HF, VHF, and UHF Systems and Technology

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Invited Paper

***Abstract*—A wide variety of unique systems and components inhabits the HF, VHF, and UHF bands. Many communication systems (ionospheric, meteor-burst, and troposcatter) provide beyond-line-of-sight coverage and operate independently of external infrastructure. Broadcasting and over-the-horizon radar also operate in these bands. Magnetic-resonance imaging uses HF/VHF signals to see the interior of a human body, and RF heating is used in a variety of medical and industrial applications. Receivers typically employ a mix of analog and digital-signal-processing techniques. Systems for these frequencies make use of RF-power MOSFETs, p-i-n diodes, and ferrite-loaded transmission-line transformers.**

***Index Terms*—Broadcasting, communication, HF, high frequency, ionosphere, magnetic-resonance imaging, meteor burst, MOSFET, p-i-n diode, radar, receiver, RF heating, transmission-line transformer, troposphere, UHF, ultra-high frequency, VHF, very high frequency.**

I. Introduction

IN THE early days of wireless, it was generally accepted that lower frequencies were better for long-range communication, and this principle was indeed true for ground-wave propagation. Radio amateurs were thus relegated to the “useless” wavebands of “200 meters and down” (1.5 MHz and above). The amateurs, however, soon (late 1921) discovered the capabilities of high frequencies (HFs) (2–30 MHz) for long-range communication via the ionosphere using only modest transmitters and antennas. Communication at VHF (30–300 MHz) and UHF (300 MHz–1 GHz) was originally thought to be limited to line of sight (LOS) distances. Circa World War II, however, a number of scattering modes (e.g., meteor, troposphere) were discovered that could reliably provide beyond-LOS (BLOS) communication. Today, a variety of LOS and BLOS communication and radar systems operate at HF/VHF/UHF.

At HF/VHF/UHF, the effects of line length and component layout are significant design issues. However, the wavelengths remain large enough that lumped elements are generally preferred to or used in conjunction with transmission lines for filtering and matching. The needs for high power and large bandwidths favor the use of components such as RF-power MOSFETs, p-i-n diodes with large time constants, and ferrite-loaded transmission-line transformers.

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II. HF Communication

HFs (2–30 MHz) offer long-range and even worldwide communication via the ionosphere. Since HF systems require only modest transmitters and antennas, and do not require external infrastructure, HF links can be easily established from remote locations, or following a natural disaster. Terminals are often connected to the local PSTN or Internet to allow remote access. HF is widely used for voice and data communication by military, diplomatic, aeronautical, marine, and amateur-radio services. However, the variable and dispersive nature of the ionosphere imposes some unique requirements on both hardware and communication protocols.

A. HF Communication Systems

The transmitting station consists of a transmitter, matching network, and antenna. The receiving station includes an antenna, matching network or active preamplifier, and receiver. Most HF equipment is operable over all or most of the 2–30-MHz range, and each group of users is typically assigned a number of frequencies or bands.

HF systems employ a wide variety of transmitting antennas [1]. Low-angle radiation is needed for long-range communication, while high-angle radiation is needed for shorter range “near-vertical-incidence-skywave” (NVIS) communication. It is not necessary to match the polarizations of the transmitting and receiving antennas because the ionosphere generally produces elliptical polarization.

Low-angle directional transmission is usually accomplished by a mechanically rotated “beam” such as a Yagi (specific frequency) or log-periodic dipole array (band of frequencies). The gains are typically in the range of 3–10 dB. Low-angle omnidirectional transmissions typically use monopoles. Conical (wire-cage) and fan configurations allow operation over a 3 : 1 frequency range with good gain at low angles. NVIS systems typically use dipoles or loops to ensure good gain at high angles. Whips (lengths 2–5 m) are generally used for mobile systems; center loading is often employed to reduce losses in the ground. Dipoles and random wires are often used for convenience in deployment.

The input impedance of a typical antenna is satisfactory for connection to the transmitter only at a limited number of frequencies or over a limited band. The antenna tuner provides impedance matching that allows operation on other frequencies. It is typically a T or Π with a series inductor and shunt capacitors. Automatic tuning is accomplished by sensing SWR and using relays or p-i-n diodes to select from banks of components with binary-stepped values (typically seven of each).

The basic elements of the transmitter are the frequency synthesizer, modulator, frequency converters, and RF-power chain. The peak output power of the transmitter is typically in the range of 10 W–1 kW. The signals include CW (Morse code), single-sideband (SSB) voice, FSK, and multitone data modulation [orthogonal frequency-division multiplex (OFDM)]. A given transmitter generally generates one or two voice-bandwidth (3-kHz) signals. Modern modulators are based upon digital signal processing (DSP), and modern transmitters operate under microprocessor control. Since the SSB and OFDM signals require linear amplification, most HF transmitters employ class-B linear amplification [2]. The Kahn technique is used for high-efficiency linear amplification in some newer equipment.

Reception at HF is limited by atmospheric noise, hence, the receiver can use either a tuned or an active antenna. An "active antenna," is typically a short whip (0.5 m) connected directly to a preamplifier with a high input impedance. Such active antennas have very wide bandwidths (e.g., the whole HF band), but are subject to intermodulation and sensitivity reduction by overload from strong signals. The receiver consists of a preamplifier, synthesizer, frequency converter(s), and demodulators (Section X). Since atmospheric radio noise is significantly impulsive, noise limiting or blanking is generally employed.

B. Propagation

The ionosphere [3], [4] is created by ionization of the upper atmosphere by ultraviolet and X-rays, and is divided into D, E, and F layers. The F layer extends from 150 to 650 km and is responsible for most long-range HF propagation. Since the ionization varies with altitude, signals are not reflected, but refracted by the ionosphere. Signals of different frequencies are thus returned to Earth at different distances (or not at all), as shown in Fig. 1. During the daytime, the "skip distance" for a 7-MHz signal might be 300 km, while that of 21-MHz signal could be 3000 km. With the lower electron densities at night, the skip at 7 MHz might increase to 2000 km, while 21 MHz would not be returned at all. Long-range communication can also be accomplished over multiple-hop paths that include a reflection from the earth or E layer. Conditions vary with the time of day, latitude, season, and solar conditions. Predictions are made by a variety of programs including IONCAP, PROPMAN, and MINIMUF.

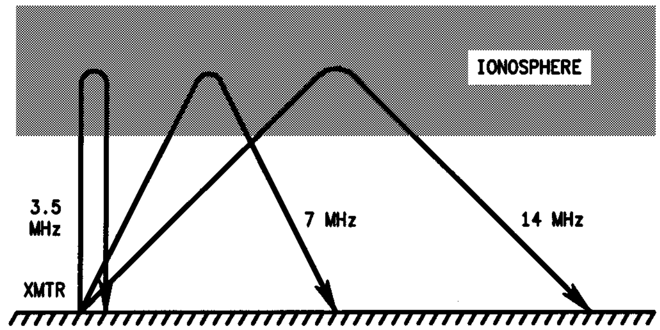

Fig. 1. Ionospheric propagation.

C. Link Establishment

The highly variable nature of the ionosphere makes it impossible to rely upon a single assigned frequency for reliable communication over a given path. Link establishment basically involves testing communications on a set of significantly different frequencies and then selecting the one with the highest link quality. In the past, this required skilled radio operators with knowledge of ionospheric-propagation characteristics. In the modern era of microprocessor-controlled radios, it is accomplished through a process known as "automatic link establishment" (ALE). The fundamental elements of ALE include selective calling and handshake, link quality analysis (LQA) and channel selection, scanning, and sounding [1], [5]. The common ALE protocol known as "2G" or "basic ALE" and specified in MIL-STD-188-141B is discussed subsequently. Some newer radios implement a refinement known as "3G ALE."

The ALE waveform provides a robust low-data-rate signal based upon eight-tone frequency-shift keying (FSK) modulation. The tones are evenly spaced at 250-Hz intervals between 750–2500 Hz, allowing them to fit into the passband of standard SSB transmitters and receivers. The symbol rate is 125 Bd and each tone represents three bits of data, resulting in a data rate of 375 b/s.

Stations are assigned addresses and can be called either individually or as part of a net or group. Prior to initiating a call, a station listens to the intended transmit channel in order not to interfere with calls or traffic from other stations. A given station can be in one of three states, i.e., available, linking, or linked. An available station is free to send or receive an ALE call frame, which transitions the station to the linking state. Upon receiving an ALE call, a station discontinues scanning and enters the linking state. If the link establishment succeeds, the station transitions to the linked state. Establishing a successful link between two individual stations consists of three ALE frames, i.e., a call, a response, and an acknowledgment.

Each time a call or sound is received, signal parameters are measured to determine the quality of the transmission. When a call is to be placed, the LQA database is searched for the best possible channel. As a minimum, the LQA information must include the signal-plus-noise-plus-distortion to noise-plus-distortion ratio (SINAD) values for both received and transmitted signal (as reported by the other station); bilateral bit-error rate (BER) and multipath (MP) information. The channels having the highest probability of successful connection (best LQA score) are attempted first.

ALE receivers listen to signals only on sets of preprogrammed frequencies called scan lists. Under normal operation, the receiver controller stops scanning if it detects ALE tones on the current receive frequency. Scanning occurs at either two or five channels per second. The length of time of a transmitter call is the dominant factor in determining the length of time to establish the link, and the maximum time between initiating the call and link establishment is 14 s. Stations are required to initiate sounding periodically to allow continual updating of the LQA memory as link conditions fluctuate.

D. Modulation

Early HF communication used CW (Morse) and some full-carrier AM signals. In the late 1950s, SSB became dominant for voice communication and FSK was used for radioteletype. While SSB continues to be used, much of the traffic is now in the form of digital voice and packetized data. Modern digital techniques are based upon PSK and offer data rates up to 14.4 kb/s [1]. Speech is encoded by the LPC-10 technique. LPC-10 is based upon linear-predictive coding with ten poles (five resonances) [6]. Basically, in each 22.5-ms time frame, the vocoder fits the five resonances to the speech waveform. The resonance information requires a data rate of 1200–2400 b/s. The receiver synthesizes the speech waveform from the resonance data.

A signal transmitted via the ionosphere is subject to fading, dispersion, Doppler shift, and MP distortion, all of which are constantly changing. The noise is generally impulsive and often occurs in bursts. Coding must extend over 1.4 ms or more to correct over 99.9% of the burst errors [1]. Standard channel models are defined for good, moderate, and poor conditions.

The ionosphere often provides multiple propagation paths with arrival times differing by up to 10%. This produces a delay spread of up to 3 ms on a 1000-km path. The first 3 ms of a received data bit is thus subject to changes as signals from different paths begin to arrive. Transmission at higher rates causes the signals from multiple data bits to overlay each other. Early digital systems avoided MP interference by transmitting at relatively low rates (75 b/s, 133-ms data-bit duration) and discarding the information from the first 4.2 ms ("guard time") of a received data bit. Modems based upon 8 FSK at 125 Bd provide data transmission at 375 b/s.

Multitone modems [7] similarly avoid MP interference, but boost the data rate by employing multiple carriers (tones). Adaptive equalization is not required, nor is a long interleaving interval. Another advantage is that signal processing can be easily divided among the tones. Due to the relatively low latency, the multitone modem is the preferred technique for HF digital voice. The standard 16-tone modem uses 75-b/s PSK to achieve a total raw bit rate of 1200 b/s. Newer 39-tone modems use a baud rate of 44.44 with 3.5-ms guard time to produce a raw data rate of 3466.66 b/s. The inclusion of a (14,10) Reed–Solomon block code to correct errors yields a data throughput of 2400 b/s. These modems employ OFDM, in which the frequency separation is set to the inverse of the symbol rate to prevent modulation on one tone from interfering with reception of another.

Fig. 2. AN/VRC-100 ground/vehicular HF transceiver (courtesy of Rockwell Collins).

Modern single-tone modems employ 8 PSK at 2400 Bd to produce a 4800 b/s raw-data rate. Filtering to minimize out-of-band spectral components results in a signal with both amplitude and phase modulation and a peak-to-average ratio of approximately 3 dB. Inclusion of a rate-1/2 convolutional error-correcting code gives the throughput of 2400 b/s. Since the duration of the data bit is less than the typical delay spread, MP must be counteracted by constant adaptive equalization of the channel. The single-tone modem tends to provide the lowest BER in many situations. However, because of the high latency (up to 9.6 s) associated with the maximum interleaving, they are better suited to packet data rather than digital-voice transmission.

The capabilities of HF modems continue to improve, and data rates as high as 64 kb/s have been achieved. Since the bandwidth of an HF channel is inherently limited to about 2.7 kHz, multiple data bits must be carried by each symbol. Trellis-coded modulation is used to maximize the distance between symbols. A 52-tone modem with 16 PSK [1] allows data to be transmitted at 7200 b/s on one sideband (one voice channel) or 14 400 b/s on both sidebands (two voice channels).

E. Typical Equipment

The AN/VRC-100 transceiver (Fig. 2) illustrates the state-of-the-art in ground/vehicular HF-communications transceivers. It operates from 2 to 30 MHz, produces power outputs to 175-W PEP, and supports a wide variety of modulation types including USB/LSB, AME, CW, and various ECCM waveforms. The AN/VRC-100 provides ALE in accordance with MIL-STD-188-141A, as well as the alternative quick call (AQC) ALE, which has the potential to reduce the call time by as much as 50%. The system consists of three line replaceable units (LRUs), i.e., receiver/transmitter, the power amplifier/coupler, and the control/display unit. Tuning time into a new load is nominally 1 s, but is reduced to 35 ms for previously tuned frequencies.

III. Meteor-Burst Communication (MBC)

Occasional bursts of energy in the VHF band were associated with the occurrence of meteor trails as early as 1929. MBC

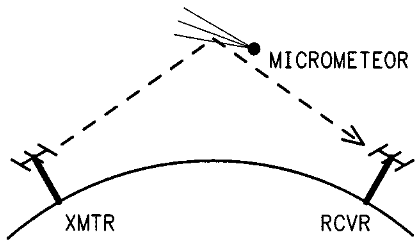

Fig. 3. Meteor-burst communication.

was investigated in the 1940s and 1950s, and the first MBC systems were developed in the 1960s and 1970s. The emergence of microprocessors has made implementation of the various control and data-handling functions relatively easy. Today, MBC (Fig. 3) provides statistically reliable communications to distances up to 2000 km [8]. MBC systems generally operate at lower VHF, transmit bursts of relatively high power, and provide low-to-moderate data rates. MBC systems operate independently of external infrastructure and can provide reliable communication to remote regions. A number of military applications are based upon the more rapid recovery of MBC than HF ionospheric communication following a high-altitude nuclear detonation. Civilian applications include tracking vehicle fleets and monitoring of the environment at remote locations [9]. Such networks typically have a large number of mobile stations that report infrequently. Coverage of the continental U.S. is accomplished with only a few base-stations.

Ionized trails are produced as meteors enter the E region of the atmosphere at altitudes of 80–120 km [3]. The length of the trails is typically on the order of 15 km, but can be as large as 50 km. While an individual trail lasts typically only a fraction of a second, the aggregate of all trails provides several minutes of communication per day. The minimum number of meteors occurs in February at 1800 local time, while the maximum number occurs at 0600 in July. The diurnal variation is somewhat sinusoidal and the random fluctuations are roughly equivalent to a variation of 10 dB in power. Meteor trails are generally classified as either underdense or overdense. Underdense trails have a typical scattering area at 32 MHz of 2.5 Mm^2 and a median persistence of approximately 0.85 s and provide the majority of the usable channel capacity.

MBC generally uses lower VHF (30–50 MHz), but has been accomplished on frequencies as high as 432 MHz. The lower frequency limit is determined by the need to penetrate the D layer of the ionosphere, while the upper frequency limit is determined by the sensitivity of the receiver and capture area of the antenna system. Galactic noise is generally dominant from approximately 20 to 150 MHz. Transmitter powers vary from 100 to 5 kW. MP delay is typically on the order of 1 μs, but can be as large as 10 μs [3]. Doppler shifts of 5 Hz are typical, but shifts as high as 18 Hz are sometimes caused by high-altitude winds.

Typically, the receiving station transmits a probe signal continuously. Upon receipt of the probe signal, the transmitting station begins sending data packets and continues until loss of the probe signal. Alternately, the transmitter can send the probe signal and wait for an acknowledgment from the receiver before beginning data transmission. The footprint of the meteor-scattered signal is an ellipse approximately 8 km $\times$ 40 km; hence, a large number of users can share the same channel without interference.

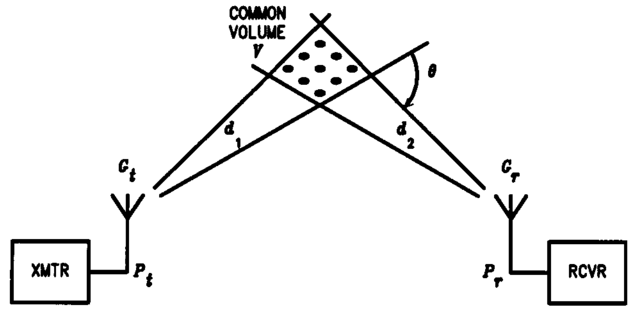

Fig. 4. Troposcatter communication.

As in a radar system, the received field strength varies with the inverse-fourth power of distance. For a typical 1000-km link with antenna gains of 10 dB on each end, approximately 1 kW of transmitter power is needed for a data rate of 1 kb/s during the duration of the meteor. MBC systems typically operate with a duty ratio of 2.5%–5%, allowing communication at an average rate of 50–100 b/s. The average delay in waiting for a suitable trail varies from 10 to 80 s. Conventional MBC equipment transmits data at a fixed rate. More modern systems [1] achieve higher data rates (factors of 2–5) by dynamically varying the data rate to track the signal strength offered by the meteor trail. For example, the instantaneous data rate might begin at 128 kb/s and drop in binary steps to 2 kb/s as the trail decays. The High ERP Meteor Burst Link Experiment (HEMBLE) system employed eight Yagi antennas with 13-dB gain and 4.8-kW PAs to achieve a throughput of 10 kb/s.

IV. Troposcatter Communication

Scattering by irregularities in the troposphere (Fig. 4) allows reliable communication at distances of up to 1000 km [11]. Frequencies from 300 MHz to 3 GHz are generally used, and troposcatter systems can provide relatively high data rates (2400 b/s–10 Mb/s). The power levels vary from moderate (100 W) to high (50 kW) as do the antenna requirements (apertures from 2 to 40 m). Troposcatter systems are essentially "self-contained" and require neither external infrastructure, nor cooperation of the ionosphere.

The two principal mechanisms for over-the-horizon (OTH) propagation at VHF and UHF [FR2] are diffraction and troposcatter. Diffraction is dominant from the end of the LOS range (20–30 km) to a maximum of about 100 km. Troposcatter dominates at larger distances and provides weak, but reliable signals. Scattering in the troposphere is produced by both turbulent motion and laminar motion. The sizes of the irregularities vary from a few meters to tens of kilometers. In either case, the irregularities produce multiple changes in the dielectric constant, resulting in multiple weak random reflections.

Both transmitting and receiving antennas view a "common volume" of the troposphere, and the scattered signal is strongest in the forward direction. In contrast to an LOS link, the link SNR improves with the square root of the antenna gain (i.e., half of the gain in decibels) because increasing gain reduces the beamwidth and with it the common volume that scatters the signal. The effective scattering volume varies with climate and season, but is essentially independent of frequency when the wavelength is small in comparison to the size of the turbulence cells.

Analog troposcatter systems typically transmit multiple voice signals as SSB subcarriers on an FM carrier (FDM/FM). Data rates of up to 2–3 Mb/s can be achieved by a conventional receiver, but greater data rates require adaptive signal processing to mitigate the effects of MP propagation. The "standard" AN/TRC-170 troposcatter system has a range of up to 300 km with a small antenna. A K-band (20 GHz) system employs a 2-m antenna and covers a distance of 240 km with 100 W per 32-kb/s channel.

Communication via spatially distributed scatterers inherently results in MP distortion and fading. At any given time and location, the MP signals can reinforce or cancel each other. Since the turbulence cells change continuously, the amplitude, phase, and frequency response also change continuously. The decorrelation time of a troposcatter channel varies from 50 ms to 10 s, with an average of approximately 1 s. The effects of fading can be mitigated by diversity reception, which is typically based upon two or more antennas separated by several tens of meters. The receiver can either select the antenna with the maximum signal or blend all received signals to maximize SNR.

A typical troposcatter signal has MP delays of up to 1 μs, which result in scrambling of information in sidebands separated by 1 MHz or more. Adaptive equalization is commonly accomplished by a tapped-delay-line (TDL) filter in which the output signal is formed from a weighted linear combination of the signals from each tap in a delay line. The RAKE filter [12], so-called because it rakes together all of the scattered signal components, adds automatic adaptation to the TDL filter.

V. VHF/UHF Mobile Communication

Decades before the cellular technologies began to provide wireless access to the masses, two-way radio met the need for mobile communications. As early as 1946, AT&T obtained approval from FCC to operate the first commercial car-borne mobile-telephone service in St. Louis, MO. It had one base-station on high ground and was equipped with six channels. Within a year, the service had expanded to 25 other cities. The applications for modern mobile radio include land, marine, and airborne use by both civilian and military organizations. There are also telemetry and one-way paging services. Each service is assigned a specific set of frequencies in the VHF and UHF bands (primarily near 160 and 460 MHz).

Conventional land-mobile radio (LMR) and private mobile radio (PMR) systems generally dedicate a single channel to a specific group of users (e.g., a local police department). Typically, a small number of base-stations with well-placed antenna systems communicate with a large number of mobile stations. Narrow-band FM (NBFM) with 25-kHz channel spacing is generally used, and most systems offer half-duplex or simplex communication. Selective signaling is accomplished by subaudible squelch tones or digital codes. Transmitter powers are typically on the order of 1–5 W for handheld, 25 W for mobile, and 100 W for base. Access times of a few tenths of a second make LMR systems very attractive for emergency services.

In a trunked radio system [also called specialized mobile radio (SMR)], a commercial radio operator provides land-mobile service to a number of different user groups. This allows more efficient use of the spectrum (since channels are shared), wider coverage, and a greater variety of services including interconnection to the Public Switched Telephone Network (PSTN). A single SMR base-station typically covers a 25-mi radius. Multiple sites are interconnected through the use of repeaters to extend coverage. Many systems also allow mobile-to-mobile "talk around" to improve local coverage. A wide variety of standards and protocols are in use. The original analog standards have been supplanted by digital standards within the last two decades.

Analog systems use FM or AM and include a control channel for digital information. Despite the proprietary nature of analog systems, some have become standard in the marketplace. Examples include Clearchannel Logic Trunked Radio by E. F. Johnson, SmartTrunk, and PassPort by Trident Micro Systems.

A number of digital systems are now being deployed. Integrated Digital Enhanced Network, iEDN is a TDMA system developed by Motorola in which up to six users share a single 25-kHz channel. A bandwidth utilization of 5.6 b/Hz is achieved by 16-QAM. The mobile burst power can be as much as 0.6 W. The Ericsson Enhanced Digital Access Communication System (EDACS) operates at 150, 450, 800, and 900 MHz and allows users to share 12.5-kHz channels through FDMA. Terrestrial trunked radio (TETRA) is a digital LMR system commonly developed in the U.K. in the bands between 150–900 MHz. Channels of 25-kHz bandwidth are shared through TDMA, and $\pi/4$ DQPSK modulation provides up to 7.2 kb/s per channel. Base-station power levels range from 0.6 to 40 W, while the mobile peak power ranges from 1 to 30 W.

Marine communication in the coastal and inland waterways use NBFM in the 150-MHz band much as land mobile. The range is typically 25–50 km. Civilian aeronautical communication uses AM in the 108–137-MHz band. The range can be up to 300 mi, depending upon altitude. Military airborne communication uses 225 to 400 MHz.

VI. Broadcasting (BC)

Broadcasting (BC) is the one-way transmission of audio, data, and/or video via radio frequencies to a multitude of users. The roots of BC lie in the first transmission of audio to ships in the Boston, MA, harbor by Fessenden on Christmas Eve, 1906, and the first commercial broadcast by station WKDR in Pittsburgh, PA, in 1920. Modern broadcasts carry a variety of news, entertainment, and educational programs. The three basic parts of a broadcast station are the studio, studio-to-transmitter link (STL), and the transmitter. Programs are created in the studio, then relayed to the transmitter by cable or microwave link. The transmitter includes the power amplifier and antenna system, and is usually located on a site (such as a mountain top) that affords good coverage. Transmissions can also be made over cable or from satellites.

A. AM BC

AM radio transmissions are used worldwide at medium frequencies (530–1700 kHz). The modulation bandwidth is typically 5 kHz. Transmitter powers typically range from 1 to 50 kW. MF AM broadcast provides local coverage (100 km) via ground-wave during the day. Selected "clear-channel" stations provide regional and even continental coverage at night via sky wave propagation. In the USA, an L–R signal from which stereo sound can be reconstructed is multiplexed by phase modulation. Multiple solid-state class-D RF PAs (5-kW modules) are generally used in combination with pulse-step amplitude modulators based upon insulated-gate bipolar transistors (IGBTs) to achieve transmitter efficiencies of 70% or more.

B. Longwave BC

In the U.K. and Africa, a low-frequency band (153–281 kHz) is also used for AM BC, primarily by governments. Transmitter powers in the range of 250 kW to 2 MW provide regional coverage.

C. Shortwave BC

The HF bands (3–26 MHz) provide international coverage and are used mainly by national entities such as the Voice of America, Radio Moscow, Deutsche Welle, etc. The signals are amplitude modulated with audio bandwidths of 5 kHz. Transmitters use both solid-state (5-kW modules) or vacuum-tube RF PAs, with power levels ranging from 10 kW to 2 MW. Directional antennas beam the programming to the target audience.

D. FM BC

FM was developed by Armstrong in the 1930s and initially transmitted on 41–44 MHz just prior to World War II. FM BC is now used worldwide in the 88–108-MHz band and offers greatly reduced noise and interference, as well as high fidelity (both lower distortion and larger audio bandwidth). The modulating signal is a composite of the primary audio and subcarriers. The primary audio [(left + right (L+R)] has a 15-kHz bandwidth and modulates the RF carrier with a 75-kHz deviation. Stereo transmission is accomplished by adding a 19-kHz pilot subcarrier and 38-kHz subcarrier with DSB/SC modulation by the L–R signal. Additional subcarriers are used for background music and the radio data system (RDS). The resultant bandwidth and channel spacing are 200 kHz.

The output power for commercial stations typically varies from 1 to 50 kW. Solid-state PAs (e.g., Fig. 5) are used to the 5-kW level and vacuum-tube PAs are used for higher powers. The antenna typically boosts the effective radiated power (ERP) by compressing the vertical radiation pattern. The antenna heights vary from 50 to 500 m, allowing coverage slightly beyond the LOS to distances up to 100 km. Recently, there is considerable interest in low-power FM stations that can be used for local coverage by educational, civic, and religious organizations.

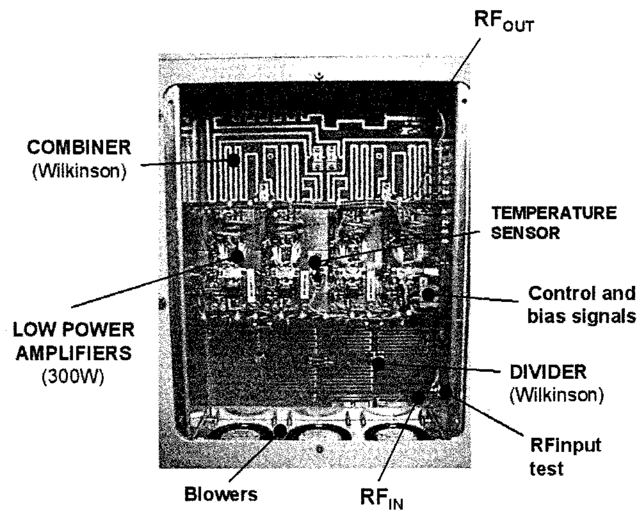

Fig. 5. Solid-state 1-kW FM BC transmitter (courtesy of OMB Sistemas Electronicos).

E. Television (TV)

The origins of TV lie in the development of the cathode-ray tube by Braun in 1897 and the work in the 1930s by Zworkin at RCA. Television became a commercial entity after World War II. Television BC uses both VHF and UHF bands (54–72, 76–88, 174–216, and 470–860 MHz). Television transmitters produce outputs from 100 W to 50 kW. VHF and lower power UHF transmitters are mostly based upon solid-state PAs, while high-power UHF transmitters employ vacuum tubes. The coverage area is similar to that of FM broadcast; i.e., to about 100 km.

North American analog television [13] is based upon the NTSC standard. The image is divided into 525 lines, which are scanned in an interlaced fashion at 30 Hz, resulting in a 15 750-Hz scanning frequency. The brightness signal (4.2-MHz bandwidth) is transmitted by vestigal-sideband modulation (VSB), which is DSB/SC with some of the upper sideband and most of the lower sideband removed, resulting in a 5.25-MHz bandwidth and a flat frequency response. The sound carrier is located 4.5 MHz above the brightness carrier and frequency modulated with a 25-kHz deviation. Color information is transmitted on a subcarrier located 3.58 MHz above the brightness carrier so that color-sideband components fall in between those from the brightness signal. The I and Q signals of the color information correspond roughly to the differences between brightness and the red–orange and blue–green components of the image. The phase alternation line (PAL) used in the U.K. and the sequential couleur avec memoire (SECAM) techniques used in France and Russia use alternate lines to transmit different color information.

F. Community-Antenna Television (CATV)

CATV originated in 1950 as a means of providing local distribution in areas where over-the-air reception was poor. Signals from a common well-placed antenna are amplified and distributed via coaxial cable. Cable television is now present in most cities and carries not only signals from local over-the-air broadcasts, but signals from distant stations and its own programming as well. CATV offers perhaps 100 channels in the frequency range from 50 to 750 MHz. Local-distribution amplifiers typically produce 1–10 W and must be very linear to avoid producing cross-modulation products among the multitude of signals carried on the cable.

G. Digital-Audio Broadcast (DAB)

In the U.K., DAB transmissions use the existing AM and FM broadcast bands, as well as a new band from 1452 to 1492 MHz, which is divided into 23 1.536-MHz channels. Sound is encoded with CD quality by the MUSICAM technique. The resulting 384-kb/s data stream is transmitted by orthogonal frequency division multiplex (OFDM) using various combinations of carriers and baud rates (e.g., 1536 carriers with 1-kHz spacing for VHF, 384 carriers with 4-kHz spacing for L-band) [14]. In the U.S., DAB will use the standard AM and FM bands with OFDM carriers at the band edges ("in-band on-channel)." Two satellite systems transmitting at S-band will also provide nationwide DAB coverage.

H. Digital Television

Digital television transmission can provide either higher resolution or multiple programs from the same station. Digital transmission eliminates most interference, resulting in a picture that is in essence perfectly received as long as the SNR is sufficient. To reduce the effects of MP, data are transmitted at relatively slow rates on multiple carriers through OFDM. The transmitter power is about the same or slightly lower than that for analog television.

In the U.S., high-definition television is based upon MPEG-2 video coding and Dolby AC-3 audio coding as specified by the Advanced Television Systems Committee (ATSC)[15]. The image is composed of 1080 lines with 1920 pixels per line, resulting in a data rate of 19.39 Mb/s, which expands to 30.28 Mb/s with the addition of error-correction coding and other overhead. The "8-VSB" transmitted signal is based upon eight-level DSB/SC modulation followed by filtering to remove most of the lower sideband, allowing it to fit into existing 6-MHz television channels. In the U.K., digital video broadcasting (DVB) is based upon MPEG encoding and OFDM using 16 or 64 QAM. The data at rates up to 31.7 Mb/s are distributed among 1704 carriers with 1.1-kHz spacings or 6816 carriers with 4.5-kHz spacings.

VII. OTH Radar

HF sky-wave or surface-wave radar tracks targets beyond the horizon, allowing surveillance in areas unreachable by microwave radar. HF radar was originally used for detection of missile launches, long-range bombers, and cruise missiles [16]. More recently, it has been adapted to monitoring of drug traffickers and ocean conditions and currents [17]. FM–CW techniques with chirp frequencies of 5–100 kHz and repetition rates of 10–60 Hz are generally used. Measured information includes range, direction, amplitude, and Doppler shift. Range is derived from the difference between the frequencies of the transmitted and received signals. Doppler shifts (e.g., 20–40 Hz for an aircraft, 0.5 Hz for ocean waves) distinguish moving targets from background clutter. Surveillance from two different locations allows derivation of the speed and direction of the target.

OTH sky-wave radars typically operate from 5 to 35 MHz and provide surveillance at distances of 500–3500 km. The antennas are large phased arrays of monopoles that can extend over 2–3 km. Each of the 10–30 transmitting elements is driven with 5 to 20-kW to produce a total transmitter power of 0.5–1 MW and a beam that can be steered $\pm 30^\circ$ in azimuth. The receiver is located 100–160 km from the transmitter and employs a phased array of 80–250 elements, resulting in beamwidths of 1°–2.5° and a target resolution from 1 to 10 km. The U.S. Air Force OTH-B system, currently in an inactive, but ready state, provides surveillance of both coasts from sites in Maine and the California–Oregon border. The U.S. Navy Relocatable Over-the-Horizon Radar (ROTHR) covers the Gulf of Mexico and Caribbean from sites in Texas and Virginia. The Australian Jindalee system is being expanded to a three-site Jindalee Over-the-Horizon Radar Network (JORN).

Surface-wave radar systems operating from 10 to 50 MHz are used for surveillance of coastal areas to distances of 300 km [18]. These systems are much smaller than their sky-wave counterparts. Typically, the transmitter employs one or more monopole elements and power levels of 50 W–1 kW. The receiver may employ a single direction-finding array consisting of two loops and a whip.

VIII. Magnetic-Resonance Imaging (MRI)

MRI uses the phenomenon of nuclear magnetic resonance (NMR) (resonance of atomic nuclei) to obtain images of the interior of an object such as the human body. The theoretical relationships between magnetic fields and atomic nuclei were developed by Stern, Rabi, Bloch, and Purcell in the 1940s and 1950s. The first human MRI scans were produced by Damadian in 1976 [19], and the first human MRI scanner (named "Indominatable") now resides in the Smithsonian. The largest commercial application of MRI is medical imaging. However, there is an assortment of emerging MR applications including magnetic resonance-spectroscopy, magnetic-resonance angiography, and functional MRI. MRI systems include a great deal of RF technology, as shown in Fig. 6.

A. Basic Principles

An atomic nucleus is a small spinning charged particle and, therefore, behaves somewhat like a small magnet. The application of a strong magnetic field causes the protons to align with the field and to precess about it, much like a child's top. The precession ("Larmor") frequency varies in direct proportion to the strength of the magnetic field. For hydrogen, which comprises 80% of the atoms in a human body, a field strength of 1 T produces precession at 42.6 MHz. The capabilities of an MRI scanner are commonly designated by the strength of the magnetic field it employs.

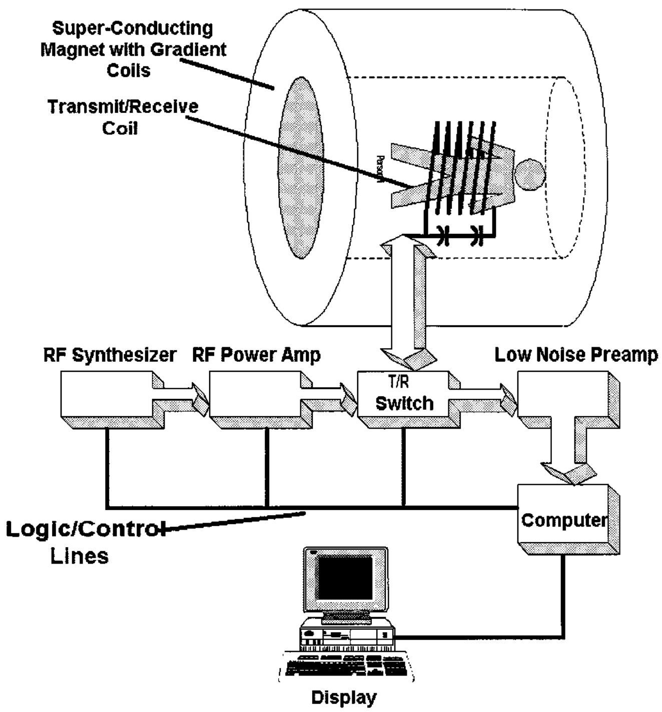

Fig. 6. Simplified block diagram of MRI scanner.

A magnetic-field of 0.1 to 9 T (versus 50 μT of the Earth) is produced by permanent or superconducting magnets in combination with gradient coils that cause it to vary slightly over the region of interest. The alignment and precession produce by the dc field are called the "equilibrium state." A multikilowatt RF pulse then causes the protons to "flip" to an orientation opposite to that of the equilibrium state.

The RF signal is then blanked (turned off) and the RF coil connected to the receiver by the T/R switch. As the spinning protons return to the equilibrium state, they emit a minute "NMR" signal, which is received by the RF coil and low-noise amplifier in the receiver. This signal is then down converted and digitized, after which it is processed to form a two-dimensional cross-sectional image of the anatomy placed in the center of the coil. Since the frequency of the NMR signal is directly proportional to magnetic-field strength, the frequency of the received signal gives information about the location from which it originates.

B. MRI Subsystems

The RF signal is synthesized with precise frequency stability and extremely low phase noise. The amplitude must be controllable (typically from 0 to 10 dBm) in small increments.

Current clinical MRI scanners use approximately 4 kW (pulse peak) for head imaging and as much as over 30 kW for whole-body imaging. Since transmissions are short bursts (e.g., 20 ms) with low duty ratios (e.g., no more than 10%), the average power is much lower. Linearity is crucial, as both amplitude and phase must be maintained over the pulse duration, dynamic range, and operating session (several minutes to a few hours). Efficiency is also of great importance. Elimination of noise during reception of the NMR signal requires the capability for rapid blanking. Solid-state PAs are now being used widely in lower power MRI systems, but vacuum-tube PAs remain in use in high-power (15 kW and larger) systems because of their relatively low cost.

When a common set of coils is used for transmitting and receiving, a T/R switch is required. Since the changeover must be accomplished in under 10 μs, switches are generally based upon p-i-n diodes (Section XI). The use of magnetic materials must be avoided as these cause distortion of the magnetic field, hence, the MR image.

The transmitter and receiver coils (often referred to as RF "probes") are one of the most complicated subsystems in an MRI scanner. The transmitter coil and matching network must meet a collection of requirements including a low voltage standing-wave ratio (VSWR), production of a uniform RF magnetic field, handling high-power levels without excessive heating, and construction from nonmagnetic materials. However, special anatomy-specific "surface coils" are used expressly for receiving NMR signals and provide better reception from specific locations.

The low-noise preamplifier provides initial amplification of the received NMR signal and sets the noise floor for reception. In addition to a low noise figure, it must be able to withstand and to recover rapidly from severe overdrive from the transmitted signal, especially when used with a receive-only surface coil.

C. Trends

Higher field strength produces both better SNR and better resolution, hence, better image quality. In the past few years, the scanners with field strengths up to 3 T have been approved for clinical use. Higher-power systems (7–9 T) currently operating at several university sites offer the capability to image sub-anatomical structures with features smaller than 100 μm. Other areas in which advances are being made include the receiver coil, low-noise amplifier, and signal-processing technologies [20].

IX. RF HEATING

The concept of heating materials using RF energy was initially explored at Raytheon in the 1940s. Since RF can heat objects more quickly and precisely than other techniques, it has found numerous applications. For example, fabric manufacturers use RF energy for rapid removal of excess water from material during the final stages of preparation, allowing the fabric to be spooled through the RF dryer as the water is boiled off. Similarly, RF can be used to cure epoxy compounds, wood, and metal in seconds. In clinical thermo therapy, RF heats and kills anomalous tissue growth, including both benign and malignant tumors. The semiconductor industry makes extensive use of RF to generate plasmas during the semiconductor wafer-fabrication process.

Applications generally use unlicensed industrial, scientific, and medical (ISM) frequencies such as 13.56, 27.12, 900–930, and 2450 MHz. Since the depth of penetration of an RF signal into a conducting material is inversely proportional to the square root of frequency, the frequency must be chosen accordingly. The power levels range from 100 W to 50 kW.

An RF-heating system consists of a power source (PA), matching network, and antenna. It is essential that such systems

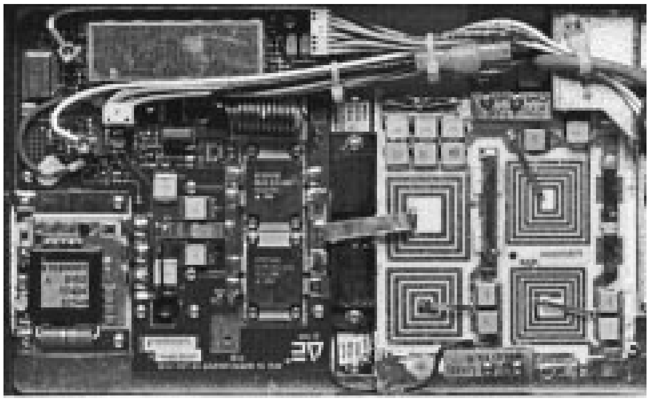

Fig. 7. 3-kW high-efficiency PA for 13.56-MHz ISM (courtesy of and copyright Advanced Energy Industries Inc., 2001).

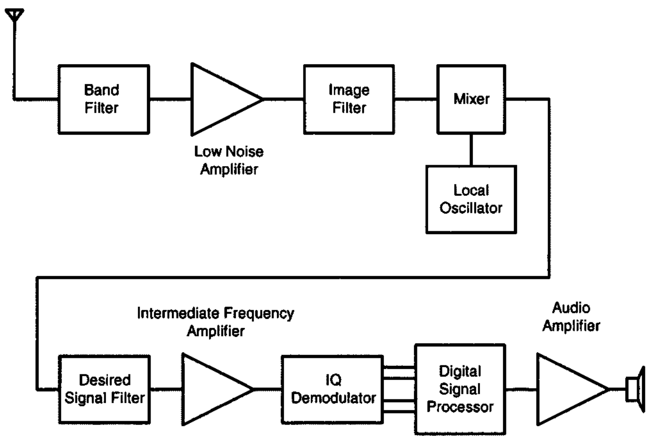

Fig. 8. Superheterodyne receiver.

be reliable and low in cost. At present, solid-state PAs operating in class D or E are used for lower power applications and vacuum-tube PAs operating in class C are used for higher power applications (tens of kilowatts). Design of the matching network is often tricky, as the load impedance may change during operation (for example, as the plasma ignites). The antenna must also be designed to deliver the RF energy to the desired part of the object to be heated. The state-of-the-art ISM PA shown in Fig. 7 uses class-E operation to achieve an efficiency of 90% and printed inductors to conserve space.

X. Receivers

A radio receiver processes the set of electrical signals on the antenna terminals by selecting the desired signal, amplifying it, and recovering the information [12]. The amplitude of the signal of interest may be only 0.01 μV at the antenna terminals, while the amplitudes of the interfering signals may be as large as 100 mV. Selecting the desired signal in the presence of strong interfering signals that are stronger by 120 dB and amplifying it by 100 dB to achieve a comfortable audio output without adding excess noise is the classic receiver design challenge.

For over 70 years, the superheterodyne has been the benchmark receiver architecture (Fig. 8). The upper blocks amplify the input band and shift its frequency using a mixer and a tunable local oscillator (LO). The lower blocks select the desired signal with a narrow channel filter, then amplify further and demodulate. A typical superheterodyne receiver may have 20 dB of gain at the input frequency and 80 dB of gain after the channel-selection filter. Shifting the input frequency to a fixed intermediate frequency (IF) for filtering and amplification has a number of benefits. The IF can be chosen to make optimum use of available filter technology. Most of the receiver gain occurs in a narrow fixed IF band containing only the desired signal, and widely separated from both the input tuning range and LO frequencies. The use of a moderate frequency for the IF band avoids problems with $1/f$ noise and high gain dc-coupled stages. Signal processing and demodulation are simplified if the IF is significantly higher than the desired signal bandwidth. The traditional approach is to use an IF approximately one-tenth of the RF frequency, and to limit the RF bandwidth to less than one-half of the IF. Broad-band HF receivers use a higher IF frequency so that the LO and spurious mixer products are well outside of the receive band [13].

The most important alternate receiver architecture is direct conversion [21]. Popular with radio amateurs since the 1960s for lightweight low-cost battery-operated portable transceivers, it has recently been rediscovered by cellular-handset designers as "near-zero-IF." Elimination of the IF filter reduces cost. Signal selection occurs at baseband, and most of the gain follows the baseband selectivity. In near-zero-IF receivers, the IF typically uses ac-coupled amplifiers. Signal selection is performed by a combination of analog, switched capacitor, and DSP filters [6]. In present-generation direct-conversion cellular handsets, the DSP sampling rate is a few megahertz or less and, in amateur receivers, the sampling rate is typically 44 kHz or less. The 96-kHz sampling rate and 24-b digitization used in audio recording is sufficient for dynamic range and interference suppression comparable to the best conventional receivers.

A next-generation receiver ("smart antenna") combines receiver and signal-processing functions with inputs from multiple antenna elements. When the received signal is strong and there is little interference, the system shuts down most of its circuitry and uses a single antenna input. If interference is present, the inputs from the various antenna elements are combined to maximize the SNR.

XI. Components

The unique components used in HF/VHF/UHF hardware include RF-power MOSFETs, p-i-n diodes with large recombination times, and ferrite-loaded transmission-line transformers.

A. RF-Power MOSFETs

At HF/VHF/UHF, silicon provides as much usable gain as does GaAs. The much larger breakdown voltage and much lower thermal resistance of silicon allow silicon transistors to produce considerably greater power than do their GaAs counterparts. The first RF-power transistors were bipolar, and BJTs continue to find use in pulsed applications. RF-power MOSFETs became available in the 1970s and today are dominant because of linearity, ease of bias, and freedom from thermal runaway [22]. The two varieties of RF-power MOSFET (Fig. 9) are differentiated by vertical or lateral current flow of

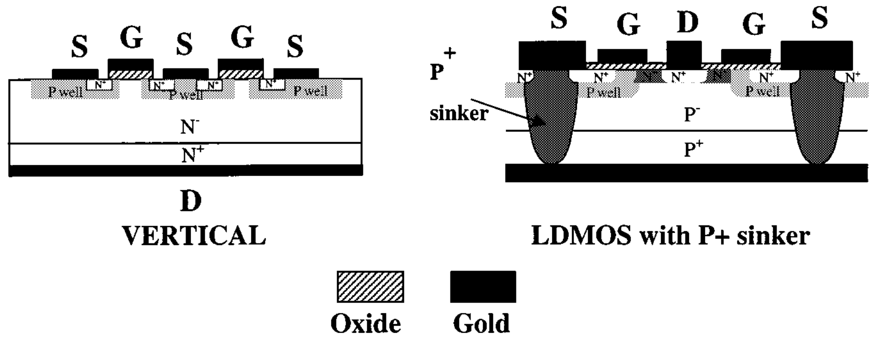

Fig. 9. Cross sections of RF-power MOSFETs.

drain current. Vertical MOSFETs (VMOS) cannot be directly attached to a metal flange since the underneath side of the die is the drain terminal. Accordingly, VMOS devices must be attached to an electrically isolating ceramic material with high thermal conductivity such as BeO or AlN. An example of the current state-of-the-art is the Semelab D1029UK, which is capable of a 350-W CW output at 175 MHz with 16-dB gain and 80% efficiency.

Practical laterally diffused MOS (LDMOS) devices employ a p+ sinker technology [23] to connect the source to the mounting flange so that the toxic BeO insulator is not needed. The traditional ceramic package can then be replaced with a low-cost plastic package. In addition, it eliminates the inductance associated with the bond wires to the source, resulting in higher gain at high frequencies. Lateral FETs are also essential for the development of RF PAs in IC form. A disadvantage of LDMOS is the drift of drain current over time. An example of the state-of-the-art is the Motorola MRF21125, which produces 125-W CW at 2 GHz with 11.5-dB gain and 46% efficiency.

MOSFETs recently developed for power-switching applications have switching speeds of approximately 10 ns and can, therefore, be used in RF applications up to 100 MHz. These devices achieve high breakdown voltages (300–900 V) by using high-resistivity silicon, which reduces the output capacitance, but increases the on-state resistance. The on-state resistance is lowered by increasing the size of the die, which also decreases thermal resistance and facilitates the use of low-cost plastic packages. However, input and feedback capacitances are also significantly increased. These MOSFETs are generally used in tuned power amplifiers for ISM applications where linearity is not a requirement.

B. p-i-n Diodes

Switching, signal routing, and level control are commonly required functions in RF circuits and systems. In the HF/VHF/UHF range, p-i-n diodes and GaAs MESFETs are widely used semiconductor devices for these functions. The p-i-n diode (Fig. 10) is well suited to high-power applications. The applied forward dc-bias current creates charges in the I region, allowing the p-i-n diode to carry RF current significantly larger than the applied dc-bias current. The on-state RF resistance of the p-i-n diode [24] is inversely proportional to the dc current, which allows its use in attenuators, as well as switches [25] Application of a reverse-bias voltage beyond the punch-through voltage causes charge carriers to be removed from the I region, yielding a high-impedance off state in which the capacitance is essentially constant. Insertion loss depends primarily upon the on-state resistance, while isolation depends upon the off-state capacitance.

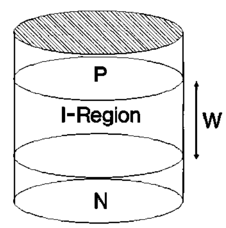

Fig. 10. Simplified construction of a p-i-n diode.

Implementation of the bias-feed network and the driver are the most challenging design problems in using a p-i-n diode. The driver must supply a significant negative voltage to produce the off state, and (for high-power systems operating at HF) significant forward current to produce the on state. The RF chokes must also be capable of operation with significant dc current.

Maximizing the ratio of charge to resistance (Q/R) at a given frequency minimizes the distortion introduced into the system by a p-i-n diode [25]. Since variable attenuators use p-i-n diodes with smaller Q/R ratios, the distortions in these circuits is greater than that of switches. As an example of Si p-i-n-diode technology, a diode with a 175-μm I-region thickness and a 1.5-μs carrier lifetime exhibits an on-state resistance of 3.0 Ω with 10-mA forward bias and an off-state capacitance of 0.3 pF.

C. Ferrite-Loaded Transmission-Line Transformers

HF/VHF/UHF systems must often operate over 1–3 decades of bandwidth. Quarter-wavelength lines are impractically large and do not have sufficient bandwidth when used for matching. Classic wire-wound transformers are of limited use because circulation of flux in the core causes significant loss. In addition, leakage inductance and interwinding capacitance reduce bandwidth and create resonances. Wide-band impedance transformation for these applications is provided by ferrite-loaded transmission-line transformers [13], [26].

The basic 4 : 1 Guanella (equal-delay) transformer (Fig. 11) uses two transmission lines that are connected in series at one end and in parallel at the other. At HF and lower VHF, one line runs through a ferrite block or beads or is wound on a powdered-iron toroid to create a large common-mode (end-to-end) impedance, which allows an arbitrary voltage from one end to

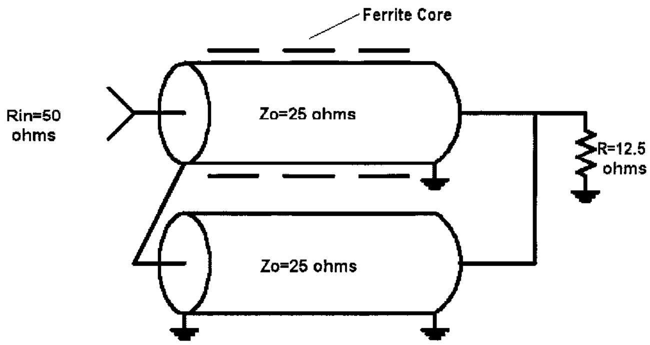

Fig. 11. Basic 4 : 1 transmission-line transformer.

the other. The line impedances must be chosen so that each line sees the proper termination at each end. The low-frequency response is limited by the common-mode impedance. The high-frequency response is in theory infinite, but in practice, is limited by parasitics associated with the connections of the ends of the coaxes. Various combinations of connections can provide transformations corresponding to the squares of small integers. An alternative topology developed by Ruthroff connects the ends of a single transmission line to produce a 4 : 1 autotransformer. The Ruthroff transformer is widely used for broad-band hybrid splitters and combiners [2].

Ferrites are ceramic materials based upon a variety of oxides of iron with nickel, manganese, zinc, or magnesium [27]. They find application in nearly all types of RF circuitry for HF and VHF. Basically, their function is to increase the inductance of a coil of a given size and shape. In the case of a toroid, they also confine the vast majority of the magnetic flux to the inductor. Relative permeabilities from 3 to 1800 are typical in components for HF and VHF. In implementing an inductor for tuning or filtering, selection of a ferrite with low loss is essential. However, in broad-band transformers and chokes, high impedance is most important, and some loss is actually helpful in suppressing unwanted resonances.

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