U.D.C. 621.391.812: 621.394.5
Indexing Terms: Data transmission, Radio transmission, Fading

High data rate transmissions over h.f. links

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SUMMARY

A review is presented of the problems inherent in transmitting data over h.f. links. The propagation medium imposes characteristics of time and frequency dispersion, fading and delay distortion upon the transmitted signal, particularly when wide bandwidths are used. The magnitude and variability of these features are quantified and a simplified expression for the received signal is derived. Techniques that have been used to transmit high data rates over h.f. links are summarized and their relative merits compared. It is concluded that the ionosphere continues to be a limiting factor in the design of an efficient modem, but that recent developments in microelectronics provide the potential to make a significant improvement in the performance of future communication systems.

1 Introduction

The high frequency (2–30 MHz) portion of the spectrum has long been recognized as a useful and economic medium for achieving wide distribution of energy over large distances. Although satellite communication systems are becoming more widely available, h.f. will continue to be extensively used by many nations for point-to-point transfer of information and for commercial shipping and aircraft communications; military forces rely heavily upon h.f. for land, sea and air operations. The major constraint for a satellite link is to maintain an adequate signal-to-noise ratio for the high data rates that are required. In contrast, constraints on h.f. links centre around the dispersive characteristics of the transmission medium and in the high levels of interference that may be encountered.

The design of h.f. systems depends upon accurate predictions and new technology to improve circuit reliability. System planners should know what frequency ranges must be covered, what transmitter powers are necessary to overcome the background noise at the receiver and what antenna configurations are most suited to the applications required.

The evaluation of h.f. link reliability has been detailed in a previous paper;[1] an air-to-ground link was chosen as an example to illustrate the concepts involved and the problems with which the communications system designer must cope. The resultant effects caused by time and frequency dispersion were not specifically addressed, however, and the conclusions reached assumed that such effects are not major. The present paper considers these dispersion effects in detail, and analyses the limitations they impose upon high data rate transmissions of an h.f. signal.

Section 2 summarizes the operational constraints of using h.f. data transmissions for point-to-point and mobile applications. The properties of the propagation medium are analysed in Section 3; each major characteristic is discussed in turn, its physical cause identified and the magnitude of its resultant effect quantified. Section 4 considers some techniques that have been used to transmit data at high rates over 3 kHz voice bandwidth channels and compares their relative merits. Sections 5 and 6 extend the study to consider the use of wider bandwidths, the problems that may arise and some techniques that might be employed. Finally, in Section 7, some future trends are briefly examined and their possible impact upon communications systems are considered.

2 Operational Constraints

2.1 Point-to-point Links

The h.f. spectrum is used extensively for long-range point-to-point communications and broadcasting; the characteristics of such links have therefore been widely studied. Commercial services are available[2,3] for predicting the optimum working frequencies and quality of communications at those frequencies. Most point-to-point land fixed h.f. communication circuits use high-gain rhombic or log periodic antennas, whilst arrays of horizontal dipoles, also with significant directivity, are popular for broadcasting using the sky wave.

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The Radio and Electronic Engineer, Vol. 52, No. 2, pp. 75–87, February 1982

0033–7722/82/020075+13 $1.50/0

Many circuits employing data transmissions have a large frequency complement. This allocation can be used to advantage to choose frequencies close to the maximum usable frequency (m.u.f.) and thus ensure that differential delays between propagation modes are small enough to provide frequency flat fading over a 3 kHz channel. Post-detection diversity combining can be employed to combat such fading by using spaced receiving antennas and multiple transmission frequencies. The digital errors that remain are then caused predominantly by either wideband impulsive noise or man-made interference; the time varying dispersive effects of the channel are of secondary importance. In principle, therefore, the performance of these point-to-point links may be optimized by good engineering design and practice in respect of the equipment and antenna systems, whilst high transmitter power is often available.

2.2 Mobile Applications

Much more difficult problems are presented by h.f. communication to mobiles. Communication is often required at ranges from a few kilometres to hundreds or even thousands of kilometres over a wide variety of terrain, and this implies different modes of propagation according to range. Physical constraints are placed upon antennas that are used for manpack or vehicle application so that efficiencies may be seriously degraded; radiation patterns are obtained that may not be suited to the propagation mode, whilst transmitter power is often severely limited.

When transmitting data to and from these mobiles, it is neither easy nor always possible to use frequencies close to the m.u.f. as in the case of point-to-point links with large frequency complements; time-varying channel dispersive effects can then become of primary importance. At the frequencies available to the mobiles, the resulting differential delays between propagation modes may be sufficient to produce narrowband frequency selective fading within a 3 kHz channel. To achieve satisfactory results over an h.f. link of this kind, careful consideration must be given to the h.f. channel characteristics, the terminal radio equipment (including modulation techniques and error coding), the planning of operational links and the management of the frequencies to be used over those links.

2.3 High Data Rate Requirements

Further complications arise when high data rate transmissions are required. For example, digital voice requirements imply data rate transmissions of $2{\cdot}4\ \text{kbit s}^{-1}$. Higher data rates would give better quality from the speech synthesis aspect, but channel bandwidth considerations show that approximately $2{\cdot}4\ \text{kbit s}^{-1}$ is the highest rate that can be tolerated in a 3 kHz channel. Military radio links may need to incorporate a high degree of immunity to electronic counter measures; complex modulation schemes involving frequency hopping and spread spectrum must therefore be adopted. This, in turn, necessitates a detailed study of the propagation medium to determine whether various forms of wide bandwidth modulation techniques can be transmitted with fidelity. The problems inherent in the design of modems to achieve satisfactory transmissions at $2{\cdot}4\ \text{kbit s}^{-1}$ over h.f. channels have not yet been adequately solved; it has been the ionosphere which has proved to be a limiting factor in the design of an efficient modem.

Table 1

General h.f. channel characteristics

Propagation mechanism	Channel characteristics	Relevant parameters
Ground wave	attenuation delay	soil conductivity terrain type range wave polarization wave frequency
Single mode sky wave	attenuation delay fading delay distortion Doppler shift Doppler spread	time of day sunspot activity season of year range wave polarization wave frequency
Multimode sky wave	time dispersion interference fading	different modes different hops high/low angle rays magnetoionic splitting relative attenuation relative delay

3 Characteristics of the Propagation Medium

Good network and frequency management are vital, particularly for the successful performance of a mobile radio system. The m.u.f. increases with range and, if a choice of receiving stations is available, it may be advantageous[4] to work to the more remote station so that higher working frequencies can be used and thus better antenna efficiencies achieved. The requirement for good frequency management of h.f. links is implicit throughout this paper.

Groundwave communication is more straightforward than skywave; it can be assumed that the groundwave is merely an attenuated, delayed but otherwise undistorted version of the transmitted signal. Ionospheric skywave returns, however, in addition to experiencing a much greater variability of attenuation and delay, also suffer from fading, frequency or Doppler shifting and spreading, time dispersion and delay distortion. These features are summarized in Table 1 and will be discussed in detail.

3.1 The Received Signal

Consider a complex transmitted baseband signal, $E(t)$, traversing a single propagation path through the ionosphere. Let it experience a delay τ. The medium is dispersive and thus the signal is subject to delay distortion, caused by the fact that the delay is a function of frequency. This distorted waveform is denoted by $\hat{E}(t)$. In addition, the signal experiences attenuation and random fading. This can be represented by multiplying the delayed, distorted signal by a random gain $G(A, \nu, \sigma, t)$ where A characterizes the attenuation $(0 \leqslant |A| \leqslant 1)$ and ν, σ represent the fading in terms of a

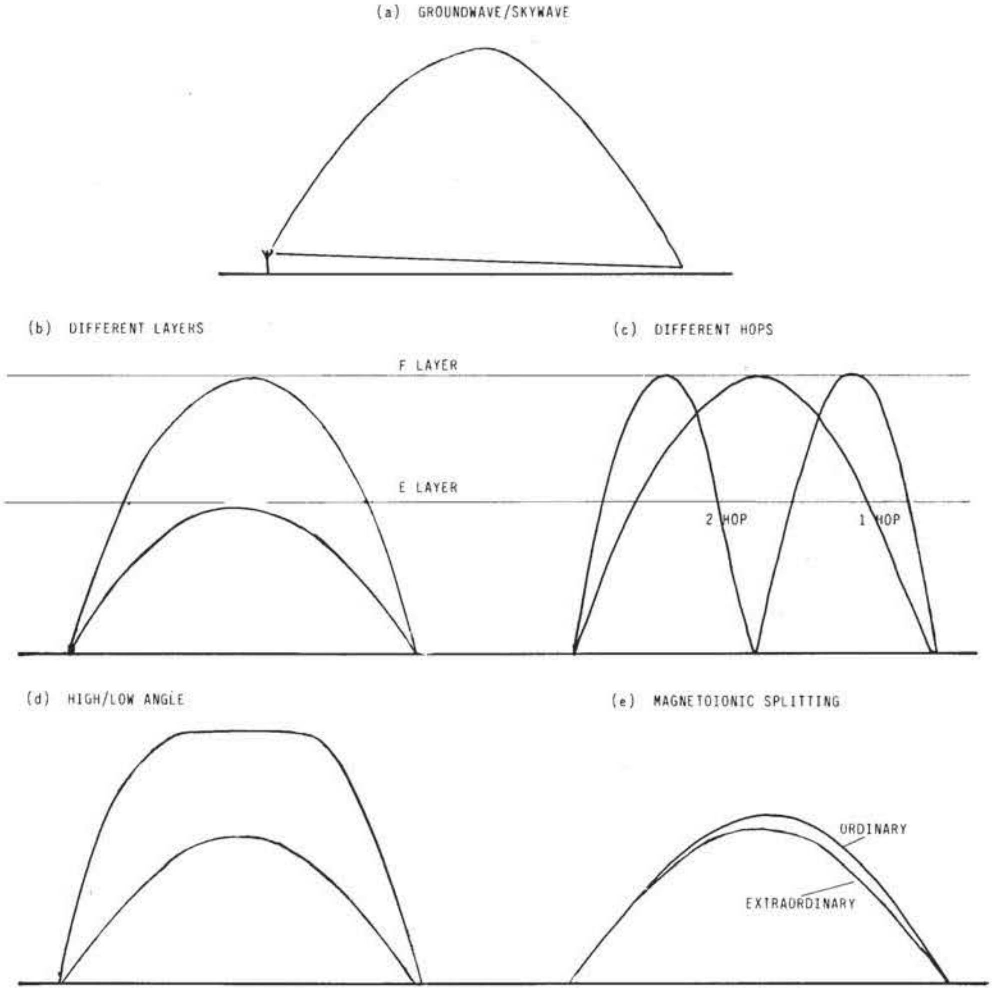

Fig. 1. Causes of multipath propagation.

frequency shift and spread respectively. The received signal $E_R(t)$ thus becomes

$$E_R(t) = G(A, \nu, \sigma, t)\,\hat{E}(t-\tau). \qquad (1)$$

Components of this signal may be returned from both the E region and F regions of the ionosphere (the latter may include both high and low angle ray paths). There are skywave returns for the ordinary and extraordinary magneto-ionic components and for multiple hop paths (see Fig. 1). Although many propagation modes are possible, all but a few experience a large attenuation; the number of 'effective' modes is generally small.

Each mode has a different value of the characteristics of equation (1). For the jth mode, the received signal is

$$E_{Rj}(t) = G_j(A_j, \nu_j, \sigma_j, t)\,\hat{E}_j(t-\tau_j) \qquad (2)$$

Consider now the groundwave. This can be assumed to experience a delay τ_g, and a non-random gain, but no distortion. Thus, $\hat{E}(t-\tau)$ becomes $E(t-\tau_g)$ and G becomes A_g $(0 \leqslant |A_g| \leqslant 1)$. The total received signal is then

$$E_R(t) = A_g E(t-\tau_g) + \sum_{j=1}^{N} G_j(A_j, \nu_j, \sigma_j, t)\,\hat{E}_j(t-\tau_j) \qquad (3)$$

where N represents the number of 'effective' skywave modes. Expressions for these terms are derived in the Appendix. It is not necessary, however, to delve into the detailed mathematics to consider the effects imposed upon the received signal by the characteristics of the propagation medium. The relevant phenomena are summarized in Table 2. Each is now discussed in more detail in terms of its cause, magnitude, variability and resultant effect.

3.2 Multipath Propagation and Time Dispersion

Multipath characteristics can be described by the dispersion produced in the unit impulse response of the medium. Time dispersion can result from one or more of the following (see Fig. 1):

(a) Groundwave and skywave paths,
(b) Skywave returns from different ionospheric layers,
(c) Skywave returns involving different numbers of 'hops',
(d) High and low angle skywave paths,
(e) Splitting of the magneto-ionic components, ordinary and extraordinary, resulting from the effects of the Earth's magnetic field.

Table 2

Causes of distortion on an h.f. channel
(Parameters referenced are those used in equation (3))

Effect	Cause Within a single mode	 Between different modes
Time dispersion	spread of τ_j, due to slightly different constituent raypaths	τ_j different for each propagation mode
Fading	G_j a function of time — movement in ionosphere — polarization variations — absorption changes	different time dependence of each G_j
Frequency dispersion	v_j, σ_j are non-zero — phase path is time dependent	relative phases between modes changes with time
Delay distortion	τ_j a function of frequency and/or time	τ_j may have a different frequency/time dependence for each mode

Each propagation path or mode has its own characteristic group delay τ_j. The time dispersion of the medium is caused by the difference in group delays between the different modes; it can give rise to intersymbol interference when the signalling rate becomes comparable with the relative multipath delays. The maximum serial data transmission rate is thus limited to the reciprocal of the range of multipath propagation times. This is itself a function of frequency, path length, geographical location, local time, season and sunspot activity. The data rate can be maximized[5] by working close to the m.u.f., although this is extremely difficult to achieve in practice for mobile applications. As the operating frequency is decreased from the m.u.f., a frequency is reached at which the spread is a maximum. For a 2500 km path, the maximum time dispersion has been shown[5] to be about 3 ms; for 1000 km it increases to 5 ms and for 200 km it is about 8 ms.

Under some conditions, the transmission rate could be increased by a factor of 100 over the normal values[5] by judicious choice of operating frequency. In practice, however, the upper limit is approximately 200 bit s^{-1} when conventional detection equipment is used. Even within a single mode of propagation, there remains an approximately 100 μs spread due to the slightly different constituent ray trajectories caused by roughness of the ionospheric layers and non-zero antenna beamwidths. Under anomalous conditions, such as spread F, when the ionosphere contains many irregularities, the time dispersion can be much greater.

There are several important effects which multipath imposes upon a given communications technique and its associated equipment when transmitting high speed digital h.f. data:

(a) The equipment is more complex, with special modems, diversity combining etc. For example, in phase shift keyed (p.s.k.) systems, abrupt phase changes occur as successive modes reach the

Table 3

Summary of fading characteristics

Type	Cause	Fading period	Correlation bandwidth	Remarks
Flutter	small scale irregularities in F region	10–100 ms	1 kHz	associated with spread F
Diffraction	movement of irregularities in ionosphere	10–20 s	50 kHz	follows a Rayleigh distribution
Polarization	rotation of axes of polarization ellipse	10–100 s	25 kHz (night) 400 kHz (day)	only effective when both magnetoionic components present in approx. equal proportions
Skip	time variation of m.u.f.	generally non-periodic		avoided by working well below m.u.f.
Focusing	curvature of reflecting layer	15–30 mins		
Absorption	time variation of ionospheric absorption	1 hour		greatest at sunset and sunrise
Groundwave —skywave	comparable strengths of different propagation modes	2–10 s	300 Hz –3 kHz	generally more severe than for skywaves alone
Skywave modes		1–5 s		
High and low angle rays		½–2 s		
Magnetoionic splitting		10–40 s		

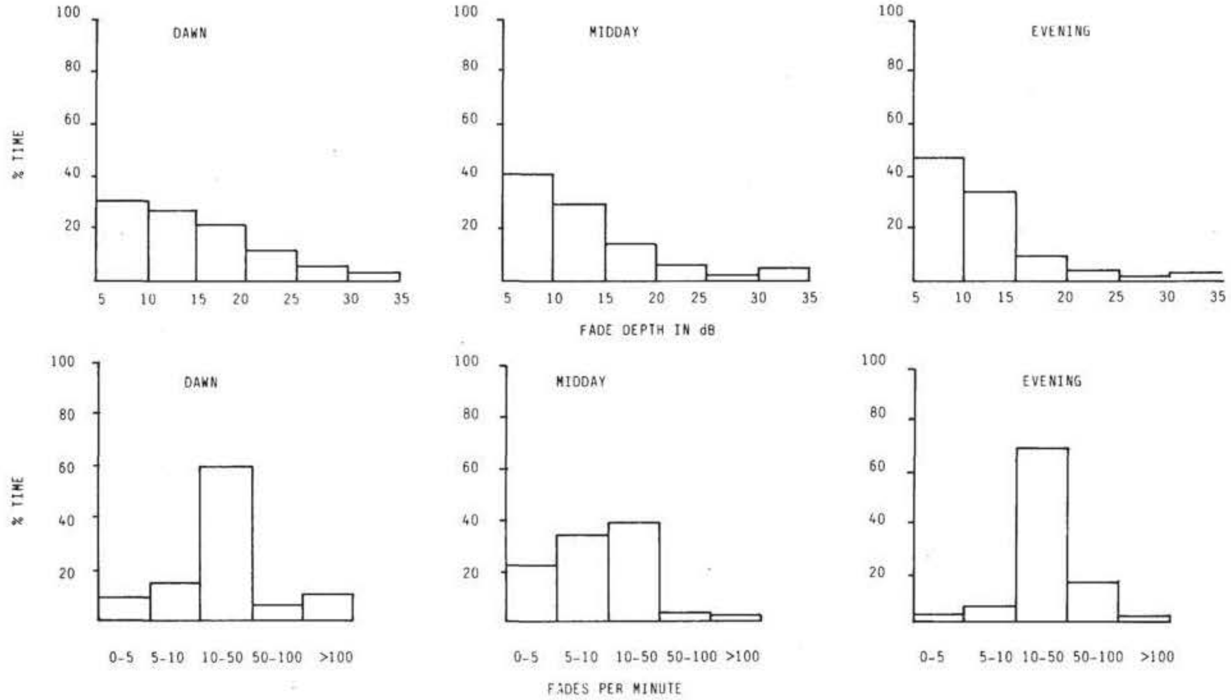

Fig. 2. Typical fade rates and depths received by a monopole.

receiver, necessitating the provision of a guard interval at the end of each signalling period. In bandlimited systems using multitone signalling, this reduces the number of tones available, since greater frequency separation is required.

(b) The error rate is degraded, as a result of intersymbol interference, and high error rates may occur even at high signal-to-noise ratios.

(c) The choice of operating frequency is limited to a small frequency band below the m.u.f. Working at frequencies too far below the m.u.f. increases the likelihood of encountering larger multipath delays.

3.3 Fading

Skywave signals characteristically fluctuate in amplitude and phase. No matter how irregular the ionosphere, the amplitude of the signal at a fixed receiver would remain steady if it were a static medium. The width of the received power spectrum (i.e. the fading rate) is then related to changes in the ionosphere.

There are a number of different kinds of fading, defined according to their origin; the main causes are movements and changes of curvature of the ionospheric reflector, rotation of the axes of the received polarization ellipse, time variations of absorption and changes in electron density. In addition to these effects which may be produced independently for each mode, more significant fading may be caused by interference between two or more modes, particularly when they are roughly of equal amplitude. The different types of fading, with their typical fading rates are summarized in Table 3.

Figure 2 presents some average fading rates for a typical h.f. channel at mid-latitudes.[6] It is clear that, particularly for the dawn and evening periods, the 10–50 fades per minute grouping is by far the most common. This is caused by interference between different skywave modes. For midday, the results are spread rather more evenly from 0 to 50 fades per minute, but again higher rates of fading are infrequent. Also shown in Fig. 2 is fade depth; fades of less than 10 dB occur most frequently.

For a two-path channel with relative delay d seconds, troughs in the amplitude-frequency response are separated by $1/d$ Hz and give rise to frequency selective fading; signals with bandwidths greater than $1/d$ Hz are thus required for in band frequency diversity. The $1/d$ Hz bandwidth is known as the correlation bandwidth and is given for different types of fading in Table 3. As the distance between two closely spaced receivers is increased, the correlation coefficient between their respective received signals decreases. The distance at which the coefficient drops to $1/e$ is called the correlation distance; it is of the order of a few wavelengths for skywave reception (i.e. $\gtrsim 100$ m at h.f.).

3.4 Frequency Dispersion

For any given single propagation path, a shift v_j in frequency can be caused by time variation of

(a) height of the reflecting layer

(b) electron density (and hence refractive index) along the path.

Thus, if ψ is the phase angle of a ray path at time t, then

$$v_j = -\frac{f}{c}\frac{\mathrm{d}\psi}{\mathrm{d}t} \tag{4}$$

for a fixed transmitter and receiver.

The frequency (or Doppler) shifts experienced at night

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