference between the traditional hardware receiver and its software counterpart–except for size, cost, etc.

At a less-trivial level, smart consumer devices operate in completely different ways than would be possible for less intelligent devices. For example, personal cellular phones can operate almost anywhere in the United States with only 0.6 W of transmitter power. A traditional mobile radio having an operating range of 6000 km (i.e., anywhere within the United States) would be expected to be much, much larger and more expensive than a cellular phone. Functionally, a very complex intelligent infrastructure with 30,000 interconnected sites has completely changed the nature of a mobile transmitter with a 6000-km range. Ever-more-complex systems should be expected in the future–perhaps adding a whole-world satellite option, along with spread spectrum and active-tracking antenna beams to give 1000 times the bandwidth and system capacity.

5.2 Examples of Smart Systems

Very few of the old traditional mobile radio systems play a major role in today's consumer or business markets. The following paragraphs describe a sampling of the systems in widespread use today or planned for use in the near future.

Cellular Telephone. Cellular telephone service was introduced in 1983. It operates at 850 MHz. The basic service is analog FM, and channels are 30 kHz wide. The rapid growth in demand for cellular service has been met by cell splitting, cell sectoring, and other techniques. Subscriber units have gotten smaller; transportable "bag" telephones have been all but replaced by much smaller portable palm-sized handheld units whose weight is measured in ounces.

Personal Communications Services. Since 1989, there has been enormous activity to develop PCS that combines the network capabilities of the public switched telephone network (PSTN) with modern wireless digital signal-processing techniques. PCS integrates voice, data, and paging/messaging systems into one entity. PCS operates near 1900 MHz. The PCS build-out began in early 1996 with service now available in most major urban areas. PCS represents a considerable technological improvement over early analog cellular services, incorporating digital voice compression, complex CDMA or TDMA access protocols, and a fast-growing variety of advanced services.

Spread Spectrum WLAN Devices. There is significant activity in unlicensed "Part 15" spread spectrum systems using the 902-928 MHz, 2.4-2.5 GHz, and 5.725-5.875 GHz industrial, scientific, and medical (ISM) bands. These devices are capable of providing point-to-point or point-to-multipoint service, can support raw channel throughput rates on the order of 19.2 kbps - 1.544 Mbps, and some are capable of providing connectivities over distances on the order of tens of kilometers. Equipment prices range from roughly $1000 for the simpler single channel units to over several thousand dollars for T1 (24 multiplexed channels, 1.544 Mbps) capable equipment.

OEM activity in the 5.8 GHz band is less common at this time, although the numbers are growing. The recent release of 300 MHz of spectrum near 5.2 GHz for Unlicensed National Information Infrastructure (U-NII) applications will likely spur companies into increased production of equipment operating in this frequency range.

Dedicated Short Range Communications. The proposed dedicated short range communications (DSRC) band of 5850-5925 MHz is intended for a wide variety of vehicle-to-roadside automotive and transportation applications [22]. Advantages of the 5.8-GHz band for the intended uses are its limited propagation coverage area and its relative immunity to rain, snow, fog, and smoke. Examples of existing users in this band are automated vehicle toll-collection services and commercial vehicle clearance (e.g., truck weigh stations) services. Planned services include “traffic incident” management driver advisories that broadcast information regarding nearby traffic hazards and local traffic congestion to alert drivers and reroute traffic. Other planned applications include intersection collision avoidance and the automated highway system (AHS) where vehicles so equipped are routed into AHS lanes and navigated automatically to their destination.

Mobile Satellite Systems. There are nearly a dozen mobile satellite companies vying for market position in the emerging mobile satellite market [23]. Anticipated launch dates commence in 1997 to around 2003. Consumer-oriented mobile subscribers will access the satellite systems using frequencies in the range of 1610-1626.5 MHz (uplink) and 2483.5-2500 MHz (downlink), although one provider, IGC, plans to use 1980-2010 MHz and 2170-2200 MHz. *Microwave Journal* [20] cites one consultant as predicting that three or four low-earth-orbiting (LEO) global satellite systems and one or two regional Asian satellite systems will be operating by the year 2002.

MMDS and LMDS. Multiband multipoint distribution service (MMDS) and local multipoint distribution service (LMDS) are terrestrial microwave and millimeter-wave systems capable of delivering broadband services to the home [24]. Examples of such services are one-way TV broadcast, and bidirectional Internet and telephone service. They incorporate a localized cellular architecture using omnidirectional central sites and directional user antennas.

The primary differences between LMDS and MMDS are frequency, bandwidth, and cell size. MMDS is authorized 190 MHz of spectrum near 2.5 GHz and LMDS is authorized over 1 GHz of spectrum near 28 GHz. MMDS architectures are designed for fairly large coverage zones, up to 50 km across. Typical MMDS reflector antennas are up to 0.6 m (2 ft) in diameter. LMDS, on the other hand, uses small cells and small antennas, with roughly 3- to 8-km coverage radius and 10 cm (4-in) flat panel subscriber antennas. Existing MMDS architectures provide up to 33 NTSC broadcast (one-way) TV channels, while LMDS provides 40-50 wideband-FM TV channels. Both services are developing digital modulation schemes (e.g., 64QAM and QPSK) with video compression algorithms, providing a five-fold increase in the number of TV channels available.

5.3 Summary of Smart Systems

The easy availability of smart equipment for today's wireless systems, and even more intelligence in tomorrow's systems, has completely overthrown the rules by which traditional mobile radio systems were designed. Short-range radio paths are not a limitation on the overall coverage area of an infrastructure-based intelligent system, but now are more closely tied to strategies for frequency reuse and improvements in total system capacity. Although these modern systems are extraordinarily complex by yesterday's standards, they are well within the capabilities of the available intelligent-device manufacturing technology, and they will furnish the foundation for tomorrow's basic consumer wireless products.

6. HISTORICAL TRENDS IN SPECTRUM USE

The development of new applications and new markets, in tandem with technological improvements, has consistently moved applications to higher and higher radio frequencies as indicated by Figure 11. Consumer broadcasting applications began with AM radio and shortwave radio in the 1930's. VHF television and FM radio, introduced in approximately 1946, used frequencies near 100 MHz. Around 1980, backyard satellite dishes (TVRO) at 4 GHz came into being. This increasing frequency trend has continued with the newest addition to satellite TV reception in 1995 at 12 GHz. Examination of broadcast frequencies versus year of commercialization shows that frequencies have increased by a factor of about 2.5 every 10 years.

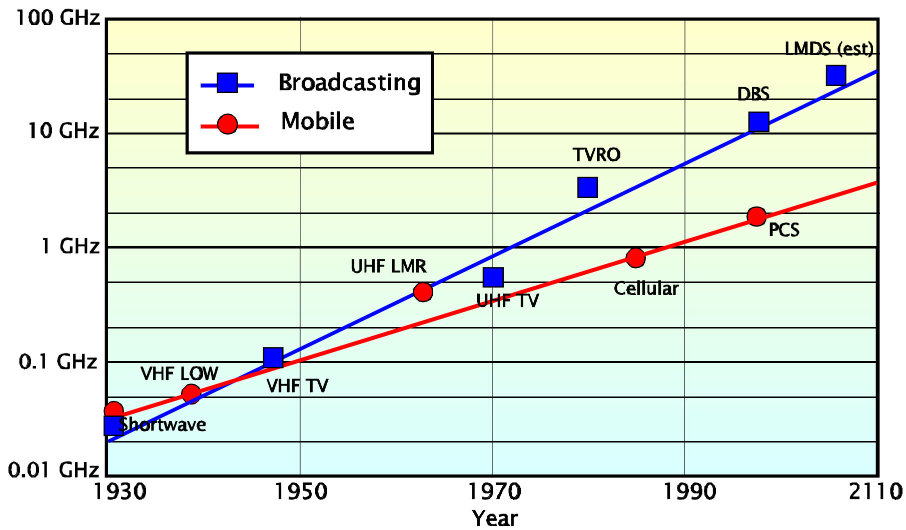

Figure 11. Radio system frequency vs. date of commercialization.

This trend is not unique to the broadcast service. A review of the historical growth of land mobile radio utilization exhibits a similar behavior. For land mobile services, the maximum frequency has also increased over time, beginning with shortwave radio in the 1920's, the introduction of UHF land mobile at 450 MHz in the 1950's, followed by cellular telephone in 1983 using frequencies near 850 MHz, and finally broadband PCS using the 1850-1990 MHz band. Examination of these events indicates that land mobile radio frequencies have increased by a factor of 1.8 every 10 years.

The difference in slopes for the mobile and broadcast trend lines may provide some insight into the use of higher frequencies. Broadcast developers have been more willing to use higher frequencies, because broadcast applications are generally fixed and can take advantage of high-gain directional antennas. Moreover, power consumption is a less serious limitation for broadcast transmitters or receivers. Thus, broadcast applications can more easily overcome the higher path loss associated with higher frequency bands. It is interesting to note that some broadcast applications are apparently morphing into "two-way digital wireless" applications (e.g., MMDS, LMDS, and DTV) and that some mobile radio bands will also provide service to fixed wireless applications. These changes suggest some merging of fixed, broadcast, and mobile services into "wireless" services. One might wonder whether there will continue to be two separate trend lines for broadcast and mobile services, or whether new system architectures will blur the distinctions between these services.

7. SUMMARY AND CONCLUSIONS

The preceding pages have suggested that higher frequencies are as good as lower frequencies for many functions. The skeptical reader might ask, "If the higher frequencies are so good, why are all the present consumers in the lower frequency bands?" The question has several answers, but the most important one is that the higher frequencies have been commercially viable for a much shorter period of time, limited especially by the availability of suitable RF devices. Only the most rapidly growing products (e.g., DBS receivers) have had enough time to generate a substantial consumer base. Second, systems that successfully exploit the higher frequencies may require the use of nontraditional technologies, where "traditional" means applicable mainly to older, lower-frequency, less complex systems. Finally, the higher frequencies may be best suited for providing nontraditional services, where customers have not yet automatically identified themselves and where system designs are not yet obvious. Taken together, these answers suggest that the use of the higher frequencies is (as it always has been) a "frontier" experience, where ingenuity and foresight will be needed to produce big returns.

Earlier systems (and many current ones) were developed to use features of long-range, wide-area, sparse user populations; fixed high-power base stations; single-function (usually voice); analog information; and "dumb" base and mobile equipment. New and proposed terrestrial systems are being developed to exploit shorter range, cellular deployments able to serve a much denser subscriber base, using multipurpose digital bit streams. These emerging systems will need to be much smarter and more complex than traditional systems, and they will demand extensive infrastructure development and integration into existing telecommunication infrastructures.

To support the substantial cost of these new systems, developers will aim for a large customer base, using relatively large blocks of spectrum for fast and flexible access. One of the most important considerations for a new service seeking spectrum allocation is relocation costs incurred by the new service when displacing an incumbent service. If new services are required to pay to relocate incumbent services to a new frequency band, relocation costs will be proportional to the number of incumbent users. This could drastically reduce the value of lower frequency spectrum as perceived by potential new services. For example, costs to be paid by the PCS industry for relocating private operational fixed microwave services to other bands is estimated to exceed $1 billion [25]. Higher frequencies have fewer current users and would therefore have lower relocation costs. Assigning new services to the less densely occupied higher frequencies will avoid these relocation costs.

Higher frequencies will become continually more attractive as (1) RF devices become cheaper and better, (2) denser base station deployments reduce the required radio path length, and (3) demand for wide bandwidth circuits and frequency reuse increases. It must be emphasized that the use of higher frequencies is "compatible and synergistic" with the new wireless paradigms, rather than the new paradigms evolving as forced responses to the necessity of using higher frequencies. For example, the dense cellular infrastructure is a necessity for serving a large customer base, rather than being forced by path loss considerations. However, the dense infrastructure "just happens" to also permit the use of higher frequencies with greater path losses.

We do not know the upper limit for frequencies that can be successfully used for consumer wireless services. We do know that it is surely substantially greater than the 3 GHz of yesterday. The upper limit is still almost doubling every 10 years, but it might not continue at that rate forever. It is also useful to look at the tendency toward the convergence of fixed, broadcast, and mobile services into general-purpose wireless services and to suggest that future wireless services will probably be different from anything that we can even imagine today. Those future systems will use a wide range of frequency bands and architectures, chosen for being the most suitable for the specific service, and limited only by the ingenuity of the developers and the demand of the users.

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