International Telecommunication Union

Handbook

Frequency-adaptive communication systems and networks in the MF/HF bands

Edition 2002

Radiocommunication Bureau

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PREFACE

This Handbook on Frequency-adaptive communication systems and networks in the MF/HF bands, was developed by a few skilled experts of Radiocommunication Working Party 9C (Systems in the fixed service operating below about 30 MHz), under the coordination and leadership of Mr. L. Barclay (United Kingdom). Major contributors were, in addition to Mr. L. Barclay, Mr. N. Serinken (Canada), Chairman of Working Party 9C, and notably Mr. J. Goodman (United States of America).

The Handbook is published to assist planners and decision-makers in the deployment of adaptive MF/HF systems in the fixed service, for both commercial and government users in developed and particularly developing countries. It provides material on current present technological capabilities in the field of adaptive MF/HF communications.

Telecommunications, mainly for remote and low populated areas, should be provided through least expensive and most reliable equipment, as far as possible, and these possibilities may be based on adaptive MF/HF systems and networks. In the event of the collapse of normal telecommunication operation due to natural disasters (e.g. earthquakes) and other emergencies, adaptive MF/HF systems using fixed transportable and mobile stations could be established in a very short period of time to provide the emergency links required, in the first phase of the alarm or during the coordination of the relief operation.

An adaptive MF/HF system is one, which automatically (i.e. without the need for intervention by a radio operator) carries out the functions of establishing radiocommunications links and exchanging of information in an optimum manner, despite the variations and the high probability of interference inherent to MF/HF frequency bands propagating through the ionosphere. In addition, adaptive systems are able to monitor spectrum occupancy in a regular manner, and select operating frequencies so as to avoid causing interference to other users more effectively than many non-adaptive systems now in operation.

It is expected that this Handbook will be great use in giving guidance on the design and use of adaptive systems, which have the ability to communicate over large distances, using the ionosphere, far beyond the near line-of-sight range of systems operating higher frequency bands. Moreover, such long distance communications may be established with a low cost of ownership.

Robert W. Jones

Director, Radiocommunication Bureau

FOREWORD

Terrestrial communication at HF to long ranges has been in use for nearly 80 years. The mode offers relatively low-cost installation and flexibility, as well as the capability of communication ranges far beyond the horizon without the costs and complexity of intermediate relay stations. However, the ionosphere is highly variable in all time scales: within an hour, through the day, from season to season and with the 11-year solar cycle. Moreover, ionospheric storms, due to solar disturbances, can cause significant rapid change to the range of frequencies available. Thus, traditionally, HF radio stations have been controlled by skilled operators who would change the operating frequencies from time to time, at least several times each day, in response to changes in signal strength and quality. However, they may not have had available appropriate frequency assignments to ensure optimum communication in all circumstances, and the crowded state of the spectrum often resulted in interference.

In recent years it has become more difficult to find and retain skilled operators, and new procedures within the Radiocommunication Bureau mean that there is now no compatibility assessment prior to inclusion of assignments in the Master International Frequency Register. Thus it might be expected that the overall service quality would progressively degrade.

Fortunately a solution is now possible through the use of newer technologies. Transmitter and receiver architectures now permit broadband designs with the capability of rapid frequency change; broadband antenna designs are available; and modulation methods combined with digital signal processing result in the ability of the receiver itself to automatically assess the circuit performance, and to initiate automatic frequency changes to find optimum conditions. These adaptive technologies have been introduced and are in use by some high performance communication networks, but the opportunity now exists for the introduction of adaptive technology for all types of HF fixed and mobile applications, from low power links to high-power, high data-rate networks. The result should be a reduction in operating cost, since attendance by a skilled operator would not be necessary, as well as an improvement in the quality of communications.

This Handbook, prepared by a small group in Radiocommunication Working Party 9C, is intended to provide some introductory information on HF adaptive systems. It is hoped that it will encourage these methods to be brought widely into use.

Les Barclay

Coordinator of the Handbook

PROLOGUE

Radio frequency (RF) transmissions between 3 and 30 MHz are designated in the Radio Regulations as High Frequency (HF) bands or "band 7", corresponding to "Decametric waves" in the metric subdivision. Similarly, symbol "MF" applies to 300-3 000 kHz (band 6) or "Hectometric waves". MF/HF communications have been widely used for nearly 80 years to provide communications to long distances and remote areas via the ionosphere. Although of lower reliability and limited bandwidth with respect to other radiocommunication systems operating in higher frequency bands, MF/HF systems allow very inexpensive telecommunication radio links over long distances and much quicker establishment than other terrestrial or satellite systems, notably in the case of natural disasters or man-made conflicts. Evolution of technologies during the last decades, such as adaptive systems, has provided the opportunity for a renewal of interest for these applications.

Radiocommunication Working Party 9C dealing with fixed service systems below about 30 MHz, decided early in 1997 to establish a group for preparation of a Handbook on adaptive MF/HF systems and networks. The decision was taken in anticipation of the World Radiocommunication Conference (Geneva, 1997) (WRC-97) that made provisions to facilitate the use of frequency adaptive technology in these bands and mainly responding to the strong expression of interest on the part of the ITU Development Sector (ITU-D), which requested more detailed information than material already available in Recommendations ITU-R F.1110 and ITU-R F.1337. The group under the leadership of Professor Les Barclay (United Kingdom) worked mainly by correspondence and reporting to every annual meeting of Working Party 9C on the progress of the work done.

The Handbook is aimed primarily at the extension of adaptive use for civil applications, emphasizing the current possible performance improvements using modern inexpensive signal processing capabilities. The material included is divided into seven chapters and two annexes:

Chapter 1: Introduction – contains background information on modern technology now offering a solution to the problem of matching the MF/HF system characteristics to the ionospheric channel variability. The Chapter continues with the historical evolution of adaptive systems since their development in the late 1970s/early 1980s. The Chapter concludes with the benefits to developing countries for both commercial and government users, and a technical description of some operational systems.

Chapter 2: The radio regulatory framework – the user of the Handbook is informed of World Radiocommunication Conference decisions relevant to the issue, namely WRC-95, WRC-97 and WRC-2000.

Chapter 3: Adaptivity techniques – introduces the concepts of automation and adaptivity. The functional parts of the radio system are represented using the model of the ISO called the Open System Interconection Reference Model (OSI-RM).

Chapter 4: The propagation environment – contains propagation aspects as one of the main reasons for adopting adaptive technologies in the extreme variability and unpredictability, in the short term. Propagation in these bands is primary by the sky-wave mode, utilizing reflection from the ionosphere, or in some cases also by the ground-wave mode.

Chapter 5: System engineering – reference is made to Recommendation ITU-R F.1610 adopted and expected to be finally approved by November 2002. Only a brief description is made.

Chapter 6: Use of sounding and channel estimation techniques – states that sounding belongs to a general class of channel estimation or evaluation techniques. Real-time channel evaluation (RTCE), requirements and its use, and ionospheric sounding that allows channel probing, occupancy/congestion monitoring and performance assessment are described.

Chapter 7: Control, including automatic link establishment (ALE) and automatic link maintenance (ALM), taking into account systems in use or standardized – describes a model that, although not universally followed, avoids the client of the system having to deal with the peculiarities of the medium. ALE and ALM are then explained.

Annex 1 provides an example of a managed HF network.

Annex 2 gives References and the list of abbreviations.

In addition to the more active participants in the preparation of the Handbook already mentioned by the Director, I would like to thank the Chairman of Radiocommunication Study Group 3, Mr. D. G. Cole (Australia) for his useful advice, and Mr. L. Casado of the Radiocommunication Bureau for the time devoted to the completion and editing of the Handbook.

Vladimir Minkin
Chairman, Radiocommunication Study Group 9

CHAPTER 1

Introduction

1.1 Background

Automatic evaluation of propagation channels and the adaptivity of system characteristics have generated resurgence in MF/HF technologies and their operational use. Until 1995, international agreements for frequency regulation and assignment for the HF fixed services were based on long-standing procedures. Proposals for new assignments were submitted to the ITU Radiocommunication Bureau (BR) (before 1993 to the IFRB). BR examined the proposal and submitted it to a technical examination for compatibility with existing assignments. If the result of the technical examination showed that the proposed use would not cause harmful interference to an existing assignment, the assignment was included in the Master International Frequency Register (MIFR). The administration then proceeded to authorize the assignment.

This process was of little technical value at HF. The use of HF is governed by the variable nature of the ionospheric propagation so that the operating frequency has to be changed several times during a 24 h period. There are also significant day-to-day changes in ionospheric conditions and interference may be caused spasmodically by very distant transmissions. To assure satisfactory operation, real-time frequency changes may be undertaken by the circuit operators who have to amend frequency schedules according to current conditions, due to short-term changes in ionospheric conditions, or due to the presence of interference. Thus frequencies actually in use may not be those predicted for that time. The propagation models used by BR in the technical examination were statistical in nature and could not include short-term considerations. Thus the frequency listing in the MIFR was an inadequate guide to actual occupancy. Moreover, it is well known that some assignments included in the MIFR have ceased to be used by operational systems and in some cases relate to circuits which have never been put into operation.

Modern technology now offers a solution to the problem of matching the HF system characteristics to the ionospheric channel variability. Automatically controlled radio systems which evaluate the circuit performance during operation and change the operating frequency, or other circuit parameters, to optimize the performance are now feasible and are in use for some high quality circuits. Whilst the use of frequency agile systems may not necessarily use the minimum overall number of frequencies, the assurance of reliable communication given by such systems should result in more efficient operation, and the minimization of the number of frequencies in use at any one time. Such systems also seek to avoid situations where interference might be caused.

Moreover the assurance of circuit availability when required for traffic should result in a reduction of idling transmissions which are in use by some circuit operators to maintain a channel when there is no current traffic; there should be no need for this practice when adaptive operation is employed;

this should also result in an increase in efficiency of spectrum utilization. In this regard it may be noted that a monitoring study undertaken in 1996 showed that 41% of transmissions observed were not being used for the transmission of traffic at that time but were only sending idling signals or call signs.

1.2 Adaptive systems

Automatic link establishment (ALE) equipment transmits signals to other stations on a network on one or more of a pre-arranged list of frequencies. Link assessment data is stored in an internal database and used to establish communications on the frequency most suited to the propagation environment. The ALE system requires the prior assignment of a suite of frequencies. These frequencies vary in number but, in the interests of establishing the link as rapidly as possible, the number is kept reasonably small (e.g. four to seven). The ideal adaptive system uses real-time ionospheric information to modify the suite of frequencies being evaluated.

The first generation of adaptive MF and HF systems were developed in the late 1970s/early 1980s. At that time, control equipment was becoming available at reasonable costs and processing power, and the latest generation radio equipment was computer controllable (mainly intended for enabling remote control capability). This generation of equipment could only establish a radio link by selecting one traffic frequency among a small number of pre-set frequencies. The link was then handed over to the operator.

More functionality was added during the 1980s, enabling fully automatic link establishment, link maintenance to ensure the quality of service during message transfer, and link disconnection. Such systems could react adaptively to changes in link conditions, e.g. by changing the traffic frequency, the transmitter power and/or the modulation format. Since manufacturers developed their own specific systems, the capability to inter-operate with systems from other manufacturers was at best limited.

In the United States of America, this resulted in a joint effort between customers and manufacturers to develop a standard, thereby fulfilling the prime objective within the United States governmental authorities, i.e. interoperability between systems from different manufacturers. This United States standard, defined in its military version as MIL-STD-188-141A and in its civilian version as FED-STD-1045A, is commonly referred to as the *ALE standard* (automatic link establishment).

Other countries have produced a standard for automatic radio-controlled systems in STANAG 4538.

In 1996, a survey revealed that at least 15 000 ALE systems had been established at that time and the United States HF Industry Association (HFIA) predicted a growth from 15 000 systems in 1996 to more than one million systems early in this century.

Today, several different types of adaptive systems are in operation or under development, taking advantage of the current capabilities of technology and signal processing which will enable high performance communication, giving faster link establishment times and higher user data rates.

The term “adaptive HF systems” has become synonymous with the current generation of automatic HF systems. So that the regulatory framework will not set unintentional restraints on the future development of these type of HF systems, a new term (not identifiable with a particular generation or system) has been suggested: frequency agile HF systems. This term only defines the method of frequency usage in the HF frequency spectrum by these systems.

The advantages of adaptive operation were recognized by the 1997 World Radiocommunication Conference through the adoption of Resolution 729 (WRC-97), see § 2.3.2 of this Handbook.

The Resolution sets a number of provisions to ensure that such use is contained within appropriate bands, to ensure that interference is minimized, and to safeguard continued use by non-adaptive systems. When adaptive systems become more widely used, there should be an improvement in spectrum utilization, which will benefit both the users of adaptive systems as well as those who continue to use non-adaptive systems. The capability of modern technology and of powerful digital signal processors would now permit the manufacture of economical equipment, which would allow many types of radio usage and application to take advantage of the improved quality possible with this type of operation.

The procedures for frequency registration adopted within the BR under TeraSys (refer to CR/118), now enable frequency agile or adaptive systems to be readily brought into use. It is no longer necessary as a regulatory procedure to make individual frequency assignments for adaptive HF links. Instead it is sufficient to identify the frequency bands available for adaptive operation, leaving the details of potential frequency complements and interference avoidance techniques to the circuit managers.

1.3 Benefits for developing countries

Adaptive systems offer special benefit to developing countries, for both commercial and government users. These include safeguards for existing users through dynamic monitoring by adaptive systems, a simplified regulatory requirement and lower-cost access to global or regional communications. Some countries have limited wired infrastructure, and they can save money by using HF instead of satellite communications in many cases. Adaptive systems make HF communication as effective as many telephones or satellite communications.

With the modern equipment already available or under development, the need for skilled radio operators can be completely dispensed with, because any frequency agile system will automatically select the optimum working frequency at any given instance, and will perform the requested communication in an interference-free environment and with the highest possible performance. In this way, the whole radio-frequency spectrum will always be available to any operator who needs to use it in a timely manner, subject only to the avoidance of interference.

It should be emphasized that authorization for the use of parts of the radio-frequency spectrum to this mode of operation, at the national level, is always under the full authority of each government, based on the principles described in § 2.3.2 of this Handbook.

1.4 Technical description of some operational systems

1.4.1 Main characteristics

The salient features of the adaptive MF and HF systems are:

– *Easy to use:* the adaptive systems will establish, maintain and disconnect the MF and HF link without the need for an operator to interact technically. This alleviates the requirement for using trained radio personnel.

– *Increased reliability:* the percentage of time in which the adaptive systems will provide a high quality service is much higher than traditional fixed frequency systems. This is ensured by the use of adaptive frequency selection, automatic repetition on request (ARQ) and more robust modulation waveforms.

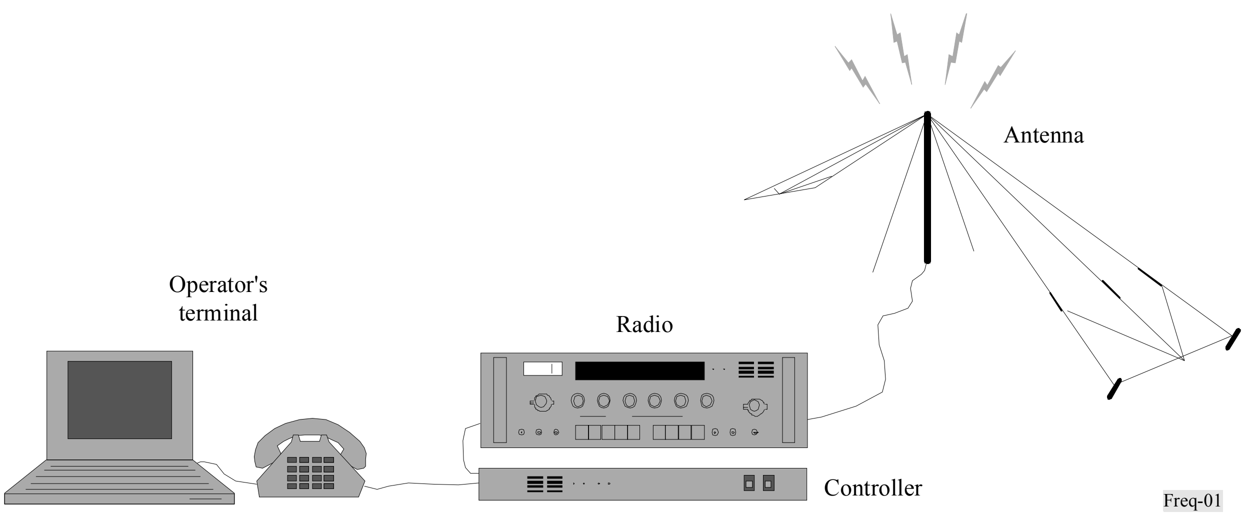
– *Flexibility:* an adaptive system continuously analyses and updates link quality assessment information making it possible to select the most suitable traffic frequency for each particular time instant. This adaptive behaviour minimizes the time periods in which stations cannot communicate, and also increases the possibility for use of low-power stations, in both the fixed and mobile services.

1.4.2 General description

The following describes a common set of functions that are embedded in most of the various types of systems that have been developed. “Common” in this respect does not necessarily mean that they have been implemented in the same way thus enabling inter-communication. It only means that the same type of functionality has been implemented. A more thorough description can be found in Recommendation ITU-R F.1110 – Adaptive radio systems for frequencies below about 30 MHz.

An adaptive station, here defined as being able to provide the operator with a radio link, consists of the following elements:

FIGURE 1



The main functions of the controller unit in an adaptive system are frequency management and link quality assessment, link preparation and establishment, link maintenance and disconnection.

1.4.3 Frequency management and link quality assessment

All frequencies that are potentially available for use for a specific link are stored by the system in a frequency pool. Some adaptive systems may differentiate between transmitter and receiver frequency, others may use the same frequency for both transmission and reception. In general, five to ten frequencies are stored in a frequency pool, but some adaptive systems have the capability to store and use up to several hundred frequencies.

When there is no traffic, a station will scan the frequencies of the pool, dwelling on each frequency for a specific time period sufficiently long as to ensure that an incoming call can be detected. Some systems will simultaneously perform a passive channel analysis by measuring the interference or noise level on each frequency.

Link quality assessment information is collected after a link has been disconnected. The information is used to select appropriate traffic frequencies between the stations in a net. If little traffic is passed within the net, an automatic sounding function may be activated to provide an assessment of link quality. At regular intervals a station will perform a special sounding call consecutively on each frequency from the frequency pool. All other stations in the net detecting this sounding call will update their individual link quality assessment table.

1.4.4 Link preparation and establishment

The operator will order a link to be initiated either by using the ordinary telephone or via the operator terminal. When a station is ordered to establish a link, it will select the assumed most suitable frequency in the frequency pool. The receiver is set to that frequency, and the controller unit will measure the interference level on that frequency. If the interference level is above a certain threshold, the frequency is rejected and the controller will test the second best frequency. If a usable frequency cannot be found, a “failure” status report will be issued to the operator. Otherwise a call will be initiated.

When a called station detects a call, it automatically responds and reports the call to its operator. The calling station confirms the reception of the response, and messages can then be transferred or alternatively the link can be handed over to the operators for voice operation.

1.4.5 Link maintenance and disconnection

If a link is under control of a controller unit, e.g. when passing text or data messages, it may react adaptively to changes in link conditions. If, for example, the link degrades, a change to a new frequency may be initiated automatically.

Either operator is able to disconnect the link. The controller unit will then issue the appropriate commands to ensure that both stations disconnect the link in an orderly manner. The stations will thereafter resume scanning the frequencies in the frequency pool.

1.5 Example adaptive network

Annex 1 to this Handbook gives a brief summary of the characteristics of an example adaptive network.

CHAPTER 2

The radio regulatory framework

2.1 The World Radiocommunication Conference (Geneva, 1995) (WRC-95)

WRC-95 had amongst its tasks a consideration of the simplification of the Radio Regulations, to aid use by the administrations, etc. and also to aid the efficiency of the work of BR. A simplified set of Regulations was agreed. However, by means of Resolution 23 (WRC-95), it was decided that BR, with immediate effect, would no longer make any technical examination of proposed frequency assignments in the unplanned frequency bands below 28 MHz.

Thus any proposals by administrations for the registration of assignments in the MIFR would take place without any check for incompatibilities, and countries which relied on this process to ensure satisfactory, interference-free communication would not now have that perceived safeguard.

The remaining Regulations following WRC-95 still require notification to BR and listing in the MIFR. However, without any checks, and thus without anything to be gained from registering the date of an assignment, it might be expected that the listing in the MIFR will progressively degenerate and that some new assignments would not in practice be notified.

ITU also has the purpose of offering technical assistance to developing countries and of promoting the development of technical facilities and their most efficient operation. It may be considered that the withdrawal of a technical examination by BR would reduce the technical assistance available, despite the imperfections of the previous arrangements. Countries without the resources for their own monitoring and planning may have been concerned that there is no longer any regular procedure which would enable them to maintain the quality of their existing services.

Another factor, which is degrading the effective use of the HF spectrum, is the shortage of skilled and experienced circuit operators. In the past experienced operators could assess the performance of the circuits, which they were managing, and make effective decisions for real-time frequency management. Such skills are now disappearing with the result that the actual performance of many HF circuits is now becoming worse.

2.2 Recommendation 720 (WRC-95)

At WRC-95 the possible use of intelligent frequency agile systems was identified. Recommendation 720 (WRC-95) – The Flexible and Efficient Use of the Radio Spectrum by Fixed and Some Mobile Services in the MF and HF Bands Using Block Allocations for Adaptive Systems, recognizes “that further studies are essential to permit the introduction of frequency agile equipment coupled with the power of digital signal processing for frequency control and error-correction techniques” and went on to instruct the Director, BR, “to ensure, in consultation with the study group Chairmen, that the studies now in hand were completed as a matter of urgency and in time for WRC-97”.

The 1995 Radiocommunication Assembly adopted two new Questions, which are relevant for the HF fixed services. These were: Question ITU-R 204/1 – Block allocations for adaptive systems in the HF band; and Question ITU-R 205/9 – Technical and operational implications of using discrete blocks of spectrum by adaptive HF systems. Both these Questions had the same purpose – to provide justification for a new regulatory environment at HF. The Study Groups had envisaged a steady series of studies extending over, say, the next four years so as to reach firm conclusions on the merit of such systems.

The work in Radiocommuniction Study Group 1, on spectrum utilization aspects, was completed with the preparation of Recommendation ITU-R SM.1266. This Recommendation includes the basic reasons for the use of system adaptivity and lists the various system parameters which may be adapted in response to changes in the channel.

In Radiocommunication Study Group 9, WP 9C, Recommendation ITU-R F.1192 was approved in 1995 which deals with the "Traffic capacity of automatically controlled radio systems and networks in the HF fixed service". Recommendation ITU-R F.1110 deals with "Adaptive radio systems for frequencies below about 30 MHz".

2.3 Results of the World Radiocommunication Conference (Geneva, 1997) (WRC-97)

2.3.1 Definition

At WRC-97 a definition was adopted in the Radio Regulations, No. 1.109A:

> "*adaptive system*: A radiocommunication system which varies its radio characteristics according to channel quality".

Although the use of frequency adaptive systems was allowed previously, with the registration of all frequencies in transmitter complement, for the first time this specifically identifies this new capability of technology. The definition is general and has applications also in other frequency bands.

2.3.2 Resolution 729 (WRC-97)

WRC-97 also adopted Resolution 729, which sets out the way in which MF and HF adaptive systems should be used.

The Resolution considers that:

– the efficiency of spectrum use will be improved by the use of frequency adaptive systems in the MF and HF bands shared by the fixed and the mobile services;

– trials of frequency adaptive systems which have been undertaken during the past 20 years have demonstrated the feasibility of such systems and their improved spectrum efficiency;

– such improved efficiency is attained through:

  – shorter call set-up and improved transmission quality by selection of the most suitable assigned channels;

- reduced channel occupancy, permitting the same channels to be used by different networks, yet decreasing the probability of harmful interference;
- minimization of the transmitter power required for each transmission;
- continued optimization of the emissions owing to the sophistication of the systems;
- simple operation by the use of intelligent peripheral equipment;
- reduced need for skilled radio operators;

– following Resolution 23 (WRC-95), the BR no longer undertakes examination with respect to the probability of harmful interference caused by new assignments recorded in the MIFR in the non-planned bands below 28 MHz;

– frequency adaptive systems will actively contribute to the avoidance of interference since, when other signals are observed on the channel, the frequency adaptive system will move to another frequency.

The Resolution then resolves:

- that, in authorizing the operation of frequency adaptive systems in the MF and HF bands, administrations shall:
  - make assignments in the bands allocated to the fixed and mobile services;
  - not make assignments in the bands:
    - allocated exclusively to the maritime or aeronautical mobile (R) services;
    - shared on a co-primary basis with the broadcasting service, radiodetermination service or the amateur services;
    - allocated to radio astronomy;
  - avoid use which may affect frequency assignments involving safety services made in accordance with Nos. 5.155, 5.155A and 5.155B of the Radio Regulations (RR);
  - take into account any footnotes applicable to the proposed bands and the implications regarding compatibility;
  - that frequency adaptive systems shall automatically limit simultaneous use of frequencies to the minimum necessary for communication requirements;
  - that, with a view to avoiding harmful interference, the system should evaluate the channel occupancy prior to and during operation;
  - that frequency adaptive systems shall be notified to the Bureau in accordance with the provisions of RR Article 11.

Thus the intention of this Resolution is to ensure that frequency adaptive use will be confined within those bands, which are allocated for the fixed and mobile services, avoiding those bands allocated exclusively to the maritime and aeronautical services or to other services. It is also intended to ensure that the simultaneous use of frequencies is minimized and that interference should not be caused, through the process of monitoring for channel occupancy prior to transmission.

The Resolution also called on ITU-R to continue its studies, and instructed the Director of the BR to make the necessary arrangements, as soon as practicable, for the notification of frequency assignments to adaptive systems, and for their recording in the MIFR, taking into account the studies already undertaken.

This has now been done, and the new Radiocommunication Bureau Terrestrial Radio-communication System (TerRaSys) (refer to CR/118), for the notification of frequency assignments includes a special form for notification, T17, for adaptive MF and HF systems. This form allows the centre frequency of a band, together with the width of the band to be notified.

2.4 The World Radiocommunication Conference (Istanbul, 2000) (WRC-2000)

No further changes were made at WRC-2000 to the provisions in the RR or to the Resolution in respect of adaptive systems, and the details given above continue to apply. It may be noted however that the agenda for WRC-03 includes items which refer to the use of digital modulation at HF, while the provisional agenda for WRC-07 includes a review of the allocations to services in the HF bands, taking account of the impact of new modulation and adaptive control techniques, from about 4 MHz to 10 MHz.

CHAPTER 3

Adaptivity techniques

3.1 Automatic and adaptive HF radio

High-frequency radio applications and spectrum utilization aspects were introduced in Chapter 1; and the regulatory framework was outlined in Chapter 2. This Chapter introduces the concepts of automation and adaptivity. The integration of these features make HF radio a more reliable communications channel and less prone to impairment in connection with ionospheric variability and disturbances.

Aside from mitigation advantages, automatic and adaptive techniques have improved the performance of HF radio under normal circumstances. Subsequent chapters show how these techniques are applied. The approach used in this Chapter is to describe the radio system in terms of layering. The lowest level is the transmission level, which is responsible for physically moving the message from point to point. Table 1 shows how this layer is related to other layers. Above this layer is the link level where the heart of the radio transceiver resides. It is in this layer that the concepts of ALE are primarily added. Above this layer is the network layer, which is responsible for bringing a series of radio systems together into a network. The uppermost layer is the operator or the higher-level system function responsible for generating and receiving the messages or data traffic. Using this concept of layers, the fundamentals of taking a basic radio and adding the features and functions of automation and adaptivity can more easily be understood.

HF radio has been used for decades for long-distance communications. HF radiocommunication has a number of positive characteristics that can be enhanced – and drawbacks that can be minimized – through the use of automatic and adaptive techniques. The positive attributes for communication in the HF band include cost-effective long-distance transmission. The negative aspects include: labour-intensive operation, variable propagation, modest overall reliability and limited data bandwidth. Communicating in the HF radio band requires the optimization of conditions to make it reasonably reliable. The reliability of HF radio transmissions is dependent on a large number of factors such as:

– operating frequency;

– the degree and distribution of ionization of the ionosphere;

– the distance between stations (number of hops);

– signalling overhead procedures (i.e. error checking, handshaking, etc.).

In the manual operational procedure which has been used until recent years to optimize HF radiocommunication, the operator must adjust the parameters of the system for maximum performance. He/she must monitor the conditions of the ionosphere, track the variable propagation conditions, and select the operating conditions (i.e. primarily the frequency) that will allow the signal to propagate best. Because of the intensive labour, experience and skill required, HF radiocommunication is an easily recognized target for justifying automation and the use of adaptive techniques. Present day automation techniques reduce the burden on the operator by adding subsystems for frequency management, link establishment, link maintenance, etc. These techniques can be used to reduce the skill-level demands and duty requirements of the HF radio operator or communicator. Typically, automation can be added to make the radio appear to be “push-to-talk on the best channel”, while actually the radio is a multichannel communication device performing many underlying functions.

Beyond these automation techniques are the “adaptive” techniques, which also can reduce the burden on the operator while making the radio more responsive to changing HF radio propagation conditions. The definition of adaptivity might be: *the process associated with automatically altering operating parameters and/or system configuration in response to changes in the time-varying channel propagation conditions and external noise.*

The functional parts of the radio system can be represented using the model of the International Organization for Standardization (ISO) called the Open System Interconnection Reference Model (OSI-RM). Adaptivity techniques exist that can be added to various levels of the radio system (see Table 1). At the transmission level, adaptive characteristics might include: data rate, waveform, error coding, power, and antenna type and pattern procedures as well as performance assessment characteristics unique to the transmission level. At the link level, adaptive characteristics might include frequency management, ionospheric sounding, channel probing, and occupancy/ congestion monitoring in addition to performance-assessment details. At the network level, adaptive characteristics might include: adaptive routing, flow control, protocol management, data exchange, and network reconfiguration, as well as performance-assessment details. At the system level, adaptive characteristics might include: system-level system management, system-level frequency management and control, in addition to performance assessment details.

TABLE 1

Adaptivity techniques and associated levels

Level	Adaptivity technique
System level	**System-level frequency management and control**
Network level	Adaptive routing Flow control Handshaking Data exchange
Link level	Frequency management and control
Transmission level	Data rate Waveform Error coding Power Antenna type Antenna pattern

3.1.1 Transmission adaptivity level

The lowest level of adaptivity (see Table 2) is concerned with the characteristics associated with a communication over a single transmission path at one or more frequencies. Such characteristics include data rate, transmission waveform, coding scheme, transmitted power, antenna pattern, and performance assessment.

Data rate

It may be possible to boost the communication data rate to the maximum rate that the ionospheric channel will support. However, when unfavourable conditions exist, the data rate will necessarily be adjusted to a lower rate. Adaptive systems can be conceived that will try communication at the maximum rate, then if the bit error ratio becomes excessive, the system will try a lower rate in an attempt to complete the transmission sequence.

Adaptive transmission waveform

The choice of modulation format is critical for HF communication because of the nature of the propagation channel. The transmission waveform should be chosen that will give the system maximum throughput while maintaining acceptable error characteristics.

Adaptive coding schemes

Error detection and correcting coding methods provide varying degrees of protection for data integrity and transmission security. It seems only natural, therefore, to visualize the development of coding schemes which are adaptive in nature. Use of the adaptive schemes can be selectable depending on the state of the channel. Some schemes are more robust in the face of channel disturbance but they carry with them a significant overhead burden. Other methods require less burden and can be relatively fast, provided the channel is only moderately disturbed, but may fail under conditions of virulent disturbance.

Adaptive power control

Adaptive power control is a very important control technique. Adaptive power control concepts can assure that adequate power is used to achieve the maximum range required while minimizing interference beyond the desired coverage area. Thus, adaptive power control should ensure that minimum necessary power is used.

TABLE 2

HF communications adaptivity levels

Level	Function
System adaptivity level – Multimedia	Higher level system management
	System level frequency management
	Stress environmental assessment
	System performance assessment
Network adaptivity level – Multimode	Message routing schemes
	Adaptive routing
	Flow control
	Protocol management
	Data exchange
	Network reconfiguration
	Network performance assessment
Link adaptivity level – Point-to-point	Frequency management procedures
	Ionospheric sounding
	Channel probing
	Occupancy/congestion monitoring
	Link performance assessment
Transmission adaptivity level	Data rate
	Adaptive transmission waveform
	Adaptive coding schemes
	Adaptive power control
	Adaptive null-steering
	Transmission performance assessment

Adaptive null-steering

An antenna system which has a controllable directivity pattern can also provide an important adaptive technique. Adaptive antennas using null-steering techniques might position a major lobe in the direction of the desired signal (beam-steered array) and/or deep nulls in the direction of the noise sources (null-steered array). One technique for reducing noise effects might be to steer the nulls within the pattern toward unwanted signals to reduce harmful effects.

3.1.2 Link adaptivity level

The link adaptivity level is relevant to point-to-point communications. The characteristics at this level include various frequency management and control functions. See Chapter 6 for a discussion of sounding and channel evaluation techniques.

3.1.3 Network adaptivity level

At the network level of adaptivity, multimode networks are involved, so the characteristics of routing, adaptive routing, flow control, protocol handling, and data exchange become issues of importance.

3.1.4 System adaptivity level

The system level is concerned with those capabilities that allow multimedia communication. Characteristics include: higher level system management, system-level frequency management and control, stress assessment of the environment, and system-level performance assessment.

CHAPTER 4

The propagation environment

One of the main reasons for adopting adaptive technologies is the extreme variability and unpredictability, in the short term, of the HF propagation environment. Propagation in this band is primarily by the sky-wave mode, utilizing reflection of radio waves from the ionosphere, or in some cases by the ground-wave mode.

The ionosphere, and radiowave propagation using it, are described in the ITU-R Handbook – The ionosphere and its effects on radiowave propagation – and in relevant Recommendations in the ITU-R P-Series. Some additional information may be found in the ITU-R Handbook – HF broadcasting system design.

In brief, the ionosphere is formed in the Earth’s upper atmosphere, at heights above about 80 km, by the effects of ionizing radiation from the sun. The height and density of the ionization depend upon the incoming radiation, the atmospheric constituents and their variation with height, etc. the Earth’s magnetic field and the circulation of the upper atmosphere. The incoming solar radiation generally varies with the solar activity cycle, which has a variability of approximately 11 years duration, as seen for example in the number of spots on the Sun’s surface.

The incoming radiation ionizes a part of the upper atmospheric gases and the resulting free electrons form the ionosphere which has the property of refracting or reflecting radio waves. In the lower parts of the ionosphere the free electrons have a limited life-time before recombining, and the density of ionization varies approximately with the elevation angle of the sun. These lower parts of the ionosphere are called the D and E regions or layers. Higher in the ionosphere, in the F region, electrons have a longer life-time and the ionization density is also strongly affected by winds and by the presence of the Earth’s magnetic field.

The maximum frequency which can be reflected vertically from an ionospheric layer depends on the ionization density and is called the critical frequency. The ionization density, and thus the critical frequency, depends on the geographical location, and is subject to hour to hour, day to day and seasonal variability due to changes in the solar radiation, the solar-terrestrial environment, the upper atmospheric winds and the Earth’s magnetic field. The lower parts of the ionosphere also attenuate radio signals, while interaction with the Earth’s magnetic field also changes the signal polarization.

Terrestrial propagation may be considered as oblique incidence reflection from the ionospheric layers and additional propagation modes may have multiple reflections from the ionosphere and the Earth’s surface. The maximum frequency of propagation for each mode depends on the critical frequency and on the elevation angle at the reflecting layer. Thus in general the received signal will comprise several modes, each with a different and variable strength; time of arrival and polarization.

These longer term variations in propagation conditions, from hour to hour, day to day, with season and with the solar cycle are predictable on a statistical basis. Prediction methods are available using Recommendation ITU-R P.533 or a variety of other methods.

Such long-term prediction methods cannot give a precise estimate of the best frequency to be used at a specific date and time on a specific radio path. Traditionally it has been the practice to use a frequency somewhat below the predicted maximum usable frequency (MUF), so as to ensure that a satisfactory signal would be received on most days of the month. A planned schedule of frequency changes through the day would be prepared for each month, so as to maintain usable communications. The radio operator managing the circuit would use these frequency schedules, together with his experience and actual conditions on the day, and select the best frequency from the limited set available to him, thus managing the circuit operation on a minute to minute basis.

The long-term predictions also give information on the active propagation modes and the elevation angles required for the antenna radiation.

The ground wave propagation mode is stable and predictable. It is described in Recommendation ITU-R P.368 and a prediction method is available in the software program GRWAVE. At HF, the mode is only significant at ranges of up to several hundred kilometres over sea, and to substantially shorter ranges over land, in the lower part of the frequency range. Nevertheless, in appropriate circumstances the mode may be important.

Circuit operation is subject to these propagation modes, to the longer term ionospheric variations, to intensity and polarization fading. However, there are other short term and largely unpredictable factors which are important.

In the lower part of the ionosphere, at about 100 km, additional ionization may occur, in a manner which cannot be adequately predicted, due to meteorological factors and trace elements, and due to other mechanisms at both high and equatorial latitudes. This “sporadic-E” ionization may have a major impact on radiowave propagation and may provide an additional propagation mode.

There are also important contributions to the incoming radiation from eruptions on the Sun’s surface, often seen as solar flares, which release ultra violet and X-rays, high energy particles and a plasma of medium energy particles which may then propagate in the solar wind, through the solar terrestrial environment, to reach the Earth. When these radiations reach the vicinity of the Earth they directly cause additional ionization. They also interact with the Earth’s magnetic field, depositing ionization into the polar regions, changing the temperature of the neutral gases in the upper atmosphere, changing the wind system and the distribution of ionization. These events are described as geomagnetic and ionospheric storms and may have a major impact on HF propagation. They cannot be forecast long in advance, and the effects cannot be accurately forecast even a few hours ahead. The skill of a circuit operator may be able to enable some continued operation during a storm, but he would have to work on a trial and error basis as experience of such events would be limited. One technique of value at high latitudes, where storm effects are most pronounced, is path diversity, using alternative radio paths to avoid the most disturbed areas but this requires rapidly available information at a network level.

Modern HF communications are now required to deliver increased data rates with wider bandwidth systems. The performance of these systems will depend on the multipath delay spread of the active propagation modes at that time, which are due to propagation from the various layers, etc. The ionization is also moving due to the atmospheric winds so that each mode will have a different frequency shift due to Doppler effects. At equatorial latitudes, near the magnetic equator, the ionospheric layers may break up after sunset into a diffuse region from which signals are scattered with large time and frequency spreads. At high latitudes, the ionospheric layers may be broken up due to ionospheric storms, again resulting in signal scattering with large time and frequency spreads.

For modern communications there is often an economic and practical requirement to use automatic equipment without a skilled radio operator, while to meet the requirements for good circuit availability for wideband systems, even an operator’s skills may not be adequate. Hence the increasing use of intelligent adaptive systems to provide good performance.

Within an adaptive system there is a need for an algorithm to steer the frequency selection in an efficient manner. A long-term frequency prediction method may be built into the system’s software, to provide the basis for automatic frequency management.

There will continue to be a need for long-term propagation predictions at the planning stage of adaptive systems to ensure that system parameters, such as radiated power, are sufficient to give the required circuit performance, and to design antenna systems with radiation at the necessary elevation angles.

CHAPTER 5

System engineering

Matters which should be considered in designing, planning and implementing HF fixed service radio systems are described in Recommendation ITU-R F.1610.

For frequency agile adaptive systems and networks, antennas should have broadband characteristics extending over the frequency range for which adaptive operation is planned. The antennas should have radiation angles appropriate for the path length over the whole of this frequency range. Where this cannot be achieved, switching between suitable antennas for the various parts of the frequency range, must be included within the adaptive control process.

For those systems where ground wave propagation is used and long range communications via the ionosphere is not required, frequencies should be selected which take advantage of propagation conditions to limit unwanted propagation. Means of achieving this include the selection, during daylight hours, of frequencies below the lowest usable frequency (LUF) of the propagation modes available and the selection, at night, of frequencies above the MUF for long paths for the antenna being used. Note that the LUF is dependent on solar cycle, increasing with higher solar cycle indices. Caution should be exercised when using frequencies above the MUF at night in tropical regions as long-distance “chordal”, or trans-equatorial propagation may be stimulated. Transmitters and receivers should also have broadband or fast tuning capabilities, again extending across the frequency range for the adaptive operation.

CHAPTER 6

Use of sounding and channel estimation techniques

6.1 General

The key to achieving significant benefits in the way that an operator or automated HF radio system controller uses the propagation medium for communication is to ensure that an adequate supply of real-time data is available for decision-making purposes. Off-line propagation analysis is the older time-proven method for getting this information. More recently automated and adaptive systems have turned to real-time collection of information to be used in propagation analyses.

Sounding belongs to a general class of channel estimation or evaluation techniques. The next section will outline the attributes of real-time-channel evaluation techniques (RTCE).

6.2 RTCE

RTCE defines a class of methods whereby properties of the HF channel are deduced in real time. *Real-time channel evaluation is the term used to describe the processes of measuring appropriate parameters of a set of communication channels in real time and employing the data thus obtained to describe quantitatively the states of those channels and hence the capabilities for passing a given class, or classes, of communication traffic* [Darnell, 1975 and 1982; Maslin, 1987; Goodman, 1992].

It is of interest to compare the definition of RTCE with a definition of adaptive HF contained in MIL-STD-188-141A:

Adaptive HF describes any HF communication system that has the ability to sense its communication environment, and, if required, to automatically adjust operations to improve communication performance.

Once a radio link is established with data or voice traffic passing across it, it is possible for a suitably equipped receiver to extract substantial RTCE information about the characteristics of the link. The data collected constitutes the HF communication channel parameters that are important for successful communication. Decisions on the message path, the channel to use, whether to use direct or indirect message handing, and how much noise and interference to expect, are usually generated by some form of RTCE and frequency management routine.

The types of RTCE which may be used are numerous and include various forms of sounding as well as indirect schemes which enable HF channel information to be calculated. In the latter case, for example, it may be possible to deduce the channel information through measurement of the ionospheric properties followed by application of ray-tracing methods. The most direct methods for RTCE involve extraction of channel properties over the same path that is used in providing a radio service, and the methods may be organic components of the system design. While generally restricted to the ionospheric context, RTCE is a very general term, with results being applicable to a range of disciplines other than HF radiocommunication, such as HF direction finding and over-the-horizon radar. Nevertheless the discussion in this Chapter will be directed toward the application of RTCE to support adaptive HF communications.

6.3 Requirements for RTCE

The need for RTCE arises because of the variability in the total environment associated with the HF channel. In most cases, it is not necessary for the communicator to know what detailed fundamental physical principles create the distortions imposed by the ionospheric medium on a particular signal, only that it is possible to measure the characteristics of the available paths and, from this, to adapt the associated communications-parameters for optimum information transfer [Galanos *et al.*, 1987]. The analysis, application, and ability to respond to RTCE information is integral to each adaptivity level, as shown in Chapter 3. This implies automation (i.e. microprocessor control) of the adaptive processes being used by the radio or controller system. Beyond automation, a comprehensive real-time frequency-management system should be used so as to be effective in reducing the data produced by the ionograms, the prediction programs, and the collected RTCE information. The frequency-management system should have the following characteristics:

– take into account all the assigned operating frequencies;

– account for high and low power levels;

– account for the various antenna types;

– take into account the modem-specific and data-rate parameters;

– issue an automatic recommendation of the optimum operating frequency.

The system would be expected to operate continually, to measure the channel characteristics, and to make recommendations based on the system characteristics such as modem, antenna, etc.

6.4 Use of RTCE and frequency management procedures

There are three stages for implementation of HF frequency management: long-term forecasting, short-term forecasting, and immediate conditions. Adaptive frequency management deals with the issues that might be used to adjust frequency use, based on network conditions. At the link-adaptive level, the primary consideration is with immediate conditions and the choice of frequency to use for a particular message. The transceiver must keep track of propagating frequencies/channels based on the results of an analysis of RTCE information to determine the best choice for message transmission. RTCE information gathering is an automatic technique that allows the receiver to adjust the frequency scanning according to information accumulated through passive or active techniques of traffic monitoring, sounding, polling, etc. Once a list of propagating channels is determined, a channel ranking can be performed by taking into account the effects of path loss, noise, interference, multipath, fading, dispersion, Doppler shift, and user requirements [Ripley *et al.,* 1996].

6.5 Ionospheric sounding

Sounding is the process of monitoring or testing the transmission medium for real-time propagation information. Soundings provide up-to-date indications of propagation characteristics over vertical (directly overhead) paths and oblique paths (along the actual communication route direction). It is not practical to sound all possible paths in a large communication network, but some benefits from sounding may still be achieved if selected paths are probed and the results are extrapolated to geographically nearby paths [Goodman, 1992].

Sounding can be divided into three subgroups for purposes of distinguishing the significance of each type. The subgroups consist of ionospheric pulse sounding, linear sweep sounding, and channel evaluation sounding [Maslin, 1987].

6.5.1 Ionospheric pulse sounding

Ionospheric pulse sounding is used to test the propagation medium characteristics for such things as channel unit impulse response, signal propagation delay, and signal amplitude [Maslin, 1987]. Pulse sounding consists of emitting a pulse sweep over a portion or all of the HF band for a period of a few seconds to several minutes. The received signal is then analysed. The results of a frequency sweep of a sounder will indicate to the user, or automatically to the equipment the range of frequencies that will propagate. Vertical-incidence-sounder (VIS) where the soundings are emitted vertically and the reflected returns are received by a nearby receiver and oblique incidence backscatter sounding where the soundings are emitted in the direction of the actual communication, and the returns scattered from a distance are gathered by a co-located receiver very near the transmitter, are general techniques which require interpretation before being of direct use to an adaptive link.

Oblique-incidence-sounder (OIS), where the sounding is emitted in the direction of the actual communications path, and the receiver is located at the remote location, is of more direct application, subject to the antennas and system parameters in use.

6.5.2 Linear swept frequency sounding (i.e. chirp sounding)

Linear FM modulation or chirp sounding consists of sending at low power 2-30 MHz [Maslin, 1987]. This method can be linear FM/CW test signal over the communication path used over either a vertical or an oblique path. The data received from the chirp sounding equipment is similar to the pulse sounding equipment, but has the advantage of causing less interference to nearby equipment.

Oblique incidence sounding technology offers benefits for adaptive HF communications systems using the 2-30 MHz bands. In addition, the frequency modulated continuous wave (FMCW) swept-frequency “chirp” method is shown to offer adaptive HF system engineers with more options in the design of HF networks. Moreover, it is found that FMCW “chirp” sounding provides the communicator with a relatively unobtrusive waveform for establishing optimum network connectivities, if the sounding is carried out in near-real time and the network consists of frequency-adaptive radios. A basis for these conclusions lies in a comprehensive analysis of propagation data obtained by organizations in the United States of America between 1993-1996, in cooperation with entities in Canada, Iceland and Sweden [Goodman *et al.*, 1997]. Data sets concentrated on mid-latitude paths during 1993 and high-latitude paths between 1994 and 1996. Over 700 000 ionograms and 40 path-years of data were collected and analysed. Special attention is directed toward the evaluation of data sets obtained in 1995 at four designated sites corresponding to different propagation regimes. The results provide estimates of link and star-net communication availabilities under a variety of frequency and station diversity conditions. Consolidated long-term availability estimates are presented. Frequency management and network design implications are given.

Recommendation ITU-R F.1337 outlines the case for frequency management of adaptive HF radio systems and networks using FMCW oblique incidence sounding. Specifically it recommends that automatic and adaptive management schemes be considered for adaptive HF networks to include dynamic selection of optimum frequencies, the sharing of frequencies within a network, and adaptive selection of alternate network paths; that FMCW "chirp" sounding be considered for use in dynamic frequency management schemes including:

– as a real-time input data source for updating resource management and propagation prediction programmes;

– as a means for updating the frequency scan lists of adaptive HF systems;

– for modification and enhancement of the link quality analysis (LQA) matrices for adaptive HF systems;

– as a complement to the exclusive use of in-band channel sounding, thereby increasing network communication capacity and reducing interference introduced by channel sounding.

6.5.3 Channel evaluation sounding

Channel evaluation sounding consists of probing only frequencies that are allocated to this system, rather than a broadband approach of the other two methods. Channel evaluation provides information used in evaluation of signal-to-noise performance such as: data error rate, speech intelligibility, and noise levels [Maslin, 1987].

6.5.4 Channel probing

A wideband channel probe can be used to collect data over a single-hop polar path using the F layer. The collected data shows a scattering function when the Doppler frequency is plotted against delay.

6.5.5 Occupancy/congestion monitoring

The channel is monitored for occupancy, congestion, and a "full" condition to determine if message traffic is possible. If the channel is busy, a back off algorithm or continual monitoring can be used to determine when message traffic is possible.

6.5.6 Performance assessment

The link adaptivity level uses the full RTCE complete set of characteristic information for making determinations associated with level. The network adaptivity level uses a network-associated subset of the full RTCE set of characteristic information.

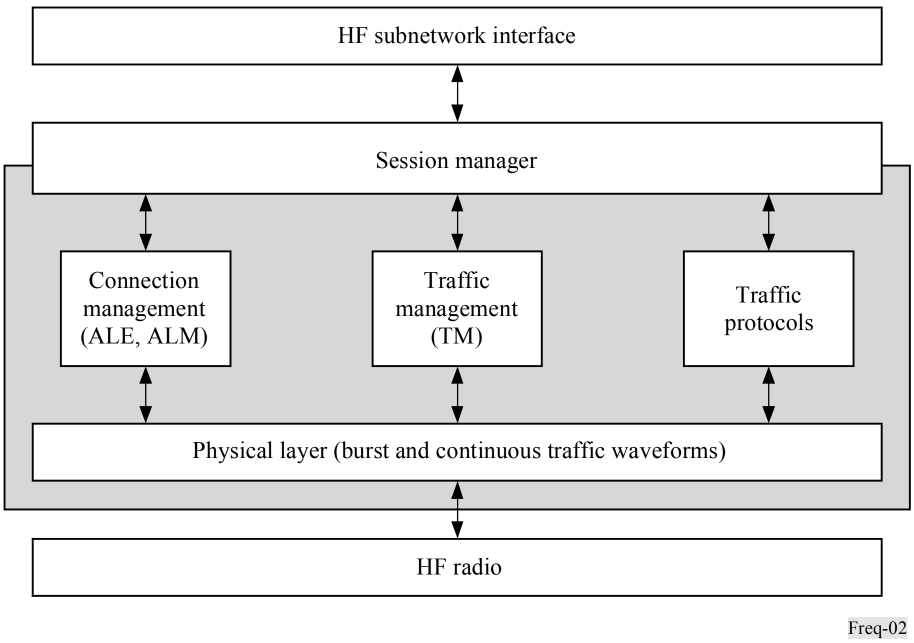
CHAPTER 7

Control, including automatic link establishment (ALE) and automatic link maintenance (ALM), taking into account systems in use or standardized

7.1 Overview

Central to the concept of automated HF radio is the notion that the HF bearer should provide communications services generally analogous to those provided by other voice and data networks. The client of the HF service should not be required to deal with the peculiarities of the HF medium. This leads to a conceptual structure of the HF controller as depicted below. Although current practice does not universally follow this model, the model does provide a useful framework for this Chapter.

FIGURE 2



Subnetwork interface. A subnetwork interface provides client services to voice users and data communication client processes. Standardization of this interface would minimize training time in the case of direct human interaction, and simplifies integration of the HF service into data communications applications including Internet access. Standardization of application programming interface primitives is addressed to varying degrees in most current HF radio automation standards (STANAG 5066, STANAG 4538, MIL-STD-188-141B, MIL-STD-188-110B).

Session manager. The notional session manager coordinates all of the activity within the HF node in response to requests for service from the local subnetwork interface and remote nodes. It requests the establishment of links, manages the transition from link setup to traffic, monitors the progress of communications during a session, and initiates link maintenance operations as needed.

Connection manager. A connection manager is specifically concerned with establishing and maintaining links of specified characteristics (e.g., SNR). It executes ALE and ALM protocols upon request of the Session Manager, or autonomously when it detects a need for such action.

Traffic manager. A traffic manager employs a traffic setup protocol to negotiate the waveforms, protocols, and related aspects of a traffic session.

7.2 ALE

As noted in Chapter 1, the first generation of ALE systems was developed in the late 1970s and early 1980s. These groundbreaking systems from numerous manufacturers collectively introduced most of the techniques now in use worldwide. However, no single system included all of the attractive features, and the various proprietary systems were not interoperable.

A cooperative effort among the manufacturers and the U.S. government led to a second-generation ALE system that incorporated features from many of the first-generation systems, and also increased linking performance. The second-generation (2G) ALE system was standardized in 1986 in MIL-STD-188-141A, Appendix A, for military use, and later in US FED-STD-1045 for all U.S. government agencies. This 2G ALE technology has become the *de facto* standard for ALE worldwide.

In the late 1990s, parallel efforts led to the development of a third-generation ALE system with higher-performance that retains interoperability with 2G ALE. This 3G ALE has been standardized in MIL-STD-188-141B Appendix C, and as the automated radio control system (ARCS) in STANAG 4538. Both 3G ALE standards mandate interoperability with 2G ALE, which remains in Appendix A of MIL-STD-188-141B.

The essence of ALE is automatic channel selection (ACS), scanning receivers, and a selective calling handshake employing robust burst modems that rapidly establishes communications between the calling and called stations.

Automatic channel selection (ACS). ALE dynamically selects a frequency for each session from a pool of assigned frequencies. This ACS function uses some combination of propagation predictions, measurements made using the ALE and other waveforms, and propagation reports provided by external systems to select a frequency that satisfies some criterion such as best estimated SNR, or minimum calling time that will satisfy a minimum acceptable SNR.

Initial channel selection is made by the station that initiates a link. In some cases (e.g., point-to-point calls using 3G ALE), the called station can override this selection to select a better channel for traffic.

Scanning receivers. ALE receivers scan through the assigned pool of frequencies, listening for calls. When receivers are scanning synchronously, according to a deterministic schedule, a short call suffices to reach a receiver. However, synchronous scanning requires network synchronization which may not be practical in all networks. Allowing network stations to scan independently, i.e., asynchronously, reduces the overhead required to synchronize the stations, but introduces the need for an extended call to capture unsynchronized receivers.

The scanning rate is bounded by the time required to detect ALE signalling (50-100 ms). Also, high scanning rates have been found to increase failure rates in antenna couplers when the coupler is retuned for each receive frequency. Current dwell times range from 100 ms in fast 2G systems to 5 400 ms in ARCS; despite the comparatively leisurely scanning rate of synchronous-mode 3G ALE, its synchronous operation usually results in faster link establishment than is achieved by 2G ALE.

Selective calling. ALE stations are assigned addresses (call signs) that are sent in ALE calls using a robust modem. The use of addresses in calls provides both a positive squelch that is effective in HF channel conditions, and a mechanism to minimize interference to stations not addressed. ALE stations recognize both individual addresses and collective addresses. The latter are used to contact multiple stations using a single call.

Link establishment handshake. The function of the ALE handshake is to manage the transition from radios that are scanning, available for calls, to radios that are positively linked on a usable channel for traffic. The initial contact is attempted by the calling station. A response from the called station(s) confirms to the calling station that the call has succeeded, but an acknowledging third transmission from the calling station to the called station(s) is needed to positively establish that the link is operational.

7.2.1 ALE modems

The requirements for an ALE modem differ significantly from those for a traffic modem. The ALE handshake consists of short transmissions. This makes long synchronization preambles unattractive, and precludes the use of long interleavers in coping with channel error bursts.

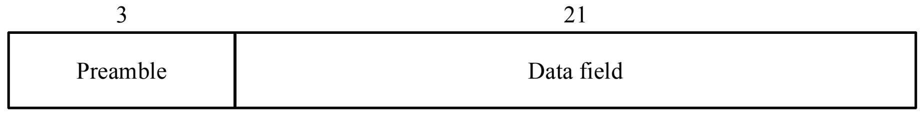
Different approaches to meeting these requirements have been followed in the early and more recent generations of ALE technology. The first and second generations were developed in the 1970s and 1980s when the cost and power requirements of signal processing hardware mandated simple waveforms. The third-generation ALE waveform links at 7-10 dB lower SNR than the second-generation waveform by taking advantage of 1990s digital signal processing technology.

7.2.1.1 FSK ALE modem (second generation)

The second-generation (2G) ALE waveform is an 8-ary frequency shift keying (FSK) modulation with eight orthogonal tones. Each tone is 8 ms in duration and ranges in frequency from 750 Hz to 2 500 Hz with 250 Hz separation between adjacent tones. Each tone represents three bits of data, resulting in an over-the-air data rate of 375 bits/s.

Forward error correction (FEC) is applied to protocol data bits sent using this waveform. First, the extended (24,12) Golay code is applied, followed by interleaving and triple redundancy. The receiver employs majority voting among the triply redundant symbols received to correct some errors. After deinterleaving the majority symbols, the Golay decoder attempts to recover error-free ALE words.

The format of 2G ALE words, shown below, includes a 3-bit preamble and 21 data bits (which are often used to convey three 7-bit ASCII characters). The on-air duration of each 2G ALE word is 392 ms. The function of each transmitted ALE word is designated by the preamble code. There are eight word types: TO, THIS IS, THIS WAS, DATA, REPEAT, THRU, COMMAND, and FROM. The uses of these ALE words are described later.



Freq-02b

Because no bits in the ALE word are spent on synchronization, acquiring word synchronization in this system employs a series of tests after each received symbol (tri-bit) is shifted in. First, the number of unanimous votes in the majority voter must exceed a threshold. Next, the Golay decoder must successfully decode both halves of the 48-bit majority word. Finally, the resulting 24-bit ALE word must contain a valid preamble and data bits (i.e., must be acceptable to the ALE protocol module). Once word synchronization has been achieved, it is automatically tracked for the remainder of the transmission using the same series of tests.

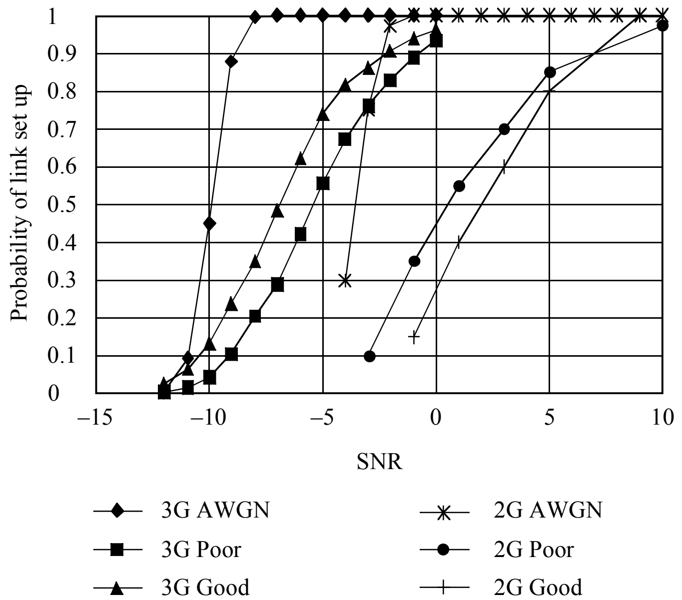
7.2.1.2 Burst PSK ALE modem (third generation)

The 3G ALE waveform is a member of a high-performance family of burst waveforms (BW) that cover the entire range of applications from link setup to traffic and link maintenance. All of the burst waveforms use an 8-ary PSK serial tone modulation of an 1 800 Hz carrier at 2 400 symbols/s. The BW0 burst used for 3G ALE carries a 26-bit payload at an effective code rate of 1/96 with a total duration (including sync preamble) of 613 ms. Other members of the BWn family are used for traffic management and link maintenance (BW1) and for ARQ (BW1 through 4).

7.2.1.3 Performance of ALE modems

Measurement of linking probability of the second- and third-generation ALE systems indicates the performance of their associated modems. Results for an additive white Gaussian noise (AWGN) channel, as well as ITU-R Good and Poor channels, are plotted in Fig. 3.

FIGURE 3



Freq-03

7.2.2 ALE protocols

The two current generations of ALE protocols were designed to meet differing needs. The 2G ALE system grew out of the need for an interoperable system with great flexibility that would ease the reconstitution of communications after natural or other unforeseen disruptions. It operates asynchronously so that no global timing reference is required.

The 3G ALE system was developed to extend the 2G system in two directions: operation in more challenging environments (e.g., lower SNR), and more efficient operation to support large networks and data-intensive applications.

Both generations require that operating variables in network member stations (e.g., channels and addresses) have at least some values in common. This may be accomplished manually (using fill devices for example) or through a network management protocol.

7.2.2.1 Second-generation ALE

Basic link establishment is accomplished in the 2G ALE system via a 3-way handshake between the linking parties. In the simplest case, the calling station transmits the address of the called station in a 2G ALE word with a "TO" preamble, repeats the TO word, and concludes with its own address in a THIS IS word. This three word transmission is the *call* phase of the handshake. The repeated address of the destination of a call is common to all 2G ALE transmissions in any handshaking protocol, and is termed the *leading call* portion of the transmission. It lasts at least two ALE words, or 784 ms.

The called station may return a *response*, which begins with a leading call addressing the calling station, and concludes with its own address in a THIS IS word. Upon receipt of the response, the calling station is assured of bilateral connectivity; it completes the 3-way handshake by sending an *acknowledgment* to the called station, so that it too is informed that both directions of the link are functional. In this simple case of link establishment, each transmission in the handshake contains only three ALE words, and lasts 1.2 s.

Addressing modes. Variations on this linking protocol include using longer addresses (up to 5 ALE words or 15 characters), addressing a network by name in the leading call, in which case the network members respond in prearranged time slots; listing a group of addressees, with response slots in the reverse of the order listed; and scanning variants of these individual, net, and group calls. The characters in 2G ALE addresses are constrained to come from a 38-character subset of the 7-bit ASCII set: A-Z, 0-9, @, and ?.

Scanning calls. When the station(s) to be called are scanning through a sequence of channels, the call (only) as described above is modified by prepending enough repetitions of the unique first address word(s) of the addressees that all scanning stations will land on the channel carrying the call at least once during this *scanning call* portion of the call. The duration of this period is computed from the scanning dwell time and number of channels scanned, and is abbreviated T_{sc}.

Link termination. Links are actively terminated using transmissions ending in THIS WAS (versus THIS IS), and may also be passively terminated upon the expiration of a wait-for-activity timer in the ALE protocol module. Upon link termination, stations that are programmed to scan resume scanning.

Orderwire commands. Additional protocols are defined for link management functions and packet data exchange which employ *message sections* embedded within ALE transmissions (i.e., between the leading call and the THIS IS or THIS WAS termination). These orderwire messages begin with an ALE word with a command message display (CMD) preamble. The remaining bits of the ALE word specify one of several control or data transfer functions. A few of the more popular are listed below:

– The automatic message display (AMD) command is mandatory in the 2G ALE standards, and provides a non-ARQ messaging capability that uses the 2G ALE waveform to convey short messages (up to 90 characters).

– The link quality analysis (LQA) command, also mandatory, is used to report measured link quality among ALE controllers so that both ends of a link are aware of the bidirectional propagation characteristics.

– Data test message (DTM) and data block message (DBM) are optional message transfer modes that provide ARQ using the ALE modem.

Quick call ALE

A recent development in 2G ALE, called alternative quick call ALE, retains much of the flexibility of the original 2G ALE while improving calling latency. Addresses are always 6 characters in length, and are sent in compressed form in two ALE words. The bits made available by this compression are used to embed selected orderwire functions into the handshake.

7.2.2.2 Third-generation ALE

Third-generation ALE (3G-ALE) is designed to establish quickly and efficiently one-to-one and one-to-many (both broadcast and multicast) links. It supports trunked-mode operation (separate calling and traffic channels) as well as sharing any subset of the frequency pool between calling and traffic. It uses a specialized carrier-sense-multiple-access (CSMA) scheme for calling channel access control, and regularly monitors traffic channels to avoid interference.

Scanning. As in second-generation ALE, 3G-ALE receivers scan an assigned list of *calling channels*, listening for 2G or 3G calls. However, 2G-ALE is an asynchronous system in the sense that a calling station makes no assumption about when a destination station will be listening to any particular channel. 3G-ALE includes a similar asynchronous mode, but it achieves its highest performance under synchronous operation.

When operating in synchronous mode, all scanning receivers in a 3G-ALE network change frequency at the same time (to within a relatively small timing uncertainty). It is not necessary that all stations monitor the same calling channel at the same time, however. By assigning groups of network members to monitor different channels in each scanning dwell, calls directed to network member stations will be distributed in time and/or frequency, which greatly reduces the probability of collisions among 3G-ALE calls. This is especially important under high-traffic conditions. The set of stations that monitor the same channels at the same time is called a *dwell group*.

Calling channel management. Assignment of channels to 3G-ALE scan lists may be static, but may also be managed dynamically via the network management protocol (HNMP or SNMP). This provides a direct means for propagation prediction programs or external sounders to optimize scan lists "on the fly".

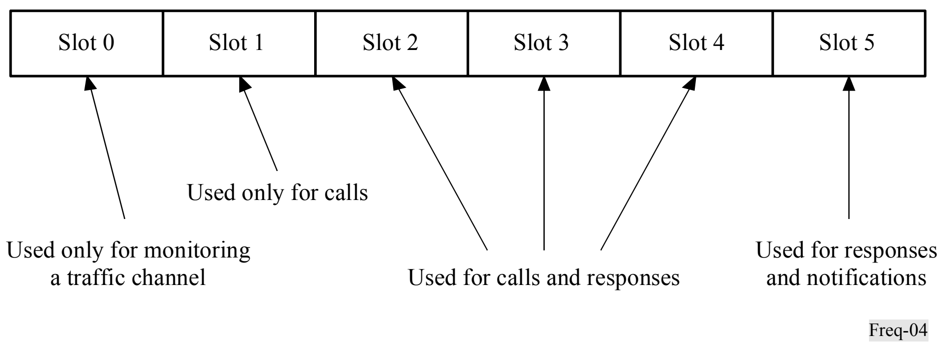
Channels will usually be assigned to scanning sequence in non-monotonic frequency order. By alternating among frequency bands in adjacent dwells (to the extent feasible for the receiving equipment) we increase the probability of linking success in the second dwell when the first frequency tried did not propagate, and so on.

Addressing. One of the functions of the subnetwork layer is translation of upper-layer addresses (e.g., IP addresses) into whatever peculiar addressing scheme the local subnet uses. The addresses used in 3G-ALE protocol data units (PDUs) are 11-bit binary numbers. In a network operating in synchronous mode, these addresses are partitioned into a 5-bit dwell group number and a 6-bit member number within that dwell group. Up to 32 dwell groups of up to 60 members each are supported (1 920 stations per net). Four additional unassignable addresses in each group (1111xx) are available for temporary use by stations calling into the network.

When it is desired to be able to reach all network members with a single call, and traffic on the network is expected to be light, up to 60 network member stations may be assigned to the same dwell group. However, this arrangement does not take full advantage of the 3G calling channel congestion avoidance techniques. To support heavier call volume than the single group scheme will support, the network members should be distributed into multiple dwell groups. This results in spreading simultaneous calls more evenly over the available frequencies.

Synchronous dwell structure. The nominal duration of each synchronous dwell is 5.4 s. The timing structure within each synchronous dwell time is as follows (see Fig. 4).

FIGURE 4



Tune time. A buffer period, generically denoted "tune time", is placed at the beginning of each dwell period. During this time, synthesizers are retuned to the new receiving frequency, couplers are tuned as necessary, and so on.

Listen time. Following the buffer period, every receiver samples a traffic frequency in the vicinity of the new calling channel, attempting to detect traffic. This "listen time" occupies the remainder of Slot 0, which has a duration of 900 ms. It immediately follows the buffer period because the radio will then be tuned to a nearby frequency, and precedes the calling slots so that stations have recent traffic channel status for use during a handshake.

Calling slots. The remainder of the dwell time is divided into 5 equal-length slots. These slots are used for the synchronous exchange of PDUs on calling channels. 900 ms per slot allows for a 613 ms PDU (including 106.7 ms for AGC settling), 87 ms of propagation, and 200 ms for synchronization uncertainty of ±100 ms.

Synchronous calling overview. The 3G-ALE synchronous calling protocol seeks to find suitable channel(s) for traffic and transition to them as quickly as possible. This minimizes occupancy of the calling channels, which is important in any CSMA system. 3G-ALE calls indicate the type of traffic to be carried (in general terms); the first traffic channel(s) that will support this grade of service will be used. The system normally does not spend time seeking the *best* channels for traffic.

When a *calling* station is directed to establish a link to a prospective *responding* station, the calling station will compute the frequency to be scanned by the responding station during the next dwell and randomly (though not uniformly) select a calling slot within that dwell time. During the listen time of that dwell, the calling station listens to a nearby traffic channel that has recently been free of traffic to evaluate its current occupancy. (A station with multiple receivers listens to multiple traffic channels during the listen time.) If not calling in Slot 1, the calling station listens on the calling channel for other calls during the slots that precede its call. If it detects a handshake, it will defer its call. If no other handshake is detected that will extend into its chosen slot, the calling station sends a Call PDU (described later) in that slot and listens for a response in the next slot.

When a station receives a Call PDU addressed to it, it responds in the next slot with a Handshake PDU. The Handshake PDU may designate a good traffic channel for transmissions to that responding station. If it does, the calling station will tune to that traffic channel and send a Handshake PDU that either confirms the usability of that traffic channel(s) or designates an alternate traffic channel. When the stations have agreed on a simplex or duplex traffic link, the calling station commences the traffic described in the call.

If the call does not result in a link, the caller will proceed to the next calling channel in the responding station's scan list during the next dwell. The calling station will again select a slot and start the handshake in this new dwell by sending a Call PDU. If the calling station does not succeed in establishing a link after calling on all calling channels, it will normally abort the linking attempt to avoid further channel occupancy.

Listen-before-transmit. Every calling station that will send a PDU during a dwell must listen on its intended calling channel during the slots that precede its transmission (except Slot 1). If it detects a handshake, it will defer its call until an available slot or until the next dwell. Thus, early slots in a dwell may preempt later slots.

Prioritized slot selection. The probability of selecting a slot is randomized over all usable slots, but the slot selection probabilities for higher-priority calls are skewed toward the early slots while low-priority calls are skewed toward the later slots. Such a scheme will operate reasonably well in all situations, whereas a hard partitioning of early slots for high and late slots for low priorities would exhibit inordinate congestion in crisis and/or routine times. Any number of priority levels can be accommodated in this way. An example set of probabilities is shown below:

	Probability of Calling in Slot			
Traffic Priority	1	2	3	4
Highest	50%	30%	15%	5%
High	30%	45%	15%	10%
Routine	10%	15%	45%	30%
Low	5%	15%	30%	50%

Third-generation ALE PDUs

The PDUs used in one-to-one calling are the Call and Handshake PDUs, as noted above. These two key PDUs are discussed below. Other PDUs are discussed later, with their respective protocols.

Call PDU

The Call PDU needs to convey sufficient information to the responder so that that station will know whether it wants to respond, and what to listen for during the traffic channel check. The Call PDU must therefore report:

– the calling station identification;

– the priority of the incoming call;

– what resources will be needed if the call is accepted;

– what traffic channel quality is required.

The Call Type field in the Call PDU specifies the type of traffic and whether the calling station or the called station will send the second (Handshake) PDU. The full called station address is not needed in the Call PDU, because the called station group number is implicit in the choice of the channel that carries the call.

Handshake PDU

The Handshake PDU is used by both calling and responding stations. It is sent only after a Call PDU has established the identities of both stations in one-to-one link establishment, as well as the key characteristics of the traffic that will use the link. The commands carried in Handshake PDUs include:

– "Continue Handshake" (link establishment is deferred until a suitable channel is found);

– "Commence Traffic Setup" (link establishment is complete, and data traffic will now be set up);

– "Voice Traffic" (link establishment is complete, and voice traffic will now begin).

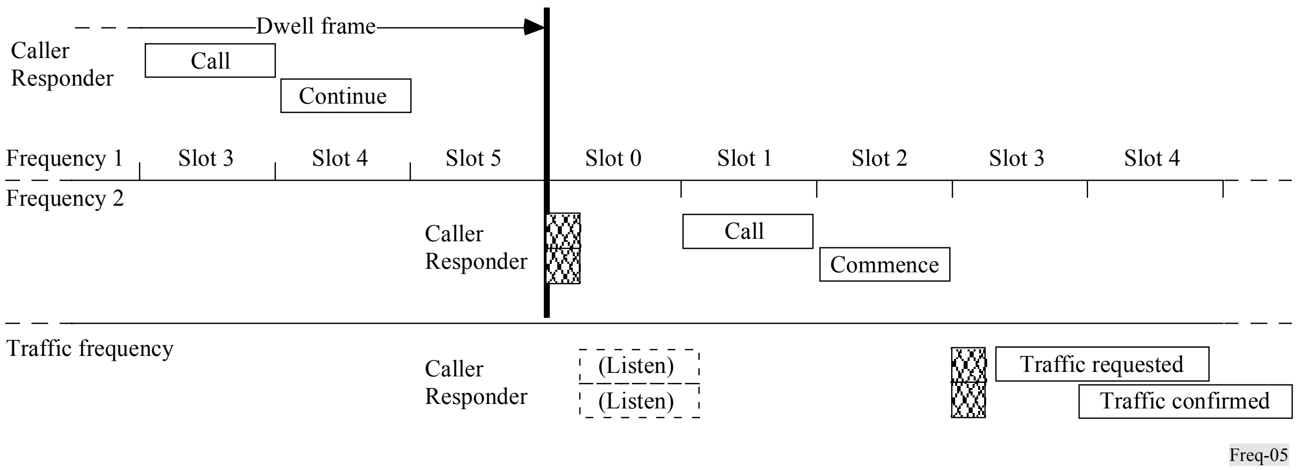
Point-to-point link establishment

The point-to-point linking protocol establishes communications on a frequency or pair of frequencies relatively quickly (i.e., within a few seconds), and minimizes channel occupancy during this link establishment process. It will conclude the link establishment process as soon as suitable frequencies have been identified, and does not attempt to find the *best* available frequencies.

A station will normally commence the link establishment protocol immediately upon receiving a request to establish a link with another station, although it may defer the start of calling until the called station will be listening on a channel believed to be propagating. The latter option serves to reduce channel occupancy, and does not preclude calling on the bypassed channels later if the link cannot be established on the favoured channel.

A 3G ALE call is illustrated in Fig. 5. The first call occurs in Slot 3. The responder receives the call, but has not identified a traffic channel suitable for the requested traffic, and therefore sends a Handshake PDU containing a Continue Handshake command.

FIGURE 5



In the next dwell, both stations tune during Slot 0, then listen for occupancy on a nearby traffic frequency. The caller selects Slot 1 this time, and the responder has determined that an associated traffic channel was available. When the Call PDU is received by the responder, the measured channel quality is sufficient for the offered traffic, and the responder sends an Handshake PDU containing a Commence Traffic Setup command that indicates the traffic channel to be used. Both stations tune to that channel in the following slot (denoted by cross-hatched areas), and the caller initiates the traffic setup protocol.

One-to-many calling

One-to-many calling (point-to-multipoint) includes both broadcast and multicast protocols. Broadcast calls are intended for all stations in a network that receive the call, while multicasts are intended only for pre-arranged subsets of the network members.

Multicast calls. A multicast call is sent using the Call PDU, as in point-to-point calling, but the call type is set to Multicast Circuit. The Handshake PDU is sent by the calling station, and will normally contain a Commence Traffic command and the channel to be used for traffic .

Broadcast calls. A Broadcast PDU directs every station that receives it to a particular traffic channel, where another protocol (possibly voice) will be used. A station may send a Broadcast PDU in every slot in a dwell (except slot 0), and it can change channels every slot to reach a new dwell group. The calling station need not check occupancy on each new calling channel before transmitting.

The Broadcast PDU contains a countdown field. At the beginning of slot 1 in the dwell after the caller sent Broadcast PDU(s) with the countdown field set to 0, the caller commences voice traffic or data traffic setup on the indicated channel.

Stations that receive a Broadcast PDU and tune to the indicated traffic channel return to scan if traffic setup does not begin within the traffic wait timeout period after the announced starting time of the broadcast. Operators can disable execution of the broadcast protocol.

Notifications. The Notification PDU carries the complete address of the sending station. The 3-bit Station Status field carries the current sending station status. This PDU is used as follows:

When stations track the departures of other stations to traffic channels, a station that completes a traffic phase and returns to scan should send a Nominal status notification on one or more channels that are believed to propagate to other network members.

Stations that are commencing radio silence (or EMCON), or that are voluntarily departing from the network, may notify other stations of this status change to reduce the effects of upper-layer routing protocols having to discover this change in status.

Notification PDUs are sent the final slot of a dwell.

Sounding. Sounding will normally be unnecessary in 3G-ALE systems. Knowledge of propagating channels can be used, as described earlier, to delay the start of calling and thereby reduce calling channel occupancy. However, with synchronous scanning, knowledge of propagating channels will have only slight effect on linking latency unless non-propagating channels are removed from the scan list (see calling channel management, above). In asynchronous 3G-ALE networks, sounding may be desired if propagation data is unobtainable by other means. In this case, periodic transmissions of a repeated Notification PDU indicating Nominal station status will serve the purpose.

Asynchronous operation. A special Scanning Call PDU is sent repeatedly to capture scanning receivers when a network is operating in asynchronous mode. As in the 2G system, the scanning call carries just the called station address. The identity of the calling station is unknown until the end of the call, which will be the normal Call PDU in this case.

7.3 ALM

After ALE has completed its work, a traffic setup protocol is normally employed to manage the transition to traffic on a link. This may include routing audio to specific channels at each station, setting initial modem rates and modulations, establishing data routing within the station, and so on.

When data traffic is passed over the link, an ARQ protocol is usually employed to correct errors. The ARQ protocol is thus acutely aware of degradation of channel conditions that may mandate a change in frequency. In the case of analog voice operation, the operators may be relied upon to request link maintenance when the channel becomes unacceptable.

Modem and data link characteristics are normally managed by the ARQ protocol. Power control is usually either absent in a system, or is managed by a dedicated process. This leaves changing the traffic frequency as the principal tool for an ALM mechanism.

7.3.1 ALM protocol requirements

An ALM action request requires the that following functions be satisfied:

– a suitable alternate frequency be discovered;

– an unambiguous means is provided to coordinate both nodes changing to the new frequency:

– interference to other nodes is minimized.

7.3.2 ALM protocol

The ALM protocol in ARCS (3G ALE) is used by the connection management (CM) process to maintain links established using 3G ALE. All stations support the mandatory function:

– forced return to link setup using the LM_Relink PDU.

The following optional functions are also defined for ARCS:

– coordinated departure to suitable alternate frequencies as required by changing propagation and interference conditions (logical link is not dropped);

– probing of candidate alternative frequencies during traffic;

– negotiation of frequencies for operating modes other than simplex (i.e., half- or full-duplex);

– renegotiation of waveform, data rate, and interleaver.

The protocol employs the robust BW1 waveform to convey its 48-bit PDUs.

A Countdown field in the LM PDUs contains the number of times the PDU will be resent before the indicated change is to take effect. The sequence of LM PDUs is sent contiguously, ending with the PDU that contains a Countdown value of 0. The number of repetitions of the LM PDU is chosen to reduce to an acceptable level the probability that it will be missed by the other station(s).

Relink. Either station in a point-to-multipoint link, or the calling station in a point-to-multipoint link, may initiate a return to link setup by sending LM_Relink PDU(s). All stations in the logical link will immediately return to scan. The station that originally set up the logical link should initiate ALE to re-establish it. No response is made to this PDU; it is simply passed to the Connection Manager process at each receiving station.

Duplex link negotiation. At any time after a link is established on a traffic channel, including the time usually used for traffic setup, a station may send a sequence of LM_Duplex PDUs that indicates a channel on which other station(s) are requested to send future transmissions to the requesting station. All of the LM_Duplex PDUs are identical except for the Countdown field. The sending station will continue to transmit on its current traffic channel after the change.

Coordinated departure to new traffic channels. Coordinated departure to new traffic channel(s) employs the LM_Simplex and/or LM_Duplex PDUs as appropriate, to indicate a new frequency on which it will *listen* for traffic.

– LM_Duplex PDU(s) indicate that the sending station will continue to *send* on its current transmit frequency until another frequency is negotiated.

– LM_Simplex PDU(s) indicate that the sending station will change its transmit frequency as well as its receive frequency to that indicated in the LM_Simplex PDU.

If the sending station detects protocol failure via timeout, or other means, after changing its receive frequency, it will execute the Relink protocol, drop its logical link, and recommence link setup.

Negotiation of waveform. A Waveform Change PDU is used to negotiate waveform(s) to be employed on a logical link, using waveform codes identical to those used in traffic setup.

ANNEX 1

An example of a managed HF network

1 Introduction

As an example of an adaptive system, the KV90 system for managed HF networks incorporates recent major advances in the field of automatic and adaptive radiocommunication systems. There is also a number of other modern available systems. Advances in such diverse areas as frequency management, ALE, modem technology, networking protocols and message handling systems have led to the possibility of separating the user from the radio. They have led to the concept of HF radio as a transparent subnetwork within a wider communications infrastructure.

The system integrates the following functions (each a system in its own right):

– automated frequency management (AFM),

– automatic channel selection (ACS),

– automatic link establishment (ALE),

– adaptive link maintenance (ALM),

– automatic traffic management and message handling,

– network management.

In addition to integrating these major elements, the system provides several modes that allow interoperability with existing systems, equipments, protocols and waveforms. The system is designed to maximize performance where the other participating units can attain such performance while being fully capable of working to lower performance specifications where necessary. The system is extremely flexible in its ability to readily adapt to different configurations, different operating modes and different user needs. It supports, for example, installation on:

– distributed fixed networks with remotely located control sites, receive sites and transmit sites and supporting a range of interconnection types (data networks, telephone networks, leased lines and private branch exchanges);

– small ship platforms, including the ability to distribute the control and radio equipment around the platform as necessary for ease of installation and operation;

– coastal radio stations;

– transportable shelters.

2 System concepts

The system is a flexible, fully-meshed, managed HF network capable of supporting a wide range of operational scenarios and diverse user requirements. It is designed to be suitable for a range of fixed and mobile applications requiring reliable and easy-to-use HF communications. The system is particularly suitable to applications where trained HF radio operators and frequency planners are not available or for systems which require unmanned operation.

Supported traffic types range from telephone voice calls to store-and-forward text formats; from Group-3 facsimile to Morse; and from X.400 messaging to real-time bit transparent data. The system is highly responsive for those services, such as real-time data or voice, that require immediate connectivity and rapid message transfer. For non real-time services the system adjusts to optimize other quality of service parameters.

One of the most important features of the system is the ability to handle high levels of traffic by using protocols and techniques that reduce *network* congestion and blocking when heavily loaded.

Survivability in the event of loss or failure of one or more sites is assured by basing the design on a distributed architecture. Communications are not dependent on the use of base stations, master sites or sounding transmissions, but can be conducted between any two or more stations with shared net data.

Open interfaces and a modular architecture allow for the use of existing in-service radio equipment. The flexible nature of the system allows it to adjust its performance in accordance with the characteristics of the radio equipment available, both locally and remotely. Asset management facilities allow resources, particularly radio equipment, to be pooled and dynamically allocated to traffic as required. This ensures efficient resource utilization and automatically copes with the failure or loss of individual radio stations.

Above all, the system is intended to be easy to use. The users of the system can send and receive traffic without any knowledge of HF radio using their standard telephones, message terminals or fax machines in the normal way.

3 System architecture

The network is made up of a number of HF nodes. Each of these nodes may have one or more radio stations. Distributed nodes can be readily reconfigured to use different transmit or receive sites, to connect to different remote control sites and to increase or decrease the number of radio stations deployed.

A simplified representation of a four-station distributed node is shown in Fig. 6. In the example, subscribers, transmitters, receivers and control equipments are located on different sites. The various equipment sets at the node can be connected via a dial up switched telephone network, a private branch exchange, a data network or leased lines.

All or some of the equipment at a node can be co-located and configured for small platforms, such as ships or vehicles. The arrangement for a two station mobile platform is shown in Fig. 7.

FIGURE 6

Distributed node architecture

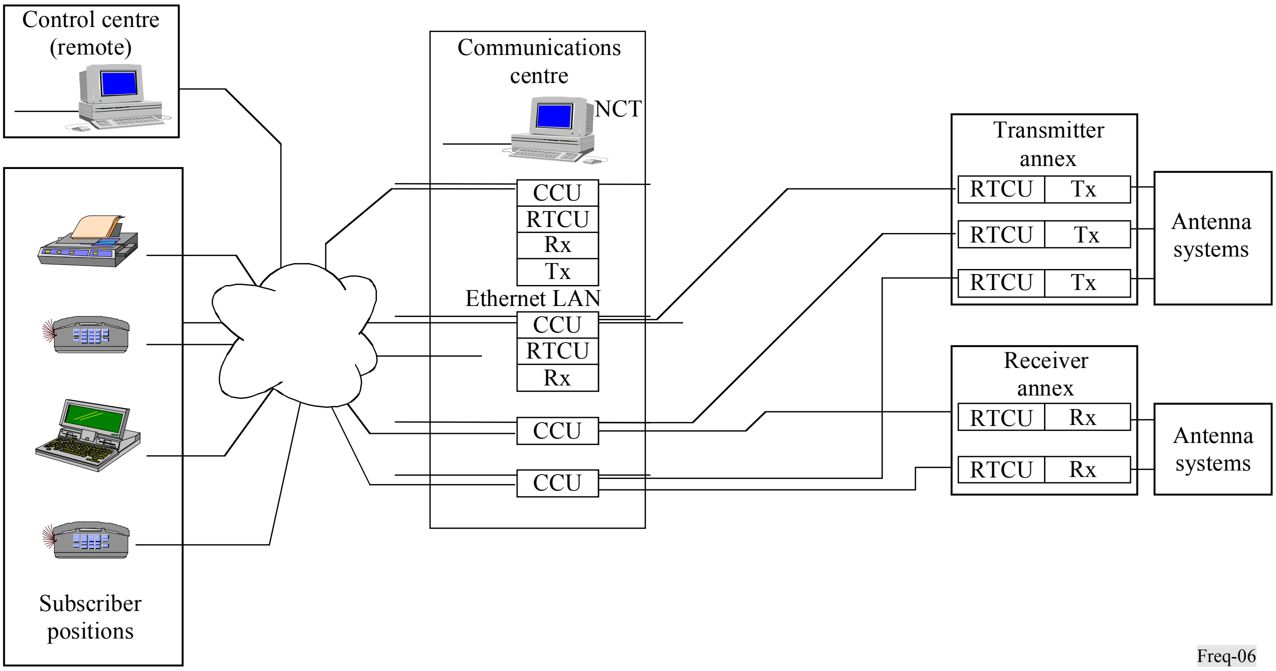
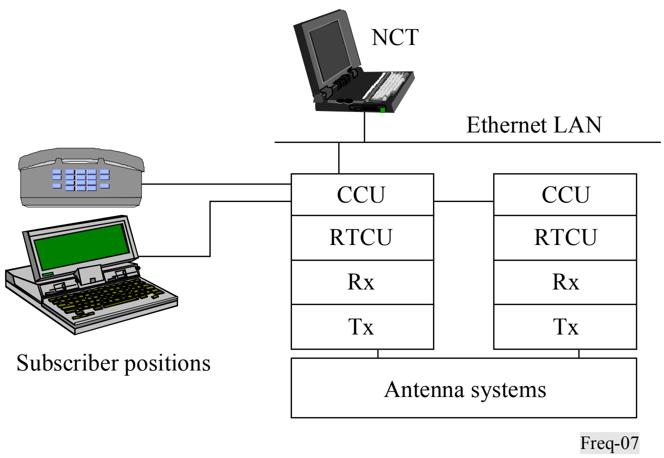


FIGURE 7

Mobile platform



The system is designed to allow unmanned operation at the control sites – once configured, the system can be used without any further operator intervention.

3.1 Node control terminal (NCT)

The NCT provides facilities for a station operator to configure and manage the node. It handles various node functions, including propagation prediction, automatic frequency management, call logging and fault reporting. The NCT can be operated in a dual-mode standby arrangement for fault tolerance.

3.2 Central control unit (CCU)

Each radio station has a CCU. The CCU is responsible for message handling and routing, queueing and traffic prioritization, ACS, ALE and ALM. The CCUs at a node exchange information over the local area network to allow dynamic allocation of resources to incoming traffic; to share link quality information for automatic channel selection and to distribute time of day information.

3.3 Receiver/transmitter control unit (RTCU)

Each receiver, transmitter or transceiver has an associated RTCU. It manages the radio equipment interfaces, antenna system control interfaces, external alarm interfaces, external modem interfaces, and various other general purpose interfaces. The RTCU deals with real-time processing of calls including FEC, encryption, contention avoidance, signal quality analysis, channel monitoring, and modulation and demodulation of data for transmission over the HF channel. The extensive use of DSP and microprocessor technology result in the ability to add new functionality or waveforms without changing the underlying hardware.

4 Key areas of system design

4.1 Control system

The control system is based on the use of the simple network management protocol (SNMP). The elements within the system are defined in a database (management information base (MIB)) as a series of managed objects. Associated with each Managed Object (e.g. receiver) is a set of management related information that defines the attributes for that object (e.g. frequency).

SNMP operates over the Ethernet LAN using the user datagram protocol. This open approach to the control interface enables higher order systems to access and control the node from remote locations, thereby allowing the control element of the system to be integrated into a wider control system. The use of SNMP provides the opportunity to create sophisticated fault management and performance management capabilities.

4.2 Frequency management

The frequency management function provides an automatic means of ensuring that each net within the network operates with the same set of frequencies at any given moment. The frequency management function first generates an active frequency range (AFR) using skywave, groundwave and sporadic-E propagation models and a noise prediction model. The AFR is calculated for various times of day and holds the predicted path characteristics for each mode of propagation.

Based on operational requirements specified in the net data, the system proceeds to calculate an active frequency pool (AFP) from the AFR. Any preferred frequencies or “non-predictable” bands can be specified in the net data. Similarly, the proportion of groundwave, skywave and sporadic-E can be forced (e.g. for maritime communications the proportion of groundwave can be increased).

The duration and size of the AFP is also defined in the net data in accordance with operational requirements. Under hostile conditions, the AFP can be changed frequently and may contain a large number of frequencies. It is generated deterministically and identically at all nodes with the same net data. This ensures that frequency allocations are consistent across a net.

In addition to generating the AFP and *predicting* the link quality for these frequencies, the frequency management function builds up a database of *measured* link quality for each frequency and link. This real-time measurement information is shared between stations at a node, retained and aged over time.

4.3 Link management

It is an observed fact that an experienced HF operator, using unsophisticated facilities, can often pass traffic over circuits which, judged by all objective criteria of path loss, noise level and co-channel interference, are statistically unusable.

Such skills are becoming increasingly rare and, in any case, the resulting message throughput rate is often too low for many operational requirements. Attention has therefore focused on systems which can attempt to replicate the skills of the traditional radio operator and make it as easy as possible for users unfamiliar with the mysteries of propagation to make full use of the HF band.

To achieve this aim, an expert system is required. An important example of this can be found in MIL-STD-188-141A, which analyses some of the "rules" that tend to be followed by radio operators in practice. These include always listening for ALE signals, tendency not to interfere with active ALE channels, exchange of link quality information, and minimizing the amount of time on channel.

These rules are a good foundation for more sophisticated managed HF networks. Further to this, such systems can replicate the learning process of the radio operator by recording various types of information over time (e.g. link quality, equipment status, and so on) and using this information as an input to future decision making.

The link management function includes the automation of the link establishment, link maintenance and channel selection processes. The channel selection process uses, as its primary input, information from the link quality database to select an appropriate channel for a particular call.

The key objectives of the link establishment process are to establish a link between two or more stations and achieve the following:

– minimize the probability of intercept;

– provide a high probability of first shot success;

– provide the link quickly;

– minimize on-air time;

– minimize spectral occupancy;

– establish the link robustly.

Most link establishment systems use one of two calling mechanisms, often referred to as asynchronous calling and synchronous calling.

The most widespread asynchronous ALE system is MIL-STD-188-141A (FED-STD-1045). Asynchronous systems are suitable for small networks or where there is little traffic loading so that only a few channels are used. This network is capable of operating in an asynchronous MIL-STD-188-141A mode, mainly for reasons of interoperability.

For higher performance, the primary link establishment mechanism used in the system is synchronous. This uses a time division multiple access (TDMA) mechanism for link establishment. A synchronous system is inherently less likely to cause congestion and blocking in a busy network since the on-air time is significantly reduced for each call. Link establishment time is faster and scan rates can be relaxed. The reduced scan rate results in less stress on the radio equipment and achieves a more robust linking mechanism and an improved probability of link establishment. It has been shown that performance in difficult conditions is superior to a comparable asynchronous system. This is to be expected given that the on-air time is reduced with a corresponding improvement in the probability of intercept. Furthermore, spectral occupancy is reduced which can only lead to benefits for other users of the HF band.

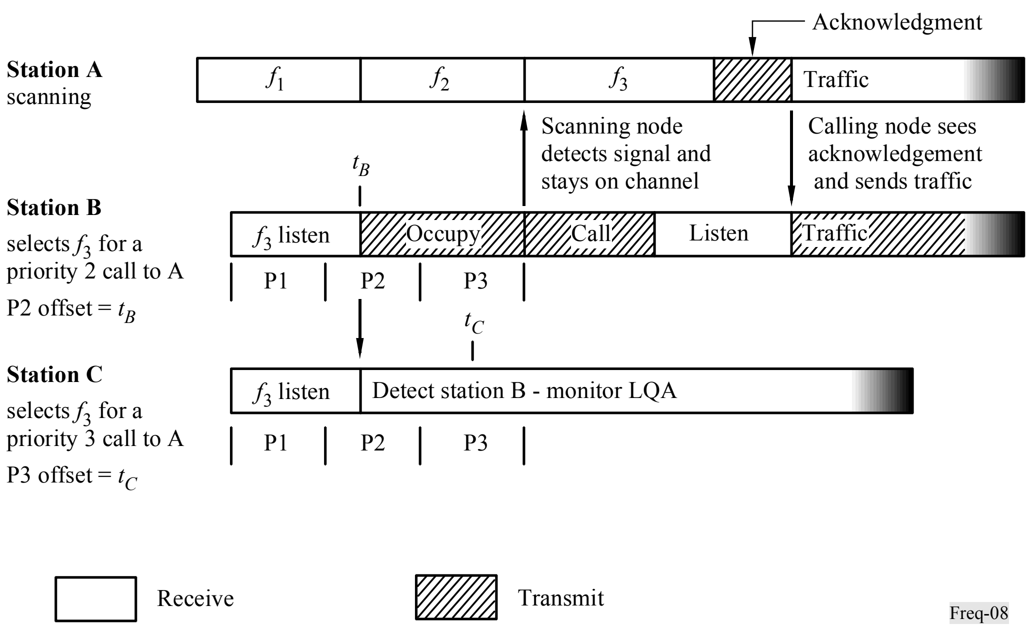
4.3.1 Contention avoidance

The synchronous calling method, almost by definition, results in an increased likelihood that users in the same net may call on the same channel at the same time. This leads to an increased risk of collisions between uncoordinated users competing for use of the same frequency slot.

Figure 8 shows the contention avoidance mechanism. A carrier sense protocol (listen before transmit) is used with a two tier approach based on priority time slots and random access.

FIGURE 8

Synchronous calling scheme



4.3.2 Late net entry

Active late net entry (ALNE) is initiated either by the node operator or following receipt of subscriber traffic at an unsynchronized station. Passive late net entry (PLNE) is used when the unsynchronized station is in radio silence or has not been triggered to attempt ALNE. PLNE involves listening for traffic within the net and decoding time information exchanges between those stations. The time required to achieve PLNE is, therefore, dependent upon the amount of traffic in the net.

4.3.3 Link maintenance

Once a link has been established, it must be maintained. There are various steps that can be taken to adaptively maintain a HF link. These can include repeated transmissions, increased power level, selection of alternative antennas or modem waveforms, modifications to the error coding scheme and the use of null steering antennas.

Whichever of the previous actions are taken, normally the last resort is to change the frequency of operation. The time taken to change frequency and pass the remaining portion of the message is compared with the time calculated to continue on the same channel. This leads to increasing reluctance to change channels as the message transmission nears completion.

The link management function provides an orderly call clear function using a three-way handshake (in confirmed modes) which is intended to avoid leaving either station in a hung-up condition.

4.4 Traffic management

The system provides a comprehensive traffic handling facility capable of automatically detecting traffic type (e.g. incoming facsimile, text or voice traffic), prioritizing and queueing the traffic as appropriate and routing it to the required destination. When used, the ARQ mechanism ensures that the traffic is delivered successfully, any calls that cannot be delivered give rise to a call log and the message is delivered to a local reject position and/or back to the originator.

4.5 Asset management

The system seeks to maximize utilization of the available equipment assets. It does this in a number of ways, not least by sharing traffic across available radio stations at the node. Radio equipment status and reports are reported via the built-in test function. The system seeks to optimize performance by holding a database of equipment characteristics such that it can adjust parameters according to the type of equipment it is working with. For example, if a call is made to a station with a slow antenna tuning unit, the originating station will allow a longer time period for the response from the slow station. When operating to a station with a fast tuning automatic tracking unit (ATU), the originating station takes advantage of the faster performance.

5 Conclusion

The challenges associated with automating the HF radiocommunications function are considerable. An integrated system that incorporates many of the functions traditionally performed by trained operators is described. These functions include generation of frequency assignments; real-time channel evaluation; link establishment, maintenance and disconnection; exchange of link quality information; equipment monitoring and control; resource allocation; and message handling. The system described provides a high degree of transparency to the subscriber and optimizes utilization of the scarce and valuable HF radio bandwidth.

ANNEX 2

References and list of abbreviations

1 References

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2 List of abbreviations

Chapter 1

ALE	Automatic link establishment
ARQ	Automatic repetition on request
BR	Radiocommunication Bureau (ITU)
HF	High frequencies (3-30 MHz)
HFIA	United States HF Industry Association
IFRB	International Frequency Register Board (former, ITU)
MF	Medium frequencies (300-3 000 kHz)

Chapter 2

MIFR	Master International Frequency Register (ITU)
WRC	World Radiocommunication Conference (ITU)

Chapter 3

ISO	International Organization for Standardization
OSI	Open systems interconnection reference model

Chapter 4

GRWAVE	Ground wave (software program)

Chapter 5

LUF	Lowest usable frequency
MUF	Maximum usable frequency

Chapter 6

OIS	Oblique-incidence sounder
RTCE	Real-time channel evaluation technique
VIS	Vertical-incidence sounder

Chapter 7

ACS	Automatic channel selection
AFM	Automatic frequency management
AFP	Active frequency pool
AFR	Active frequency range
ALM	Automatic link maintenance
ALNE	Active late net entry

AMD	Automatic message display
ARCS	Automatic radio control system
ATU	Automatic tracking unit
AWGN	Additive white Gaussian noise
BW	Burst waveforms
CCU	Central control unit
CM	Connection management process
CMD	Command message display
CSMA	Carrier-sense multiple access
DBM	Data block message
DTM	Data test message
FEC	Forward error correction codes
FSK	Frequency shift keying modulation
HNMT	High NMT
IP	Internet protocol
LM	Link maintenance
LQA	Link quality analysis
NCT	Node control terminal
NMT	Network management protocol
PDU	Protocol data units
PLNE	Passive late net entry
RTCU	Receiver/transmitter control unit
SNMP	Simple network management protocol
SNMT	Single NMT
SNR	Signal-to-noise ratio
TDMA	Time division multiple access
2G/3G	Second/third generation