The Froehlich/Kent
ENCYCLOPEDIA OF TELECOMMUNICATIONS

VOLUME 15

Editor-in-chief: Fritz E. Froehlich

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CRC Press
Taylor & Francis Group

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VOLUME 15

RADIO ASTRONOMY to SUBMARINE CABLE SYSTEMS

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First published 1998 by Marcel Dekker, Inc.

Published 2021 by CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 1998 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

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ISBN 13: 978-0-8247-2913-4 (hbk)
ISBN 13: 978-0-367-40083-5 (pbk)
ISBN 13: 978-1-003-20882-2 (ebk)

DOI: 10.1201/9781003208822

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Library of Congress Cataloging-in-Publication Data

The Froehlich/Kent Encyclopedia of Telecommunications / editor-in-chief, Fritz E.
Froehlich ; co-editor, Allen Kent.
p. cm.
Includes bibliographical references and indexes.
ISBN 0-8247-2902-1 (v. 1 : alk. paper)
1. Telecommunication—Encyclopedias. I. Froehlich, Fritz E.,
Kent, Allen.
TK5102.E646 1990 90-3966
384′.03—dc20 CIP

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 90-3966

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Radio Astronomy

What Is Radio Astronomy?

Radio astronomy refers to astronomy using radio waves naturally generated by cosmic bodies. The term excludes *radar astronomy*, which consists of studying radar echoes from objects in the solar system.

Today, astronomy (or, better, astrophysics) research is generally independent of wavelength or frequency. Modern astronomers combine observations from many wavelength ranges to study particular astronomical phenomena.

For astronomers, *radio* is an imprecise term that today might include the electromagnetic spectrum between λ 300 μm (micrometers) and λ 30,000 m (meters), a range of 10^8. Overlaps with other named bands occur. The far infrared band includes submillimeter wavelengths. The International Telecommunication Union specifies the use of radio bands from 9 kilohertz (kHz) (λ 33,333 m) to 275 GHz (gigahertz) (λ 1.1 millimeters [mm]) to minimize conflict of radio services.

Conducting astronomy research at radio wavelengths requires understanding astrophysics in general and, specifically, the physical mechanisms that generate cosmic radio emissions. Observationally, it means understanding the specialized equipment designed to respond quantitatively to cosmic radio waves.

Early Years

Radio astronomy began in the first half of this century. Thomas Edison suggested observations of radio waves from the sun around 1890. Sir Oliver Lodge unsuccessfully searched for radio emissions from the sun between 1897 and 1900. Karl G. Jansky is considered the father of radio astronomy through his discovery of cosmic radio emission at a frequency of 20.5 MHz from the Milky Way (our galaxy) in 1932 (1). To honor his discovery, the fundamental unit of radio flux density is the Jansky, and the United States' National Radio Astronomy Observatory awards the Jansky Lectureship annually to someone who has made significant contributions to the field.

Following Jansky's detection, in 1938 Grote Reber built a 30-ft diameter parabolic reflector in the back yard of his Wheaton, Illinois, house and a radio receiver to investigate the Milky Way emission at a frequency of 3300 MHz (2).

Unable to confirm Jansky's results, he decreased his observing frequency to 910 MHz, still without success. Finally, reducing the frequency to 162 MHz, he was able to confirm Jansky's detections. These observations were the first indications that the cosmic radiation emission was nonthermal. In the 1940s, Reber surveyed the sky at 160 MHz with greatly improved electronics. This time, in addition to the Milky Way, he detected the supernova remnant Cassiopeia A and the sun. Changing frequency to 480 MHz, he again detected the Milky Way but also variable radio emission from the sun.

The great improvements in radio and radar technology driven by World War II contributed to the emergence of radio astronomy (3). Many radar and radio operators detected signals of unknown origin in the frequency range 55 to 80 MHz. Generally, these reports were classified. One proved to be variable emission from sunspots, later reported by James S. Hey in 1946 (4). Another was the 1942 detection of the emission from the quiet sun at 9.4 GHz, later published by G. C. Southworth in 1945 (5).

At least one theoretical study carried out during World War II proved especially important to astronomers. In occupied Netherlands, H. C. van de Hulst considered the possibility of detecting line emission at radio frequencies from the most abundant constituent of cosmic gases, hydrogen. Publishing this paper in 1945 after the war (6), he predicted that astronomers should be able to detect line emission from atomic hydrogen at λ 21 cm (centimeters) (1420 MHz). In 1951, the line was detected on March 25 by H. I. Ewen and E. M. Purcell at Harvard University (Cambridge, Mass.) (7), on May 11 by C. A. Muller and J. H. Oort at Leiden (Netherlands) (8), and on July 12 by W. N. Christiansen and J. V. Hindman in Sydney, Australia (8). The availability of radio line radiation allowed the study of cold gases from which stars form. The line frequency uniquely identified hydrogen as the emitter, thereby facilitating measurements of line-of-sight velocities of cold cosmic gas through the Doppler effect.

Following these detections and others, radio astronomy grew rapidly in many countries, attracting the attention of both theorists and observers. Several countries formed national centers for radio astronomy to accommodate astronomers wanting to observe in the radio domain. These observatories, sometimes associated with particular universities, are usually open to astronomers everywhere on a competitive basis.

These centers made radio astronomy available to nonspecialists. Their engineers provide state-of-the-art instrumentation. When needed, staff astronomers and telescope operators assist visiting astronomers with observing. The centers free astronomers to concentrate on astrophysical problems without having to know the technical details of the instrumentation. In this way, radio astronomy evolved from a peculiar research specialty into the full field of general astronomy that it is today.

Technical Aspects

Specific aspects distinguish modern radio astronomy from telecommunications: sensitivity, angular resolution, observing techniques, and the transmission of the earth's atmosphere. This article considers these rather than the general technology of receivers and antennas also used in radio astronomy and discussed elsewhere in this encyclopedia.

Coupling of Radiation to Antennas

Cosmic radio emission is often weak compared to optical emission. The brightness or specific intensity (9), I_ν, emitted by cosmic sources at any frequency has units of

$$[I_\nu] = \text{energy/time/area/unit frequency interval/solid angle} \tag{1}$$

as it passes through a unit area in space and confined to a solid angle. There is a wavelength form of specific intensity,

$$I_\lambda d\lambda = I_\nu d\nu \tag{2}$$

The specific intensity radiated by black bodies, that is, in thermal equilibrium, is

$$I_\nu = B_\nu \tag{3}$$

$$= \frac{2h\nu^3}{c^2} \frac{1}{\exp\,(h\nu/kT) - 1} \tag{4}$$

where B_ν is the frequency form of the Planck function for a body with a temperature T. At the long wavelengths characteristic of much of radio astronomy,

$$B_\nu \approx \frac{2kT}{\lambda^2}, \qquad h\nu \ll kT \tag{5}$$

which is the Rayleigh–Jeans approximation for the red end of the spectrum. Note that this approximation often does not hold for cold gases radiating at millimeter and submillimeter wavelengths.

Much of astrophysics involves determining and applying the appropriate form of I_ν. Many cosmic processes emit nonthermal radiation, only near-thermal radiation, or a mixture of both. Here, B_ν would not apply.

Astronomical telescopes detect spectral flux density, a quantity independent of solid angle. The spectral flux density, F_ν, detected by an antenna in a particular direction

$$F_\nu = \int_{\text{source}} I_\nu(\Omega)\, d\Omega \tag{6}$$

where I_ν is the specific intensity. The units of F_ν are Janskys, 10^{-26} W/m^2/Hz.

The detected signal power per unit bandwidth, P_ν, in that direction is

$$P_\nu = F_\nu A \tag{7}$$

where A is the capture area of the antenna, which may not be the same as the physical collecting area (10). Detection causes an effective increase of the antenna temperature T_A due to the source at that frequency and in that direction:

$$\begin{aligned} T_A &= P_\nu / k && (8) \\ &= F_\nu A / 2k && (9) \end{aligned}$$

where the factor of 2 arises because usually only one polarization and, hence, only half the power can be detected. In practice, there are additional factors depending upon whether the source is larger or smaller than the antenna beam and upon the shape of the antenna beam (10,11). The situation is more complex at low frequencies because of the ionosphere and at millimeter and submillimeter wavelengths because of atmospheric extinction (12).

There are alternative ways to include the effective receiving pattern of the antenna. These lead to different forms of the equations above. However, the principles and quantitative results remain the same.

Sensitivity

Astronomical signals at radio wavelengths are generally weak when observed with conventional radio telescopes. Many are measured in units of milliKelvins or even microKelvins with telescopes with large collecting areas. There are exceptions. At long wavelengths, cosmic emission can be strong. Even at centimeter wavelengths, some "point" sources have large antenna temperatures when seen with sufficient angular resolution.

To enhance sensitivity, astronomers use antennas with large collecting areas and extremely low noise receivers. At centimeter wavelengths, parabolic antennas often have collecting areas measured in thousands of square meters. At meter wavelengths, phased-array telescopes can have even greater collecting areas. Receiver elements are often cooled to temperatures of 4 K or lower. Today, effective receiver noise temperatures at centimeter wavelengths are characterized by the rule-of-thumb 1 K/GHz or better. Receiver noise temperatures at a frequency of 10 GHz may be approximately 10 K and at 30 GHz, 30 K. Typical receiver noise temperatures at 100 GHz are 50 K, including all of the optics; at 230 GHz, they are 70 K.

Averaging observations over long time periods can enhance the sensitivities. Thermal receiver noise dominates most observations. The rms (root-mean-square) amplitude of this noise σT depends on the relationship

$$\sigma T = \text{const}\ \frac{T_{\text{sys}}}{\sqrt{B_w t}} \tag{10}$$

where B_w is the detected bandwidth and t is the length of the integration. The "system temperature" T_{sys} characterizes all sources of noise associated with the telescope, including the receiver, antenna, and the atmosphere. The constant is of the order 1 to 2, depending on the details of the observing technique. For differential observing in which signals from two parts of the sky – for example, a source and a reference position – are subtracted, the constant can be greater than or equal to 2.

Typically, radio astronomy observations range from minutes to hours. Exceptions would include detection of time-varying bursts from, say, the sun or pulsars involving very short integration times or from searches for extremely weak spectral lines involving integration times measured in days. Long integrations and careful calibrations produce precise, accurate measures of T_{sys}, making possible measurements of small increases (i.e., a few times ΔT) in antenna temperatures due to a cosmic source.

While increasing the bandwidth B_w in Eq. (10) will also increase sensitivity, in practice this is not always possible. For example, radio spectral lines from atoms and molecules are important sources of information for astronomers. Their full widths at half intensity rarely exceed 10^{-4} of their rest frequencies and are usually very much less. The shapes of the lines convey important information regarding the temperature environment and the velocity field of the emitters. Expanding the bandwidth wider than the lines would destroy much of the value of the observations. This problem can also exist for "continuum" sources, for which wide bandwidths can enhance detection but mask inflections in the continuum emission essential for understanding the emission mechanisms.

Transmission of the Atmosphere

The earth's atmosphere limits the cosmic radiation available to ground-based astronomers. Figure 1 shows the zenith transmission through the earth's atmosphere with total precipitable water vapor of 1 and 5 mm, values typical of arid and merely dry sites, respectively. Atmospheric molecules, principally O_2 and H_2O, form wide absorption bands with "windows" between them. The transparency of the windows becomes increasingly sensitive to water vapor toward high frequencies. Not shown is absorption below several (e.g., 30) megahertz by the ionosphere.

These windows limit ground-based astronomy. First, only cosmic radiation within the windows can reach ground-based telescopes. Second, the opacity of the warm atmosphere radiates noise that increases T_{sys}, making detection of weak cosmic signals more difficult. Third, observations of cosmic radio sources are usually made in directions other than the zenith, thereby increasing the path length of signals through the atmosphere and, correspondingly, the effective absorption and radiation of the atmosphere. Astronomers working at high frequencies situate their telescopes at high altitudes in arid climates to facilitate observations.

Interference

An enormous problem for astronomy at radio wavelengths is interference from man-made signals. The great sensitivities of the receivers render them particu-

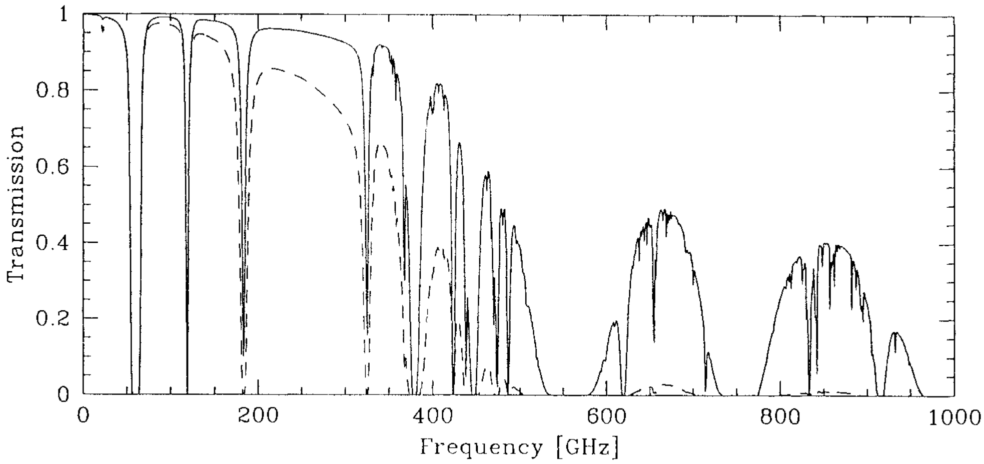

FIG. 1 The zenith transmission of the earth's atmosphere as a function of frequency. The solid line corresponds to precipitable water vapor of 1 mm, typical of a high-altitude dry site like Mauna Kea, Hawaii; the broken line, for precipitable water vapor of 5 mm, is typical of a moderately dry site.

larly vulnerable, although the angular selectivity of the telescopes gives some protection. The explosion of artificial radio signals from cellular telephones, pagers, satellite communication links, navigational radars, arcing electrical fences, and television and radio transmitters is creating an increasingly hostile environment for astronomy. These artificial signals consist of nonrandom emissions that add to T_{sys} but do not decrease with integration, drastically decreasing the sensitivity of radio telescopes. An analogy is the effect of city lights on optical telescopes.

Linked to the physical laws of nature, cosmic radio signals have immutable frequencies with respect to an astronomer. Spectral lines radiate at specific frequencies determined by the physical characteristics of the emitter. "Continuum" emission involves emission best observed at specific wavelengths. It may be impossible to choose different frequencies to study these astronomical phenomena.

Angular Resolution

Angular resolution has always been a concern of astronomers, particularly at radio wavelengths. Most radio telescopes are diffraction limited; the angular resolution improves as the diameter of the telescope in wavelengths increases. The precise beam width in radians obtained with a parabolic dish is a function of the degree of illumination taper but is usually around $1.2\lambda/D$. To be effective, radio telescopes need to be large because radio wavelengths are so much larger than optical wavelengths. To obtain an angular resolution comparable to the eye at optical wavelengths, a radio telescope operating at a wavelength of 1 meter has to be a mile or more wide.

Today's radio telescopes are divided between filled-aperture instruments such as a parabolic dish and interferometric designs. With a filled aperture such as a parabolic dish, low side lobe performance may be more important to a radio astronomer than the highest antenna gain or lowest possible beam size. Stray radiation such as thermal radiation from the ground enters the receiving system through side lobes, thereby degrading the ratio of telescope gain to system temperature (G/T) that ultimately defines the system sensitivity. Side lobes may also prevent the study of weak celestial sources near strong emitters and may make the telescope more vulnerable to terrestrial interference. With a parabolic dish, tapering the illumination of the surface toward the edge of the dish reduces side lobes. Minimizing aperture blockage such as that caused by feed support legs or instrumentation at the prime focus of the telescope also reduces side lobes. One approach to reducing aperture blockage and obtaining the lowest possible side lobe level is the offset parabola, such as the 7-m telescope of AT&T Bell Laboratories in Holmdel, New Jersey (13), and the 100-m Green Bank Telescope (GBT) of the National Radio Astronomy Observatory now being constructed in Green Bank, West Virginia.

Interferometry provides a way to achieve much higher angular resolution. In 1946, astronomers used antennas situated on a high cliff near the sea to generate interference patterns. The fringe pattern resulted from the interference of the direct waves from the cosmic radio source with those reflected from the sea; this is the radio analog of Lloyd's mirror (14). The narrow interference lobes allowed more precise determination of source positions and angular sizes.

Astronomers generalized this principle by building antennas separated perhaps by several miles but bringing the signals together to a central site. A breakthrough in technique was the introduction of the phase-switching interferometer (15). Especially noteworthy was the development of aperture synthesis with connected-element interferometers at the Mullard Radio Astronomy Observatory of the University of Cambridge, England, which led to the Nobel Prize in Physics being awarded in 1974 to Sir Martin Ryle.

Today, connected-element arrays used for aperture synthesis radio telescopes are common. Perhaps the most spectacular is the Very Large Array near Magdalena, New Mexico, which consists of 27 parabolic antennas 25 meters wide located on railroad tracks laid out in the shape of a Y. The combination of centimeter wavelengths and the 35-km (kilometer) size of the Y produces radio images with angular resolutions of a few hundredths of an arc second, better than the best images produced from ground-based optical telescopes. The movable antennas allow astronomers to select the combination of angular resolution and field of view most appropriate to their investigations.

The extreme of aperture synthesis is very large baseline interferometry (VLBI). In this technique, wideband tape recorders and atomic clocks replace the cables connecting the elements of the usual radio interferometer. Observations are made by pointing each antenna—perhaps separated from its closest neighbor by thousands of kilometers—to the same cosmic radio source and recording the received signals on magnetic tape. Later, cross-correlation of the tapes against each other, using special-purpose hardware and computers, provides the visibility information needed to construct an astronomical image.

Imaging in Radio Astronomy

For imaging in radio astronomy, radio telescopes are capable of producing detailed images of objects. With a filled-aperture telescope like a parabolic dish, the image of a celestial object may be built up point by point, by physically moving the antenna each time to point its single beam at different parts of the source, following some regular grid. This technique requires spending sufficient time integrating on each pixel to satisfy the sensitivity requirements of a given observation. For spectral line observations, a complete spectral map might require 1000 frequency points at each pixel. This becomes a three-dimensional imaging problem: two celestial coordinates plus the frequency domain.

Using multiple receivers may speed up spectral mapping so that integration occurs simultaneously at several pixels of the image. For example, the submillimeter common-user bolometer array (SCUBA) system on the James Clerk Maxwell Telescope on Mauna Kea, Hawaii (16), contains 37 separate feeds at $\lambda 850$ μm and 91 at $\lambda 450$ μm, speeding up the mapping process by the same factors, respectively.

There are other methods of forming images in radio astronomy. For a filled-aperture telescope using a phased array as a feed, simultaneous multiple beams may be formed electronically by amplifying, splitting, and phasing the signals from the much smaller elements making up the complete array. However, it is not necessary to have a fully filled aperture. A sparsely populated array can be used, with pairs of elements connected as interferometers. The potential angular resolution is then set by the maximum separation, in wavelengths, of the outer elements of the array, rather than the size of individual elements.

Too few elements result in inadequate images. Early attempts at imaging with simple interferometers produced too few “visibility points” (see below) to create unambiguous radio images of the sky. Using various assumptions, astronomers produced crude images by fitting models to these data. Nevertheless, these images often were sufficient to place useful constraints on the distribution of emission from a given object, such as total angular extent, even though a unique image could not always be formed.

Interferometers and Aperture Synthesis

The complex visibility function is the fundamental data produced by a radio interferometer. When two antennas are connected to form a coherent interferometer, the output signals are electronically multiplied to give both in-phase and in-quadrature terms. The hardware performing the multiplication is called a correlator, and the correlated signal is usually known as the (complex) visibility function. McCready, Pawsey, and Payne-Scott in 1947 were the first to point out the intensity distribution across the source is the Fourier transform of correlated power received by an interferometer (14).

A given pair of antennas records one Fourier component of the angular source intensity distribution. If the relative position of one antenna is moved with respect to the other, the system responds to a different Fourier component. If enough relative antenna positions are used, it is possible to build an adequate description of the source in terms of Fourier components of its brightness distribution. A simple Fourier transform then yields the angular source distribution. This process is known as *aperture synthesis.* The potential angular resolution is set by the maximum separation of antennas, and it is not essential to measure the Fourier components simultaneously.

Using an interferometer with many antenna elements and using the rotation of the earth, astronomers can synthesize a large, single telescope. Seen from a distant cosmic source, a two-element interferometer with fixed spacing will appear to rotate and to change spacing as the earth turns. Several hours of observing will create a track of source visibilities in the two-dimensional, complex visibility U-V plane, often signified by $f(U,V)$. Changing the linear separation of antennas will produce a different visibility track. Combining multiple tracks will fill the U-V plane with a distribution of visibilities. A Fourier transform of these data will produce an image of the source $f(\theta,\phi)$ similar to what would have been observed by a large, filled-aperture radio telescope, that is, the two domains are related by (17)

$$f(U,V) \supset f(\theta,\phi), \tag{11}$$

where the operator indicates a two-dimensional Fourier transform and the symbols and θ and ϕ indicate orthogonal angular dimensions on the sky.

In 1962, the One Mile Telescope of the Mullard Radio Astronomy Observatory of the University of Cambridge, England, was constructed to use these principles. The first data from this telescope were obtained in 1963. The image quality was equivalent to what might have been obtained from a one-mile diameter paraboloid with a beam that was scanned point by point across the source.

The number of antenna elements determines the number of visibilities that can be measured instantaneously. An aperture synthesis telescope with N elements gives $N(N - 1)/2$ possible pairs of antennas that can be correlated together at any instant to give the same number of visibilities. The Very Large Array (VLA) telescope near Magdalena, New Mexico, has 27 antennas, giving 351 instantaneous visibilities. Depending on the complexity of the astronomical source being studied, with a suitable configuration of the 27 antennas on the ground, an adequate, almost instantaneous image (known as a "snapshot") may be obtained. By continuing to take data as the earth rotates, each of the 351 pairs of antennas contributes a track of visibilities.

Details of the sampling of the U-V plane depend on the geometry of the antenna elements, the range of time over which the data are taken, and the celestial coordinates of the source. Depending on how irregularly sampled the U-V data are, a straightforward Fourier transform of the visibility data may

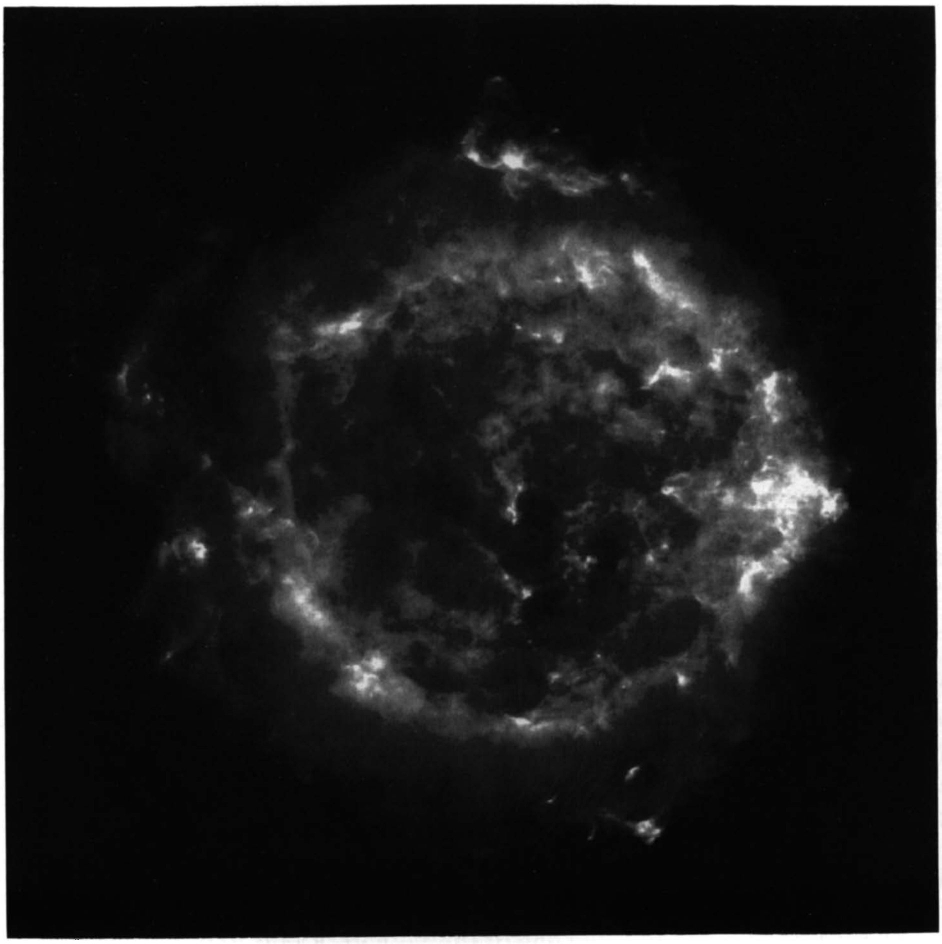

FIG. 2 Radio image of Cassiopeia A. The "A" designates the strongest radio source in the constellation Cassiopeia (the name of a mythical Ethiopian queen). The image was made with the very large array synthesis telescope at $\lambda 20$ cm at a resolution of $1''.3$. The false color image shows nonthermal radio emission emitted by relativistic electrons trapped in magnetic fields, called synchrotron emission. This emission is the remains of a supernova, a star in our Milky Way galaxy that exploded in the year 1572. The filaments move at speeds exceeding 4000 km s^{-1} with respect to each other. Supernovas typically occur in spiral galaxies at a rate of a few per hundred years, enriching the interstellar gas from which other stars will form. (Courtesy of the National Radio Astronomy Observatory, Ref. 22.)

yield a poorly synthesized beam shape with high side lobes. The measurement defects may contribute artificial features to the computed image.

Powerful techniques have been developed to eliminate this artificial structure. Most involve a system for rationally guessing the information missing from the observations of the visibility function. One of the most widely used is CLEAN (18). This technique is equivalent to iteratively constructing a model image of the source that, when convolved with the true point spread function with its high side lobe level, is consistent with the measured visibility points. The model distribution is conventionally convolved with a clean beam such as a two-dimensional Gaussian distribution of appropriate half-power width. This best "CLEAN map" is then presumed to be the best estimate of the true source image within the limits of angular resolution of the observations. The more independent visibility points that are measured, the closer the CLEAN map result is to a unique image of the radio source.

Other image-processing algorithms are routinely used to enhance radio astronomical images. A particularly powerful one is the maximum entropy method (MEM) originally developed for seismic images in geosciences (19). It uses principles from information theory to minimize image distortions arising from flaws and omissions in observations of the visibility function.

The earth's atmosphere also limits the quality of an aperture synthesis image (20). Fluctuations in the electrical path length through the troposphere can introduce phase errors in the complex visibility function measured between antennas. These errors are analogous to optical "seeing," which limits the angular resolution attainable from the earth's surface. A powerful algorithm, SELF-CAL, developed in 1980 (21), often eliminates these atmospheric problems. The technique rests on the fact that calibration errors caused by tropospheric fluctuations are antenna based, while the number $N(N - 1)/2$ of instantaneous visibilities measured on the source is proportional approximately to the square of the number of antennas. With sufficient antennas, with very weak assumptions about the source distribution or using the redundancy available when more than one pair of antennas has measured the same source visibility function, it is possible to solve for these antenna-based calibration errors and to construct an image almost as if there had been no perturbations from the atmosphere. This technique is now used routinely, often with some spectacular results (see Fig. 2) (22).

The Future

The future will undoubtedly bring substantive improvements in radio astronomy techniques. These might include placing antennas on earth satellites to extend interferometer baselines to enhance angular resolution greatly. Orbiting antennas would also eliminate absorption by the earth's atmosphere and allow observations at much higher frequencies. This would extend our knowledge of the cosmic information radiated in atomic and molecular spectral lines. In orbit the absence of local gravity would permit construction of truly giant parabolic antennas impossible to build on earth to gain sensitivity. Observatories on the far side of the moon would be shielded from the growing radio interference from earth.

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Radio Systems—Digital

(see Digital Radio Systems)

Radio Wave Propagation

(see Electromagnetic Signal Transmission)

Radiocommunication Sector of the ITU

(see The International Telecommunication Union—Radiocommunication Sector)

Radio-Frequency and Microwave Radiation Biological Effects: An Overview

Introduction

This article briefly introduces the physical description of the applicable portion of the electromagnetic (EM) spectrum that includes the nonionizing radio-frequency (RF) and microwave energy (also termed "RF and microwave radiation"). Such a description involves the wavelengths and frequencies, and the associated quantum energies. The electric (E) and magnetic (H or B) field components are described, as are some of the representative sources and uses of the energy. These uses include communications applications, especially the cellular and personal communications services (PCS) "wireless" applications of RF energy. The concepts of exposure, incident energy, dose, dose rate, and specific absorption rate (SAR) are briefly discussed (in general, nontechnical terms). Comments are made relating to the potential exposure of various populations associated with the use of this energy.

In connection with concern for the potential for risk to the health of personnel exposed to RF energy, an overview is presented of the biological effects and clinical responses (as contained in the published scientific, engineering, and biomedical literature) to the EM energy at these frequencies. Attempts are made to note the magnitude (i.e., the intensity and/or field strengths) of the energy necessary to produce the observed biological effect ("bioeffect") or "biological change." The issue of the reversibility of the change produced is also noted, with emphasis on the alleged adverse effects thought to be of concern to humans. Examples of the problems, deficiencies, and criticisms of some of the published scientific and engineering studies are pointed out, as are the major implications from the applicable studies. Some of the recognized effects of EM fields on implanted medical (and related) devices, and on sensitive electrical equipment are also noted. Recommendations are made relating to needed research in these areas. The basis for the human exposure standards, recommendations, and guidelines that have been developed for this portion of the RF spectrum, is briefly discussed.

Radio-Frequency Electromagnetic Energy

General Characteristics

Significant increases in the development and use of equipment that produces nonionizing radiant energy have occurred in the past 25 years. Many questions have been raised as to whether adequate measures have been, and are being, taken to protect the user, the patient, and the public from possible adverse health effects that may be associated with exposure to such energy. Nonionizing

EM energy (in contrast to ionizing EM energy, or ionizing radiation) is of longer wavelength and therefore lower frequency, and is intrinsically less energetic (i.e., lower photon or quantum energy) in its interaction with biological tissue. Consequently, nonionizing radiation generally does *not* produce ions in biological materials as it interacts with the tissue.

The term *nonionizing radiation* refers to the group of electromagnetic radiations with energies less than about 10 electron volts (eV), corresponding to wavelengths in the near ultraviolet (UV), visible (VIS), infrared (IR), and RF/microwave portions of the spectrum (Fig. 1). This includes some of the energy often referred to as "optical" radiation, that which is termed "light," and most coherent laser/maser energy. In addition, ultrasound (which is due to pressure variations and mechanical vibration) is also included under the heading of non-

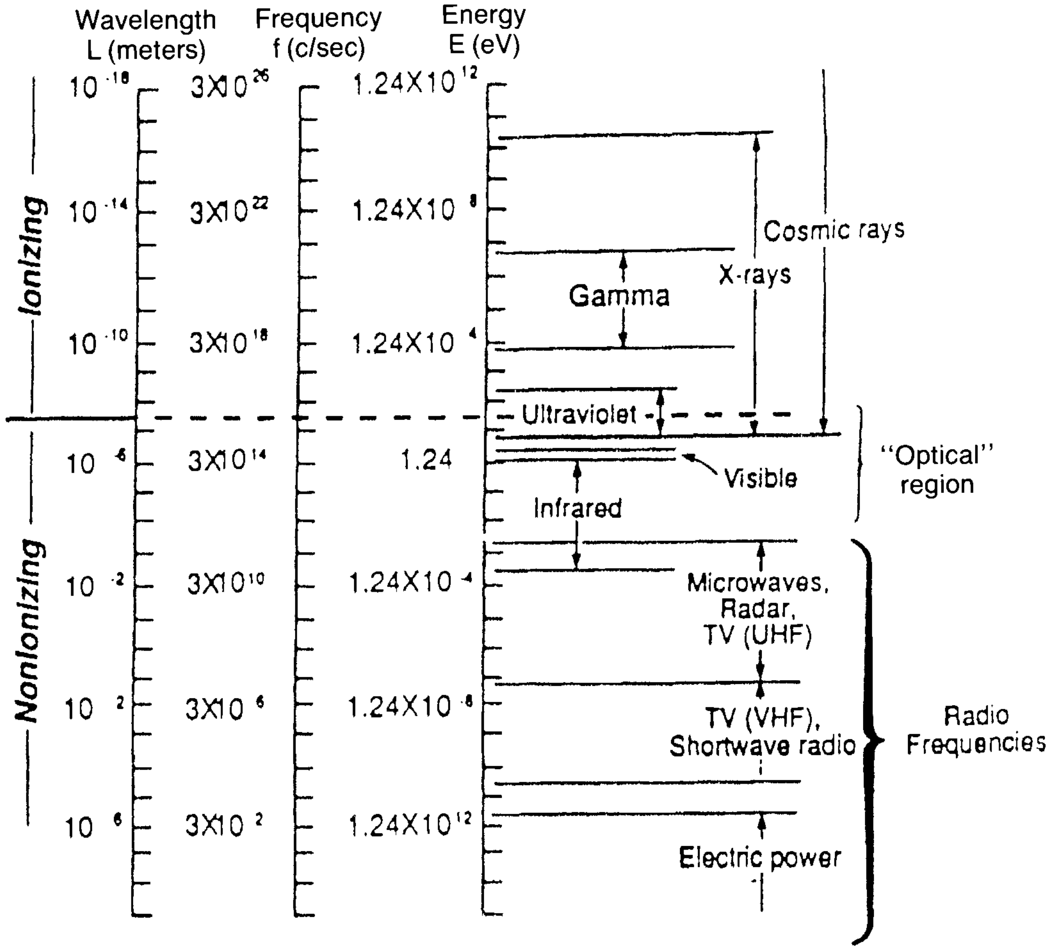

FIG. 1 Comparison of the wavelength, frequency, and energy of the electromagnetic spectrum. Nonionizing radiation is that portion of the electromagnetic spectrum with energies less than about 1-10 electron volts (UHF = ultra-high frequency; VHF = very high frequency). (From Ref. 1.)

ionizing radiation. The reader is reminded that ultrasonic energy is *non*-electromagnetic energy. The RF region of the EM spectrum includes millimeter waves, radio and TV broadcast, power transmission, and low-frequency electric and magnetic fields.

The portion of the EM spectrum referred to as the RF and/or microwave region is the subject of this article. The RF region usually applies to the spectral region having frequencies between 300 megahertz (MHz; million cycles/second) and DC (i.e., direct current; 0 cycles/second), but often is generalized to include the microwave region, and is described as extending to a frequency of 300 gigahertz (GHz; billion cycles/sec).

Devices and processes that use or generate RF nonionizing energy, and its various applications, are widely found in industry; medicine, dentistry, and veterinary science; telecommunications and the entertainment industry; many research laboratories; building and construction; navigation; various military applications; educational applications; geodesy; transportation; advertising; commercial food preparation; various leisure activities; and in the home. Nonionizing energy in its various forms generally pervades our entire environment, exposing all (to various degrees) and, except for the narrow band of visible energy to which the retina of the eye responds, is not perceived by any of the human senses* unless its intensity becomes so great that it is felt as heat.

The depth of penetration and the sites of absorption of RF energy by the human body depend (to a great extent) on the wavelength of the energy, and consequently vary widely. Absorption of RF energy refers to the conversion of EM energy into other forms of energy, and usually results in the attenuation of the wave energy as it passes into an absorptive medium (i.e., a "lossy" dielectric). Many questions remain regarding the immediate and long-term consequences of acute and/or chronic exposure to various intensities and types of RF energy. These questions include considerations of potential occupational risks, public health hazards, risks to patients (and others), and certain environmental issues (including the exposure of large populations to the generally low exposures associated with power lines, and power transmission and distribution). Continued examination of exposure standards, protection strategies, and their application and enforcement is under way to ensure the safest possible use of RF energy.

It is also important to recognize that certain nonionizing radiation-producing devices utilize or generate ionizing radiation as a by-product, or as a requirement for their operation. Considerations for the protection of personnel from this energy are also necessary.

Historical Perspectives and Important Contributors

Faraday, Oersted, Ampere, James Clerk Maxwell (1864), Heinrich Hertz (1886), and Guglielmo Marconi (1901) are names familiar to many students of physics.

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*It is recognized that under certain circumstances, some individuals can "hear" (i.e., can perceive via auditory or other cues) pulsed RF energy of the correct pulse width, pulse shape, intensity, and modulation.

(The years noted here are those of significant discovery, invention, or event.) These scientists and engineers all made significant contributions to the experimental observations and theoretical descriptions of the (at that time) newly discovered high-frequency electrical "energy." They performed early studies and experimental work with radio-frequency energy, wave propagation, and high-frequency energy detection. The frequency unit (i.e., the term) for cycles per second, the *hertz* (Hz), has been established in honor of the many contributions of that scientist. The implications of these findings were clear to researchers such as Marconi and deForest, who engineered the development of wireless communication using the newly recognized RF energy.

During and following World War II (1940–1945), many significant developments were made in the areas of radio communications, navigation, radar, and other uses of the RF spectrum. During this period, investigation also began into the study of the biological effects resulting from exposure to RF energy. This evolved, in part, due to some accidental exposures (i.e., "overexposures") that occurred with some of the investigators and their technicians. The true nature of the very real occupational exposure problem was not fully appreciated until relatively recently, however.

Other technical developments followed, leading to the microwave oven, precision navigation and radar detection, long-range radio communication using tropospheric reflection and scatter, radio and television transmission ("broadcast"), induction furnaces and dielectric heaters, communications using earth-orbiting satellites, "plasma" generation, cellular phones, PCS, and other so-called wireless applications of RF energy. (These latter items have been termed elements in the "wireless revolution" taking place in communications.)

Basic Physical (and Related) Principles of Radio-Frequency Energy

Physical Description, Characteristics, and Biological Interactions

Figure 2 portrays schematically the relationship between the electric (E) field, and the magnetic (H or B) field components (vector quantities) of a propagating EM wave. Intensities of the E and H fields are represented by the amplitude (magnitude) of the x and y axes, respectively. *Field strengths* (the measure of the intensities of the E and H [or B] fields) are expressed in units of volts/m (for E), and amps/m (for H). *Power density*, the time-averaged energy flow, or the power incident on a cross-sectional area perpendicular to the direction of propagation of the wave front, are described in units of watts/square meter (W/m^2), or milliwatts/square centimeter (mW/cm^2). *Current density* refers to the current flow (in $amps/m^2$) through a given cross-sectional area (such as in biological tissue), and often is used for interspecies comparison of experimental bioeffects results.

Early in the development of RF communications, D'Arsonval, a physician, used low-frequency and RF electrical energy to investigate the electrophysiological properties of nerves and muscles. He detected distinct differences in the effects of low- and high-frequency RF EM fields on tissue preparations; one significant difference was that high-frequency fields induced tissue heating. Be-

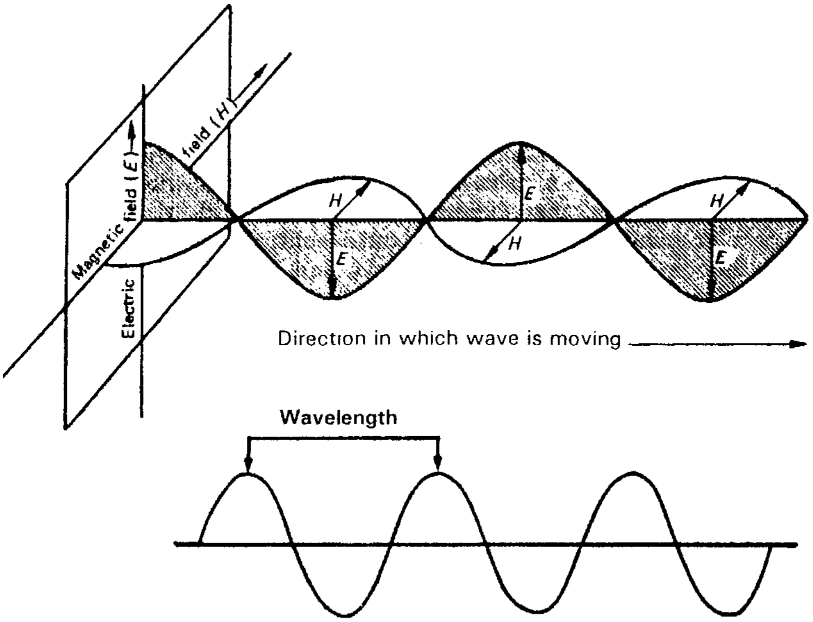

FIG. 2 An electromagnetic monochromatic wave. Electromagnetic waves consist of electrical and magnetic forces that move in consistent wavelike patterns at right angles to one another.

lieving that this heating was therapeutically beneficial, D'Arsonval (and others) applied RF fields to the treatment of various human ailments, including cancer. Diathermy (the general term used to describe tissue heating) has been the principal therapeutic application of RF and microwave energy.

Electrocautery, which uses RF energy to control bleeding following surgical procedures, has been widely used since the mid-1930s. Diagnostic medical applications, as well as other exciting therapeutic applications (including bone and wound repair, and pain control), of RF energy are now also being investigated.

A frequency continuum exists from static fields (at 0 Hz), through the regions referred to as extremely low frequency (ELF) and very low frequency (VLF) fields, medium frequency (MF), high frequency (HF), very high frequency (VHF), ultra-high frequency (UHF), super-high frequency (SHF), the microwave and millimeter wave regions, and so on.

The relationship between the wavelength (L) of the energy, and the frequency (f), within the EM spectrum is shown in Fig. 1. The relationships between the quantum energies (E) and f and L are also shown.

Some typical sources and applications of RF energy were mentioned earlier.

Exposure Considerations and Dosimetry. *Exposure* is the irradiation or contact of part or all of the target (i.e., the animal or human body) with E or H fields or with electric currents induced by those fields. Exposure can occur in an "open" system, such as from a horn or dipole (or other) antenna element transmitting RF energy, or within a "closed system," such as within a microwave oven cavity. *Incident energy* is the sum of the total energy impinging on the target (the animal or human). *Dosimetry* is a quantitative measure of the amount of incident energy actually deposited within (or absorbed by) the exposed body (i.e., the "dose"). A number of phenomena can occur that result in the incident energy being significantly different from the energy actually absorbed. These phenomena include (but are not limited to) reflection, refraction, diffraction, and transmission of the incident energy. The RF energy absorbed by the target is usually converted to heat, especially by water molecules (of which animals and the human body are largely composed). Absorbed RF energy may be reradiated at different wavelengths (e.g., within the infrared portion of the spectrum).

Specific Absorption Rate. The SAR is the mass-normalized deposition of power. It is used as the criterion by which comparison is possible for biological effects studies and for determination of exposure criteria.

Other Considerations Relating to the Biological Responses to Radio-Frequency Exposure

Many considerations and factors can have an influence on an animal's or individual's response to exposure to EM energy. Among these are the dose, temporal and spatial considerations (i.e., issues relating to the timing of the exposure, its delivery, and the portion[s] of the body directly [and/or indirectly] exposed), and the possibility of concomitant exposure to other physical agents, chemicals, and drugs (those that are prescribed, as well as the possibility of "street drugs"), biological agents, psychological stress, and other factors. Rarely in "real life" does exposure occur to an isolated, single stress or agent. This likely exposure to multiple stresses often complicates the interpretation of the observed biological effects following exposure to RF energy.

Other important considerations that can affect an individual's response to exposure to EM fields include age, gender, height, weight, body type, heredity, health and nutritional status, fitness/physical conditioning, presence of certain medications in the body, diet, smoking history, and more. In addition, many variables associated with the EM exposure are possible and require consideration. These include whether the RF energy is continuous wave (CW) or pulsed; if pulsed, the pulse shape, its pulse width, its peak power, and so on need to be considered.

Effect of Environmental Factors on Human and Animal Responses to Electromagnetic Exposure. A number of factors (e.g., ambient temperature, humidity, task or work rate, fluid intake and electrolyte balance, ventilation considerations, type and amount of clothing present, whether protective equipment is being worn, etc.) also can significantly influence the response of a biological organism (such as an animal or human) to RF exposure. Since much (but not all) of the response to the exposure to an external source of RF energy has been demonstrated to be the well-known physiologic response to a source of heat, factors that adversely affect the organism's ability to cope with the added thermal stress can or will influence the animal's physiologic, chemical, and behavioral responses.

Exposure Criteria and Type. *Acute exposure* often refers to a high dose and/or to the immediate response (if any) following such exposure. *Chronic exposure* often refers to a low or lower dose and/or to long-duration (i.e., low-level) exposure, and sometimes to the long-term consequences of such exposures. Exposures may be fractionated (i.e., delivered in small increments) as opposed to given all at once. It has frequently been shown that a fractionated exposure often allows the repair mechanisms and processes to occur between the exposure segments, and thereby enabling many organisms to receive more total energy compared to the exposure situation in which all the energy is delivered at one time. This is often the case with exposure to ionizing radiation.

Accidental exposures to high doses of RF EM energy, and the resulting adverse biological effects, began to be recognized as an occupational risk within the group of physicists and electrical engineers who were developing the early RF communications and radar systems. Such exposures were generally of short duration and at intensities sufficient to cause significant tissue heating.

The hypothesis emerged that the biological effects of RF energy were principally indirect or nonspecific thermal effects. It was assumed that by limiting the intensity (or power density) of incident RF fields to values that did not induce significant tissue heating (i.e., a temperature increase of 1 °C or less), adverse biological effects would be averted. This reasoning, together with data from experimental studies (of the effects of exposure to RF energy) conducted on laboratory animals, resulted in the early recommendations for a maximum safe exposure intensity for humans of 10 milliwatts per square centimeter (mW/cm^2, independent of the RF frequency (2,3).

Later exposure recommendations for workers and the general public were based on much more extensive (and sophisticated) experimental research (often using animals "higher" in the evolutionary chain, isolated organs, *in vitro* preparations [i.e., in test tubes], and more sensitive indicators of exposure), on computer modeling and theoretical predictions, on "accident" and overexposure reports, and on the limited quantity of data involving human exposures to RF energy. It should be noted that broad extrapolation (often across decades of the frequency spectrum), and from small animals to humans, were necessary to arrive at the next generation of human exposure recommendations. This has been a constant (but probably appropriate) criticism of the "standards" for human exposure to RF energy. Additional comments are provided below relating to the limitations of the existing biological effects studies.

Interactions of Radio-Frequency Energy with Matter

Radio-frequency energy interacts with biological tissue at the atomic, molecular, cellular, and whole-body levels. The microscopic interactions are usually averaged on the macroscopic level (i.e., on the scale of the live, intact animal), and usually manifest themselves as responses to applied electric and/or magnetic fields. Mechanisms for the interaction include (at the molecular level) alignment of polar molecules, molecular rotation and bond vibration, and the transfer of kinetic energy to electrons and ions. As molecules vibrate and rotate, they meet with resistive forces and experience the interactions associated with neighboring molecules, which result in frictional heating within the material.

The oscillation of electrons and ions has important consequences for the interaction and functional activity of biological macromolecules and related materials. As noted above, the absorption of RF energy by a biological material is generally accompanied by reflection, refraction, diffraction, reradiation, and scattering of the incident energy. The actual situation is quite complex because the target animal or human body is nonhomogeneous; composed of layers of tissues having different dielectric characteristics. These differences produce multiple interfacial reflections and standing waves between the various tissue layers and at the air-tissue interface.

Factors important in the absorption of RF energy include the relationship between the size (i.e., dimensions) of the target material and the wavelength of the incident energy; the wave polarization relative to the geometrical length (i.e., the long axis) and girth (or axial ratios) of the target; the dielectric properties of the target material; and the presence of conductive and/or reflective surfaces in the local environment. In addition to these considerations, other factors have an important role in influencing the absorption of RF energy by a biological material. These include the issue of geometrical resonance(s) in objects of a certain size and shape, and oriented in specific ways within the EM field, and the possible presence of a ground plane on which the target is placed. The SAR can vary significantly depending on the orientation of an object in the exposure field, and the frequency at which maximum absorption of energy occurs can be significantly altered by the presence of a ground plane. As noted above, the possibility of the generation of induced and/or contact currents also enters into the complex exposure considerations.

Physical Parameters That Determine Energy Transfer

Physical parameters that determine energy transfer (especially into the human body) include conduction, coupling, and the various absorption mechanisms. All are dependent on the wavelength (L) of the energy, and on the body's distance (d) from the RF-emitting or RF-radiating source.

The distance relative to wavelengths L and the corresponding interaction mechanisms are

0 L = Conduction (contact)
0–0.2 L = Coupling (direct transfer of a charge)
>0.2 L = Absorption (conversion to internal heat at frequencies greater than about 1000 MHz)

Conduction. Conduction occurs when the body makes contact with an RF source (e.g., an antenna element or an exposed transmission line). The resulting detrimental effects include electrical shock, burn, and an involuntary reflex (i.e., nervous system activation of muscle) resulting in a "jerking" action, which can result in additional injury. Falls from elevated locations, such as metallic ladders or platforms, are possible as the individual making contact may lose grip and/or footing as a result of the shock/burn.

At frequencies above 100 kHz, most of the energy delivered through contact with an RF source will be absorbed within a few millimeters of the RF current's travel through the tissue. In these cases, the SARs involved may be significant if a small volume of tissue absorbs a large amount of energy.

The exposure limits (ELs), guidelines, and standards developed to prevent RF shock and burns are intended to limit induced RF current flow through the body for frequencies less than about 100 MHz.

Coupling. An individual can be exposed to the stored energy fields (at frequencies lower than about 1000 MHz) that are present close to antenna elements or transmission lines. The body absorbs this energy through capacitive or inductive coupling, which is the direct transfer of a charge from one conductor to the body. Physical contact need not actually occur, and the SARs are difficult to predict and to measure. When a conducting object (such as a human) is placed in an RF radiative field, the object will absorb three- to fivefold more RF energy due to coupling if the field is at the absorbing object's resonant frequency.

Resonance occurs when an object's dimensions approximate one-half the wavelength of the incident energy. The human body standing in a vertically polarized field is resonant in the frequency band between 30 and 100 MHz; that is, a person 175 cm in height would be resonant at a frequency of 85 MHz (with 175 cm = 0.5 of the wavelength L at this frequency). This resonance exists because the body acts as an antenna. As body size decreases, the frequency for resonance increases (Fig. 3). A number of other factors also influence the resonance frequency to a varying extent.

The permissible exposure level (PEL) in the resonance frequency region for humans is reduced slightly from the PEL in the nonresonant region. The SAR still remains 0.4 watts per kilogram (W/kg), and the effects are still thermally induced. Only the PEL, which is derived from the SAR, changes.

Absorption. Absorption is the principle mechanism for energy transfer at frequencies greater than about 1000 MHz. At lower frequencies, RF energy transfer occurs through a combination of radiation conduction, coupling, and absorption.

The PEL at frequencies greater than about 1000 MHz is still based on a whole-body SAR of 0.4 W/kg. This SAR corresponds to the absorption of 100% of the RF energy incident on the body, and equates to a measured power density of about 10 mW/cm. For energy absorption at frequencies greater than about 1000 MHz, the biological effects are thought to be induced primarily thermally.

Biological Effects and/or Responses to Exposure to Radio-Frequency Energy

The absorption of energy is the primary mechanism by which RF EM fields affect living cells. Electric and magnetic fields are induced within a biological

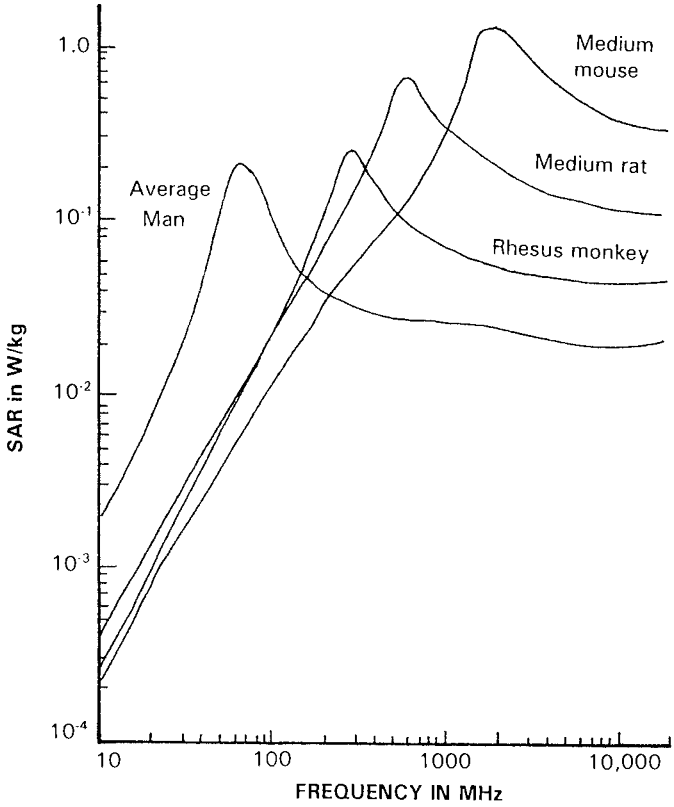

FIG. 3 Whole-body-averaged specific absorption rate of prolate spheroidal models of average human, rhesus monkey, medium rat, and medium mouse for E polarization at incident plane-wave power density of 1 mW/cm^2. (From Durney, C. H., Johnson, C. C., Barber, P. W., et al., *Radiofrequency Radiation Dosimetry Handbook*, 2d ed., Publication No. SAM-TR-78-22, U.S.A.F. School of Aerospace Medicine [RZP], Brooks Air Force Base, Texas, 1978.)

system exposed to microwave or RF energy. As noted earlier, such energy is transformed from these electric and magnetic fields into one or more types of energy modes (similar to translational, vibrational, rotational, and other modes) in the target material (i.e., the biological tissue). When translational modes are excited, the ambient cell temperature rises due to the heat generated by these modes. If the temperature rise is sufficient, proteins denature and their internal bonding becomes disrupted, which results in a change in their three-dimensional shape, resulting in their inability to participate in certain biochemical reactions.

Depositing RF energy into the body increases its overall thermal load. The body's thermoregulatory system responds to the increased thermal load by transfer of energy to the surrounding environment through convection, evaporation of body water, and reradiation (primarily of infrared [IR] energy). When the absorption of RF energy causes localized heating of certain organs, such as the eye or the testes, prolonged exposure to this thermal stress can result in serious damage (usually irreversible) to that organ.

To understand the resulting biological effects (upon irradiation with RF energy), it is necessary to determine the induced field strengths at various internal points within the system. Knowing the electrical and geometrical characteristics of the irradiated object and the external exposure conditions, it is possible, in principle, to calculate the rate at which energy is absorbed throughout the interior of the irradiated object.

The magnitude of interior and exterior scattered and reflected fields associated with an irradiated object depends on many factors: the frequency and configuration of the incident field, the electrical properties of the various layers (i.e., biological tissues) of which the irradiated system is composed, the shape, the size relative to the wavelength, and the relative orientation of the system. Biological systems are usually of complex exterior and interior geometry, and consist of several layers with various electrical properties (complex permitivity). As a result, the internal energy deposition in biological systems is usually of a nonuniform nature. Depending on the thermal properties and blood flow of tissues, there can be marked differences in the magnitude and the rate of increase in temperature, and thermal gradients within the exposed object can result.

The intensity of the internal electric field, or the amount of energy absorbed per unit time per unit mass (i.e., the SAR) are both used in RF and microwave dosimetry. The most generally used units for SAR are W/kg and mW/g.

Measurements of internal electric fields within various dielectric media are possible if a small, insulated dipole array is used. Such a device has been developed in miniature form and has been used to measure the internal electric fields in "phantoms" (i.e., models that exhibit the desired physical dimensions and the correct electrical [e.g., dielectric] properties) and in various animals (including carcasses, live anesthetized animals, and unrestrained animals).

It is important to note that many of the early (and even relatively recent) studies of the biological effects of exposure to RF EM energy have implied that the effects are primarily "thermal" in nature, and are an indirect consequence of RF energy absorption. Data from a number of more recent studies (including those demonstrating a number of cellular alterations) have provided strong evidence of possible direct RF field effects on biological systems. Such effects are "potentially significant in assessing bioeffects because they introduce the possibility of low-field intensity thresholds, frequency specificity, and dependence on the instantaneous induced electric or magnetic field strength per se" (4). Additional studies in these areas are under way, and the results must be examined very carefully.

Biological Effects of Radio-Frequency and Microwave Energy

A number of excellent descriptions and thorough discussions exist on the interaction of this nonionizing EM radiation with biological tissue. The resulting biological effects and, in some cases, the hazards, are also described in many well-written books and articles (including some that are scholarly and some written for the lay reader). It is beyond the scope of this article to include much discussion of this specific topic); however, some references to this literature are provided in the bibliography. One should note that, in most cases, the data available regarding human exposure are limited, and may (in part) result from accidental exposure and/or overexposure incidents, and may (to some degree) not involve careful and/or reproducible dosimetry.

Effects from Low-Level Radio-Frequency Exposure

Much controversy exists regarding the possibility (and the extent and/or the reversibility) of biological effects at low levels (i.e., low doses) of RF exposure. Low-level effects are often not easily observable. Research studies have included controlled exposures of cells, organs, and/or animals; computer simulations and modeling; evaluation of accident/overexposure incident reports involving humans; and sophisticated epidemiologic analysis (including retrospective and concurrent studies) of animal and human exposures. The point (or, more usually, the range of exposures) at which "effects" demonstrated in various organisms and in animals represent a "hazard" to humans has been widely debated.

Summary of the RF Bioeffects Literature

Biological effects and clinical responses to RF exposures discussed (as in the literature) can be classified into a number of categories:

- Acute (immediate response) and/or chronic (long-term) responses (as noted above, the term *acute* is also sometimes used to refer to a short-term, high-dose exposure, and *chronic* has been used to imply an exposure of long duration but low dose).
- Molecular and cellular studies (so-called *in vitro* studies because they often are conducted in test tubes, not actually on intact [live or otherwise] vertebrate animals). Includes studies of macromolecules, cell membranes, enzyme activity, and mitochondria; studies of carbohydrate, lipid, and protein metabolism; studies of clinical chemistry (involving blood), serum proteins, and electrolytes; studies of various microorganisms, such as bacteria, fungi, and viruses; studies of protozoa and other unicellular organisms; and studies on invertebrates.
- Vertebrate animal studies and studies conducted on isolated biological tissue and organs (so-called *in vivo* studies conducted on intact, live [but often restrained and/or anesthetized] animals); includes thermal- and pain-perception studies. Problems (such as the effect on the study results of the anesthetic agent) exist with some of these data.
- Experimental studies involving deliberate exposure to RF energy of humans are mostly absent; accident reports and case histories do exist, but the data

are generally not of reliable quality and generally do not have accurate dosimetric data.

- Human and animal studies on thermoregulatory responses, metabolism, and modeling. These include studies on the physiologic regulation of temperature by higher animals, hyperthermia, and cell kinetics; adaptation of animals to thermal stress; acute lethality to whole-body exposure of animals to RF energy; response to localized exposure to RF energy; comparison of RF exposure of animals versus exposure of the animals to infrared energy; and therapeutic application of RF energy (such as diathermy).
- "Perception" of RF energy by such mechanisms as the "RF hearing" phenomena.
- Studies of shock and burns (i.e., "contact" currents).
- Studies demonstrating that "induced currents" can be produced in the body (i.e., so-called "foot current").
- Behavioral effects and physiology; includes effects on the performance of various learned tasks following exposure of the animal to RF energy, behavioral "baseline" studies, and studies demonstrating altered sensitivity to certain drugs following exposure to RF energy.
- Eye effects/ophthalmic responses; demonstrates that cataracts can be produced on exposure to high doses of RF energy (the cataract occurs in the lens of the irradiated subject), effects produced on other structures of the eye (including the retina and the cornea), and biochemical changes produced in the eye. Frequent reports of the "dry eye" phenomena.
- Effect of exposure to RF energy on certain "biorhythms" (including sleep, ovulation/menstruation).
- Endocrine and neuroendocrine responses, including studies demonstrating changes in the concentration of growth hormone following exposure to RF energy, the hypothalamic-hypophysial-adrenal (HT-HP-adrenal) response to RF exposure; the HT-HP-thyroid response to exposure, and neuroendocrine activity and cardiovascular function.
- Immunologic responses to RF exposure have been demonstrated. The immune system is a physiological defense of the body against a large spectrum of pathogens, including bacteria, viruses, fungi, parasites, tumors, toxins from organisms, and miscellaneous chemical substances. Since there often is considerable adaptability and redundancy in the immune system, many of the demonstrated perturbations of the immune system may not have clinical significance.
- Neural effects and nervous system/neurologic responses, including electroencephalographic (EEG) changes, biochemical changes, histopathologic changes, changes in the influence of drugs on the body, central nervous system structural alterations, and blood-brain barrier studies.
- Hematologic responses, including suggested changes, following RF exposure, in the blood and blood-forming system, in hematopoiesis and the production of hemocytological shifts, and in the blood chemistry of exposed subjects.
- Cardiovascular and cerebrovascular responses to RF exposure have included changes in blood flow and pharmacodynamics, and reports of atherosclerosis (i.e., plaque formation).

- Epidemiologic data and related evidence includes nervous system and cardiovascular studies, ocular effects, fertility and sterility studies, growth and developmental changes, and studies of cancer production/causation. Some problems and criticism include the difficulty of determining (especially in retrospective studies) who actually was exposed, and determining dose and duration also often is very difficult.
- Reproduction, development, growth, and genetic effects include studies of embryonic development; fertility; spermatogenesis and egg production, fertilization, and implantation; reproductive efficiency; sex ratios (per litter) of the newborn; embryo and fetal toxicity; numbers of stillbirths; production of sterility; mutagenicity and teratogenicity (i.e., production of mutations and birth defects).

Other Effects Resulting from Exposure to Radio-Frequency Energy

Other effects resulting from exposure to RF energy include the effects of EM fields on implanted medical/electrical devices, and effects of EM fields on sensitive electrical equipment/devices (not implanted).

Radio-frequency energy can also pose a threat to the health of personnel through EM interference (EMI, also termed RF interference or RFI) with sensitive electronic devices, especially medical equipment (such as cardiac monitors and some other types of patient monitors) by disrupting their normal operation. The EMI can also affect the normal operation of certain implanted devices, such as electronic cardiac pacemakers, nerve stimulators, implanted drug delivery pumps, and the like. Interaction of EMI with some video display terminals (VDTs) also has been demonstrated. Fortunately, methods have been developed (including shielding, redesign, and other techniques) to make many of these devices and equipment less susceptible to EMI/RFI.

Other exposure concerns include combined stress caused by exposure to RF/microwave energy *plus* exposure to certain chemicals/drugs, biological compounds, and/or other physical agents has been demonstrated to often result in synergistic responses (i.e., heightened response to the combined stresses, compared to exposure to each stress alone). There also appears to be a psychological stress contribution, as if the individual (or animal) is aware that exposure to RF energy is taking place.

Standards/Guidelines for Human Exposure to Nonionizing Radiation

Basis for the Standards/Guidelines

Some of the standards and/or applicable guidelines relating to exposure to various modalities of nonionizing radiation of equipment users/operators (i.e., occupational exposure), patients, and/or members of the general public (i.e., environmental exposure) are very simple and straightforward. Other standards/guidelines are much more complicated and vary with frequency/wavelength of the energy, the duration and/or repeatability of the exposures, and/or a number of other considerations. The reader is reminded that exposures of patients (therapeutic and/or diagnostic) are performed under the direction and control of licensed practitioners of the healing arts following consideration by the practitioner of the risks of exposure and the benefits to the patient. The reader of this article is referred to some of the applicable standards/guidelines (for human nonionizing radiation exposure) cited in the reference section.

The reader is alerted that some of the standards/guidelines are presently undergoing revision or updating due to the evaluation of new bioeffects data. Consequently, the reader is cautioned to ensure that the standard or guideline applicable to the particular exposure situation (i.e., occupational, environmental, or medical) is the most recent.

Other Considerations

Other considerations relating to protection from RF exposure include the measurement and quantitation of RF/microwave E and/or H fields to determine the risk for exposure of personnel. This is very important, but discussion is not included here.

Also, limitation of exposure and exposure control(s) and protection (including engineering and administrative controls and protective equipment) are very important, but a detailed treatment is beyond the scope of this article. However, the topic includes

- Health and safety (i.e., exposure) standards and guidelines (relating to the absorption of energy) for occupational groups or for the general public (the population at large) or relating to medical exposures or for environmental (or other) exposure(s).
- Performance criteria (i.e., emission standards) for specific types or items of RF-emitting equipment (e.g., microwave ovens).
- Shielding (often can be placed between the personnel and the source of RF energy to reduce exposure of individuals).
- Distance of personnel from the source of RF energy. Usually, the exposure decreases as the distance from the source of energy increases.
- Exposure time limitations. Generally, nonpreventable exposures to RF energy should be kept as short as possible.
- Beam access limitations. Access of personnel to intense beams of RF energy, or to other areas in which intense RF energy is present, often can be prevented using a variety of techniques, including locked enclosures, interlocked doors, key control of power supplies, floor and wall markings, alarms, recorded warning messages, and so on.
- Personal protective equipment (PPE) can be utilized to reduce (or eliminate) exposure to RF energy. Such PPE includes goggles, protective clothing, and the like.

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ZORACH R. GLASER

Real-Time Communication

Introduction

When a computer is used to control a physical system, the time scale for the physical system is defined by its dynamics in that the time for the physical system continues to change even if the computer application does not execute due to preemptions, and the like. For such systems, the computer applications must conform to the temporal requirements of the physical system. The term *real-time application* is often used for such applications. Analogous to this, *real-time communication* refers to the communication, which must meet functional and temporal requirements for communications needed by these applications.

Note that the majority of communication networks, such as the Internet, has been designed to deliver what is known as "best-effort" performance. Best effort strives to achieve good average performance. These networks work well for applications for which long delays and high data loss under heavy load conditions are acceptable. These applications are designed so that delays and data loss at arbitrary times during their execution result in no functional harm. They simply try to make progress as fast as they can. In contrast, real-time applications put stringent requirements on data loss, as well as latencies.

Recent technological advances have led to the development of high-performance switches and high-bandwidth links, resulting in *high-speed networking*. However, "real fast is not real time" in that having a very fast network does not assure meeting the temporal requirements of the applications under all conditions. While a lightly loaded high-speed network may be able to meet all the temporal requirements of applications without making any special provisions, it cannot guarantee that it will continue to meet the temporal requirements when the load changes. Since the standard designs of high-speed networks still show a significant variability in performance, real-time guarantees cannot be given to applications. A network capable of supporting real-time communication has to be able to respond to the communication requests with specific temporal requirements.

Traditionally, real-time communication has supported hard/soft real-time applications running in a distributed environment and interacting/controlling a complex physical system such as a power plant, avionics, chemical process plant, automobile, and so on. The current development of high-speed networking enables new application areas for which the communication has to satisfy real-time constraints. Among these applications are *multimedia* applications such as video broadcasts and *process control* applications such as command-and-control systems, automated manufacturing, remote process control, and flight control systems.

When we consider the real-time applications, their communication requirements can be characterized according to their ability to tolerate data loss. Typical process control applications assume that all the data will be delivered in a timely manner with no losses. In contrast, multimedia applications, which often display the results to a human operator, can tolerate some loss of data. Therefore, the requirements these applications place on real-time communications are not only in terms of delays but also of acceptable losses. These combined are usually referred to as *quality of service* (QoS). The parameters of interest for QoS include delay, delay jitter, bandwidth, and loss rate.

Note that process control applications often require a point-to-point communication that is connection oriented. The multimedia applications, on the other hand, require support not only for point-to-point communication, but also for point-to-many or many-to-many communications, leading to multicast and broadcast requirements. It is inevitable that new routing support is required in order to provide QoS requirements while maintaining effective multiparty communications.

This article is dedicated to a discussion of current techniques for the support of real-time communications with special emphasis on multimedia applications.

Background

Consider a packet going from Node S to Node D via Nodes A, B, and C and Links 1, 2, 3, and 4. If the network is carrying no other traffic, the transfer of the packet uses the links and nodes in time order as shown in Fig. 1. The time $t_k - t_0$ is the latency of this transfer. As shown in this figure, the packet processing at each location begins as soon as it can, leading to $t_k - t_0$ as the minimum latency. Achieving this minimum latency requires that the network resources, nodes as well as links, be available and ready to process the packet at the time instants shown in the figure.

As a network typically will handle other traffic also, the links and/or nodes may not be in a position to start processing this packet immediately as they may be processing other packets. In such a case, the packet has to wait, causing

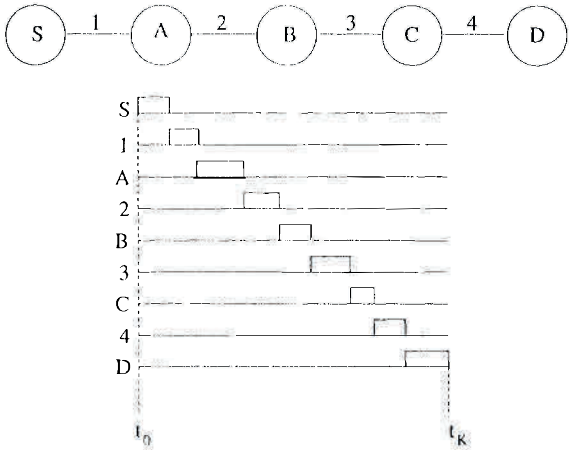

FIG. 1 Minimum latency of a packet transmission.

additional delays. The waiting requires that a buffer be available for the duration of the wait; if that is not the case, the network may drop the packet, resulting in packet loss. Therefore, the real-time communication schemes have to address the problems of resource management and resource reservations in order to assure the QoS.

Network Model

Let us consider an arbitrary topology packet-switched network model with links and switches (or nodes). Links have bounded propagation delay. They can be transmission media or subnetworks with delay bound guarantees, such as asynchronous transfer mode (ATM) and fiber distributed data interface (FDDI) networks. Switches have a number of input and output links. Each output link has a separate buffer of a finite size. A packet arriving to an input link is routed to its output link correctly. Packets at each output link are independently scheduled by a server according to a service discipline. Packets are of variable size.

A source application running on a source node can send a packet to a destination application running on a destination node. Each packet leaving its source node follows a route (or a path), which is a series of (*link*, *switch*) pairs, the last switch being the destination node. The switches between the source and destination nodes are called *intermediate* nodes. A packet transmission is modeled as the traversal of the packet on a series of servers at the output links of the switches along the path.

Source Traffic Models

Typically, there are three different types of traffic in the network: digital continuous media (voice and video) of multimedia applications, periodic sensor/actuator data of process control applications, and the traditional data sources of traditional data applications. These can be categorized based on their generation rate. Some traffic sources generate fixed-size packets at fixed time intervals. These are called *constant bit rate* (CBR) sources. Uncompressed voice and video and data generated at sensors or sent to actuators all fall in this category.

Some continuous media applications apply compression or adaptation techniques to reduce the size of the data to be transmitted. They generate packets at a variable bit rate and are commonly referred to as *variable-bit-rate* (VBR) sources. Specifically, to reduce the size of the voice traffic, no data are generated during the silent periods. This results in *on-off sources*, for which the source alternates between a period in which fixed-size packets are generated at fixed time intervals and an idle period. Size of the video traffic is reduced by compression applied to individual frames. This results in *compressed media sources*, in which variable-size packets are generated at regular intervals.

Traditional data sources include file transfer, interprocess communication in distributed computations, and interactive data (e.g., remote log in). They either involve one long message (as in file transfer) or a number of short messages at widely spaced intervals (as in interprocess communication and interactive data such as rlogin and Telnet). Traditional data sources use best-effort services and do not have stringent QoS requirements.

Informally, traffic sources can also be classified as either *smooth* or *bursty*, depending on the ratio of the peak rate to the average rate of their traffic. A smooth traffic source does not have too much variation in its traffic rate. All CBR sources and some of the VBR sources have smooth traffic. A bursty traffic source, on the other hand, has occasional long bursts of traffic that cause a big variation in its traffic rate. Many of the VBR sources have bursty traffic.

Service Model

The service model should be able to support both real-time and best-effort communication on a packet-switched network.

A real-time communication requires a guaranteed worst-case performance. Network resources required to satisfy the guarantees depend on the traffic volume of the communication. To bound the required resources, traffic is specified through a *traffic characterization* that bounds the volume of data to be sent over a specified period of time. Any application requiring a real-time service needs to supply to the network the traffic characterization and the performance requirements of the communication.

A real-time communication is connection oriented, with the explicit connection establishment phase used as a connection admission control. The network tries to find a route such that there are enough resources over the route to provide the required guarantees for this connection without destroying the guarantees already given to other real-time connections. If such a route is found, then the required resources are reserved and the connection is accepted. Otherwise, the connection is rejected.

Each connection is a contract between the applications that use it and the network. The network promises to give the required performance only if the source satisfies its traffic characterization. A rate-based flow control uses *traffic shaping* at the source and *traffic policing* at the network to guarantee that the source application is not misbehaving.

At each switch, incoming traffic from several connections may be multiplexed for transmission. Multiplexing causes network load fluctuations such that traffic of a connection might get burstier and no longer satisfy its characterization even though it satisfies the characterization at the source. The service discipline has to protect the service guarantees given to one connection from the overloaded traffic of another connection. This is provided by rate-based service disciplines in which each connection is guaranteed a minimum service rate (enough to satisfy its traffic characterization) regardless of the incoming traffic rate of other connections.

Integrating best-effort service into the service model is straightforward. Best-effort communication can be connection oriented or connectionless, and it can choose its own flow control and service discipline independently. Choices are generally a window-based flow control and a first-come, first-served (FCFS) or a round-robin service discipline. Then, each server at an output link of a switch may have two service disciplines at different priority levels. The higher priority service discipline is used to serve real-time traffic. The lower priority service discipline is used to serve best-effort traffic. Since best-effort traffic will be served only when there is no packet to serve from real-time traffic, best-effort traffic cannot hurt the performance guarantees given to real-time connections.

In summary, the components of such a service model include

1. *Connection Specification:* A data structure that is used as an interface between an application and the network. It describes the traffic characterization and the performance requirements (QoS parameters) of the connection.
2. *Connection-Level Control:*
   a. *Routing:* Finds unicast or multicast path(s) that can satisfy the performance requirements.
   b. *Admission Control and Resource Reservation:* Decides whether any of the paths suggested by routing has enough resources to provide the performance guarantees for the given traffic characterization. If it finds such a path, it accepts the connection and reserves the resources. Otherwise, the connection is rejected.
3. *Packet-Level Control:*
   a. *Flow Control:* Protects the guarantees given to connections from misbehaved sources. It forces each connection to stick with its traffic characterization by shaping it at the source and policing it at the network edge.
   b. *Service Discipline:* Schedules incoming packets for transmission. For real-time connections, rate-based service disciplines are used to protect the guarantees given to connections from network load fluctuations and best-effort traffic. They guarantee a minimum service rate to individual connections regardless of the traffic of other connections.

Connection Specification

Quality of Service Performance Parameters

Unlike best-effort communication service, for which the service tries to optimize the average performance, real-time communication service has to guarantee a bound on the worst-case performance of individual connections. Some of the performance parameters (also known as QoS parameters) of interest are bounds on delay, delay jitter, bandwidth, and loss rate.

The most important parameter in a real-time communication is the end-to-end delay bound assigned to individual connections. Successful delivery of a packet depends not only on the intact receipt of the packet, but also on the time it is received. If the time to deliver a packet exceeds its delay bound, then the packet is effectively lost.

Digital continuous media applications such as voice and video need a constant delay between the transmission of a packet at the source and its playback at the receiver. Delay variation in the network delivery necessitates the use of buffers at the receiver. Delay jitter is typically defined as the difference between the maximum and the minimum end-to-end delay. Then, for a lossless playback, the buffer size at the receiver should be the size of the maximum traffic that can be received during a period that is the length of the delay jitter. This is bounded by peak-rate X delay jitter. Therefore, for these applications, providing a tight delay-jitter bound reduces the buffering required at the receiver.

Internal buffering is needed along the path of a connection to minimize packet loss. At a server, the buffer space required for a connection is the maximum amount of traffic that can be received from the connection during a period that equals the longest residence time of a packet of the connection at that server. In all the proposed service disciplines, a tight bound on delay jitter implies a tight bound on the residence times at the intermediate servers. Therefore, controlling the delay jitter reduces the internal buffering required also.

For a real-time connection, the traffic load is bounded by a traffic characterization. This bound also defines the bound on bandwidth guarantee given to the connection.

Packets of a connection are lost in cases of delay-bound violation, delay-jitter bound violation, buffer overflow, and data corruption. Since data corruption is rare in fiber-optic links of high speed, it is generally ignored. The loss-rate bound of a connection is defined as a stochastic bound on the percentage of lost packets of the connection. A *deterministic service* has zero loss rate, and a *statistical service* has a nonzero loss rate.

A deterministic service does not lose any packet even in the worst case, which makes it appropriate for hard real-time, process control applications. A statistical service, on the other hand, can tolerate a certain amount of loss and therefore requires fewer network resources. It is appropriate for multimedia applications for which some loss can be tolerated.

Other performance parameters include bounds on blocking probability and delay distribution. Blocking probability is defined as the probability of a new connection being rejected by the admission control. Delay distribution is the stochastic distribution of delay values for changing loss rates. It can be used to adjust loss-rate-versus-delay guarantees of an already established connection.

Traffic Characterization

Traffic characterization is the term used to specify the data-generation characteristics of the source by identifying the amount of data generated for sending at different time instants. For real-time communications, typically such characterization is specified in terms of bounds on the volumes. Bounding the volume of the traffic limits the amount of network resources necessary to provide the required QoS guarantees. During connection establishment, resources are reserved based on the traffic characterization and QoS requirements. If not protected, a source can misbehave by violating the traffic characterization and sending more traffic than it is allowed. This may result in resource contention