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R.D. Carsello, R. Meidan, S. Allpress, F. O'Brien, J.A. Tarallo, N. Ziesse, A. Arunachalam, J.M. Costa, E. Berruto, R.C. Kirby, A. Maclatchy, F. Watanabe, H. Xia, "IMT-2000 standards: radio aspects", *IEEE Personal Communications,* Vol. 4, No. 4, pp. 30-40, August 1997.

Abstract

One of the key characteristics of IMT-2000 is the advanced radio technologies that will offer a whole new range of capabilities to the users of international mobile telecommunications. This article starts by comparing the significant differences between second-generation mobile systems and the major objectives envisioned for IMT-2000, with particular emphasis on the satellite component. It also describes the flexible modular architecture for IMT-2000, which will facilitate the introduction and evolution of new capabilities. The article overviews the technology facilitators that, by the year 2000, will greatly assist the economic implementation of these new systems. Finally, the ITU process for the selection of radio technologies that will fulfill these ambitious requirements is also outlined.

IMT-2000 Standards: Radio Aspects

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As summarized in a companion article in this special issue on International Mobile Telecommunications-2000 [1], IMT-2000 has a greatly expanded range of service capabilities and covers a very wide range of operating environments. This significantly impacts the various radio technology choices necessary to optimize IMT-2000 performance. This article explains the flexible modular architecture envisaged for IMT-2000, which will facilitate the introduction of new capabilities and also seamless evolution from the substantial installed telecommunications base expected by the year 2000. The process chosen by the International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R) to evaluate radio transmission technology proposals for IMT-2000, and the evolving system and component technologies that will facilitate achieving the ambitious objectives of IMT-2000 are also discussed.

Some of the year 2000 techniques that will greatly assist the economic realization of such improvements in IMT-2000 performance are:
- Optimized radio channel management
- Availability of bandwidth on demand
- Dynamic channel equalization and coding
- Optimized modulation and spreading
- Efficient traffic multiplexing and compression
- Smart/adaptive antenna systems
- Increasing software control of radio characteristics

To help understand the major objectives envisioned for IMT-2000 and the significant differences from the second-generation mobile systems operating today, the key aspects are briefly summarized in Table 1.

Evolution Capabilities of IMT-2000

In developing the standards for IMT-2000, it has been recognized that one of the most important requirements is *flexibility*. Indeed, flexibility is needed not only to allow for evolution from pre-IMT-2000 systems to IMT-2000, but also to facilitate the evolution of IMT-2000 systems toward more advanced capabilities as user demands increase and technology progresses. Also, flexibility is needed to support different environments with minimum changes in the technology. A handbook on "Principles and Approaches on Evolution to IMT-2000/FPLMTS" has been produced by the ITU, identifying issues and considerations that must be addressed to facilitate evolution options [2].

In terms of the radio interface, increased flexibility has been identified as of the utmost importance by future IMT-2000 operators [1]. IMT-2000 systems will have to be flexible in terms of deployment, service provision, resource planning, and spectrum sharing.

Some of the items that need to be considered are:
- The ability to balance capacity versus RF signal quality as long as minimum performance requirements are met
- The adaptability of system(s) to different and/or time-varying propagation and traffic environments
- Ease of radio resource management
- The ability to accommodate fixed wireless access (FWA) architecture
- Ease of service provision, including bandwidth-on-demand, circuit- and packet-switched, as well as multimedia services
- Adaptation to the different spectrum allocations available in the various regions

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Aspects	Second-generation systems	Third-generation systems (IMT-2000)
Digital technology	All use digital technologies for modulation, speech, and channel coding, and implementation of control and data channels.	Increased use of digital technologies, including programmable radios.
Commonality for different operating environments	They are primarily optimized for specific operating environments, for example, the vehicular and pedestrian environments, although they may be applicable to other operating environments such as fixed wireless access (FWA).	A key objective is maximizing the commonality and optimization of radio interfaces for multiple operating environments, that is, vehicular, pedestrian, office, FWA, and satellite operation, preferably, via the use of a single flexible or scalable radio interface.
Frequency bands	They operate in multiple frequency bands, e.g., 800 MHz, 900 MHz, and 1.5, and 1.8 GHz.	Use of a common global frequency band for both terrestrial and satellite components, as identified at WARC '92 and WRC '95.
Data services	Data services, though continuing to evolve, are currently limited to data rates less than 32 kb/s.	Significantly higher transmission speed capabilities encompassing circuit- and packet-switched as well as multimedia services.
Roaming	Subscriber roaming is generally limited to a specific region, although the use of SIM or UIM modules is facilitating broader roaming capability.	Improved global roaming due to global frequency coordination, increased use of SIM/UIM for IMT-2000, use of ITU radio and network interface standards, and the availability of global satellite coverage.
Technology	Spectrum efficiency, overall cost, and flexibility are primarily limited by system design objectives and the technology existing at design inception and implementation.	Spectrum efficiency, flexibility, and overall costs will be improved as a result of building upon second-generation wireless system design experience and the utilization of year-2000 technologies.

■ **Table 1.** *Comparison of second- and third-generation systems.*

Also, particularly for terrestrial:
- Ability to accommodate mixed-cell (e.g., pico, micro, and macro) architecture;
- Suitability for multiple operators in the same/overlapping service areas which would include the ability to:
  - efficiently share a common spectrum allocation
  - share network infrastructures (for example in areas of low subscriber density)
  - provide for handover between systems run by different operators

Although the ITU World Radio Conferences (WRCs) have attempted to harmonize spectrum allocations for IMT-2000 to the greatest extent possible, there will still be considerable differences in timing and what spectrum is available in the various regions around the world. Roaming mobiles will need to follow a standardized initialization process to locate suitable broadcast channels and learn what spectrum allocations, operators, and services are available locally.

For operators of existing telecommunications networks there are various options for the evolution of their networks toward IMT-2000 which depend on the current network and the approach adopted to build up to the target network configuration.

Not only must multiple generations of radio interfaces be capable of being served from a common backbone network, but IMT-2000 radio transmission systems must also be able to operate efficiently from a wide range of possible "fixed" and "mobile" network platforms. This clearly requires a modular approach to standardization of IMT-2000.

To facilitate evolution, particularly when different radio interfaces and different networks are considered, the ITU has produced a new recommendation entitled "Framework for Modularity and Radio Commonality within IMT-2000" [3]. It describes the modularity principles that should be adopted in the development of the radio-related aspects of IMT-2000. This approach will encourage convergence toward a common "vision," effectively merging the various alternative paths to third-generation systems.

The IMT-2000 system model in Fig. 1 shows the proposed modularity concept. It is based on a clear separation between the *radio access network* and *core network* domains. This separation identifies a single *radio access network interface* and reference point between the two main system components; this interface represents the key item, in addition to the IMT-2000 *radio interface* itself, to be standardized by the ITU.

The radio access network interface allows future innovative radio segments to be connected to multiple pre-existing networks and also for the IMT-2000 core network to connect to multiple pre-existing radio access subsystems.

The radio access network, for both IMT-2000 and second-generation systems (pre-IMT-2000), is considered in two parts:

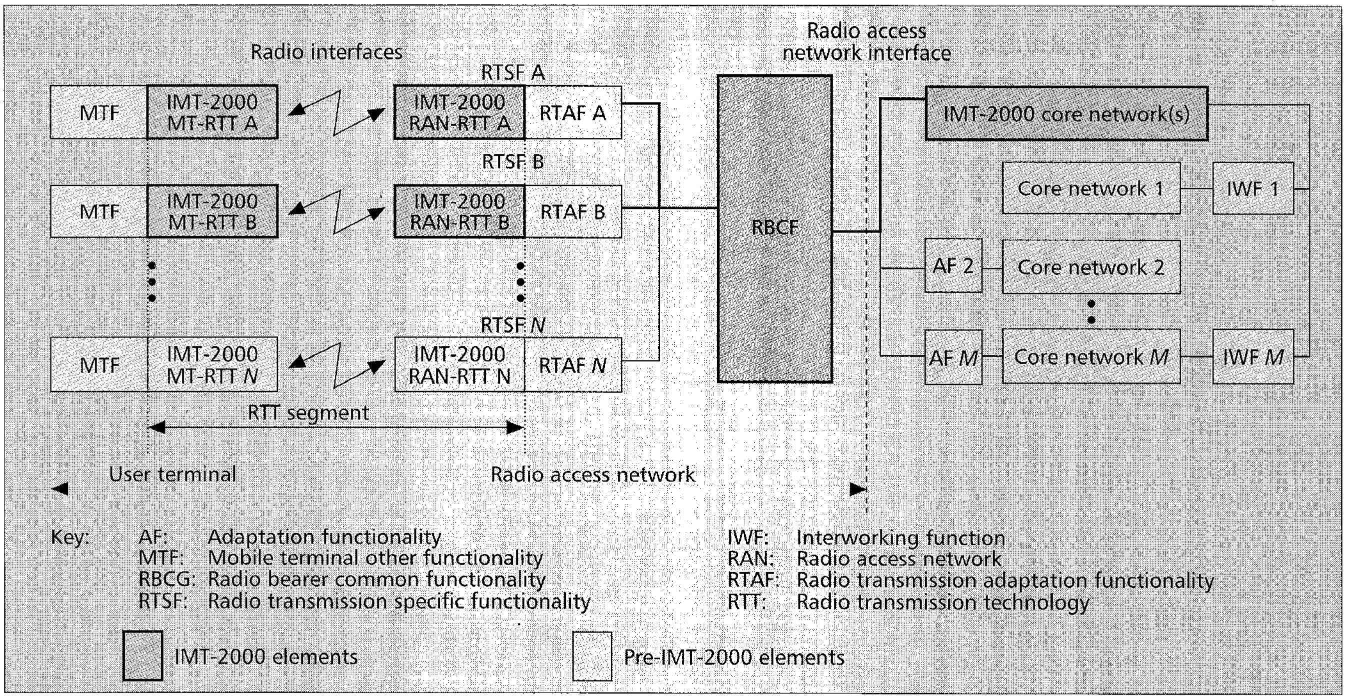
Radio Bearer Common Functionality (RBCF) – embodying all the control and transport functions that are independent of the adopted radio access technology. The RBCF is used to adapt between the relatively error-free high-bandwidth core network(s) and the more error-prone band-limited radio transmission technologies serving the various IMT-2000 operating environments.

Radio Transmission Specific Functionality (RTSF) – embodying the radio-technology-dependent functionality, further divided into radio transmission technology (RTT) and the relevant radio transmission adaptation functionality (RTAF). The latter adapts different RTTs to the common access part.

The radio transmission technology functions are present on both sides of the radio interface (mobile terminal and radio access network).

On the core network side, in addition to the IMT-2000 core network, earlier core networks are also supported. In this case, the connectivity with IMT-2000 is guaranteed through suitable interworking functions (IWFs). The same earlier core networks can also directly support the IMT-2000 radio access network (and relevant terminals) if appropriate adaptation functions (AF) are implemented.

The above arrangement makes possible different evolution paths to the third generation, but frames their development within a single target system model. The adoption of the recommended modular structure allows the development of a



■ **Figure 1.** *Basic IMT-2000 system model plus pre-IMT-2000 systems.*

"future-proof" design where different radio access and network "building blocks" can easily be arranged and connected in a tailored way, due to the plug-in approach.

Thus, individual operators can select their own evolution path toward IMT-2000, by considering their present infrastructure, preferred strategies for the introduction of new services and coverage areas, and relevant regulatory constraints.

The Satellite Component

Two major issues for any radio-based system are capacity and coverage. For mobile systems operating in an urban environment, capacity in terms of offered load per unit area is the paramount requirement, while for rural or remote environments coverage is more important.

Terrestrial-based systems provide high capacity through the use of moderate- to small-sized cells, which give high spectrum reuse and hence high capacity. However, there are limits to terrestrial-based global coverage capabilities since densely inhabited areas cover only a small fraction of the world's area, and economics dictate that large portions of the world will not enjoy terrestrial-based radio coverage. Satellite-based systems, however, can provide ubiquitous global services to handheld personal units in all places and at all times. The service has been termed MSS (mobile satellite services) or S-PCN (satellite personal communications networks).

Satellite-based mobile systems are intended to be used in a complementary mode to terrestrial systems. Having low capacity in terms of the number of users per unit area, with some service limitations and generally higher cost, it is usually to the advantage of the user to use a terrestrial-based system whenever available; *hence, the IMT-2000 vision of the terrestrial and satellite-based systems as two components of one integrated system.*

At WARC '92, as part of the 230 MHz identified for IMT-2000/FPLMTS, 30 MHz (paired with 30 MHz) was identified for the satellite component as follows: 1980–2010 MHz paired with 2170–2200 MHz.

Satellite-based communications differs from terrestrial-based systems in many respects. The following are the main areas of difference.

Satellite Orbits

Satellite orbits are divided into various categories, each characterized by unique features. GEO (geostationary earth orbit) has been used in the past for MSS, mainly for maritime services, with subsequent upgrade to land and aeronautical services [4]. However, GEO suffers from some inherent limitations for providing true global personal communications services. First, it does not provide full global coverage, since high latitude and polar regions are not covered. Second, in view of the high altitude, unless the satellites have very large antennas, the link budget does not allow true handheld services. Last, a long time delay, due to long propagation delays, makes true duplex telephone conversations difficult.

The nongeostationary (NGEO) family of orbits are subdivided into LEO (low earth orbit), with altitudes ranging 800–1600 km, and MEO (medium earth orbit), sometimes called ICO (intermediate circular orbit) with orbit altitude around 10,000 km. The advantage of NGEO orbits is the option to provide full global coverage with a much better link budget from small satellites, thus allowing handheld operation with fade margins and much smaller time delays. The satellites are smaller in dimensions and weight than GEO and can be launched more economically. Also, only small aperture antennas are required to reduce each beam's footprint size, which provides a better global frequency reuse factor.

However, NGEO systems require a relatively large number of satellites which are not stationary as viewed from the earth. In fact, the lower the orbit, the larger the number of satellites and the faster the satellites rotate relative to the earth. As with GEO systems, the global traffic load distribution is not uniform. There are large areas of the globe (seas, deserts, etc.) where service requests are expected to be particularly light. It follows that these may be regions where the available spectrum of an NGEO satellite is not fully utilized. However, as mentioned below, the traffic capacity of a satellite is also power-limited, and the light loading in these global areas can be used to charge the batteries, thereby providing a power-averaging or balancing effect for those areas requiring higher traffic loads. The ubiquitous coverage on a global scale that can be designed into an NGEO constellation can be used for the benefit of communications to every place in the world, particularly to the underdeveloped regions of the world.

The Generation Gap

There has been considerable experience with terrestrial systems, and the terrestrial component of IMT-2000 is considered a third-generation system. However satellite-based systems are much younger. In fact, first-generation NGEO systems are only now in the construction stages with plans to start commercial services by the end of 1998 [5–8]. This means that when IMT-2000 becomes operational, these first-generation NGEO satellite systems will be potential candidates for integration into IMT-2000.

Most of these NGEO systems are being constructed in frequency bands not directly identified as IMT-2000/FPLMTS satellite bands (e.g., 1610–1626.5 MHz paired with 2483.5–2500 Mhz bands). The lower band is used for earth-to-space communications on a primary basis (space-to-earth on a secondary basis for TDD operation) and the upper band for space-to-earth communications. However, at this stage, at least one such system is addressing the IMT-2000/FPLMTS bands identified at WARC '92.

The Power Limit

In view of the cost of launching satellites into orbit, satellite-based systems are generally power limited, in contrast to terrestrial-based systems which are basically interference limited. This implies that fade margins achievable with satellite-based links are limited compared to the terrestrial-based case. This effect is offset by the need for high fade margins in urban areas where high blockage occurs, while in rural and remote areas less blockage occurs requiring less fade margin.

The Data Rate Limit

Corresponding with the above power restrictions the maximum data rate is also limited. More accurately, the cost of communicating a bit per second is much higher compared to the terrestrial case. This implies that a higher degree of source coding and compression is required (e.g., 4800 or 2400 b/s for voice services).

Global vs. Local Coverage Architecture

Various types of architectures have been proposed, such as an independent global system or a regional system tied into local terrestrial systems for coverage extension on a local or regional basis. Naturally, the former approach will allow true global coverage.

Onboard Processing vs. Bent-Pipe Operation

The state of technology enables onboard satellite processing, rather than the traditional bent-pipe operation. Bent-pipe satellites simply receive signals in one band, convert the frequency to another band, and transmit; they are repeaters. With onboard processing the satellite plays the role of the base site. With bent-pipe operation the gateway is in effect the base site. The onboard processing, in conjunction with a cross-link network interconnecting the constellation, allows flexibility in routing the call. In this way, the constraints on the location of the gateways that exist in the bent-pipe case are removed. In particular, this allows full coverage of the large water bodies, in spite of the low satellite orbits. A challenge in designing on board processing is providing a means to adapt to changing traffic and service requirements. The so-called software radio is a key tool which can allow this flexibility; for example, new software could be uploaded to the satellites as required to accommodate changes.

The Multibeam Antenna

In terrestrial-based systems the isolation between the cells is assisted by geometrical attenuation of the radio waves. In the satellite case, cell isolation is accomplished by the antenna pattern (i.e., a multibeam antenna draws the cellular pattern on the surface of the earth). In a typical LEO S-PCN 48 beams are served by one satellite; such an antenna is based on phased array technology.

Cell Dimensions

In view of the geometry, the cell sizes of the satellite-based systems are huge, on the order of hundreds of kilometers in diameter. This affirms that the capacity of the satellite systems is small in comparison to terrestrial systems and matches the lower traffic density expected in rural, remote, and ocean regions.

The Radio Link

The satellite-based radio link has different propagation characteristics than a terrestrial-based system. The propagation path is longer, implying increased time delays and large distance-related geometric attenuation. It also has a shorter delay spread with broad coherence bandwidth. Shadowing and multipath is a function of the subscriber environment and movement. Clear line of sight is an optimistic assumption, since there will be shadowing due to trees and buildings; operation in vehicles and buildings should also be considered.

Access Methods

Both time-division multiple access (TDMA) and code-division multiple access (CDMA) methods have been defined for S-PCN systems. However, comparison between access methods for satellite-based links is not the same as for the terrestrial environment, since the radio link parameters are different. For example, the considerable time delay associated with the satellite link does not allow fast power control for a satellite system. Also, the delay spread of satellite-based systems is small with a rather wide coherence bandwidth, implying that the bandwidth allocated for the system is unlikely to be sufficient to gain frequency diversity by spreading the spectrum.

Worldwide Frequency Harmonization

Because satellite-based systems have large cell sizes often covering more than one country, it is mandatory for efficient operation that the frequency allocations for these systems be harmonized on a global basis.

Handover

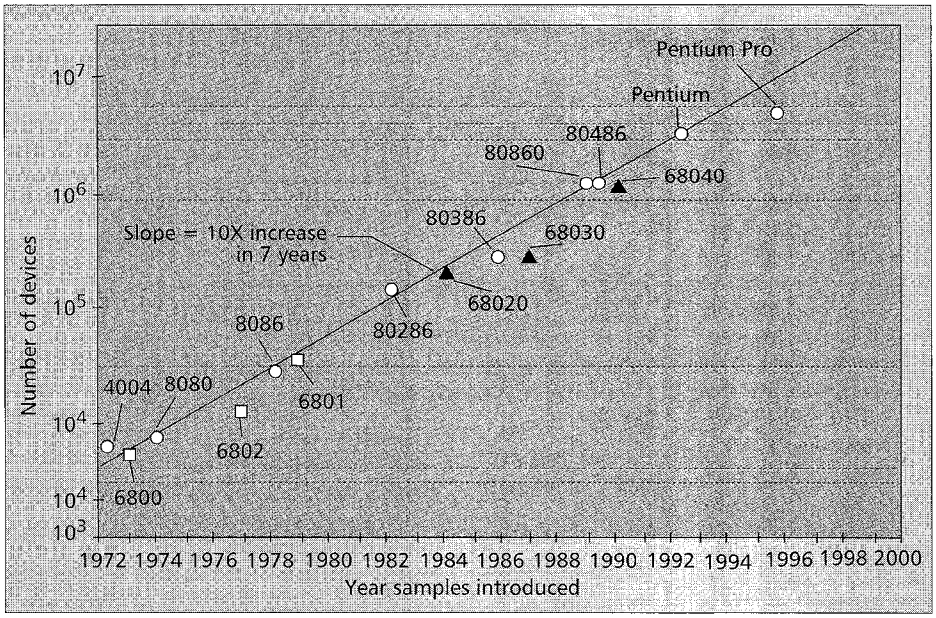
Another unique feature of NGEO satellite-based systems is beam-to-beam handover due to the fast motion of the satellites. Unlike terrestrial-based systems where handover is due to subscriber motion, and hence random from the system point of view, satellite-based system handover is basically deterministic.

Doppler Shift and Time Delays

Doppler shifts and time delay variations for NGEO systems are on the order of tens of kilohertz and tens of milliseconds, respectively, depending on the satellite orbits.

Equipment in Space

Putting the equipment in space means that there is no way to get there in case of need, implying that the approaches to solving the issues of maintenance, control, evolution, and so forth are different than for terrestrial-based systems. Terrestrial-based systems may be implemented in an incremental manner and modified incrementally to match user needs. Satellite systems, on the other hand, require a fairly complete constellation before commercial service can begin.



■ **Figure 2.** *Microchip and microprocessor complexity vs. time.*

IMT-2000 Technology Facilitators

The contribution of future component and system technologies to third-generation wireless systems is critical to their success. Considering the role of these technologies in present-generation products, it is important to try to determine how improvements by the year 2000 will impact performance and also facilitate meeting the challenging IMT-2000 objectives. Key technology facilitators are envisioned to be:

- Battery technologies
- Digital signaliing processor/integrated circuit (DSP/IC) technologies
- Antenna technologies
- Software radios

Battery Technologies

Personal communications products are continually decreasing in size and weight. If IMT-2000 is to be competitive, personal units with an expanded range of service capabilities will need to be similar in size and weight to existing wireless communicators. Higher-bit-rate services defined for IMT-2000 require more energy per bit (E_b) to maintain service quality and system range. These higher-rate services will require increased battery power for both signal processing and RF power radiation functions. Batteries for today's cellular radios make up approximately 50 percent of the radio volume and weight. Considering these factors, it is extremely important that battery improvement technology trends continue, to enable achievement of IMT-2000 objectives.

Lithium battery technology trends indicate that significant improvement in both the volumetric and gravimetric energy density can be expected in future units. Solid state lithium batteries available within the next few years are predicted to have almost four times the energy density capability of the NiCad batteries currently used extensively in wireless communicators. In addition, a 2:1 volumetric energy density improvement over NiCad is also projected.

Unit costs which have been inhibitors to more rapid acceptance of lithium technology as the primary energy source for wireless communicators are projected to decrease rapidly. It is likely that the dollars per watt hour for lithium batteries will be approximately equal to those of current NiCad units by the year 2000.

Considering these trends, it appears reasonable to assume that ongoing battery technology improvements will support the higher DC power requirements of IMT-2000 personal communicators without requiring a greater percentage of the total unit volume and weight after the year 2000.

DSP/IC Semiconductor Technologies

Continuous improvements in semiconductor processing technology over the past three decades have enabled system and product designers to provide significant end-user benefits for many industries, including wireless communications. The trend from mobile to personal communications over the past decade would not have been possible without these semiconductor industry contributions. The major IMT-2000 objectives of minimizing complexity, cost, and size, and enhancing flexibility and performance will require a continuation of these semiconductor improvement trends.

Since product implementations will vary, they will in all likelihood include microcomputers/microprocessors, DSPs and application-specific ICs (ASICs) in varying amounts.

Considering this fact, it is instructive to look at some of the specific semiconductor performance trends to determine if they will enable IMT-2000 technologies as they have previous generations of wireless products.

Figures 2 and 3 illustrate that both microprocessor complexity and speed/power characteristics have consistently improved.

Figure 2 illustrates that approximately 10^8 devices/chip will be available to support the increasing complexity requirements of IMT-2000. This assumption assumes that 12-in wafers and 0.18 μ technology will be readily available after the year 2000.

Similarly, speed/power characteristics as measured in milliwatts per MIP for both microprocessors and DSPs have been improving by tenfold every two-and-a-half years. This is illustrated in Fig. 3. This improvement is primarily the result of semiconductor process and design improvements utilizing lower voltages. This important trend impacts battery size and personal communicator talk/standby time.

Although not illustrated, ASICs have followed a similar power improvement trend. The power efficiency advantage of dedicated ASIC logic as compared to software logic utilizing DSPs is well known. By the year 2000, it is projected that dedicated ASIC logic will have a tenfold power efficiency advantage versus software logic design. As such, less complex, lesser featured IMT-2000 personal communicators may utilize ASIC technology to implement the required functions as IMT-2000 systems become more widely accepted.

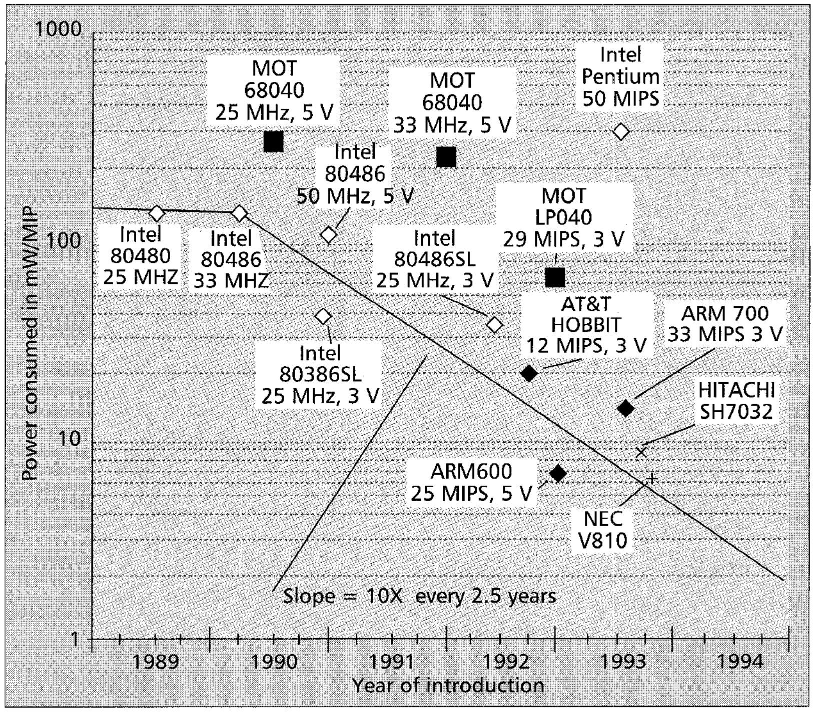
Considering these trends, it appears reasonable to forecast that continuing semiconductor processing and design enhancements will provide the desired capability to meet IMT-2000 objectives, and also enable designers to develop a broad array of products ranging from those with significant complexity, such as software radios, to less sophisticated and featured, small, longer-battery-life personal communicators.

Infrastucture and Subscriber Antenna Technologies

The technologies employed in IMT-2000 antennas will go significantly beyond those found in today's mobile systems. In current systems antennas are generally a secondary part of the system, and while great effort was devoted to the development of the modulation, coding, framing, and protocols, significantly less was focused on antenna technology. The demand for capacity, coverage, quality, and a level of services comparable to and even exceeding those provided by the land line network, together with the reality of limited spectrum and the hostility of the wireless environment, will require highly sophisticated development of all aspects of radio technology for the IMT-2000 network, including the antenna systems.

Today's wireless systems are characterized by three properties that will drive the technological advances of IMT-2000 antenna systems:

- Current systems utilize antennas with relatively limited directivity, since neither the base station transceiver nor the subscriber transceiver has precise knowledge of the other unit's location. This results in the expenditure of extra energy to transmit microwave signals that serve no useful purpose in maintaining a reliable communication link, but also create interference on parallel links, ultimately limiting overall system capacity. Ideally, highly directive antennas at both ends of the link, pointed at each other, provide optimum performance. This, however, requires that each transceiver "know" the location of the other unit in order to properly "point" the antenna.
- Current systems deploy large antennas, towers, cables, and related hardware that do not readily gain public acceptance, and are viewed as a potential source of revenue by local governments and private antenna site owners. As a consequence, a great deal of time and resources are expended just establishing the antenna-related portion of the infrastructure end of the wireless network. This problem primarily plagues the infrastructure provider, but the physical size required by the antenna can also become a problem at the subscriber end as terminals continue to get smaller and more portable. An ideal system would utilize small, unobtrusive antennas that virtually disappear in the environment, and can be located nearly anywhere.
- Installing new antenna systems as part of the infrastructure, and optimizing the system for maximum coverage with minimum interference in neighboring cells, can be costly and time-consuming. The wide variety of outdoor and indoor propagation environments makes this, of necessity, a custom process in many instances. An ideal system would use "standard," readily installed antennas that achieve optimum performance with little or no customization.



■ **Figure 3.** *Speed/power characteristics of microprocessors vs. time.*

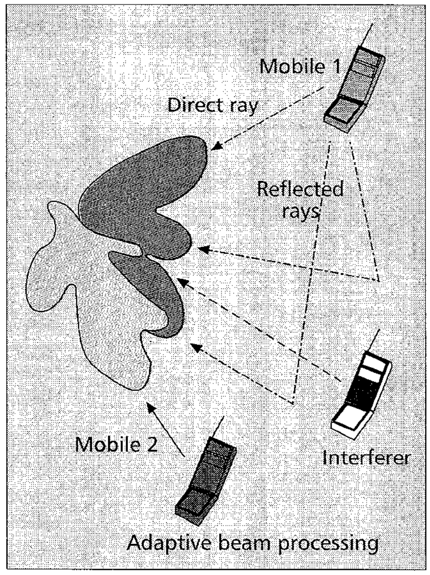
Advanced antenna technology for the IMT-2000 network will require the evolution of "intelligent" antennas to a highly developed state. The term "intelligent antenna" is applied today to a broad class of antenna systems which use electronic "intelligence" to create directive antenna beams that "point" in the right direction to achieve an enhancement in the communication link. Current systems vary greatly in level of sophistication and in their ability to equally enhance the uplink and downlink. Some of the more sophisticated systems derive their technological approach from adaptive system technology developed for military systems such as phased array radars and sonar.

The need for higher-gain, more directive antennas on an intelligent system that "steers" the antenna beams to a position that optimizes the communication link directly addresses a number of issues limiting today's wireless systems. Higher-gain antennas offer greater range, better building and vehicle penetration, and improved capacity via interference suppression. Power consumption at the base station and battery life at the terminal may both be improved if high-gain antennas are used to reduce transmitted power. The ability to point or "shape" the antenna beam, through narrow fixed beams or adaptive arrays, provides the above-mentioned interference suppression. This concept is illustrated in Fig. 4.

Meeting the demands for highly directive antenna arrays for the IMT-2000 network will result in yet another dominant trend in antenna technology: integration of passive antenna elements with active circuitry. The deployment of active electronics on the antenna tower is by no means a universal practice in today's mobile systems, largely because of reliability and maintenance issues. Voltage surges created by atmospheric disturbances such as lightning and harsh thermal environments can give rise to high failure rates unless costly design and manufacturing procedures are followed. Many wireless service providers have chosen to avoid these issues, even though it is well known, for example, that typical cellular base stations lose 2–5 dB of sensitivity and RF power output due to losses in the coaxial antenna cables. The simple addition of low-noise preamplifiers at the tower top can regain the receiver sensitivity loss and permit use of smaller, lower-cost antenna cables as an added benefit. Widespread use of highly directive intelligent antenna arrays, however, will force the acceptance of integrated active and passive electronics.

Intelligent antenna systems will require a significant increase in the number of signals that pass between the base station and the radiating elements, driving the need for a new interface to replace existing large coaxial cables which frequently exceed one inch in diameter.

Another issue impacting antenna technology for the IMT-2000 network, beyond gain/capacity, performance, and size, is the need for self-configuring systems that virtually eliminate the need for custom "tuning" of antennas. Wireless system engineering often requires balancing contradicting needs, such as maximizing coverage within a cell while minimizing interference to adjacent cells; and the need for highly sensitive receivers in order to maintain communications with distant users while avoiding overload due to users standing adjacent to the antenna. These issues are combined with the need to operate transparently in a multitude of environments. Advanced infrastructure antenna technology, combined with adaptive channel and resource allocation, as well as flexible software radios, will be instrumental in approaching the goal of "self-engineering" systems. The ability to tailor antenna beam shape in any direction and adapt over time on a per-user basis will enable continuous optimization in a particular cell. When such intelligence at the base station level is augmented by intelligence at the network level, significant system-level self-configuration and optimization will be possible.



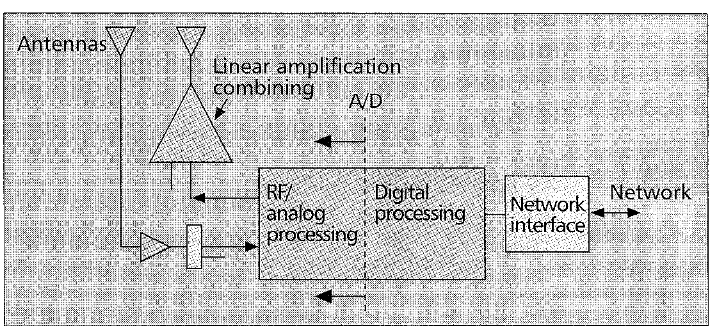
■ **Figure 4.** *Beam patterns of base stations with adaptive array.*

Software Radio Technologies

A software radio is a highly flexible radio base station or subscriber terminal platform, incorporating many advanced features and technologies which enable it to provide flexibility and programmability well beyond conventional analog or digital radios [9]. In a software radio, many of the functions traditionally implemented in "rigid" analog or digital hardware, such as channel filtering and IF conversion, as well as baseband processing, are based on reconfigurable or software-programmable devices, processors, and subsystems, thus allowing those functions to be literally coded in software. The ultimate software radio would allow full flexibility in frequency band, RF channel bandwidth, air interface, and network protocols, with enough processing power to deal with any future features and air interfaces. In reality, practical software radios will provide a subset of this utmost functionality due to technical and economic constraints.

Software radio will be an important enabling technology for IMT-2000 because of the inherent requirement to offer a wide range of data rates and services, in diverse operating environments, in order to gain worldwide acceptance. Software radio can provide a common platform that can support multiple standards and services. As standards evolve and services are improved or added, software radio base stations and customer units can adapt to new technologies rapidly without the need for major equipment changes or replacements, thus providing a level of hardware investment protection for the service provider and end user. Both will also benefit from a reduced time-to-market for the deployment of new services and features.

Historically, the relatively low number of prevalent standards, as well as the state of the art and the high cost of key software radio components, has limited the benefits and use of true software radios. Certainly, as digital, RF, and DSP technologies have improved, base stations have evolved to furnish more and more flexibility and functions associated with software radios. Because of cost, size, and power constraints, mobile terminals have generally provided one, or at most two fixed modes of operation. However, as key digital and analog technologies mature, and particularly with the advent and needs of IMT-2000, software radio architectures are likely to be a part of both base station and mobile terminal equipment.



■ **Figure 5.** *Analog-to-digital migration.*

Software Radio for Base Stations

There are a number of key features that differentiate software radios from conventional radios. In a base station application, a major feature is the use of a wideband RF/IF front-end in both transmit and receive directions to enable the operators' entire licensed band to be digitized and processed. The constituent RF and bearer channels are only treated as individual signals once they have entered the digital domain and can be processed by software elements. This allows the radio to be independent of modulation, access methodology, and channel spacing.

Although the ultimate implementation of radio functions in a software radio is via software, technology advancements in hardware have been the most significant drivers in the viability of software radio. There are four key enabling hardware technologies driving the paradigm shift from traditional narrowband radio transceivers to wideband software radios:

- Development and availability of low-cost, high-speed, large dynamic range analog-to-digital converters (ADCs) and digital-to-analog converters (DACs)
- Rapid improvements in the performance and price of fixed-point DSP technology
- Availability of low-cost, high-dynamic-range, wideband RF components
- Improvements in linear power amplification technology

Advances in these important technology areas have resulted in a strong drive to push the digital processing section further up the radio chain and closer to the antenna, as illustrated in Fig. 5.

Moving the digital processing closer to the antenna has been the trend for both narrowband and wideband radios.

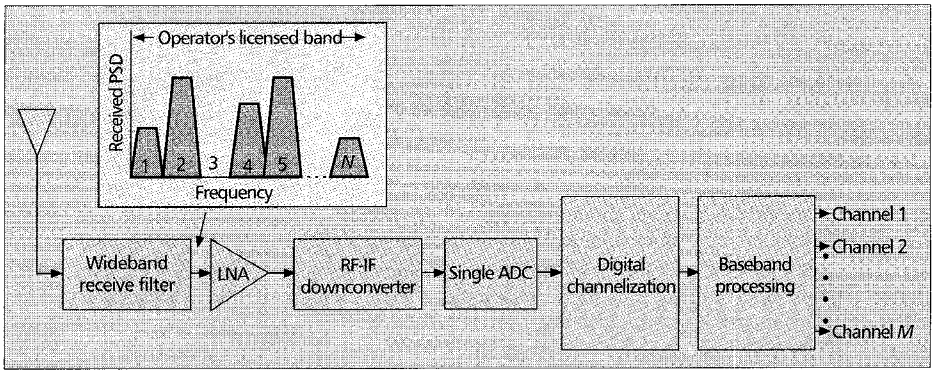
The ability to digitally sample at high speeds allows the use of a common wideband RF section, thus permitting the costs associated with the analog portion of the transceiver to be shared among a large number of baseband channels. Furthermore, the channelization process can now be moved from the rigid hardware domain to the much more forgiving and flexible software domain. Baseband processing, already in the domain of DSPs, will continue to become capable of higher and higher performance. This provides the basis for a compact, software-definable radio.

A wideband software receiver architecture example is illustrated in Fig. 6.

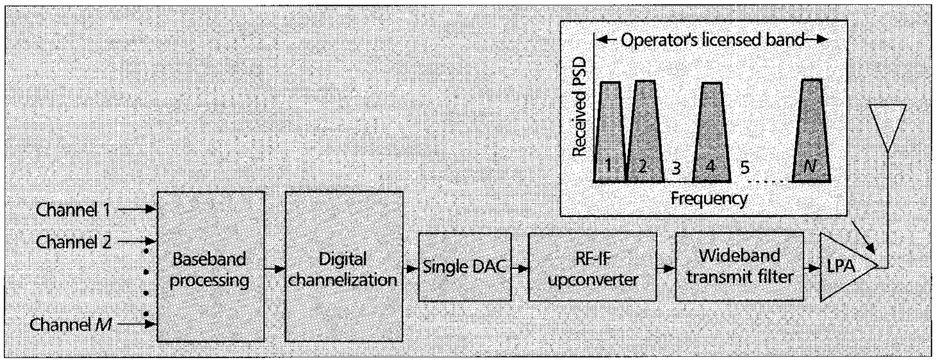
Here, a wideband front-end is shared by all the channel processing resources, and an entire band or subband is digitized by the ADC. The digital channelization function [9] may then be performed by programmable digital filter devices or high-performance general-purpose DSP devices. In the near future, single-chip DSPs with the capability of the equivalent of several hundred to over 1000 MIPs of performance are expected to be available.

Baseband processing, again DSP-based, can now also be treated as a common resource pool, allowing dynamic processing and resource management.

The wideband software radio transmitter architecture, shown in Fig. 7, is essentially a mirror image of the wideband software receiver. After baseband processing, channels are digitally combined and upconverted using the counterparts of the wideband receive process. An alias component from the DAC output, at a sufficiently high IF, can be selected by filtering before being upconverted to RF. A wideband linear power amplifier is now required with extremely good intermodulation distortion performance. Recent advances in linear power amplifier size, cost, and performance will make wideband transmitters more cost-effective than their narrowband counterparts in many cases.



■ **Figure 6.** *Wideband software receiver architecture.*



■ **Figure 7.** *Wideband software transmitter architecture.*

Software Radio for Subscriber Terminals

While many of today's digital terminals are DSP-based, they are not truly downloadable and reconfigurable in the same sense as a software radio. Some minimal configuration and parameter-setting capability has been introduced with the use of over-the-air activation, but terminals are for the most part fixed-programmed for one or two major modes of operation, with some multiband terminals becoming available. Also, terminals with multiple speech coding algorithms are becoming more common. Due to constraints in cost, size, and power consumption, "full" software radios will make their way more slowly into subscriber terminals. Narrowband front-ends, which capture a particular maximum RF channel bandwidth rather than an entire band, combined with some software programmability, will continue to be more appropriate for terminals initially. Continued significant reductions in the cost and power consumption of wideband front-ends, ADCs, DACs, and the associated processing are still required for widespread use of very wideband radios in handsets.

For these reasons, software-programmable terminals will emerge gradually in stages as systems evolve to IMT-2000.

Appropriate over-the-air protocols and messaging will need to be standardized to permit secure and reliable software downloads to terminals.

Full over-the-air programmability, allowing a terminal to be reconfigured for a large number of different services, as well as for totally different standards (e.g., to allow worldwide roaming in the absence of global standards) is obviously the "brass ring." Practical limitations, as well as the reality that some subscribers will not require (or be willing to pay for) this ultimate flexibility, will of course dictate the degree to and rate at which programmability is introduced into terminals. As advanced services are introduced, users of higher-end multifunction terminals who require more flexibility than users of single-mode voice-only counterparts may be willing to pay more for the convenience offered by this increased flexibility.

IMT-2000 Radio Interface Technology Evaluation Process

The IMT-2000 radio interfaces will have to serve a very wide range of radio operating environments. It is a design objective that the number of different IMT-2000 radio interfaces be minimized and, if more than one interface is required, that there should be a high degree of commonality between them. The ITU has recently approved Recommendation ITU-R M.1225, "Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000" [10]. The development of IMT-2000 radio interface specifications will be performed jointly by the various manufacturers, operators, organizations, and standardization bodies that participate in the work of the ITU.

A formal request by the ITU-R for submission of candidate radio transmission technologies (RTTs) for IMT-2000 has been distributed by the ITU, with a closing date of June 1998. Independent evaluations of these proposals, based on Recommendation ITU-R M.1225, will be carried out by various ITU-R members and submitted to ITU-R, with completion by September 1998. Consensus on the key characteristics of the IMT-2000 radio interfaces is planned by March 1999, with the objective of completing detailed ITU-R standards in time for service to begin shortly after the year 2000.

During the complex evaluation and consensus-building process, proponents of the various transmission technologies will be encouraged to combine the best features of their proposals to lead toward the best possible overall global standard. This will be necessary because it is unlikely that any one proposal will be the best for all possible combinations of radio operating environments and service capabilities.

The resources committed by the global telecommunications industry to this standardization process, and particularly the resources allocated to analysis of any given proposed technology, will be market-driven, which should greatly assist the ITU in identifying the best approach based on real market needs.

Many market and business-related factors, in addition to purely technical considerations, will influence the final ITU choices for the key characteristics of the IMT-2000 RTTs

The details of the process are contained in a circular letter issued by the ITU [11]. Candidate technologies will be compared against the technical requirements and objectives given in the relevant IMT-2000 Recommendations. Candidate technologies must also meet certain minimum performance capabilities, which include user bit rates ranging from 9600 b/s for the satellite test environment to 2048 kb/s for the indoor office test environment. The test environments are described below.

Test Environments and Their Propagation Models

In order to evaluate the performance of candidate terrestrial and satellite RTTs for IMT-2000, the reference scenarios (test environments and deployment models) and propagation models are established in Recommendation ITU-R M.1225. The reference models are used to measure spectrum and coverage efficiency (for terrestrial RTTs) and power efficiency (for satellite RTTs). The necessary parameters include the test propagation environments, traffic conditions, user information rate for voice and data services, and objective performance criteria for each test operating environment. While simple models are adequate to evaluate the performance of individual radio links, more complex models are needed to evaluate the overall system-level reliability and suitability of specific technologies. The evaluation of RTTs will be based on system and link-level simulations using propagation and traffic models.

Test Environments

The test operating environments are considered as a basic factor in the evaluation process of the RTTs. The following five environments were selected in Recommendation ITU-R M.1225 as appropriate test operating environments:

- Indoor office
- Outdoor to indoor and pedestrian
- Vehicular
- Mixed-cell pedestrian/vehicular
- Satellite

The above test environments are intended to adequately span the overall range of possible IMT-2000 operating environments.

IMT-2000 may include both mobile and fixed wireless applications. However, for the purpose of evaluation, operation in the fixed environment is considered to be covered by the more stringent mobile test environments. While the fixed wireless channel model will be less complex due to lack of mobility, the various trade-offs between fixed and mobile applications are assessed under the qualitative evaluation criteria.

Propagation Models

For the purpose of evaluation, the propagation effects are divided into three distinct types: mean path loss, slow variation about the mean due to shadowing and scattering, and rapid variation in the signal due to multipath effects. Mean path loss can be expressed as a function of separation distance between base and mobile stations. The slow variation is generally considered to be log-normally distributed and described by the standard deviation.

Propagation models are identified in Recommendation ITU-R M.1225 for each of the test operating environments except the mixed-cell test environment. For indoor environments, the path loss equations are derived from a picocell model [12]. For pedestrian and vehicular environments, the path loss equations are derived from an analytical macro-/microcell model [13]. Power efficiency is considered to be more critical than coverage efficiency in the satellite environment, so no path loss equation is given in Recommendation ITU-R M.1225 for evaluation of satellite RTTs. The standard deviation of slow variation is specified in dB for all terrestrial test environments. The decorrelation length of long-term fading is also given for the vehicular test environment [14].

A channel impulse response model based on a tapped-delay line model is given for each of the terrestrial and satellite test environments . The model is characterized by the number of taps, the time delay relative to the first tap, the average power relative to the strongest tap, and the Doppler spectrum of each tap.

Link Budgets and Deployment Models

Link budgets and deployment models are used to extract critical performance parameters of RTTs. The two most important parameters for terrestrial RTTs are coverage efficiency and spectrum efficiency. For satellite RTTs, power efficiency is the most significant parameter as well as spectrum efficiency. The link budgets and deployment models also give a general idea of the amount of infrastructure required to provide service to the specified model deployment scenario.

For terrestrial RTTs, spectrum efficiency is calculated for the higher offered traffic levels and the given spectrum allocation. Spectrum efficiency is dependent on the frequency bandwidth allocation and is not linearly scalable between different bandwidth allocations. For the purpose of evaluation, a duplex bandwidth of 30 MHz is assumed and is to be divided between forward and reverse links as required by the RTT implementation.

Coverage efficiency is defined as the total number of cell sites per square kilometer required to meet the coverage requirements specified for each terrestrial test environment. Coverage efficiency is to be calculated at low traffic levels since the system will most probably be interference-limited at high traffic load.

For terrestrial test environments, link-level simulations based on impulse response models are used to determine the required $E_b/(N_o + I_o)$ and hence the required carrier-to-interference ratio (C/I) of the RTT to meet the IMT-2000 performance criteria. Path loss formulas are then used to determine the maximum range and the coverage area.

Criteria for Evaluation of Radio Transmission Technologies

The technical criteria described below, only some of which can be numerically evaluated, were chosen among other significant (technical and nontechnical) characteristics because they represent a good range of criteria to assess the essential system aspects impacted by the RTTs.

Spectrum Efficiency – In general, the more telecommunications traffic that can be handled at a given quality for a given frequency band, the more efficiently the spectrum is used. Voice traffic capacity and information capacity are considered in the evaluation of spectrum efficiency.

The voice traffic capacity is the total traffic that can be supported by a single cell (not per sector) in Erlangs/MHz/cell. The information capacity is the total number of user-channel information bits which can be supported by a single cell in Mb/s/MHz/cell.

Technology Complexity: The Effect on the Cost of Installation and Operation – This criterion expresses the impact of a given RTT on the complexity, and hence cost, of implementation (e.g., equipment, infrastructure, installation) of the infrastructure, including base stations. The impact on complexity of mobile terminals is considered by other criteria, such as "handportable performance optimization capability." In order to achieve the minimum cost and best reliability of equipment, the technologies selected should have a level of complexity consistent with the state of technology, desired service objectives, and radio environment. Some technologies have several possible methods of implementation which allow a compromise between complexity/cost and performance.

Quality – One of the important features that has been considered a basic principle of IMT-2000 is to provide high-quality services essentially equivalent to those of the fixed telecommunication networks. Therefore, most of the quality parameters are minimum requirements that must be met and are not to be treated as evaluation criteria. Typical characteristics to be considered in the evaluation of quality include transmission processing delay, handover quality, voice quality, and system overload performance.

Flexibility of Radio Technologies – IMT-2000 should be designed to handle situations where the traffic density varies in different areas and the traffic patterns also vary with the type of service. It should be applicable to highly populated urban as well as rural areas. As described earlier, typical characteristics to be considered are adaptability of a system to different propagation and traffic environments, ease of radio resource management, ability to accommodate fixed wireless access (FWA) architecture, ease of service provision (e.g., bandwidth on demand, packet data, and multimedia capabilities), flexibility in the use of the frequency band, spectrum-sharing capabilities, ability to accommodate mixed-cell architectures, and existing system evolution capabilities.

Implication for Network Interface – It is desirable to minimize the impact of the radio subsystems on fixed network interfaces. The choice of RTTs may affect both the actual network interfaces required in IMT-2000 for multi-environment operation and the information passed over them. The need for synchronization between base stations and between systems sharing common location and spectrum may be different. The requirements placed on the networks by the handover procedure may be different. Cross-environment operation (e.g., PSTN to wireless private branch exchange call transfer) may require additional PSTN functionality. In particular, the number of signaling messages, actual switching requirements, and transmission capacity from base stations to switches may be different.

Handportable Performance Optimization Capability – Handportable IMT-2000 terminals will be used in a broad range of user environments and applications. The capability for handportable voice and personal data applications will impact the market acceptance and success of IMT-2000 as with second-generation mobile systems. Typical characteristics relating to this criteria are average and peak terminal power output, acoustical isolation requirement between handportable microphone and speaker, power control characteristics, linear transmitter requirements, diversity schemes, frequency stability, and DSP requirements (e.g., MOPS, memory requirements, gate counts).

Coverage Efficiency – The minimum number of base stations per square kilometer (km^2/base site) for a given frequency assignment to offer a certain amount of traffic with the required coverage is important in terrestrial systems at low traffic levels. At low loading, the system will be noise-limited and the number of base stations constrained by the maximum range achievable by the technology. At low loading, range and coverage efficiency are the major considerations, while at high loading, capacity and spectrum efficiency are more important. Technologies providing the desired level of coverage with fewer base sites for a specific test environment are defined as having higher coverage efficiency.

Power Efficiency – In satellite systems the DC power available for conversion into usable RF power is limited and fixed for any given satellite. It is important that this power be used efficiently and yields the maximum number of traffic channels of a given quality. The power efficiency as defined here is not applicable to terrestrial systems.

Normalized power efficiency is defined by the supported information bit rate per required C/N_0 (carrier power to noise density ratio) for the given channel performance under the given interference conditions. The efficiency is evaluated for voice only traffic and for voice plus data mixed traffic conditions. The minimum required value of C/N_0 to achieve the objective performance in terms of frame and/or bit error ratio under the designed full-load condition is estimated by using computer simulations and/or experimental measurements.

Conclusion

This article compares IMT-2000 to existing wireless systems and explains the flexible modular architecture envisaged for IMT-2000, which will facilitate seamless evolution from the substantial installed telecommunications base expected by the year 2000. The process for evaluation of RTT proposals from ITU-R members is also outlined. This evaluation process will consider criteria described in this article and other factors of importance such as technology risk, timing, and regional market considerations, and will result in determination of the key technical characteristics of the IMT-2000 radio interface by early 1999. Based on these key characteristics, ITU-R radio interface specifications (standards) will be finalized by the year 2000, after which system implementation, testing, and commercialization will progress at a rate determined by local market needs in the various global regions.

Although IMT-2000 performance objectives are very demanding, as described in this article and the other articles in this special issue, the required system and component technologies are indeed either currently available or will be in the very near future. The completion of the remaining work, leading to a complete set of IMT-2000 specifications, is greatly dependent on future ITU member contributions and continued open and constructive participation from all three ITU Regions throughout the consensus-building and final decision-making processes.

Acknowledgments

In addition to the contributing authors, the editor would like to acknowledge a number of individuals who have either contributed to the preparation and writing of this article or made significant contributions to the work of TG-8/1 in the development of IMT-2000 ITU-R Recommendations. They are G. Jenkinson (Telstra, Australia), G. Rappoport (AT&T, USA), A. Kumar (India), R. Tompkins (DTI, UK), H. Ding and M. Li (China), K. Wee (Korea),), F. DeRyck (France Telecom), M. Shafi (Telecom New Zealand), W. Davis (Motorola, USA), and C. J. Pagano and M. Solondz (Lucent Technologies, USA).

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