REPORT 889-2*

REAL-TIME CHANNEL EVALUATION OF HF IONOSPHERIC RADIO CIRCUITS

(Study Programme 27B/6)

(1982-1986-1990)

Contents

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* This Report is brought to the attention of Study Groups 3 and 8.

1. Introduction

In order to take full advantage of the HF communications potential of the ionosphere and to overcome its inherent variability, frequency management should be implemented in three stages, namely long-term prediction, short-term forecasting and real-time channel evaluation (RTCE).

1.1 Long-term prediction

Long-term prediction of monthly median parameters is the traditional approach to frequency management and system design. Frequency planning predictions based on historical ionospheric data are made using methods such as described in Reports 252 and 894. Frequencies are selected which are aimed at the achievement of at least a 90 per cent reliability for communications at all times of day, during any season, and at all parts of the solar cycle. Engineering decisions such as transmitter power and suitable antennas are also made at this stage.

Optimum working frequencies (OWF) for a particular circuit are derived for each hour of the day, usually for a month at a time, based on empirically derived algorithms. Use of predictions in this manner continues to yield acceptable, though not necessarily high quality, communications for many purposes such as voice and telegraph transmissions.

Difficulties associated with long-term predictions include:

a) The optimum working frequencies may provide communications for only 90% of the days of the month.

b) The predictions do not take into account the effects of ionospheric storms and other short-term changes of the ionosphere.

c) The signal and noise estimates are not always accurate and signal-to-noise ratio is not necessarily a sufficient criterion for choosing frequencies for some types of communication.

d) Reliable long-term predictions of sporadic E are not available.

e) No account is taken of interference from other users.

f) Discrepancies between the observed values of foF2 and the values obtained from the CCIR maps (see Report 430) lead to errors in predicted propagation modes and maximum usable frequencies (MUF).

1.2 *Short-term forecasting*

The next stage of sophistication in communications planning is to specify which of the assigned frequencies are actually available at a given time, taking into account the short-term variability of the ionosphere. Techniques based on real-time observations of the sun, of the ionosphere and of frequencies actually being supported on a given circuit are described in Reports 727 and 888. Real-time monitoring of the ionosphere and forecasts on the time scale of minutes to days are possible, overcoming points a) and b) above. Short-term forecasting techniques at HF have not been fully tested due to lack of suitable solar monitoring systems. Rothmuller [1978] found in operational tests using solar data from the Solrad HI satellite, that HF outages due to propagation were reduced by 15% and that the duration of outages was reduced by 15 to 20%.

These techniques do not, however, indicate which of the assigned frequencies propagating at a given time would be the best to use for a given form of communication. Nor is the forecast frequency range completely accurate because of inevitable errors in the forecasting techniques.

1.3 Real-time channel evaluation (RTCE)

RTCE is the process of measuring appropriate parameters of a set of channels in real time and of employing the data thus obtained to describe quantitatively the states of those channels and hence their relative capabilities for passing a given class, or classes, of communication traffic.

RTCE is potentially capable of yielding high quality HF communications under even the most adverse propagation conditions. It is at this stage that all potentially useful assigned frequencies are examined in real time to see which is the best to use for the given communications purpose.

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, but rather that he, or the automatic management portions of the radio system, should have access to the values of the parameters of an appropriate real-time model which describes the path behaviour adequately. Once these have been obtained, the model can be used to adapt optimally the signal format and signal processing algorithms for the associated communications link.

RTCE can be used to overcome the problems c), d), e) and f) listed in § 1.1. RTCE systems have no need to rely on synoptic models of atmospheric and man-made noise, since the systems can measure the noise at the working frequency in real time. Alternatively, the system may measure parameters more relevant to the type of signal modulation in use. They can also take advantage of sporadic-E propagation modes which often support propagation at frequencies above the basic MUF of the F layer and offer very low error ratios. Interference is taken directly into account in RTCE systems. Because of their ability to select frequencies above the predicted basic MUF, this allows use of higher frequencies which tend to suffer from lower levels of interference.

2. Factors affecting channel quality

2.1 *Time and frequency dispersion*

In general, there are two basic sources of signal distortion associated with HF paths – time dispersion and frequency dispersion. The effects of these mechanisms are presented conveniently by the "channel propagation function", an illustrative example of which is given in Fig. 1. This is a composite function showing the dispersive effects of the path on an ideal impulse in the time-domain and a single CW tone in the frequency domain.

In the example, three distinct propagation modes are shown: these may be due to reflections from different ionospheric layers and/or multiple reflections by the same layer. In practice, often both the time dispersions and the frequency dispersions of different modes are liable to overlap, particularly when F-scatter propagation, high and low-angle rays or magnetoionic splitting is involved. Any given propagation function is a valid description of the path behaviour only for a specified RF carrier frequency and over a period in which the ionosphere remains sensibly constant. It is also a function of the combined transmitting and receiving antenna directivities and gains. In the longer term, time variations of the path parameters will cause changes in the number of modes, mode amplitudes and delays, and the shape of the distributions associated with each of the modes.

Most path models employed in RTCE systems are related to the propagation function and tend to fall into either a time or frequency domain category, depending on the nature of the signals to be transmitted over the corresponding communications link.

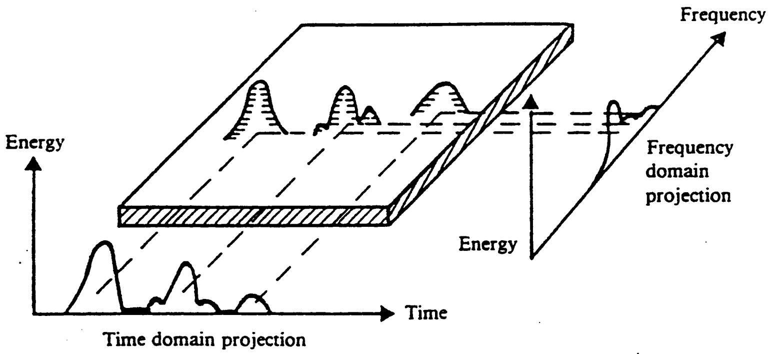

FIGURE 1 – *Typical channel propagation function* [*Darnell, 1975*]

2.1.1 *Time dispersion*

The time-domain projection of the propagation function yields mode amplitude and relative delays of the multi-mode propagation. Such propagation has been widely recognised as a major source of error in phase-shift-keyed (PSK) digital data transmissions, usually evident as an irreducible error-ratio, not improved by increasing signal-to-noise ratio. This effect, called intersymbol interference, arises when the spread in propagation delays becomes comparable with the duration of the digital-data frame period.

2.1.2 *Frequency dispersion*

The consequences of frequency dispersion are less widely recognized. It almost invariably accompanies time dispersion but the converse is not necessarily true – frequency dispersion can exist in the absence of significant time dispersion [Clarke and Tibble, 1978]. Frequency dispersion arises because the components of an ionospheric skywave pass through different regions of the ionosphere and therefore suffer different Doppler frequency shifts. The resultant wavefield fades at a rate dependent on the Doppler frequency spread. An analysis of a 75-baud parallel tone DPSK transmission between Townsville and Sydney demonstrated a pronounced positive correlation between the bit error ratio and the Doppler frequency spread of a CW tone within the 3 kHz passband of the data signal [Clarke, 1979].

2.2 External noise and interference

In addition to the influence of ionospheric variability and the channel propagation function on HF sky-wave channel quality, external noise and interference from other users of the radio spectrum are also important considerations. Interference is the more troublesome to the normal operations of a properly planned radio system. The characteristics of interfering signals depend on the services which they provide. Strong broadcast signals are relatively predictable in their behaviour while the multitude of short-lived narrow-band data transmissions are, individually, unpredictable. One of the major roles of RTCE techniques in modern radio systems is to adapt the signal transmission and processing algorithms so that interference is minimized while the required ionospheric channel is maintained.

Quantitative information on the character of HF interference at locations in the United Kingdom is available [Gott et al., 1982; Gibson and Arnett, 1988].

2.3 *Parameters indicating channel quality*

There are many different forms of RTCE systems and many different measurable parameters on which a particular RTCE scheme can be based. Examples of time and frequency dependent parameters which might be measured at the RTCE receiver are:

– ionospheric mode of propagation;
– spread in signal propagation time;
– signal amplitude;

- background noise intensity;
- background interference intensity;
- signal-to-noise ratio;
- signal phase stability;
- Doppler frequency spread;
- signal pulse shape;
- quality of the received signal, e.g. speech intelligibility, bit error ratio.

These measures and some other potentially useful channel assessment techniques are addressed in the following sections.

3. Methods of measuring channel quality

Several different approaches to the problem of channel assessment have been made. Some of the earliest methods involved swept-frequency ionospheric sounders and these techniques are still widely used. More recently RTCE systems have been fully integrated with the traffic carrying radio system so that more detailed appraisals for specific assigned frequencies are possible. Consequently, the role of the radio operator is changing and for a fully adaptive radio system, he no longer needs to concern himself with frequency management matters.

3.1 Swept-frequency ionospheric sounding

3.1.1 *Oblique-incidence* sounding

A widely used form of RTCE is oblique-incidence sounding of which several forms are available. The simplest type is a pulse sounder employing time and frequency synchronized transmission and reception [Darnell, 1978] (Report 249). Another form of oblique incidence ionosonde is the "chirp" or Frequency Modulated Continuous Wave (FMCW) sounder [Barry and Fenwick, 1975]. An oblique-incidence ionogram, shown in Fig. 2, can be used to avoid interference bands and to select frequency ranges where single-mode propagation exists. Alternatively, if no regions of single-mode propagation exist, a figure of merit for a particular channel might be derived by considering the relative powers of the individual propagation modes at that frequency. This method of channel evaluation is based on the premise that single-moded propagation will yield the best communications channel since this limits the total time dispersion for the path and thus limits intersymbol interference [Darnell, 1978].

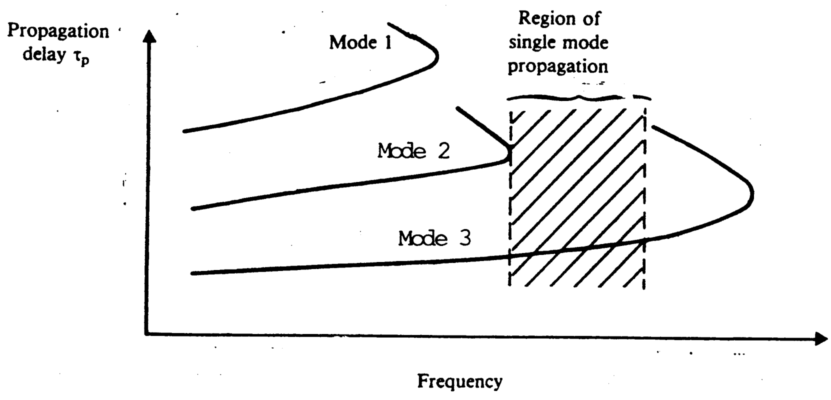

FIGURE 2 – *Idealized oblique – incidence ionogram showing the frequency range over which only one ray path is supported [Darnell, 1978]*

In Japan, a network of five ionosondes operates with coordinated starting times to provide real-time channel evaluation for common users at remote sites by means of synchronized reception [Kuriki and Takeuchi, 1986]. This system is similar to the United States' concept of a Common User Radio Transmission System (CURTS) [Probst, 1968].

From oblique incidence ionograms it is possible to identify propagation modes, to measure the maximum observed frequency (MOF) and to determine the range of frequencies over which only one propagation mode is supported. Antenna and frequency channels appropriate to the prevailing conditions can then be selected [Barry and Fenwick, 1975]. Signal-to-noise data may also be used if they are available.

Transmissions of Kineplex data between Townsville and Sydney revealed that the number of propagation modes present at a given frequency is not a good indicator of associated circuit quality [Clarke, 1979]. The best reception was obtained during summer months, when propagation was via the sporadic-E layer at frequencies above the F-layer MOF. During winter and equinoctial months, when there was usually no sporadic E, and propagation was via the F layer, no overall correlation was found between data quality and the number of modes, although on individual occasions the error-ratio was reduced by two orders of magnitude by changing from multi-moded to single-mode F-layer propagation. Data errors tended to occur in bursts which coincided with amplitude fades greater than about 20 dB [Clarke, 1979]. However this may not apply to modern systems given adequate bit interleaving and receiver dynamic range.

The lack of overall correlation between data quality and number of modes presumably resulted from the fact that even when several modes were present, the lowest order was typically at least 10 dB stronger than the other modes at the same frequency. Propagation is thus effectively single-moded even though the ionogram shows the presence of several modes.

Even when an ionogram indicates single-moded F-layer propagation, the propagation in fact may comprise multipath components which are not resolvable on the ionogram. These may be magnetoionic components, the result of ionospheric curvature caused by travelling ionospheric disturbances or still smaller scale irregularities such as spread F [Clarke and Tibble, 1978]. These effects, particularly spread F, can cause severe amplitude fading and a consequent reduction in data quality even though the oblique incidence ionogram indicates that propagation is single-moded [Clarke, 1979].

Under certain circumstances it may be possible for some propagation parameters (e.g., fading) over a point-to-point circuit to be non-reciprocal [Jull and Pettersen, 1964; Budden and Jull, 1964].

One problem associated with the use of an oblique incidence ionosonde for RTCE is that interpretation of ionograms is required to make maximum use of the instrument, whereas the ideal RTCE system would be automatic. Work is in progress to develop efficient algorithms to allow automatic interpretation of ionograms but this is a major task involving complex pattern recognition techniques. Another potential difficulty with oblique incidence sounding is any difference which might exist between the sounding system sensitivity and antenna performance and those of the main communication system.

An important consideration when oblique incidence soundings are used to infer conditions on a different path or at a different time is the spatial and temporal correlation of the chosen RTCE parameter. Goodman and Daehler [1988] discuss these factors for measurements of the maximum observed frequency.

3.1.2 *Vertical incidence sounding*

A vertical incidence sounder emits a sounding signal which can take any of the forms previously described for oblique sounding. The reflected signals are processed by a synchronized sounder receiver to produce a vertical incidence ionogram. One of the more important developments of recent years is the digital ionosonde [Bibl and Reinisch, 1978; Wright and Pitteway, 1979] and the automated scaling of ionograms that it affords [Reinisch and Huang, 1982].

The vertical incidence data can be used directly in propagation model formulation for short distance sky-wave paths, e.g., out to about 300 km. For longer paths, geometrical factors can be applied to the ionogram data to calculate oblique incidence properties. The value of such calculations depends on how closely the ionosphere at the circuit reflection points match the ionosphere at the sounder station. The extent to which an observation at one point can be used to infer ionospheric conditions at another has been discussed by Rush [1976], McNamara and Wilkinson [1986] and by Milsom [1986].

3.1.3 *Backscatter sounding*

Backscatter sounding can be carried out at a single site, with the transmitted energy radiated obliquely. The received signal is due to energy which has propagated via the ionosphere and has been scattered either from the ground or directly from the ionosphere back to the sounder following a similar ionospheric path.

Attenuation in such a system is large because of the very high losses at the ground and much higher transmitter powers are required than for vertical or oblique incidence ionosondes. The definition in the backscatter ionogram is also inferior to that in oblique or vertical incidence ionograms. However, backscatter sounding does give a good indicator of usable frequency ranges for single-hop paths. The multi-hop case tends to produce excessive path losses. The forms of modulation used for oblique incidence sounders can be employed in backscatter systems. Backscatter sounding has been reviewed by Croft [1972] and is also covered briefly in Report 726. It can be performed either at a fixed frequency or swept frequencies and is usually performed with highly directional antenna arrays both to improve received signal/noise ratios and to limit surveillance areas.

Backscatter sounding has been used operationally in the fields of HF radar and HF broadcasting. In the latter, this is accomplished by means of the addition of a virtually inaudible modulation to the broadcasts and the subsequent reception of the modulated energy via backscatter. Such soundings could help the transmitter personnel determine the optimum broadcasting band and transmitting antenna for each desired area of coverage. This process is made more accurate by deploying transponders in the coverage area so that a ground range calibration can be performed.

In practice the transmitted frequency is not generally changed in the short-term and any operational changes in real-time would be to use an alternative transmitting antenna with more appropriate beam elevation characteristics. The bulk of the energy reflected from the ionosphere is then directed on to the target area overcoming the day-to-day variations of the circuit geometry due to the corresponding variations of the ionosphere.

The significance of backscatter sounding with regard to HF radar has been described by Headrick and Skolnik [1974]. David *et al.* [1976] have studied a process for ensuring that reception conditions on a radio-channel pre-selected in accordance with an appropriate operational schedule are satisfactory. Earl and Ward [1986] have described a backscatter sounding system used in conjunction with an HF radar. This system yields real-time estimates of calibrated backscatter power levels and simultaneous estimates of HF noise intensities.

Backscatter sounding can also be used to monitor sporadic-E propagation on a circuit since the backscatter echoes have a characteristic signature [Croft, 1972]. Sporadic-E propagation modes often yield exceedingly low error ratios. However, interpretation of the backscatter echoes is a very complex problem and requires an operator, whereas frequency monitoring systems (section 3.2.1) can detect sporadic-E modes more simply by virtue of their almost-zero Doppler shift.

3.1.4 Transionospheric sounding

Transionospheric sounding is based on measurements of group delay at frequencies close to the critical frequency [Avdyushin et al., 1983]. Observations with the Intercosmos-19 and Cosmos-1809 satellites have demonstrated the following capabilities:

- measurement of bottomside electron density profiles;
- determination of the MUF;
- measurement of horizontal electron density gradients;
- measurement of the presence, location and concentration of ionospheric inhomogeneities.

This method supplements the capabilities of ground-based vertical incidence and oblique incidence sounding and satellite-based topside sounding [Danilkin, 1985]. A large volume of the ionosphere can be probed by utilizing the motion of the satellite in conjunction with simultaneous measurements from multiple ground stations. It may be used either to complement conventional sounders or in a stand-alone capacity.

3.2 Passive channel evaluation

Information on the behaviour of the ionosphere and the interference present on assigned radio channels can be collected using transmitters of opportunity and passive receiver-monitoring methods. Also channels which are unusable owing to high noise and interference levels can be logged.

3.2.1 *Frequency monitoring*

The original form of single-site RTCE is that in which the frequency band is scanned manually with a receiver in order to assess which identifiable transmissions are propagating from a given site, together with their relative qualities. The assumption of reciprocity allows an estimate of the frequency which should be used for transmission to a specified location. This procedure might now be made more comprehensive by the use of adaptive or steerable receiving antenna arrays which would enable "pencil beam" steering to be carried out in both azimuth and elevation. Such a procedure would allow non-identifiable transmissions to be included in the passive RTCE process since their positions could be computed approximately by measurements of azimuthal and vertical angles of arrival.

Darnell et al., [1988] propose a global common-user system in which agencies equipped with suitable receiving equipment will be able to acquire RTCE information at various levels of sophistication.

3.2.2 Noise and interference monitoring

Cottrell [1979] gathered noise statistics which indicated that one 3 kHz channel from ten should be adequate for an operational system during daytime. For night-time operation, when HF channel occupancy is higher, it is likely that more candidate channels will be needed to ensure that at least one is usable. The optimum channel will not vary significantly over a period of one minute.

Interference measurement to a resolution of 3 kHz can be a useful criterion for channel selection. Assessment of the availability of an ionospheric path by means of long term predictions and short term forecasting can also form part of the selection procedure. Test signals on the actual circuit of concern are a reliable means of deducing the prevailing ionospheric conditions and provide a means of conveying information about interference conditions to distant sites in a network.

Gott et al., [1983] have indicated the existence of important interference components within a 3 kHz bandwidth. Interference monitoring within a 3 kHz bandwidth is highly desirable so that it can be avoided or excised.

The above observations clearly demonstrate the benefit of passive noise and interference monitoring in RTCE.

3.3 In-channel sounding

3.3.1 Signal strength monitoring

A measure of signal strength available within a sky-wave channel is not in its own right a good indication of link quality. Trials of both high speed and 75-baud modems have eliminated this channel characteristic from the list of viable channel quality measures.

3.3.2 Signal-to-noise ratio monitoring

Signal-to-noise (including interference) ratio has been used as a link quality measure in several past systems [Probst, 1968; Stevens, 1968]. In each case the addition of this feature proved advantageous. This option appears to be a viable RTCE criterion for systems which are intended to carry low-speed data. A single channel 75-baud tone exchange link falls in this class. For medium or high speed links a measure of signal-to-noise ratio alone is probably inadequate. Under these circumstances time dispersion in the form of discrete multipath will play a critical role in determining channel quality.

In one of the most comprehensive comparisons of rival link quality measures, Humphreys and Shearman [1985] show signal-to-noise ratio to be a good choice for low-speed data links. This selection was especially valuable under high error ratio conditions.

While the time-average signal level at frequencies within a 3 kHz bandwidth will not vary significantly the same is not true of underlying interference which will often be present. Careful consideration should be given to the bandwidth in which the noise part of this ratio is measured. If potentially useful channels are first assessed in a 3 kHz bandwidth and those with a low signal-to-noise ratio discounted, then the remainder can be searched for optimum tone placements to a higher resolution. In this way the time lost in searching for a satisfactory channel can be minimized.

Devices have been developed [Darbyshire and Gott, 1986] to excise narrow-band interference within a normal 3 kHz voice channel. Similarly, the benefits of in-band tone agility have been widely discussed [Darnell, 1978, 1979; Gott and Hillam, 1979; Sloggett, 1979].

A practical RTCE system which has been developed in Canada is termed CHEC (Channel evaluation and calling) [Stevens, 1968]. This is an "in-channel" sounding system, i.e. it sounds in the frequency channels actually assigned to the user. On each of a relatively small number of channels, the CHEC base transmitter emits a signal of several seconds duration which is encoded with a selective calling code, data on the base station interference level in that channel and a CW section. At the remote receiver specified by the selective call, the base station interference level in each of the alternative channels is decoded and a measurement of signal strength made using the CW section of the transmission. Assuming reciprocity, a processor at the remote station computes the optimum channel for transmission to the base using the criterion of predicted signal-to-noise ratio at the base due to the remote transmitter. The CHEC technique yields a significant improvement in channel availability.

The original CHEC system is no longer operational. A microprocessor controlled system of the CHEC type has been developed [Chow et al., 1981; McLarnon, 1982], termed RACE (Radiotelephone with automatic channel evaluation).

3.3.3 Error-ratio measurement

The error-counting technique discussed by Darnell [1978] employs a test signal with essentially the same parameters as the traffic signal. The test signal occupies each of the assigned channels in turn and a bit error-ratio established for each channel. This technique has obvious merit in that a direct measure is made of digital-data quality. With some forms of traffic, it is possible to derive the RTCE data from the normal operating system, i.e. a channel may be evaluated while it is actually passing traffic. Darnell [1978] has described results of tests of an RTCE system based on error-counting techniques which used ten possible channels carrying two types of traffic on two European paths.

The circuit peformance using two frequencies selected during traditional frequency prediction techniques was compared with that obtained using frequency selection based on the RTCE data. The former technique was restricted to the use of one "day" and one "night" frequency. The results of the tests indicated that for the two types of traffic considered, a substantial percentage increase in circuit reliability on average about 45%, can be achieved by the RTCE rather than 2-frequency selection techniques.

3.3.4 Pseudo-error counting

A technique aimed at accelerating the accumulation of error counting has been developed which is usually referred to as "pseudo-error" counting. Rather than use a system's normal detection circuit, the operation is degraded in some way so that the final error count becomes more sensitive to flaws in the channel quality [Leon, 1973].

One method of pseudo-error generation might be implemented by relaxing the detection thresholds for the identification of digital "zeros" and "ones". Another approach is to use the margins of "soft decisions" and this too should be regarded as another form of error ratio acceleration [Darnell, 1978; Chase, 1973; Humphreys and Shearman, 1985]. McLarnon [1982] describes the use of pseudo-error ratio monitoring in the design of an automatic HF radiotelephone system.

3.3.5 Phase-error measurement

Circuit quality for tone exchange modulation links may be assessed by sampling the phase stability of a pilot tone transmitted with the communication traffic. Usually the pilot tone would lie between the "mark" and "space" frequencies. The phase of the pilot tone is sampled at a synchronous rate of approximately 100 Hz. The frequency with which the phase difference between consecutive sample phases exceeds some predetermined threshold can be used as a measure of channel integrity [Darnell, 1978; Betts and Darnell, 1975].

Betts and Darnell [1975] described an experiment to verify the theoretically derived relationships between a pilot-tone phase error ratio and the frequency-shift keying (FSK) data error ratio. A set of three trials was performed, for circuit lengths of 850, 1700 and 9800 km.

The results of all trials have confirmed the predicted relationships between FSK data error ratio and pilot-tone phase error ratio. Significant deviations occurred for less than 1% of the total duration of the recorded data. These deviations were attributable to two main causes: the first was very fast fading (greater than 1 fade/s) and the second some unusual and very intense man-made interference.

Betts and Suleiman [1979] suggest from theoretical analysis, laboratory simulation and field trials that phase-error information can be used to support any form of digital modulation. Betts and Suleiman also outline a second generation pilot-tone technique in which the multipath time delay difference between signals in a two-path multipath circuit is made. The method uses more than one pilot tone and a correlation technique to determine the structure of frequency selective fading.

A disadvantage of the phase-error method is the lengthy period of time required to evaluate a channel.

3.3.6 Spectral broadening of CW tones

Clarke [1980] describes a RTCE scheme which applies to a 2400 bit/sec Kineplex modulation format. Experiments have shown that the error ratio on such circuits shows a pronounced positive correlation with the broadening of spectral components within the data signal. A frequency management technique based on the spectral width of CW tones at each allocated frequency is under consideration. A hybrid approach has been adopted in which channels are classified on the basis of measured signal-to-noise ratio, fading statistics, and tone width. According to Clarke, ten channels can be evaluated every 5-10 minutes.

3.3.7 Pulse shape

Gott and Dutta [1979] describe a diversity combiner which adapts its combining method according to the quality of each propagation path where circuit quality is analysed depending on the regularity of the FSK signal transitions (jitter). A similar scheme can be adapted to perform frequency selection rather than diversity branch selection. Shaw et al., [1988] present a theoretical appraisal of zero-crossing filter RTCE. The technique has the advantage that channel evaluation can take place during the transmission of ordinary traffic.

Humphreys and Shearman [1985] on comparing rival circuit quality measures for low-speed HF data links identify telegraph distortion as useful but not as important as signal-to-noise ratio.

3.3.8 Automatic repetition (ARQ)

Many HF systems utilize the error-control technique called ARQ. The method is very successful and several workers have suggested that the rate at which repeat requests are made might be used to assess channel quality during the normal passage of traffic [Darnell, 1978; Elvy, 1985; Borgmann, 1988]. Others [see for example Reed and Hopkinson [1988]] use information gained from the error control code correction rate to assess link quality.

3.3.9 Channel estimation/equalization

The conventional means of transmitting data at rates of order 2400 bit/sec is multiplexing data between several separate channels in the frequency domain each carrying low-speed data. George and Halligan [1985] have described a practical "channel quality sounder" for use on such data circuits at rates of 2400 to 4800 bit/s. New HF transmission techniques are emerging which enable high-speed data to be carried on a single modulated tone. One modem using such a technique has been described by Currie and Weale [1985], but there are several others. Opinions vary over the best signal processing approach, the two general schemes are referred to as "channel estimation" [Clark, 1981] and "channel equalization". Both methods require that the receiving signal processor holds a great deal of information about the channel impulse response, or its inverse. Under these circumstances, there is clear potential for sophisticated circuit quality analyses based on overall time dispersion, proportion of energy in the dominant sky-wave mode, measured fading of individual modes, a measure of phase stability and statistical measures of "confidence" in the channel model. Pennington [1983] discusses RTCE for this class of modem.

4. Current trends

Over the past few years microcomputer and sophisticated signal processors are increasingly becoming an integrated part of radio communication systems for exploiting or mitigating electromagnetic propagation effects, and so improving their operational performance [AGARD, 1989]. RTCE circumvents the problems encountered with oblique incidence sounding techniques (see section 3.1.1). These new systems are becoming fully integrated with the traffic-carrying radio equipment. This offers considerable cost advantages compared with stand-alone systems.

With the increasing use of RTCE there is a need for equipment from various manufacturers to be compatible. This entails the standardization of protocols for the sounding process and the subsequent establishment of communication. It is likely that such protocols will need to be standardized for each application (i.e. point-to-point link protocols are likely to be different to tactical network protocols).

5. Conclusions

Given the uncertainties inherent in forecasting, RTCE can be regarded as the best available technique for choosing an operating frequency for HF communications. The allocated frequencies are tested in real time, the "best" one selected and the communications link changed accordingly. In principle any of the parameters of the link can be adjusted but at the present time practical RTCE schemes deal almost exclusively with the choice of operating frequency.

The potential advantages accruing from the use of RTCE techniques have been summarized by Darnell [1975, 1986]:

- the effect of man-made noise and interference can be measured and specified quantitatively [Darnell 1979];
- the facility for real-time, on-line measurement of propagation and interference allows the use of relatively transient propagation modes e.g. sporadic-E layer propagation;
- RTCE evaluation allows a more efficient use of the frequency spectrum by tending to select frequency channels higher than those which would be chosen via prediction techniques. Thus spectrum congestion is reduced;
- RTCE will provide a means of automatically selecting the best frequency and simultaneously indicating preferred stand-by channels;
- transmitter power can be minimized, consistent with providing an acceptable quality of received traffic;
- RTCE data can be used to adapt other parameters of a communication system optimally for the prevailing path conditions, e.g. bandwidth, data rate, modulation type, start time and duration of the transmission, signal processing algorithm at the receiver, elevation angles for antenna array beams, diversity type and adaptive equalization;
- the provision of off-line propagation analysis requirements can be eliminated for fixed link operations; however, these will still be valuable for system planning purposes.

The selection of which frequencies to evaluate should be made on the basis of long-term predictions updated by short-term forecasts. Also, with a communications network, the full range of assigned frequencies must be parcelled out according to some overall plan, in order to avoid unnecessary interference between members of the network.

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