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AM Broadcast Emergency Relay (AMBER)

Final Report

Edward Bedrosian, Elwyn D. Harris, Karl J. Hoffmayer,
Carroll R. Lindholm, Eliza I. Wojtaszek

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This report presents the results of an investigation of the technical feasibility of establishing a nationwide digital network using commercial AM radio broadcast stations that can support both voice and data transmission. The proposed network, called AMBER (AM broadcast emergency relay), is meant to support emergency communications for civilian and military users when other communication facilities are not available. The authors describe AMBER assets and users; consider key network issues and technical considerations; present preliminary cost estimates; describe the AMBER data link; and discuss a large-scale, nationwide computer simulation that has been developed for AMBER at RAND, including the propagation and noise models incorporated into this simulation and the methodology, host computer, and components of the AMBER simulation. The report concludes with a study of the connectivity of an illustrative network.

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PREFACE

This is the final report of a multiyear investigation of the technical and economic feasibility of establishing a nationwide emergency communications network using commercial AM radio broadcast stations. The network is called AMBER (AM Broadcast Emergency Relay). Its purpose is to provide emergency communications for civilian and military users in both pre- and postattack environments. Network survivability stems from the proliferation of broadcast stations and autonomous network adaptability. The cost of AMBER is low because it takes advantage, with minor modifications and augmentations, of existing AM broadcast stations. Also, it relies heavily on state-of-the-art technology.

This effort was supported by the Defense Advanced Research Projects Agency in RAND's National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense. The research was performed in RAND's Engineering and Applied Sciences Department as an element of the Applied Science and Technology Program.

SUMMARY

AMBER (AM Broadcast Emergency Relay) is a proposed long-haul, CONUS-wide, digital network formed by internetting existing commercial AM radio broadcast stations. Receivers at these stations will pick up transmissions from neighboring stations and forward them to their destinations. The network will support emergency communications (voice and data) when other facilities are not available or will supplement other existing or planned networks. AMBER will serve both civilian and military users located CONUS-wide in fixed and mobile sites. AMBER is designed to operate at relatively low data rates in peacetime on a noninterfering basis with commercial AM broadcast stations. This will allow the network to be thoroughly checked out so that it will be ready during an emergency.

AMBER offers the advantages of flexibility, survivability, and low cost. It would adapt autonomously in an emergency to the loss of stations resulting from an attack or malfunction. Survivability of the network relies on redundancy (over 4000 commercial AM broadcast stations are available) and the ability of the network to reconfigure itself. Moreover, since AM broadcasting relies primarily on groundwave propagation, the network would be less vulnerable to ionospheric disturbances. The cost of the AMBER network can be viewed as the marginal cost associated with the design, development, fabrication, installation, and operation of AMBER-specific equipment. Existing commercial AM broadcasting stations would supply not only the facilities but also day-to-day operation and maintenance.

USER/NETWORK INTERFACE

An AMBER node would consist of an existing AM transmitter, a set of receivers, a modem (modulator/demodulator), and, as in a computer network, an IMP (interface message processor). The IMP provides user access to AMBER and performs the processing necessary to gain the desired interconnection with IMPs at other nodes. The IMPs and the links that interconnect them constitute the communication subnet. The users in AMBER play the same role as the hosts in a computer network. However, the AMBER design does not require that users be located at AMBER nodes. Users can be anywhere in CONUS (ground or airborne) so long as an auxiliary communication system, which is not integral to AMBER, is available to provide user access to an AMBER node.

AMBER users will receive signals directly off the air using an AMBER multichannel PM receiver and an AMBER demodulator. To generate a message and inject it into the system, the user must have either a direct tieline to an AM station or a transmitter capable of reaching one using preselected frequency bands. The injected signals would be picked up by the AMBER user-access receiver and passed into the AMBER signal processor for transmission.

RESOURCES

The entire inventory of commercial AM stations is an important resource for AMBER, because the network will include a mixture of all classes of stations as well as a wide range of frequencies. Because AMBER supports strategic communications during both pre- and postattack periods, the 596 stations in the Federal Emergency Management Agency's (FEMA)

Broadcast Station Protection Program (BSPP) are especially important. FEMA has also defined high-risk areas which, in the case of a massive nuclear attack, would probably receive blast overpressure of 2 psi or more (thought to be sufficient to destroy most AM antenna towers). Of the BSPP stations, 331 are outside these areas. Stations in high-risk areas will be included in AMBER, as in BSPP, but it would not be prudent to rely on them for postattack connectivity.

OPERATIONAL CONCEPT

The AMBER network will have a normal peacetime mode in which it operates at a low data rate for exercise and familiarization on a noninterfering basis with routine AM broadcasts. Much of the research on the AMBER user data link is directed at achieving this important noninterfering capability. In crises, and in a postattack period, the entire capacities of its component stations would be used to provide CONUS-wide multichannel voice communication for military and government users.

NETWORK AND TECHNICAL ISSUES

A number of key issues such as error control, packet routing, preferred modulation techniques, and VOCODER technology have been addressed. Although often posing engineering challenges, no fundamental obstacles are seen to their satisfactory solution. In most instances, state-of-the-art approaches will suffice. In a few, advanced methods may be required.

PRELIMINARY COST ESTIMATES

The AMBER modem consists of a modulator, signal processor, and a receiver pair; all are protected against EMP (electromagnetic pulse) and use commercial design practices. The modem is expected to cost about $100,000 per station. It is estimated that a useful CONUS-wide system can be implemented using from 100 to several hundred stations.

THE AMBER DATA LINK

The user data link has been examined extensively. Computer simulations established basic performance characteristics that were verified by bench tests and on-the-air measurements. Synchronization, error, and sensitivity tests were successfully performed using KNX (1070 kHz) in Los Angeles at ranges from 110 to 200 statute miles.

NETWORK COMPUTER SIMULATION

To determine AMBER connectivity under a variety of conditions, an extensive computer simulation of a nationwide AMBER network was constructed and exercised. All U.S., Mexican, Canadian, and Caribbean AM broadcast stations were incorporated into the model. It also contained realistic models of skywave and groundwave signal propagation, and of atmospheric, galactic, and manmade sources of noise. The propagation effects of atmospheric nuclear explosions have not yet been included in the simulation.

Network connectivity was determined for an exemplary system consisting of the 288 FEMA-protected stations thought not to be at risk in a major terrestrial nuclear war. Sixteen environments, consisting of dawn, noon, dusk, and midnight at 90° W longitude for the four seasons of the year were considered. The results indicated a connectivity that varied considerably with time of day and season of the year, and was poor at times. More research is required to derive preferred configurations of stations for AMBER.

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GLOSSARY

AM	Amplitude Modulation
AMBER	AM Broadcast Emergency Relay
AABNCP	Advanced Airborne Command Post
APD	Amplitude Probability Distribution
ANMCC	Alternate Military Command Center
APPLS	AM-PM Physical Link Simulator
ASCII	American Standard Code for Information Interchange
BSPP	Broadcast Station Protection Program
BPSK	Binary Phase Shift Keying
BER	Bit Error Rate
BSIU	Broadcast Station Interface Unit
CONUS	Continental United States
CPCS	Common Program Control Station
CINC	Commander in Chief
C^3	Command, Control, and Communications
CCIR	International Radio Consultative Committee
CPE	Circular Probable Error
CINCLANT	Commander in Chief, Atlantic
DCWS	Direction Control and Warning System
DECAC	Defense Electromagnetic Compatibility Analysis Center
EMP	Electromagnetic Pulse
EBS	Emergency Broadcast System
EAM	Emergency Action Message
EOC	Emergency Operating Center
EBU	European Broadcasting Union
FEMA	Federal Emergency Management Agency
FCC	Federal Communications Commission
FSK	Freqency Shift Keying
FFT	Fast Fourier Transform
GWEN	Ground Wave Emergency Network
HF	High Frequency
IMP	Interface Message Processor
IOC	Initial Operational Capability
ICBM	Intercontinental Ballistic Missile
ISO	International Standards Organization
IF	Intermediate Frequency
LCC	Launch Control Center
LDR	Low Data Rate
MOSF	RAND's Military Operations Simulation Facility
MF	Medium Frequency
MSK	Minimum Shift Keying
MSE	Mean Square Error
NS/EP	Natonal Security/Emergency Preparedness
NCC	National Coordinating Center
NCS	National Communication System
NCA	National Command Authority
NEACP	National Emergency Airborne Command Post

NORAD	North American Aerospace Defense Command
NEMS	National Emergency Management System
NRZ	Non Return to Zero
NMCC	National Military Command Center
Order Wire	A portion of a communication system capacity set aside for control functions
OPRS	Originating Primary Relay Station
PM	Phase Modulation
PACCS	Post-Attack Command and Control System
PSD	Power Spectral Density
PCM	Pulse Code Modulation
RF	Radio Frequency
Real Circuit	A path, usually two way, in a communications network provided exclusively to a pair of users
rms	root mean square
SFSK	Sinusoidal Frequency Shift Keying
SAC	Strategic Air Command
SNR	Signal-to-Noise Ratio
TW/AA	Tactical Warning/Attack Assessment
UHF	Ultra High Frequency
ULDR	Ultra Low Data Rate
UT	Universal Time
VOCODER	Voice Coder
VHF	Very High Frequency
Virtual Circuit	A path, one way or two way, in a communications network provided to a pair of users. It may be shared wholly or in part, but on a noninterfering basis, with other users
VLDR	Very Low Data Rate
VLF	Very Low Frequency

I. INTRODUCTION AND OVERVIEW

This report presents the results of an investigation of the technical feasibility of establishing a nationwide digital network using commercial AM radio broadcast stations that can support both voice and data transmission. A number of technical reports were prepared during the course of the research, which extended over a period of several years. The present report draws on these to produce a comprehensive documentation that covers the entire project.

The objective of the proposed communication network is to support emergency communications for civilian and military users when other communication facilities are not available. The network is called AMBER (AM Broadcast Emergency Relay). It can serve as a standalone emergency communication network, or it can be used as a supplement to other existing or planned communication networks. The network is designed to operate at relatively low data rates in peacetime on a noninterfering basis with commercial AM broadcast stations. This allows the network to be thoroughly checked out, and for users to become familiar with it, so that it will be ready to provide communication support during an emergency.

The AMBER concept consists of (1) modifying existing AM broadcast stations by replacing the local oscillators with more stable ones better suited to phase modulation, (2) phase modulating with digital data before amplitude modulating, and (3) adding special multichannel receivers to pick up the radiated signals from other AMBER nodes and feed them into the signal processor for retransmission. During peacetime operation, the AMBER network would function independently of the commercial AM stations, relying on them for day-to-day manning of the station, and maintenance and operation of the transmitter, backup power supply, and broadcasting facilities; AMBER-unique equipment would be maintained, as needed, by a special crew.

During crises, or in a postattack period, selected stations would be used in a dedicated manner to enhance the communication capability of the network by using both the AM and PM capacity of these stations. During such periods, the AMBER network, as well as the commercial AM stations, would rely mainly on the Federal Emergency Management Agency's (FEMA) Broadcast Station Protection Program (BSPP) package for blast and fallout protection and reserve power. It may be necessary to expand the BSPP to enhance the performance of AMBER. During an emergency, the AMBER network would autonomously adapt to the loss of stations resulting from attack or malfunction by rerouting messages through surviving stations. Survivability of the network relies on redundancy (over 4000 commercial AM broadcast stations are available), and the inherent ability of the network to reconfigure itself.

Because AMBER provides an exercise and familiarization capability in peacetime and can support communications for a wide range of users during crises and in a postattack period, and because of the close coordination needed between the commercial AM broadcast industry and the government to bring it into being, AMBER will probably be directly affected by Executive Order Number 12472 (signed 3 April 1984 by President Reagan) establishing the National Communication System (NCS). That order coordinates responsibilities within the federal government for National Security/Emergency Preparedness (NS/EP) of telecommunication functions. The NCS ensures a consolidated national telecommunication structure and serves as a focal point for joint industry and government NS/EP planning. Also established under the NCS was a joint industry-government National Coordinating Center (NCC) to coordinate NS/EP telecommunication services and facilities under all possible conditions.

Although the idea of phase modulating the carriers of commercial AM broadcast stations dates back to at least the early 1960s, recent interest stems from a convergence of technical advancements in signal processing, linear predictive coding, efficient modulation schemes, error control, and data bandwidth compression. In addition, recent Federal Communications Commission (FCC) deregulation policies and FEMA's progress in providing protection for AM stations against nuclear effects have contributed to the economic feasibility of the AMBER concept. The major contributions to the economic feasibility of the concept are (1) the use of existing commercial AM broadcast stations (capital investment in existing buildings, towers, broadcast equipment, land, etc., exceeds a billion dollars), and (2) the day-to-day operation and maintenance provided by the commercial stations. As a consequence of these two factors, the cost of the AMBER network can be viewed as the marginal cost associated with the design, development, fabrication, installation, and operation of AMBER-specific equipment.

Another system, known as GWEN (Ground Wave Emergency Network), bears a resemblance to AMBER. The original concept of GWEN was, in fact, identical to that of AMBER. However, its military mission (principally emergency action message (EAM) dissemination) and the associated requirement for physical and electronic survivability soon led the GWEN system in a different direction. It operates at about 200 kHz using only groundwave propagation. Also, it has its own hardened and heavily EMP-protected sites, antennas, and radio equipment. It consists currently of a thin-line version in which 60 nodes are distributed CONUS-wide in a figure-eight pattern serving the Commander in Chief, Strategic Air Command (CINCSAC).

AMBER assets and users are described in Sec. II. There are approximately 4400 commercial AM broadcast stations in the United States. They are categorized into four classes and allocated channels in the AM broadcast band (535 to 1605 kHz). FEMA has included 596 of these in the BSPP so that they can participate in the Emergency Broadcast System (EBS). Their presumed ability to function after a nuclear attack makes them attractive candidates for the AMBER system. AMBER can be used by military or government leaders during crises and in a postattack period. Such users are identified in Sec. II, and their locations are shown to be compatible with the coverage provided by AMBER. The section concludes with a description of the user-network interface.

Several key network issues are considered in Sec. III. The first of these is the operational concept, which consists of a normal peacetime mode and a crisis/postattack mode. In peacetime, a low-data-rate phase modulation is used on a noninterfering basis for demonstration and familiarization, or to provide low-data-rate order-wire exercise. In the crisis/postattack mode, the entire capacity of the AMBER stations is used to provide a high-data-rate order wire and a number of VOCODED voice channels per station. The general architecture of such networks is then described and related to AMBER. The section concludes with a discussion of error control and packet routing. Error control is an important process that must be integrated into the design of AMBER to insure that it can meet its performance goals under adverse conditions. Packet routing, which must be done without centralized control in AMBER, is the mechanism used in the order wire to establish, maintain, and finally dismantle the circuits that permit users to communicate. The problem is complicated by the lack of a fixed configuration for AMBER.

Several key technical considerations are treated in Sec. IV. First, modulation techniques are discussed in a general way to establish the important differences between amplitude and phase modulation (AM and PM) and their hybrid form. This leads to a discussion of bandwidth compression, which is essential to AMBER if high data rates are to be achieved without interference. Then, modern VOCODER technology, on which AMBER must rely, is described. AMBER is basically a digital system, so user voice transmissions must be digitized. VOCODERs are an efficient means for doing this, the most common device being the LPC-10, which operates at 2400 bps. However, others, operating at lower data rates, may become available. Finally, a performance estimate is made for the contemplated modes of operation using standard and advanced VOCODERs assuming state-of-the-art and advanced signal processing.

Preliminary cost estimates are presented in Sec. V. The AMBER package is estimated to cost $96,000 per node assuming commercial design practices and EMP protection consistent with the FEMA BSPP. Four illustrative examples are then costed: These range from a 100 station initial operational capability (IOC) system at $9.7 million to an enhanced survivable system of 714 stations at $77.9 million.

The AMBER data link, which is fundamental to the AMBER network, is treated in detail in Sec. VI. It commences with a treatment of typical PM waveforms and their resulting modulation spectra. It is shown that sinusoidal frequency shift keying (SFSK) has desirable spectral properties and may be adequate for initial consideration. A computer simulation used to verify these characteristics is then described. The section concludes with a description of the AMBER data-link test program. Bench tests were conducted to determine the interference potential of superposing digital PM on a conventional AM transmission. It was determined that interference-free operation could be attained at 75 bps and, with advanced modulation techniques, at 150 bps or more. The problem of compatibility with stereo AM broadcasting was also investigated and found to be achievable at the lower data rates. On-the-air tests were conducted using an existing nonoptimal digital PM transmission on KNX (1070 kHz) in Los Angeles. Synchronization, error, and sensitivity tests were performed at distances of from 110 to 200 statute miles; the results were satisfactory.

The three concluding sections deal with a large-scale, nationwide computer simulation that has been developed for AMBER at RAND. The propagation and noise models incorporated into this simulation are described in Sec. VII. The AM broadcast band lies in a portion of the radio spectrum (535 to 1605 kHz) that displays considerable diurnal, seasonal, and solar sunspot variability in both propagation and noise. Skywave propagation, by which signals can range over thousands of kilometers by reflection from the earth's ionosphere, is considered first. The existing models are examined and a suitable one is selected for the AMBER simulation. Groundwave propagation, by which signals travel reliably along the surface of the earth for 100 km or so, are then considered. The existing models are reviewed and modified for use in the AMBER simulation. Finally, external noise (receiver noise is seldom a factor in this frequency range), which has atmospheric, galactic, and manmade components, is treated and a composite noise model is developed for the AMBER simulation.

It is well known that nuclear explosions in or above the earth's atmosphere can disrupt the ionosphere and can impair or cause outages in many communication systems. The principal effects are the generation of noise and the attenuation of radiowaves within the ionosphere. For AMBER, the attenuation of the skywave component is likely to be the dominant factor. This will manifest itself by a weakening or elimination of paths that depend on skywave propagation and a reduction in the background of atmospheric noise that comes via skywaves. Hence, paths should be shorter, deriving principally from groundwave propagation, and the noise environment should be quieter. Future research should assess these effects for realistic scenarios.

The methodology, host computer, and components of the AMBER simulation are presented in Sec. VIII. The idea is to create a database of technical information for all U.S.

and adjacent foreign AM radio stations. From these, AMBER subsets can be selected and the usable paths determined. These, then, determine the connected network (i.e., its topology). The routing algorithm, the random message generators that will simulate the offered communication traffic, and the procedures for evaluating system performance, such as call waiting time, message throughput delay, etc., have yet to be implemented. The host computer is the RAND Military Operations Simulation Facility (MOSF), and the database contains all U.S., Mexican, Canadian, and Caribbean stations. A philosophy for selecting stations suitable for inclusion in AMBER is presented, and the computational procedure for calculating usable paths is described using an environment file that prescribes the conditions appropriate to each path being considered. The question of overall network connectivity is shown to be related to the adjacency matrix, which is a fundamental descriptor of the connectivity of each network station to its immediate neighbor. The section concludes with a brief discussion of run statistics and computational complexity.

The report concludes with a study of the connectivity of an illustrative network in Sec. IX. The one selected for analysis consists of all 288 FEMA-protected stations outside the 2 psi risk area. Interference is assumed to come from all foreign broadcast stations and all domestic broadcast stations outside the 2 psi risk area. That is, it is assumed that all U.S. broadcast stations inside the 2 psi risk area are destroyed. Then, with typical assumptions for sunspot number and minimum usable signal-to-noise or signal-to-interference ratios, and with the rejection of signals on the channels adjacent to the one being used by the local station, the usable paths at each station are determined. These are done for 16 environments consisting of dawn, noon, dusk, and midnight at 90° W longitude for each of the four seasons of the year. The outputs consist of: (1) scatter plots showing the signal margin as a function of path length for all of the usable paths, (2) path plots showing the usable paths graphically on a map of the United States, (3) adjacency and reachability matrices for each station in the network, and (4) connectivity plots showing the usable connected components of the network. Each output is shown for each of the 16 environments. The result is a network whose connectivity varies considerably over the course of the day for each season.

The research to date has been directed toward the development of an architecture for AMBER that will result in a system capable of performing a useful civil and military function in a severe postattack environment. To this end, a large-scale computer simulation has been prepared to assess its performance under a variety of conditions. It is anticipated that these conditions will be derived by making suitable modifications to the peacetime propagation and noise models incorporated into the simulation. Thus, the apparent emphasis on peacetime conditions does not reflect the wide-ranging utility of the simulation, which can readily be adapted to a variety of trans- and postattack conditions. This permits an accurate estimate of the development, testing, and exercise problems in a peacetime environment, as well as the actual operation of AMBER in a wartime environment.

It is clear that a number of issues that bear heavily on the technical feasibility of AMBER remain to be addressed. The support to date by DARPA has been generous and continuing, but the research is now at a point where it should be taken over by an operating agency. Future efforts should include not only additional analytic work and computer simulations but also a limited experimental program to verify propagation and networking effects in the field.

Finally, it is desirable to comment on the role AMBER should play during the era into which it might come into being. At its inception, the role envisioned for AMBER was largely military and concentrated in the transattack period. There was great emphasis, at that time, on increasing the reliability of EAM dissemination to strengthen the credibility of assured response to a major nuclear attack. Systems available for this purpose were primitive and often of questionable reliability. Today, systems such as GWEN, which will assure EAM dissemination to the Minuteman strategic missiles during the early postattack period, and AFSATCOM, which will serve the strategic bomber force during the entire postattack period, have reduced the urgency of the need. Nonetheless, AMBER can play an important supporting role during this period.

With the easing of concern about transattack communications and the growing awareness of the importance of providing relief and support to a surviving population by insuring an orderly and efficient continuity of government, interest has extended to the postattack era. It is to this period that the utility of AMBER has been addressed in this study. The research indicates that AMBER can indeed perform an important function in this regard. Yet here, too, events have transpired to provide alternatives to AMBER. Examples are NETS (Nationwide Emergency Telecommunications System) and CSI (Communication Satellite Interconnectivity). However, the relatively low cost of AMBER may nonetheless make it an attractive augmentation to these or similar systems.

The greatest challenge AMBER can pose to system planners concerned with the postattack communication needs of the United States is to determine the configuration and function of AMBER that can make the greatest contribution. The point to remember is that AM broadcast stations exist in large numbers and that they can be interconnected into a regional or CONUS-wide network at relatively low cost. An imaginative application of the capabilities of AMBER to an inadequately addressed communication need can result in a valuable new system.

II. AMBER ASSETS AND USERS

The AMBER network uses existing commercial AM broadcast stations. Because AMBER provides an exercise and familiarization capability during peacetime and supports strategic communications during the postattack period, the subset of commercial AM stations that has been included in the FEMA BSPP is of particular interest for the initial AMBER network. However, because of the uncertainty in the number of stations and specific locations that will ultimately be needed for the final CONUS AMBER network, the entire inventory of commercial AM stations is considered an important AMBER resource.

AMBER users are expected to include both civilian and military leaders located CONUS-wide in fixed and mobile sites. Consequently, the AMBER network provides access at each AMBER-equipped AM station and an adaptive routing capability to allow stations to leave the network freely if they experience propagation anomalies, mechanical failure, or damage during a direct attack.

Commercial AM broadcast stations, FEMA-protected stations, and user categories, locations, and access to AMBER are discussed below.

COMMERCIAL AM BROADCAST STATIONS

Over 4000 AM broadcast stations operate in the United States. The frequency band assigned to the AM broadcast service ranges from 535 to 1605 kHz, with stations assigned at 10 kHz intervals beginning at 540 kHz, thus providing 107 frequencies or channels. The FCC regulates the AM broadcast network by (1) allocating space in the radio frequency spectrum to the broadcast services and to many nonbroadcast services; (2) assigning stations in each service within the allocated frequency bands with specific location, frequency, power, and operating times to avoid interference with other stations on the same channel (frequency) or adjacent channels; and (3) monitoring station operations for compliance with FCC rules, assigning station call letters, licensing transmitter operators, and so forth.

The FCC authorizes four classes of AM stations (FCC, 1984):

1. Class I stations operate on "clear" channels, usually with 50 kW power (never less than 10 kW) to serve remote rural areas as well as large population centers. The United States has Class I priority on 45 clear channels. As can be seen from Table 2.1, 59 stations are in the Class I category with unlimited operating time. Most of these stations operate on separate channels; however, 14 channels have two stations assigned to them. Because of the FCC's noninterference requirement, stations sharing a channel are generally widely separated geographically; e.g., WTIC in Hartford, Connecticut, and KRLD in Dallas, Texas, both operate on 1080 kHz.
2. Class II secondary stations operate on "clear" channels with 250 W to 50 kW power to serve a population center and adjacent rural area. These stations must not interfere with the major Class I clear-channel stations. Twenty-nine channels are assigned to Class II stations and about 1400 stations in the United States (Table 2.1). Because of interference considerations, most of these stations operate at greatly reduced power levels at night when the skywave is dominant outside the primary service area.

Table 2.1

AM BROADCAST STATIONS
(535 to 1605 kHz)

Class	Power	No. of Channels	Service	No. of Stations
I Primary (clear channel)	10 kW to 50 kW	45	Large population centers and remote rural areas	59
II Secondary station on clear channel	250 W to 50 kW	29	Population center and surrounding rural area	1382
III Regional channel	500 W to 5 kW	41	Population center and surrounding rural area	2026
IV Local channel	< 1 kW day or < 250 W night	6	Limited area	926
Total				4393

3. Class III regional stations share channels with numerous similar stations, using 500 W to 5 kW power to serve a population center and the adjacent rural area. There are 41 regional channels and more than 2000 Class III stations. A major portion of these stations operate at greatly reduced power levels at night to satisfy FCC interference requirements.
4. Class IV local stations operate on a few channels that are shared by many similar stations across the country using a maximum daytime power of 1 kW and nighttime power of 250 W. Six channels are assigned to this class, each occupied by 150 or more stations.

There is some sharing of channels among the various classes of stations. Hence, the sum of the channel allocations in Table 2.1 slightly exceeds the total number of channels available.

Although all of the AM broadcast stations are candidates for a CONUS-wide AMBER network, selection considerations include: (1) *class*—clear-channel stations operating at high power levels are more desirable than local stations; (2) *operating frequency*—ground- and skywave propagation from low-frequency stations is generally better than from high-frequency stations; (3) *location*—to provide CONUS-wide coverage, stations located in remote, as well as populated, areas must be considered; and (4) *total number of stations*—inasmuch as network survivability must be achieved by proliferation, a network with a large number of stations is more desirable than one with minimum connectivity. These considerations are not hierarchical—they must be treated together. For example, it is expected that the ultimate CONUS-wide AMBER network will include a mixture of all classes of stations as well as a wide range of frequencies.

Of particular interest is the consideration of a nuclear attack on the United States and its implications for the availability of commercial AM stations during the postattack period. FEMA has identified areas considered most likely to experience direct weapons effects (blast, heat, and initial nuclear radiation) from a nuclear attack on CONUS. These areas are termed high-risk areas. For planning purposes, FEMA assumed that the metropolitan areas of the country, as well as some other areas of military, industrial, or economic importance, are at high risk from blast and fire effects of a nuclear attack. The high-risk areas shown in Fig. 2.1

represent those areas subject to a 50 percent or greater probability of receiving blast overpressure of 2 psi or more.[1] Of the over 4000 AM stations located in the United States, about 2700 stations are outside the high-risk area.

A conservative view might constrain the AMBER network to the use of stations able to survive such an attack. However, depending on the severity of the attack, the uncertainties associated with it, and the requirement that AMBER also provide peacetime connectivity, it can be argued that stations located within the risk area should also be included in the AMBER network. This may be beneficial because of the more restrictive requirement for noninterfering operation during peacetime. As will be discussed in Sec. IX, additional stations will enhance the signal-to-noise margin and connectivity of the network. For postattack AMBER connectivity, however, stations within the risk area cannot be relied upon.

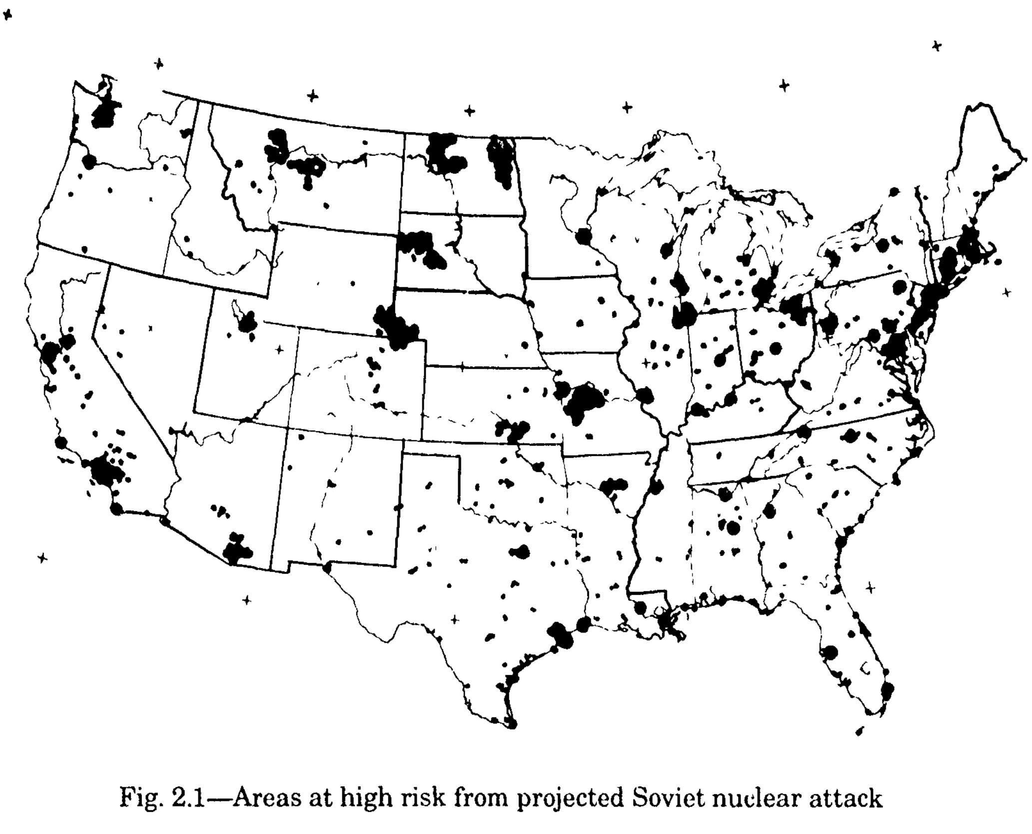

Fig. 2.1—Areas at high risk from projected Soviet nuclear attack

[1]For this analysis, FEMA assumed that all weapons were airburst, system reliability was 0.9, and circular probable error (CPE) was 0.5 nautical miles. Targets included: (1) U.S military installations, (2) industrial, transportation, and logistics facilities supporting the military, (3) other basic industries and facilities that contribute significantly to the maintenance of the U.S economy, and (4) population concentrations of 50,000 or more (FEMA, 1979).

FEMA-PROTECTED STATIONS

Some of the commercial AM broadcast stations have been protected by FEMA as part of their participation in EBS. These stations constitute the initial AMBER-protected network. FEMA's BSPP includes about 600 AM broadcast stations, as shown in Table 2.2; of these, 331 are outside the 2 psi high-risk area.[2] The geographical distribution of the protected stations is shown in Fig. 2.2. In selecting stations for BSPP, FEMA has tried to achieve wide-area coverage by including 75 percent of all Class I clear-channel stations, while at the same time achieving nearly complete population coverage by including a large percentage of Class III (regional) and Class IV (local) stations.

For a station to be included in BSPP, the individual station owner must agree to be part of EBS. In exchange, FEMA (with federal funding) provides the station with a fallout shelter, an emergency generator, EMP protection devices, programming equipment, auxiliary remote pickup units (if appropriate), equipment to monitor or tie into FEMA's EBS, and the capability to operate under emergency conditions for 14 consecutive days (Table 2.3). With the exception of the EMP protection devices, the station owner procures all of the above equipment to FEMA specifications; the EMP protection devices are provided by FEMA. After installation, the station owner is reimbursed and gains title to the shelter and EMP protection devices. Title to the generator and other equipment passes to the government, but stations are able to use the equipment (except for the remote pickup unit) as needed during the course of normal business.

The fallout protection shelter is designed to attenuate gamma radiation by a factor of 100. The size of the shelter ranges from 150 to 300 sq ft of floor area. Adequate emergency provisions (i.e., food, water, and sanitation) are provided for 14 days, assuming an occupancy factor of 50 sq ft per person (FEMA, 1982b).

The EMP protection provided by FEMA consists mainly of lightning arresters and other devices to ensure that EMP will not damage the communication equipment (DCPA, 1972, 1976a, 1976b; FEMA, 1983, 1982a, 1982c). This does not prevent upsets of memories and other solid-state devices, but it is assumed by FEMA that operations, although temporarily halted because of EMP, will resume after the equipment is reset.[3] For the concept of

Table 2.2

FEMA PROTECTION PROGRAM

Class	Total No. Stations	FEMA Protected: Inside 2 psi Risk Area	FEMA Protected: Outside 2 psi Risk Area
I	59	32	12
II	1382	30	36
III	2026	179	158
IV	926	24	125
Total	4393	265	331

[2]The terms risk area, high-risk area, 2 psi risk area, etc., are used interchangeably throughout the report.

[3]This design philosophy differs from that used for GWEN in that GWEN operation must never be interrupted by EMP. As a result, much more elaborate and costly EMP protection is provided for the GWEN equipment than for AMBER.

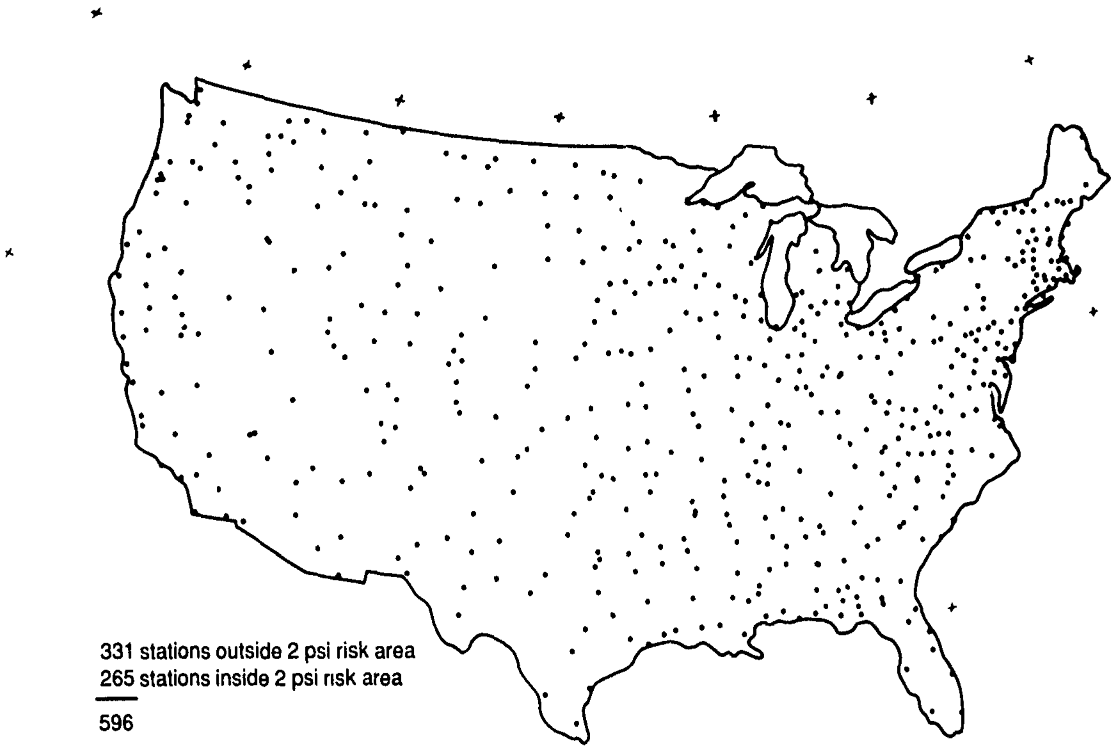

Fig. 2.2—AMBER-protected network

Table 2.3

FEMA'S BROADCAST STATION PROTECTION PROGRAM

Purpose	
Harden AM stations against nuclear fallout and EMP	
Equipment	
Reserve power generator and fuel	
Fallout shelter (50 sq ft per person), 100-fold reduction	
Emergency programming equipment	
Remote pickup	
Emergency operating center	
EMP protection	
Cost	
Average $70,000 per station (FEMA)	
Program status	
Stations fully protected	85
Stations with everything except EMP	511
Total	596

operations envisioned for AMBER, the level of EMP protection provided by FEMA appears to be adequate. Similar EMP protection must be provided for the AMBER-specific equipment located at the AM stations.

As shown in Table 2.3, FEMA has fully protected 85 AM broadcast stations and provided everything except EMP devices for an additional 511 stations. The total number of stations in the BSPP is currently 596. The average cost to FEMA for this protection package is about $70,000 per station, of which $2500 is the cost for the EMP devices. FEMA plans to provide EMP protection for the remaining 511 stations and to extend BSPP to include additional (possibly up to 2700) stations. The policy for equipping new BSPP stations that are within the 2 psi risk area, but are important for EBS, is to provide the full BSPP package except for fallout protection. The station selection priority for extending FEMA's BSPP is to:

1. Enhance national broadcast coverage.
2. Add Common Program Control Stations (CPCS-1), which enable local officials to reach the public with emergency information.
3. Add more Originating Primary Relay Stations (OPRS) for state entry points.
4. Add stations that support both risk and nonrisk areas for crisis evacuation.
5. Add state relay network stations.

As the AMBER CONUS-wide network connectivity studies progress, FEMA's plans for expansion of BSPP will be included; however, the AMBER network will not necessarily be limited to stations protected by FEMA. If additional stations are needed for network connectivity or survivability, AMBER will provide them with protection packages. Further study may also justify excluding some of the stations included in FEMA's BSPP.

USERS: CATEGORIES, LOCATIONS, AND ACCESS TO AMBER

Two user categories are envisioned for the AMBER network: military and government leadership. For the military, AMBER can provide connectivity between the National Command Authorities (NCA) and CINCs and the military forces located at intercontinental ballistic missile (ICBM) sites and SAC bases to provide tactical warning and attack assessment (TW/AA) information and transmission of emergency action messages. Generally, these are time-urgent transmissions between fixed installations, such as the PAVEPAWS early-warning radar sites at Otis and Beale Air Force Bases and CINCSAC at Omaha. With AMBER's current state of development, it is not clear what time delays will be encountered. Conceptually, dedicated circuits through the AMBER network can be established in peacetime connecting critical military installations. This mode of operation provides near-real-time communications within the data-rate limitations and error-correction capabilities of the network in the absence of EMP. In the presence of EMP, momentary transmission errors may occur; hence, delays may be incurred if error correction is inadequate and retransmission is required.

Other important military users are those located on mobile platforms—either land-based or airborne. They include PACCS (Post-Attack Command and Control System), AABNCP (Advanced Airborne Command Post), NEACP (National Emergency Airborne Command Post), and any of the ground mobile command centers being developed for SAC, NORAD (North American Aerospace Defense Command), and the NCA. Increasing the survivability and endurance of the U.S. command structure is the objective of the move toward mobile command posts. Although mobile users are currently scheduled to be connected primarily through communication satellites, AMBER, with its wide-area-coverage broadcast mode of operation, offers a supplementary means of maintaining connectivity, thus enhancing the survivability of U.S. strategic command, control, and communications (C^3). The importance of reaching these mobile military users after a massive nuclear strike is paramount. The types of messages transmitted at such a time would include force status, damage assessment, and revised mission orders.

The locations of potential military users of AMBER are shown in Table 2.4. Of the fixed users, there are seven command sites, six tactical warning and attack assessment sites, five launch control centers (LCC), and 19 SAC bases.

The list of government users is drawn primarily from the National Emergency Management System (NEMS) architecture design that provides for an overall nationwide (federal, regional, and state) infrastructure to support: (1) emergency management decisionmaking, (2) dissemination of emergency information to the public, and (3) national recovery. This infrastructure includes regional headquarters, Emergency Operating Centers (EOC), and a mobile Direction Control and Warning System (DCWS). FEMA has established a headquarters in each of ten FEMA regions and an EOC for each of the contiguous 48 states and is planning to have DCWS operating CONUS-wide (one per region).

Table 2.4

LOCATIONS OF POTENTIAL MILITARY USERS OF AMBER

NCA/CINCs	TW/AA	LCCs	SAC Bases	Mobile Command Centers
NMCC	PAVEPAWS	Whiteman, MO	Blytheville, AR	CONUS-wide
Washington, D.C.	Otis AFB, MA			
	Beale AFB, CA	Minot, ND	Little Rock, AR	
ANMCC				
Frederick, MD	Buckley ANGB	Ellsworth, SD	Altus, OK	
	Denver, CO			
NORAD		F. F. Warren, WY	McConnell, KS	
Pueblo, CO	SPS			
	Cornhusker, NB	Malmstrom, MT	Grand Forks, ND	
CINCSAC				
Omaha, NE	VLF, TX		Loring, ME	
	Cutter, ME			
Alt. CINCSAC			Plattsburgh, NY	
March AFB, CA				
Barksdale, LA			Pease, NH	
CINCLANT			Griffiss, NY	
Norfolk, VA				
			Sy Johnson, NC	
			Robbins, GA	
			Grissom, IN	
			Wartsmith, MI	
			K. I. Sawyer, MI	
			Carswell, TX	
			Dyers, TX	
			Fairchild, WA	
			Vandenberg, CA	
			Davis-Montham, AZ	

The locations of all of the fixed military and government users described above are shown in Fig. 2.3 along with the 331 FEMA-protected AM broadcast stations that are outside the 2 psi risk area. Both the users and stations are reasonably uniformly distributed over the entire CONUS, suggesting that an AMBER network consisting of all the FEMA-protected stations could probably provide connectivity for these users A detailed connectivity study of a CONUS-wide AMBER network based on the FEMA-protected AM broadcast stations outside the 2 psi risk area is presented in Sec. IX.

The user-network interface envisioned for AMBER is depicted in Fig. 2.4. The four radio towers typify stations in the AMBER network, with MF (broadcast band) transmissions taking place between them. The AMBER-specific equipment suite at each station includes: (1) the AMBER modem (a multichannel receiver and signal processor), (2) a user-access receiver, and (3) the FEMA protection package.[4]

After the AMBER multichannel receiver picks the MF signal off the air, the signal processor prepares it for retransmission. This process is repeated at AM stations located on the

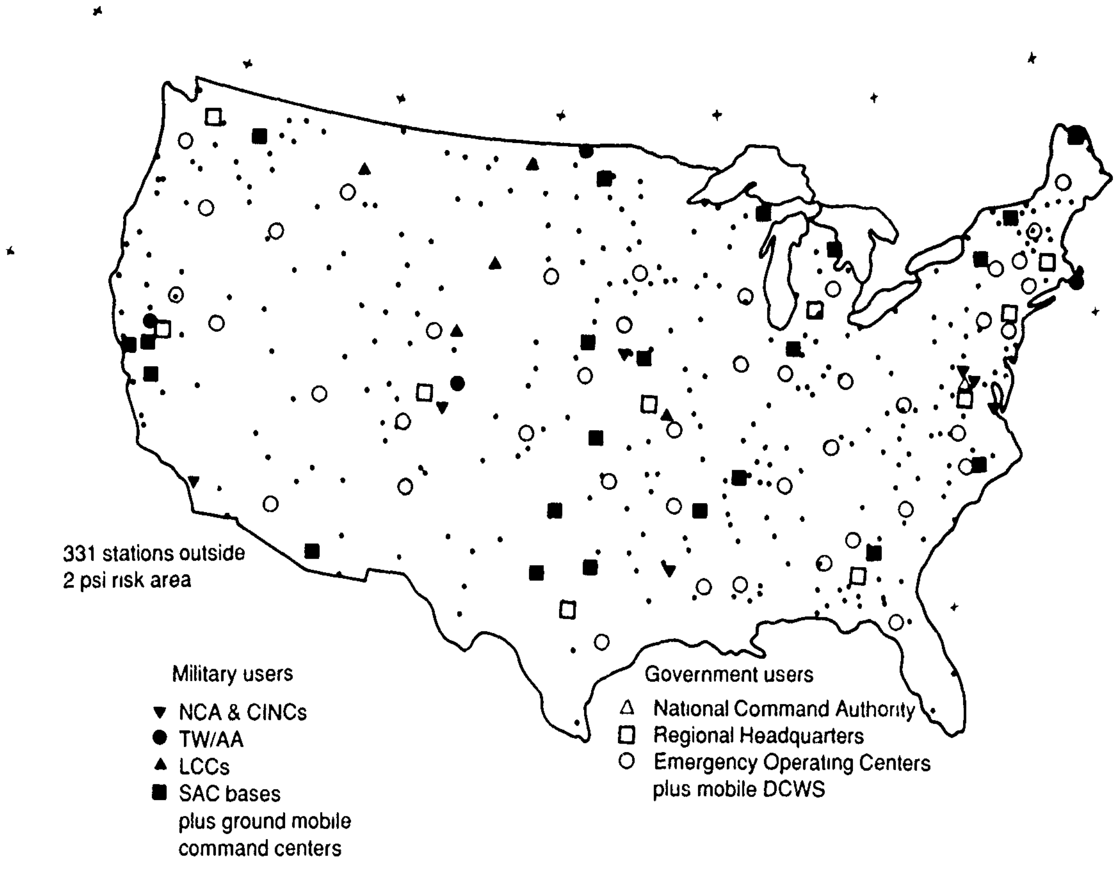

Fig. 2.3—Military and government users of AMBER

[4]The equipment designed for the AMBER modem is discussed in Sec. VI and in Martinez and Landsman (1984).

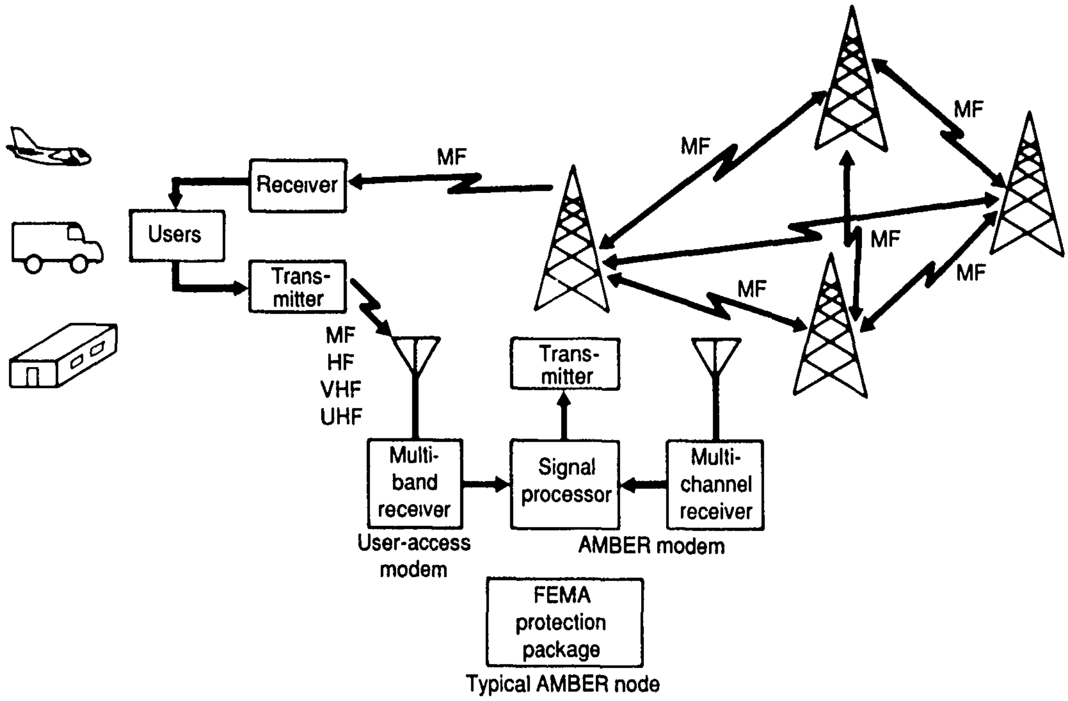

Fig. 2.4—AMBER user-network interface

circuits between a pair of users according to a routing algorithm.[5] All users of the AMBER network can also receive the MF signal directly off the air, if they have an AMBER multichannel receiver. Users include airborne and ground mobile units as well as those located at fixed installations. The user must also have an AMBER demodulator and a decryption capability to read out the message.

If one-way communication is adequate—and there will probably be a number of receive-only users—then the above equipment is all that is necessary. However, if the user wants to generate a message and inject it into the AMBER network, then a transmitter using a suitable frequency band (e.g., MF, HF, VHF, or UHF) must be available at the user location capable of reaching an AM broadcast station. The injected signals would be picked up by the AMBER user-access receiver and passed into the AMBER signal processor for transmission to the designated user. Allowing the user to pick up the AMBER signal directly from an AM broadcast station is advantageous because of the long range at which it can be received. This approach is especially useful for mobile users at remote locations. For two-way communication from ground-based mobile sites, the user transmitter (i.e., power, antenna height) and operating frequency will determine the maximum standoff range from an AMBER AM broadcast station for message injection.

[5]The routing algorithms are briefly discussed in Sec. III More detailed descriptions appear in MILCOM, Inc. (1984) and Baker (1985).

III. NETWORK ISSUES

OPERATIONAL CONCEPT

Normal Peacetime Mode

To provide survivable, postattack, CONUS-wide, voice communications by internetting selected existing AM broadcast stations, AMBER will have to be exercised in peacetime. This mode of operation will be on a noninterfering basis; that is, there will be no noticeable interference to the reception of normal programming material by conventional AM receivers. By careful design this may be possible even for AM stations that are broadcasting in stereo.

Bench tests (reported in Sec. VI) using a nonoptimal phase-modulation scheme and a variety of commercial receivers indicate that it may be possible to transmit data without noticeable interference at rates up to about 150 bps using SFSK, which is a modern, low-interference type of PM. By using advanced signal-processing techniques that can achieve bandwidth compression factors of up to about four, it should be possible to transmit data at rates up to as much as 600 bps without interference to normal AM broadcasting. Such a capability will permit two useful peacetime functions:

1. **Demonstration and familiarization.** The available data rate will be used to establish one low-data-rate order-wire channel and one very-low-data-rate VOCODER channel per station.[1] This can be used to exercise the peacetime capability of AMBER to give it credibility in the eyes of potential users and to familiarize them with it.
2. **Order-wire exercise.** In this case, the entire, available, noninterfering data rate will be used to form one high-data-rate order-wire channel[2] that will be used to demonstrate that large numbers of users can be accommodated during crises and in a postattack period. This will entail systematically establishing, maintaining, and then dismantling large numbers of hypothetical voice circuits between users.

Crisis/Postattack Mode

Selected stations would be used in a dedicated manner to enhance the communication capability of the network by using both the commercial AM and AMBER PM capacity of these stations. The normal peacetime capability would provide a high-data-rate order-wire channel; the balance of the station's broadcasting capability would provide from two to dozens of voice channels per station. Operating in this mode, AMBER could satisfy much of the high-priority communication requirements that will exist when other communication systems have been

[1]Packet switching, with suitable routing algorithms, will be used to establish and maintain the voice circuits between pairs of users. Because of the broadcast nature of radio stations, and the asymmetries among them, only one-way links can be formed, in general. Thus, a duplex (two-way) voice circuit usually requires two simplex (one-way) circuits between user pairs. With the preattack limitation to one voice channel per station, it can be seen that two simplex circuits cannot usually pass through a given relay station; this constraint may be removed in the postattack mode of operation.

[2]An order wire is an auxiliary communication circuit used to adjust, maintain, and service the equipment in a communication system. It is usually included in the system by allocating a suitable fraction of the system capacity for that purpose. For AMBER, the order wire has the function of setting up the successions of links that form the virtual circuits over which users communicate.

disrupted or destroyed. Inasmuch as other emergency uses are planned for the AM broadcast stations, provisions would be made to share selectively each station's broadcasting capability.

ARCHITECTURE

The Structure of AMBER

The AMBER network provides data communications between civilian and military users in much the same way that computer networks interconnect machine users (called hosts). Inasmuch as there has been much research in this relatively new but rapidly maturing field, it is convenient to use its terminology and research results, where applicable, to facilitate the development of AMBER.[3]

AMBER is a CONUS-wide long-haul network formed by interconnecting existing AM broadcast radio stations. Receivers at these stations pick up transmissions from neighboring stations; they are then forwarded by retransmission until they reach their destinations. An AMBER node consists of an existing AM transmitter, a set of receivers, a modem (modulator/demodulator), and, as in a computer network, an IMP. The IMP provides user access to AMBER and performs the processing necessary to interconnect with IMPs at other nodes. The users in AMBER play the same role as the hosts in a computer network. However, the AMBER design does not require that users be located at AMBER nodes. Users can be anywhere in the CONUS (ground or airborne), as long as an auxiliary communication system, which is not integral to AMBER, is available to provide user access to an AMBER node.

There is a natural interface at the boundary between the users and the IMPs with which they access AMBER. The IMPs and the links that interconnect them constitute the communication subnet. The users, of course, are indifferent to the specifics of the interconnections within the subnet; they simply request, via their IMPs, that messages be sent or circuits be established to other users. Within the subnet, the IMPs accomplish the desired function using available links, via intermediate relay IMPs if necessary.

Subnet topologies are usually categorized according to whether the interconnections, or links, are point-to-point or broadcast. A point-to-point topology results when IMPs are interconnected by dedicated links that serve specific IMP pairs. These could be cables, leased telephone lines, or microwave radio relay links. A broadcast topology results when each IMP is interconnected with one or more other IMPs, usually by a nondirectional radiating system. Both topologies usually assume that the interconnections are two-way. Basically, point-to-point links are private and independent of one another, whereas broadcast links are public and require that the IMPs share them in some fashion.

The AMBER links are not only of a broadcast nature but they are also variable and usually one-way, or simplex. The ability of one station to be heard at another depends on the transmitter power, the operating frequency, the propagation conditions, the presence of interfering transmissions, and the noise level at the receiver. Transmitter powers range from 100 W to 50 kW, and there are 107 channels in the 535 to 1605 kHz band, with great attendant differences in propagation. Furthermore, local noise conditions differ greatly from one receiving site to another. Thus, it is common for one station to be heard at another but not vice versa.

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[3]The discussion presented here is adapted from Tanenbaum (1981).

Propagation takes place either by groundwave, which is a stable relatively short-range (up to 1000 km) mode that dominates during the day, or by skywave, which is a variable mode that appears at night and which may dominate the groundwave, often allowing reception at great distances (up to several thousand kilometers). The skywave can also enhance noise by propagating disturbances from distant thunderstorms. The diurnal and seasonal variability of skywave propagation leads to the frequent and often unpredictable availability of the AMBER links at night.

Layered Architecture

A layered structure is used in computer networks to reduce their complexity for purposes of analysis and design; this will also be done for AMBER. The procedure is to establish protocol hierarchies. Each layer, or level, in the hierarchy offers a service to the one above it, thereby freeing the upper layer from concern as to details of how the service is provided. In effect, each layer at one user establishes a horizontal virtual communication with the corresponding layer at another user. These communications are referred to as peer processes and are conducted according to the protocols established at each layer. Adjacent layers communicate with one another vertically across the interface that exists between them. Physical communication between one IMP and another takes place only at the lowest level. Much of the AMBER research to date has been on the analytical and engineering aspects of this physical line (see Secs. IV and V), and the computer simulation of the network topologies that can be supported using selected subsets of existing AM broadcast stations (see Sec. IX). The set of layers and protocols is called the network architecture.

A network architecture for AMBER, based on the "Reference Model of Open Systems Interconnection" developed by the International Standards Organization (ISO, 1982), is shown in Fig. 3.1. Other architectures are also being considered (Cerf and Lyons, 1983; Cerf and Cain, 1983; Selvaggi, 1983). However, the differences, which are apparent only outside the communication subnet, do not significantly affect the description of the AMBER architecture presented here. The functions and processes at the various layers are most conveniently described by working downward from the top of Fig. 3.1. The discussion will be limited, at each layer, to those aspects of interest to AMBER.

At the application layer, the major concern is to agree on protocols and procedures when different types of user equipments are involved. Standardization of equipments and system functions could simplify or eliminate this layer.

The principal functions to be performed at the presentation layer are text compression (e.g., converting ASCII symbols into compressed bit patterns), code conversion (e.g., ASCII to some other code), and encryption for security. Again, standardization can simplify or eliminate all but encryption.

The human user interfaces with AMBER at the session layer. It is here that one user requests a communication session with another. Authentication of user identities and agreement as to the type of service to be provided are done at this level.

The transport layer is the lowest user-to-user or end-to-end layer outside the communication subnet. The messages from the session layer are processed into messages of a structure and character best suited for the specific properties of the particular communication subnet being used (multiplexing or channelizing are examples of such processing). It is below this layer that data are handled by the IMPs in the communication subnet.

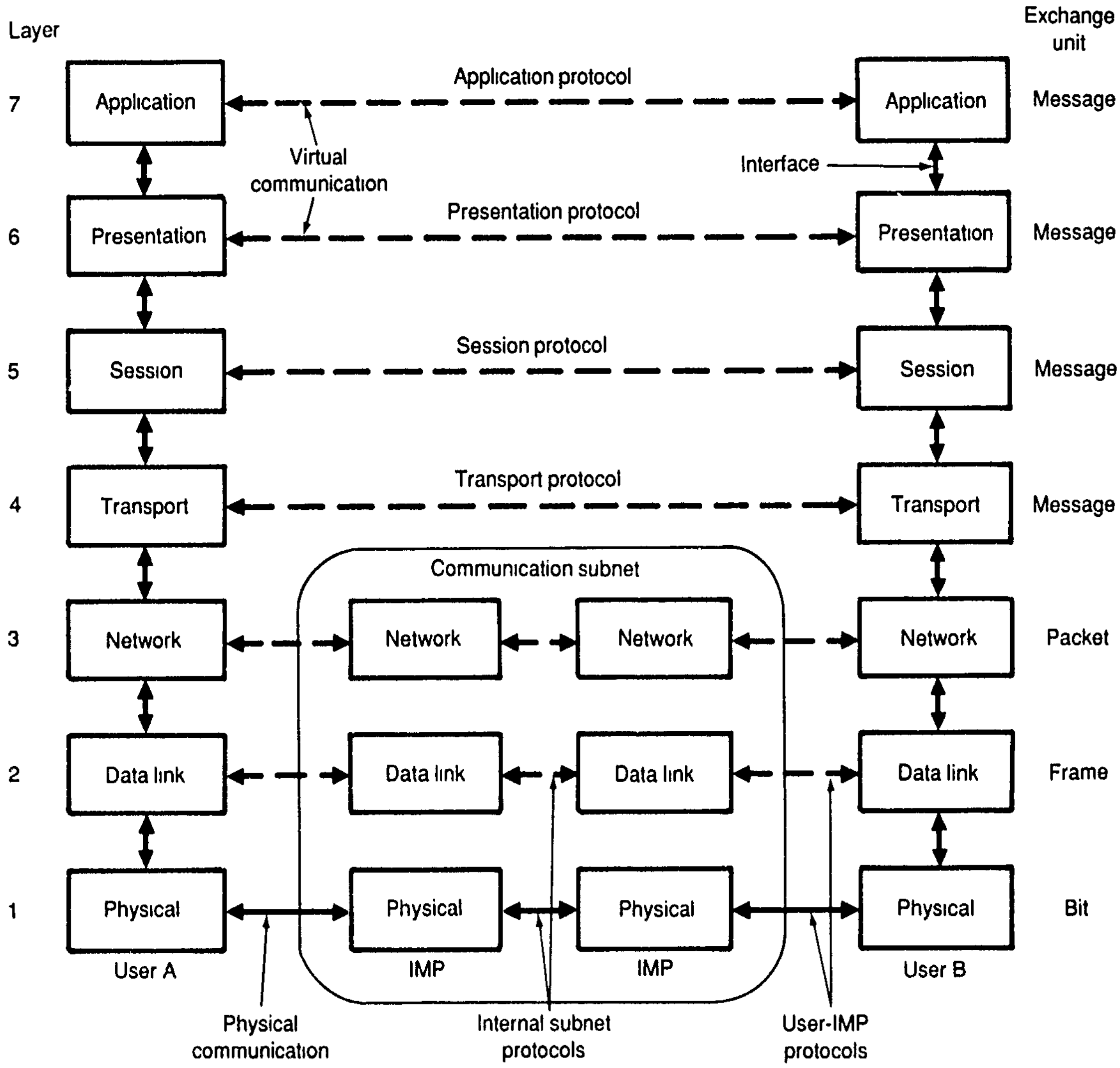

Fig. 3.1—The AMBER network architecture

Packets are formed and processed at the network layer, where routing and congestion control are handled. Packet reassembly and end-to-end acknowledgment are also at this level.

At the data-link layer, packets are formed into frames or fields designed to assure virtually error-free communication. Error control may include error detection, error correction, and repeat requests. (Error correction is discussed below and techniques for the statistical estimation of errors are described.) Buffering and other techniques for data flow control may be used in this layer.

Physical communication (layer 1) involves the transmission and reception of raw data bits. The physical links between users and their IMPs are provided by the auxiliary communication systems mentioned above. The modem, transmitter, and receivers at each AMBER node provide physical broadcast communication from its IMP to those at other AMBER nodes within reception range.

Traffic Switching

Traffic may be handled in one of two ways in its transfer from one user to another. The first is known as packet switching, in which the sender's data are formed into well-defined blocks called packets. These packets are sent from one IMP to another until they reach their destination.

The paths, or routes, that the packets follow through the subnet are established by routing algorithms that are discussed below. The paths may be established, as required, for the transmission of a given set of packets, in which case they are referred to as virtual circuits. The packets stream along these paths sequentially; virtual circuits may cross or coincide in part so packets from a number of users may be interspersed from time to time at a given node. To be useful for AMBER, the virtual circuits must be established by the packets themselves, rather than by a central controller. On a less organized basis, the paths may be determined individually, even stochastically, for each packet at each IMP, in which case the network is referred to as a store-and-forward network. Inasmuch as the various packets may follow considerably different routes in such a case, they may arrive out of order at the destination and require collating.

The second method of serving users is known as circuit switching. In this case, real circuits, dedicated specifically to the requesting users, are established.[4] The circuit may be one-way simplex, as might be required for a one way teletype link, in which case it would consist of a concatenation of one-way simplex links from the source IMP to the destination IMP via intermediate IMPs. The circuit may also be duplex, or two-way, as might be required for voice communication, in which case it could consist of either one duplex circuit or a pair of oppositely directed one-way simplex circuits. Only the latter appears feasible in AMBER.

Both packet switching and circuit switching are planned for AMBER. Circuit switching will be used to support teletype or voice communication, and packet switching will be used either to send formatted messages between users or to provide an order wire. The order wire provides the functional mechanism for establishing, maintaining, and finally dismantling the real or virtual circuits.

ERROR CONTROL

Error control, a function performed at the data-link layer of the network architecture, is particularly important in a network such as AMBER where the link qualities may be variable and often marginal. The problem is best understood by first examining the basic AMBER requirements for error control. The ways in which errors are produced can then be considered in light of these requirements to arrive at useful mitigation techniques.

Modes of Operation

Packet switching can be used in two ways: (1) to relay messages as datagrams, and (2) to provide an order wire. In both cases, virtually error-free transmission is required. For example, a typical military requirement might be for an end-to-end error probability of 10^{-6} for a

[4]The only difference between a real and a virtual circuit in AMBER is that a real circuit is dedicated

1000-bit datagram. Clearly, such a requirement reflects not only the importance of correct reception but the fact that formatted messages contain little or no natural redundancy that might otherwise make errors obvious. The requirement could be relaxed somewhat for an order wire whose continuous function provides the opportunity for correction by repetition, but avoiding errors in the first place is undoubtedly preferable. Except for certain special exceptions, both datagram transmission and order-wire operation can tolerate delays of many seconds or even minutes, thereby simplifying error control.

Circuit switching poses different requirements. Some users may require simplex (one-way) circuits for the transmission of continuous data streams, as for teletext or telefax. Others may require half-duplex (alternate one-way) or full-duplex (simultaneous two-way) circuits for teletype or voice communication. The simplex and half-duplex circuits can probably tolerate delays similar to those for datagrams. However, delays can be annoying in duplex circuits intended to support voice communication because delays of as little as one second can seriously inhibit conversation. Fortunately, the redundancy inherent in speech, even when digitized and compressed by VOCODERs, permits useful operation at error rates as high as about 1 in 10^3

Error Detection and Correction

When digital data must be transmitted accurately on a noisy channel, it is customary to add redundancy in a controlled manner so as to permit the detection and, if desired, the correction of errors. Error-control techniques fall into two general categories: (1) block coding, in which blocks, or groups, of information data bits have redundant bits added to them, and (2) convolutional coding, in which redundant bits are added continuously to a running set of information bits. Various specific codes of each type have been developed. As might be expected, they have considerably different characteristics as to their rates (the ratio of information to total bits), their powers (the numbers of errors that can be detected and corrected), their complexities (the computer power and memory required), and other characteristics (delay, robustness, cost, etc.). The problem is one of selecting the optimum design for a particular application considering its requirements and constraints.

Random and Burst Errors

If the source of errors is an uncorrelated random noise process, the result will usually be the occurrence of random single errors. (Double errors may occur occasionally: Triple, or still higher-order, errors are unlikely.) However, if the error source is a correlated one, whether noise or signal, the result will be bursts of random numbers of errors at random intervals. Codes exist for dealing with both single and burst random errors, usually doing one well at the expense of the other.

A particularly simple and effective technique, which will probably be used in AMBER, is block coding to correct random errors, in conjunction with interleaving to combat burst errors. The interleaving procedure is to randomize blocks of coded data. On reception, the deinterleaving procedure restores the coded data to the original sequence—as a result, bursts of errors become distributed randomly over the block. To be effective, the interleaving depth, i.e., the length of the block to be randomized, must be much greater than the length of the typical error burst that is anticipated. The buffering delay can be significant for long bursts, such as those induced by lightning or deep propagation fading, and have a significant impact on routing, delay, congestion, etc. This question deserves further study.

The AMBER Coding Problem

The AMBER network poses unique and difficult requirements for error control. A typical message may traverse many links in going from source to destination. Unlike applications in which there may be only one or two fairly stable links, AMBER offers concatenations of large numbers of diverse and variable links. If the link signal-to-noise ratios were stable, a bit error probability could be estimated or measured and used to specify the required level and type of coding to be used. In AMBER, it is more likely that a level and type of coding will be adopted after consideration of other relevant factors, and a minimum usable link signal-to-noise ratio or maximum allowable link bit error probability will then be established. The system-level problem will then be to determine whether or not a given link is usable.

Another approach to coding is to make it adaptive, that is, use only as much as is required on a given link. This has the advantage that it economizes the amount of coding needed, but it increases its complexity. It also ultimately causes a variable delay, which may not be tolerable.

In the case of a voice circuit, the problem is compounded by the fact that the failure of a link (perhaps as the result of a gradual degradation of its quality as the signal weakens or the noise intensifies) must be anticipated and the user switched to another circuit if there is not to be an annoying or unacceptable outage. In the case of a data circuit, the problem can be more serious. Unless the coding technique can unambiguously signal the existence of more errors than the code can correct, the result can be the reception of an erroneously decoded message that is apparently correct. Voice or text at least reduces to recognizable gibberish.

Ideally, coding and decoding for error control should be restricted to the source and destination user terminals and this will probably be done for transmissions on real or virtual circuits. The quality of the circuit will be assured, link by link, by other means and transmission can take place end-to-end in real time. This will not be possible for adaptively routed datagrams or order-wire packets because they contain headers bearing information that must be acted upon at each intermediate node. Thus, all or part of each packet must be decoded, modified as required, and then reencoded at each intermediate node quite apart from whether or not there are correctable errors. Clearly, the amount of such message processing must be minimized to reduce the delay encountered and the computing required en route.

Link Quality Estimation

The amount of coding that is required can be minimized by constantly monitoring each link to insure that it is virtually error-free. This process can also be used to anticipate the incipient inadequacy of a slowly degrading link, thereby permitting rerouting before link failure occurs. Unfortunately, this requires estimates of the quality of a link while it is still good, and therefore generating few, if any, errors. One way to estimate the quality of a link is to use a narrow-band signal-strength meter to measure the carrier power and a wide-band signal-strength meter to measure the total modulated-carrier-plus-noise power. If the signal-to-noise ratio is high, the signal power is approximately given by the latter. However, the noise power alone cannot be measured directly because of the presence of the signal in the channel.[5] As a result, the signal-to-noise ratio is not available directly.

[5] If an adjacent channel is not occupied, the noise power in the channel of interest can be taken to be equal to that in the adjacent channel. This assumes, as is usually seen to be the case, that the noise is "flat" over large portions of the AM broadcast band. There is also the problem of deciding, without human monitoring, that the adjacent channel is indeed not occupied

Another way is to estimate the bit error probability, which can be done by counting the number of errors over some suitable interval. Unfortunately, errors occur infrequently in operative links, so the time required to arrive at a good estimate may be excessive. For example, if the probability of error is 10^{-4}, there will be only one error, on the average, per 10^4 bits. Inasmuch as a good estimate requires the occurrence of no less than about 10 errors, about 1300 sec or 22 min would be required to observe the necessary 10^5 bits at a data rate of 75 bps.

Two techniques are available for estimating the error rate accurately in shorter periods of time. The first of these, which is described in detail in Ghazvinian et al. (1984), measures pseudo errors. Normally, the noisy received signal is compared with a detection threshold at the bit sampling times to arrive at a decision as to whether, say, a 0 or a 1 has been transmitted. If a large noise excursion causes the received signal to be on the "wrong" side of the detection threshold, a "real" error occurs.[6]

Inasmuch as such real errors occur too infrequently to be of practical value in estimating link quality, three extrapolation thresholds are established at appropriate levels on either side of the actual detection threshold. Then, the more frequent smaller noise excursions that are incapable of exceeding the detection threshold and causing real errors might cross the more easily reached extrapolation thresholds and cause "pseudo" errors.[7] It is possible, by this procedure, to reduce the time required to arrive at an estimate of the link error probability by a factor of about 10. (The procedure is akin to making soft decisions in decoding algorithms.)

An alternative to counting actual or pseudo errors to estimate the error rate is to examine the statistical properties of the received signal and use statistical estimation techniques to infer the error rate. The procedure is described in detail in Reed (1983). It is based on the assumption that the noise is a gaussian process and on prior knowledge of the set of transmitted data signal states. The fluctuations in the received signal are analyzed to arrive at estimates for the signal and noise powers, and, hence, a measure of the bit error probability on a bit-by-bit basis. These are then averaged over a suitable interval to arrive at the estimated average bit error probability. From this, a rejection criterion is developed to permit confident discarding of a message that may contain more errors than can be corrected or of a link that is no longer a usable element of a circuit.

A practical way to use this estimation technique would be to maintain an estimated accumulated error count in the header of each packet as it traverses the network. The body of the packet would then need to be corrected and reencoded only when the estimated error count nears the correctable limit.

PACKET ROUTING

As mentioned in connection with traffic switching, packet switching will be used in AMBER either to send formatted messages between users or to provide an order wire. Once formed, the order wire will provide the functional mechanism for establishing, maintaining, and finally dismantling the real or virtual circuits. Hence, the question of packet routing becomes central to the successful implementation of AMBER. The problem of routing packets in computer networks has received considerable attention. Many algorithms suitable to such networks have been devised and tested. Although much remains to be done to improve them

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[6]For the recipient to become aware that an error has occurred, he must (1) have prior knowledge of what was transmitted, as might be the case if the channel was being probed for errors with a specified test signal, or (2) employ an error detection and correction scheme to signal error occurrence

[7]For these pseudo errors to be interpreted correctly, the effects of real errors must be accounted for

and adapt them to emerging computer networks having special characteristics, there are many workable algorithms. Unfortunately, it does not appear possible to modify them in a simple way to make them suitable for use in AMBER.

The difficulty stems in part from the fact that all of the AMBER links are of the broadcast variety. Hence, they are inherently one-way. Also, the great differences that can exist between AMBER nodes because of different radiated powers, operating frequencies, local noise conditions, and propagation characteristics make it frequently possible for one station to be heard at another, but not vice versa, so direct duplex operation is usually not possible between a pair of nodes. Finally, the topology of AMBER can be expected to change frequently as stations enter or leave the network or as links become usable or fail. This factor can become important, or even dominating, if the network status must be reliably and rapidly disseminated.

Two routing algorithms capable of operating in AMBER have been devised—cellular routing, which is described in MILCOM, Inc. (1984), and receipt routing, which is described below. These are briefly discussed here to illustrate the considerably different approaches that are being considered; they are critiqued in Ghazvinian et al. (1984).

Cellular Routing

The cellular routing approach uses a decentralized adaptive routing algorithm that is appropriate to a network like AMBER, whose order wire is a low-data-rate system (75 bps) that may have many more nodes (1000 or more) than are found in computer networks. The application dictates that control of the network be distributed for survivability, so it is assumed that the algorithm must be decentralized. The variability of the network requires that the algorithm be adaptive to ensure timely and reliable delivery of messages and set-up of calls. However, although routing algorithms such as the one used in ARPANET are adaptive and decentralized, they cannot be used in AMBER because the combination of the low link data rate and the large number of nodes poses an overhead requirement for updating the network status database at each node that cannot be accommodated for practical rates of change of the network topology.

In cellular routing, the nodes of the network are separated into a nonoverlapping set of cells each containing a manageable number of nodes (e.g., 16). Fully adaptive routing can then be carried out in each cell without incurring an unacceptable communication overhead for establishing the cell-internal database that it requires.

Routing from a node in one cell to a node in another is accomplished by using a simpler cell-external database that can be maintained network-wide, again without incurring an unacceptable communication overhead. The algorithm identifies the preferred next cell from the cell-external database, then selects the optimum route to an appropriate border node from the cell-internal database.

The algorithm is suboptimum in the sense that the optimum cell-internal route to the border node of the next cell may not coincide with the optimum overall route from the source to the destination. The overall optimum route might go to a different border node or even to a different cell, if the destination node is in a still more distant cell. However, the reduced overhead requirement will justify the procedure if the loss in efficiency is not great.

Receipt Routing

In this approach, no attempt is made to establish and maintain a conventional network database at each node. It is reasoned that inasmuch as the purpose of such a database is to furnish a (local or global) picture of the network topology, and evaluate the costs (i.e., delays) of using the available links, then the same purpose can be achieved by probing at the time a packet is to be transmitted, and using the responses to arrive at the same information. It amounts to developing an ad hoc database when needed rather than maintaining a continuously updated one.

In receipt routing, the probing is done by simply broadcasting the packet that is to be forwarded. The recipient nodes advise the radiating node and one another of successful receipt by transmitting acknowledgments that also give their individual queue lengths or other appropriate measures of their suitability to serve as nodes for subsequent relay. When this process is completed, the recipient nodes each have the same basic data about one another. Each recipient node uses these data in a uniform procedure to determine which of their number is best suited to relay the packet. Depending on the effectiveness of the receipt acknowledgment exchange process, the result will be an unambiguous mutual agreement.

Receipt routing is suboptimum because knowledge of the network topology and queue status is limited to the recipient-node set. It is, in fact, a highly limited form of flooding, which may be sparing of communication overhead when traffic is light, but inefficient when traffic is heavy. However, it may be highly effective in taking advantage of the unpredictable long-range links that can often be expected in AMBER (e.g., as a result of skywave).

The nationwide computer simulation described in Sec. VIII does not yet contain either a random message generator to simulate offered traffic or a routing algorithm to set up the required virtual circuits. More research is required to determine whether or not cellular or receipt routing is practical. Other approaches should also be considered.

IV. TECHNICAL CONSIDERATIONS

INTRODUCTION

The technical feasibility of AMBER depends on successfully engineering a complex communication system. To achieve this goal, a number of technical issues must be considered. Some of these are discussed in an elementary way below to illustrate the practical and technological constraints that must be observed in configuring AMBER.

The AM broadcast band extends from 535 to 1605 kHz in the MF band. Carrier frequencies are designated at every 10 kHz from 540 to 1600 kHz. However, only every other one is allocated in a given area. Most stations use program material extending to only 5 kHz; given the double sideband nature of AM, this causes them to occupy only a 10 kHz band, which constitutes a nominal channel. The unused adjacent channels then serve as guard bands against other nearby stations operating at the next-adjacent carrier frequencies. In these terms, the AM broadcast band can be said to consist of 107 10 kHz channels.

A few high-fidelity stations currently use program material extending to 7 or 8 kHz so that their spectra extend 2 to 3 kHz into the adjacent (guard-band) channels.

MODULATION TECHNIQUES

The modulation techniques available to AMBER are AM, PM, or hybrid AM/PM, which is a combination of the two. Their general characteristics are given below.

Amplitude Modulation

This linear process results in a signal whose spectrum has a width equal to twice that of the modulating signal. Its spectrum consists of a carrier and two mirror-image sidebands whose shapes are identical with that of the modulating signal. As a result, questions of spectrum control and channel occupancy are largely restricted to eliminating imperfections in transmitter design. Amplitude modulation is inefficient because the modulated signal consists of a carrier that contains about 75 to 80 percent of the average power but bears no intelligence; information is conveyed only in the two sidebands that contain the balance of the power. Thus, if an existing commercial AM transmitter is used to send data, there will be a wasteful carrier present.[1]

Phase Modulation

This nonlinear process results in a signal whose spectrum is theoretically infinitely wide. However, in practical cases, most of the power is contained in the vicinity of the carrier frequency. The power spectrum consists of symmetrical sidebands. Modern forms of digital phase modulation, such as SFSK, can be used to reduce the magnitude and extent of these sidebands. For practical data transmission systems, the resulting PM spectrum has about the same "width" as that of an AM signal.

[1]Ordinary AM receivers, which are asynchronous, use envelope detectors that require the presence of the carrier. This inefficient system of transmission and reception continues in use because it is adequate to the purpose, and because there is a large investment in transmitters and receivers

Phase modulation is more efficient than conventional AM because the modulating process requires no power; when properly implemented, the carrier disappears as all of its power is converted into useful information-conveying power. This not only results in greater link reliability or transmitting range but also in greater postattack station endurance, because a station operating on auxiliary power from a limited fuel supply needs less power if it is using PM rather than AM with a carrier.

Another advantage of phase modulation is that no modifications need be made to the radio station baseband (i.e., audio) equipment, as would be the case with AM. This is because phase modulation can be performed on the carrier reference oscillator external to the transmitter amplifier chain and audio modulator stage. The crisis/postattack capability can therefore be embedded in the peacetime modulator software, and the switchover to the crisis/postattack mode need only entail cessation of amplitude modulation.

Hybrid AM/PM

Roughly speaking, this modulation scheme superposes the spectral properties of AM and PM[2] so that the channel can be "doubly occupied." However, calculations of the properties of specific schemes can become very complex and much research remains to be done to identify the most desirable embodiments. The distortions experienced by the amplitude and phase demodulation of such hybrid AM/PM signals when passed through practical bandpass filters are treated in Bedrosian (1986).

Bandwidth Compression

Another aspect of efficient signaling, which is closely related to the modulating schemes discussed above, is the development of techniques for reducing the bandwidth occupancy of data-bearing signals. The bandwidth of a signal is given roughly by the rate at which symbols are transmitted. For binary systems, each symbol contains one bit of information, and the information spectral occupancy for practical waveshapes is about 1 bps/Hz. When used directly to form an AM signal or with SFSK to form a PM signal, the result will have a two-sided spectrum with an information spectral occupancy of about 1/2 bps/Hz in the RF (radio frequency) channel. Thus, a conventional AM or SFSK PM signal occupying a 10 kHz channel can transmit binary data at a rate of about 5 kbps.

It is a straightforward matter to increase the number of bits per symbol and thereby increase the transmitted data rate by any desired amount. For example, structuring the signal to contain 4 bits/symbol will quadruple the data rate without increasing the signal bandwidth. However, such an elementary form of bandwidth compression is inefficient in terms of the exponentially increased signal-to-noise ratio required to achieve a given error rate.

Interest in signaling at high rates through channels that cannot be widened has spurred interest in recent years in devising bandwidth compression schemes that conserve power. As a result, many new techniques have been discovered though much remains to be done in understanding their characteristics adequately.

For the most part, the good bandwidth compression schemes use complex symbol waveforms that overlap one another in time, often substantially. By the use of coding and proper symbol design, it is possible to send 2 to 4 bps/Hz with power penalties of about only 10

[2]The exact spectrum is the convolution of the AM and PM spectra. As a result, its "width" is somewhat greater than that produced by either phase or amplitude modulation alone.

to 20 dB, as shown in Fig. 4.1. The Shannon channel capacity is valid only for a noise-like modulated signal—the heuristic channel capacity applies to modulated signals of constant amplitude such as the PM signal used in AMBER. The data points indicate that practical systems are within about 5 dB of the theoretical limit. The results differ, of course, according to the type of modulation that is used, but the results appear promising as a means for accommodating more voice channels per AMBER station. However, the robustness of these techniques must be better understood before they can be considered for use in AMBER. The complexity of the coding and signal processing used in these schemes also raises the question as to how rapidly they can recover when they are disturbed or an error is made. Some of these issues are discussed in Zakhor and Bedrosian (1985).

VOCODER TECHNOLOGY

The final technical area of importance is that of VOCODER performance and availability. High-quality voice transmission by ordinary analog techniques requires about 4.8 kHz of bandwidth. When digitized and quantized into high-quality PCM (pulse code modulation), a data rate of about 48,000 bps would be required.[3] A VOCODER is a device that uses linear predictive coding (LPC) to remove the redundancy from speech without significantly affecting its quality or intelligibility. High-quality LDR (low data rate) VOCODERs operating at 2400 bps are commercially available and there is currently an effort to encourage widespread use of such a device (the LPC-10) in the government and the military (Federal Standard, 1984).

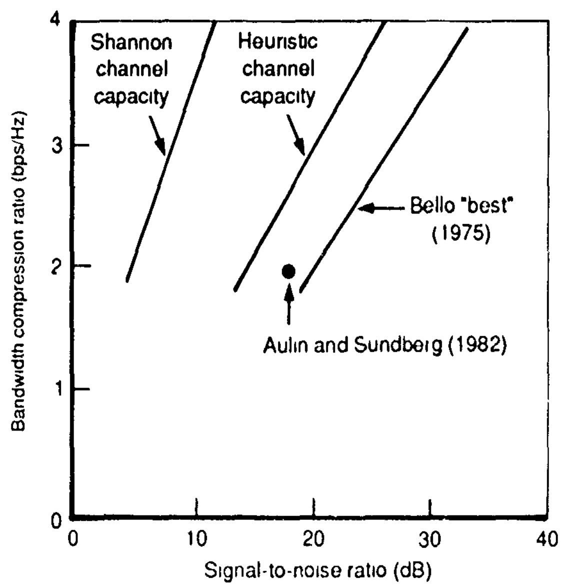


Fig. 4.1—Power tradeoff for bandwidth compression

[3]The minimum sample rate is equal numerically to twice the bandwidth, or 9600 samples per sec. Quantizing to 32 levels produces an information content of 5 bits per sample leading to a data rate of 48 kbps. Other data rates result from differing bandwidths and numbers of quantization levels

One VLDR (very low data rate) VOCODER is available as an engineering prototype. Developed at Lincoln Laboratory, it operates at 1200 bps by deleting alternate frames generated in the conventional 2400 bps LPC VOCODERs (Paul, 1984). Its quality and intelligibility are almost as good as that of the 2400 bps LPC-10. Other VLDR VOCODERs, developed at TRW (Fransen, 1983) and Lincoln Laboratory (Paul, 1982, 1983), use pattern matching (also known as vector quantization or block encoding) (Gersho and Cuperman, 1983) to reduce the data rate by quantizing the data contained in a sequence of frames into prespecified patterns. They achieve data rates of 800 bps or less but have reduced intelligibility and quality. They also require a substantial computational capability and are not available as engineering prototypes.

A number of ULDR (ultra low data rate) VOCODERs are in the research stage (Roucos, Schwartz, and Makhoul, 1982a, 1982b; Schwartz and Roucos, 1983). They further reduce the data rate by refining the pattern-matching techniques used in the VLDR VOCODERs, and introducing adaptation or tailoring. In adaptation, the VOCODER adjusts its filter parameters as the user speaks to adapt its speech analysis and synthesis process uniquely to the user and thereby further remove speech redundancy. In tailoring, the speech patterns of prospective users are analyzed beforehand to furnish a key (to be presented by the user when he requests a circuit) that permits optimum modeling and redundancy removal. Data rates as low as 150 bps with acceptable quality have been reported (Roucos, Schwartz, and Makhoul, 1983). Unfortunately, these techniques require large amounts of computer memory and are not likely to be available in the near future, even as engineering prototypes. Limited production may be many years off. It should be noted that both adaptation and tailoring entail a time delay of a minute or more to permit the receiving VOCODER to establish the appropriate set of patterns against which to match. Speech slurring and tone monotony inevitably increase as the data rate is lowered—speaker and, even, sex recognition can be lost at the very low data rates.

PERFORMANCE ESTIMATES

The operational concept and the technical considerations are brought together here to arrive at performance estimates for AMBER at various levels of technology. These are displayed in matrix form to facilitate comparison.

Four levels of technology can be identified as suitable for the near-term implementation of AMBER:

1. **State-of-the-art signal processing.** This refers to the use of conventional signal-processing techniques. These are robust and well understood with data-handling capacities of about 1 bps/Hz; their use entails little risk.
2. **Advanced signal processing.** This refers to the use of bandwidth compression techniques capable of data-handling capacities of 2 to 4 bps/Hz. This increasingly risky approach offers a two- to fourfold increase in capacity over the state of the art. Fortunately, it can be implemented in an evolutionary manner as improvements are developed.
3. **Standard VOCODER.** This refers to the use of LDR VOCODERs (2400 bps). Inasmuch as such VOCODERs are currently available, this level has low risk. Also, although they provide a reduced, though still useful, capability in comparison with advanced VOCODERs, they may be easier to integrate into other communication systems as the numbers of VOCODERs in use grow.

4. **Advanced VOCODER.** This refers to the use of VLDR (1200 bps) or ULDR (600 bps) VOCODERs. This approach has the additional cost and delay associated with getting such VOCODERs into limited production but offers a significant increase in capacity over the state-of-the-art approach.

Normal Peacetime Mode

There is no choice but to use PM (e.g., with SFSK) in this mode to transmit data as the station continues to use AM to air its regular program material. To be noninterfering, the data stream must be limited to a bandwidth of about 150 Hz. With state-of-the-art signal processing, the usable data rate will be about 150 bps, which can be used to provide one LDR order-wire channel per station. (Only a very efficient 150 bps ULDR VOCODER, which is not considered to be available in the near term, could be used to provide voice at such low data rates.)

At the advanced-signal-processing level of technology, bandwidth compression of up to 4 bps/Hz will increase the usable data rate to as much as 600 bps. This can be used to provide one high-data-rate order-wire channel per station or one low-data-rate order-wire channel, and one 600 bps ULDR VOCODER voice channel per station.

These performance estimates are summarized in Table 4.1. It is seen that if the noninterfering, peacetime mode of operation is to be implemented as described above, it will be necessary to pursue its development at the advanced level of both signal-processing and VOCODER technologies. It may even be necessary to spur the development of ULDR VOCODER, at least for demonstration purposes.

Crisis/Postattack Mode

When a radio station stops using AM to air its program material, the entire broadcast channel is available for data transmission. Thus, any of the modulation schemes (AM, PM, or hybrid AM/PM) can be used. Rough estimates of AMBER voice-channel capacities per station can be obtained by considering each of the three modulation methods with the various combinations of levels of technology. The resulting performance matrix is shown in Table 4.2. (Though not explicitly introduced into the computations, it is assumed that a suitable fraction of the station capacity is set aside for use as a high-data-rate order-wire channel.)

Table 4.1

AMBER PERFORMANCE PER STATION, NORMAL PEACETIME MODE (PHASE MODULATION)

Levels of Technology	State-of-the-Art Signal Processing (150 bps)	Advanced Signal Processing (600 bps)
Standard VOCODER (2400 bps)	1 low-data-rate order wire, no voice	1 high-data-rate order wire, no voice
Advanced VOCODER (600 bps)	1 low-data-rate order wire, no voice	1 high-data-rate order wire or 1 low-data-rate order wire plus 1 voice channel

Table 4.2

AMBER PERFORMANCE PER STATION, CRISIS/POSTATTACK MODE (NUMBERS OF VOICE CHANNELS PER STATION)

	State-of-the-Art Signal Processing (1 bps/Hz)		Advanced Signal Processing (2 bps/Hz)	
Modulation Scheme	Standard VOCODER (2400 bps)	Advanced VOCODER (1200 bps)	Standard VOCODER (2400 bps)	Advanced VOCODER (1200 bps)
Pure AM	2-4	4-8	4-16	8-32
Pure PM	2-4	4-8	4-16	8-32
Hybrid AM/PM	4-8	8-16	8-32	16-64

The ranges of numbers in Table 4.2 were obtained by considering combinations of 5 to 10 kHz modulation bandwidth (10 to 20 kHz channel bandwidth); 2400 bps for the standard VOCODER; 1200 bps for the advanced VOCODER; 1 bps/Hz for standard signal processing; and 2 bps/Hz for advanced signal processing. Amplitude and phase modulation (with SFSK) were considered equivalent in being able to accommodate 1 bps/Hz in their modulation bandwidths; hybrid AM/PM was assumed to be able to modulate at 2 bps/Hz. As an example, the 8-32 entry for the pure PM modulation scheme at the advanced VOCODER and advanced-signal-processing levels of technology comes from first considering 1200 bps VOCODERs in 5 kHz using 2 bps/Hz to arrive at eight channels, or in 10 kHz using 4 bps/Hz to arrive at 32 channels.

With respect to the state-of-the-art signal-processing-level of technology, the ranges are fairly meaningful. This is because they relate to parameters, such as the modulation bandwidth, that are well understood. This is less the case with the advanced-signal-processing-level of technology because the practicability of these schemes relates to their threshold signal-to-noise ratio requirements and robustness, as well as to their bandwidth compression capabilities. Thus, the entries are more nearly worst case/best case, and practical values are no doubt somewhere near the center of the indicated ranges.

V. PRELIMINARY COST ESTIMATES

THE AMBER PACKAGE

The costs of providing a broadcast station with the AMBER equipment package, plus installation and acceptance testing, were determined from commercial equipment analogs and estimates by Altran Electronics, based on their own in-house commercial development of similar equipment for load management.[1] The AMBER equipment package is assumed to be built to commercial rather than military standards and specifications to achieve the lowest possible cost at a given level of reliability. In general, commercial equipment differs from military equipment—in mechanical packaging, grades of components used, environmental qualification, support and engineering documentation, and amount of built-in self-test features. Because of these differences, commercially procured equipment costs less. The resulting estimated costs are summarized in Table 5.1.

FEMA BSPP AND EMP PACKAGES

By the beginning of FY 85 FEMA had provided BSPP packages to 596 AM stations at an average cost of $70,000 and EMP protection packages at an average cost of $2,500 to 89 of those with the BSPP package. These stations are characterized as being "inside" or "outside" a 2 psi overpressure area created by a hypothetical Soviet nuclear attack (FEMA, 1979). Of the 596 AM stations with the BSPP package, 265 are inside and 331 are outside the 2 psi area. Of the EMP protected stations, 41 are inside and 44 are outside the 2 psi area.

The FEMA BSPP package consists of the following elements:

Table 5.1

ESTIMATED AMBER COSTS PER NODE

AMBER modem		
Multichannel receiver and antenna	$20,000	
Phase modulator	$20,000	
Microcomputer (interleaving, error control, communication security, message processing, etc.)	$30,000	$70,000
User-access modem		
Multiband receiver and antenna	$10,000	$10,000
General		
Spares	$12,000	
Installation and acceptance testing	$4,000	$16,000
Total		$96,000

[1]Altran Electronics, now RTT (Radio Telecom and Technology), is the subcontractor that produced the modulation and demodulation equipment reported in Sec. VI.

Fallout shelter: 50 square feet per person, minimum floor area of 150 square feet, maximum floor area of 300 square feet, located at either the studio or the transmitter (which is the preferred location).

Programming facilities (installed in the shelter): wiring and terminal facilities for connecting shelter equipment as necessary; channel mixer, control equipment and remote amplifier, turntable or tape recorder and player, microphone, console.

Emergency generator (outside the shelter): large enough to permit full broadcast of assigned power plus additional capacity for lighting, cooling, and ventilating the shelter and equipment.

14-day operational capability: fuel, food, and supplies for 14 days.

Remote pickup units, if authorized: to provide a communication link between the station and the emergency operating center; they include a transmitter, receiver, antenna, and necessary connections to existing equipment.

EMP protection package: to protect against directly induced transients into system circuits, conducted transients from power lines and other long external conductors, and pulse energies collected by large broadcast antenna.

ILLUSTRATIVE EXAMPLES

For illustrative purposes the following cases provide cost estimates for adding the AMBER package and, where required, additional FEMA BSPP and EMP protection packages to different station groupings of interest. The first case is for an IOC obtained by selecting 100 FEMA-protected stations capable of providing CONUS-wide coverage. The second case considers a basic survivable system incorporating 200 selected FEMA-protected stations. The third case considers an augmented survivable system that includes all 596 FEMA-protected stations. Case 4 considers an enhanced survivable system that adds an additional 118 stations thereby including all CPCS-1 stations, which are the entry points for local operating regions in the Emergency Broadcast System.

Case 1: IOC (100 selected FEMA-protected stations): $9.7 million
Case 2: basic survivable system (200 selected FEMA-protected stations): $19.5 million
Case 3: augmented survivable system (all 596 FEMA-protected stations): $58.3 million
Case 4: enhanced survivable system (714 stations, including all FEMA-protected and CPCS-1 stations): $77.9 million

VI. THE AMBER DATA LINK

INTRODUCTION

In this section, the data links that interconnect the AMBER nodes are examined. A typical data link consists of a phase modulator that impresses the AMBER data stream onto the carrier of an AM station; the amplifiers and the amplitude modulator that impresses the normal audio program material onto the amplified phase-modulated carrier; the channel in which the radiated signal propagates, often imperfectly, and in which the signal is corrupted by noise; and the AMBER receiver that demodulates the signal to obtain the relayed data stream. Also of interest is the typical AM receiver whose output may contain interference introduced by the phase modulation.

The engineering objective in the AMBER peacetime data link is to achieve as efficient a transmission of data as possible without interfering with AM receivers. The basic parameters of interest are the data rate, which is to be maximized, and the signal-to-noise ratio required for a specified data bit error probability, which is to be minimized. The design procedure consists of analyzing the various phase-modulation schemes that are available to determine which one best meets the requirement. This requires analyzing these schemes to determine their relevant properties and to see how these properties are affected by imperfections in the transmitter and receiver and disturbances in the propagation channel. The analytical treatment is augmented by computer simulation to verify the theoretical results and to take care of cases that are impractical to analyze theoretically. It is further augmented by laboratory and field testing to demonstrate the performance of real equipment in the real world.

The work to date is summarized in this section to provide a convenient overview. It is drawn largely from Ghazvinian et al. (1984) and Martinez and Landsman (1984), in which it is described in detail.

ANALYSIS

The idea of interconnecting existing AM broadcast stations to form a CONUS-wide emergency communication network is not new. For example, Lindholm (1962) examined the feasibility of such a network in the southwestern United States. That work was based on pioneering studies by Baran (1962a, 1962b) and considered signal propagation and noise conditions in generating a usable network with computer assistance. Little attention was focused on modulation methods because feasibility was suspected to hinge strongly (as it does today) on the networking problems introduced by the variable propagation conditions, and high levels of impulsive noise known to exist in the AM broadcast band (535 to 1605 kHz). It was generally held that a few teletype or one voice channel could be supported by using a station's existing amplitude-modulating equipment. Alternatively, it was speculated that a teletype channel could be supported without interrupting normal programming by using narrowband FSK (frequency shift keying).

The FSK approach was tested successfully in 1966 in the northeastern United States (Griffith et al., 1966) but interest in the basic concept was not sustained. A few years later, the idea was revived in modified form using a more sophisticated phase-modulation scheme and operating in the LF band (about 200 kHz) (Ramsey, 1981). Initially, the plan was to modify existing AM radio stations to permit diplex operation (i.e., for the AM radio station at MF, and the network data section at LF, to use the AM broadcast station's antenna at the same time). It soon became apparent that it would be preferable, and perhaps no more expensive, to use dedicated stations. This work led to the GWEN system (Kvitky, Burger, and Scheckelles, 1983), which is currently under development (see Appendix A).

The AMBER approach is a return to the original concept of using existing AM broadcast stations but with modern phase-modulation techniques. To facilitate early development and take advantage of commercial developments in electric power load-management and distribution automation, the initial AMBER feasibility study was awarded to Altran Electronics, which had developed and marketed this concept (Martinez, 1981).

The commercial electric power load-management system has a low-data-rate control link formed by using a small-angle phase modulation that does not interfere with standard AM broadcasting. This phase-modulation technique, called Sinusoidal Manchester On-Off, is adequate for the electric power load-management application, but it was felt that a more efficient modulation technique should be used in AMBER to improve its performance. For this reason, an approach known as MSK (minimum shift keying) was initially favored because of its superior signaling and spectral properties (Martinez and Landsman, 1982). Based on the known performance of Sinusoidal Manchester On-Off at 20 bps, and on a comparison of the spectral and signaling properties of Sinusoidal Manchester On-Off with those of MSK, it was believed that interference-free operation could be achieved at 75 bps using MSK.

At the inception of the present study, a premium was attached to early on-the-air experiments. As a result, it was decided that the development of a 75 bps MSK modulator and receiver should be deferred. Instead, the already operating 20 bps Sinusoidal Manchester On-Off modulator was improved and its data rate increased to 75 bps. (The improvement, which entailed finer quantization of the modulation waveform in time and amplitude, and increases in the data rate and the modulation index, is discussed in more detail below.) It was felt that gaining early experience with actual propagation conditions outweighed the poorer performance, the effect of which could be accounted for by using the known theoretical properties of Sinusoidal Manchester On-Off and MSK. However, for comparative purposes the analytical properties of SFSK—a more efficient scheme—were also considered.

In the following, the spectral and signaling properties of these and other modulation techniques are compared using results obtained from theoretical calculations and computer simulations.

Modulation Waveforms

A waveform that is simultaneously modulated in both amplitude and phase can be written

$$s(t) = A(t) \cos [2\pi f_c t + \theta m(t)] \tag{6.1}$$

where $A(t)$ is the amplitude modulation, f_c is the carrier frequency, and $\theta m(t)$ is the phase modulation. The interest here is in phase modulation so $A(t)$ is disregarded; the modulation waveform, $m(t)$, is chosen to have a peak amplitude of unity, so θ is the peak phase deviation. For data modulation, it is convenient to characterize the phase-modulating waveform as $m_0(t)$ and $m_1(t)$, which represent, respectively, the waveforms to be used in transmitting the data bits 0 and 1. The waveforms for the phase-modulation techniques of principal interest are shown in Fig. 6.1. The bit length is equal to T_b.

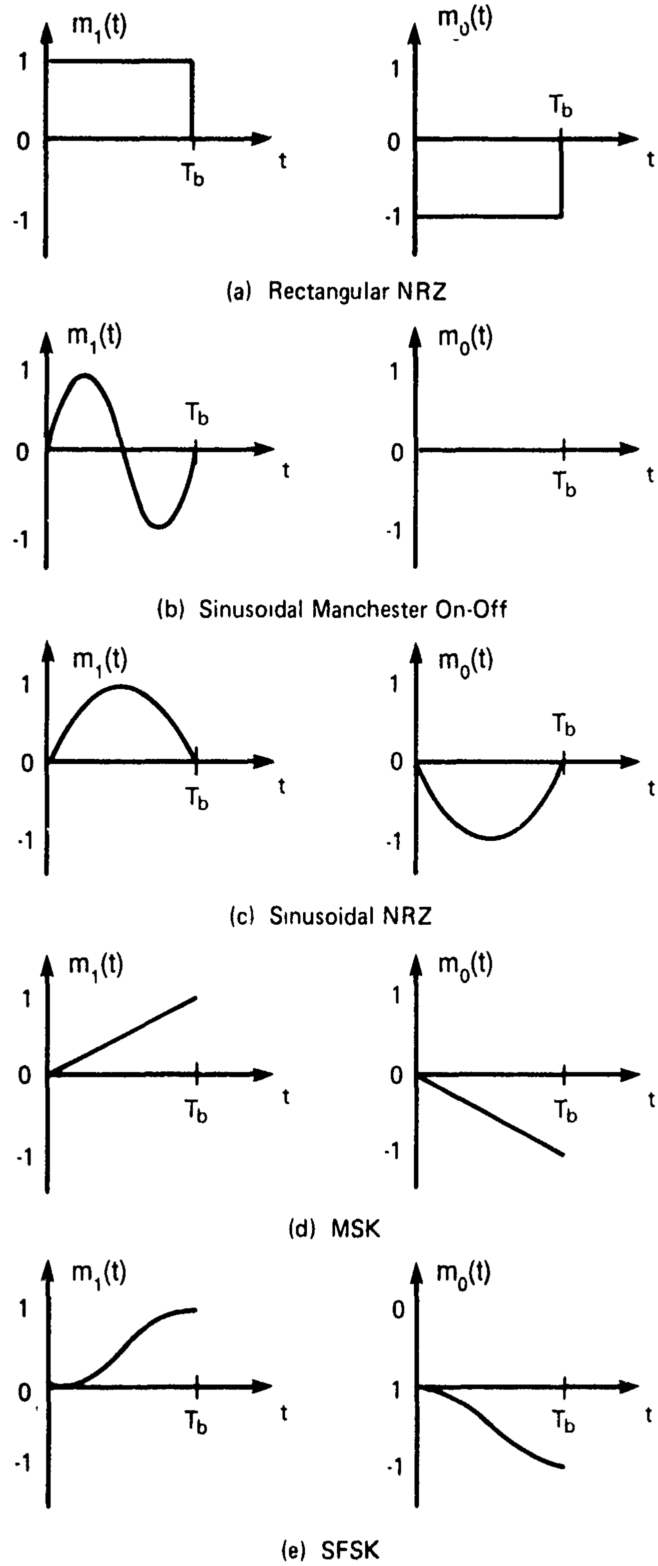


Fig. 6.1—Phase-modulation waveforms

The Rectangular NRZ (Non-Return to Zero) waveform shown in Fig. 6.1(a) is the elementary one usually taken as the basic reference. During each bit interval, the carrier phase is either advanced or retarded by an amount θ and held at that value throughout the bit interval. When $\theta = \pi/2$ (90 deg), it is known as BPSK (binary phase shift keying) and the signaling is optimum with respect to noise immunity, although the spectrum has excessive sidelobe levels, as will be shown.

The Sinusoidal Manchester On-Off waveform is shown in Fig. 6.1(b). With $\theta = \pi/6$ (30 deg), it is the waveform used by Altran in its commercial load-management application. In the DARPA application, it can be modulated up to $\theta = \pi/2$. The Sinusoidal NRZ waveform shown in Fig. 6.1(c) is a smoothed form of Rectangular NRZ that is included to facilitate comparison.

The MSK and SFSK waveforms shown in Figs. 6.1(d) and (e), respectively, are intended to be used with a peak phase deviation, $\theta = \pi/2$. They are, like BPSK, optimum with respect to noise, but have much more desirable spectral properties. Unlike the other waveforms, which return to a reference value at the end of a bit interval, MSK and SFSK can accumulate phase in the course of modulation, thereby often leading to large phase excursions that must be reduced modulo 2π for analysis and demodulation.

Modulation Spectra

The power spectrum of a signal, *s(t)*, is given by

$$S(f) = \left|Fs(t)\right|^2 = \left|\int_{-\infty}^{\infty} s(t)e^{-i2\pi ft}dt\right|^2 \tag{6.2}$$

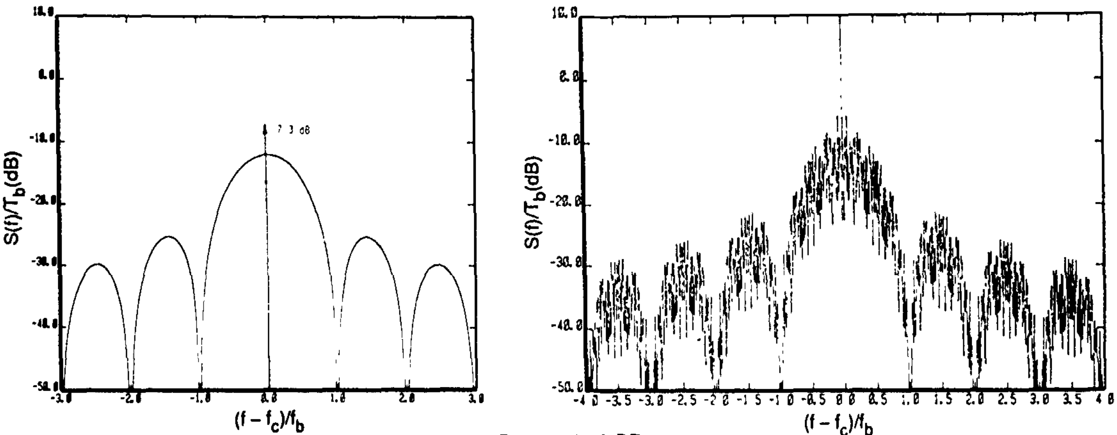
where F denotes the Fourier transform. When the signal is modulated by data waveforms that depend on the data sequence to be transmitted, the power spectrum is calculated by assuming that the data sequence is random. In some cases, this can be done analytically, but in others it is necessary to use computer simulations in which pseudo-random sequences are used. Both methods are used here; they are distinguishable by the sharp amplitude variations induced in the spectra by the simulation procedure.

It is customary to show the power spectra of modulated waveforms only for positive frequencies, because mirror symmetry exists for negative frequencies. Also, it is convenient to plot the spectra about the carrier frequency, f_c, and normalize the abscissa to the data rate, $f_b = 1/T_b$. This is done in the plots that follow; thus, an abscissa value 0 refers to the carrier frequency, f_c; $\pm$ 1 to $f_c \pm 1/T_b$; $\pm$ 2 to $f_c \pm 2/T_b$; etc. The ordinates show the power spectral density normalized to the bit length, T_b. Also shown are discrete components representing the carrier component or other tones in the modulated spectrum. Inasmuch as *A(t)* was taken as unity in Eq. (6.1), the total power in the modulated signal has a reference value of 0.5 and the total power in each plotted spectrum is equal to 0.25 because only positive frequencies are shown.

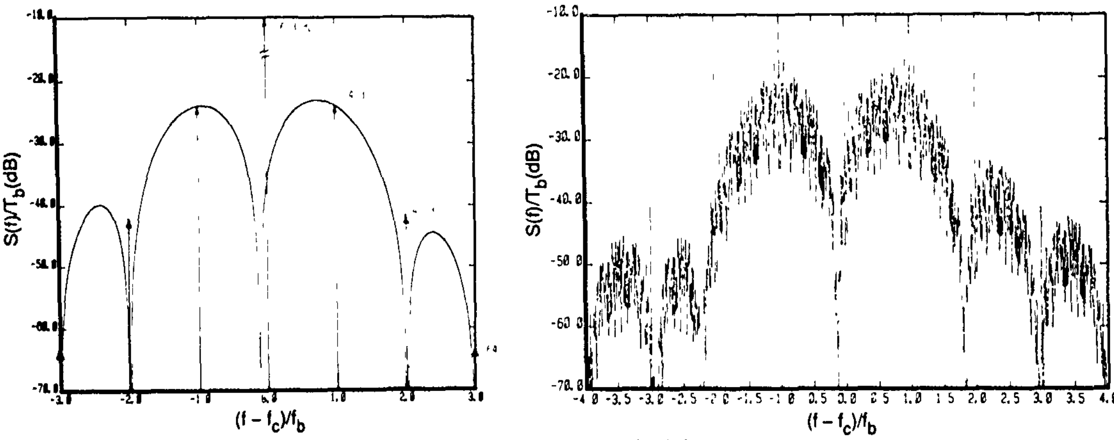
The normalized power spectra for Rectangular NRZ, Sinusoidal Manchester On-Off, and Sinusoidal NRZ, all for $\theta = \pi/6$, are shown in Fig. 6.2. Both theoretical and simulation results are shown to demonstrate the capability of the simulation in duplicating theoretical results.

The Sinusoidal Manchester On-Off spectrum shown in Fig. 6.2(b) for $\theta = \pi/6$ is, except for the effect of quantization, the spectrum of the current load-management system. It is characterized by a discrete carrier component and side tones at multiples of the data rate. The continuous part of the spectrum has unique, unsymmetrical mainlobes roughly centered on the carrier frequency. The spectral width (between the first zeros of the spectrum) is equal to $4f_b$.

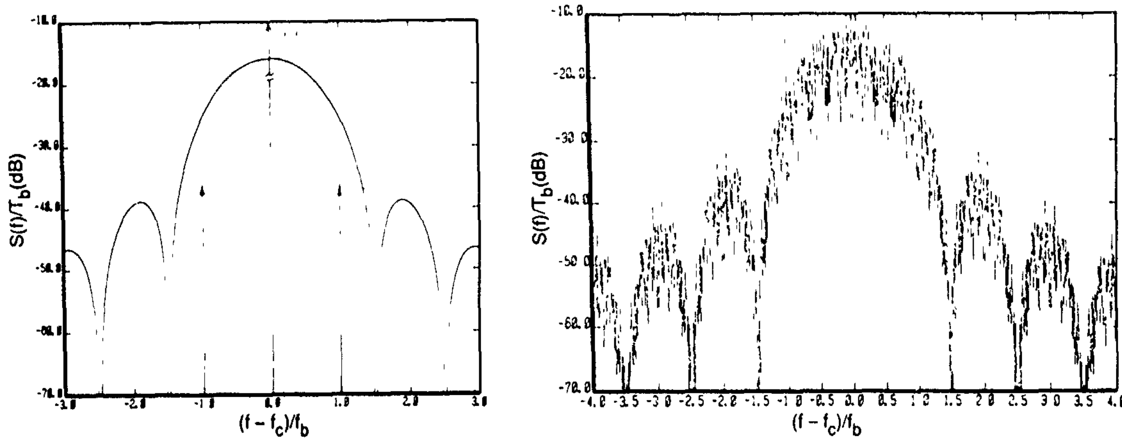
Theoretical Simulation



(a) Rectangular NRZ



(b) Sinusoidal Manchester On-Off



(c) Sinusoidal NRZ

Fig. 6.2—Normalized power spectra for $\theta = \pi/6$

In contrast, the spectra for Rectangular (Fig. 6.2(a)) and Sinusoidal (Fig. 6.2(c)) NRZ have but a single mainlobe with widths of $2f_b$ and $3f_b$, respectively. The spectra of Rectangular and Sinusoidal NRZ both contain discrete carrier components, and, although the spectrum of Sinusoidal NRZ contains tones at multiples of the data rate, these are negligible in comparison with those of Sinusoidal Manchester On-Off.

The result of increasing the modulation index to $\pi/2$ is shown in Fig. 6.3 for the same three schemes. The effect on Rectangular NRZ (BPSK) is seen in Fig. 6.3(a) to be the complete deletion of the carrier with no change in spectral shape. For Sinusoidal NRZ in Fig. 6.3(c), the discrete carrier and tones are reduced in power, the mainlobe is narrowed somewhat, and the sidelobes are slightly greater but the change is not significant. The effect on Sinusoidal Manchester On-Off in Fig. 6.3(b), however, is drastic; the asymmetry has become marked and the lower mainlobe has coalesced with the first lower sidelobe. In addition, the sidelobe levels have increased.

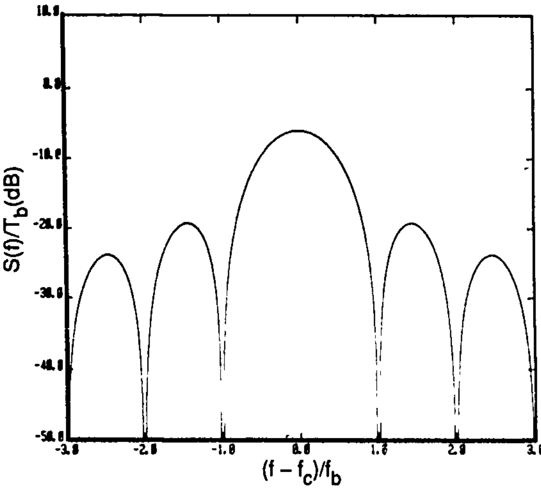
The quantization of the Sinusoidal Manchester On-Off waveform alluded to above is illustrated in Fig. 6.4. Such quantization is a natural consequence of synthesizing modulation waveforms digitally, which is the preferred implementation. Inasmuch as this is likely to be the case for other modulation schemes as well, it is instructive to determine the effect of such quantization on Sinusoidal Manchester On-Off as an example. The normalized spectrum of the embodiment currently used by Altran for load management is shown in Fig. 6.5(a); the modulator has 15 quantization levels in amplitude and 32 time slots or steps per data bit. The corresponding spectrum of the nonquantized waveform is shown in Fig. 6.5(b), from which it can be seen that there are some differences in the continuous parts of the spectra outside the mainlobes. The principal difference is the significant increase of the side tones in the discrete spectrum. The improved Sinusoidal Manchester On-Off modulator uses 128 quantization levels in amplitude and 256 time steps. Its spectrum is indistinguishable from that of the nonquantized case, as indicated in Fig. 6.5(b).

The spectral behavior of advanced phase-modulation techniques is illustrated in Fig. 6.6. The spectrum of Sinusoidal Manchester On-Off is shown, for comparison, in Fig. 6.6(a) (same as Fig. 6.5(b)). The contrast with MSK in Fig. 6.6(b) and SFSK in Fig. 6.6(a) is striking. These spectra have no carrier component or side tones and have a single mainlobe or width of about $1.5f_b$ and rapidly diminishing sidelobes, particularly for SFSK. In addition, they both have the same optimum performance with respect to noise as BPSK. At the moment, SFSK seems to be adequate for conventional applications, but other schemes, which may have even better spectral properties, need to be considered. These were discussed in general terms in Sec. IV.

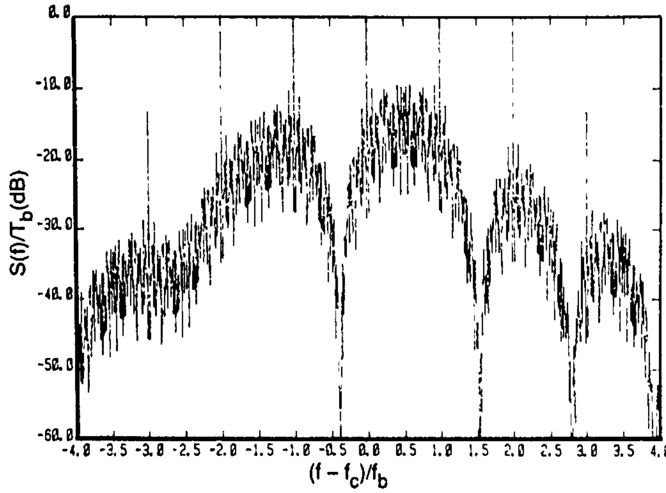
Bit Error Probability

The bit error probability provides the fundamental measure of the performance of a data transmission system.[1] Calculations are made by assuming that the signal is received against an additive background of a specified type of noise. The results are then given in the form of a bit error probability as a function of the signal power, S, the data bit length, T_b, and the noise

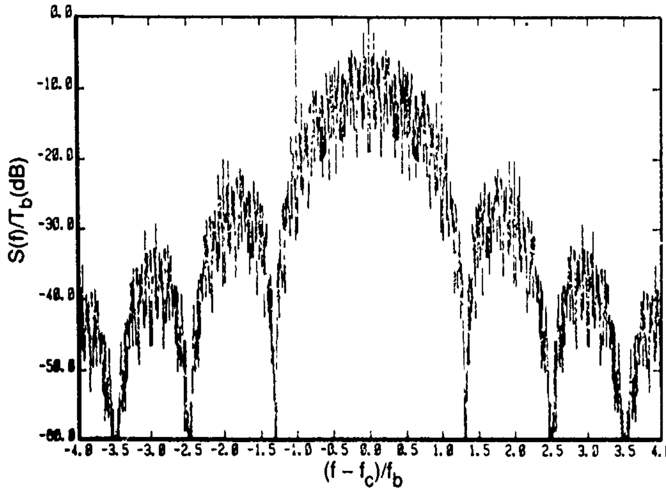
[1]The term "system" is used here to distinguish the modulation technique from the transmission system, which includes the propagation channel and the detection scheme.



(a) Rectangular NRZ (BPSK)



(b) Sinusoidal Manchester On-Off



(c) Sinusoidal NRZ

Fig. 6.3—Normalized power spectra for $\theta = \pi/2$

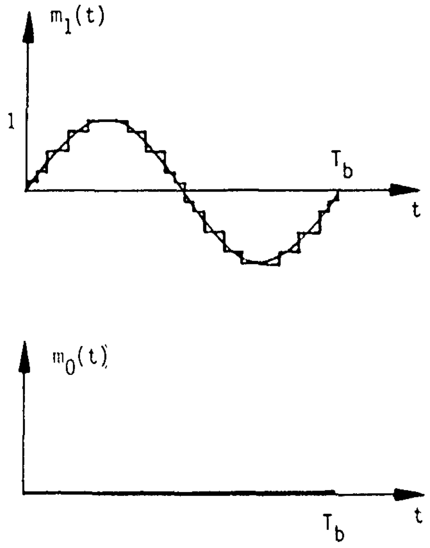


Fig. 6.4—Quantized Sinusoidal Manchester On-Off waveforms

spectral density, N_0. Alternatively, the signal power and the data bit length are combined into a single quantity, the bit energy, E_b, where

$$E_b = ST_b \tag{6.3}$$

The performance of the phase-modulation schemes depicted in Fig. 6.1 was first obtained for a background of white gaussian noise. The results, which provide a very useful comparison of the efficiency of the various modulation schemes, are summarized in Table 6.1. As mentioned above, MSK, SFSK, and Rectangular NRZ for $\theta = \pi/2$ (BPSK) are optimum systems. For them, the bit error probability, P_e, for the case of additive white gaussian noise, is given by

$$P_e = Q\left(\frac{2ST_b}{N_0}\right) = Q\left(2\,\frac{E_b}{N_0}\right) \tag{6.4}$$

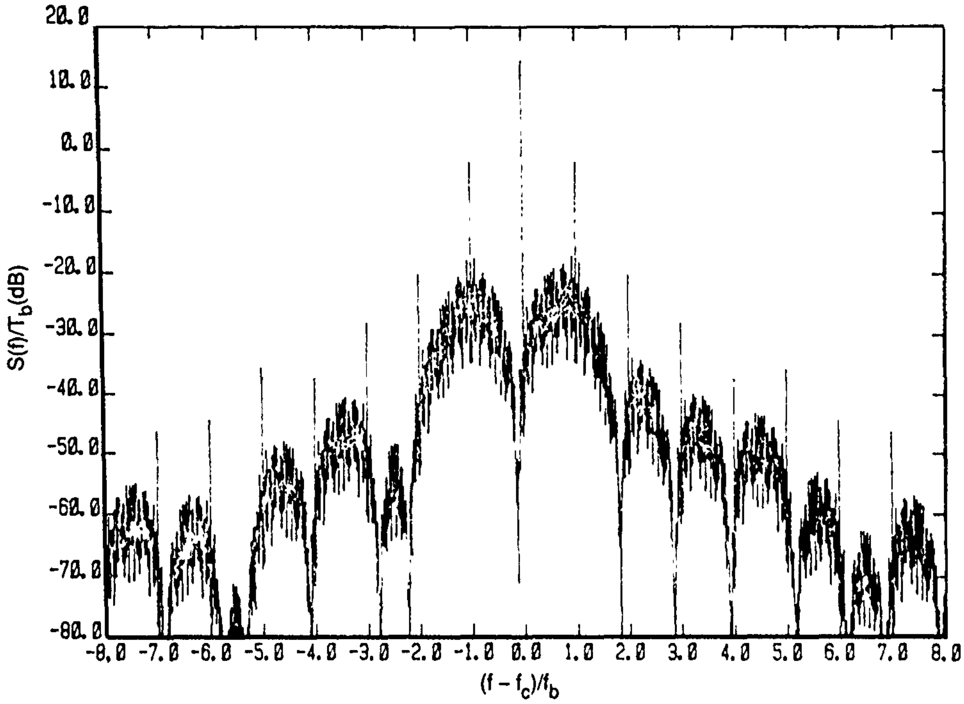
where the Q, or complementary error, function is given by

$$Q(\alpha) = \frac{1}{\sqrt{2\pi}} \int_{\alpha}^{\infty} e^{-x^2/2} dx \tag{6.5}$$

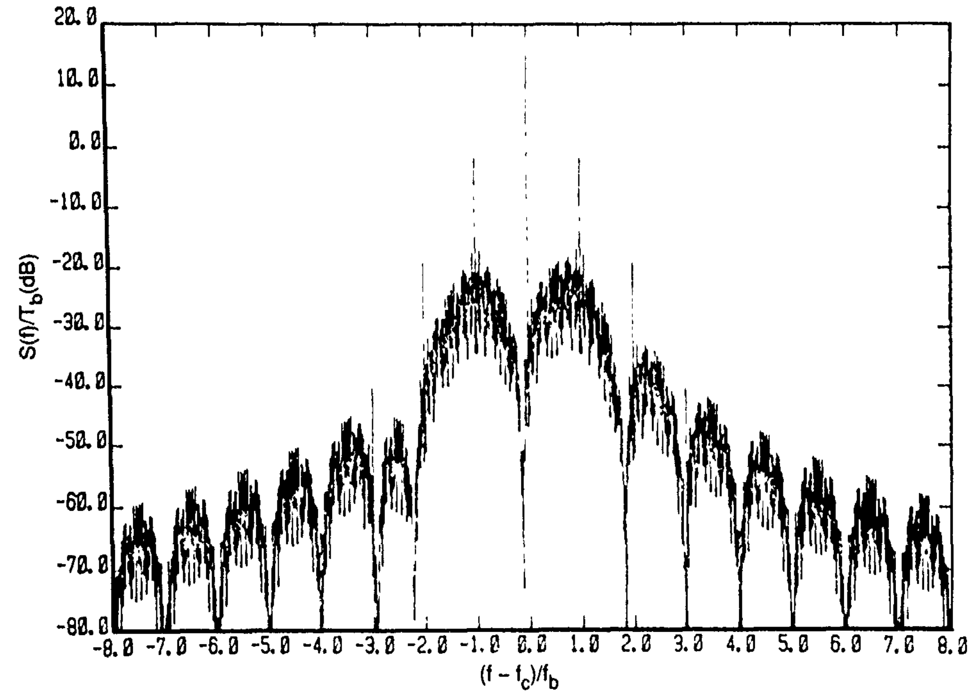
No modulation system can achieve better performance.[2]

The entries in Table 6.1 give the amounts by which the signal powers of the other modulation systems must be increased to achieve the same bit error probability as the optimum systems. Clearly, the performance improvement to be gained by using the optimum peak phase deviation of $\pi/2$ is highly desirable. Sinusoidal Manchester On-Off, particularly at a peak phase deviation of $\pi/6$, imposes an unacceptable performance penalty of almost 15 dB.[3]

[2]There is no simple relationship between the shape of the spectral distribution, and the error performance of data-modulation systems. If detection is inefficient, the wide bandwidth of some modulation systems is a detriment, as it requires the detector to accept more background noise. With matched filter detection, on the other hand, the spectral shape is irrelevant.

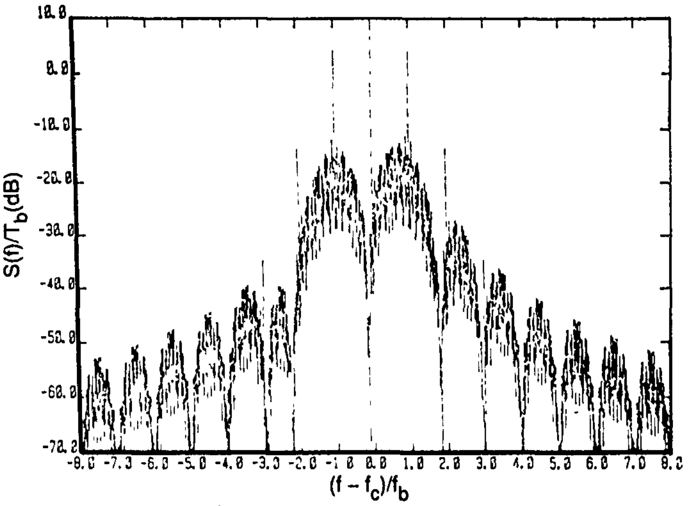


(a) 15 quantization levels and 32 time slots

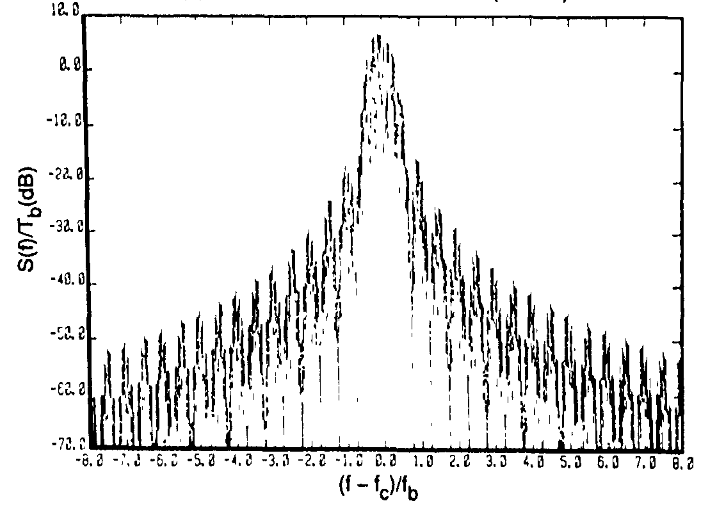


(b) Unquantized, also 128 quantization levels and 256 time slots

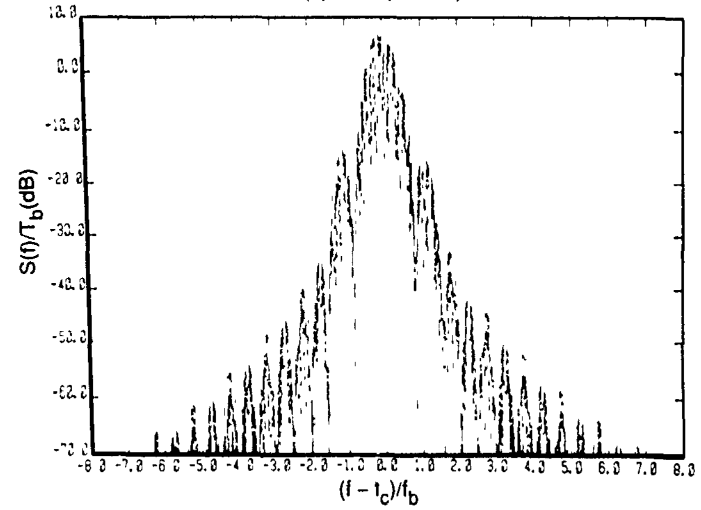
Fig. 6.5—Normalized power spectra for quantized Sinusoidal Manchester On-Off ($\theta = \pi/6$)



(a) Sinusoidal Manchester On-Off ($\theta = \pi/6$)



(b) MSK ($\theta = \pi/2$)



(c) SFSK ($\theta = \pi/2$)

Fig. 6.6—Normalized power spectra for Sinusoidal Manchester On-Off ($\theta = \pi/6$), MSK ($\theta = \pi/2$), and SFSK ($\theta = \pi/2$)

Additional work has characterized the performance degradation that occurs when impulsive atmospheric noise is encountered. Atmospheric noise is frequently the dominant noise on channels in the MF band. A model for atmospheric noise was developed in conjunction with the simulation of channel noise. This model was used to obtain analytically the additional signal-to-noise ratio required under atmospheric noise to provide a given bit-error-rate (BER) performance. Although the noise model depends on the specific filtering and structure of the data receiver, and the particular noise parameters (like the degree of its impulsiveness), typical conditions were assumed and it was found that for a matched-filter receiver (which is only optimum for additive white gaussian noise) about 12 dB of extra signal-to-noise ratio is needed to match a 10^4 BER performance in gaussian noise.

SIMULATION

It was noted above that a purely theoretical analysis of the typical AMBER data link is impractical because of its considerable complexity. This was evident even with respect to the first element in the data link, the phase modulator, for which simulation was required to determine some of the output spectra. To cope with this problem, a link simulation package called APPLS (AM-PM Physical Link Simulator) was developed; it is shown in block diagram form in Fig. 6.7. APPLS is a software package implemented in FORTRAN.

The APPLS link simulator simulates the actual passage of data and audio programming material through the radio transmitter, the propagation channel, and the analog AM audio and digital PM data receivers. It computes and plots the power spectral density (PSD) of the signals at various stages in the data link (as already seen in Figs. 6.2 to 6.6). It also calculates the mean square error (MSE) at the output of the AM receiver to give a quantitative measure

Table 6.1

PERFORMANCE OF PHASE-MODULATION SYSTEMS IN THE PRESENCE OF ADDITIVE WHITE GAUSSIAN NOISE

Modulating Signal, $m(t)$	Peak Phase Deviation, θ	
	$\pi/6$	$\pi/2$
MSK or SFSK	NA	Optimum
Rectangular NRZ	6 0 dB	Optimum
Sinusoidal NRZ	8.9 dB	1.9 dB
Sinusoidal Manchester On-Off		
Dual channel	14.8 dB	6 5 dB
Single channel	14 9 dB	7.9 dB

NOTE: Entries denote degradation with respect to the optimum systems.

[3]Dual-channel reception uses information in both the in-phase and quadrature components of the received signal and is, therefore, more efficient than single-channel reception, which uses only one. The improvement in efficiency gained by using both channels approaches 3 dB as optimum performance is neared. The improvement can be considerably less for inefficient systems, as can be seen by the lower-left hand entries in Table 6.1 in which the improvement is only 0.1 dB

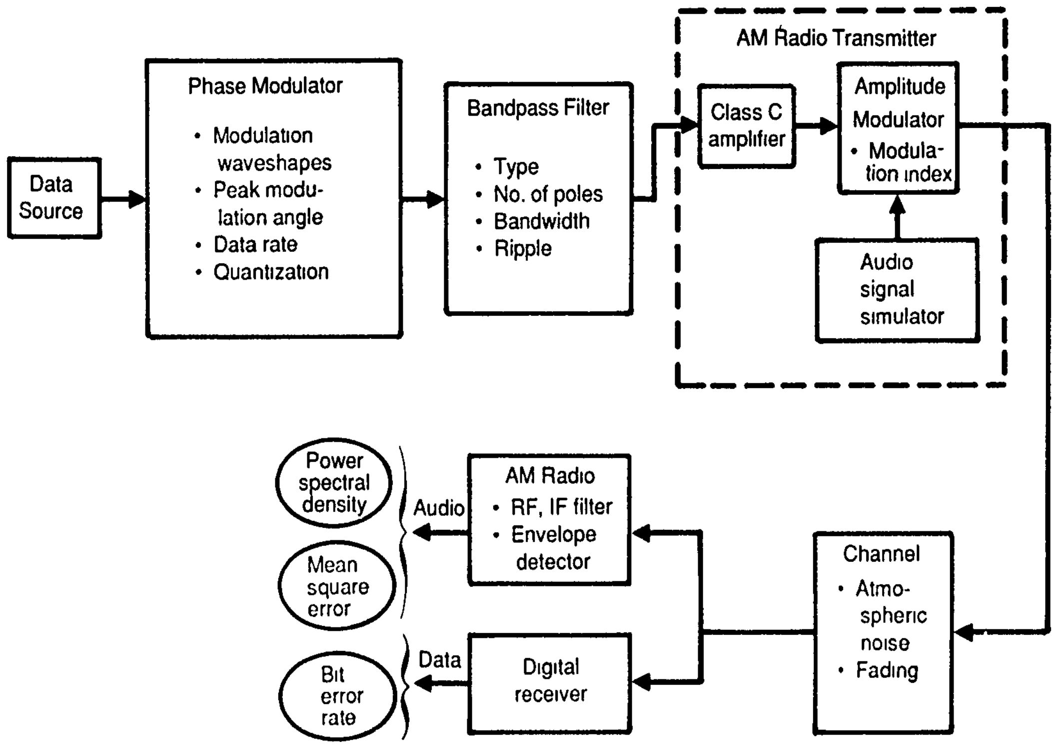


Fig. 6.7—Block diagram of APPLS

of the interference induced by the digital phase modulation, and the bit error rate at the output of the digital PM data receiver to give a quantitative measure of the performance of the data link.

It can be seen that the link simulator serves two important functions. First, it supplements theoretical calculations by verifying them, and by allowing the examination of cases for which the theoretical calculations are not practical. Second, it supplements testing of hardware by providing an analytical test bed that adequately approximates the real world. Thus, the effects of varying parameters of existing equipments, or of completely new equipments, can be determined relatively cheaply and easily compared with actually building and testing new or modified hardware. It also permits testing under propagation conditions that may be difficult to encounter or duplicate in the field.

The elements of the link simulator are described in detail in Ghazvinian et al. (1984); they will be discussed only briefly here. The data source is an 8192-bit pseudo-random sequence that has been specially scrambled to improve its properties of randomness. The phase modulator provides a discrete time sample of the instantaneous phase-modulated carrier for each time sample of the data source. The input to the phase modulator can be virtually any modulation waveform that is of interest (e.g., Fig. 6.1). These can be used with any peak phase deviation (up to $\pi/2$) with quantizing to any number of amplitude levels and time slots (Fig. 6.4). Each sample of the modulating phase is used to compute the complex value of the phase-modulated carrier at the time of the sample. The power spectral density is then calculated using an FFT (Fast Fourier Transform).

The bandpass filter simulates a Butterworth or Chebychev filter of given bandwidth, number of poles, and ripple (for Chebychev filters). This permits analyzing the effect of filtering introduced for spectrum control. The Class C amplifier simulates the highly nonlinear power amplifier stages used in AM broadcast stations to bring the signal to a level suitable for radiation. The audio signal simulator produces random samples of an audio spectrum chosen to resemble typical audio programming material. Finally, the amplitude modulator simulates the actual amplitude modulator used in a broadcast station. Care is taken to coordinate the complex phase-modulated carrier samples with those of the audio amplitude-modulating signal.

The propagation channel is designed to accommodate atmospheric noise and fading typical of the MF broadcast band in the Continental United States. The noise is assumed to be white (i.e., having a flat spectrum) with a probability distribution of amplitudes ranging from Rayleigh, which is typical of gaussian noise, to a peaked one typical of the amplitude "spikes" caused by lightning. The fading, which is caused by a skywave component (particularly at night) adding to the normal groundwave, is described by a Rician distribution. Input parameters specify the exact noise distribution and depth of fading that is to be used. No attempt has been made at this point to include the effects of nuclear explosions on the ionosphere.

The important components of the AM receiver are the filters in the RF and IF (intermediate frequency) amplifiers, and the envelope detector used to remove the amplitude modulation from the received signal. They are simulated in APPLS and used to derive the output audio signal. The simulation of the digital receiver includes a matched filter that can be tailored to the modulation scheme under consideration.

Power spectral densities calculated using the APPLS link simulator are shown here to illustrate its power and versatility. The spectra in Figs. 6.8 and 6.9 show the effect of filtering after the phase modulator and of passing the filtered signal through a Class C amplifier.

The behavior of Sinusoidal Manchester On-Off with $\theta = \pi/6$ is shown in Fig. 6.8. The spectrum at the top is the same as that shown at the right in Fig. 6.2(b). The spectra in the center and at the bottom show the effect of bandpass filtering, and Class C amplification, respectively. As can be seen, the filtering virtually eliminates the second- and higher-order sidelobes and greatly reduces the tones at $\pm\ 3f_b$. The nonlinear process of Class C amplification raises the sidelobes somewhat, though not to the level in the original signal; the side tones, however, are sharply increased.

A similar behavior is noted for Sinusoidal NRZ with $\theta = \pi/2$, as shown in Fig. 6.9. The spectrum at the top is the same as the one shown in Fig. 6.3(c). Again, filtering greatly reduces the second- and higher-order sidelobes, but Class C amplification somewhat restores them. Also, the tones at $\pm\ 3f_b$, which are not clearly distinguishable in the original or the filtered signal, are seen to be pronounced in the nonlinearly amplified signal.

Another set of spectra of interest are shown in Fig. 6.10. These show the effect on the overall spectrum of simultaneous phase modulation of data at 75, 150, and 300 bps using Sinusoidal NRZ with $\theta = \pi/2$ and amplitude modulation using the typical audio spectrum incorporated in the link simulator.

The dotted lines in Fig. 6.10 show the spectrum that would result if there were only amplitude modulation. The spectrum of the phase modulation alone is shown in Fig. 6.3(c); it can be seen that at a data rate of 75 bps (Fig. 6.10(a)), the spectrum of the combined or hybrid AM/PM signal is essentially equal to the sum of the individual spectra. That is, there is virtually no apparent interaction between the spectra. At 150 bps (Fig. 6.10(b)), the bandwidth of the PM data component has doubled, as anticipated, and there is some noticeable interaction with the AM audio component at its extreme high and low frequencies. At 300 bps (Fig. 6.10(c)), the effect is pronounced.

These spectra are theoretical in the sense that they are not observable in ideal analog AM or digital PM receivers. These receivers respond to only the amplitude-varying or the phase-varying components, respectively, of the received hybrid AM/PM signal. Thus, the spectra are of value mainly in showing the way the two types of modulation interact spectrally. One would suspect (correctly) that the greater the interaction, the greater the potential for the phase modulation of the data to manifest itself as interference in the output of the AM receiver. The interference of concern is a consequence of the imperfections present in practical receivers, particularly in the millions of existing AM receivers.

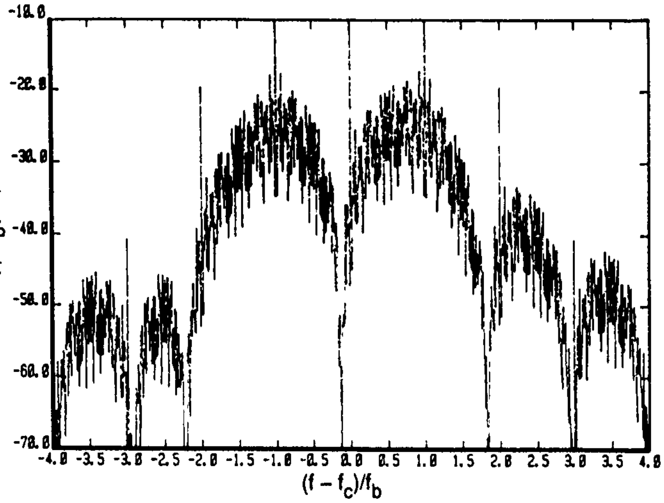
With this in mind, it may be concluded that interference would be negligible at a data rate of 75 bps, where the interaction between the AM and PM portions of the combined spectrum is small. The interference could become noticeable at 150 bps, where the spectra are beginning to interact more strongly, and would most likely be objectionable at 300 bps, where the interaction is significant. This general conclusion is consistent with the experimental data described below.

TESTING

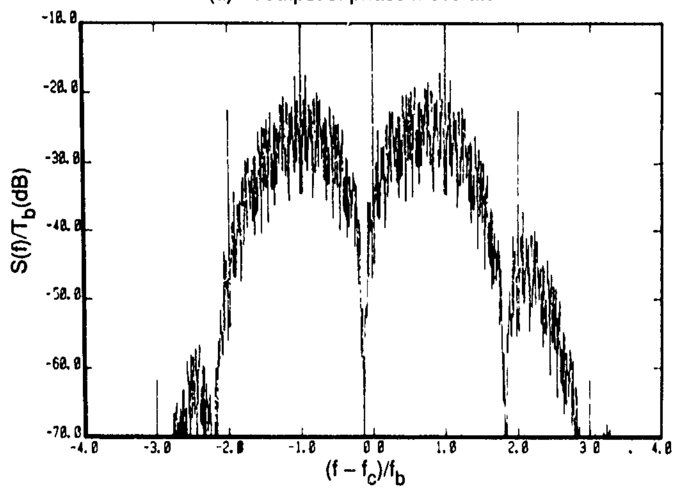
The phase modulator and data receiver used in the load-management system operate over radio station KNX in Los Angeles at a carrier frequency of 1070 kHz and at a data rate of about 20 bps. The phase modulator uses Sinusoidal Manchester On-Off keying (see Fig. 6.1(b)) with a peak phase deviation of $\pi/6$ rad; the modulating waveform is quantized into 15 amplitude steps using 32 sample points in each bit interval (see Fig. 6.4). The data rate is derived from the carrier frequency so the two are commensurable.

The BSIU (Broadcast Station Interface Unit), as it is known, is shown in Fig. 6.11 in block diagram form. Duplicate units incorporate reference, or carrier, oscillators that substitute for the station's oscillator in a fail-safe mode of operation. The BSIU oscillators provide the greater stability and reduced phase noise required to support low-data-rate phase modulation; as can be seen, the modification to the radio station is minimal. The data stream to be transmitted enters at the left, and the appropriate data waveforms, which also provide for synchronization and other system functions, are generated by the two microprocessors. Phase modulation is achieved by using a tapped delay-line down which the carrier signal is propagated. At each time sample point, the delay-line tap at which the carrier has the phase shift nearest to the desired value is selected by the multiplexer, filtered to smooth the waveform, then fed into the transmitter. The amplitude quantization steps are seen to correspond to the tap spacings in the delay line.

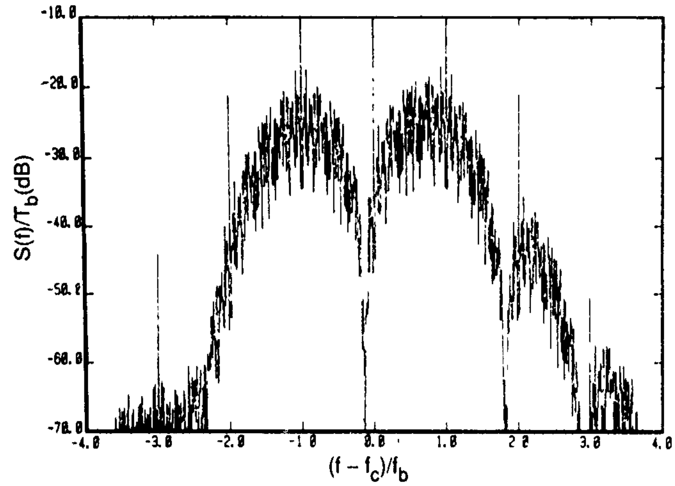
As mentioned above, it was decided that the BSIU would be improved and used to facilitate early testing because of its demonstrated on-the-air capability. The modifications included increasing the maximum data rate to 300 bps, the peak phase deviation to $\pi/2$ rad, the number of quantization amplitudes to 128, and the number of time samples to 256 per bit interval. In addition, the synchronization procedure was improved, and a new data receiver was developed. The known nonoptimum performance of Sinusoidal Manchester On-Off keying was accepted as a concomitant to taking this approach; not only would working equipment be available sooner, but persuading radio station KNX to permit its use would be easier. Unfortunately, an unanticipated interference problem nonetheless prevented on-the-air testing, even with the modified BSIU. As a result, on-the-air experiments were conducted using the operating load-management system BSIU, and the modified unit was used for bench testing in the laboratory.



(a) At output of phase modulator

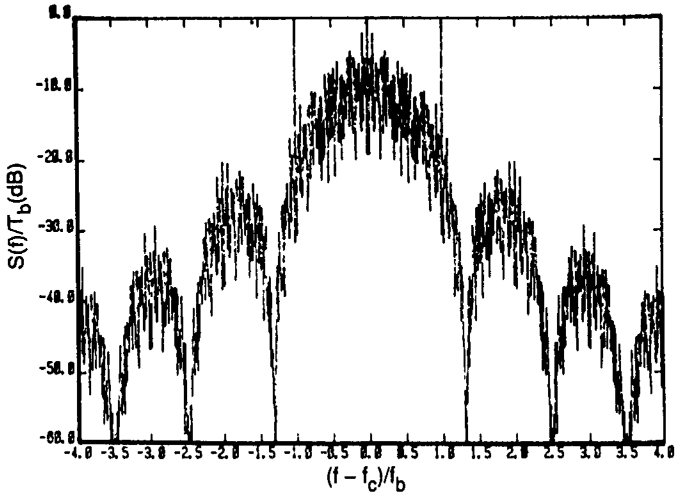


(b) At output of bandpass filter

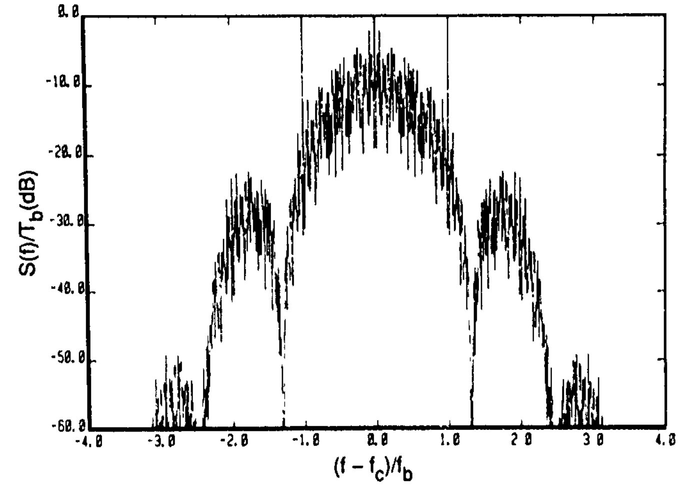


(c) At output of class-C amplifier

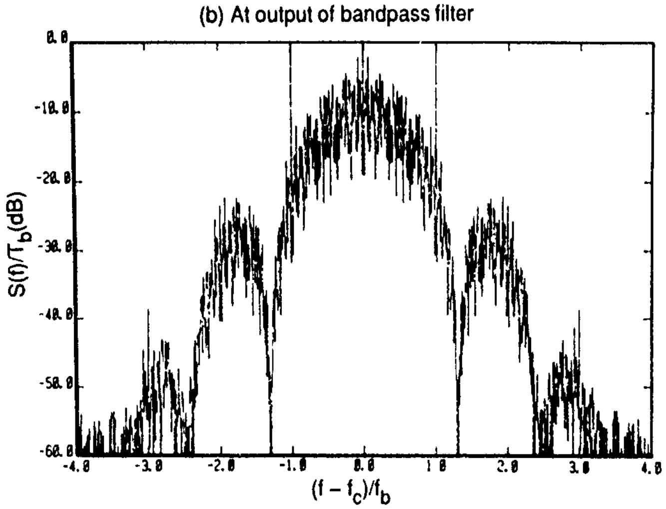
Fig. 6.8—Normalized power spectra for Sinusoidal Manchester On-Off ($\theta = \pi/6$)



(a) At output of phase modulator



(b) At output of bandpass filter



(c) At output of class-C amplifier

Fig. 6.9—Normalized power spectra for Sinusoidal NRZ ($\theta = \pi/2$)

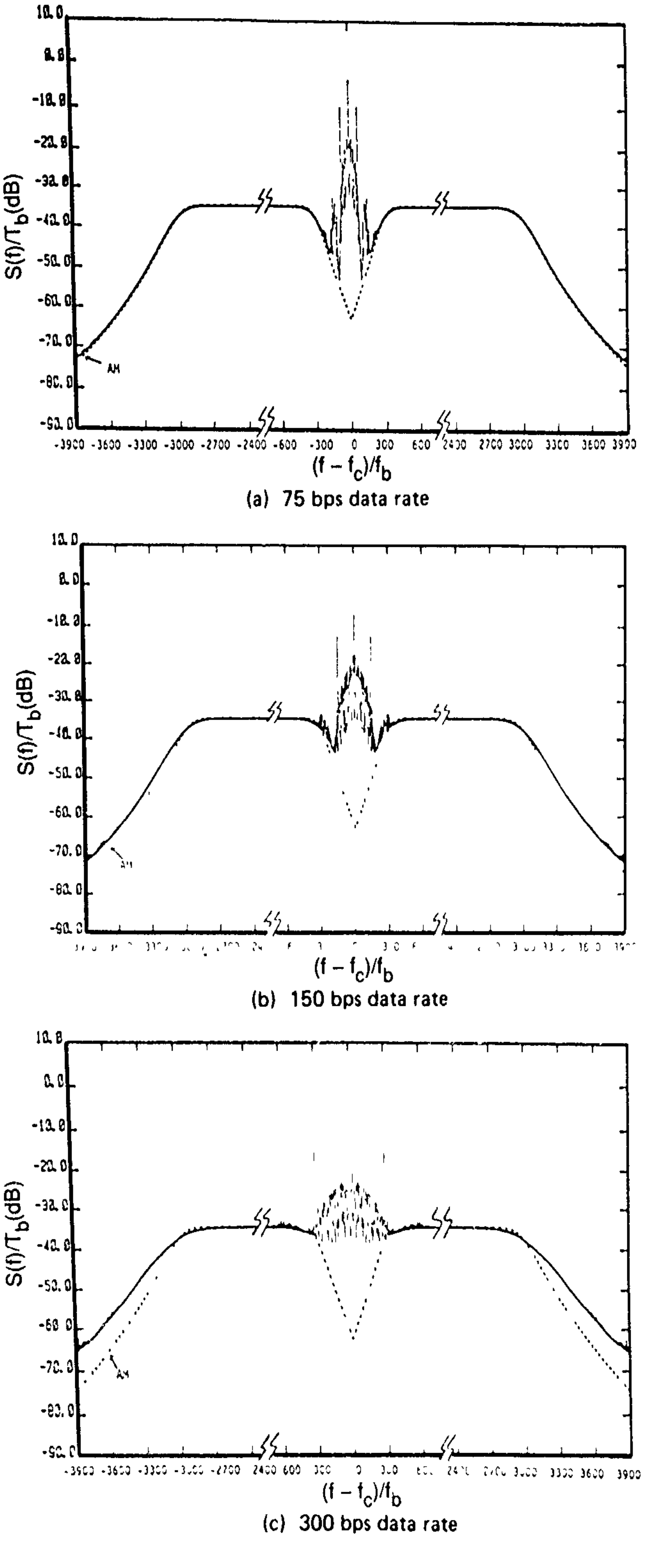


Fig. 6.10—Normalized power spectra of combined AM/PM modulation using Sinusoidal NRZ ($\theta = \pi/2$)

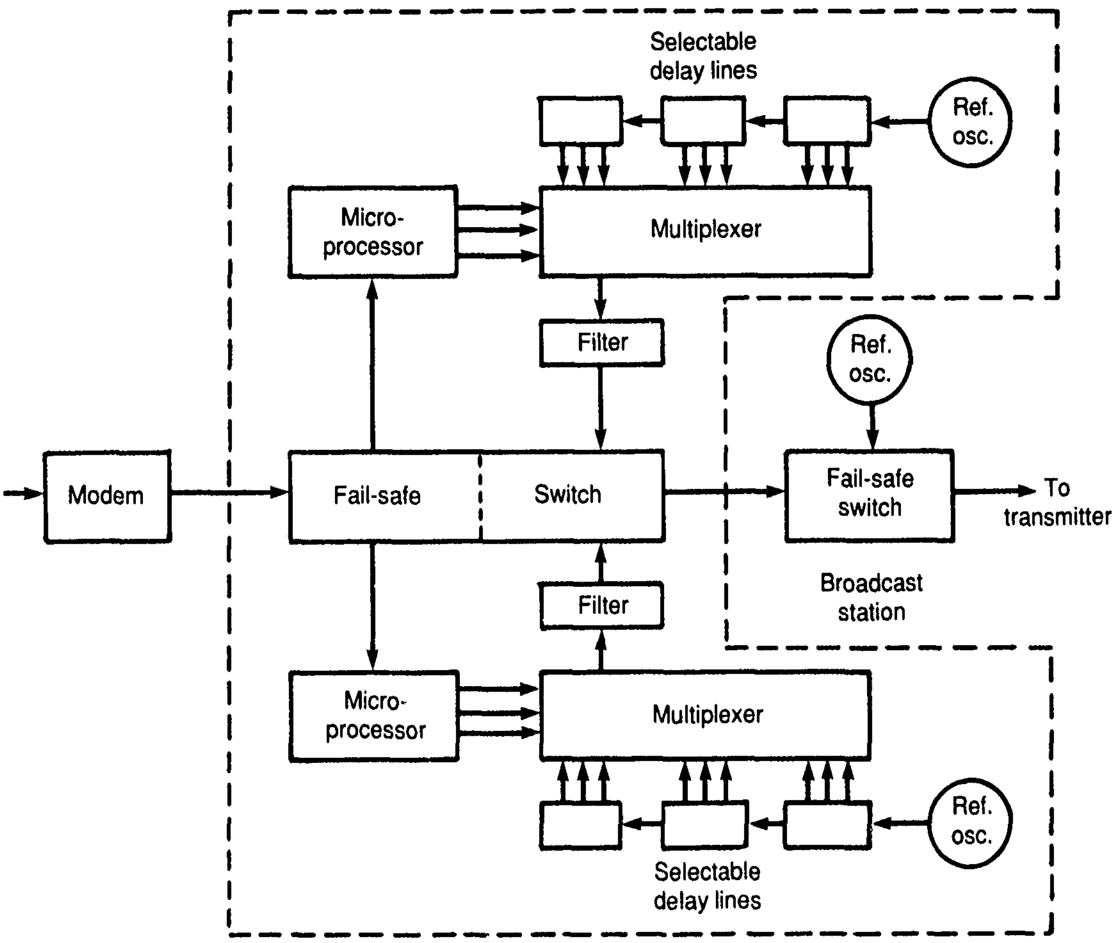


Fig. 6.11—Existing load-management phase modulator

Bench Tests

The laboratory setup used for bench testing is diagramed in Fig. 6.12. The modified BSIU described above was used to drive a low-power, but otherwise conventional, screen-grid-modulated, Class C amplifier.[4] The BSIU could be driven by periodic data streams or by a 32,767 bit pseudo-random data sequence derived from a maximal-length, 15-stage, feedback shift register. The AM receiver being tested for interference was located in a shielded room.[5] A

[4]Most standard broadcast transmitters use a final Class C power amplification stage that is plate-modulated by a push-pull Class B or Class AB modulator; others use screen-grid modulation. Novel types involve phase-to-amplitude low-level modulation, and audio-controlled pulse-duration modulation. More detailed descriptions can be found in Scholes (1960) and Stern (1975).

[5]Inasmuch as the modified BSIU was designed to operate at 1070 kHz for use on KNX, extensive shielding was required to prevent interference by the actual KNX on-the-air signal, which was being radiated only a few miles away at 50 kW.

number of receivers were used, including Kahn, Delco, and Sony "Walkman" AM stereo receivers. The interference was assessed qualitatively by listening tests using a spectrum analyzer to measure power spectra at various points in the setup and an oscilloscope to observe waveforms.

The principal test results using Sinusoidal Manchester On-Off keying with a peak phase deviation of $\pi/6$ rad, and using a noise-like data sequence,[6] are summarized below. They apply, with only minor differences, to all of the AM receivers that were tested.

> **With no simultaneous AM.** At 75 bps, the interference was very faint with the receiver tuned properly and the volume turned up all the way. With improper tuning, the interference was heard more clearly. It was established that the interference was related to the 75 Hz spectral side tone associated with this modulation scheme (see Fig. 6.2(b)). At 150 bps, a similar but more noticeable interference was noted; it was again enhanced by improper tuning.

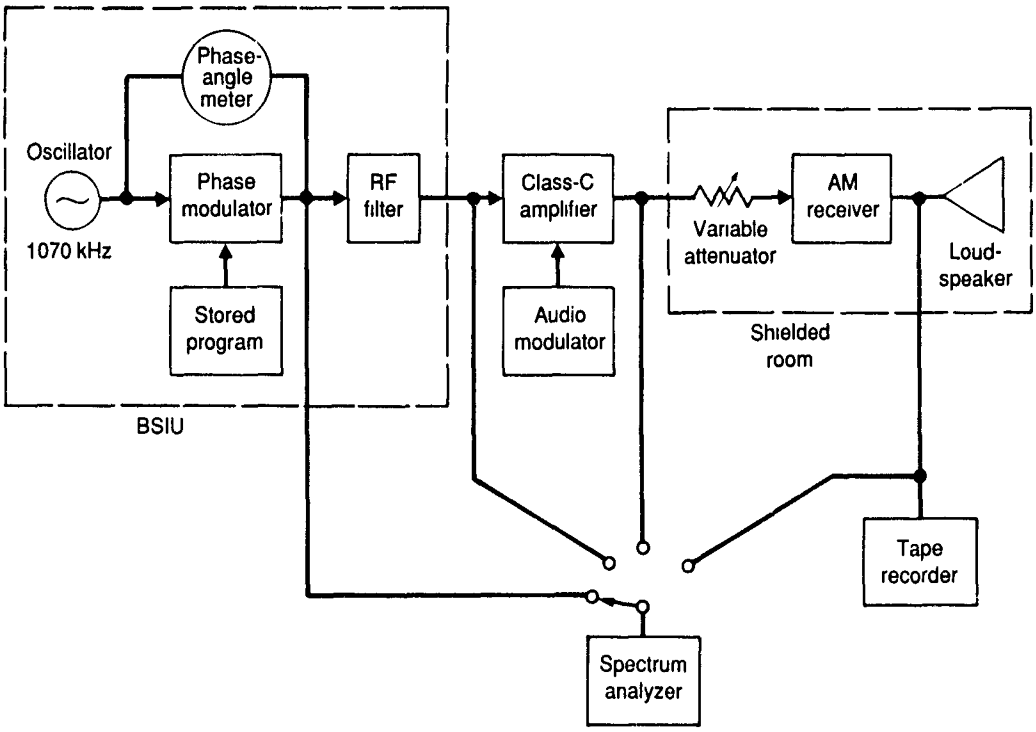


Fig. 6.12—Bench test

[6]To simplify synchronization, an ascending series of 8-bit binary numbers from 1 to 200 was used instead of the 32,767-bit pseudo-random shift requester sequence that had been developed. The randomness properties of this number sequence were not investigated but they were deemed adequate for the listening tests as no periodicity was discernible to the ear and no quantitative analyses were to be performed.

With simultaneous AM. A male voice monolog was used to simulate KNX broadcast material. With proper tuning and the receiver operating at a comfortable listening level, no interference could be detected at 75 bps; with improper tuning, the interference was again noted. At 150 bps, the interference was still heard but not as clearly; with improper tuning, the interference was heard much more clearly and was disturbing.

It was concluded that Sinusoidal Manchester On-Off keying at a peak phase deviation of $\pi/6$ may be acceptable at 75 bps with a premium attached to proper tuning. Tests of this modulation technique at a peak phase deviation of $\pi/2$ rad indicate that it would be objectionable at 75 bps. This suggests that modulation schemes such as MSK and SFSK, which have no carrier and no side tones, and which have more rapidly diminishing sidelobes (see Fig. 6.6), would probably be acceptable at 75 bps and, possibly, at 150 bps. Unfortunately, this cannot be substantiated until equipment capable of generating these waveforms is developed.[7]

Stereo AM

A special circumstance arises with AM stereophonic broadcasting systems, four of which are being used in the United States. Originally, five systems were considered in a competition to determine the one to be standardized for AM broadcast use (Mennie, 1978). However, the FCC trend toward increasing deregulation led to a decision to let the marketplace determine the matter (FCC, 1982). As a result, there is some initial confusion that has had an undesirable impact on the development of AMBER.

First, inasmuch as these systems all use some form of hybrid AM/PM modulation to generate a stereophonic signal, there is the basic question as to whether phase-modulated AMBER data can be added to such a transmission without interfering with stereo AM receivers. That question has not been addressed yet in the AMBER study, which assumes, for the time being, use of only conventional monaural AM broadcast stations. For example, experimentation is currently limited to KNX in Los Angeles, which, as a "talk" station, has little incentive to broadcast in stereo.

Second, there is the concern, even if the AMBER data are phase-modulated onto a monaural AM signal, about interference in stereo receivers that might respond to the AMBER data signal as if it were the added PM component in a stereo AM signal. To prevent accidental operation of the stereo circuitry in an AM stereo receiver when the broadcast material is monaural, all of the AM stereo systems use phase-modulated pilot tones[8] to activate the stereo circuitry only when it is needed. Normally, the AM stereo receivers use selective filters to extract these pilot tones. The Sinusoidal Manchester On-Off data signal has undesired side tones that are similar to the pilot tones, but tests have shown that neither these tones, which are not at the stereo pilot-tone frequencies, nor the incidental data signal energy in the vicinity of the pilot tones, is sufficient to activate the stereo circuitry. Thus, there is no problem with such interference in receivers that are tailored to specific stereo systems.

Unfortunately, there is a problem with the Sony "Walkman," which is a general-purpose AM stereo receiver that was designed to demodulate any of the stereo AM schemes. To

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[7]The modified BSIU could not be used for this purpose because it is limited to a peak phase deviation of $\pi/2$ rad, whereas MSK and SFSK require π rad with provision for continuation modulo $\pi/2$.

[8]These tones are at 5 Hz for the Magnavox system, 15 Hz for the Kahn, 25 Hz for the Motorola, and 55 to 96 Hz for Harris. The latter is variable to serve also as an aid to automatic gain control.

accomplish this, its pilot-tone circuitry was apparently widened to accept all of the various pilot tones. Bench tests revealed that the 75 bps modified BSIU PM data spectrum had enough side tone and data energy in this widened pilot-tone passband to activate the stereo circuitry randomly. The result was a noticeable interference that precluded on-the-air tests with this unit.[9] The operating 20 bps load-management BSIU does not have this problem because its lower-frequency phase-modulation spectrum cannot couple into the pilot-tone circuitry enough to activate it.

On-the-Air Tests

The experimental setup used for the on-the-air tests is shown in Fig. 6.13. A mobile laboratory was instrumented with test recording equipment to permit measurements at various locations and under various conditions. As already mentioned, it was not possible to use the modified BSIU, so tests were confined to the operating 20 bps load-management BSIU at KNX in Los Angeles. To simulate the circumstances of the modified 75 bps BSIU, the receiver bandwidth was increased to accept the correspondingly larger noise level. The test results are presented in detail in Martinez and Landsman (1984) and are synopsized briefly here for convenience.

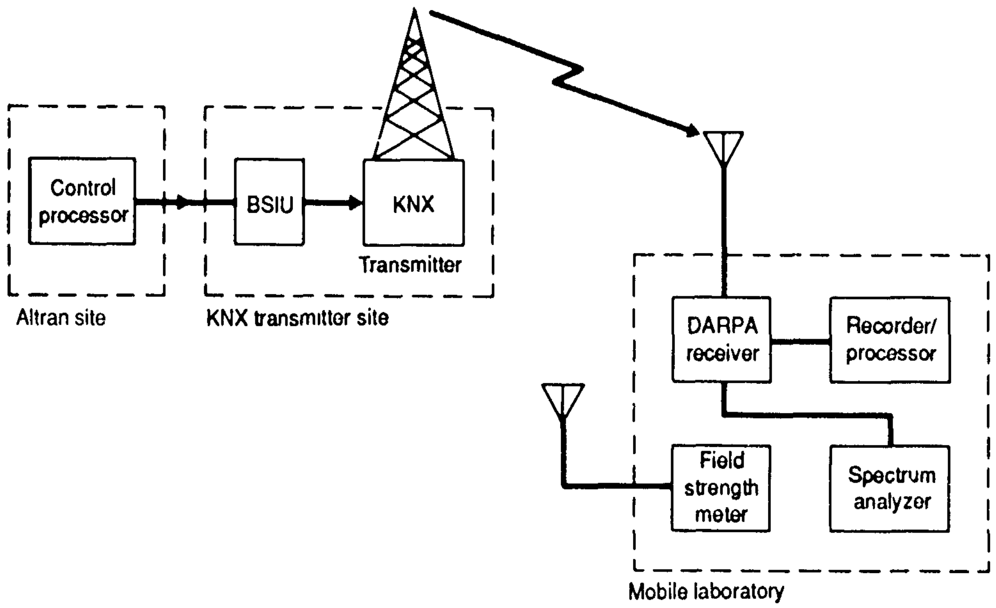


Fig. 6.13—On-the-air experiment

[9]Incidentally, the problem will not occur if the receiver is properly operated; it has a front panel MONAURAL/STEREO switch that should be placed in the MONAURAL position when listening to a station not broadcasting in stereo It also develops that this Sony receiver can respond in a similar manner to the phase noise generated by the poor carrier oscillators found in some AM radio stations. This effect, plus comments directly from Altran, are expected to lead to an improved design by Sony that may not be affected by AMBER data signals

Preliminary receiver synchronization tests were conducted during the day at Palm Springs (110 st mi), Fresno (200 st mi), and Blythe (230 st mi) using a specially designed loop antenna pointed in directions between the null and the maximum of its response. Even though the received field strengths were up to 6.7 dB below the minimum used for design, synchronization was immediately achieved and held without interruption.

Error and sensitivity tests were conducted at Bakersfield (110 st mi) and Fresno (200 st mi) during the daytime, at twilight, and at night. Records were compiled for 19 to 25 minute periods, and actual errors counted. The observed SNRs (signal-to-noise ratios) were found to agree fairly well with the predicted values obtained by using standard propagation and noise models. The actual error counts were small, leading to estimated bit error probabilities ranging from 3.5×10^{-5} to 7.0×10^{-4}.

The performance of the operating, load-management BSIU is very encouraging. Although it was designed to operate in the primary service area of KNX, its ability to transmit data at very low error rates at distances on the order of 200 st mi suggests that optimized systems may be capable of demonstrating the performance required to make AMBER feasible.

VII. PROPAGATION AND NOISE MODELS

INTRODUCTION

To ensure that a radio communication network, such as AMBER, operates satisfactorily requires a knowledge of all parameters affecting the system operation. Principal among these are the propagation characteristics of the signal between the given transmitter-receiver pair and also the interference environment that determines whether or not the signal is usable for the transmission of information.

Radio signals that travel from a transmitter to a receiver near the earth's surface may take one of several possible paths. Groundwaves travel over the earth's surface and skywaves travel up to the ionosphere, where they are reflected and then return to the receiver. There may be more than one ionospheric reflection between a given transmitter and a receiver. Each reflection from the ionosphere or the ground results in a loss of signal strength. Local communication is commonly provided by groundwaves. Skywave propagation is important during nighttime when ionospheric absorption is much reduced, allowing communication paths to distant locations. Propagation of signals over long distances via the skywave mode at night may also lead to interference at a given receiver site.

Interference consists of undesired signals and noise. The undesired signals can originate locally on a nearby channel because of the strong radiation from a collocated transmitter or on the desired channel from a distant transmitter via either groundwave or skywave transmission. Noise can be internal to the receiver system or external or environmental noise—atmospheric, galactic, and manmade being three important types. Internal receiver noise is negligible in the MF frequency range compared to external noise.

The following subsections describe the models used in the AMBER simulation to estimate AM signal propagation characteristics based upon groundwave and skywave modes, and the properties of the external noise environment.

SKYWAVE PROPAGATION

Radio signal propagation via skywaves is complicated by the complex characteristics of the ionosphere. Hence, a certain number of approximations must always be made if calculations for a network containing hundreds of AM stations are to become practical. The models discussed in this section are for a peacetime environment. Future work should incorporate changes that will reflect the propagation disturbances associated with nuclear explosions.

The ionosphere is that region of the upper atmosphere that is ionized, primarily by solar radiation. The structure of the ionosphere depends on time of day, season, latitude and longitude, and solar activity. The electron density peaks in two main layers in the ionosphere: E and F. The actual behavior of each layer is very complicated (Rush, 1986) and detailed modeling of physical mechanisms is beyond the scope of this study. To the first order of approximation, it is assumed that for the E layer, the electron concentration is maximum at a height of about 100 km; for the more heavily ionized F layer, the maximum electron concentration is assumed to occur in the range 200 to 400 km.

MF waves trace out a curved path in the ionosphere, characterized by a gradual refraction in the lower sections of the trajectory, and total reflection at the crest. Calculations and measurements show that by day, MF waves reflected from the ionosphere are attenuated to such a degree that ionospheric propagation may be fully ignored with existing transmitter powers. MF waves propagate by groundwaves by day. and by both groundwaves and skywaves at night. Only in winter and at high latitudes do skywaves produce a significant field at a receiver site during the day.

The electromagnetic properties of the ionosphere are greatly influenced by the presence of the earth's magnetic field, which causes electrons to revolve around the magnetic field lines at a gyromagnetic frequency of about 1.4 MHz. Hence, a radio signal (plane wave) incident on the ionosphere will experience Faraday rotation and the emerging reflected wave will be elliptically polarized and consist of ordinary and extraordinary waves. The ordinary wave is the only component that contributes significantly to the received signal in the MF band. Because the gyromagnetic frequency falls within the MF band, the extraordinary wave is heavily attenuated. Because only the ordinary wave reaches the receiver, and because its polarization will not in general match that of the receiving antenna, received signal strength will be reduced as a result of polarization mismatch.

Theoretical Approaches

Two general theoretical approaches exist to calculating the field strength and the path loss of MF skywave signals between a transmitter and a receiver: the wave-hop method and the waveguide-mode method.

Wave-hop method. The wave-hop method involves ray tracing between the transmitter and the receiver, with each ray representing an energy path stemming from one or more ionospheric reflections. The total field at the receiver is the vector sum of the fields resulting from each wave path. This method requires a knowledge of the ionospheric reflection coefficient, which can be theoretically obtained by two techniques. The first technique assumes that the ionosphere is a homogeneous medium with a sharp boundary at the air-ionosphere interface. For an incident plane wave, the polarization of the reflected wave is elliptical and the resultant reflection coefficient is a matrix. The second technique—usually called the full-wave theory—is applied when the change in the medium within one wavelength is large. This technique involves dividing the ionosphere into thin discrete strata such that the ionosphere can be regarded as homogeneous within each stratum and then solving the differential equation within each stratum.

For an incident plane wave be[illegible]onosphere, in general four characteristic plane waves are present in each stratum [illegible]g and downgoing, ordinary and extraordinary. These waves undergo reflection and t[illegible]ission at the boundaries between the strata. The reflection and transmission coefficients are found by imposing boundary conditions on the electromagnetic field. In every layer, an infinite number of components constitute these waves. The full form of this theory accounts for all of these components and involves many laborious calculations. Some simplifications are possible if the reflection coefficients are extreme (small or large), so only one reflection or transmission per stratum needs to be considered. Even with simplifications, the second technique, i.e., full-wave theory, involves many more calculations than the first technique.

Waveguide-mode method. This method considers the signal as a sum of modes propagating in the earth-ionosphere waveguide and is not practical in the MF band because the series of waveguide modes is only slightly convergent and requires the addition of many components.

In conclusion, the wave-hop method is the simplest and most efficient theoretical approach to calculating MF skywave field strength and path loss. However, this method requires the inclusion of an appropriate model of the ionosphere. Such models are generally very complex, require extensive computational effort, and are often limited. The purely theoretical methods are therefore inappropriate for the purpose of this study. Consequently, a semi-empirical approach will be used.

Semi-Empirical Models

Several internationally acceptable semi-empirical skywave field-strength prediction models can be applied to determine the performance of an ionospheric-dependent radio system. Models applicable to Region 2 (the Americas) include: the FCC curves, the CAIRO curves, the CCIR 1978 method, the Wang 1979 method, and the IWP 4/6 method. Much of the discussion provided below follows from the work of PoKempner (1980).

The FCC curves. Two sets of FCC curves are contained in FCC *Rules and Regulations* (FCC, 1976): the 1935 curves and the 1944 curves. The first set of curves is based on measurements of 500 transmission paths at frequencies ranging from 640 to 1190 kHz and distances of 160 to 4000 km, taken during a relatively low solar-activity period, in February, March, and April of 1935. Measurements were taken two hours after dark on the entire path. The curves are normalized to an equivalent transmitting antenna radiating 160.9 $\mu V/m$ at 1 km at the vertical angle corresponding to one ionospheric reflection. The second set of curves is based on an extensive measurement program made in the United States and Canada from 1939 to 1944. Measurements were made on 23 paths ranging from 400 to 3500 km and for frequencies from 540 to 1500 kHz. All measurements were made two hours after sunset at the western end of the path. The FCC used only data collected during 1944 in generating the second set of curves, because 1944 was the year of minimum solar activity when maximum skywave field strengths were expected to occur.

Both sets of curves include graphs of the field strengths exceeded 10 and 50 percent of the year for the period of observation, up to distances of 4300 km for the 1935 curves, and about 4000 km for the 1944 curves.

The FCC uses the 1935 curves to determine frequency assignments for inter-regional clear-channel broadcasting stations. The curves were adopted by treaties between the United States, Canada, Cuba, the Dominican Republic, and Mexico. The 1944 curves are given as a function of geographic latitude and are used by the FCC to determine frequency assignments for domestic non-clear-channel broadcasting stations.

The CAIRO curves. The Cairo curves are based on measurements taken in the northern hemisphere during the winters of 1934/35, 1935/36, and 1936/37 (CCIR, 1978a). Measurements were made at frequencies between 695 and 1185 kHz on 23 paths between North America and Europe, North America and South America, and South America and Europe. The measurement data were reduced to two curves: a north-south curve representing transequatorial propagation, and an east-west curve representing propagation at high latitudes. The original curves were given in terms of the quasi-maximum value of the skywave field strength, given in $\mu V/m$ for a 1 kW radiated power, versus distance. This was defined as the value exceeded not more than 5 percent of the time, with the median being about 0.35 of this quasi-maximum value. Subsequently, CCIR reduced these values by 9 dB to approximate a medium value. The CAIRO curves are in good agreement with recent measurements by the European Broadcasting Union (EBU) for paths up to 2000 km long originating in Europe. Beyond a distance of 2000 km, the CAIRO curves are independent of frequency, geographic location, and solar activity.

The CCIR 1978 method. The CCIR 1978 method is the current recommended skywave field-strength prediction method (CCIR, 1978b, and 1982). The method gives F, the annual median of half-hourly median skywave field strength, expressed in dB ($\mu V/m$), for a given transmitter cymomotive (i.e., wave launching) force, V, at a given time t, relative to the reference time. The reference time is taken as six hours after the time at which the sun sets at a midpoint on the surface of the earth. The parameter F is given by

$$F = V + F_0 - L_t$$

where

V is the transmitter cymomotive force, dB above the reference 300 V,
F_0 is the annual median field strength, dB above $\mu V/m$, at the reference time, and
L_t is the hourly loss factor.

The term F_0 is a function of geomagnetic latitude, slant propagation distance, solar activity, polarization, and the proximity of the receiver and the transmitter to salt water (sea gain). It is given by

$$F_0 = 106.6 - 2 \sin \varphi - 20 \log p - 10^{-3} K_R\, p - L_p + G_s$$

where

φ is the geomagnetic (dipole) latitude parameter,
p is the slant distance in km,
R is the 12 month smoothed Zurich sunspot number,
K_R is a loss factor dependent on R,
L_p is the excess polarization coupling loss (dB), and
G_s is the sea-gain correction (dB).

The loss factor is given by

$$K_R = k + 10^{-2}\, bR$$

where

$$k = 3.2 + 0.19\, f^{0.4} \tan^2 (\varphi + 3)$$

and where f is the frequency in kHz. The solar activity dependence factor, b, is equal to 4 for North American paths. The complete prediction method and description of the pertinent parameters is given in CCIR (1978a) and PoKempner (1980).

The CCIR method agrees better than the FCC curves with measurements on paths in the United States and the southwestern parts of Canada (Wang, 1983).

The Wang 1979 model. The Wang 1979 model is a modification of the CCIR 1978 method with changes to the basic propagation loss factor, k, and the solar activity dependence factor, b (Wang, 1979). The modification simplified the CCIR method and improved the accuracy of predictions for high and low latitude areas and for a solar activity index appropriate to Region 2.

The modified basic loss factor is independent of frequency and is given by

$$k = (0.0667 \; |\varphi| \; + 0.2) + 3 \tan (\varphi + 3) \text{ for } (0 \le |\varphi| \le 60 \text{ deg})$$

The modified solar dependence factor, b, is dependent on the geomagnetic latitude factor, φ, and is given by

$$b = 0.4 \; |\varphi| \; -16 \text{ for } |\varphi| \ge 45 \text{ deg}$$

$$b = 0.0 \text{ for } |\varphi| < 45 \text{ deg}$$

The IWP 6/4 method. The CCIR interim working party met in a special session in Geneva in October 1979 to determine an appropriate method for MF skywave prediction for Region 2. This method, described in detail in CCIR (1982), follows the Wang (1979) method rather closely except that it is confined to periods of low solar activity, i.e., $b = 0$.

Comparison of prediction models. A number of studies have been undertaken to evaluate the relative accuracy of the above methods by comparing calculated results with measured data collected in Region 2 (Barghausen, 1966; Crombie, 1979; Wang, 1979; PoKempner, 1980; Wang, 1983). The most recent detailed study was carried out by PoKempner, who concluded that there was no significant difference between the different model predictions for path lengths less than 2000 km. For path lengths longer than 2000 km, the Wang (1979) model and the closely related IWP 6/4 method gave the best overall estimate of field strength for Region 2. For very long paths (> 8000 km), the CAIRO model was best. Because AMBER skywave path lengths do not exceed 8000 km, the Wang (1979) model was selected for this study.

AMBER Skywave Model

The AMBER simulation model uses the Wang (1979) method to predict skywave field strength. The method has been implemented by the Defense Electromagnetic Compatibility Analysis Center (DECAC) (Strickland, 1986).

The AMBER simulation requires computation of signal field strengths for a large number of propagation paths, hence the efficiency of the model is of critical importance. The DECAC-Wang model has been extensively optimized and modified by RAND to ensure maximum computational speed. It has also been further extended by including automatic computation of sea-gain parameters. The following is a short qualitative description and further explanation of pertinent model parameters.

Cymomotive force. The cymomotive force is defined as the field strength at a distance multiplied by the distance. For a 1 kW omnidirectional monopole transmitter, the cymomotive force is 300 V.

Reference time. The CCIR and Wang methods assume that the reference time is six hours after sunset, or approximately local midnight at the midpoint of the path. This corresponds to the expected maximum skywave field strength.

Sunspot activity. Sunspot activity varies according to an 11-year cycle, which has been observed and measured since the middle of the 19th century. Solar activity has been found to correlate with the number and grouping of sunspots; hence, a measure of solar activity based on the number of sunspots has been adopted. The 12-month smoothed Zurich sunspot number is a commonly used index of solar activity and is computed by averaging the mean monthly sunspot numbers for 12 months, centered on the month of interest. The increased solar activity during the sunspot maxima corresponds to an increase in ion density of ionospheric layers.

Sea gain. The strength of a low-angle MF skywave signal received from a vertically polarized transmitter depends on the conductivity of the ground near both the transmitter and the receiver. This is because both the transmitted and the received signal are the vector sums of direct and ground-reflected waves. For vertical polarization, this sum is the greatest when the antenna is surrounded by the sea or is near the coastline, because the reflection coefficient for sea water is approximately equal to unity (Knight and Thoday, 1969).

Polarization coupling loss. A signal reflected from the ionosphere will, in general, be elliptically polarized. When this signal is collected by a vertically polarized receiving antenna, signal losses occur. The loss is small near the magnetic poles but becomes important at lower geomagnetic latitudes. For most of North America, the magnetic inclination or dip angle I is less than 45 deg, and the polarization coupling losses are very small ($L \simeq 0$).

GROUNDWAVE PROPAGATION

The following is concerned with the problem of groundwave propagation from a point source transmitter over a curved earth with a troposphere whose index of refraction varies with height only. Both the transmitter and a receiver are assumed to be located on the surface of the earth.

This is a classical problem in the theory of electromagnetic wave propagation that was originally studied by Sommerfeld (1909), and later by Norton (1936, 1941), and by van der Pol and Bremmer (1937, 1939). A historical background to the subject is given in texts by Bremmer (1949) and Wait (1970).

The characteristics of radiowave propagation over the earth via groundwave mode are determined by the earth dielectric properties and the physical configuration of the surface of the earth, including vegetation and manmade structures. For frequencies below 10 MHz, the earth dielectric properties are of primary importance. These properties are given in terms of two parameters: dielectric constant and conductivity. In the MF band, the soil conductivity is the dominant factor and can vary over a wide range. The effective soil conductivity is determined not only by the nature of the soil but also by its moisture content and temperature, by the general geological structure of the ground, and by the effective depth of penetration and lateral spread of the groundwave. The soil moisture content is probably the major factor determining its dielectric properties. Soil conductivity should be measured in the field along and in the vicinity of the groundwave path to accurately predict the groundwave field strength at the receiver (CCIR, 1974).

Groundwave Models

Several models exist for predicting groundwave field strengths in the MF range. CCIR Recommendation 368-2 (CCIR, 1975) contains a set of ground propagation curves for frequencies between 10 kHz and 10 MHz, for great circle path distances up to 10,000 km. The curves were derived from analytical work by van der Pol and Bremmer (1937, 1939). The CCIR curves do not account for tropospheric effects. CCIR has frequently been advised to replace these curves with a new set calculated using an exponential atmosphere, because this type of variation more closely represents average atmospheric conditions than does a linear refractive variation. Rotheram (1981) has recently derived a new set of propagation curves using an exponential atmosphere profile for the frequency range from 10 kHz to 30 MHz.

In the United States, the FCC allocates frequencies and establishes technical standards for predicting broadcasting signal coverage in the MF band. The FCC groundwave prediction method (FCC, 1982) is the one generally accepted for the United States. Volume III contains a set of 20 graphs applicable to the frequency range between 540 and 1640 kHz, each set consisting of 16 curves for conductivity ranges between 0.5 and 5000 mmhos/m. The curves are drawn for distances less than about 2000 statute miles, measured around the great circle path of the earth. The transmitter is a small ideal vertical dipole that would radiate a field of 100 mV/m at a distance of 1 mile if placed on a perfectly conducting infinite plane earth (inverse distance field).

The curves refer to a smooth homogeneous earth. When the wave encounters regions of mixed conductivities (nonhomogeneous smooth earth), the use of the curves must be modified. There are various analytical and semi-empirical methods of determining the propagation of groundwaves over such mixed paths (Wait, 1956a, 1961; Senior, 1957; Millington, 1950). Analytical formulations are generally difficult to apply in practical cases. The FCC recommends the use of the principle of continuity of boundary conditions in the form of an equivalent distance method. This method considers a wave to propagate across a path segment of a given conductivity according to the curve for homogeneous earth of that conductivity. When a transition between segments of different conductivity is encountered, the equivalent distance of the receiver from the transmitter changes but the electric field is continuous across the interface. From the point just inside the second path segment, the transmitter appears to be located at that distance at which, on the curve for a homogeneous earth of the second conductivity, the field is equal to the value that occurred just across the interface in the first conductivity path.

The FCC curves are based on the analytical formulation of Norton, van der Pol, and Bremmer and Wait and are verified by measurements. At short distances from the antenna, such that the curvature of the earth does not introduce an additional attenuation, the fields were computed using Sommerfeld surfacewave field equations (Sommerfeld, 1909) that were further investigated by Norton (1936, 1941).

At greater distances, diffraction must be accounted for and different calculation methods are required. For these greater distances, predictions were made using the van der Pol and Bremmer theory (van der Pol and Bremmer, 1937, 1939; Bremmer 1949) and incorporated into the curves.

The FCC curves include the effect of tropospheric refraction (a linear decrease of refractive index of the troposphere with height), by the use of an equivalent radius of the earth equal to 4/3 the real radius based on work by Burrows (1935), Bremmer (1949), and Wait (1956b).

For nearly three decades, the FCC propagation graphs were used manually in conjunction with a map of soil conductivities to determine the final value of the received field strength. To improve the prediction methodology, the FCC recently developed a set of computer programs and associated databases to automate the calculations (Anderson, 1980).

The AMBER groundwave model is based on the FCC computer programs and associated databases obtained from DECAC. The databases include digitized FCC propagation curves and the ground conductivity map for CONUS. The program subroutines and their interfaces with the two databases have been extensively modified by RAND to improve the overall efficiency of the program. The AMBER simulation requires the computation of a large number of groundwave paths, which necessitates the use of extremely efficient models.

Volume III of the FCC *Rules and Regulations* (FCC, 1982) contains a map of estimated ground conductivities in the United States. The DECAC ground conductivity database contains a digitized version of this map. The digitization of the conductivity map was carried out in terms of segments in a latitude-longitude coordinate system that delineated different conductivity zones to the east and west for segments running north-south, and to the north and south for segments running east-west. This structure of the database required great computational effort to execute. The database was subsequently redesigned by RAND and now contains a digitized matrix of conductivities in the Lambert conical transformation coordinate system. The matrix elements are digitized with segments about 8 km in length in the transformed coordinate system. The determination of different conductivity segments for use in the equivalent distance method now amounts to a fast matrix look-up operation.

EXTERNAL NOISE

A knowledge of radio noise is required to determine the minimum signal level necessary for satisfactory radio reception in the absence of other unwanted signals. Radio noise arises from a number of noise sources, such as resistors, semi-conductor devices, the galaxy, lightning discharges, and electric machinery.

At the input to the receiver, the noise power is the sum of the internal (receiver) and external noise. The internal noise has the characteristics of thermal noise and is due to antenna and transmission line losses or to the receiver itself. For a particular receiver, antenna, and transmission line configuration, the internal noise can be determined quite accurately. However, in the MF frequency band, the external noise usually dominates. There are three main types of external noise: atmospheric, cosmic, and manmade.

The current internationally accepted method of predicting atmospheric noise is outlined by the CCIR in Report 322 (CCIR, 1963), which presents worldwide predictions for the expected values of the average noise power, and its statistical characteristics, for frequencies from 10 kHz to 100 MHz, for four seasons of the year, and for six four-hour periods of the day within a season. The data presented in Report 322 summarize measurements collected from 1957 to 1961 by a network of 16 recording stations distributed over the world. Since 1961, more data have been collected and analyzed and an updated set of atmospheric radio noise estimates produced (Spaulding and Washburn, 1985). The major improvement in the updated CCIR model is the incorporation of data from a network of ten stations in the Soviet Union. For the CONUS region, there were no significant changes in the noise characteristics. In addition to the atmospheric noise maps and figures, Report 322 predicts the dependence of galactic and manmade noise on frequency.

The purpose of this section is to describe a simplified but practical external-noise model used in estimating signal-to-noise plus interference ratios in minicomputer-based MF propagation-prediction programs that are part of the AMBER network simulation. CCIR (1963) is the basis of the AMBER external-noise model.

Atmospheric Noise

Atmospheric noise, also known as precipitation static and atmospherics, originates from naturally occurring electrical discharges, such as lightning flashes. It is the most non-gaussian of the three external-noise types. The noise is a function of geographic location, time of day, season of the year, operating frequency, bandwidth of the receiving system, and azimuthal direction.

Both local and global thunderstorms contribute to the atmospheric noise because of the ability of a noise signal to propagate over a long distance at MF. The operation of a receiver may therefore be affected by atmospheric noise even when there are no nearby thunderstorms.

During the day, when ionospheric absorption is high, the contribution from distant sources is reduced and the local sources are important. The diurnal maximum occurs at night, when the strength of the propagated noise from distant disturbances dominates noise from local disturbances.

Description of Parameters Used

Atmospheric noise is a random process characterized by rapid fluctuations. However, if the noise power level is averaged over several minutes, the average values are found to be almost constant during a given hour, except near sunrise or sunset, or near a local thunderstorm.

It has been found that no single parameter is sufficient to relate the interference potential of the noise to system performance. Mean noise power is generally the most significant parameter and is the basis of noise predictions. Noise power is measured in terms of F_a, the noise power available from a lossless antenna, expressed in dB above kTb, where $k = 1.38 \times 10^{-23}\ J/K$ is the Boltzmann constant, $T = 288.39$ deg K is the reference temperature, and b is bandwidth in Hertz.

CCIR (1963) contains maps of noise levels as a function of geographic location and frequency, in terms of the median values of F_a, and the atmospheric noise parameter, F_{am}. The values of F_{am} are grouped for each of six four-hour periods of the day (0000–0400 to 2000–2400 hours) called time blocks, and for each of the four seasons. The data presented are smoothed values and the measurements on a specific frequency at a particular geographic location will, in general, differ from the values obtained from the curves. A measure of the error introduced by the smoothing procedure is given by the standard deviation of F_a. Given the value of F_a, the total power, P, in dB above 1 W, available at the terminals of a lossless antenna is given by

$$P = F_a + B - 204 \quad \text{dBW}$$

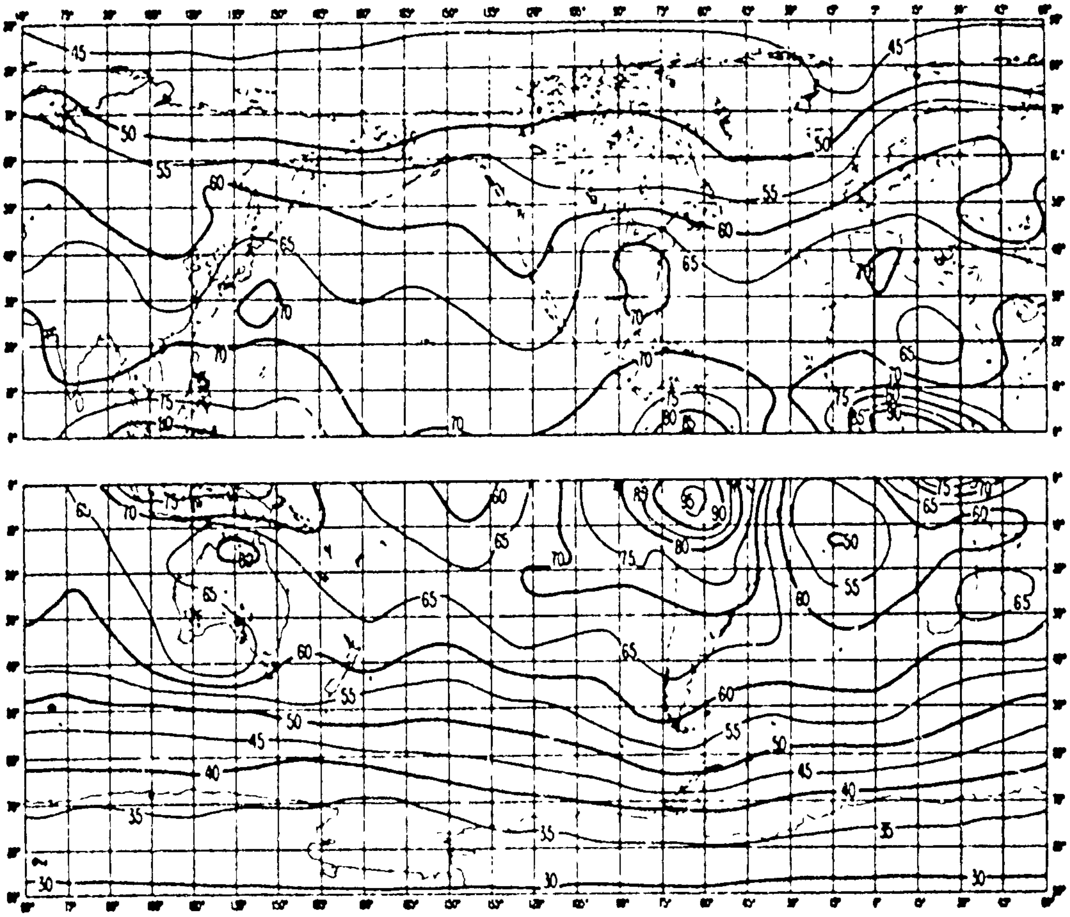
where $B = 10 \log b$, and b is the bandwidth in Hertz, and where

$$10 \log kT = 204$$

The statistical distribution of the individual values of F_a is given in terms of values exceeded for 10 percent and 90 percent of the hours, expressed as upper and lower decile ratios. The upper decile ratio is defined by $Du = F_{au} - F_{am}$, where F_{au} is the value of F_a exceeded 10 percent of the time; the lower decile ratio as $D_l = F_{am} - F_{al}$, where F_{al} is the value for the F_a exceeded 90 percent of the time.

Figures 7.1 and 7.2 are taken from CCIR (1963). Figure 7.1 gives F_{am} at 1 MHz as a function of latitude and longitude for the winter months and the local time block 0000–0400 hours. To obtain F_{am}, Fig. 7.2 is used to convert the 1 MHz value to the value corresponding to a particular frequency. Figure 7.2 also shows the statistical data on noise variability and variations, i.e., the standard deviation of F_{am}, the upper and lower decile ratios, and their standard deviations.

The parameters discussed above represent fluctuations in the long-term characteristics of the noise, that is, from one time block to the next, and from season to season. Knowledge of the short-term characteristics of the noise may also be required. Atmospheric noise is a random bandpass process, characterized by independent envelope and phase processes. The phase process is known to be uniformly distributed. The probability density of the amplitude can be obtained from the envelope amplitude distribution. The atmospheric noise envelope statistics



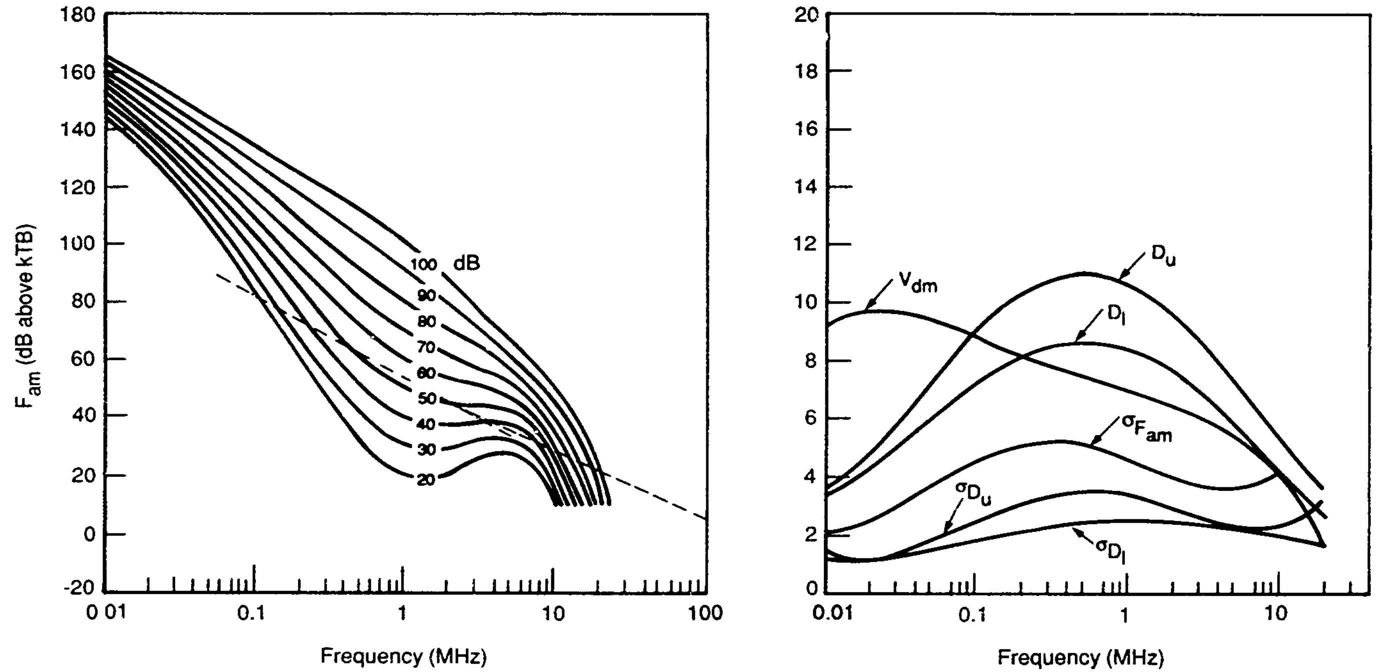
SOURCE CCIR (1963)

Fig. 7.1—Expected value of atmospheric radio noise, F_{am} (dB above kTB at 1 MHz) (winter: 0000–0400 hours)

are usually given as a cumulative exceedance distribution, called APD (amplitude probability distribution). For a given envelope level, E, the APD gives the percentage of time during which the envelope is above the given level E. Various statistical moments of the received noise envelope have been measured over a period of many years. The summary of results is presented in the CCIR (1963) as V_d, the dB difference between the average voltage and the rms voltage.

AMBER Atmospheric Noise Model

Numerical maps are used in the AMBER simulation to represent geographic and frequency variations of the atmospheric noise parameter F_{am} for a fixed hour of universal time, UT, and a fixed three-month season.



Variation of radio noise with frequency
(winter: 0000–0400 hours)

——— Expected values of atmospheric noise
- - - - Expected values of man-made noise at a quiet receiving location
—-—- Expected values of galactic noise

SOURCE: Adapted from CCIR (1963).

Data on noise variability and character
(winter: 0000–0400 hours)

$\sigma_{F_{am}}$ = Standard deviation of values of F_{am}
D_u = Ratio of upper decile to median value, F_{am}
σ_{D_u} = Standard deviation of values of D_u
D_l = Ratio of median value, F_{am}, to lower decile
σ_{D_l} = Standard deviation of value of D_l
V_{dm} = Expected value of median deviation of average voltage. The values shown are for a bandwidth of 200 Hz

Fig. 7.2—Variation of external radio noise with frequency and statistics of the atmospheric noise, F_{am}

The method and database developed by Zacharisen and Jones (1970) for geographic dependence were used. The diurnal variation at each geographic grid point (latitude, longitude) was represented by a Fourier analysis of the local time block F_{am} values. Then, a Fourier analysis was made of the longitudinal variations for a fixed latitude. Finally, the geographic variation of each Fourier coefficient was expanded in a series of functions analogous to surface spherical harmonics. The result is a two-dimensional representation in latitude and longitude at fixed UT for each season.

A method and database developed by Lucas and Harper (1965) was used to obtain frequency variations of F_{am} by a least-squares mapping of the data by a power-series expansion. A total of 14 coefficients were required to represent each of the 24 frequency variations (each season and four-hour time period). The other parameters, the upper and lower decile ratios, and the standard deviations were all generated by a fourth-degree polynomial in x, where x is the logarithm of frequency. A subroutine GENFAM (see, for example, Sailors and Brown, 1982) was adopted for that purpose, with an appropriate interface between local time corresponding to the universal time of interest at the receiver site.

The current AMBER assessment methodology does not include short-term variations of the atmospheric noise, as described by the APD curves. In anticipation of future assessments, the APD curves have been included in the AMBER simulation model. The numerical APD model is based on the method of Crichlow et al. (1960) and adopted from Spaulding and Washburn (1985). The APD curve is fitted with two straight lines connected by the arc of a circle on a coordinate system. The ordinate of the coordinate system is the envelope of the voltage level in dB; the abscissa is the percentage of time the ordinate is exceeded. The coordinates are such that the envelope of the Rayleigh distribution (envelope of gaussian noise) plots as a straight line with a slope of −0.5.

Galactic Noise

Galactic noise originates from various radio sources in and outside the galaxy and from the sun. Detailed maps of the distribution of radio sources in the sky have been compiled and their emissions measured. It has been found that the galactic radio emission rate is extremely steady in magnitude; its variations are caused by variable absorption in the atmosphere.

The expected values of galactic noise level, extrapolated to 1 MHz frequency, are given in CCIR (1963) on frequency plots. The low-frequency cutoff of cosmic noise is determined by the peak density of the ionosphere, since radiowaves of frequency less than the critical frequency of the F-region cannot propagate to the ground. Cosmic noise is seldom a dominant noise type for an MF system in the ambient environment. At times when it is possible to see the galaxy at the operating frequency, the median galactic noise, F_{gm}, dependence on frequency can be approximated by a straight line.

The variability of galactic noise in terms of upper and lower decile ratios, D_{ug} and D_{lg}, can be taken to be 2 dB about the median (CCIR, 1963).

AMBER Galactic Noise Model

The AMBER galactic noise model uses a straight-line approximation to the galactic noise curve of the form

$$F_{gm} = 52.0 - 22.0 \log f \quad \text{dBW/Hz}$$

where F_{gm} is median galactic noise and f is the operating frequency in MHz. The corresponding noise power available from the equivalent lossless antenna, P_{ng}, is given by

$$P_{ng} = F_{gm} - 204 \quad \text{dBW/Hz}$$

Manmade Noise

Manmade noise originates from a number of sources, such as power lines, industrial machinery, and ignition systems, and has widely varying characteristics. Because it propagates primarily over power lines, and in a groundwave mode, its range of effects is limited, and its average value depends mainly on the location of the receiving site relative to the manmade sources. Manmade noise data have been collected for the frequency band 250 kHz to 250 MHz, for various environmental sites in the United States (Spaulding and Disney, 1974). Three environmental categories were designated: rural (agricultural), residential (urban or suburban), and business. The results of measurements were analyzed statistically and least-squares fits for the median value of noise were obtained. In all cases, the results were consistent with a linear dependence of the mean value of noise, F_{mm}, on the logarithm (base 10) of frequency of the form

$$F_{mm} = c - 28 \log f \quad \text{dBW/Hz}$$

where $c = 67.2$ for rural, 72.5 for residential, and 76.8 for business, and f is the operating frequency in MHz.

AMBER Manmade Noise Model

The AMBER simulation program uses the above straight-line approximation to the expected value of the manmade noise level as a function of frequency. The corresponding noise power available from an equivalent lossless antenna is given by

$$P_{mm} = F_{mm} - 204 \quad \text{dBW/Hz}$$

Combination of Three Types of Noise

When the noise collected at the receiver is due to several different sources with similar distributions, they can be summed by taking the different phases into account. For the three types of noise considered here, the phases are independent and continuously variable. Hence, the noise power can be summed with the resultant median noise given by

$$F = 10 \log (10^{F_a/10} + 10^{F_g/10} + 10^{F_m/10} \quad \text{dBW/Hz}$$

where F_a, F_g, and F_m are atmospheric, galactic, and manmade noise, respectively.

VIII. NATIONWIDE AMBER SIMULATION

INTRODUCTION

This section discusses the preparations for a CONUS-wide AMBER network simulation. A preliminary study by Bedrosian and Harris (1984) investigated a four-state area of the southwestern United States that was felt to contain a good representation of problems likely to be met in the full study. This early study, although it gave promise of sufficient connectivity to serve AMBER, and encouraged preparation for a full-scale approach, was flawed in some respects. These flaws have been addressed in this much larger program. In particular, these aspects now receive treatment here:

- All U.S., Canadian, Mexican, and Caribbean stations of a given frequency are considered as potential sources of interference.
- Noise and propagation models are more up to date and realistic. Skywave propagation is included.
- A very large number of paths must be calculated causing heavy emphasis to be placed on computational efficiency.
- Much heavier use of graphics is emphasized to help the analyst understand issues more clearly and to allow quicker changes.

METHODOLOGY

The procedure pursued to meet the goals described above is as follows:

1. Form a database of AM station information for the United States and adjacent foreign countries.
2. Choose a subset of U.S. AM stations suitable for an AMBER network.
3. At each network station determine all usable paths to the station.
4. Determine the connectivity of the resulting network.
5. Evaluate the results.

The remainder of this section discloses how each of these steps is handled by the newly assembled system. These steps vary widely in their computational difficulty. Step 1 is a straightforward, if tedious, database preparation. Step 2 is critical to the work that follows; more work should be done on the problem of network selection. Step 3 consumes the majority of the computation time and exercises most of the software prepared. Step 4 is the simplest part. Step 5 does not directly involve computation.

THE RAND MOSF

The RAND MOSF was used for all the activities reported here. Full details concerning this facility can be found in Donohue, Bennett, and Hertzog (1986). For this project the following equipment was used:

- Interactive high-resolution workstations (SUN 3/280) networked (via Ethernet) to a high capacity (1.5 gigabyte) fileserver.
- Apple LaserWriter supported by the Adobe Systems TransScript software package enabling full use of the PostScript language for graphics hardcopy.

This equipment complement affords state-of-the-art computing and display capability together with a large database storage capacity. The databases used were the FCC AM Radio Engineering Database, the World Data Bank II Map Database, and numerous smaller sets of data such as the Ground Conductivity Database from the FCC.

Programming was in a mix of C and Fortran reflecting the capabilities and interests of project personnel and appropriateness to a particular task.

AM-RADIO DATABASE CREATION

The SUN MicroIngres Database Management System is used within the MOSF. This system is a general relational database model with the additional advantage of interfacing easily to programs written in C and Fortran. Thus, statements can be written in C to retrieve data from the system and process it with C statements. This flexibility was heavily used. However, the excessive memory required for the entire Ingres system caused serious performance degradation in the final program, so a compact database representation was created especially for the path calculation runtime-environment.

The database in Ingres was formed from:

- Much of the FCC AM Radio Engineering Database.
- Lists from FEMA giving:
  - Stations equipped with the FEMA protection package.
  - Stations equipped with CPCS-1[1] facilities.
  - Stations equipped with EMP protective devices.
- Overpressure data from FEMA. This classifies stations as within or outside of a 2 psi overpressure region. The map used was from FEMA.

The finished database lists 6649 stations (U.S. and foreign). The only difficulties encountered in forming it were due to the FEMA lists (mentioned above) being based on call letters of the stations involved. Many of these call letters could not be found in the database, and some considerable work was involved in determining which current entry in the database corresponded to the station equipped by FEMA several years earlier.

SELECTION OF A NETWORK

The most complicated operational problem occurs here. The choice as to which stations to select to form the network depends on a large number of factors. These include.

- Proximity to the users.
- Propagation factors: high power, low frequency, etc.
- Connectivity needed for the traffic load planned or required.

[1]CPCS-1 facilities are provided by FEMA as entry points to the Emergency Broadcast System.

- Survival following nuclear attack.
- Cooperation of station management with goals of network.
- If used for public dissemination of messages, the size of the listening audience.

The solution is clearly an iterative one. It is best started by choosing a network . s automatically as possible, then augmenting and adjusting it to overcome objectional aspects as revealed by the analyst's studies.

For the initial test, the following methodology was used: From the AMBER database all stations meeting these criteria were chosen:

- FEMA equipped.
- Outside 2 psi overpressure.
- Nonzero nighttime power.

This gave 288 stations nationwide. For each station in this list, a parameter equal to the daytime power divided by the square of the frequency was calculated. (This gave a rough measure of station "strength," since low frequencies propagate better than high ones.) The 288 stations were then listed according to decreasing values of this parameter; the top 100 stations in the resulting list were then used to form the network.

Those 100 stations are plotted · ·th their ID in Fig. 8.1. It is seen that a moderately uniform geographic coverage results exc. , for New York, New Jersey, Connecticut, Rhode Island, and Massachusetts. Strangely, these states are omitted by these arbitrary criteria, probably because those with desirable properties were located within the 2 psi overpressure area. There are, of course, several stations within these states among the 188 that were omitted, and they constitute stations that could be added manually in the next iteration.

A large interactive program called AMBERTool was built on the SUN workstation using its windowing and graphics capabilities to present data concerning the AM database. Figure 8.2 shows the screen while in operation. Selection of a station, via the mouse, presents a data block describing the station as derived from the database. Such items as frequency, city, state and country, class of station, day and night powers, and serial numbers within the database are thus available at the touch of a button. Selection mechanisms exist allowing only stations meeting some requirement to be displayed. Thus, stations on a specific frequency having nighttime power might be selected. In addition, full pan and zoom are available via the mouse. The area described in the main viewing screen is shown outlined on the fixed map display located in the upper left corner of the screen. By this means easy and convenient adjustments in pan and zoom can be made. Network station selections can be edited with this screen making the iteration process described above a good deal easier.

THE COMPUTATIONAL PROCESS

Organization of the computations is important to the success of the project. It would be unrealistic to submit one huge month-long job to the computer and hope for successful completion. Also, enough experimental activities take place in the MOSF that occasional outages do occur. By structuring the task into smaller subtasks whose results can be merged, an overall control is achieved. If these subtasks are independent, they can be rerun with no impact on the entire job. The highest levels of the program read as follows:

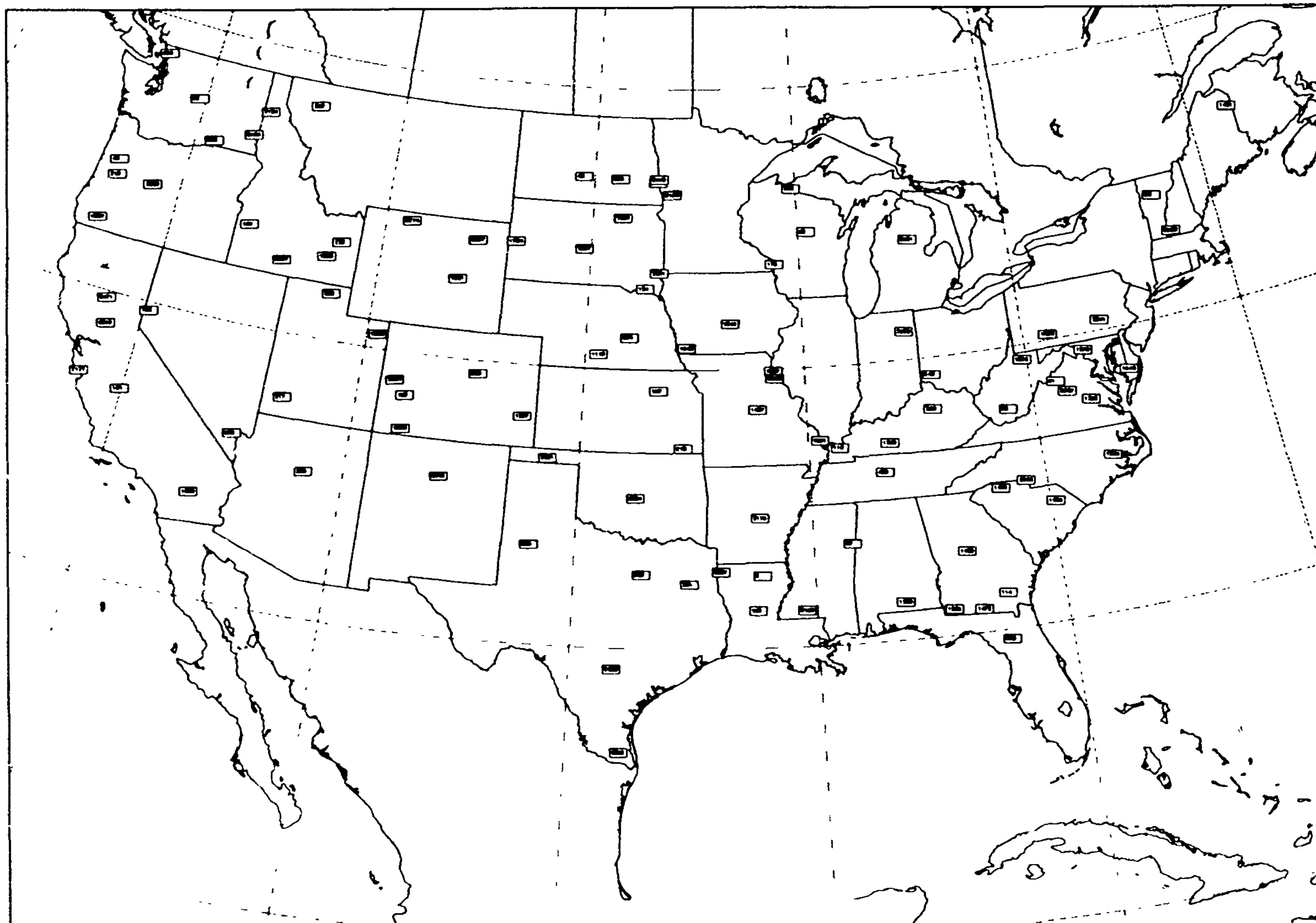


Fig. 8.1—Network example using 100 stations

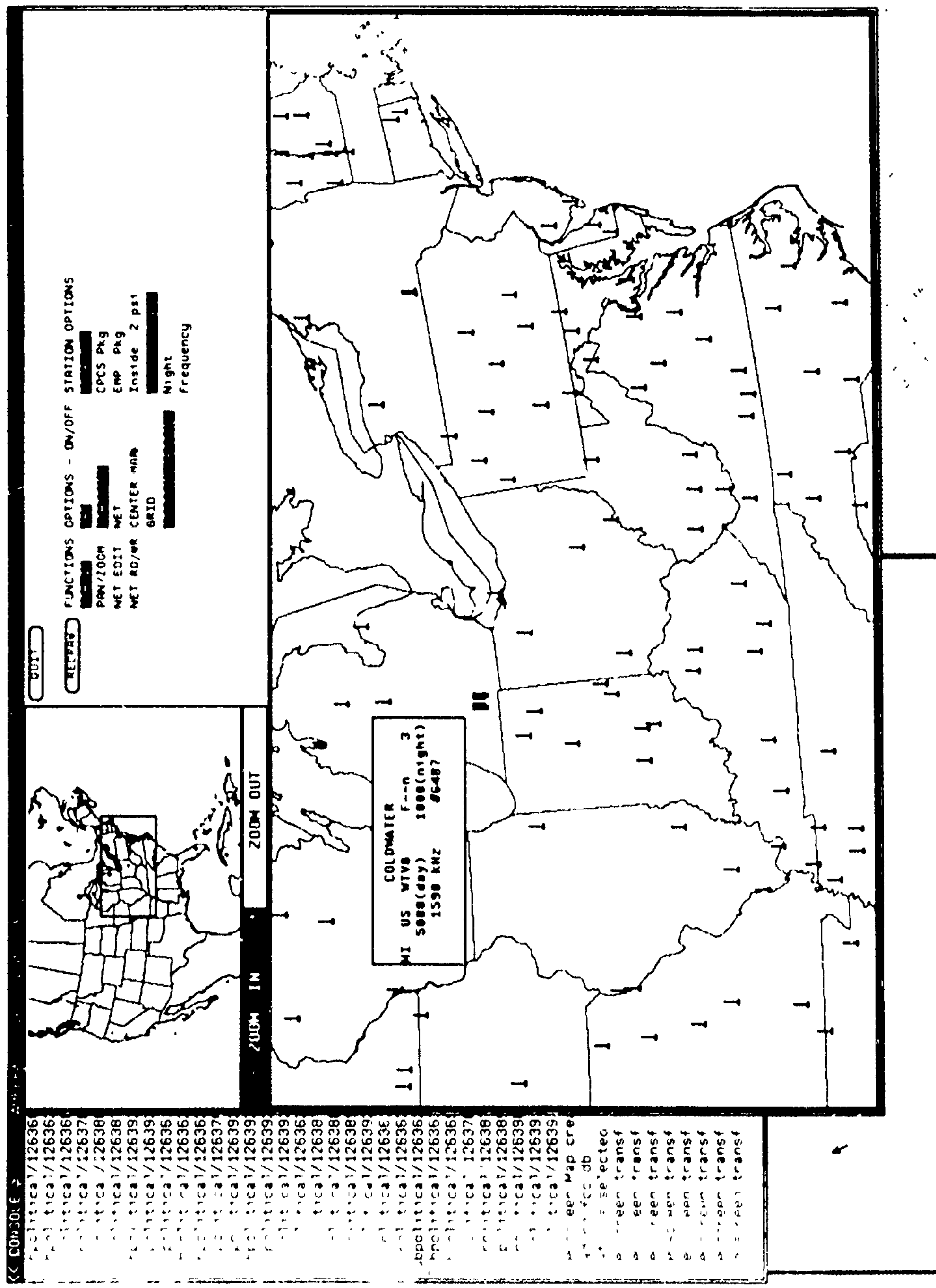


Fig. 8.2—Screen of AMBERtool

```
For each environment E to be studied (season, time of day, sunspot number, margins, etc.)
    At each network node receiver R
      Do
          Pathstudy(E,R)
      End
    End
End
```

"Pathstudy" is the minimum module that can be run. Its inputs are an environment file and a network receiver ID. Its outputs are a list of successful paths meeting requirements specified in the environment file and a set of statistics concerning and summarizing the run. If the example network has 100 nodes, there will be 100 runs of "Pathstudy" for each environment. By collecting all selected paths for the 100 runs, the network connectivity can be studied for the environment E.

Pathstudy itself implements the following algorithm:

```
Pathstudy: With the given environment at the given receiver, R
    For each active network frequency not too close to R's transmitter
        Calculate noise level and put in signal list.
        For each network station on this frequency
            Calculate groundwave signals, put in signal list.
            Calculate skywave signals, put in signal list.
        For each interfering station on this frequency
            Calculate groundwave signals, put in signal list.
            Calculate skywave signals, put in signal list.
        Sort signal list.
        Evaluate signal list (yields one good path or none).
        End
    End
```

To evaluate the sorted signal list, the rule applied is:

If top of list is not a network station, reject all paths.
Else, if next on list is less than (margin) dB below top, reject all paths.
Else, accept path at top of signal list.

The effect is to accept a path when the interference seen is sufficiently low and to reject the entire frequency at this receiver when it is not. The values placed in the signal list are the calculated signal and noise levels in dB. Associated with each value is the identity of the corresponding station and whether groundwave or skywave calculation led to the value. This allows different margins to be used in the two cases. Because of fading caused by skywave, for example, a greater margin might be desired than would be required for groundwave.

THE ENVIRONMENT FILE

Many parameters are required for a network study. For example, propagation and noise depend on sunspot number, time of day, and season. Transmitter powers may change at local sunrise and sunset, which in turn depend on time of day at the station as well as season. All parameters that affect a computer run are specified in the environment file. Hence, running the same network configuration with different environment files can give dramatically different results.

More mundane parameters such as threshold values for detection of groundwave and skywave signals as well as required thresholds with respect to interference levels are also to be found here. These are used by the path evaluator to accept or reject paths and are thus critical. Actual values to enter into an environmental file come from a wide variety of places. The threshold values referred to above come from studies of the properties of specific modulation methods, whereas times are chosen to give interesting effects. Thus 6:00 PM on the 90th meridian gives nighttime behavior along the East Coast while still showing daytime behavior on the West Coast. Actual time is 90th meridian local time (known as Central Standard Time) but is entered as Universal Time (essentially Greenwich). Thus 6:00 PM is entered as 12:00 PM (0000 UT).

Latitude and longitude find their way into a great many formulas that are often used to find local time or to determine sunrise or sunset time, and, hence, allowed station powers.

Another value found in the environment file is the separation, *sep*, in frequency required from the transmitter collocated with the receiver. It is clearly impossible to receive other stations on your own transmitter frequency. With great care, considerable expense, and, perhaps, some physical separation it might be possible to receive on adjacent channels, so *sep* measures this receiver quality factor. Setting *sep* to 20 kHz means that adjacent channels are not receivable but that the next adjacent ones (plus and minus 20 kHz) are.

CONNECTIVITY

The connectivity of a network answers questions like:

- Who hears whom?
- What is the number of links via the shortest path from A to B?
- Which stations are in the network? And, conversely, which are not?

It develops that nodes are such that less than half of the paths are two-way. It is possible to study only two-way paths in a network, but, for example, with the receipt-routing algorithm it frequently cannot be determined which route is being used until the entire circuit is set up. Because of this, and to permit more generality, our connectivity information is derived assuming the use of both two-way and one-way paths.

A path is represented by an element of a "from-to" matrix called the adjacency matrix. The row identifies a source node (transmitter) and the columns correspond to destination nodes (receivers). A "one" is placed in the matrix at element (i,j) to represent that a path exists from the ith station to the jth station. All other elements are made 0. In particular, the (i,i) element is made 0. The resulting matrix represents the nearest neighbor relation, and can reveal immediately whether there is a direct path from i to j.

Now consider forming the square of the adjacency matrix A. The (i,j) element of the square is:

$$\sum_{k=1}^{s} A_{ik} \times A_{kj}$$

For this to be nonzero, there must be at least one k such that both A_{ik} and A_{kj} are nonzero. This corresponds to a sequential path from i through k to j. Thus, the square of the adjacency matrix identifies stations connected via a pair of paths. It is easy (by simple induction) to show that the Mth power of the adjacency matrix identifies stations connected through M successive paths (see Harary, 1969).

The powers generate new information about paths, and, in fact, generate loops after a while. For example, if a is connected to b, the third power identifies the path $a \rightarrow b \rightarrow a \rightarrow b$, which is highly redundant. Thus, as powers are generated, new information alone should be collected. For this purpose, the reachability matrix R_N is used. R_N reveals if a path with N or fewer links exists in the network. Its elements are Boolean values. Thus, $R_1 = A$, the adjacency matrix while $R_2 = R_1 +$ ("ones" where A square has "ones"), and generally $R_N = R_{N-1} +$ ("ones" where A^N has "ones"). In practice, R_i is formed until a point is reached where $R_i = R_{i-1}$; that is, no further links are found. The value of $i - 1$ then gives the maximum number of paths needed to link the most remote pair of nodes.

Thus a simple arithmetic procedure can yield answers to questions such as:

- What is the average number of paths used in a call setup?
- Which stations (nodes) are not in the network?

Coupled with distance information, the average path length between pairs of stations can be calculated, and so on.

Connectivity is definitely a function of traffic. Once a path is set up and in use, it reduces the capacity of the network for additional uses. A further measure of connectivity is then given by the answer to the question: How many paths can be removed from a network before it is disconnected? This can also be studied by matrix manipulations (corresponding to minimum cut set calculations).

RUN STATISTICS

The evaluation process is tedious and generates a large amount of data before answering the final question: Does a path exist? There is more than a simple yes or no answer to this question. The program collects data helping answer the following questions:

- If no path was found, was the reason interference from
    - A network station?
    - A U.S. station?
    - A foreign station?
    - Natural noise?
- If a path was found, was the nearest interferer
    - Another network station?
    - A U.S. station?
    - A foreign station?
    - Natural noise?
- When a path was rejected, by what power level did it fail?
- What fraction of existing paths are skywave or groundwave?

COMPUTATIONAL COMPLEXITY

It is simple to write a straightforward program to accomplish the goals set for this project. It is a different task to get results in reasonable time. Much of the effort expended on the project was devoted to enhancing the computation speeds of various programs. A prime example was the groundwave propagation calculation. In a desire for simplicity, existing programs were used to perform this basic step. When adapted, the program took nearly two minutes to calculate the path loss of a "typical" path. A careful analysis showed that this was due to iterative sequences of calculations involving spherical trigonometry coupled with locating intersections of conductivity value contours along the route of the path. Considering that the final application involves calculating several million path losses, two minutes per path clearly results in an unacceptably long run time. A hundredfold improvement in this calculation was required; to achieve this, the path loss functions were significantly rewritten for groundwave propagation. The goal was met, but about two man-months were consumed in the process. A path-loss calculation now takes about a half second. One of the results was an improved digitization of the standard FCC conductivity curves onto a grid developed about a Lambert Conformal Conic Projection. Radio paths are nearly straight lines under this transformation, with significant departures from linearity occurring only for very long (over 2000 km) paths. Groundwave signal levels for such paths are normally too low for network use.

IX. ILLUSTRATIVE NETWORK CONNECTIVITY STUDY

INTRODUCTION

This section presents the results of the computer study outlined in the previous section. There is a large mass of data available; it has been summarized in the form of tables, graphs, maps, and pictorial matrices. These are less interesting for the specific details they present than for the insight they afford to communication planning. Numerous interesting statistics are gathered but the real goal is to evaluate the parameters present in the network pictured and to identify problems, extensions, and questions concerning implementation of AMBER.

Over 31 million path calculations were performed (half groundwave, half skywave) in 16 distinct environments. The presentation is in order from network selection through connectivity calculations:

- The network
- Environments
- Scatter plots
- Path plots
- Run statistics
- Matrices
- Connectivity

THE NETWORK

Three networks were studied by computer simulation. The first, NET1, was chosen as described in the previous section as being the 100 "best" stations from the FEMA 288 station collection. The results were disappointing and it was not obvious whether the criteria for selection were at fault or whether the number of stations was too small to do an adequate job of covering CONUS. It was decided therefore to deal with the entire FEMA collection, choosing subsets from the results of runs over the entire collection.

NET2 consisted of all 288 FEMA-equipped stations outside 2 psi in accordance with earlier discussions. But retained were all interfering stations, both domestic and foreign, including FEMA stations inside 2 psi. However, it was decided subsequently that this was unnecessarily pessimistic because removing all stations inside 2 psi as network stations should also preclude their acting as interferers.

Finally, NET3 was formed consisting of all FEMA stations (still 288 in number) outside 2 psi, but experiencing no interference from stations, FEMA or otherwise, inside 2 psi. All other domestic and foreign stations are still present to generate interference. A plot of the 288 stations is shown as Fig. 9.1. It is this net that is covered in this section.

Following an analysis of the results, it is easier to pare down the number of stations. Many have no connectivity, many others only seasonal connectivity, others duplicate coverage in a geographic region. Thus, the number of usable stations is less than 288, closer to 150, but for other reasons the network must be "enriched" with filler stations to connect existing islands of connectivity (see the discussion under Connectivity, below).

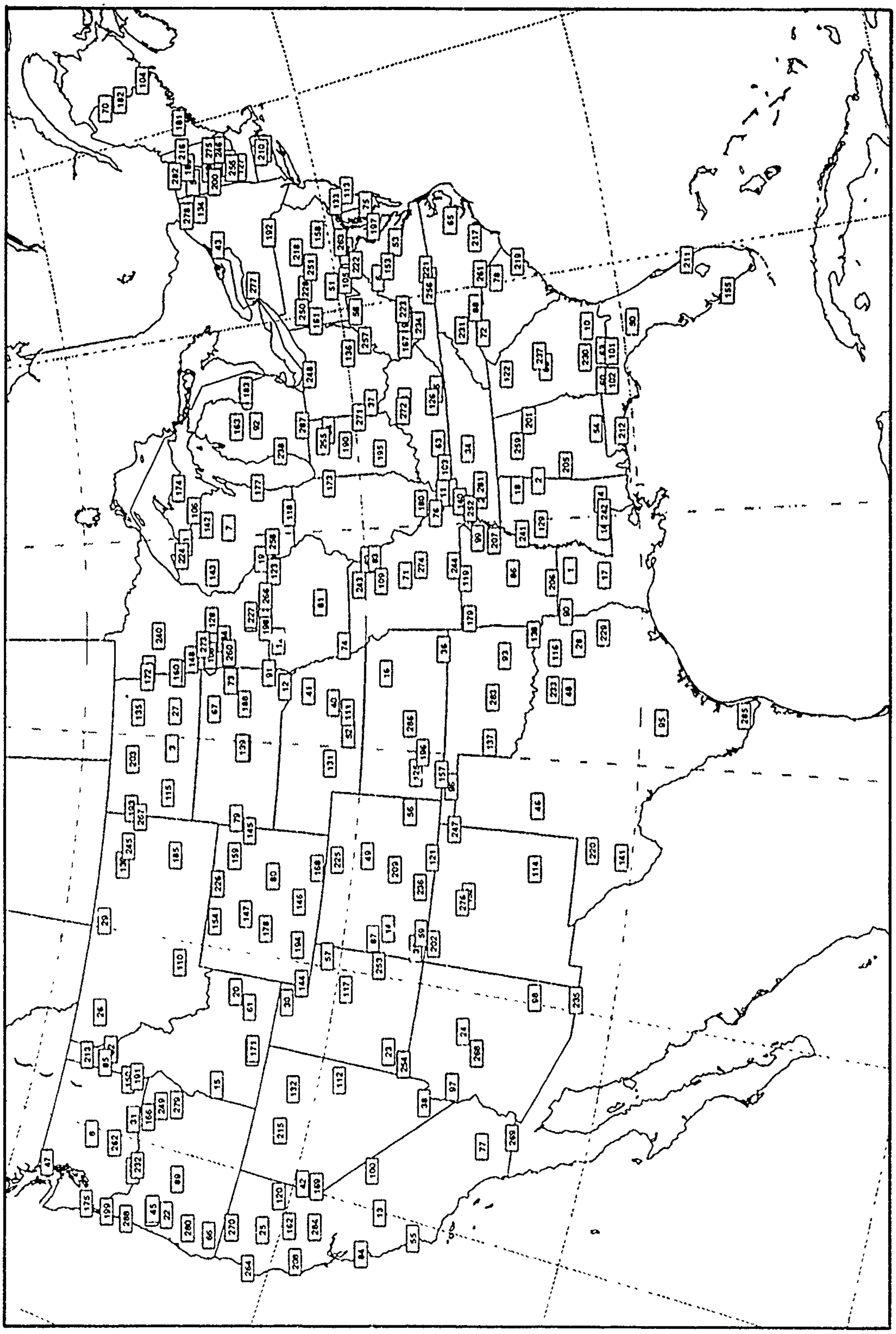


Fig. 9.1—Network example using 288 stations

NET3 has the following statistics:

- 288 network stations
- 6649 stations in the AM database
- 1,954,140 paths calculated per environment
- 74 frequencies used
- 3302 interfering stations (foreign and domestic)

ENVIRONMENTS

Because of the very large size of the networks, and the long calculation times, only the most critical parameters were varied. The greatest differences among runs of data were for season of year. Four were chosen: winter (December 22), spring (March 22), summer (June 22), and fall (September 22). Then, for each season four times of day were chosen (midnight, dawn, noon, and dusk, where time means local standard time at the 90th Westerly Meridian). This gives 16 distinct set of parameters alone. Other parameters chosen, but fixed throughout all runs, are:

- Bandwidth: 10 kHz
- Sunspot number: 70
- Minimum receiver detection margin: 10 dB
- Minimum separation between local transmitter and any received channel: 20 kHz

Generally, inferences can be made to other parameter values based on these. Decreasing bandwidth may improve margin, increasing separation will result in loss of paths, etc. The bandwidth chosen (10 kHz) is sufficient to accommodate up to four secure VOCODED voice circuits, though the accompanying margin of 10 dB may not be adequate depending on the robustness of the modulation method. Similarly the sunspot number of 70 is a reasonable average, though values between 10 and 120 or more may be found.

SCATTER PLOTS

To get a preliminary picture of the path set, the scatter plot was used. These plots, Figs. 9.2 to 9.5, show one point for each path, with its distance and margin being abscissa and ordinate, respectively. For example, Fig. 9.4c shows the summer-noon paths of NET3 (1269 paths) plotted this way. The decrease in signal strength (margin) with distance is easily noted here. There are no skywave paths in this set. At summer-dawn, however, Fig. 9.4b shows two distinct sets of paths. The first is like that of noontime but augmented at greater distances. This is a combination of groundwave and skywave paths. The second set (beginning at 2000 km) is composed of skywave paths alone. Figure 9.4a shows the summer-midnight scatter plot. The only groundwave paths are those below about 200 km path length. All others are skywave. The low number of groundwave paths is attributable to skywave interference, which is dominant for this time of day. Summer-dusk in Fig. 9.4d shows a few skywave paths (200) but mostly groundwave paths.

The scatter plot is useful for judging how many paths would remain if margin requirements were raised by 10 or 20 dB. But, of course, no geographic information is contained here, so no estimate of connectivity can be gleaned.

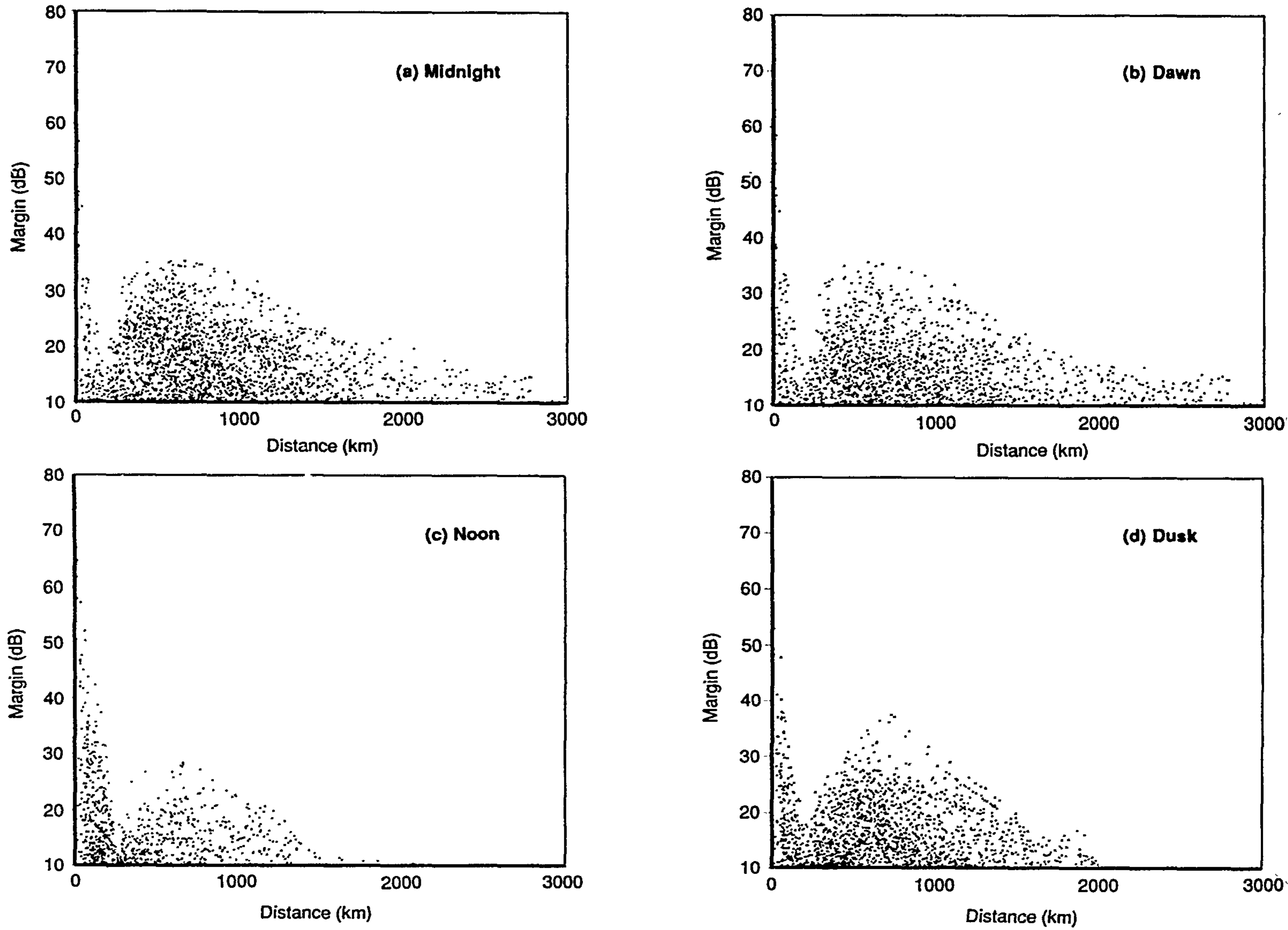


Fig. 9.2—Scatter plots, NET3, winter

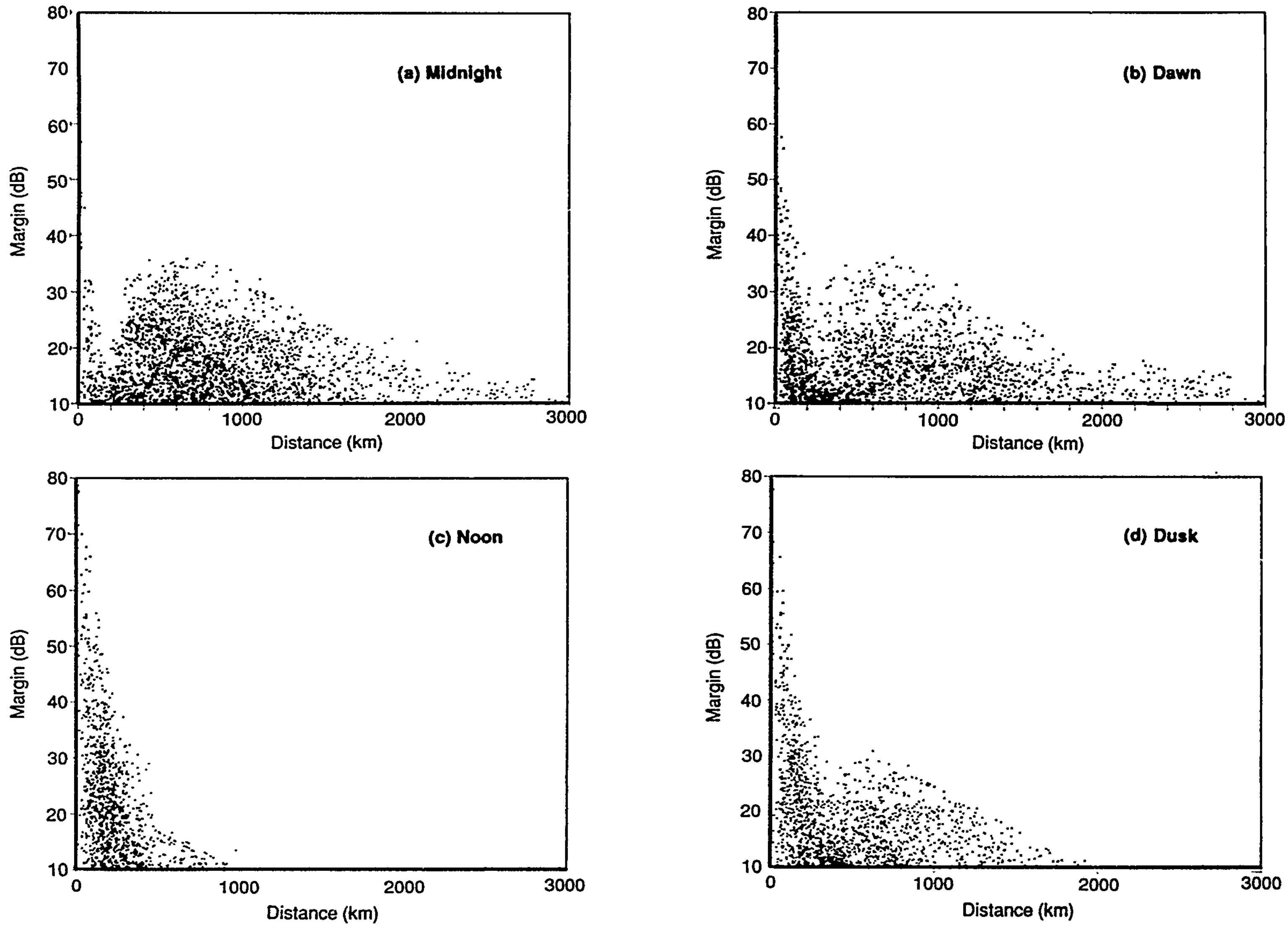


Fig. 9.3—Scatter plots, NET3, spring

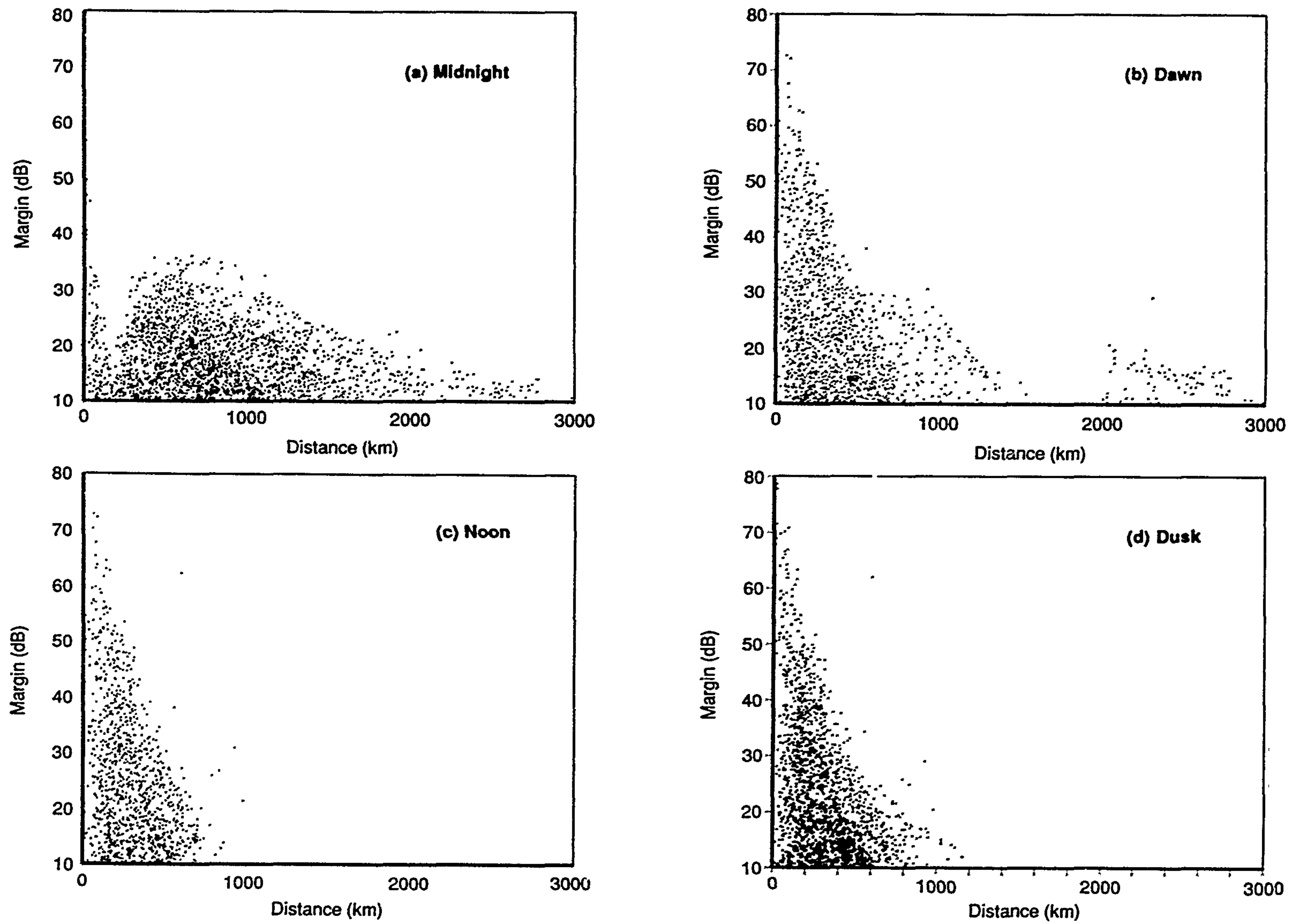


Fig. 9.4—Scatter plots, NET3, summer

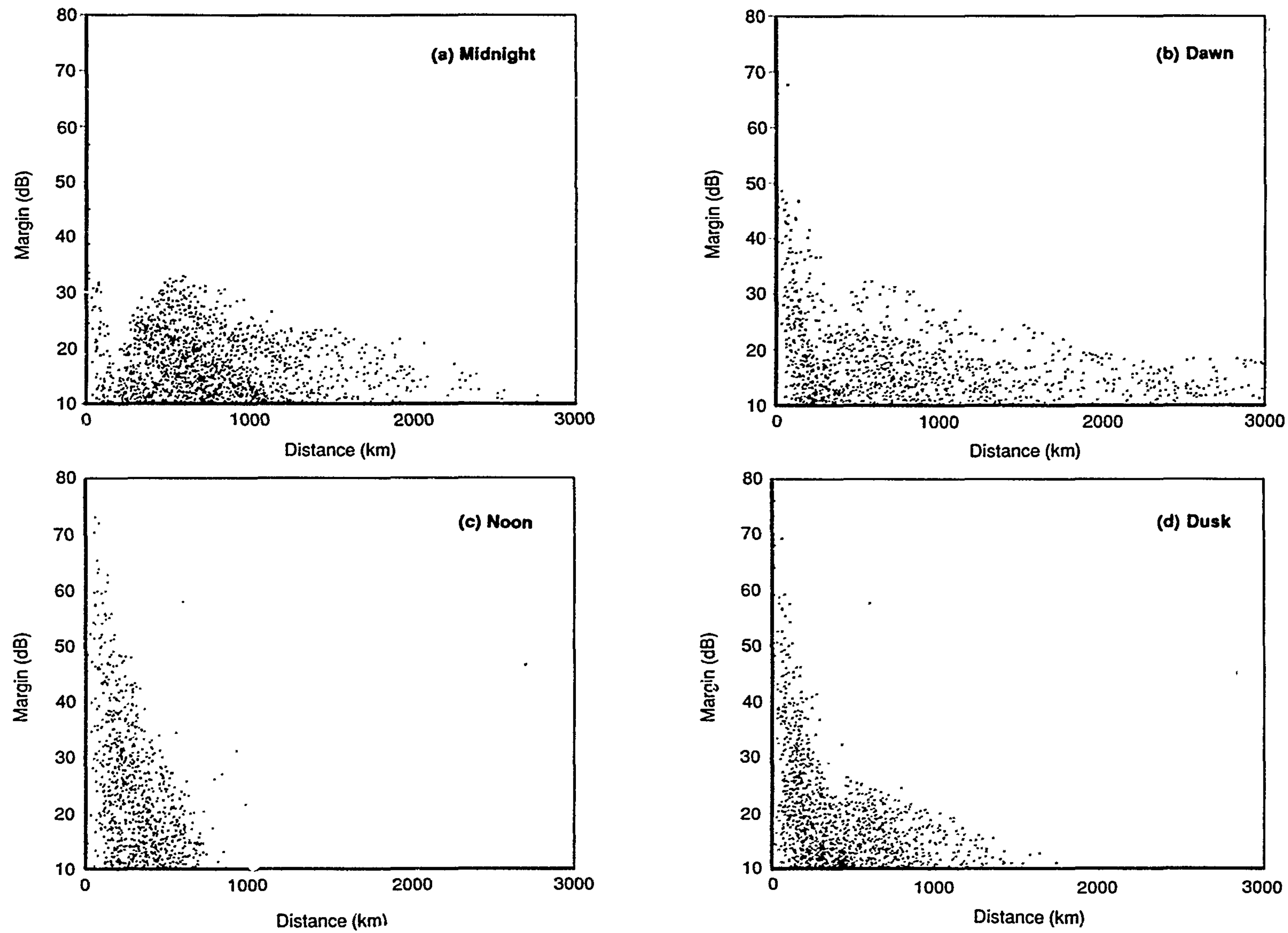


Fig. 9.5—Scatter plots, NET3, fall

A major factor affecting available groundwave paths is local noise at the receiver. This noise, a combination of atmospheric noise, urban manmade noise, and cosmic noise (not usually a factor at MF) is sufficient in summer to constitute the major daytime groundwave degradation at the receiver. At summer-noon 11,570 paths failed because noise dominated. Nearly the same was true at fall-noon.

If, at each of the 288 receiver locations, the frequencies that can be heard (avoiding self interference) are added, 20,533 possible paths result. On each frequency there are from a few to a few dozen stations at various distances and powers. The receive algorithm accepts a path only if both of the following are true:

- The strongest station is a network station.
- The strongest exceeds the next strongest by at least 10 dB.

Note that the comparison here is among the groundwave and skywave signals plus the noise signal on that frequency. The ratio 20,533/288 shows that the average number of paths investigated was 71.3 per receiver. The number of paths actually salvaged is typically less than a tenth as many.

PATH PLOTS

All of the paths are plotted on a basemap, one plot for each environment, in Figs. 9.6 to 9.9. Although most paths are in fact one-way, that is not shown here. Later, connectivity maps that identify one-way and two-way paths are shown.

RUN STATISTICS

Once it was fully automated, a run (i.e., full set of calculations for one environment) took between 20 and 28 hours depending on the machine used and how many other users were being accommodated. The MOSF facility has a great many machines and often runs were submitted simultaneously to several of them. Sample results from NET3 yielded the propagation statistics shown in Table 9.1. These numbers in some cases come from calculations and will be discussed below.

Each run on one environment was subdivided into path calculations for each receiver site and thus, consisted of 288 separate calculations whose results are merged in the table. But for each receiver, and each frequency to which it could be tuned, facts were gathered for the resulting status. These could be divided into the following categories:

1. Network station was received at least 10 dB above all other interfering sources, such as other network stations, interfering stations, and local noise. These constituted valid paths and were added to the selected paths database.
2. Network station had inadequate margin to work.
3. Interfering groundwave station dominated.
4. Interfering skywave station dominated.
5. Local noise level dominated.

Category 1 stations are listed under paths accepted. which breaks them down into groundwave and skywave. A later analysis of the adjacency matrix shows whether they are one-way or two-way paths. Note that two-way paths form a small minority of all accepted paths.

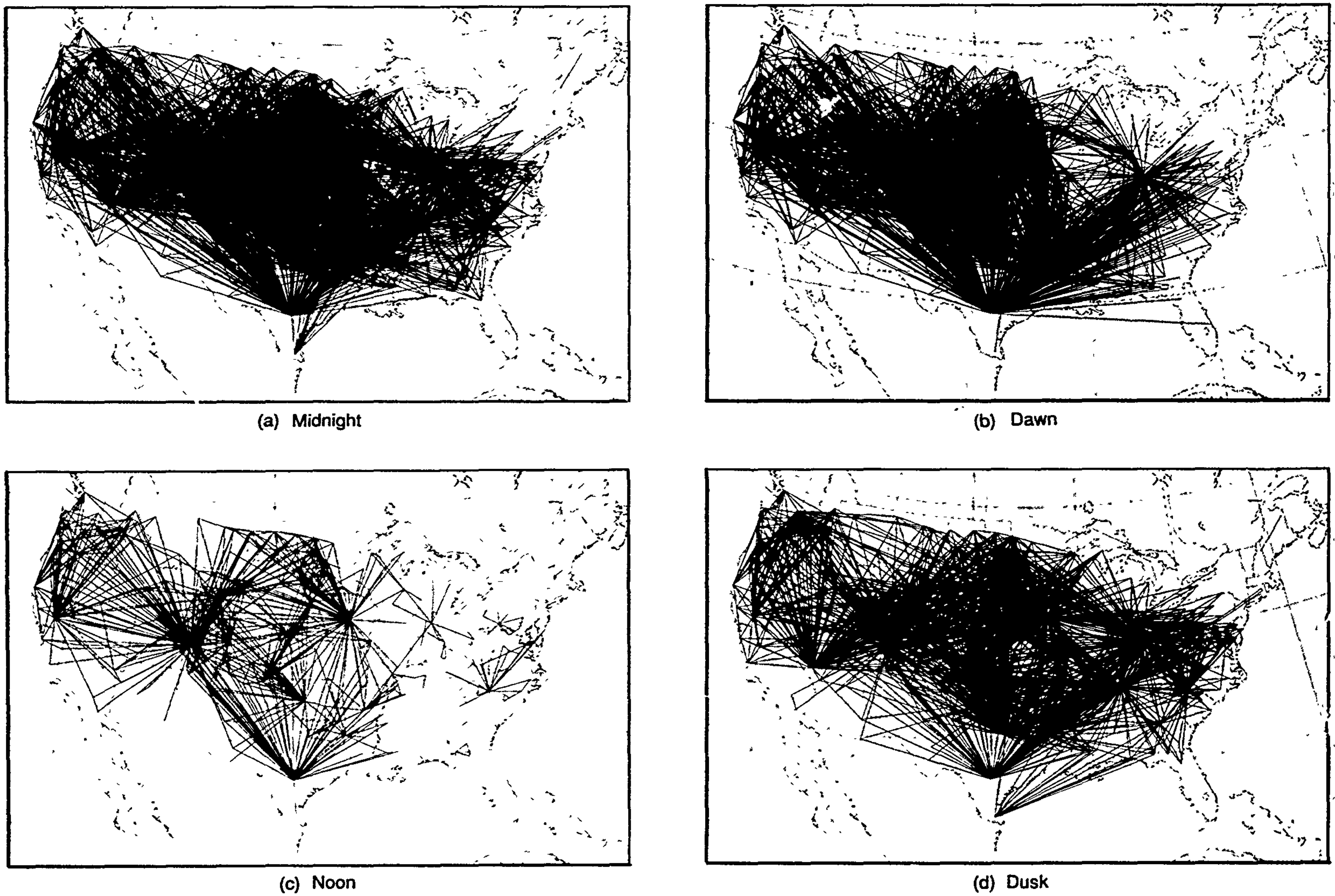
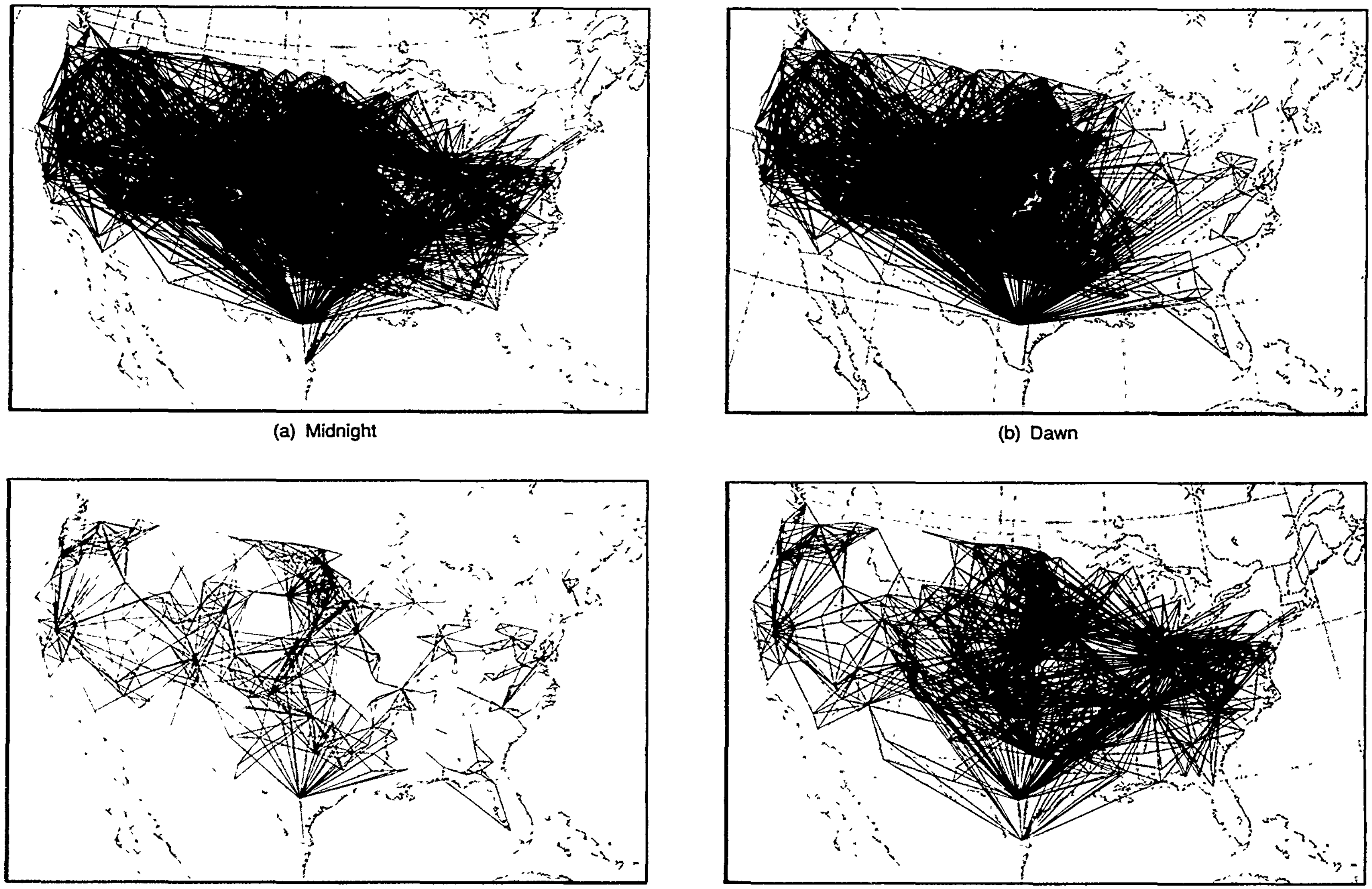


Fig. 9.6—Path plots, NET3, winter



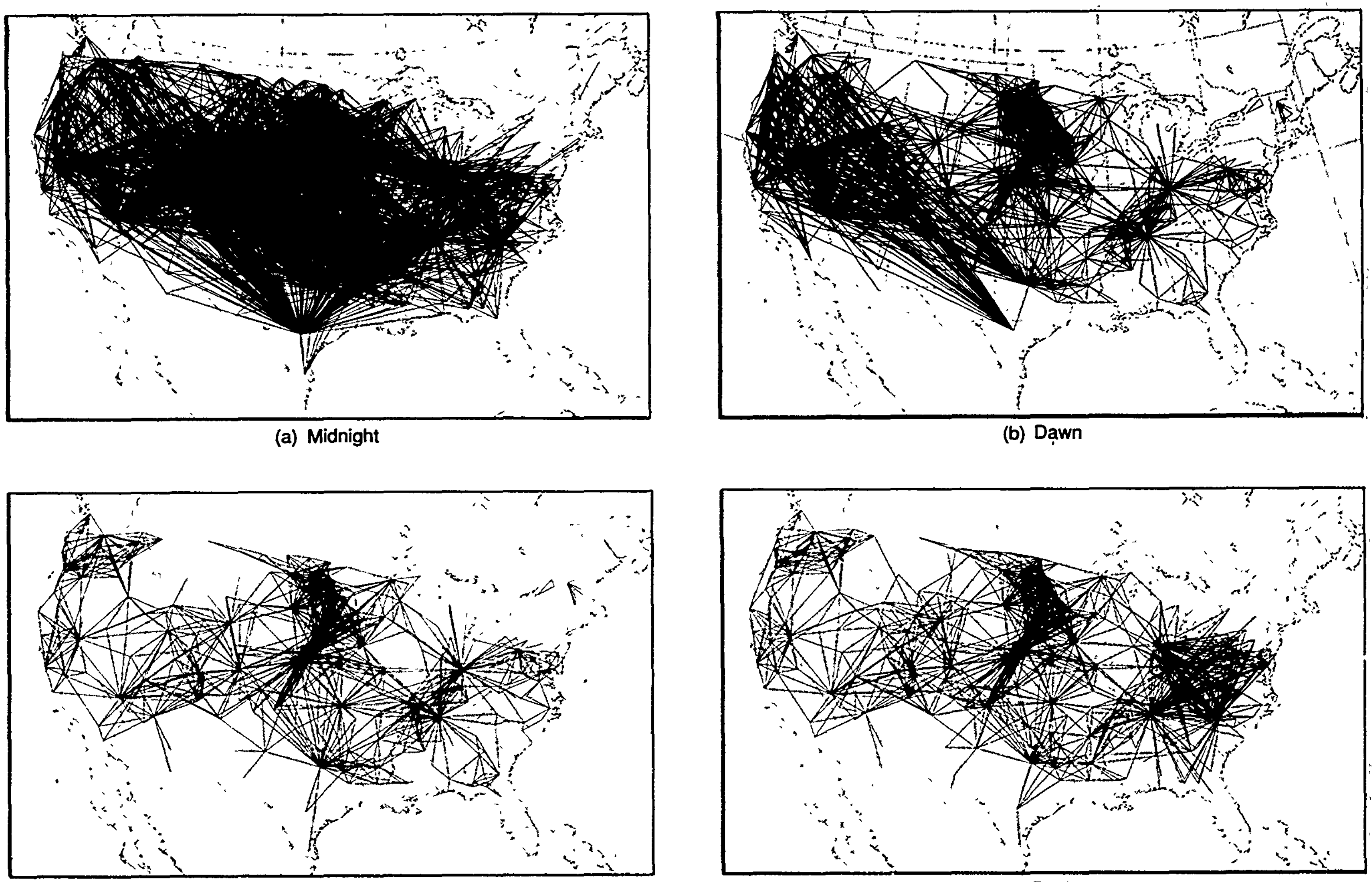
(a) Midnight

(b) Dawn

(c) Noon

(d) Dusk

Fig. 9.7—Path plots, NET3, spring



(a) Midnight

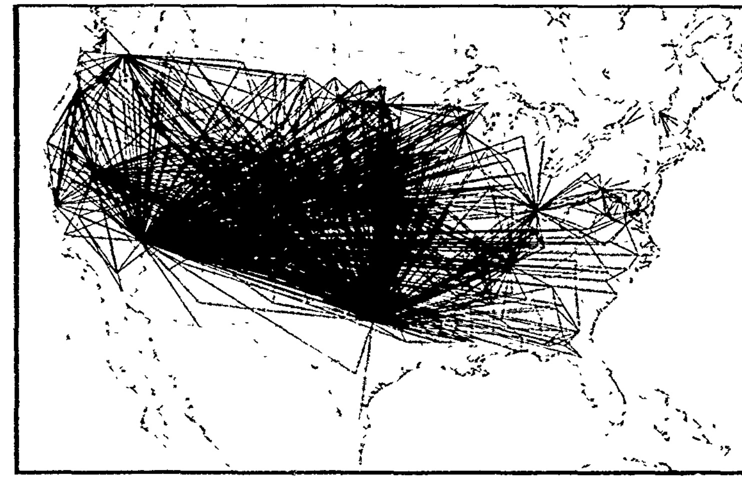
(b) Dawn

(c) Noon

(d) Dusk

Fig. 9.8—Path plots, NET3, summer

(a) Midnight



(b) Dawn

(c) Noon

(d) Dusk

Fig. 9.9—Path plots, NET3, fall

Table 9.1

PATH AND CONNECTIVITY STATISTICS FOR NET3 FOR THE ENVIRONMENTS INVESTIGATED

	Winter				Spring				Summer				Fall			
	Midnight	Dawn	Noon	Dusk	Midnight	Dawn	Noon	Dusk	Midnight	Dawn	Noon	Dusk	Midnight	Dawn	Noon	Dusk
Paths accepted																
Groundwave	123	123	489	267	125	502	1126	830	132	1180	1269	1608	94	408	985	869
Skywave	2343	1668	450	1508	2335	1526	84	918	2297	332	0	200	1705	832	0	697
One-way	2246	1619	677	1587	2242	1688	650	1286	2211	1166	971	1094	1667	1140	829	1090
Two-way	110	86	131	94	109	170	280	231	109	173	149	357	66	50	78	238
Total paths	2466	1791	939	1775	2460	2028	1210	1748	2429	1512	1269	1808	1799	1240	985	1566
Paths failed																
Inadequate margin	4337	3381	2105	3977	4356	3287	1714	3419	4329	1378	719	1505	2920	1875	626	3091
Groundwave interference	956	1680	5150	2541	959	5576	10022	5325	998	5463	6975	8587	545	2689	4948	5394
Skywave interference	12660	10539	5063	12190	12750	6906	2047	9258	12572	2958	0	4680	7310	3166	18	8073
Noise	114	3142	7276	50	8	2736	5540	783	205	9222	11570	3953	7959	11563	13956	2409
Connectivity																
Max. no. of paths	10	9	14	18	11	14	21	18	10	11	21	17	8	10	12	18
No. of components	8	12	21	16	8	30	19	11	9	16	11	14	9	10	8	10
No. of stations—largest component	64	34	74	62	64	72	126	135	66	79	78	165	37	25	28	137
Total stations in net	78	69	122	110	78	157	188	159	82	126	104	196	55	54	64	159

Categories 2 through 5 are also tabulated in Table 9.1. Seasonal and diurnal effects are prominent here. The total of potential paths in all categories is 20,533—this is the number of receiver-frequency combinations investigated.

MATRICES

At this point there is a collection of paths, some one-way and some two-way. The focus now is on the connectivity of this set of paths. For this purpose it is very convenient to use the methods of adjacency and reachability matrices. Each path is represented by an element of a from-to matrix called the adjacency matrix and denoted by A.

Since the focus is on overall connectivity, another matrix formed from these powers of the adjacency matrix and called the reachability matrix is used. The reachability matrix R sums (again by Boolean arithmetic) the powers of A. R collects the added information from higher powers of A until a stage is reached when additional powers of A contribute nothing new. This means that all stations are as connected as possible according to the particular path set. It takes only a few minutes of computer time to calculate these matrices and they help add insight to the connectivity picture. They are shown in Figs. 9.10 to 9.17.

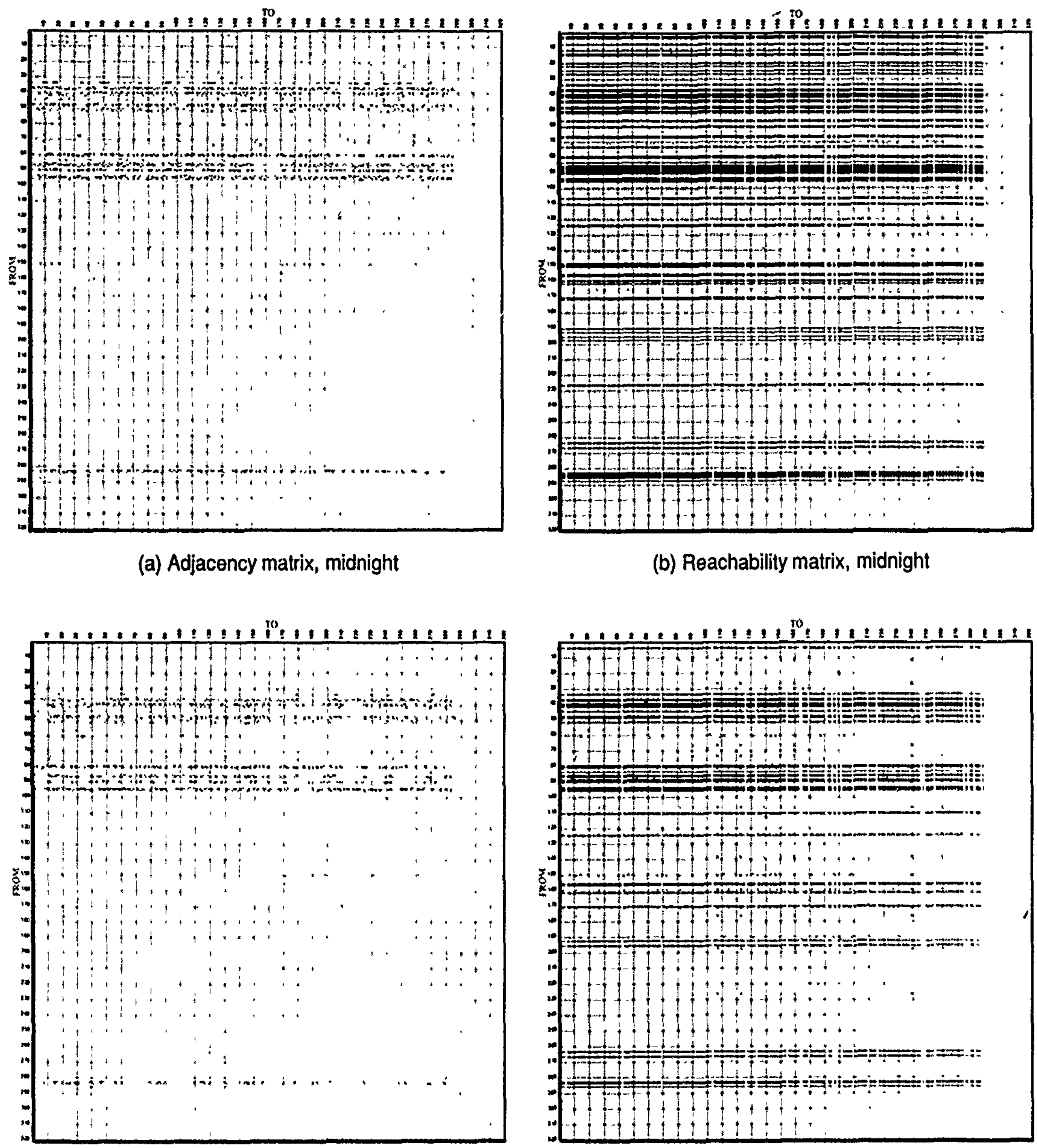
To make this more tangible, Fig. 9.15a shows the summer-noon adjacency matrix and Fig. 9.15b its associated reachability matrix $R21$. The "21" means that the maximum connection was achieved with the 21st power of the adjacency matrix. Thus, at least one station pair required 20 intermediate relay stations for full connectivity. The associated program studies the network connectivity as each additional power of A is added to R. From these intermediate results we can see that later powers offer only few additional network paths. The summer-noon adjacency matrix has 1269 paths connecting some of the 288 network stations. There are 149 two-way paths and 971 one-way paths in this matrix. $R21$, however, shows 3031 two-way paths and 13,910 one-way paths. This shows the dramatic power of intermediate relay stations.

CONNECTIVITY

Paths maps show where paths exist but do not show whether connected two-way communications can take place over them. The matrices show which stations are eventually connected. It is necessary to join these separate parts into one overall picture. The connectivity maps, shown in Figs. 9.18 to 9.21, were constructed from the information in the reachability matrices. One-way and two-way paths are discriminated and stations not capable of supporting or participating in two-way network connections were deleted. New and interesting problems are revealed. Most noticeable are "islands of connectivity," that is, clusters of stations that form subnets lacking any connection to their neighbors.

Contrast the path map for summer-dawn (Fig. 9.8b) with the corresponding connectivity map (Fig. 9.20b). In the connectivity map, two-way paths are shown with solid lines, whereas one-way paths are portrayed with dotted lines having an arrowhead at the destination end. Table 9.1 shows that there are 1166 one-way paths and only 173 two-way paths.

The connectivity map is generated from the reachability matrix by tracing paths from node to node until the process terminates. This forms one component. Then, another node not in the first set is used to perform the same process. This gives sets of connected stations. From these the map is prepared.



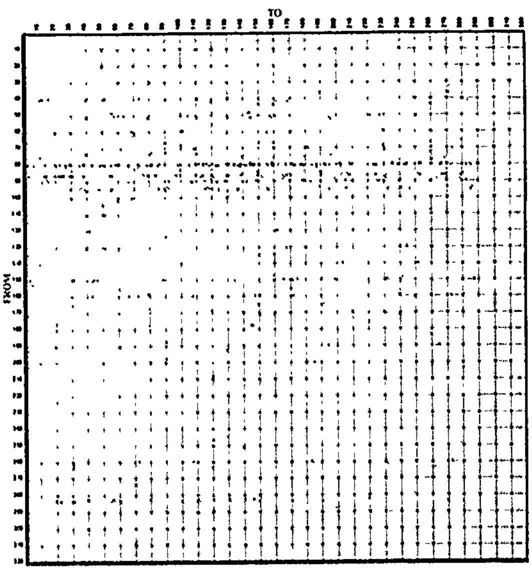
(a) Adjacency matrix, midnight

(b) Reachability matrix, midnight

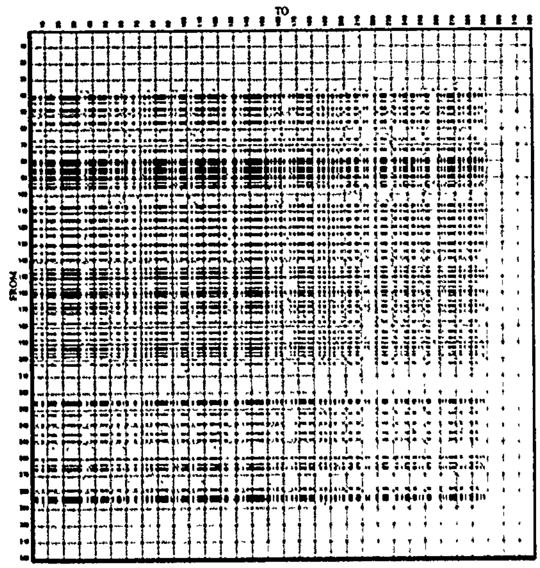
(c) Adjacency matrix, dawn

(d) Reachability matrix, dawn

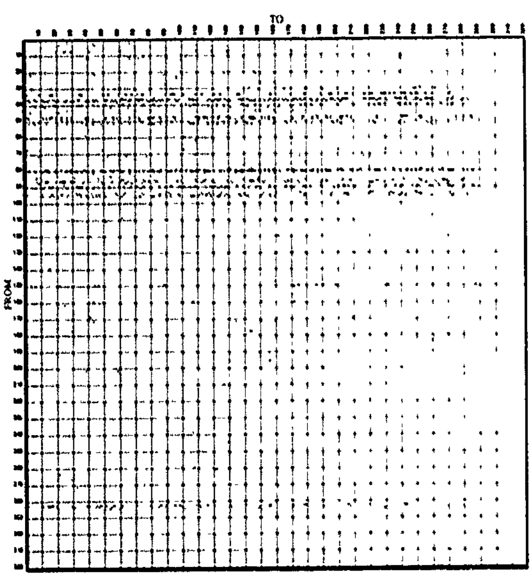
Fig. 9.10—Matrices, NET3, winter, midnight and dawn



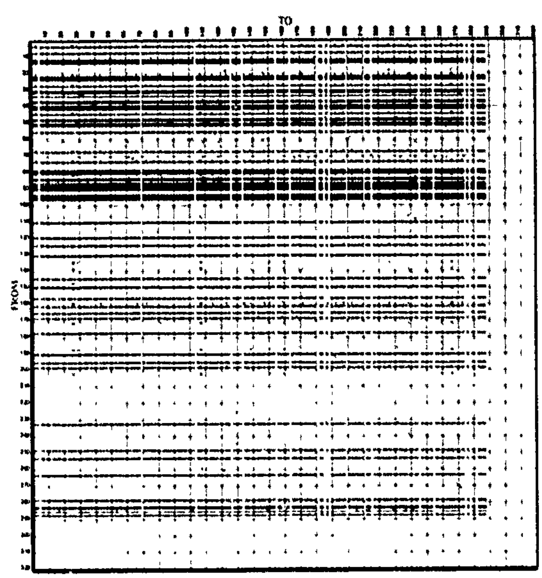
(a) Adjacency matrix, noon



(b) Reachability matrix, noon

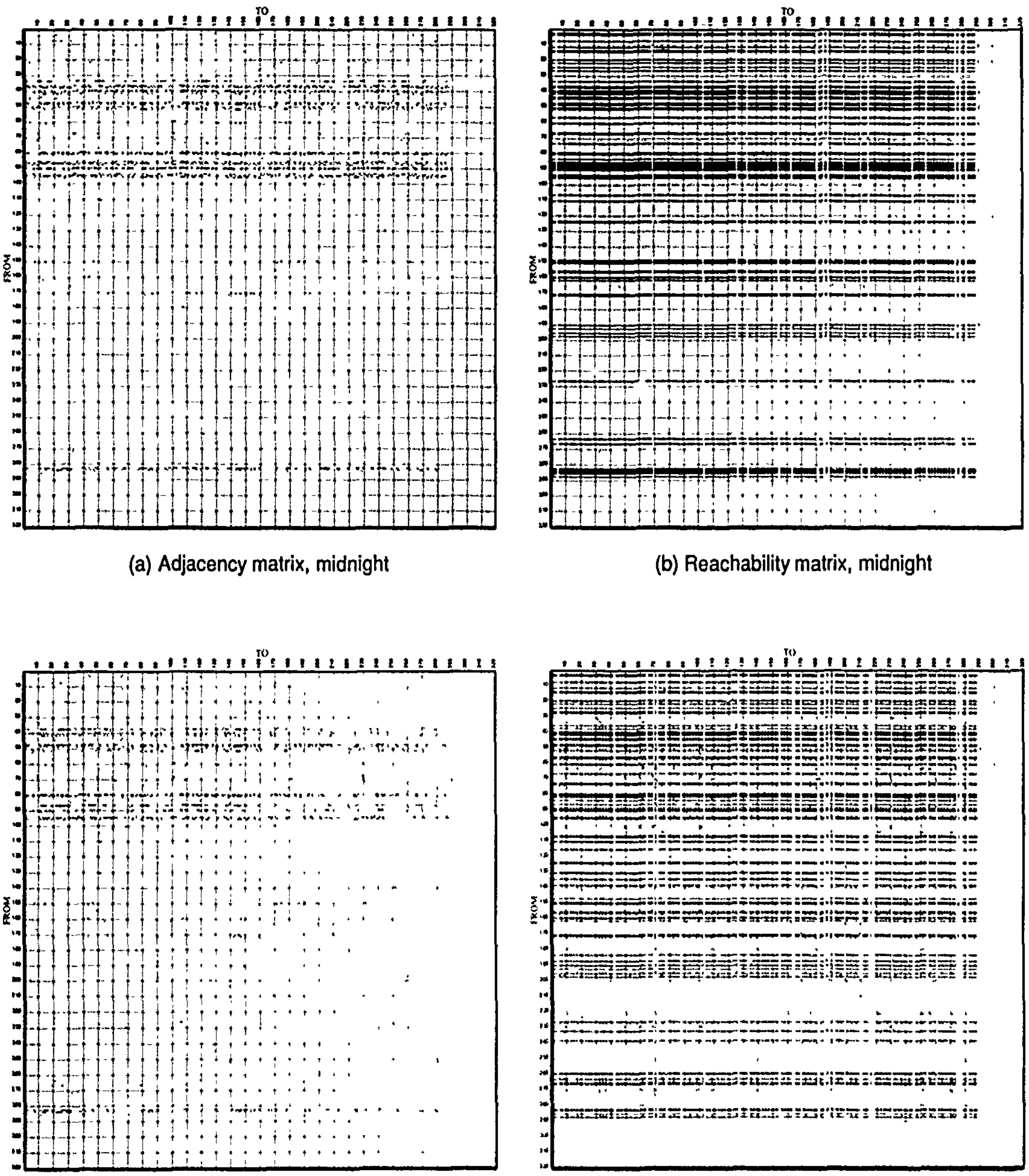


(c) Adjacency matrix, dusk



(d) Reachability matrix, dusk

Fig. 9.11—Matrices, NET3, winter, noon and dusk



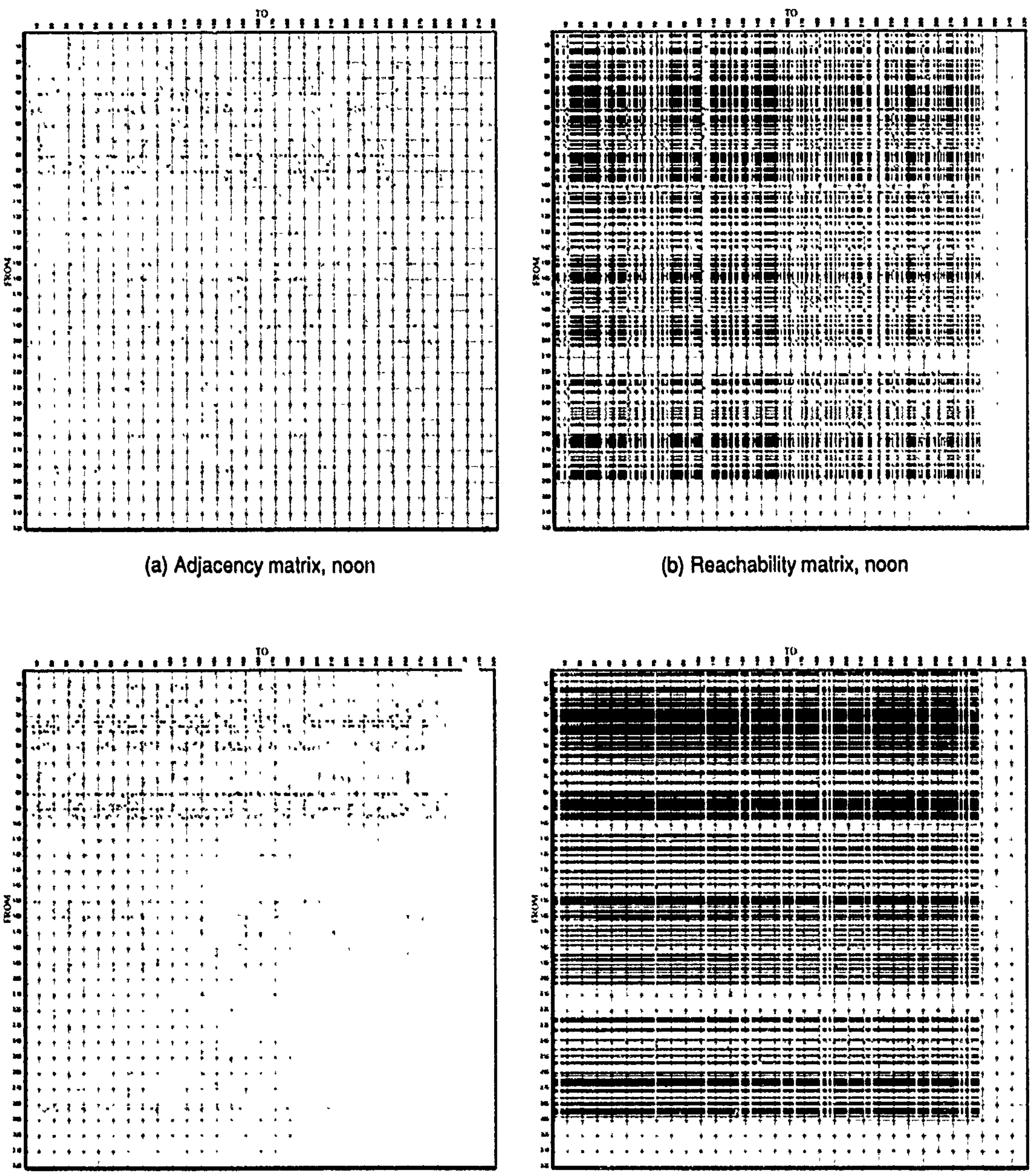
(a) Adjacency matrix, midnight

(b) Reachability matrix, midnight

(c) Adjacency matrix, dawn

(d) Reachability matrix, dawn

Fig. 9.12—Matrices, NET3, spring, midnight and dawn



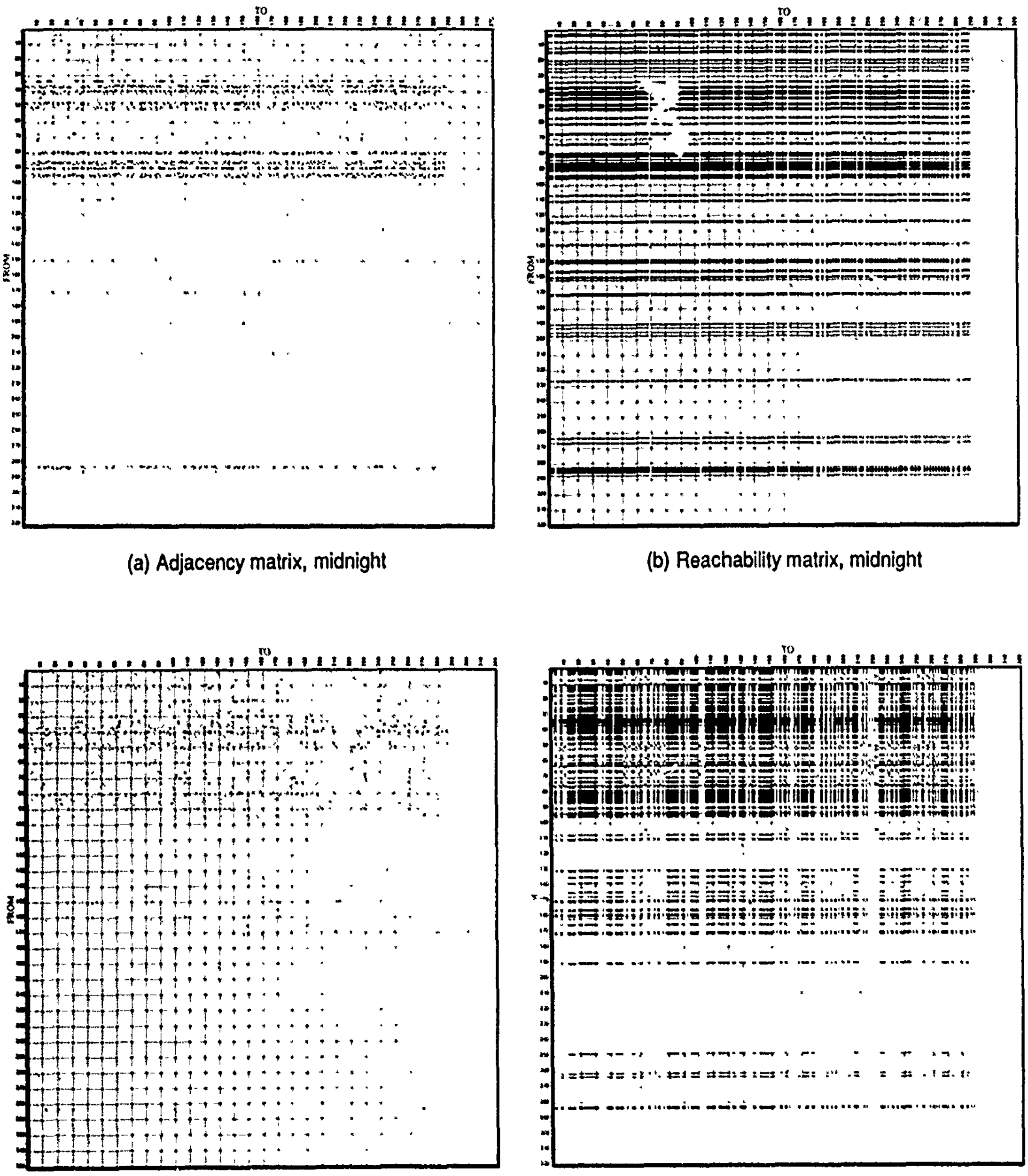
(a) Adjacency matrix, noon

(b) Reachability matrix, noon

(c) Adjacency matrix, dusk

(d) Reachability matrix, dusk

Fig. 9.13—Matrices, NET3, spring, noon and dusk



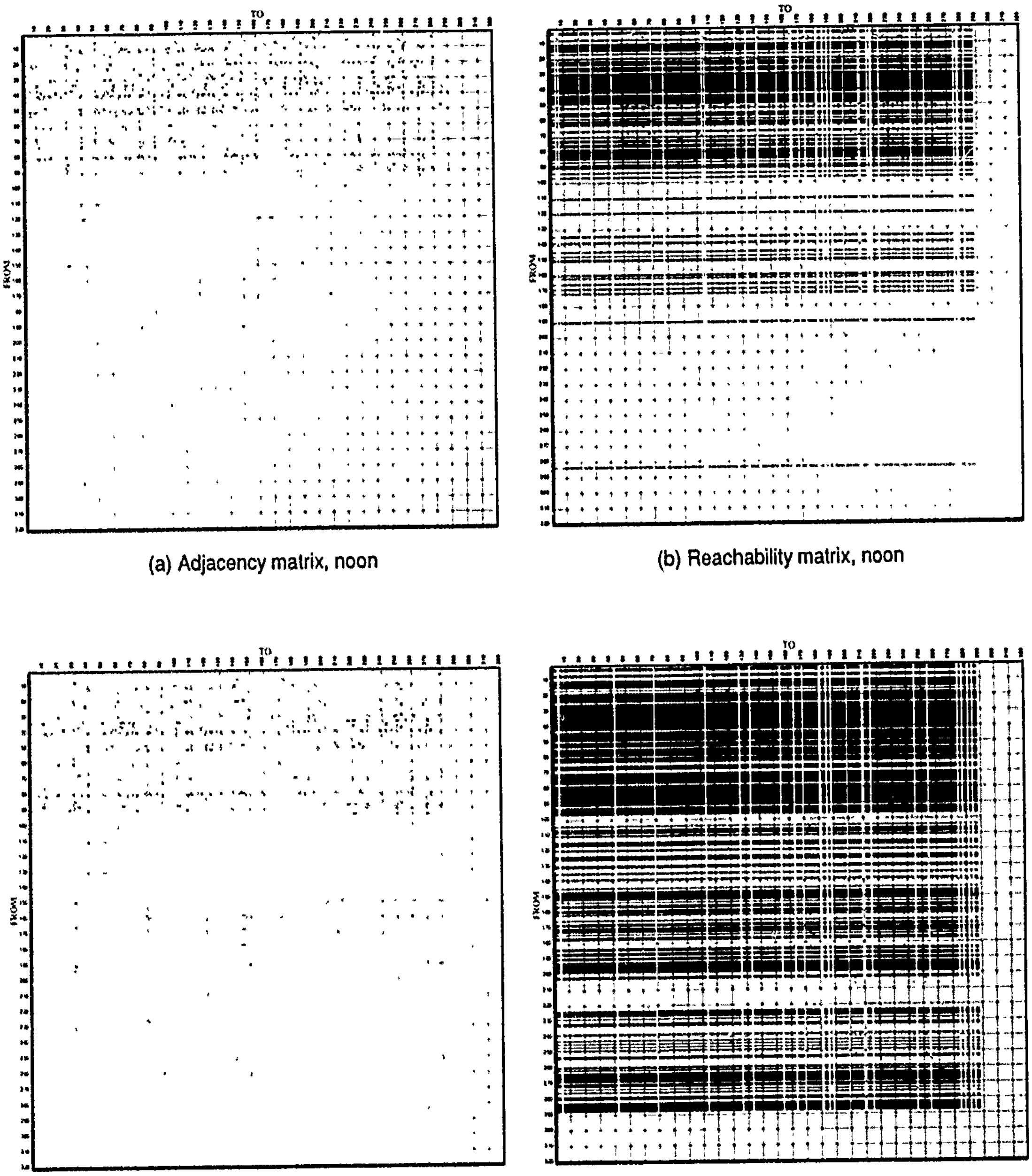
(a) Adjacency matrix, midnight

(b) Reachability matrix, midnight

(c) Adjacency matrix, dawn

(d) Reachability matrix, dawn

Fig. 9.14—Matrices, NET3, summer, midnight and dawn



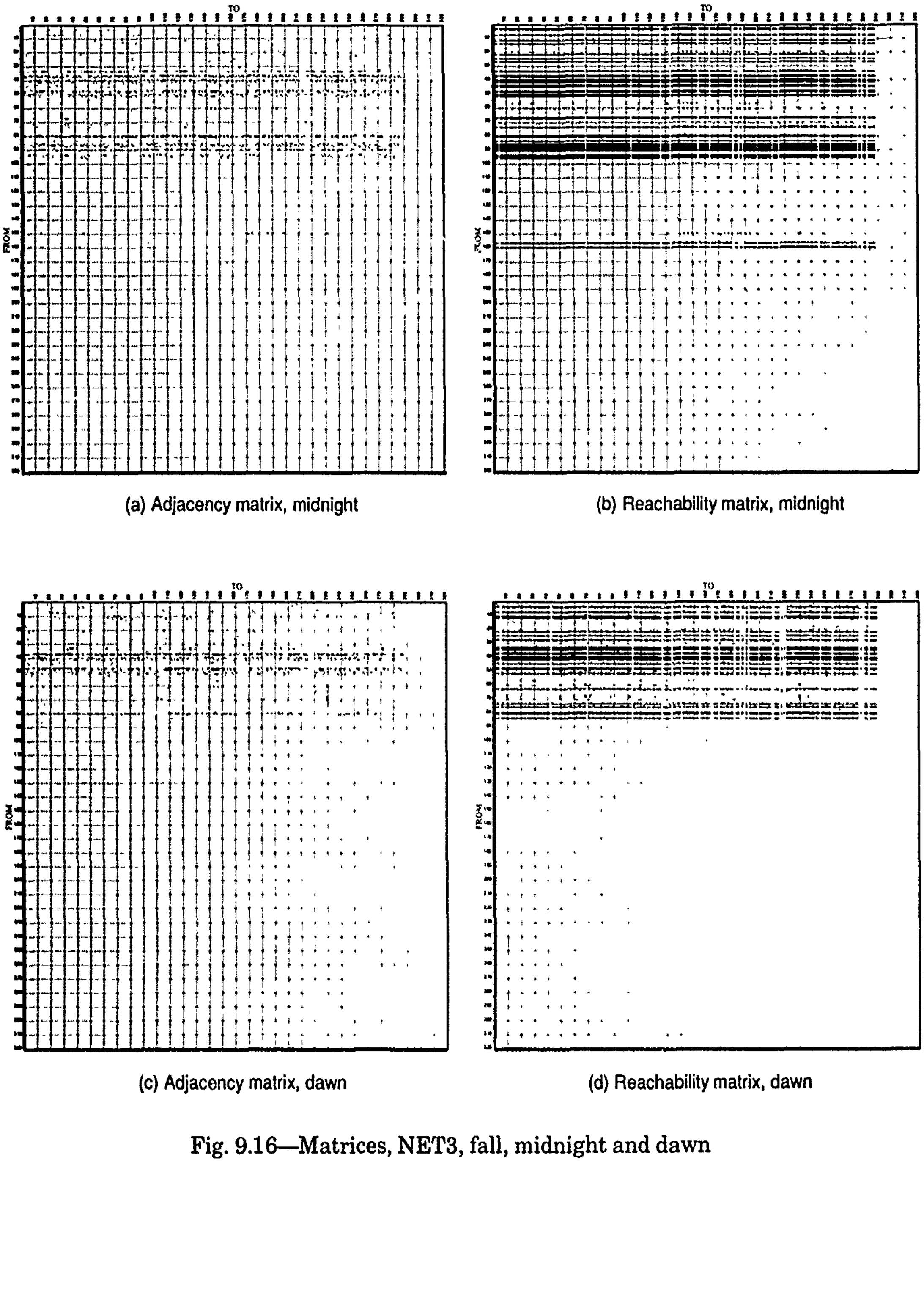
(a) Adjacency matrix, noon

(b) Reachability matrix, noon

(c) Adjacency matrix, dusk

(d) Reachability matrix, dusk

Fig. 9.15—Matrices, NET3, summer, noon and dusk



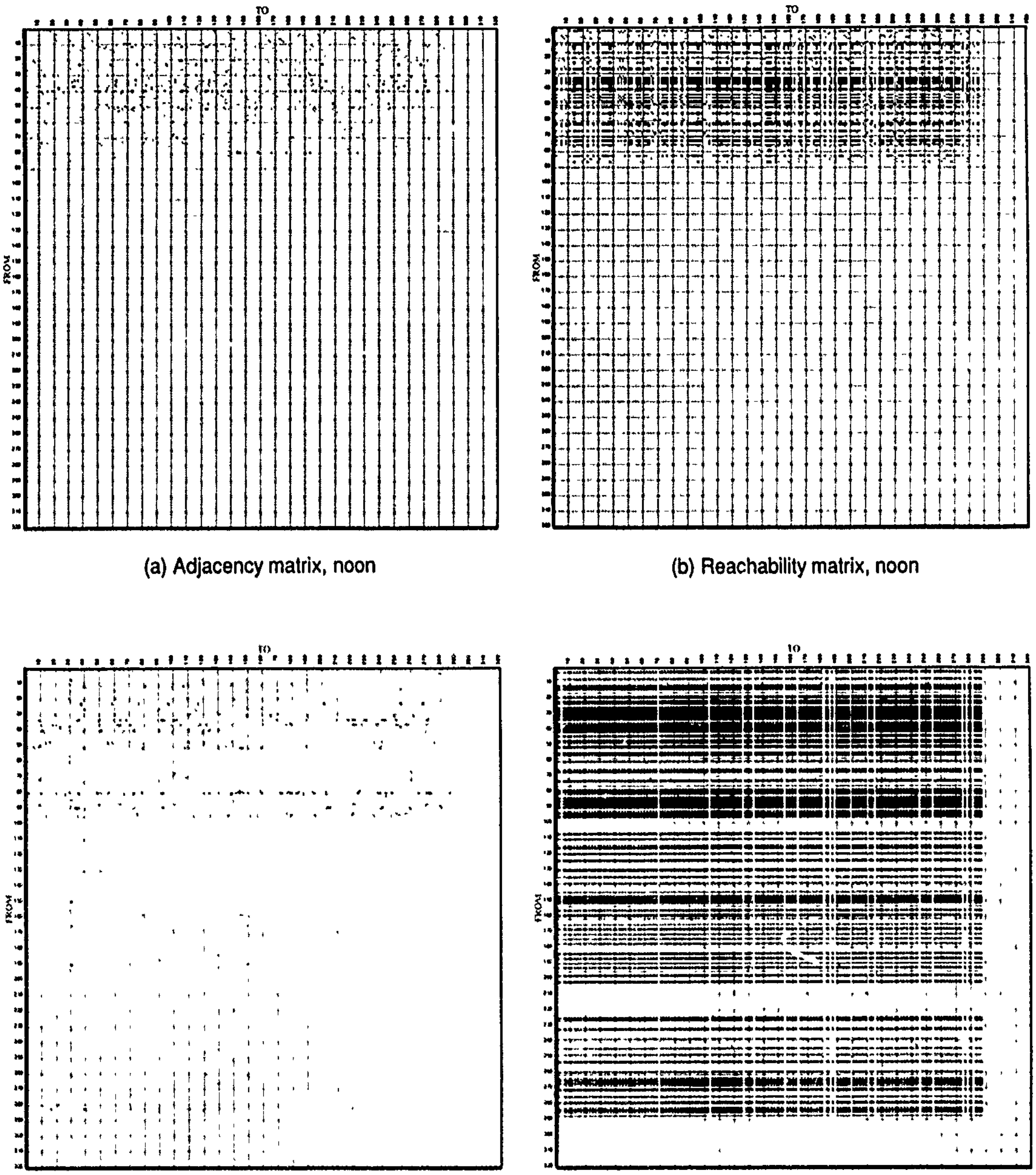
(a) Adjacency matrix, midnight

(b) Reachability matrix, midnight

(c) Adjacency matrix, dawn

(d) Reachability matrix, dawn

Fig. 9.16—Matrices, NET3, fall, midnight and dawn



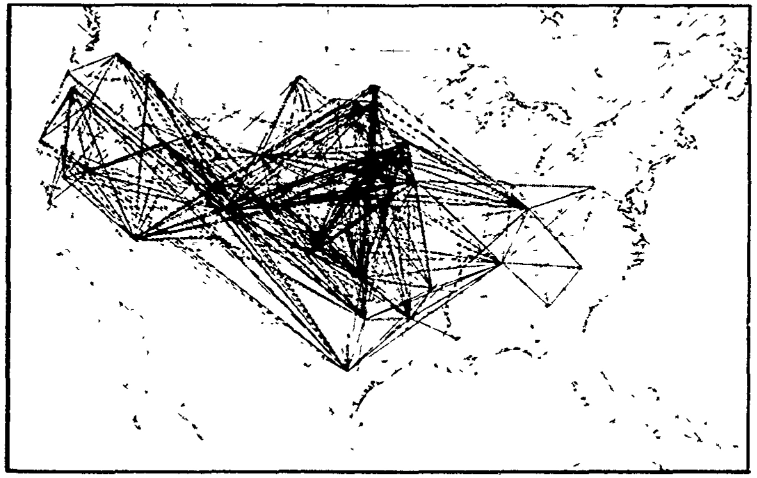
(a) Adjacency matrix, noon

(b) Reachability matrix, noon

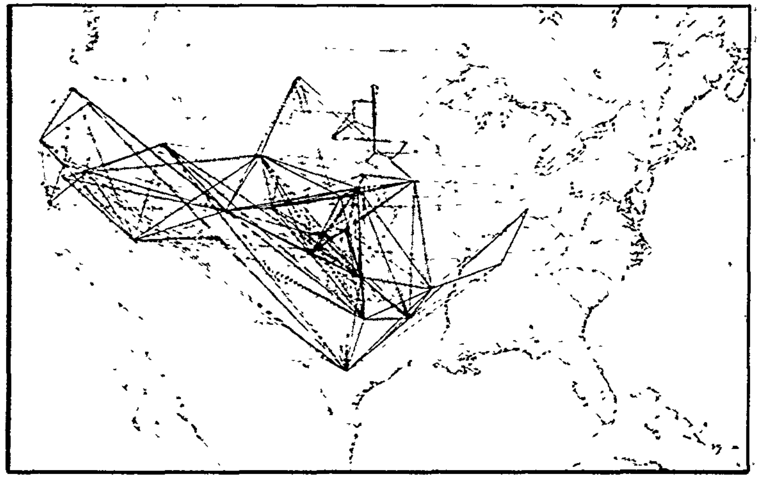
(c) Adjacency matrix, dusk

(d) Reachability matrix, dusk

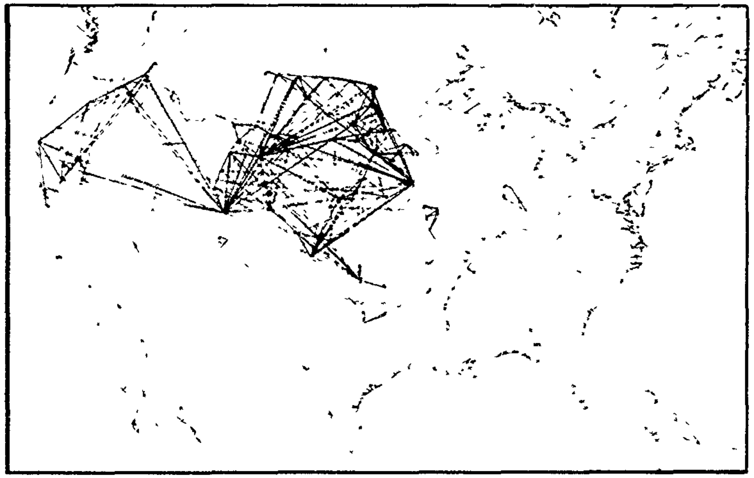
Fig. 9.17—Matrices, NET3, fall, noon and dusk



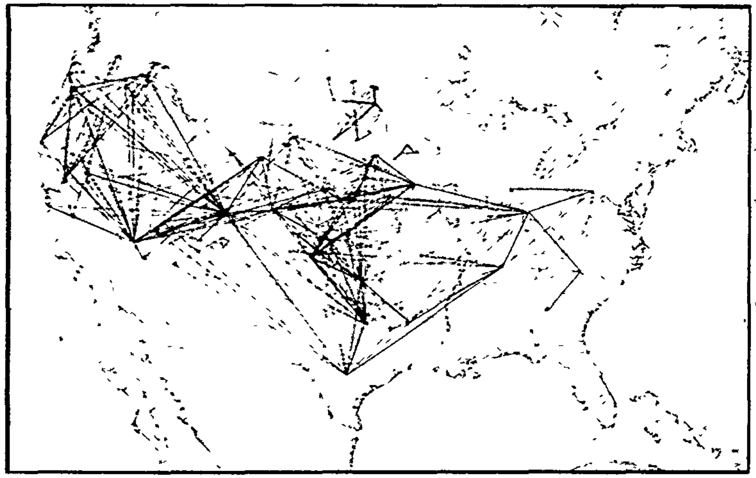
(a) Midnight



(b) Dawn



(c) Noon



(d) Dusk

Fig. 9.18—Connectivity plots, NET3, winter

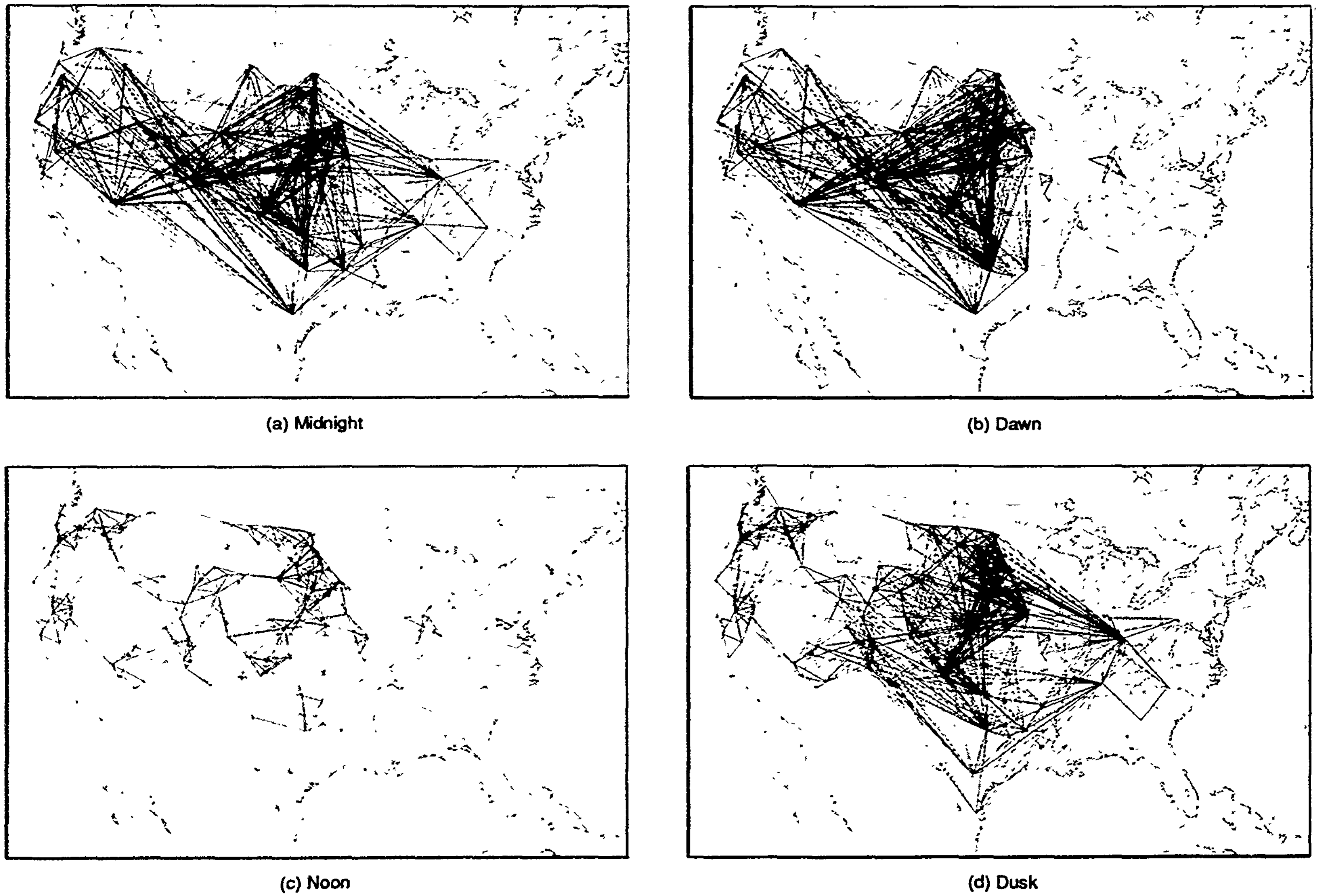


Fig. 9.19—Connectivity plots, NET3, spring

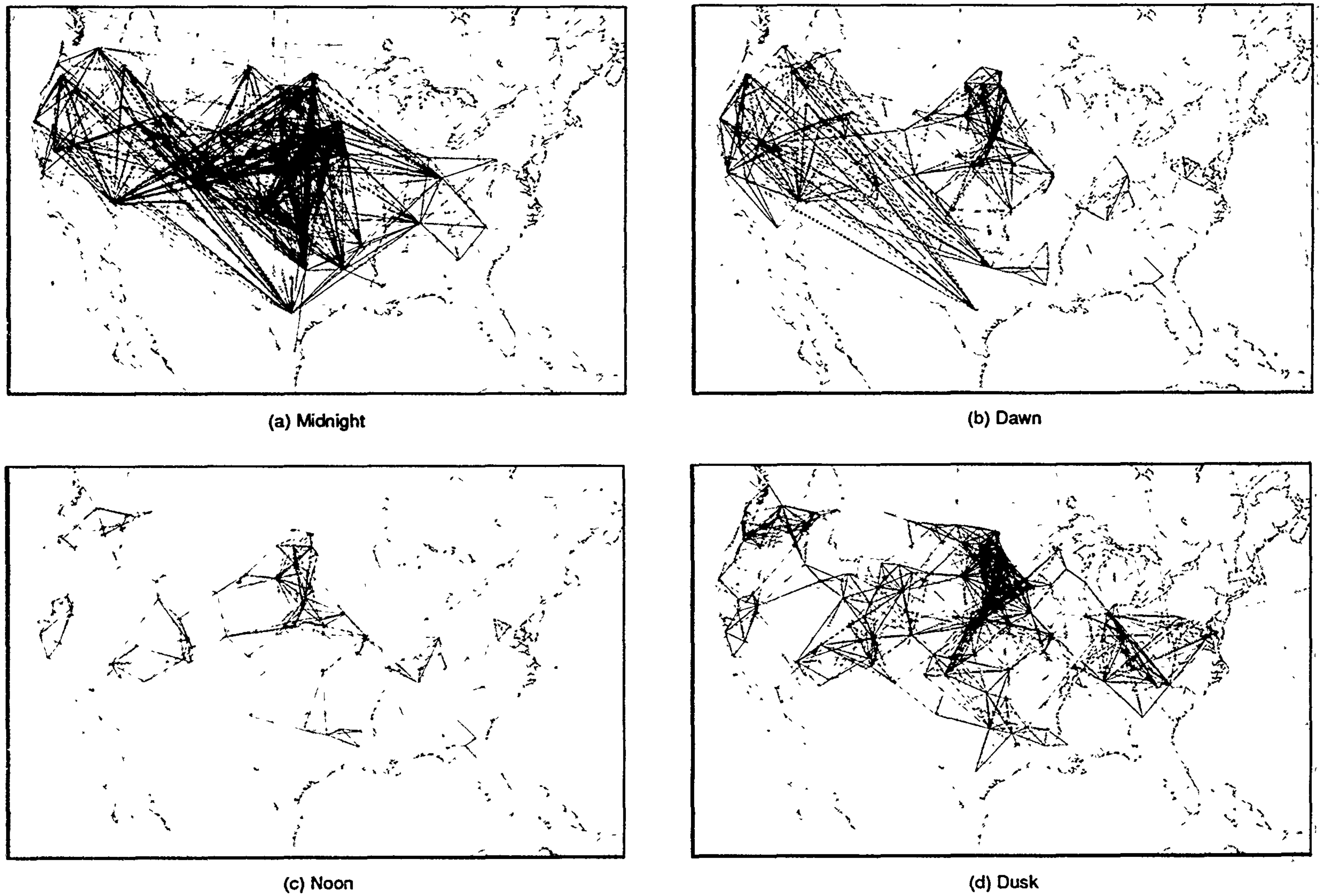
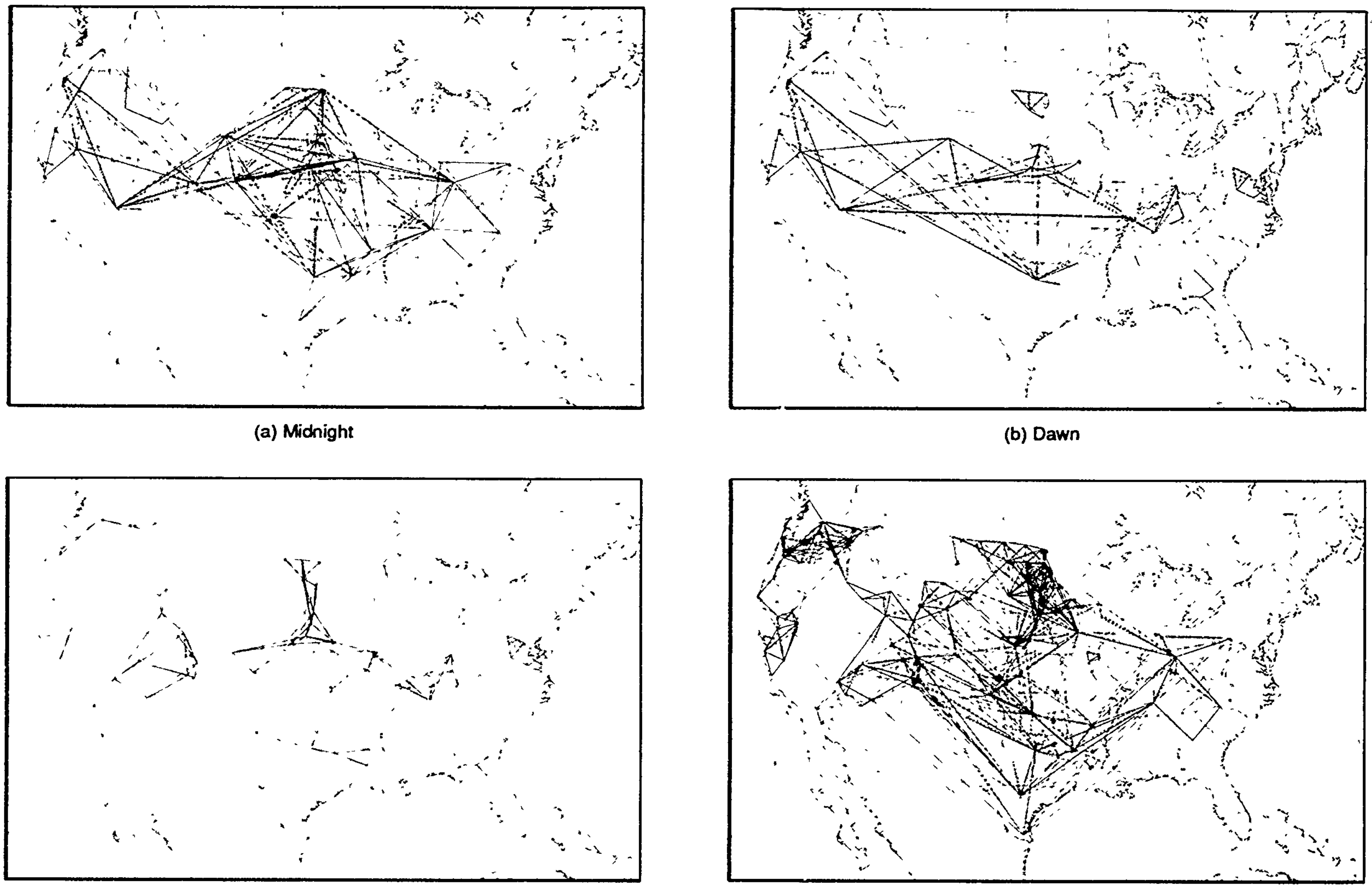


Fig. 9.20—Connectivity plots, NET3, summer



(a) Midnight (b) Dawn (c) Noon (d) Dusk

Fig. 9.21—Connectivity plots, NET3, fall

The summer-dawn case shows the following components:

1 component of 79 stations,
1 component of 8 stations,
1 component of 7 stations,
1 component of 5 stations,
1 component of 4 stations,
1 component of 3 stations, and
10 components of 2 stations each

Thus there are 16 "islands" of connectivity. Of greater significance is the fact that only 126 stations are involved. This is less than half of the 288 total. The largest component of 79 stations is barely one-quarter of the total.

Finally, the connectivity results for all 16 environments permit ranking all stations according to their participation in the network. Table 9.2 shows all station IDs ranked by the number of environments they were found in.[1] Thus station 37 (first on the list) was used in all environments, whereas station 229 (bottom of the list) was useful in only one environment. Furthermore, 72 stations (exactly one-quarter) played no role whatsoever.

[1]See the appendix for a listing of the 288 network stations by ID number.

Table 9.2

PARTICIPATION OF CONNECTED STATIONS FOR NET3 IN THE 16 ENVIRONMENTS INVESTIGATED

Station ID	No. of Environments	Station ID	No. of Environments	Station ID	No. of Environments	Station ID	No. of Environments
37	16	284	13	69	7	226	5
38	16	57	12	75	7	254	5
40	16	68	12	97	7	255	5
41	16	85	12	109	7	262	5
42	16	88	12	120	7	271	5
44	16	95	12	152	7	285	5
48	16	124	12	159	7	2	4
49	16	156	12	169	7	10	4
52	16	193	12	188	7	18	4
62	16	198	12	233	7	29	4
67	16	239	12	249	7	58	4
83	16	264	12	260	7	92	4
87	16	266	12	276	7	102	4
4	15	267	12	1	6	106	4
12	15	283	12	17	6	117	4
27	15	32	11	35	6	127	4
45	15	73	11	47	6	163	4
51	15	125	11	50	6	174	4
61	15	196	11	55	6	185	4
74	15	286	11	63	6	190	4
80	15	288	11	93	6	204	4
81	15	56	10	99	6	221	4
84	15	71	10	116	6	224	4
3	14	86	10	119	6	253	4
8	14	272	10	140	6	268	4
14	14	28	9	147	6	280	4
20	14	39	9	149	6	19	3
22	14	59	9	154	6	78	3
33	14	76	9	168	6	101	3
34	14	77	9	175	6	153	3
82	14	135	9	176	6	173	3
91	14	148	9	178	6	195	3
94	14	170	9	184	6	197	3
96	14	210	9	202	6	222	3
107	14	13	8	203	6	261	3
139	14	21	8	207	6	263	3
150	14	23	8	243	6	281	3
151	14	36	8	244	6	287	3
157	14	60	8	252	6	126	2
160	14	64	8	256	6	158	2
165	14	79	8	265	6	200	2
166	14	108	8	269	6	201	2
172	14	130	8	274	6	214	2
192	14	131	8	279	6	228	2
227	14	145	8	6	5	230	2
15	13	171	8	7	5	242	2
31	13	199	8	46	5	246	2
89	13	245	8	66	5	247	2
90	13	11	7	72	5	259	2
111	13	24	7	105	5	275	2
162	13	25	7	115	5	142	1
187	13	26	7	164	5	177	1
191	13	30	7	194	5	180	1
232	13	53	7	225	5	229	1

X. CONCLUSIONS

This research has analyzed the technical and economic feasibility of netting the commercial AM broadcast stations into a CONUS-wide communications network to support military and civilian users during emergency periods. Although considerable research remains before an AMBER network can become operational, no fundamental technical obstacles were identified. However the issue of adequate connectivity remains open. A preliminary cost analysis indicates that an AMBER network can be implemented at a cost of about $100,000 per station, with useful CONUS-wide systems containing from 100 to several hundreds of stations. Other applications to limited areas of coverage could consist of fewer numbers.

An examination of key network and technical issues has revealed that solutions within the state of the art are currently available and that desirable improvements and augmentations should be available in the near term by pursuing advanced approaches. Technical computer simulations and experimental data obtained from bench tests and on-the-air measurements using nonoptimal initial implementations have verified theoretical results and offer encouragement as to the feasibility of an actual AMBER network.

Connectivity studies on a nationwide computer simulation reveal that more thought must be given to the selection of the stations constituting the AMBER network. An illustrative network consisting of the 288 FEMA-protected stations thought to be capable of surviving a massive nuclear attack was seen to have excellent connectivity and CONUS coverage at times, such as at midnight in the winter. At other times, such as at noon in the summer, the connectivity and coverage were considerably reduced and would clearly be of limited usefulness. The interplay between transmitter power, operating frequency, and the noise and propagation environment is complex, so more cases must be studied to explore these relationships and arrive at satisfactory network configurations.

Appendix

LISTING OF THE 288 STATIONS IN NET3

The 288 FEMA-protected stations used in NET3 (see Sec. IX) are listed in this appendix in order of increasing frequency. The column headings have the following meanings:

id:	Sequential identification number assigned to the NET3 stations.
ser:	Serial number by which the station is identified in the FCC database.
freq:	Station carrier frequency—dicates center of 10 kHz channel.
call:	Commonly used call letters—initials K and W in the United States.
City: St: Co:	City, state, and country in which station is located.
Fema:	Code to identify level of FEMA BSPP—blank if not applicable. F: FEMA-protected (see Sec. II) C: has CPCS-1 console (see Sec. V) E: has EMP package (see Sec. V) N: not in 2 psi risk area (see Fig. 2.1)
dc:	Domestic class (see Sec. II)
p day:	Daytime radiated power, W
p night:	Nightime radiated power, W
lat:	Latitude, deg. north
long:	Longitude, deg. west

id	ser	freq	call	city	st	co	fema	dc	p.day	p.nite	lat	long
1	5	540	KNOE	MONROE	LA	US	FC-n	2B	5000	1000	32.543	−92.179
2	37	550	WCBI	COLUMBUS	MS	US	F--n	3	1000	500	33.541	−88.396
3	43	550	KFYR	BISMARCK	ND	US	FCEn	3	5000	5000	46.853	−100.544
4	45	550	KOAC	CORVALLIS	OR	US	FC-n	3	5000	5000	44.637	−123.192
5	50	550	WDEV	WATERBURY	VT	US	F--n	3	5000	1000	44.352	−72.752
6	51	550	WSVA	HARRISONBURG	VA	US	FCEn	3	5000	1000	38.451	−78.908
7	53	550	WSAU	WAUSAU	WI	US	FC-n	3	5000	5000	44.857	−89.587
8	92	560	KPQ	WENATCHEE	WA	US	FC-n	3	5000	5000	47.453	−120.329
9	93	560	WJLS	BECKLEY	WV	US	FC-n	3	5000	500	37.778	−81.161
10	114	570	WACL	WAYCROSS	GA	US	FCEn	3	5000	1000	31.262	−82.324
11	116	570	WKYX	PADUCAH	KY	US	FC-n	3	1000	500	37.015	−88.613
12	124	570	WNAX	YANKTON	SD	US	FC-n	3	5000	5000	42.913	−97.316
13	151	580	KMJ	FRESNO	CA	US	FCEn	3	5000	5000	36.694	−120.054
14	152	580	KUBC	MONTROSE	CO	US	FC-n	3	5000	1000	38.426	−107.882
15	155	580	KFXD	NAMPA	ID	US	F--n	3	5000	5000	43.560	−116.401
16	157	580	KKSU	MANHATTAN	KS	US	F--n	3	5000	500	39.217	−96.586
17	159	580	KALB	ALEXANDRIA	LA	US	FC-n	3	5000	1000	31.307	−92.417
18	162	580	WELO	TUPELO	MS	US	FC-n	3	1000	500	34.303	−88.705
19	173	580	WKTY	LA CROSSE	WI	US	F--n	3	5000	1000	43.740	−91.206
20	202	590	KID	IDAHO FALLS	ID	US	FC-n	3	5000	1000	43.560	−111.921
21	206	590	WJMS	IRONWOOD	MI	US	FC-n	3	5000	1000	46.424	−90.208
22	213	590	KUGN	EUGENE	OR	US	FC-n	3	5000	1000	44.097	−123.072
23	217	590	KSUB	CEDAR CITY	UT	US	FCEn	3	5000	1000	37.699	−113.179
24	238	600	KCLS	FLAGSTAFF	AZ	US	FC-n	3	5000	500	35.191	−111.670
25	240	600	KSXO	REDDING	CA	US	FC-n	3	0	1000	40.620	−122.332
26	252	600	KGEZ	KALISPELL	MT	US	FC-n	3	5000	1000	48.161	−114.281
27	255	600	KSJB	JAMESTOWN	ND	US	FC-n	3	5000	5000	46.817	−98.709
28	261	600	KTBB	TYLER	TX	US	F--n	3	5000	2500	32.272	−95.206
29	293	610	KOJM	HAVRE	MT	US	FC-n	3	1000	1000	48.580	−109.648
30	302	610	KVNU	LOGAN	UT	US	FC-n	3	5000	1000	41.675	−111.935
31	305	610	KONA	KENNEWICK-RICHLAND-PASCO	WA	US	FC-n	3	5000	5000	46.173	−119.069
32	338	620	KWAL	WALLACE	ID	US	F--n	3	1000	1000	47.508	−116.005
33	380	630	WLAP	LEXINGTON	KY	US	FCEn	3	5000	1000	38.124	−84.446
34	430	650	WSM	NASHVILLE	TN	US	FCEn	1A	50000	50000	35.997	−86.792
35	469	680	WCTT	CORBIN	KY	US	F--n	2	1000	1000	36.902	−84.081
36	513	690	KGGF	COFFEYVILLE	KS	US	FC-n	2B	10000	5000	37.149	−95.474
37	540	700	WLW	CINCINNATI	OH	US	F--n	1A	50000	50000	39.353	−84.325
38	598	720	KDWN	LAS VEGAS	NV	US	F--n	2	50000	50000	36.073	−114.972
39	654	740	KVFC	CORTEZ	CO	US	FCEn	2B	1000	250	37.349	−108.541
40	694	750	KMMJ	GRAND ISLAND	NE	US	FCEn	2	10000	10000	41.135	−97.994
41	751	780	WJAG	NORFOLK	NE	US	FCEn	2	1000	1000	42.032	−97.496
42	752	780	KROW	RENO	NV	US	FC-n	2	50000	50000	39.678	−119.802
43	792	790	WTNY	WATERTOWN	NY	US	FC-n	3	1000	1000	43.946	−75.948
44	795	790	KFGO	FARGO	ND	US	FCEn	3	5000	5000	46.718	−96.801
45	797	790	KWIL	ALBANY	OR	US	FC-n	3	1000	1000	44.632	−123.016
46	805	790	KFYO	LUBBOCK	TX	US	FC-n	3	5000	1000	33.521	−101.902
47	809	790	KGMI	BELLINGHAM	WA	US	FC-n	3	5000	1000	48.719	−122.445
48	932	820	WBAP	FORT WORTH	TX	US	FC-n	1A	50000	50000	32.611	−97.167
49	988	850	KOA	DENVER	CO	US	FCEn	1B	50000	50000	39.506	−104.766
50	990	850	WRUF	GAINESVILLE	FL	US	FCEn	2	5000	5000	29.643	−82.420
51	1006	850	WJAC	JOHNSTOWN	PA	US	FC-n	2	10000	10000	40.182	−78.889
52	1119	880	KRVN	LEXINGTON	NE	US	FC-n	2	50000	50000	40.517	−99.389
53	1259	910	WRNL	RICHMOND	VA	US	F--n	3	5000	5000	37.614	−77.514
54	1280	920	WKYD	ANDALUSIA	AL	US	FC-n	3	5000	500	31.318	−86.446
55	1286	920	KVEC	SAN LUIS OBISPO	CA	US	FCEn	3	1000	500	35.299	−120.673
56	1287	920	KLMR	LAMAR	CO	US	FC-n	3	5000	500	38.115	−102.621
57	1323	920	KVEL	VERNAL	UT	US	FC-n	3	5000	1000	40.492	−109.529
58	1326	920	WMMN	FAIRMONT	WV	US	F--n	3	5000	5000	39.467	−80.206

id	ser	freq	call	city	st	co	fema	dc	p.day	p.nite	lat	long
59	1360	930	KIUP	DURANGO	CO	US	FCEn	3	5000	1000	37.229	-107.864
60	1365	930	WMGR	BAINBRIDGE	GA	US	F--n	3	5000	500	30.907	-84.551
61	1366	930	KSEI	POCATELLO	ID	US	FC-n	3	5000	5000	42.962	-112.497
62	1367	930	WTAD	QUINCY	IL	US	FC-n	3	5000	1000	39.892	-91.424
63	1369	930	WKCT	BOWLING GREEN	KY	US	F--n	3	5000	500	37.031	-86.438
64	1370	930	WFMD	FREDERICK	MD	US	FCEn	3	5000	1000	39.415	-77.461
65	1384	930	WRRF	WASHINGTON	NC	US	F--n	3	5000	1000	35.526	-77.079
66	1387	930	KAGI	GRANTS PASS	OR	US	FC-n	3	5000	1000	42.423	-123.334
67	1389	930	KSDN	ABERDEEN	SD	US	FCEn	3	5000	1000	45.423	-98.519
68	1423	940	WMAZ	MACON	GA	US	FCEn	2	50000	10000	32.885	-83.731
69	1472	950	WGOV	VALDOSTA	GA	US	F--n	3	5000	1000	30.802	-83.355
70	1481	950	WKZX	PRESQUE ISLE	ME	US	FC-n	3	5000	5000	46.717	-68.018
71	1487	950	KLIK	JEFFERSON CITY	MO	US	FCEn	3	5000	500	38.520	-92.178
72	1499	950	WSPA	SPARTANBURG	SC	US	FC-n	3	5000	5000	34.976	-81.989
73	1500	950	KWAT	WATERTOWN	SD	US	FC-n	3	1000	1000	44.870	-97.114
74	1543	960	KMA	SHENANDOAH	IA	US	FC-n	3	5000	5000	40.780	-95.356
75	1546	960	WSBY	SALISBURY	MD	US	FC-n	3	5000	5000	38.429	-75.624
76	1551	960	KGIR	CAPE GIRARDEAU	MO	US	FC-n	3	5000	500	37.316	-89.485
77	1600	970	KVIM	COACHELLA	CA	US	F--n	3	5000	1000	33.687	-116.159
78	1635	970	WJMX	FLORENCE	SC	US	FC-n	3	5000	1000	34.230	-79.802
79	1704	980	KDSJ	DEADWOOD	SD	US	F--n	3	5000	1000	44.382	-103.662
80	1931	1030	KTWO	CASPER	WY	US	FCEn	2	50000	50000	42.843	-106.219
81	1945	1040	WHO	DES MOINES	IA	US	FCEn	1A	50000	50000	41.653	-93.349
82	2057	1060	KGFX	PIERRE	SD	US	FC-n	2	10000	1000	44.287	-100.338
83	2086	1070	KHMO	HANNIBAL	MO	US	FC-n	2	5000	1000	39.629	-91.376
84	2127	1080	KSCO	SANTA CRUZ	CA	US	FC-n	2	10000	5000	36.962	-121.981
85	2134	1080	KVNI	COEUR D' ALENE	ID	US	FC-n	2	10000	1000	47.616	-116.719
86	2175	1090	KAAY	LITTLE ROCK	AR	US	FCEn	1B	50000	50000	34.600	-92.225
87	2226	1100	KIIO	GRAND JUNCTION	CO	US	FCEn	2	50000	10000	38.951	-108.420
88	2266	1110	WBT	CHARLOTTE	NC	US	F-En	1B	50000	50000	35.132	-80.890
89	2269	1110	KBND	BEND	OR	US	FC-n	2	10000	1000	44.075	-121.294
90	2337	1130	KWKH	SHREVEPORT	LA	US	FCEn	1B	50000	50000	32.704	-93.881
91	2391	1140	KSOO	SIOUX FALLS	SD	US	FCEn	2	10000	5000	43.480	-96.684
92	2437	1150	WCEN	MOUNT PLEASANT	MI	US	F--n	3	1000	500	43.577	-84.766
93	2448	1150	KNED	MCALESTER	OK	US	FC-n	3	1000	500	34.937	-95.733
94	2583	1190	WOWO	FORT WAYNE	IN	US	FC-n	1B	50000	50000	40.996	-85.352
95	2630	1200	WOAI	SAN ANTONIO	TX	US	FCEn	1A	50000	50000	29.267	-98.274
96	2651	1210	KGYN	GUYMON	OK	US	FC-n	2	10000	10000	36.676	-101.383
97	2737	1230	KAAA	KINGMAN	AZ	US	FCEn	4	1000	250	35.197	-114.022
98	2739	1230	KATO	SAFFORD	AZ	US	FC-n	4	1000	250	32.825	-109.758
99	2743	1230	KBTM	JONESBORO	AR	US	F--n	4	1000	250	35.841	-90.662
100	2746	1230	KBOV	BISHOP	CA	US	FC-n	4	1000	250	37.346	-118.395
101	2761	1230	WMAF	MADISON	FL	US	F--n	4	1000	250	30.473	-83.436
102	2764	1230	WCNH	QUINCY	FL	US	F--n	4	1000	250	30.582	-84.600
103	2784	1230	WHOP	HOPKINSVILLE	KY	US	FC-n	4	1000	250	36.882	-87.512
104	2790	1230	WQDY	CALAIS	ME	US	F--n	4	1000	250	45.182	-67.266
105	2793	1230	WALI	CUMBERLAND	MD	US	FC-n	4	1000	250	39.643	-78.743
106	2798	1230	WIKB	IRON RIVER	MI	US	F--n	4	1000	250	46.065	-88.638
107	2804	1230	KYSM	MANKATO	MN	US	FC-n	4	1000	250	44.172	-94.040
108	2805	1230	KMRS	MORRIS	MN	US	F--n	4	1000	250	45.603	-95.887
109	2814	1230	KWIX	MOBERLY	MO	US	FC-n	4	1000	250	39.403	-92.432
110	2815	1230	KBMN	BOZEMAN	MT	US	F--n	4	1000	250	45.701	-111.047
111	2820	1230	KHAS	HASTINGS	NE	US	FC-n	4	1000	250	40.578	-98.405
112	2821	1230	KELY	ELY	NV	US	FC-n	4	250	250	39.262	-114.863
113	2825	1230	WCMC	WILDWOOD	NJ	US	F--n	4	1000	250	39.002	-74.813
114	2830	1230	KRSY	ROSWELL	NM	US	FC-n	4	1000	250	33.417	-104.511
115	2844	1230	KDIX	DICKINSON	ND	US	FC-n	4	1000	250	46.896	-102.785
116	2881	1230	KSST	SULPHUR SPRINGS	TX	US	F--n	4	1000	250	33.117	-95.585
117	2884	1230	KOAL	PRICE	UT	US	FC-n	4	1000	250	39.629	-110.847

id	ser	freq	call	city	st	co	fema	dc	p.day	p.nite	lat	long
118	2898	1230	WCLO	JANESVILLE	WI	US	F--n	4	1000	250	42.660	-89.042
119	2934	1240	KTLO	MOUNTAIN HOME	AR	US	FC-n	4	1000	250	36.345	-92.394
120	2945	1240	KSUE	SUSANVILLE	CA	US	FC-n	4	1000	250	40.395	-120.626
121	2949	1240	KCRT	TRINIDAD	CO	US	FC-n	4	250	250	37.146	-104.512
122	2957	1240	WGGA	GAINESVILLE	GA	US	F--n	4	1000	250	34.317	-83.829
123	2974	1240	KWLC	DECORAH	IA	US	FC-n	4	1000	250	43.311	-91.811
124	2976	1240	KICD	SPENCER	IA	US	FC-n	4	1000	250	43.167	-95.146
125	2977	1240	KIUL	GARDEN CITY	KS	US	FC-n	4	1000	250	37.998	-100.907
126	2982	1240	WSFC	SOMERSET	KY	US	FC-n	4	1000	250	37.118	-84.612
127	2989	1240	WHAI	GREENFIELD	MA	US	F--n	4	1000	250	42.589	-72.619
128	2996	1240	WJON	SAINT CLOUD	MN	US	FC-n	4	1000	250	45.560	-94.137
129	2998	1240	WGRM	GREENWOOD	MS	US	FC-n	4	1000	250	33.532	-90.194
130	3005	1240	KLTZ	GLASGOW	MT	US	FC-n	4	1000	250	48.219	-106.648
131	3009	1240	KODY	NORTH PLATTE	NE	US	FC-n	4	1000	250	41.154	-100.773
132	3010	1240	KELK	ELKO	NV	US	FC-n	4	1000	250	40.844	-115.749
133	3012	1240	WSNJ	BRIDGETON	NJ	US	FC-n	4	1000	250	39.461	-75.206
134	3020	1240	WNBZ	SARANAC LAKE	NY	US	F--n	4	1000	250	44.316	-74.119
135	3029	1240	KDLR	DEVILS LAKE	ND	US	FCEn	4	1000	250	48.112	-98.845
136	3031	1240	WHIZ	ZANESVILLE	OH	US	F--n	4	1000	250	39.928	-81.985
137	3033	1240	KADS	ELK CITY	OK	US	FC-n	4	1000	250	35.381	-99.407
138	3034	1240	KBEL	IDABEL	OK	US	FC-n	4	1000	250	33.882	-94.819
139	3048	1240	KCCR	PIERRE	SD	US	FC-n	4	1000	250	44.351	-100.319
140	3054	1240	WENK	UNION CITY	TN	US	F--n	4	1000	250	36.424	-89.038
141	3055	1240	KVLF	ALPINE	TX	US	F--n	4	1000	250	30.375	-103.660
142	3075	1240	WOBT	RHINELANDER	WI	US	F--n	4	1000	250	45.635	-89.372
143	3076	1240	WJMC	RICE LAKE	WI	US	F--n	4	1000	250	45.507	-91.774
144	3078	1240	KEVA	EVANSTON	WY	US	FC-n	4	1000	250	41.258	-110.943
145	3079	1240	KASL	NEWCASTLE	WY	US	FC-n	4	1000	250	43.846	-104.212
146	3080	1240	KRAL	RAWLINS	WY	US	FC-n	4	1000	250	41.782	-107.261
147	3081	1240	KTHE	THERMOPOLIS	WY	US	FC-n	4	1000	250	43.645	-108.204
148	3156	1250	KBRF	FERGUS FALLS	MN	US	F--n	3	5000	1000	46.289	-96.105
149	3158	1250	WHNY	MCCOMB	MS	US	FC-n	3	5000	1000	31.269	-90.434
150	3185	1250	KWSU	PULLMAN	WA	US	FC-n	3	5000	5000	46.696	-117.246
151	3237	1260	KROX	CROOKSTON	MN	US	F--n	3	1000	500	47.789	-96.594
152	3245	1260	KVSF	SANTA FE	NM	US	FC-n	3	5000	1000	35.682	-105.972
153	3267	1260	WCHV	CHARLOTTESVILLE	VA	US	FC-n	3	5000	1000	38.043	-78.482
154	3274	1260	KPOW	POWELL	WY	US	FC-n	3	5000	1000	44.700	-108.767
155	3301	1270	WNOG	NAPLES	FL	US	F--n	3	1000	1000	26.152	-81.752
156	3307	1270	KTFI	TWIN FALLS	ID	US	FC-n	3	5000	1000	42.558	-114.533
157	3313	1270	KSCB	LIBERAL	KS	US	FC-n	3	1000	500	37.054	-100.894
158	3341	1270	WKBR	LEBANON	PA	US	FC-n	3	5000	1000	40.360	-76.458
159	3357	1270	KIML	GILLETTE	WY	US	FCEn	3	5000	1000	44.303	-105.498
160	3413	1280	KVOX	MOORHEAD	MN	US	F--n	3	5000	1000	46.819	-96.766
161	3429	1280	WKST	NEW CASTLE	PA	US	F--n	3	1000	1000	40.954	-80.317
162	3471	1290	KHSL	CHICO	CA	US	FC-n	3	5000	5000	39.733	-121.786
163	3491	1290	WJGS	HOUGHTON LAKE	MI	US	FC-n	3	5000	5000	44.297	-84.707
164	3500	1290	WKNE	KEENE	NH	US	FC-n	3	5000	5000	42.949	-72.306
165	3503	1290	WNBF	BINGHAMTON	NY	US	FC-n	3	5000	5000	42.059	-75.954
166	3510	1290	KUMA	PENDLETON	OR	US	FC-n	3	5000	5000	45.674	-118.747
167	3525	1290	WVOW	LOGAN	WV	US	FC-n	3	5000	1000	37.858	-81.971
168	3528	1290	KOWB	LARAMIE	WY	US	F--n	3	5000	1000	41.284	-105.581
169	3580	1300	KPTL	CARSON CITY	NV	US	F--n	3	5000	500	39.166	-119.727
170	3638	1310	WICH	NORWICH	CT	US	F--n	3	5000	5000	41.553	-72.076
171	3646	1310	KLIX	TWIN FALLS	ID	US	F--n	3	0	2500	42.552	-114.367
172	3673	1310	KNOX	GRAND FORKS	ND	US	FCEn3	3	5000	5000	47.844	-97.025
173	3733	1320	WKAN	KANKAKEE	IL	US	F--n	3	1000	500	41.136	-87.819
174	3744	1320	WDMJ	MARQUETTE	MI	US	F--n	3	5000	1000	46.546	-87.444
175	3777	1320	KXRO	ABERDEEN	WA	US	FC-n	3	5000	1000	46.958	-123.807
176	3851	1330	WBTM	DANVILLE	VA	US	FC-n	3	5000	1000	36.610	-79.430

id	ser	freq	call	city	st	co	fema	dc	p.day	p.nite	lat	long
177	3858	1330	WHBL	SHEBOYGAN	WI	US	F--n	3	5000	1000	43.721	-87.734
178	3859	1330	KOVE	LANDER	WY	US	FC-n	3	5000	1000	42.843	-108.744
179	3886	1340	KBRS	SPRINGDALE	AR	US	F--n	4	1000	250	36.204	-94.134
180	3920	1340	WHPI	HERRIN	IL	US	F--n	4	1000	250	37.834	-89.027
181	3935	1340	WFAU	AUGUSTA	ME	US	FC-n	4	1000	250	44.329	-69.765
182	3938	1340	WHOU	HOULTON	ME	US	F--n	4	1000	250	46.146	-67.843
183	3942	1340	WLEW	BAD AXE	MI	US	F--n	4	1000	1000	43.799	-83.022
184	3953	1340	KWLM	WILLMAR	MN	US	F--n	4	1000	250	45.133	-95.043
185	3963	1340	KATL	MILES CITY	MT	US	FCEn	4	1000	250	46.400	-105.819
186	3970	1340	WDCR	HANOVER	NH	US	F--n	4	1000	250	43.700	-72.280
187	4000	1340	KIHR	HOOD RIVER	OR	US	FC-n	4	1000	250	45.702	-121.536
188	4013	1340	KIJV	HURON	SD	US	FC-n	4	1000	250	44.346	-98.209
189	4033	1340	WSTJ	SAINT JOHNSBURY	VT	US	FC-n	4	1000	250	44.418	-71.996
190	4125	1350	WIOU	KOKOMO	IN	US	F--n	3	5000	1000	40.417	-86.114
191	4164	1350	KRLC	CLARKSTON (LEWISTON, ID)	WA	US	FC-n	3	5000	1000	46.394	-116.994
192	4232	1360	WKOP	BINGHAMTON	NY	US	F--n	3	5000	500	42.067	-75.906
193	4235	1360	KEYZ	WILLISTON	ND	US	FCEn	3	5000	5000	48.124	-103.724
194	4261	1360	KRKK	ROCK SPRINGS	WY	US	FC-n	3	5000	1000	41.620	-109.239
195	4299	1370	WGTC	BLOOMINGTON	IN	US	FC-n	3	5000	500	39.190	-86.634
196	4303	1370	KGNO	DODGE CITY	KS	US	FCEn	3	5000	1000	37.792	-100.010
197	4311	1370	WKIK	LEONARDTOWN	MD	US	FC-n	3	1000	1000	38.320	-76.669
198	4314	1370	KSUM	FAIRMONT	MN	US	F--n	3	1000	1000	43.629	-94.483
199	4331	1370	KAST	ASTORIA	OR	US	FC-n	3	1000	1000	46.175	-123.847
200	4438	1380	WSYB	RUTLAND	VT	US	FC-n	3	5000	1000	43.593	-72.990
201	4467	1390	WHMA	ANNISTON	AL	US	FC-n	3	5000	1000	33.709	-85.854
202	4495	1390	KENN	FARMINGTON	NM	US	FC-n	3	5000	1000	36.719	-108.209
203	4503	1390	KKOA	MINOT	ND	US	F--n	3	5000	1000	48.212	-101.242
204	4515	1390	WTJS	JACKSON	TN	US	F--n	3	5000	1000	35.646	-88.832
205	4546	1400	WXAL	DEMOPOLIS	AL	US	F--n	4	1000	250	32.502	-87.819
206	4554	1400	KELD	EL DORADO	AR	US	F--n	4	1000	250	33.212	-92.663
207	4556	1400	KWYN	WYNNE	AR	US	F--n	4	1000	250	35.256	-90.797
208	4563	1400	KUKI	UKIAH	CA	US	FC-n	4	1000	250	39.167	-123.217
209	4565	1400	KRLN	CANON CITY	CO	US	FC-n	4	1000	250	38.460	-105.224
210	4571	1400	WILI	WILLIMANTIC	CT	US	F--n	4	1000	250	41.715	-72.190
211	4573	1400	WIRA	FORT PIERCE	FL	US	F--n	4	1000	250	27.435	-80.361
212	4574	1400	WNUE	FORT WALTON BEACH	FL	US	F--n	4	1000	250	30.424	-86.639
213	4589	1400	KSPT	SANDPOINT	ID	US	F--n	4	1000	250	48.304	-116.542
214	4627	1400	WFOR	HATTIESBURG	MS	US	F--n	4	1000	250	31.334	-89.319
215	4639	1400	KWNA	WINNEMUCCA	NV	US	FC-n	4	1000	250	40.956	-117.713
216	4640	1400	WBRL	BERLIN	NH	US	F--n	4	1000	250	44.482	-71.182
217	4655	1400	WKSE	WALLACE	NC	US	F--n	4	1000	250	34.758	-78.000
218	4674	1400	WRAK	WILLIAMSPORT	PA	US	FC-n	4	1000	250	41.239	-77.041
219	4676	1400	WGTN	GEORGETOWN	SC	US	F--n	4	1000	250	33.369	-79.292
220	4693	1400	KIUN	PECOS	TX	US	F--n	4	1000	250	31.436	-103.504
221	4705	1400	WHLF	SOUTH BOSTON	VA	US	FC-n	4	1000	250	36.707	-78.924
222	4706	1400	WINC	WINCHESTER	VA	US	FC-n	4	1000	250	39.187	-78.152
223	4712	1400	WRON	RONCEVERTE	WV	US	FC-n	4	1000	250	37.760	-80.455
224	4716	1400	WATW	ASHLAND	WI	US	F--n	4	1000	250	46.573	-90.866
225	4778	1410	KCOL	FORT COLLINS	CO	US	FC-n	3	1000	1000	40.593	-105.105
226	4836	1410	KWYO	SHERIDAN	WY	US	FCEn	3	5000	500	44.771	-106.927
227	4889	1420	KTOE	MANKATO	MN	US	F--n	3	5000	5000	44.168	-93.910
228	4907	1420	WCED	DU BOIS	PA	US	FC-n	3	5000	500	41.142	-78.802
229	4915	1420	KLNX	LUFKIN	TX	US	F--n	3	5000	1000	31.367	-94.766
230	4966	1430	WWGS	TIFTON	GA	US	FC-n	3	5000	1000	31.456	-83.561
231	4989	1430	WMNC	MORGANTOWN	NC	US	F--n	3	5000	1000	35.752	-81.717
232	5080	1440	KODL	THE DALLES	OR	US	FC-n	3	1000	1000	45.592	-121.199
233	5090	1440	KDNT	DENTON	TX	US	F--n	3	5000	500	33.162	-97.105
234	5095	1440	WHIS	BLUEFIELD	WV	US	FC-n	3	5000	500	37.276	-81.252
235	5122	1450	KDAP	DOUGLAS	AZ	US	FC-n	4	1000	250	31.355	-109.552

id	ser	freq	call	city	st	co	fema	dc	p.day	p.nite	lat	long
236	5137	1450	KGIW	ALAMOSA	CO	US	FC-n	4	1000	250	37.472	-105.854
237	5155	1450	WMVG	MILLEDGEVILLE	GA	US	F--n	4	1000	250	33.083	-83.250
238	5186	1450	WHTC	HOLLAND	MI	US	F--n	4	1000	250	42.795	-86.106
239	5192	1450	KATE	ALBERT LEA	MN	US	F--n	4	1000	250	43.633	-93.371
240	5193	1450	KBUN	BEMIDJI	MN	US	FC-n	4	1000	250	47.466	-94.910
241	5197	1450	WROX	CLARKSDALE	MS	US	F--n	4	1000	250	34.211	-90.578
242	5198	1450	WCJU	COLUMBIA	MS	US	F--n	4	1000	250	31.237	-89.840
243	5205	1450	KIRX	KIRKSVILLE	MO	US	FCEn	4	1000	250	40.207	-92.575
244	5207	1450	KWPM	WEST PLAINS	MO	US	FC-n	4	1000	250	36.741	-91.834
245	5213	1450	KVCK	WOLF POINT	MT	US	FCEn	4	1000	250	48.088	-105.655
246	5216	1450	WKXL	CONCORD	NH	US	F--n	4	1000	250	43.194	-71.555
247	5220	1450	KLMX	CLAYTON	NM	US	FC-n	4	1000	250	36.444	-103.190
248	5237	1450	WLEC	SANDUSKY	OH	US	F--n	4	1000	250	41.441	-82.686
249	5243	1450	KLBM	LA GRANDE	OR	US	FC-n	4	1000	250	45.329	-118.067
250	5246	1450	WFRA	FRANKLIN	PA	US	FC-n	4	1000	250	41.391	-79.812
251	5250	1450	WMAJ	STATE COLLEGE	PA	US	FC-n	4	1000	250	40.809	-77.841
252	5261	1450	WDSG	DYERSBURG	TN	US	F--n	4	1000	250	36.051	-89.369
253	5273	1450	KMOB	MOAB	UT	US	FC-n	4	1000	250	38.585	-109.562
254	5275	1450	KDXU	SAINT GEORGE	UT	US	FC-n	4	1000	250	37.082	-113.576
255	5277	1450	WMMJ	BRATTLEBORO	VT	US	FC-n	4	1000	250	42.870	-72.560
256	5281	1450	WMVA	MARTINSVILLE	VA	US	FC-n	4	1000	250	36.700	-79.852
257	5288	1450	WIKS	PARKERSBURG	WV	US	F--n	4	1000	250	39.290	-81.527
258	5291	1450	WRCO	RICHLAND CENTER	WI	US	F--n	4	1000	250	43.316	-90.375
259	5333	1460	WFMH	CULLMAN	AL	US	FC-n	3	5000	500	34.179	-86.866
260	5361	1460	KDMA	MONTEVIDEO	MN	US	F--n	3	1000	1000	44.935	-95.747
261	5374	1460	WEWO	LAURINBURG	NC	US	F--n	3	5000	5000	34.783	-79.511
262	5394	1460	KMWX	YAKIMA	WA	US	FC-n	3	5000	5000	46.608	-120.462
263	5446	1470	WTTR	WESTMINSTER	MD	US	F--n	3	1000	1000	39.577	-77.022
264	5518	1480	KRED	EUREKA	CA	US	FCEn	3	5000	680	40.741	-124.201
265	5532	1480	WRSW	WARSAW	IN	US	F--n	3	1000	500	41.222	-85.838
266	5545	1480	KAUS	AUSTIN	MN	US	F--n	3	1000	1000	43.622	-92.991
267	5548	1480	KGCX	SIDNEY	MT	US	F--n	3	5000	5000	47.774	-104.115
268	5605	1490	KYCA	PRESCOTT	AZ	US	FCEn	4	1000	250	34.551	-112.462
269	5612	1490	KICO	CALEXICO	CA	US	FC-n	4	1000	250	32.699	-115.503
270	5618	1490	KSYC	YREKA	CA	US	FC-n	4	1000	250	41.724	-122.650
271	5647	1490	WKBV	RICHMOND	IN	US	FC-n	4	1000	250	39.825	-84.931
272	5655	1490	WFKY	FRANKFORT	KY	US	F--n	4	1000	250	38.213	-84.875
273	5673	1490	KXRA	ALEXANDRIA	MN	US	F--n	4	1000	250	45.875	-95.358
274	5681	1490	KTTR	ROLLA	MO	US	FC-n	4	1000	250	37.945	-91.746
275	5686	1490	WEMJ	LACONIA	NH	US	FC-n	4	1000	250	43.541	-71.462
276	5688	1490	KRSN	LOS ALAMOS	NM	US	F--n	4	1000	250	35.896	-106.289
277	5692	1490	WBTA	BATAVIA	NY	US	F--n	4	500	250	42.977	-78.187
278	5694	1490	WICY	MALONE	NY	US	F--n	4	1000	250	44.846	-74.269
279	5715	1490	KBKR	BAKER	OR	US	FC-n	4	1000	250	44.788	-117.810
280	5716	1490	KRNR	ROSEBURG	OR	US	FC-n	4	1000	250	43.227	-123.345
281	5734	1490	WDXL	LEXINGTON	TN	US	F--n	4	1000	250	35.635	-88.393
282	5751	1490	WIKE	NEWPORT	VT	US	F--n	4	1000	250	44.941	-72.226
283	5984	1520	KOMA	OKLAHOMA CITY	OK	US	F-En	1B	50000	50000	35.333	-97.504
284	6019	1530	KFBK	SACRAMENTO	CA	US	FCEn	1B	50000	50000	38.848	-121.483
285	6052	1530	KGBT	HARLINGEN	TX	US	FC-n	2	50000	10000	26.375	-97.894
286	6479	1590	KVGB	GREAT BEND	KS	US	FC-n	3	5000	5000	38.314	-98.793
287	6487	1590	WTVB	COLDWATER	MI	US	F--n	3	5000	1000	41.909	-85.006
288	6513	1590	KTIL	TILLAMOOK	OR	US	FC-n	3	5000	1000	45.457	-123.877

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