REPORT ITU-R F.2061

HF fixed radiocommunications systems

(2006)

1 Introduction

HF system emissions can be categorized as adaptive and non-adaptive. Non-adaptive systems depend on operator training and skill level to assess propagation variables and interference to find a clear, reliable channel. Adaptive systems automate this process. Although adaptive systems have many advantages, including decreased operator training, non-adaptive systems will continue to be operated in the foreseeable future. There is potential for interference between these two types of systems. The emission characteristics of adaptive and non-adaptive systems require separate sets of characteristics data to enable accurate electromagnetic compatibility analysis in a given environment.

Modern communications in the HF band also have specific attributes that make a viable solution for many emergency response requirements. HF systems and networks provide a highly versatile means of communications to a broad base of users engaged in public protection and humanitarian efforts. Such systems can also bring inexpensive and reliable equipment to remote and lightly populated areas.

In the event of the collapse of normal telecommunication operation due to natural disasters (e.g. earthquakes) and other emergencies, MF/HF systems 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.

2 Non-adaptive systems

2.1 Introduction

In the manual non-adaptive operational procedure, the operator must adjust the parameters of the system for maximum performance by monitoring the conditions of the ionosphere, tracking the variable propagation conditions, and selecting the operating conditions (i.e. primarily the frequency) that will allow the signal to propagate best.

There is 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 refraction of radio waves from the ionosphere, or in some cases by the surface-wave mode.

2.2 Propagation

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 (ITU-R P.368, ITU-R P.369, ITU-R P.371, ITU-R P.434, ITU-R P.531, ITU-R P.532, ITU-R P.533, ITU-R P.534, ITU-R P.535). Some additional information may be found in the ITU-R Handbooks – "HF broadcasting system design" and "Frequency adaptive communications systems and networks in the MF/HF bands".

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 period 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 solar angle, 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, 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 software on the ITU-R website. 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 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.

3 Adaptive systems

3.1 Introduction

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 a manner that copes with 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.

3.2 Operational characteristics

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

– *Decreased Operator Training:* 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 adaptive selection of the most appropriate modulation waveforms.

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

MF and HF radio has been used for decades for long-distance communications. MF and 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;
  a) the degree and distribution of ionization of the ionosphere;
  b) the distance between stations (number of hops);
– operating power;
– modulation;
– SNR requirement;
– 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 by monitoring the conditions of the ionosphere, tracking the variable propagation conditions, and selecting 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 and MF 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 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.

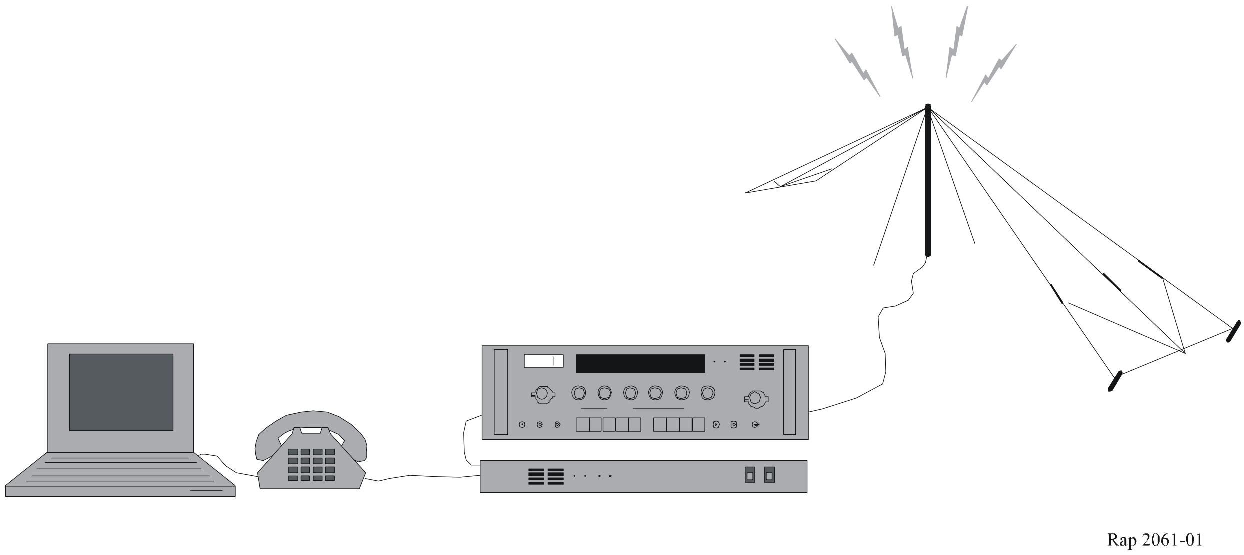
3.2.1 General description

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 intercommunication. 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

Typical adaptive station



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.

3.2.2 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. Some adaptive systems employ trunking, in which a subset of available frequencies is stored in a pool for calling, while the remaining frequencies are used only for traffic; selection of traffic frequencies for a link is coordinated using the calling frequencies. 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 not engaged in 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 transmission on each frequency from the frequency pool. All other stations in the net detecting this sounding transmission will update their individual link quality assessment table.

3.2.3 Sounding

The sounding signal is a unilateral, one-way transmission performed at periodic intervals on unoccupied channels. To implement, a timer is added to the controller to periodically initiate sounding signals (if the channel is clear). Sounding is not an interactive, bilateral technique, such as polling. However, the identification of connectivity from a station by hearing its sounding signal does indicate a high probability (but not guarantee) of bilateral connectivity and it may be done passively at the receiver. As a minimum, the signal (address) information is displayed to the operator and, for stations equipped with connectivity and link quality analysis (LQA) memories, the information is stored and used later for linking. If a station has had recent transmissions on any channels that are to be sounded on, it may not be necessary to sound on those channels again until the sounding interval, as restarted from those last transmissions, has elapsed. In addition, if a net (or group) of stations is polled, their responses can serve as sounding signals for the other net (or group) receiving stations. All stations can be capable of performing periodic sounding on clear prearranged channels. The sounding capability may be selectively activated by, and the period between sounds can be adjusted by the operator or controller, according to system requirements.

When available, and not otherwise committed or directed by the operator controller, stations automatically and temporarily display the addresses of all stations heard, with an operator selectable alert.

The structure of the sound is similar to that of the basic call; however, it is only necessary to send the identification of the transmitting station. Asynchronous mode sounding in both 2nd Generation (2G) and 3rd Generation (3G) ALE (automatic link establishment) systems employs an extended transmission to ensure that scanning receivers will dwell on the active channel at least once during the transmission. Sounding is optional in synchronous mode 3G ALE systems; when needed, synchronous 3G ALE sounding transmissions are less than one second in duration.

3.2.4 Link preparation and establishment

A link is initiated either by using the ordinary telephone, data networks 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 RF energy level on that frequency. If the energy level is above a certain threshold, the frequency is assumed to be occupied by another user and it is rejected. 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.

3.2.4.1 2G ALE Systems

Regarding multiple stations and choosing a best frequency in multiple-base-station networks, typically the system chooses the best frequency/base station pair for each link to a mobile node. There are two approaches: caller chooses and responder chooses.

In the first case, if the mobile originates the call, it will consult its local database of measurements, and rank the channel/station pairs. Calls are then placed to specific stations on the specific frequencies in descending order of that ranking until success. When the call originates from the fixed side, a unified database is used to route calls to the mobile via the base station with the best channels to that mobile.

In the second case, the mobile addresses its call to the network as a whole, and the base stations compare received signal quality to decide which one responds.

In point-to-point operation, there is no choice of which station to call, and frequencies are simply ranked for order of linking attempts.

There's no guarantee that the best frequency is used in every case. Recent measurements are used to set the order that channels are tried, but current propagation, occupancy, and interference determine which channel is actually used. The system attempts to link on the best frequency, but accepts the first one that works.

Regarding channel access efficiency 2G ALE listens before transmitting. As a 2G ALE network is overloaded, its throughput flattens out at a saturation value, versus falling throughput as load is added.

Systems use various algorithms for ranking channels for placing ALE calls. Typically a good channel is sought. Although, a good channel may not be the best channel.

3.2.4.2 3G ALE Systems

3G ALE was specifically designed to cope with heavy traffic, and is an improvement to 2G ALE in making efficient use of the spectrum. It uses a synchronous, slotted channel access protocol with separate calling and traffic channels. The separate traffic channels can be used at throughputs approaching 100% of capacity, while the calling channel utilization varies with the application, but typically is lower than that of the traffic channels. As in cellular and trunked radio services, less call setup channels are needed when compared to traffic channels, there is better efficiency in trunked mode than when calling and traffic are mixed on the same frequencies.

Regarding best channel selection in 3G ALE, the call setup is completed on the first calling channel in the synchronous scan set that works. The traffic is then carried on a frequency that is negotiated by the participants during call setup, not necessarily in the same band as the call setup channel. In the course of traffic, 3G ALE link maintenance can periodically re-evaluate and change frequency to maintain adequate performance.

3.2.4.3 Scanning rate

3.2.4.3.1 2G ALE System

Typical scan rates are between two and ten channels per second (dwell times of 100 to 500 ms per channel). Higher scan rates are possible. Receivers that detect 2G ALE signalling will extend the dwell time for up to 784 ms per channel while attempting to synchronize to the incoming signal.

3.2.4.3.2 3G ALE System

Trunking is an optional feature of 3G ALE systems. When not engaged in any of the 2G ALE or 3G ALE protocols, 3G ALE systems continuously scan assigned calling channels, listening for 2G ALE and 3G ALE calls. They leave the scanning state when called or when placing a call.

3G-ALE synchronous-mode receivers scan at a synchronized rate of either 1.35 or 5.4 s/channel. Stations may be assigned to dwell groups by the network manager. Each dwell group listens on a different channel during each dwell period, in accordance with the following formula:

$$D = ((T / 5.4) + G) \bmod C$$

where:

D: Dwell channel number

T: Seconds since midnight (network time)

G: Dwell group number

C: Number of channels in scan list

Note that this yields channel numbers in the range 0 to C-1.

3G ALE systems using asynchronous mode 3G ALE scan assigned calling channels at a rate of at least 1.5 channels/s. For scan rates at 10 channels/s, the corresponding dwell period of 100 ms may be extended to up to 667 ms as required when evaluating received signals. If a 3G ALE burst preamble has not been detected within 667 ms, the system can resume scanning. 3G ALE systems include mechanisms to maintain synchronization among all station time bases in a network. When 3G ALE is operating in synchronous mode, the difference between the earliest time and the latest time among the stations must not exceed 50 ms. In asynchronous networks, the permissible range of network times is determined by the current level of linking protection, if any.

An external synchronization means is provided to set the local time from sources such as a Global Positioning System (GPS) and GLONAS receiver. The internal time base can differ by no more than 1 ms from the external source immediately after such a time update. Time base drift typically does exceed 1 part per million.

When an external source of synchronization is not available, 3G ALE systems can maintain synchronization using over the air synchronization management protocols.

Sounding will normally be unnecessary in 3G-ALE systems. Knowledge of propagating channels can be used in synchronous networks 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. When a synchronous network contains multiple "server" stations to provide geographic diversity for "client" stations calling into the server pool, the servers should sound to provide a database of propagation measurements at the client stations for use in selecting the best server to call. A synchronous sound consists of a single notification protocol data unit (PDU). In asynchronous 3G-ALE networks, sounding may be desired if propagation data is unobtainable by other means.

3.2.5 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 or controller unit 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.

3.3 Waveform characteristics

3.3.1 2G ALE waveform

3.3.1.1 Introduction

The 2G ALE waveform is designed to pass through the audio passband of standard SSB radio equipment. This waveform provides for a robust, low-speed, digital modem capability used for multiple purposes to include selective calling and data transmission. This section defines the waveform including the tones, their meanings, the timing and rates, and their accuracy.

3.3.1.2 Tones

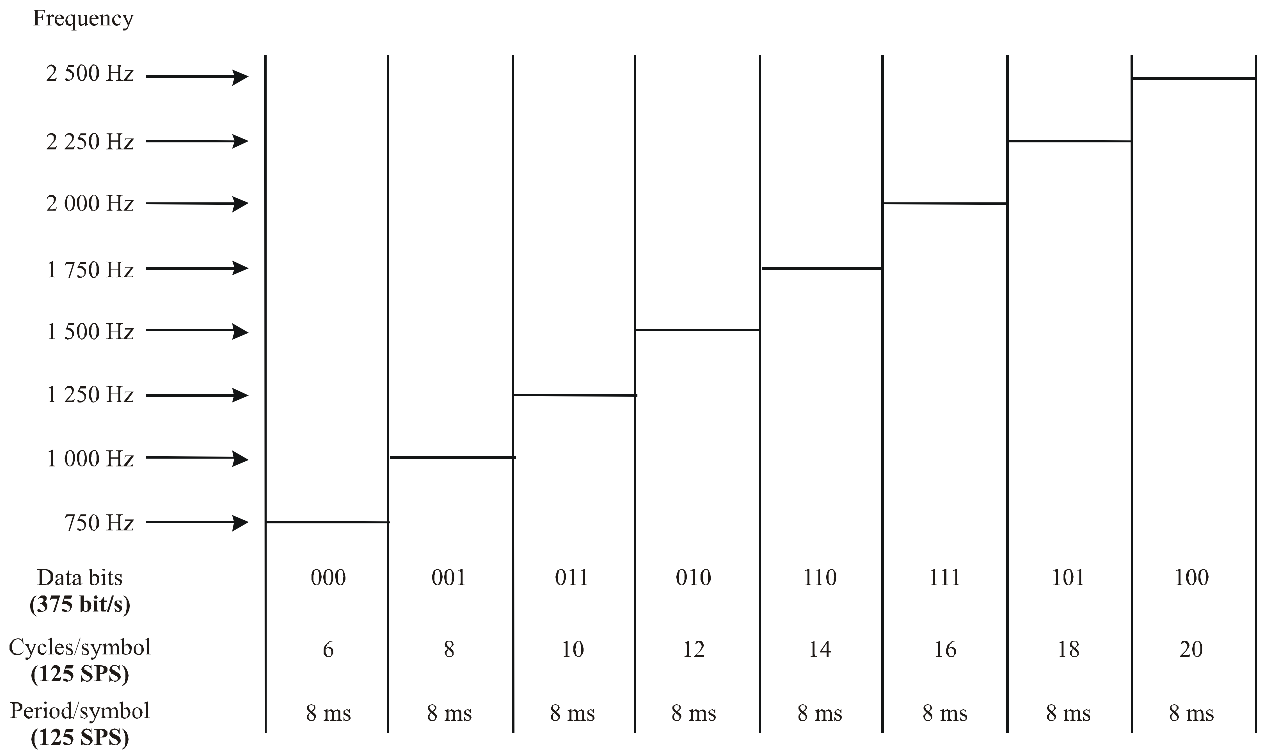
The waveform typically is a frequency shift-keying (FSK) modulation with eight orthogonal tones, one tone (or symbol) at a time. Each tone represents three bits of data as follows (least significant bit (LSB) to the right):

750 Hz	000
1000 Hz	001
1 250 Hz	011
1 500 Hz	010
1 750 Hz	110
2 000 Hz	111
2 250 Hz	101
d2 500 Hz	100

Figure 2 depicts the arrangement of the eight FSK tones in the passband, their durations in terms of seconds and cycles, and the bit assignments for use in ALE signalling. Note that the bit assignments are arranged so that demodulation errors of one tone result in only a single bit error.

FIGURE 2

8-ary FSK modulation for 2G ALE



Note – Symbol transitions shall be phase continuous.

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3.3.1.3 2G ALE Word

The fundamental unit of 2G ALE transmissions is the ALE Word. Each ALE Word contains 24 bits of protocol data, which normally comprises a 3-bit preamble (identifying the type of the ALE Word), followed by 21 bits of call sign or other ALE operating data. FEC coding is applied to each ALE word to increase its robustness, including rate 1/2 Golay encoding and triple redundancy. The on-air time of each coded ALE Word is 392 ms. The shortest 2G ALE transmissions contain three words; this short transmission is common in 2G ALE handshakes. Longer transmissions that are used to initiate link establishment include a scanning call phase on the order of 10 s. The longest possible 2G ALE transmission (rarely used) lasts up to 20 min.

3.3.1.4 2G ALE data waveforms

A range of data modulations is currently used to deliver data over HF channels, including both parallel tone (OFDM) and serial tone (PSK and QAM) modulations. For operation in nominal 3 kHz channels, the serial-tone modulations are currently the most popular.

3.3.2 3G ALE waveform suite

A suite of scalable burst waveforms is used for the integrated 3G ALE protocols: ALE (also called link setup or LSU), Traffic Management (TM), automatic link maintenance (ALM), low-latency data link (LDL), and high-throughput data link (HDL).

3.3.2.1 Modulation

The 3G ALE waveform employs short bursts of phase shift keyed modulation. Variations on this burst waveform are also used for 3G ALE link management and data transmission. Characteristics of the 3G ALE waveform family are summarized in the table below.

TABLE 1

Example characteristics of the typical 3G waveform

Wave form	used for	burst duration	payload	FEC coding	inter-leaving	data format	effectrive code rate[1]
BW0	3G-ALE PDUs	613.33 ms 1 472 PSK symbols	26 bits	rate 1/2, $k = 7$ convolutional (no flush bits)	4 × 13 block	16-ary orthogonal Walsh function	1/96
BW1	Traffic management PDUs; HDL acknow-ledgement PDUs	1.30667 s 3 136 PSK symbols	48 bits	rate 1/3, $k = 9$ convolutional (no flush bits)	16 × 9 block	16-ary orthogonal Walsh function	1/144
BW2	HDL traffic data PDUs	640 + (n × 400) ms 1 536 + (n ×960) PSK symbols, n = 3, 6, 12, or 24	n × 1881 bits	rate 1/4, $k = 8$ convolutional (7 flush bits)	none	32 unknown/ 16 known	variable: 1/1 to 1/4

TABLE 1 (*end*)

Wave form	used for	burst duration	payload	FEC coding	inter-leaving	data format	effectrive code rate[(1)]
BW3	LDL traffic data PDUs	373.33 + (n × 13.33) ms 32n + 896 PSK symbols, n = 32 × m, m = 1, 2, ... , 16	8n + 25 bits	rate 1/2, k = 7 convolutional (7 flush bits)[(2)]	convolut-ional block	16-ary orthogonal Walsh function	variable: 1/12 to 1/24
BW4	LDL acknow-ledgement PDUs	640.00 ms 1 536 PSK symbols	2 bits	None	none	4-ary orthogonal Walsh function	1/1920

(1) Reflects forward error correction (FEC) and Walsh-function coding only; does not include known data or convolutional encoder flush bits.

(2) In this case, the number of flush bits exceeds by one the minimum number required to flush the convolutional encoder; this makes the number of coded bits a multiple of four as is required for the Walsh-function modulation format.

Other waveforms, including the serial tone modem waveform and high data rate waveform, can be used to deliver data and digitized voice signalling on circuit links established using the 3G-ALE and TM protocols.

3.3.2.2 Code combining

The 3G ALE data link protocols employ an advanced adaptive technique called code combining to boost the value of each energy burst sent over the HF channel. The soft decisions of each received symbol are retained at the receiver when a frame of data contains uncorrectable errors. Retransmissions of the frame carry additional error-correction bits which are combined *in an analogue manner* at the receiver with the previously received signal energy, so that the symbols that arrive with stronger SNR are given higher weight in the combining function. This provides a measurable reduction in frame error rate for a given SNR, and boosts the ability of 3G ALE systems to deliver data through channels with low SNR and high interference.

3.4 Techniques to increase data speed

Channel banding can be employed which is based on the use of several 3 kHz channels.

3.4.1 Independent sideband operation

Modems are currently fielded that convey data in multiple independent sidebands simultaneously. Such modems contain independent PSK/QAM modulators for each audio channel, but employ a single forward error correction encoder, whose output bit stream is distributed over the individual channels for transmission. When these channels are carried by contiguous frequencies, the SNR of the channels tend to be similar, although channel errors are not perfectly correlated. Thus, some improvement in output is achieved using diversity combining.

ISB modems currently offer data rates up to 32 kbit/s in two 3 kHz (nominal) channels and up to 64 kbit/s in four channels.

3.4.2 Operation in noncontiguous channels

When continguous channels are not available in sufficient quantity to support data requirements, operation in non-contiguous channels is necessary. In this case, channel SNR values may vary significantly so the distribution of a single coded bit stream over the complete set of channels is not optimal. Instead, separate coded bit streams are generated for each channel band. Flow control operates independently for each channel band so that overall data throughput is maintained near the maximum possible for the frequencies in use.