Jaguar-V frequency-hopping radio system

P.J. Munday, M.A., M.Sc., C.Eng., M.I.E.E., and M.C. Pinches, B.Sc., C. Eng., F.I.E.E.

Indexing term: *Radiocommunication*

Abstract: The electronic threat to VHF tactical communications systems is reviewed, and possible countermeasures are discussed. The principles of the Jaguar-V frequency-hopping system are described, together with some aspects of the radio-system design and technical features of its implementation. Operational aspects of system performance are also discussed.

1 Introduction

1.1 Tactical communications

The most widely used radiocommunications system in most modern armies throughout the world is known as combat net radio (CNR). This system provides short- and medium-range communications over typical distances of up to 50 km throughout the main forces deployed in exercise or battle areas, generally using very high frequencies in the range of 30–76 MHz.

Conventional frequency modulation is employed, with frequencies allocated at 50 or 25 kHz intervals. Operation is normally based on the 'net' principle, with one net used for simplex communications between a group of users on an 'all-informed' basis. Fig. 1 shows a scenario of part of a battle area, comprising a net using two frequencies linked by a station which can provide a repeater facility by automatically rebroadcasting messages from one frequency to the other.

Such system are often complex, involving many nets with provision for communication over larger areas by interoperating with fixed-line communications, radio relay systems etc. In addition, CNR systems are increasingly being used for digital-message purposes and encrypted speech transmissions. The VHF Clansman range of equipments, now in service with the British Army, is typical of the modern conventional radio systems now in service and includes a low-power portable synthesised radio, manpacks and larger equipments for use in soft-skinned and armoured vehicles. These equipments are designed to operate under adverse environmental conditions such as extreme temperatures, high vibration levels and humidity etc.

1.2 Threat

Any communications system which is an essential part of command, control and communications strategy must now expect to be assessed for its vulnerability to attack by the new weapons of the electronic armoury.

Surveillance is the first requirement for any such electronic attack, and modern surveillance systems can readily permit detection and monitoring of radio traffic under battle conditions [1]. Even with the use of sophisticated encryption devices, or communication security (COMSEC), useful intelligence can still be gained. For example, knowledge of the frequency of a communication link enables jamming or direction finding to be employed. Patterns of activity can tell experienced operators a great deal, and, if the use of COMSEC devices is restricted to important links only, such links are immediately identified. A first priority is therefore to provide protection against interception.

An enemy can try to deny the use of the frequency spectrum for communications by jamming, and he is most likely to use this approach at a critical point in the battle when communications are vital. Modern jamming equipment can be compact, operable on the move, and can be programmed to watch a number of frequencies. In addition, there is the possible future threat of expendable jammers, delivered by parachute, covert patrols or even artillery fire. We must therefore provide protection against jamming.

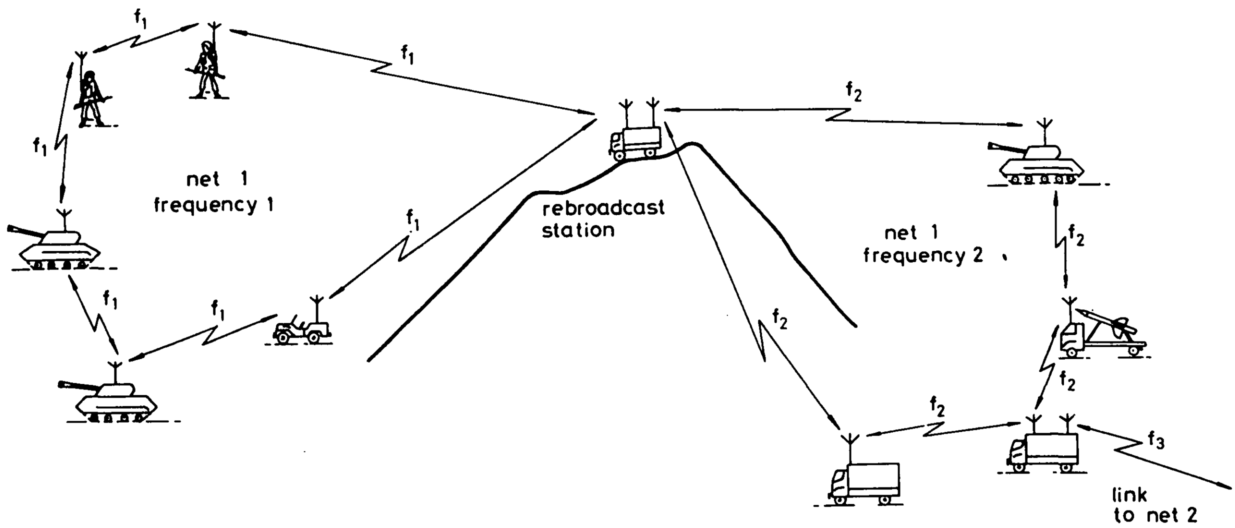

Fig. 1 *Typical CNR system*

Finally, the use of direction-finding and position-fixing techniques to plot the position of transmitters must be considered. Information on the location of field headquarters is of particular benefit to the enemy. At a headquarters, there would often be many radios operating on different nets, and,

Paper 1896F, first received 5th January and in revised form 16th March 1982

Mr. Munday is with Racal Research Ltd., 11 Bennet Road, Reading RG2 0PZ, England, and Mr. Pinches is with Racal-BCC (British Communications Corporation Ltd.), 23 Stonefield Way, South Ruislip, Middlesex HA4 0YH, England

0143–7070/82/030213 + 10 $01.50/0

by correlating position-fixing information from different nets, field headquarters could be identified and located.

1.3 Possible solutions

It is obviously possible to reduce vulnerability to electronic attack from any of the means above by the adoption of good practice in the use of conventional communications equipment. Minimising the power and duration of transmitted messages is the most obvious strategy, and this can be further assisted by the use of 'burst'-message techniques. However, these techniques give only a modest amount of protection.

Hence we are forced to look for further protection. Spread-spectrum techniques [2] and antenna nulling appear to offer promising solutions.

We can categorise methods of spreading the radiated energy of our transmission in many ways, and the most commonly recognised categories are:

(*a*) direct sequence
(*b*) frequency hopping
(*c*) chirp
(*d*) time hopping.

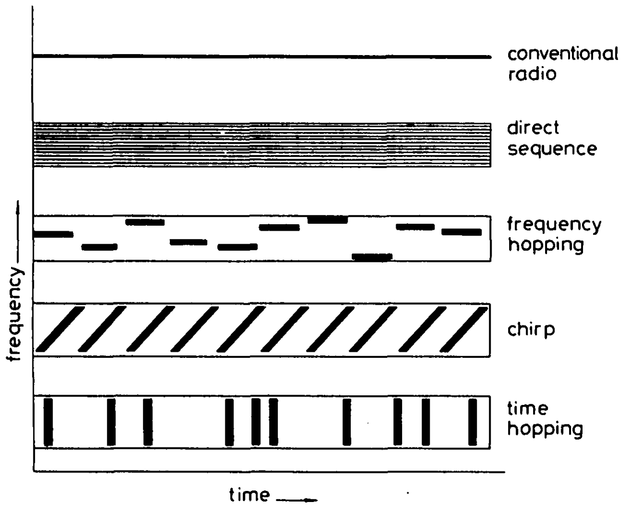

Fig. 2 *Spread-spectrum techniques*

Fig. 2 shows the relationship between these categories in terms of energy density against frequency and time, with relative energy density per unit of transmitted bandwidth indicated by intensity of grey scale.

Direct-sequence (DS) techniques rely on spreading the energy of the baseband transmission continuously over the required bandwidth by multiplication with a pseudorandom digital code sequence at an appropriate rate.

Frequency hopping (FH) is based on changing the instantaneous frequency of the narrowband transmission in a pseudorandom manner over the required bandwidth.

Chirp techniques require the instantaneous frequency of the transmission to be swept across the required bandwidth in an appropriate manner. Depending on the rate of frequency sweep, chirp can normally be regarded as a special case of either direct sequence or frequency hopping.

Time hopping requires high-power bursts of wideband transmission at pseudorandom intervals in time.

However, of the four spread-spectrum systems quoted, all but one can quickly be eliminated for use in the role of communication links for tactical combat net radio.

Direct sequence has been used successfully in satellite links. Although its use has been postulated in land mobile radio [3–5], its performance would be extremely poor owing to the 'near/far' problem, i.e. trying to receive a weak signal from a distant transmitter in the presence of a nearer transmitter within the spread bandwidth.

Consider, for example, a VHF FM signal of 15 kHz bandwidth spread by a digital code sequence of 3.75 MHz. The resulting spectrum is shown in Fig. 3. The mainlobe of the spread-spectrum signal is 7.5 MHz wide, and the 'processing gain', defined as

$$\frac{\text{code rate}}{\text{information bandwidth}} \text{ or } \frac{\text{width of mainlobe}}{2 \times \text{information bandwidth}}$$

is 24 dB. Suppose there is now a single-tone interfering signal at frequency separation f from the centre of the spread signal. After despreading in the receiver, the energy in the interfering signal is spread as shown, and a fraction of this energy falls inside the receiver bandwidth. This fraction is -24 dB for $f = 0$ and falls to -32 dB for $f = 2.5$ MHz. In other words, interfering signals in the middle 5 MHz of the spread bandwidth will be effectively attenuated by between 24 and 32 dB relative to the wanted signal. If the wanted-signal range is 20 km, the 24 and 32 dB figures correspond to ranges of 5 km and 3.3 km for an equal-power transmitter (assuming inverse fourth-power propagation law). Thus any transmitter, of equal power to the wanted transmitter, anywhere within this 5 MHz bandwidth and closer to the receiver than 3.2 to 5 km will cause a signal/noise ratio of less than 0 dB at the receiver detector, and hence prevent communication. This marked susceptibility to nearby transmitters within the spread bandwidth effectively rules out direct sequence for land mobile radio.

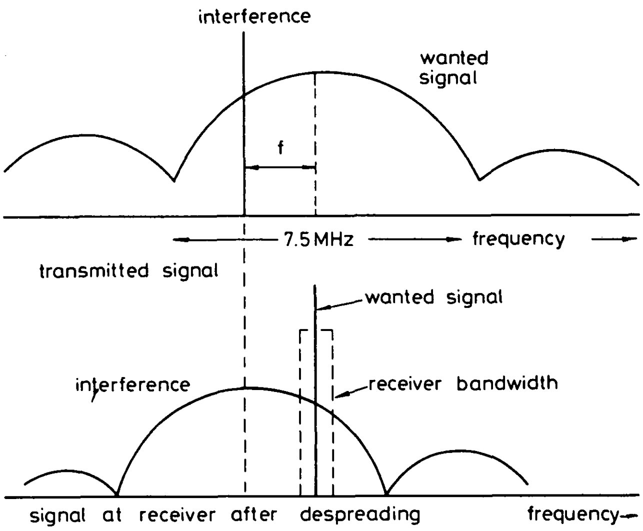

Fig. 3 *Effect of interference on direct-sequence transmission*

With chirp, the enemy could fairly easily determine the characteristics of the chirp and transmit spurious chirp signals to capture or jam the chirp receiver. Fast chirp, in addition, suffers from the same near/far problem as direct sequence.

Time hopping, like direct sequence, requires a wide instantaneous bandwidth, and similar arguments about the near/far problem apply. In addition, high-peak-power transmitters are required, which are technically difficult and not cost effective.

Antenna nulling, which makes use of an antenna array with electronically steerable nulls, can also provide resistance against jamming. However, the equipment required is more complex than for, say, frequency hopping and is more vulnerable to intelligent jamming, e.g. pulse jamming. The antenna array required is not suitable for manpack roles. In addition, antenna nulling does not provide any real protection against interception, monitoring or direction finding. Although nulls in transmit can be produced, there are technical problems with doing so, and transmit nulls have no real value, except in the unlikely event of the direction of the enemy's surveillance station being known in advance.

Frequency hopping, by contrast, has a good near/far performance and can be implemented with less complex circuitry than the other techniques. It can be made to have good resistance to the various forms of electronic attack, and it is by far the most suitable technique for overcoming interception, direction finding and jamming. It has also been considered for use in civil mobile-radio applications [6].

2 Principle of the Jaguar-V frequency-hopping system

2.1 Basic parameters

Fig. 4 shows a simplified schematic diagram of the basic frequency-hopping principle, with the extra parts not normally used in conventional radio shown in broken outline.

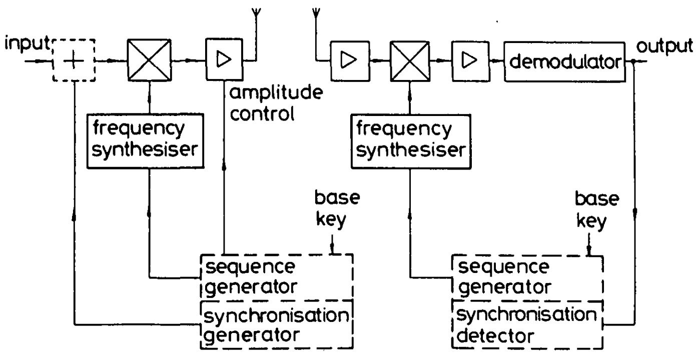

Fig. 4 *Frequency-hopping-system schematic diagram*

The frequency of the synthesised transmitter is controlled by a sequence generator, which is, in turn, programmed with a code (known as base key) in order to achieve a specific sequence of frequencies of transmission. At the receiver, the same sequence is produced by an identical generator, provided the same base key has been programmed, and, once synchronisation is achieved, communication is established. Synchronisation data are added to the transmission at times, and the receiver requires a detection system for these data in order to acquire and maintain synchronisation.

The main parameters to be established for such a system are as follows:

(i) hop rate = the number of frequency changes per second

(ii) hop bandwidth = the maximum frequency range over which the transmission is spread

(iii) hop sequence = the relationships between the frequencies of consecutive transmissions

(iv) synchronisation system.

We shall now consider each of these in further detail.

2.2 Hop rate

Clearly, the more frequently that the frequency of transmission is changed, the greater is the problem faced by the opposing force. However, there are a number of other factors to be taken into account. Fig. 5 gives an indication of how the different factors tend to be affected by hop rate. The vertical scale gives an arbitrary figure of merit, and the position of the curves with respect to the horizontal axis (hop rate) is only approximate. The curves represent possible frequency-hopping systems so far identified by the authors, but this is not to say that systems with different characteristics are not possible.

Protection against *detection* and *direction finding* tends to increase with hop rate. The shorter the hop period, the harder it is for the energy due to a single hop to be detected, although this is to some extent offset by the greater rate at which a particular frequency is used. Modern automatic direction-finding systems can in theory operate very quickly, but in practice need to average a number of bearing readings in order to give reasonable accuracy. The faster the hop rate, the fewer the number of bearing measurements that can be made on a single hop. Correlating the bearing measurements over different hops is possible but more difficult to do, especially if there are many frequency-hopping transmitters active at the same time.

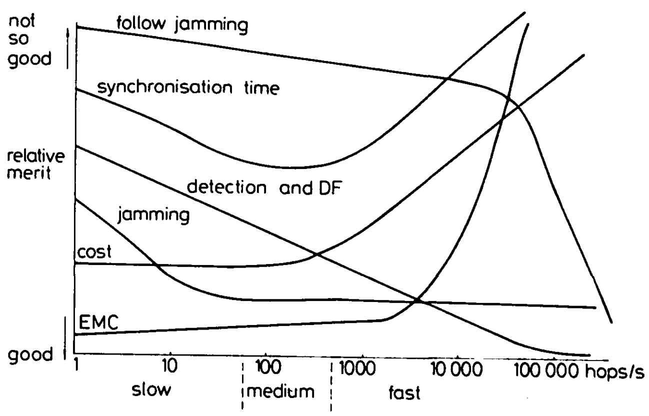

Fig. 5 *Hop-rate trends*

Protection against a sophisticated *fast follower jammer*, having the ability of search for, and lock on to, transmissions virtually instantaneously, cannot be guaranteed until individual transmissions become comparable in duration with the typical propagation-path delay to and from the jamming source. This can easily be shown to be equivalent to hop rates of at least 10 000 hops/s. However, fast follower jammers are unlikely to become a serious threat in practice. An algorithm to track one individual frequency-hopping transmission would have to monitor changes in energy levels on all, or most of, the hop channels. Within the hop bandwidth of the target transmission, there are likely to be many other signals, fixed frequency and frequency hopping, continually appearing and disappearing. There would also be energy changes on the hop channels due to either signal modulation, multipath signals from moving transmitters, or beating effects between signals. (As an example of the last effect, if there were an interfering signal 6 dB below the target signal on a given channel, the beating effect between these would cause an amplitude variation of 10 dB as the two signals went in and out of phase.) All these factors would tend to make the tracking algorithm virtually unworkable unless the target frequency-hopping transmission was much stronger than most of the other signals in the hop band, i.e. the jammer would have to be very close to the target transmitter.

All the viable *synchronisation* systems so far identified by Racal, i.e. those which are resistant to intelligent jamming or 'spoofing', tend to exhibit the characteristic of having an optimum at medium rates. At slow hop rates, the possibility of several channels being jammed in sequence results in potentially long synchronisation times, whereas, at fast hop rates, only a limited synchronising signal can be sent on each transmission.

In the case of simple *jamming*, a poor performance results at low hop rates, since blocked channels result in bursts of interference comparable in length with the syllabic content of speech.

The *cost* of a hopping system will tend to escalate at rates of greater than 1000 hops/s or so because of the need for more complex circuitry, e.g. fast switching synthesisers, and more accurate frequency standards.

The *electromagnetic-compatibility* (*EMC*) aspects also become very significant above about 1000 hops/s, for two reasons. First, the receiver IF filters 'ring' when the receive frequency is changed, and, unless sufficient time is allowed for the 'ringing' to decay, the EMC performance is seriously degraded. Secondly, a fixed time needs to be allowed for powering the transmitter up and down in a controlled way and for changing frequency. Therefore a higher proportion of the hop period must be 'wasted' as the hop rate increases, forcing the transmission to become wider in bandwidth.

Following an evaluation of these factors, the hop rate of the Jaguar-V system was chosen to be at a medium speed, in the region of 50–500 hops/s.

2.3 *Hop bandwidth*

The VHF band of frequencies normally used for combat net radio extends from 30 to 88 MHz, although, in many countries, not all this band is available for military purposes, at least in peacetime.

Clearly, the wider the bandwidth of the hopping transmission, the greater the problem faced by an opposing force. Again, however, there are other factors to be considered, and we shall show in Section 3 that the requirement for simultaneous close proximity operation of transmitters and receivers is a crucial factor.

In its normal operating mode, the Jaguar-V system is designed to hop over a bandwidth of 6.4 MHz, corresponding to 256 channels at 25 kHz spacing, and this provides 9 hop bands, as shown in Fig. 6.

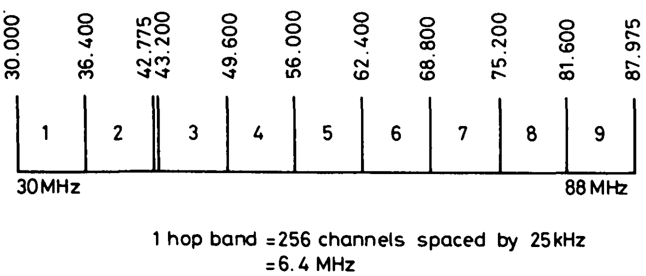

Fig. 6 *Frequency-hopping bands*

This spread bandwidth provides a processing gain (PG), defined as 10 log (number of hop channels), of 24 dB. The figure of 24 dB gives an indication of the extra power required to jam a frequency-hopping radio link compared with that required to jam an equivalent fixed-frequency radio link. The precise amount of extra power depends on how the jammer might attack the two links. The optimum strategy against fixed frequency would probably be to pulse the jammer on and off at a duty cycle of about 50%, as this would render the speech unintelligible. The optimum strategy against frequency hopping would be to spread the jammer power over about half the hop channels, again blocking about 50% of the speech. The relative mean jammer powers required for the above strategies would be 24 dB (the processing gain), although the relative-peak-jammer-power ratio is 21 dB. This figure assumes that the enemy knows which hop band the target net is using. If a number of frequency-hopping nets are active and all the hop bands are in use, it would be difficult for the enemy to determine which hopping net is which, and he may need to jam all nine hop bands to be sure of jamming a particular net. The processing gain would then become approximately 34 dB.

2.4 *Hop sequence*

The sequence of frequencies used in a hopping system needs to be produced in a manner that will not readily permit opposing forces to predict the next frequency to be used from knowledge of the previous transmission frequencies. In order to achieve this, a highly nonlinear pseudorandom sequence is used, and, for maximum security, it is of such complexity that it does not repeat in less than 24 h. This sequence is generated by a keystream generator (KG), which consists of a complex arrangement of feedback shift registers loaded with the base key. In the case of the Jaguar-V system, the base key comprises 25 digits, each of which may be an octal number, i.e. comprising 3 bits.

Hence 2^{75} possible code sequences exist (approximately 10^{22}), and it can be seen that the task of predicting the next frequency from knowledge of previous transmissions poses major difficulties.

Of course, like any other cryptographic system, it is essential that knowledge of the base key is available to all who wish to communicate and that it is not available to any opposing forces.

2.5 *Synchronisation system*

The most important aspect of any frequency-hopping system is the synchronisation method adopted and its performance under limit range conditions and under EW attack. The main requirements for synchronisation (sync) are as follows:

(*a*) It must be automatic and rapid.

(*b*) It must operate with marginal signal levels.

(*c*) It must be resistant to interference, deliberate or accidental.

(*d*) It must only synchronise to signals with the correct code.

(*e*) It must have provision for stations to join at any time.

(*f*) It must not affect the quality of the wanted message.

(*g*) It must be resistant to enemy manipulation by the transmission, or retransmission, of spurious synchronisation signals, known as 'spoofing'.

In addition, it is highly desirable that the system does not require absolute time information to be entered before synchronisation can occur.

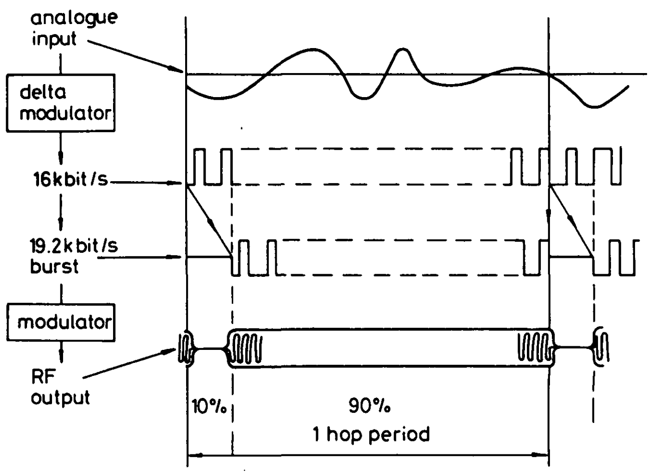

Fig. 7 *Transmission method*

In order to pass digital synchronisation signals in a manner that will not be recognisable to opposing forces, all transmission are in digital form. Fig. 7 shows the method of digitising and compressing speech in order to allow time for changing frequency. First, analogue speech (or data) is encoded via a delta modulator into 16 kbit/s data. This is then stored and extracted in bursts at 19.2 kbit/s as required, to allow time for changing frequency. In addition, storage is provided such that synchronisation data can be sent on certain frequencies during normal transmission, again in such a way that a completely transparent communication path is provided at 16 kbit/s.

Normal synchronisation is carried out on a subset of the 256 available channels, these being derived from base key and being carefully distributed across the full band. Sync transmissions occur periodically but are irregularly spaced in time.

The sync signal itself is based on a sync word, encoded with forward error correction and masked by an autocorrelation sequence. The sync word contains a number of items of information, including an arbitrary time and the type of message being transmitted.

This basic synchronisation process is varied under certain conditions, namely for initial synchronisation (when a communications link is first established) and at the start and end of a transmission. This is done to provide very rapid synchronisation and resynchronisation under these conditions.

In addition, in order to provide interoperability with conventional radio equipment, a receiver in the hop mode, but not receiving a hopping transmission, carries out a search of a defined frequency at intervals and will provide a burst of 'hailing' tone to alert the operator if a transmission is found on that frequency. The receiver operator may then revert to fixed-frequency mode in order to communicate if he wishes, or he may choose to ignore the hailing tone.

3 Radio-system design

3.1 RF parameters

The introduction of a new concept such as frequency hopping requires a reappraisal of all aspects of conventional system design.

One of the primary design parameters of such a system results from the desire of most users to transmit and receive simultaneously with two equipments mounted in close proximity and operating on frequencies spaced by as little as 10% separation. Often, the two equipments are required to be within the same vehicle, and for practical reasons, such as the mounting of antennas on the rotating turrets of armoured vehicles, antenna separations of 2 m are considered normal.

This frequency separation of 10% may seem generous to those familiar with civil land-mobile-radio practice, but significant differences between the two superficially similar cases exist. In the case of a typical duplex base station for land mobile use, the two frequencies used may be only 5% apart but are generally fixed by the licensing authority. If more than one channel is used, a very close spread is normal. Highly selective mechanical filters can be used, often physically large, and the exact relationship between the wanted and the unwanted signal is known in advance. In the tactical case, however, rapid channel switching over the whole VHF band is required, with no prior knowledge of the exact frequency relationship between the wanted and unwanted signals.

Consider the dynamic range involved in such an example:

transmitter power (50 W)	+ 47 dBm
receiver sensitivity (1 μV)	− 113 dBm
antenna coupling (typical)	13 dB

Hence the interfering transmitter power level at the receiving antenna can be as great as + 34 dBm, and a dynamic range of 147 dB is required.

In previous generations of fixed-frequency equipment, such as the Clansman range in current use by the British Army, highly selective antenna-matching units are frequently used. In the case of the Clansman unit (BCC 543 manufactured by Racal BCC Ltd.) typical selectivity is − 27 dB at ± 10% from the tuned frequency. However, the provision of such selectivity, capable of switching at Jaguar-V hop rates, has not been found to be economically viable, and broadband antenna matching is therefore required. In particular, if matching over at least individual 6.4 MHz-wide bands is to be provided, then insignificant selectivity can be incorporated against close-proximity signals. Consequently, the main design problem of the Jaguar-V system has been to improve the overall dynamic range of the transmitter and receiver by some 30 dB compared with previous generations.

In order to provide this range, particular attention must be paid to the spectral purity of oscillators used in both transmit and receive paths. For example, from the figures given above, a noise level of greater than − 113 dBm from the transmitter within the receiver bandwidth will prevent reception of 1 μV-level signals. Thus the transmitter carrier/noise ratio has to be better than 147 dB at the required offset frequency. Since the receiver bandwidth is 20 kHz, this corresponds to a spectral noise density of − 190 dB/Hz relative to the transmitter carrier level.

To achieve this level of sideband noise suppression, it is necessary to operate oscillators at power levels of the order of 1 W and to use the latest low-noise devices for power amplification.

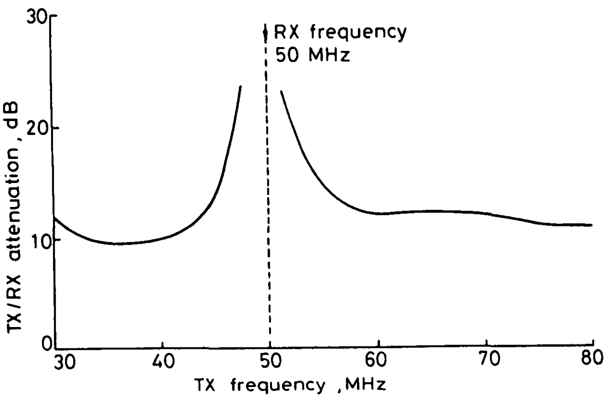

Fig. 8 *Co-siting performance (fixed-frequency mode)*

The typical co-siting performance of the Jaguar-V system is shown in Fig. 8.

This measurement is carried out by establishing the minimum attenuation between a 50 W Jaguar-V transmitter whose frequency is being varied and a Jaguar-V receiver set to 50 MHz receiving a signal 6 dB above nominal sensitivity.

From Fig. 8, it can be seen that, provided antenna separations corresponding to path losses of greater than 12 dB or so can be provided, co-siting is possible for frequency separations of greater than 10% in the fixed-frequency mode. Antenna separations of 2 m typically correspond to path losses in the region of 14–18 dB across the frequency band.

In the frequency-hopping mode, the co-siting performance has to take account of the statistical nature of the interference that may result. For example, if adjacent hop bands are used for a rebroadcast (or retransmission) station, some interference will result in hop periods when the transmit/receive frequency separation is less than, say, 10%, if the transmitter power is 50 W and 2 m antenna spacing is used. To eliminate

Table 1: Co-siting capability, frequency-hop mode

Power	Antenna separation	Frequency separation	Interference level
W	m		
50	2	1 guard band	negligible
50	20	adjacent bands	negligible
50	100	same band	low
4	2	adjacent bands	low
4	2	same band	acceptable

this interference, either the power must be reduced, the antenna spacing must be increased, or greater frequency separation must be used. If the hop bands used by the two radios are separated by one 'guard' hop bandwidth, the problem is substantially eliminated. This gives a very simple form of frequency planning for multiple-hopping radio fits. Table 1 lists the typical performance of various co-siting configurations that may be considered in the frequency-hopping mode.

3.2 Modular configurations

Recent emphasis on aspects such as total life costs and logistic support has encouraged the designer towards a modular approach to the overall requirements for new generations of communications systems. The Jaguar-V system is designed to meet a wide range of requirements from appropriate combinations of a range of compatible units.

The basic modules comprise:

R/T unit	basic 4 W transmitter/receiver
vehicle-interface unit (LP)	adapts R/T unit for vehicle use
vehicle-interface unit (HP)	long range (incorporates 50 W PA)
antenna-matching unit	for vehicle installation

These are supplemented with a wide range of items, such as:

COMSEC unit (communication security) – encryption system
manpack carrying frames, batteries and antennas
audio ancillaries – headsets/handsets etc.
extended- and remote-control units
data-adaptor unit
programming devices
fast battery chargers
vehicle intercom/radio control system (Harness)

In addition to the modular system philosophy, a similar approach has been used in the design of the individual units.

Fig. 10 *Jaguar-V vehicle radio*

The R/T unit, for example, comprises eight fully interchangeable plug-in modules, each designed for ease of maintenance. Fig. 9 shows the overall block diagram for the R/T unit, partitioned according to the module content. Two low-power CMOS microprocessors are used, one in the keyboard and display and one in the main control unit. It may be noted here that two versions of the control unit have been designed, the simpler version offering conventional fixed-frequency operation only, at reduced cost.

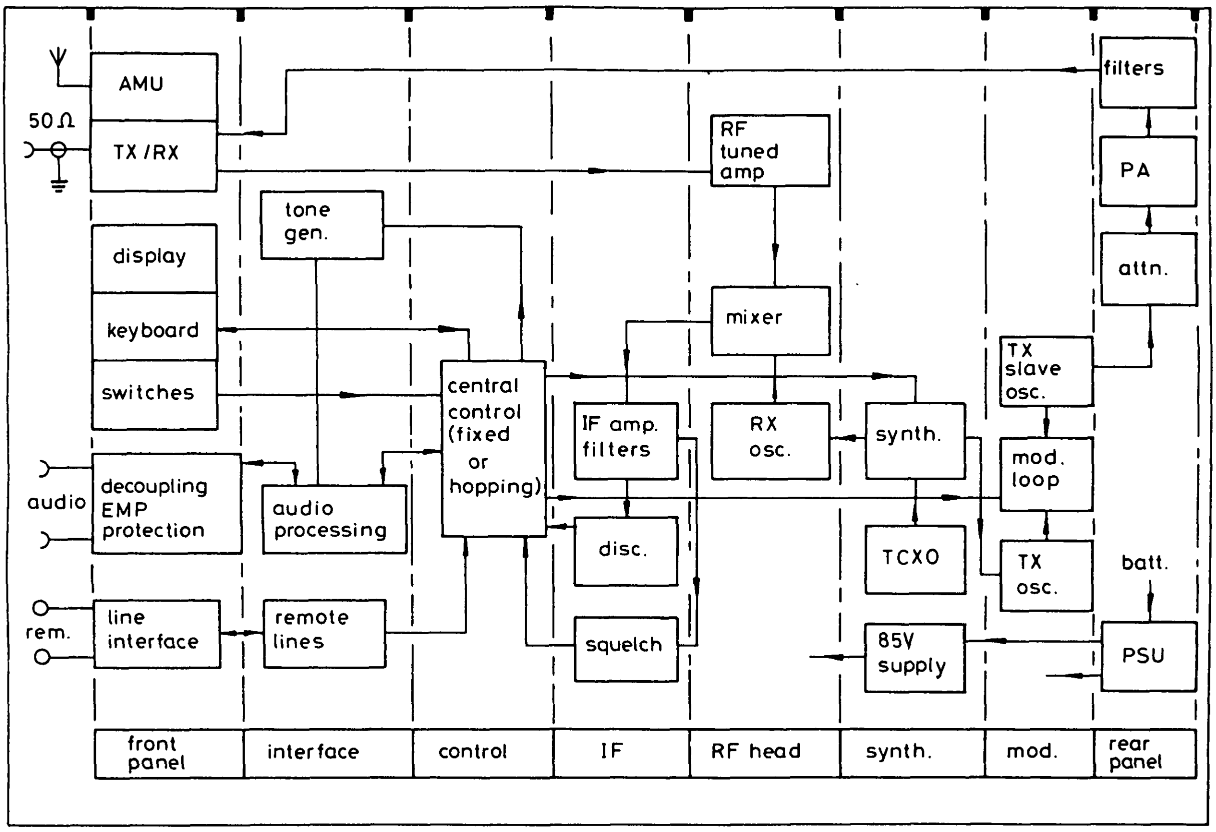

Fig. 9 *VHF-R/T-unit schematic diagram*

Fig. 10 shows a typical 50 W vehicle installation, comprising (from left to right) the optional COMSEC (or encryption) unit, the R/T unit and the long-range vehicle interface unit.

4 Technical features of the Jaguar-V system

4.1. Frequency synthesiser

The main requirement for a frequency-hopping radio is for the synthesiser to carry out frequency changes to the required accuracy within a small part of the hop period. For the Jaguar-V synthesiser system, a target of 10% of a hop period to be within 1 kHz of the new frequency was required.

The solution adopted is based on a conventional single-loop approach with the use of a dual modulus prescaler (Fig. 11), but it has been found necessary to use additional techniques during frequency changes. in order to achieve the required lock-up times. The parts of the schematic diagram enclosed within the dotted lines in Fig. 11 have been implemented in a single custom LSI circuit by Racal Microelectronic Systems Ltd. using CMOS technology.

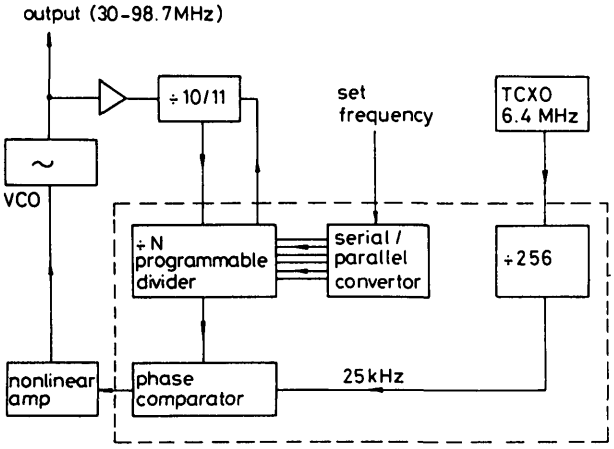

Fig. 11 *Frequency synthesiser*

The alternative possibility of using two simple synthesisers and switching between them is superficially attractive but requires duplication of oscillator and prescaler components and introduces significant additional spurious-signal considerations as a result of the need to have two oscillators operating simultaneously.

4.2 Noise performance

As outlined earlier, the noise performance required by the Jaguar-V system necessitates a noise level from the transmitter of less than − 190 dB/Hz relative to the 50 W power level at frequencies greater than 10% from the carrier. This target is achieved in two parts as follows.

4.2.1 Basic R/T unit: A noise performance of better than − 180 dB/Hz relative to the nominal 4 W power output level is achieved by the use of MOS-technology oscillator and power amplifier devices. This level is more than adequate to ensure the required co-siting performance at the 4 W level.

4.2.2 Vehicle interface unit (long range): This interface unit, which provides a gain of about 12 dB, incorporates an additional stage of selectivity in between the two stages of amplification. This selectivity reduces the noise sidebands at frequencies greater than 10% from the carrier by at least 10 dB, and hence the overall target is achieved.

The selectivity is, of course, required to be switchable at the hop rate and to operate at a power level of 10 W. Fig. 12 shows a schematic diagram of the system, which uses a PIN-diode switched-capacitor network controlled by frequency information in the form of serial data from the R/T unit.

4.3 RF envelope shaping

During frequency transitions, it is clearly necessary to inhibit the transmitter output in order to prevent uncontrolled spurious transmissions across the frequency band. In addition, the RF power is required to be turned off and on in a manner designed to minimise AM sidebands.

In order to achieve this, a constant-impedance attenuator is used at the high-power oscillator output, which is controlled via a shaping circuit to achieve the optimum rise- and falltimes. The overall attenuation during frequency transition is greater than 70 dB, and it will be noted that subsequent gain stages are therefore required to be substantially linear.

Note that there is no need for analagous measures to be taken in the receiver, since the interference caused by spurious reception during frequency changes occurs, by definition, during gaps in the wanted signal. It is, however, important to ensure that the IF filters have recovered from such impulses before wanted signals are again present, which can present major difficulties to the designer of fast hopping systems.

4.4 16 kbit/s line system

A feature of the Jaguar-V system, although not directly linked with the ECCM capability, is the provision of facilities for remote control over two-wire field-telephone cables over distances of up to 3 km.

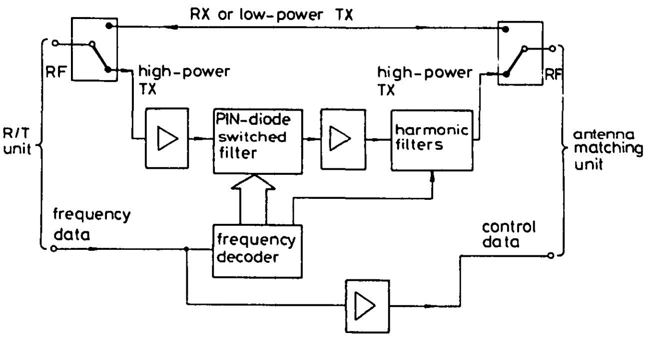

Fig. 12 *Vehicle interface unit*

Power supply, audio and other functions not shown

In addition to the normal capabilities of such systems for remote radio and automatic repeater operation with two radios, the Jaguar-V system permits 16 kbit/s data or encrypted speech to be sent over the line, allowing the use of encryption systems separated from the radio.

In addition, two Jaguar-V equipments can be connected via the line system to permit one equipment to control the operating mode and frequency of the other.

5 Operational aspects

5.1 Effect of blocked channels

With conventional fixed-frequency radios, a signal/noise or interference ratio of typically 3 dB or better is required at the receiver in order to be able to communicate. With frequency hopping, communication would be possible even if there were large negative signal/noise or interference ratios on a significant proportion of the hop channels. Table 2 shows the subjective effect of differing proportions of 'blocked' hop channels on the speech quality with Jaguar-V frequency-hopping radios. A blocked channel is defined to be one on which the signal/noise or interference ratio is less than about 3 dB.

Table 2: Effect of blocked channels on speech quality

Porportion of blocked channels	Speech quality
%	
5	noticeable effect, but not objectionable
10	some degradation
20	degraded but readable
30	difficult to understand
50	unreadable

Blocked channels often arise on frequency-hopping links owing to either multipath cancellation effects or interfering signals on certain channels, or both. These effects will now be considered.

5.2 Multipath propagation

Multipath effects cause an enhancement of signal level on some frequencies and a reduction in signal level on others, depending on whether the multipath components tend to add in phase or antiphase. On fixed-frequency links, multipath can be either beneficial or adverse. Moving the receiving antenna by the order of one wavelength (a few metres at VHF) can often change the signal level quite significantly.

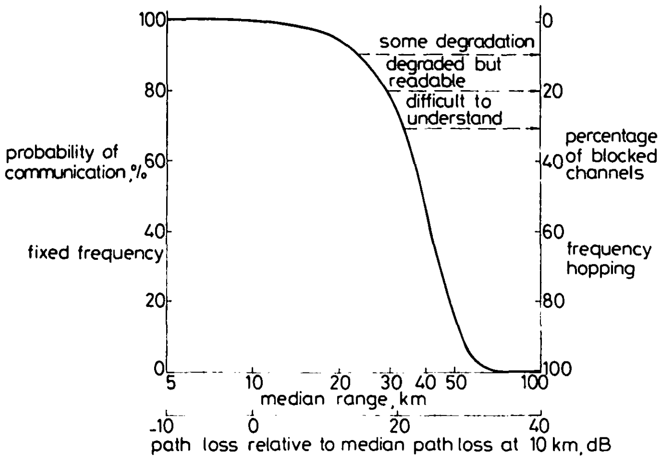

Fig. 13 *Effect of multipath on range*

For fixed frequency, use left-hand ordinate. For frequency hopping, use same curve with right-hand ordinate

Some studies have found that multipath effects tend to give rise to variations in field strength that can be represented by log-normal probability distributions, while other studies have indicated a Rayleigh distribution [7]. The latter is more likely in areas containing buildings. The effect of multipath (using a Rayleigh model) on achievable 'median' ranges for fixed-frequency and frequency-hopping radio links is shown in Fig. 13 for Jaguar-V 50W radios (which have a median range of 39 km). It can be seen that, for fixed frequency, in 10% of cases, the range exceeds 52 km owing to beneficial multipath effects, whereas, in another 10% of cases, the range is less than 25 km owing to adverse multipath effects. For frequency hopping, the signal/noise ratio will vary for different hop frequencies, and the average proportion of blocked channels is shown in Fig. 13. It can be seen that, at a range of 25 km, 10% of channels will be blocked, giving rise to speech quality with 'some degradation'. At 29 km, 20% will be blocked, giving 'degraded but readable' speech. At 32 km, 30% will be blocked, and the speech will be 'difficult to understand'. Moving the receiving antenna will change the signal levels on different frequencies, but the proportion of blocked channels will hardly change. Thus, in fixed frequency, one might be either 'lucky' or 'unlucky' with regard to multipath, unless there is freedom to move the receiving antenna to search for a good site. In contrast, with frequency hopping, the effect of multipath is averaged out, and ranges are much more predictable. (It must be pointed out that Fig. 13 is intended to demonstrate multipath effects only. Reference 7 shows that the effect of hills and valleys is to give further and more significant variability to ranges, designated 'large terrain variations', which are effectively independent of frequency. Median values for large terrain variations have been assumed in Fig. 13. The effect of the large terrain variation can be taken into account in Fig. 13 by using the lower horizontal axis. For example, for a 20 km range and at a point where the large terrain variation gives a field strength 8 dB below median, the path loss relative to the median path loss for 10 km range is 12 dB + 8 dB = 20 dB, the probability of communication is 70% for fixed frequency, and there are 30% blocked channels for frequency hopping.)

When either the transmitter or receiver, or both, are in moving vehicles, the relative phases of the multipath signal components change continuously, and therefore so does the signal level. The rate of change depends on vehicle speed. This can lead to an annoying 'flutter' on fixed-frequency links, which can be serious if it is close to the syllabic rate of speech. For radios in helicopters, reflections from rotor blades cause similar problems. With the Jaguar-V frequency-hopping system, the signal constantly hops between 'good' and 'bad' frequencies, but the hop rate is too fast for any flutter to be audible, and practical trials in moving vehicles and helicopters have shown a marked improvement in speech quality when frequency hopping is used.

5.3 Effect of interfering signals

In VHF radio links, there are often large numbers of other transmissions, all of which could be potential interfering signals. Defensive forces usually employ frequency planning, but often the same frequency has to be allocated two or more times, albeit to radio nets geographically dispersed. Of course, the enemy's radios would not be frequency planned with one's own, and neither might be allied forces' radios in the same battle area. Thus, for a given net in fixed-frequency mode, there would probably be other radio nets using the same frequency, and it would be a matter of chance whether or not one of these nets was transmitting at the same time as the given net, and a matter of chance whether or not the interfering signal exceeded the wanted signal at the receiver. Thus reliable communication cannot always be guaranteed, although one might at times be 'lucky' and have no interference on the channel, and thus be able to communicate over long ranges.

With frequency-hopping nets, the effect of interference on the hop channels tends to be averaged out, so that the element of chance with fixed frequency, discussed above, is virtually eliminated. Thus more predictable performance is achieved. In addition, owing to the reliable synchronisation system, no interference is heard unless a wanted signal is present.

Racal has carried out extensive computer modelling to ascertain the ranges likely to occur in practice in congested VHF scenarios. The modelling is quite complex, and a number of assumptions have to be made. The main features of the model are given below.

A plan of the assumed battlefield is given in Fig. 14. Opposing forces, arranged in divisions, face each other across the front line of troops (FLOT). The forward divisions occupy an area 20 x 40 km, and the reserve divisions 40 x 40 km. Each division has 256 radio nets. It is assumed that, in the front half of the forward division, one member in each net is actively transmitting, i.e. utilisation (u) = 100%. (This utilisation figure corresponds to extremely high radio activity at the height of the battle. It is likely that the actual utilisation will often be considerably lower.) Elsewhere, only half the nets are actively transmitting. It is assumed that frequency planning exists between the two forward and one reserve division that form a corps, but that no frequency planning exists between corps. This has been taken into account in the model by assuming that 75% of the fixed-frequency radios in the battlefield (all the enemy's and half of one's own side's) are potential interferers with the fixed-frequency radios under consideration.

Some results from this modelling are given in Fig. 15, which show the probability of communication for different ranges for 50 W fixed-frequency and frequency-hopping nets close to the FLOT. It can be seen that the range giving 90% probability of communication for fixed frequency is 13 km, and, for frequency hopping, it is between 12.5 and 8.5 km, depending on the speech quality that is acceptable. It can be seen that the frequency-hopping probability curves are steeper than those for fixed frequency, reflecting the removal of the element of chance concerning interference. The cause of the curves not being vertical lines is the 'large terrain variations' referred to earlier, which affect all frequencies equally. The cause of the fixed-frequency ranges being slightly larger is the slight advantage that frequency planning within the corps gives to fixed frequency.

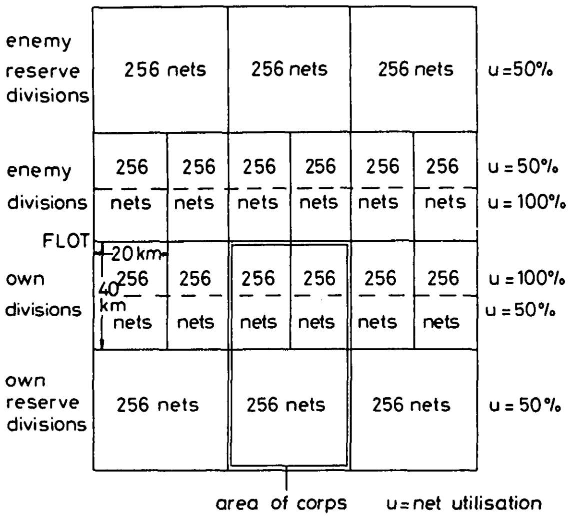

Fig. 14 *Model of the battlefield*

It is sometimes suggested that it would be advantageous for different frequency-hopping nets to hop in co-ordinated non-interfering (orthogonal) sequences. However, the advantage would be slight, as there are likely to be many more fixed-frequency than frequency-hopping nets, and the interference due to the former will be the more significant. Orthogonal hopping will not help against this interference, and so will give only a small increase in range. It will also lead to serious technical and operational problems. All the hopping nets would need to be in a common state of synchronisation and use the same 'base key' for the hopping sequence. The former would be extremely complex to set up and maintain and would lead to operational restrictions. The latter would lead to a security compromise of all hopping nets if the enemy could discover the common base key as a result of the capture of just one radio which has not been 'zeroised', i.e. it has base key still intact.

5.4 Effect of deliberate jamming

The ranges of frequency-hopping nets will be slightly less than those for fixed-frequency nets, in the absence of jamming. However, when deliberate jamming is introduced by the enemy, there will be a significant advantage for frequency hopping. The advantage of frequency hopping over fixed frequency, against optimum jamming strategies, has been shown in Section 2.3 to be around 24 dB for Jaguar-V. This means that, for frequency hopping, ranges in the presence of jamming will be around four times those for fixed frequency (assuming inverse fourth-power propagation law). Jamming might typically reduce the range of fixed-frequency nets to 4 km, while allowing ranges of around 16 km for frequency-hopping links. The jammer would need to have its energy spread over a significant proportion of the hop bandwidth, and hence the energy in any one channel would be reduced. This will ease the position of fixed-frequency radios affected by the jammer. By spreading the jamming power, the enemy runs an increased risk of jamming some of his own communications.

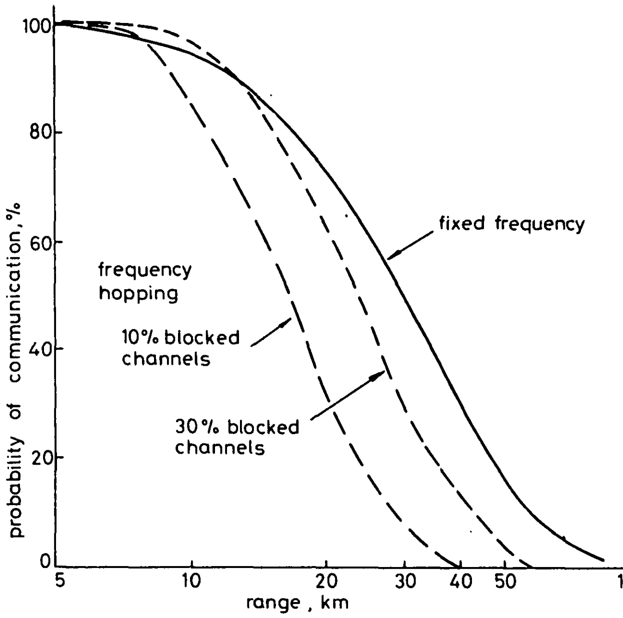

Fig. 15 *Effect of battlefield interference on range*

The above calculation has assumed that there is a single jammer deployed against the radio link (whether fixed frequency or hopping) and that the fixed-frequency radio cannot avoid the jammer by changing frequency, either because it is operationally not possible, or because the jammer could easily discover the new frequency, or both. Also, the effect of multipath and battlefield interference has been neglected. The effect of these would, in fact, be relatively small at the 16 km range quoted. (From Fig. 15, there would be, on average, around 10% blocked channels owing to battlefield interference, and the jammer would still need to jam around 50% of the hop channels to ensure that the speech is rendered unintelligible.)

5.5 Interoperability

The design and development of frequency-hopping radio systems is being undertaken independently by several contractors in various countries of the world, notably in the USA as part of the SINCGARS-V program for the US Army Electronics Command. This program, for a single-channel ground and air radio system (VHF), is scheduled to commence re-equipment during the late 1980s for the US Army and is intended to provide a similar operational capability to the Jaguar-V system. Obviously, the potential need for interoperability between such systems must be considered, particularly among allied forces of more than one country. Interoperability in the conventional fixed-frequency mode is, of course, possible, but it is clear that, in the hop mode, this can only be achieved if virtually all parameters of the hop system are identical, and of course, the same base keys are used. In practice, this can only happen if identical equipment is deployed, or conceivably if a highly complex international standard is formulated, publicised and time allowed for its adoption.

It seems more realistic to accept the alternative view, for land tactical forces, that the benefits of any such standard will be more than offset by the problem posed if several different systems are encountered by an enemy.

6 Acknowledgments

The development of the Jaguar-V frequency-hopping radio system has been the result of co-operation between teams from several companies within the Racal Electronics Group, and the authors gratefully acknowledge assistance from all those involved in this project. They would also like to thank G.J. Lomer of Racal Electronics Ltd. for permission to publish this paper.

7 References

1 HESTER, K.J., and DUCK, D.R.: 'A very wide range receiver for use in a tactical surveillance system'. Proceedings of IERE conference on radio receivers and associated systems, Leeds, July 1981, pp. 257–262

2 DIXON, R.C.: 'Spread spectrum systems' (John Wiley, 1976)

3 SAMUEL, R.J.: 'The application of spread spectrum modulation to land mobile radio'. *IEE Conf. Publ. 188*, 1980, pp. 29–34

4 MATTHEWS, P.A., and DRURY, D.A.: 'Direct sequence spread spectrum system analysis for land mobile radio communication'. *IEE Conf. Publ. 184*, 1980, pp. 187–191

5 SHIPTON, M.S., and ORMONROYD, R.F.: 'Improvements in use of congested spectrum for land mobile radio service by adoption of bandsharing spread-spectrum system with TV broadcast channels', *IEE Proc. F, Commun., Radar & Signal Process.*, 1981, **128**, (5), pp. 245–260

6 GOODMAN, D.J.: 'Frequency-hopped multi level FSK for mobile radio', *Bell Syst. Tech. J.*, 1980, 59, pp. 1257–1277

7 EGLI, J.J.: 'Radio propagation above 40 MHz over irregular terrain', *Proc. IRE*, 1957, **45**, pp. 1383–1391