SIMULCASTING WITHOUT (too many) TEARS

This document is based upon a paper that was originally presented at the 1989 APCO Conference in Sparks Nevada by Robin Atack of Philips Radio Communication Systems Ltd of Cambridge, England under the title of:
OPTIMIZING AND MAINTAINING HIGH QUALITY SIMULCAST WITH MINIMUM EFFORT

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Introduction

Despite a history spanning more than thirty years the practice of simulcasting (aka Quasi-Sync) is still subject to much criticism. One would have thought that by now all the perceived "black art" would have been overcome and present-day simulcast systems would be totally free from problems. Unfortunately there are many simulcast systems around whose performance at best is marginal.

Many of the problems undoubtedly occur through the use of unsuitable equipment. Equally many however, actually arise from a general lack of thorough understanding of all of the interactive effects. As a consequence, equipment design is often a compromise and the basic procedures necessary to eradicate the worst of the effects are overlooked. Perhaps this is a little bit of an over-simplification, but as is explained in the following document, it **is** possible to plan and engineer single-frequency simulcast systems for virtual freedom from any of the problems associated with factors directly under human control.

Simulcasting is not just a case of putting up many transmitters on nominally the same frequency and feeding the same modulation to each. It is a case of precise system engineering and accurate control of all controllable parameters.

Consider this fact, single frequency simulcasting is not the only condition which presents the same information from multiple sources simultaneously to a mobile; multipath propagation does too, with little, if any, distortion of the audio. Under the circumstances, it has to be possible to engineer simulcast systems to behave similarly, thus providing the enhanced coverage required with systems of "engineered" multipath.

Appreciation of the various simulcasting effects, their production and control is not easy, but considering the interactive carrier effects separately to modulation matching does simplify matters.

Carrier interactive effects.

Whenever two carriers of near identical frequency are presented simultaneously at the input of a receiver they will constructively and destructively combine, producing a carrier fluctuating in level at their difference frequency. As shown diagrammatically in fig 1, when both carrier levels are identical the resultant fluctuates from zero to a maximum of 2V.

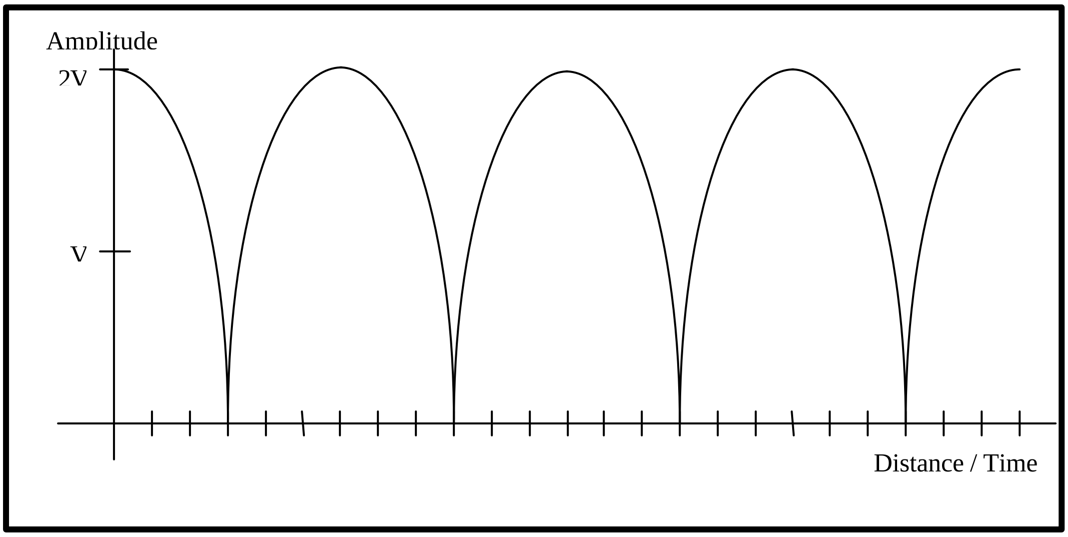

Fig. 1 Signal strength variation in equi-signal area

Since receivers have finite sensitivity thresholds, whenever the input signal falls below this threshold, a pulse of noise will be produced or the mute will drop out. This is illustrated in Fig 2 for the condition of two relatively low level signals.

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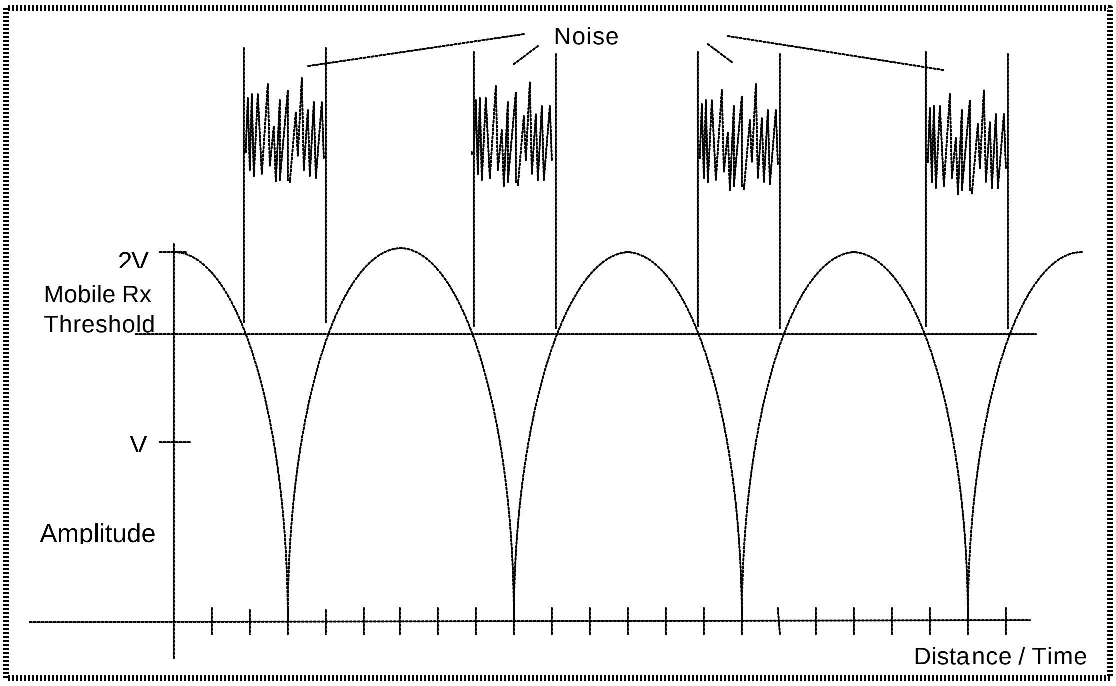

Fig. 2 Typical Carrier as seen by a Mobile in a weak Equi-Signal Area

Under these circumstances the effects can be particularly annoying since the period during which the signal is below the mobile receiver threshold can be considerable.

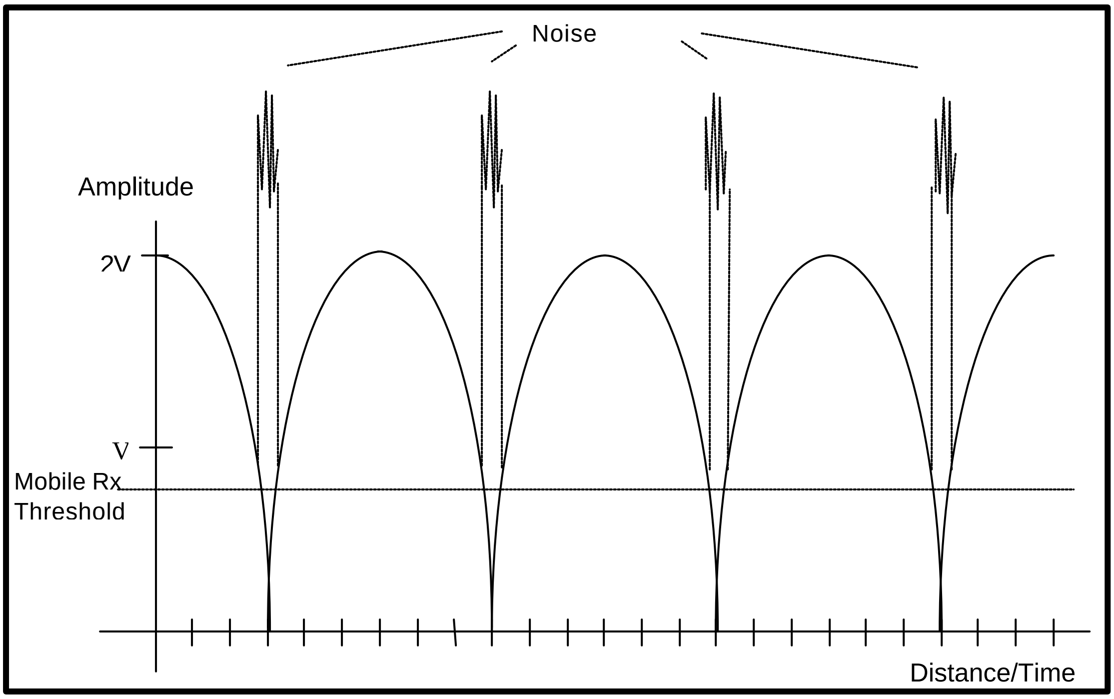

Fig. 3. Typical Carrier as seen by a Mobile in a strong Equi-Signal Area

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Conversely, as illustrated in fig 3, raising the signal levels in relation to the notional threshold reduces the period during which the signal falls below threshold and will result in a much-reduced period of noise and corresponding annoyance.

The improvement brought about by increasing signal levels is shown quite dramatically if the previous hypothetical conditions are considered for a typical modern receiver. For example, when a typical modern receiver is subject to two equal level 0.5µV signals, the noise profile generated will be similar to fig 4 below.

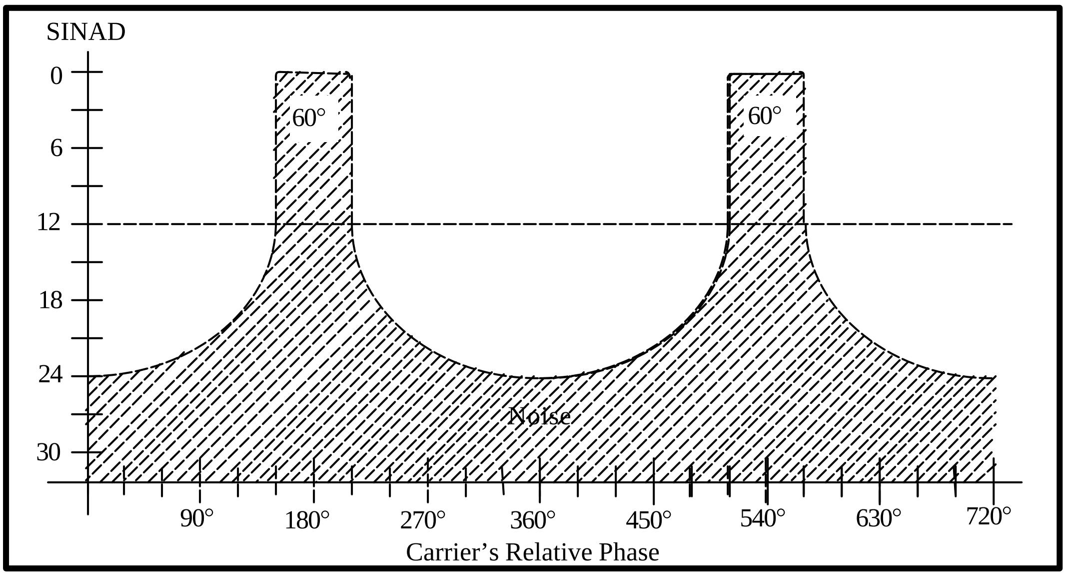

Fig 4. Rx Noise profile produced by two 0.5µV signals.

This diagram shows that the output noise pulse occupies about one sixth of the total beat period when two 0.5 µV Pd signals beat together. Compare this with fig 5 which shows the huge ten-fold reduction in noise period brought about by increasing the signal levels to around 5µV pd; it is now less than one sixtieth of the total beat period.

If the two signals differ in level, then clearly the resultant input to the receiver can no longer fall to zero, and the noise pulse may not even exist. In practice, differentials have only to exceed the limiter threshold of the mobile, and the resultant "beats" of amplitude variation will not be demodulated and can generally be ignored. This situation is illustrated in Fig. 6

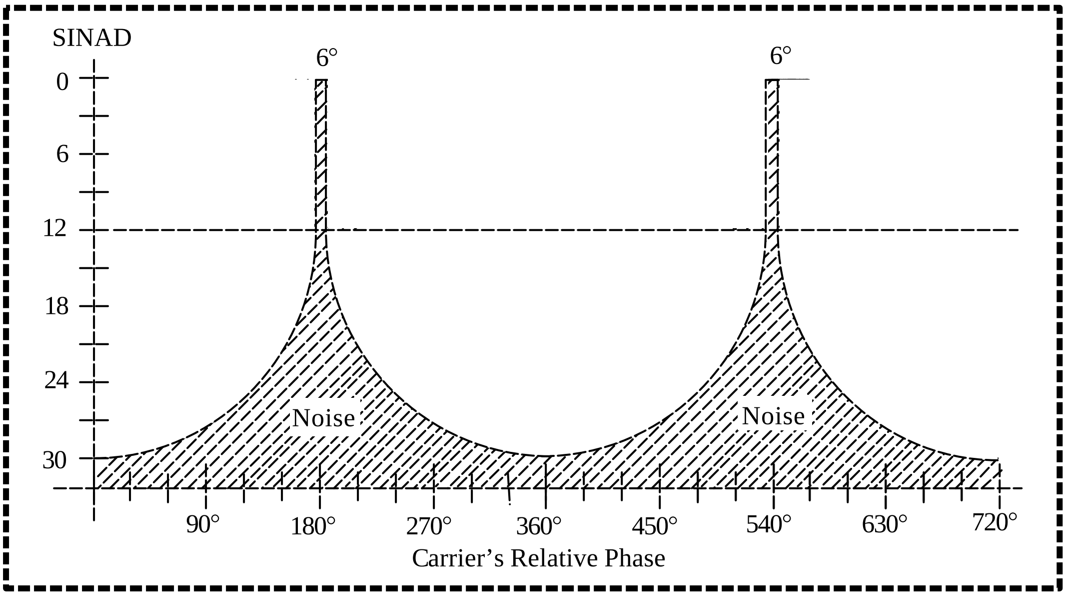

Fig 5 Rx noise profile produced by two 5.0µV signals.

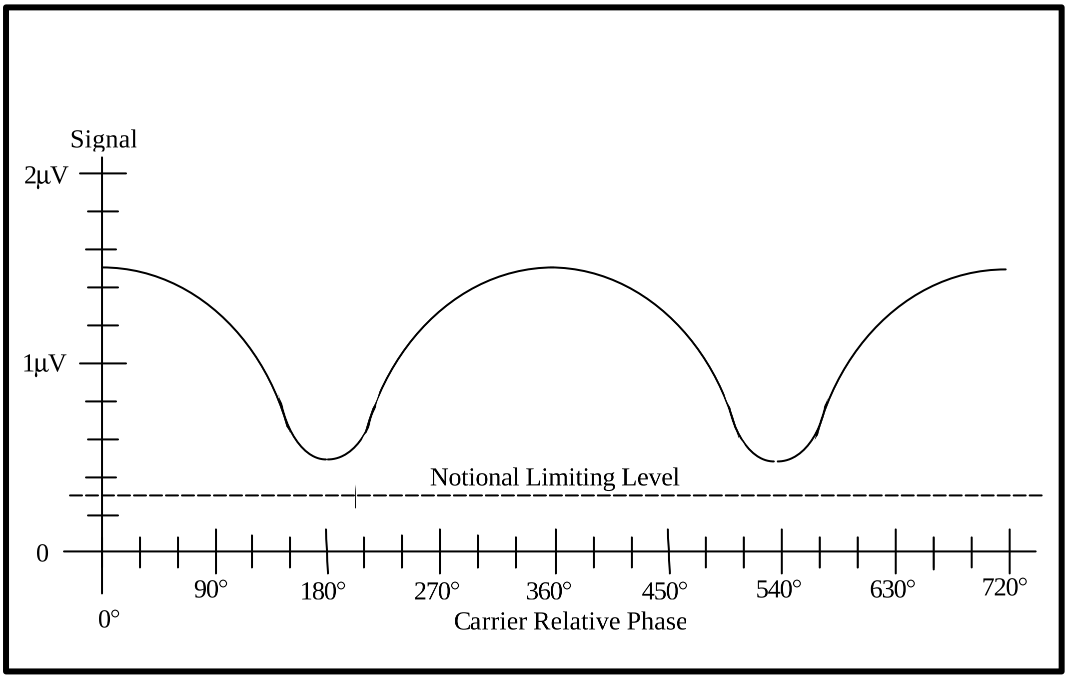

Fig 6 Signal strength variation for 2:1 level differential

Effect of inter-site spacing

The relationship between signal strength and distance from a radio site is shown diagrammatically below in fig 7.

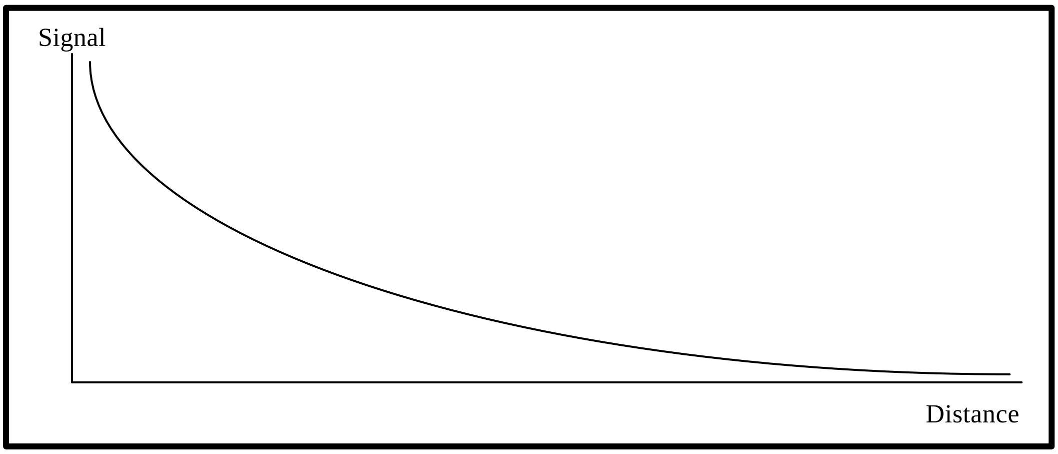

Fig 7 Signal strength Variation as a function of distance from site

Signal level gradients are greatest close to the site, and fall slowly at large distances from the transmitter. Thus a mobile operating a long way from a site would have to move a considerable distance to effect any reasonable change in mean carrier level.

Extrapolation of this relationship for two interactive sites is shown in figs 8 & 9.

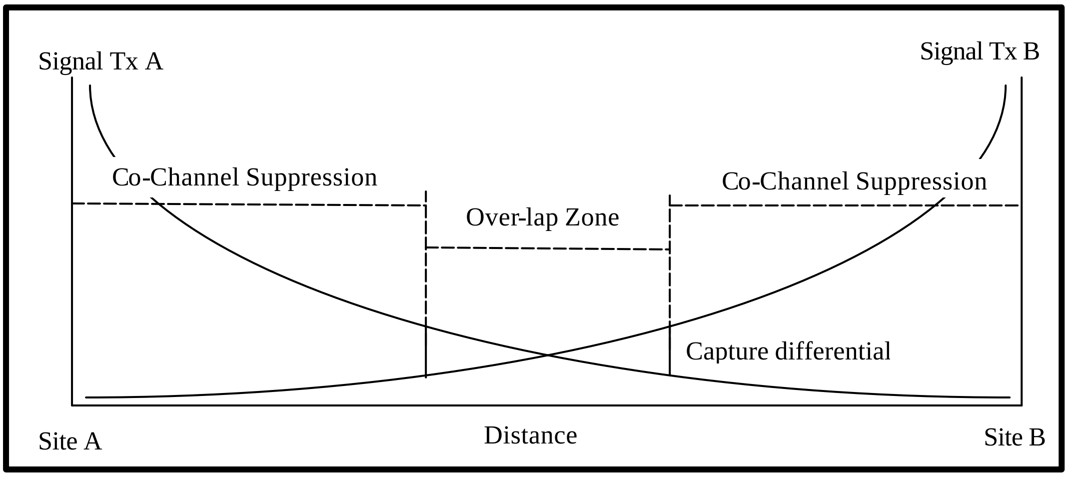

Fig 8 Variation in signal strength as a function of distance between sites - sites relatively far apart.

It is clear in comparing figs 8 & 9, that for a given signal differential producing domination or capture by any one site, the area affected by carrier interaction is greater the farther apart the sites are spaced.

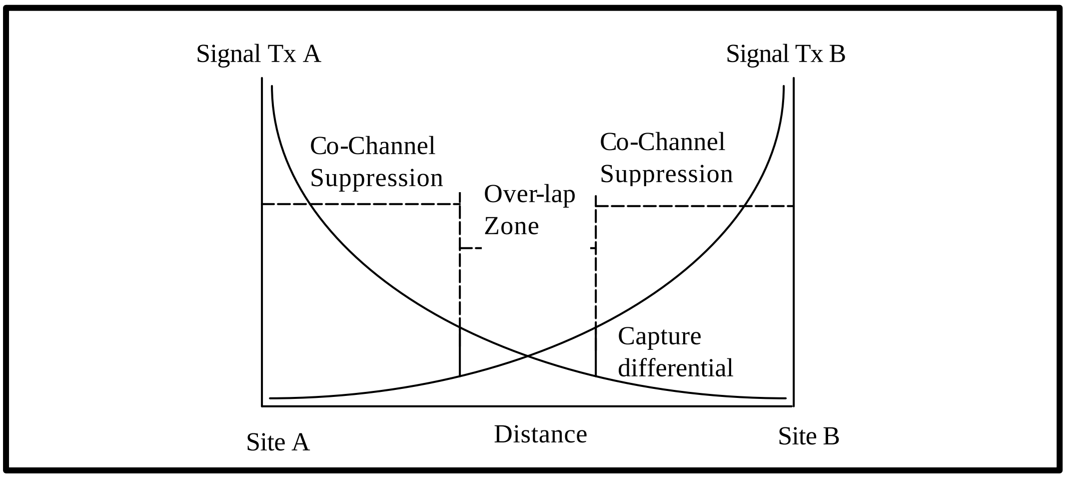

Fig 9 Variation in signal strength as a function of distance between sites - sites relatively close together.

Positioning sites reasonably close together gives rapid change in signal level in relation to distance travelled and thus smaller areas of "overlap", it also produces relatively high levels of signal in the overlap area. Both these factors result in minimum amounts of noise both in terms of duration of the pulses and the area over which they are likely to be obtained.

The effect of raising transmitter powers

Increasing the transmitter powers does not have the same effect as decreasing the spacing between transmitters. The area over which carrier interactive effects are noticeable is related primarily to a fixed ratio between the signal levels, and therefore to the spacing between the sites. Thus, even high power transmitter sites will result in large areas of noticeable interaction if they are spaced a long way apart. The increased transmitter power will, however, reduce noise pulse duration and give an improvement over low signal levels, but there will still be larger areas subject to carrier beats than if the sites were closer together.

The conclusions are obvious; simulcast systems must be planned very carefully. Sites must not be spaced too far apart thereby ensuring that signals in the overlap areas are both adequate and the signal level gradients are as large as practical. The importance of minimal sizes of overlap areas will also be further highlighted in the section relating to the maintenance of phase equalisation that follows later, since large areas of overlap result in an inability to maintain adequate equalisation of the modulation over the whole area.

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Carrier beat rates and transmitter stability

Whilst short noise pulses may be acceptable if occurring when no speech is present, should such pulses occur during speech and at the same rate as the syllabic rate, and then severe degradation to the intelligibility can result.

The normal range for speech syllabic rate in western languages' is between about 7 to 15 Hz. Carrier beats that occur within this range are generally disturbing even if the intelligibility is not lost. Thus, basic system carrier frequency offset differentials should not be set within this range.

Very, very slow beats, of the order of 0.1Hz and below in equi signal areas may also be problematical on systems with little natural Rayleigh fading. Such slow beats may actually result in the total loss of complete words or sentences in equi-signal areas, as a resultant of carrier levels falling below the receiver threshold for protracted periods. In practice such problems are very rarely encountered on systems using frequencies above 200MHz, unless totally featureless terrain is being covered.

Over the years many organisations have experimented with different offsets between transmitter carrier frequencies on simulcast systems. The consensus today is that carrier offsets for systems using frequencies above 400MHz should ideally be totally synchronous or between 0.1Hz and 3Hz. Systems operating below 100MHz should be set between one half cycle and 3Hz to give the most satisfactory results, whilst systems operating in the 150 - 200 MHz band should have similar off-sets if operating in wholly rural areas and may be synchronous if used for personal portables in urban areas.

Transmitter carrier frequency stability requirements

The minimum permissible carrier offset and minimum practical carrier offset both serve to define the necessary crystal stability requirements. If the minimum pre-set offset is taken to be 0.5 Hz at 75MHz with a minimum allowable offset 0.1 Hz, then relating this to an acceptable period between adjustments we can arrive at the requirements for drive source differential stability.

Once systems have settled down, it is generally accepted that periods of about 6 months between checks, and possible adjustment of offsets, is a permissible economic interval. If, during this 6-month period, the carrier offsets are not to be allowed to drift more than about 0.4 Hz, then the differential ageing of the frequency sources can be defined.

System Frequency	Differential Ageing Stability
75MHz	6×10^{-9}
150MHz	3×10^{-9}
450MHz	1×10^{-9}

This requires quite exceptional crystal units that have been achieved by selecting crystals of very low intrinsic ageing characteristic. Such characteristics are met by the use of stress compensated (SC) cut 5MHz crystals enclosed with the oscillator circuitry in an oven whose operating temperature has been selected for the particular crystal to minimise drift. These units are very expensive to produce, being built with military standard components and undergoing many weeks of pre-ageing to ensure the characteristics are stable, remain stable and are within specification.

Typical oscillators are able to offer ageing rates as low as 1×10^{-8} per annum after initial ageing and which generally improves over the years. Units which have been in the field un-disturbed for two or three years are often exhibiting less than 0.5Hz differentials at final frequencies of 460MHz when checked one to another, this equating to a differential ageing of $< 1 \times 10^{-9}$ per annum.

Of course maintaining such tight parameters is not just so easy as this! In practical systems the effects of temperature stability must also be considered. Whilst simulcast systems are primarily used for wide area radio communications, the area over which such systems are installed is not that great in global terms. It can be assumed therefore, that apart from transitory variations, climatic changes affecting one location in a system will generally also affect all other sites in a system. The largest differences in environmental conditions for crystal units are likely to be solely due to totally different types of location and standards of site. For instance, the differences between a basic mountaintop site and a low level urban site in a heated building will be large unless some environmental control is exercised at the sites. Since one is interested in minimising the differentials between sites it becomes sensible to plan sites to have similar internal conditions by affecting some sort of local internal environmental control. By the use of simple heating and ventilation controls, site differentials can usually be reduced about 20° F / 10° C which is sufficient for the differential drift between crystal units to be very small indeed.

Doppler Shifts

The accurate setting of carrier frequency offsets and control of site conditions will take care of static conditions. However, no account has yet been taken of the change to this static offset produced by Doppler shift when a mobile is actually in motion! The effect of Doppler shift is to vary the effective offset, in relation to the speed of the vehicle relative to the contributing radio sites.

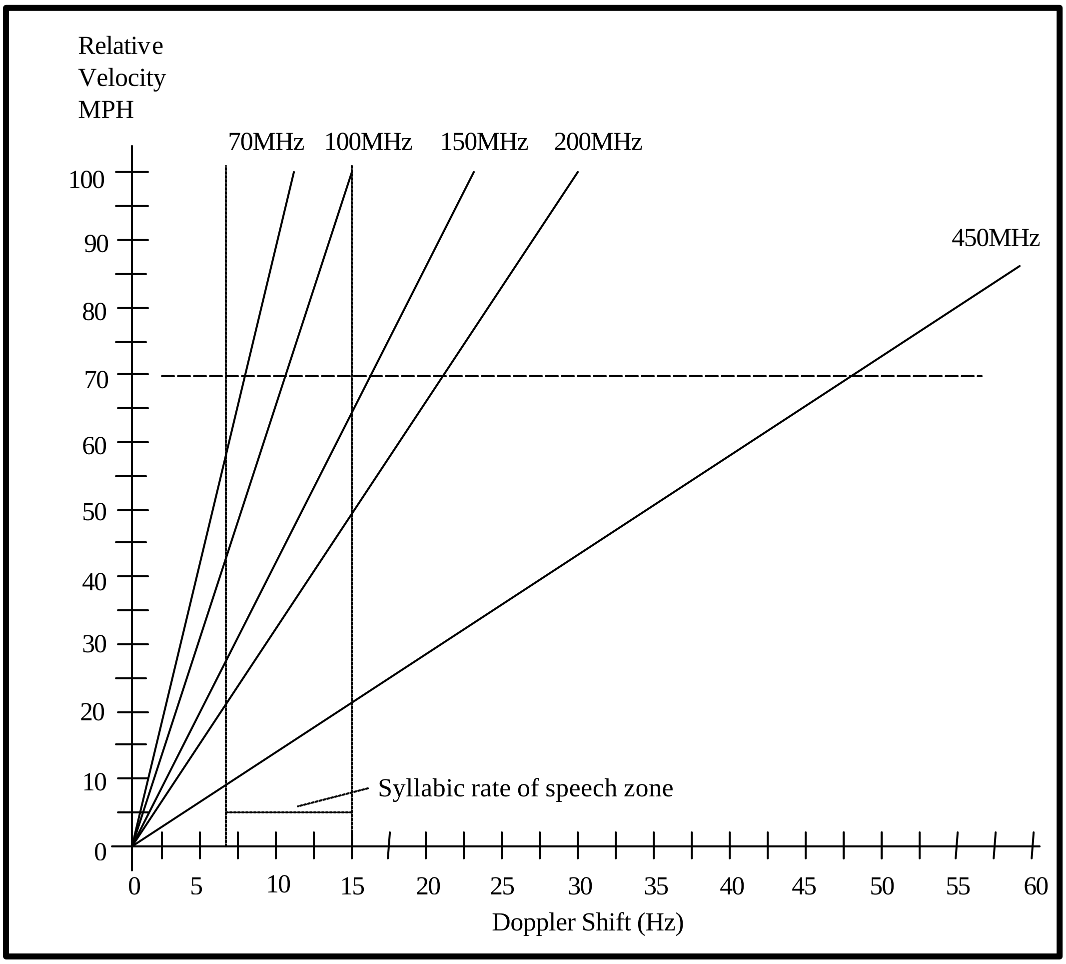

Fig 10 Doppler Shifts v Road Speed for Selected frequencies - attributable to a single source

These graphs of Doppler shift related to both operating frequency and relative vehicular speed show that the beat may be as high as 80 - 100 Hz, or may almost be zero Hz. Equally it may also fall within the syllabic rate of speech at critical operating speeds.

In interpreting the graphs it should be born in mind that since two sites will be shifted, sometimes one positively and the other negatively, the beat attributable to Doppler shift could be as much as twice that shown. To obtain the actual beat frequency at a given vehicular speed it is necessary to

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calculate the **relative** velocities with respect to the sites involved and to add them algebraically before referring to the graphs.

Since no engineer can claim Deity and directly influence physical laws, all that can be done is to try to prevent beats occurring within the 7 -15Hz region when mobiles are either stationary or whilst cruising at motor-way speeds. This requires a careful choice of operating band; initial offset adjustment and positioning of sites relative to the communication routes. Even so, ***all that can be achieved is a compromise carrier beat, effects cannot be removed altogether, their effect can only be minimised.*** As highlighted previously, if the adequate signal level conditions are achieved with sites not too far apart, then areas affected by such effects can be very small and isolated.

Fully Synchronous Systems

It is possible, using a common reference source, for simulcast systems to be produced with totally synchronised carriers.

Operating a system with fully synchronised frequency references will remove any carrier beats whilst stationary. It may also introduce the possibility of the stationary mobile being positioned directly at a point where the signals from the radio sites cancel fully. In practice this effect will normally only be noticed on systems operating in the lower frequency bands, the shorter wavelengths at the higher frequencies meaning smaller distances between a peak and trough tending to ensure that such conditions are difficult to locate and accurately hold. In general UHF sites tend to be closer together which also results in higher voltage gradients This means that movement of the vehicle or field pattern by only a few millimetres or so results in the signal being re-acquired from a null. Ensuring that carrier levels are strong in overlap areas also aids the re-acquisition of signal under these circumstances too.

These factors being considered, it can be beneficial to introduce fully synchronous operation to UHF personal portable communication systems. Static operation with such systems eliminates all carrier beats and communication quality can be greatly enhanced. However, once the mobile receiver starts to move, Doppler shifts will reintroduce carrier beats once again and there will be no real difference between a synchronous and a semi-synchronous system other than the actual beat frequency. Indeed there is no way of totally avoiding carrier beats, just ways of minimising their impact upon the communications

It is not possible to get fully synchronous systems using simple high stability oscillators, such systems can only ever be quasi-synchronous even when utilising atomic standards for their sources. Fully synchronous operation requires a single common reference to be utilised at all sites. This is most readily achieved using an off-air reference such as the Ground Positioning Satellite system (GPS) or Rugby / Droitwich to lock the local oscillators.

Even so, in practice there will still be some small phase differences which are constantly corrected but which are imperceptible on an operational system.

Such systems normally compare the local oscillator with the off-air reference, occasionally “nudging” the control voltage to correct for any minor phase error due to temperature or ageing drift. Good systems accumulate a history of past corrections in relation to external physical and environmental changes and are able to continue to make relatively accurate corrections even in the absence of the off-air reference for short periods. The better the quality of the controlled oscillator, the longer and more stable operation under such conditions will be.

Propagation planning

The importance of getting the initial propagation planning stage right cannot be over emphasised; there is little point in trying to control the match between the modulation products on a system with large areas of weak signal overlap. A system with inadequate signal levels is always going to be a poor system!

Obviously there has to be a compromise between having high levels of overall signal and having too few sites. In the vast majority of cases where systems have failed to live up to expectation the cause can be attributed to trying to do too much with too little in the way of base-stations and area covered. It is far better to have a larger number of sites and relatively high signal strengths than to have fewer sites with duplicated equipments for reliability. The extra sites will give enhanced coverage and quality of communication, and will, on a well-planned system, provide system resilience. Often the loss of one site on such systems will result in only a slight degradation in communications as the other sites fill in the resultant hole.

Regarding signal levels in overlap areas, this has been the source of much discussion. In the author’s wide experience, signal levels in overlap areas require to be in the order of the notional value of the Rayleigh Fading figure **above** the specified mobile receiver 12dB SINAD sensitivity threshold.

Rayleigh fading figures vary depending upon the topographical features of the area being considered. For instance, the figure can be as high as 20dB in urban areas and as low as 6dB in rural areas.

Obviously the signal levels in the field are dynamically varying due to multi-path fading etc., and it is normal to quote field strengths in relation to the mean over a certain distance, for instance 100 or 500 metres. If this mean figure exceeds the receiver threshold by the value of the fading, say 10 -12dB in a semi-rural area, then the effect is to minimise the incidence of the instantaneous carrier levels falling below the threshold value. Since with Quasi-sync we are operating a system with "designed in" additional multipath from two or more transmitters, we are able to ensure that the incidence of the sources being both equal and at the 12dB threshold level is minimised.

Modulation matching aspects

Assuming that adequate forward planning has produced a system with the sites optimally sited, how is it possible to ensure that the mobile user is unaware that more than one site is contributing to the signal? Obviously there is need to ensure that the information is precisely the same and precisely in phase when it reaches the receiver. In a nutshell, one must be able to achieve total coherence of all modulation side bands contributing to the mobile's output.

Such accuracy of matching has not always been readily achieved. Determination of the limits for various modulation parameters used to be based upon empirical testing. Whilst this resulted in systems that were considered acceptable at the time, most being Amplitude Modulated systems anyway, many of the FM systems exhibited distortion in the overlap areas - some considerably more than a just a little!

Reasons for the relatively poor performance of many FM systems were the result of muddled understanding of the root causes of distortion. Granted, numerous papers and articles on the subject have been published in journals, however, most were just a little too theoretical, or mathematical, for the practical systems engineer to wade through and appreciate fully.

Unfortunately it is not possible to totally bypass theory, since a full understanding of the effects of, and cures for modulation mismatching depends upon a thorough understanding of the intertwined relationship between phase and delay. However, it is hoped that the following explanations will result in a clearer understanding for all readers.

An extensive series of laboratory tests and field trials conducted by the author, confirmed the results of previous research (1). In expressing the results in a more practical manner (2), a better understanding has been obtained of the mechanics of equalisation of simulcast systems. The trials also resulted in the development procedures and use of specialised equipment that allow systems to be set up very accurately and result in virtually distortion-free communications in the primary overlap areas.

Both phase and frequency modulated systems produce side-band phase differences between two identical frequency sources if either the level or the phase of the modulation to one is varied relative to the other.

Matching of level characteristics

Circuits feeding the various transmitters often not only have different frequency responses but also different dynamic responses too. To obtain the required degree of match requires that dynamic responses are the same and that amplitude - frequency responses are also matched, most unlikely if different transmitters are mixed within a system.

Matching of the frequency responses will often require adjustment of high and low frequency responses by selective boost or cut. This is usually achieved by the use circuitry incorporating simple "tone controls", similar to those found on Hi-Fi amplifiers. With such techniques it is usually possible to effect a match to better than ± 1 dB.

The dynamic amplitude characteristics such as sensitivity settings, onset of limiting, or the start of compressor action of all transmitters also require close matching. It is most unlikely that an adequate match can be effected other than by using identical types of transmitters, since even these will have variations in response one to another.

Most of the authorities that have conducted tests over the years, agree that distortion caused by level miss-match only becomes noticeable when errors exceed ±1dB. In practice, the matching of amplitude characteristics is usually fairly simple and results in distortion produced by amplitude level differences being much less than that obtained by phase differences.

Effects of Phase miss matching

The same ease of assessment and adjustment cannot be applied to phase matching. The authors' investigations have shown that there is a sudden onset in both measured and observed distortion as audio modulation phase errors approach and exceed approximately 20°.

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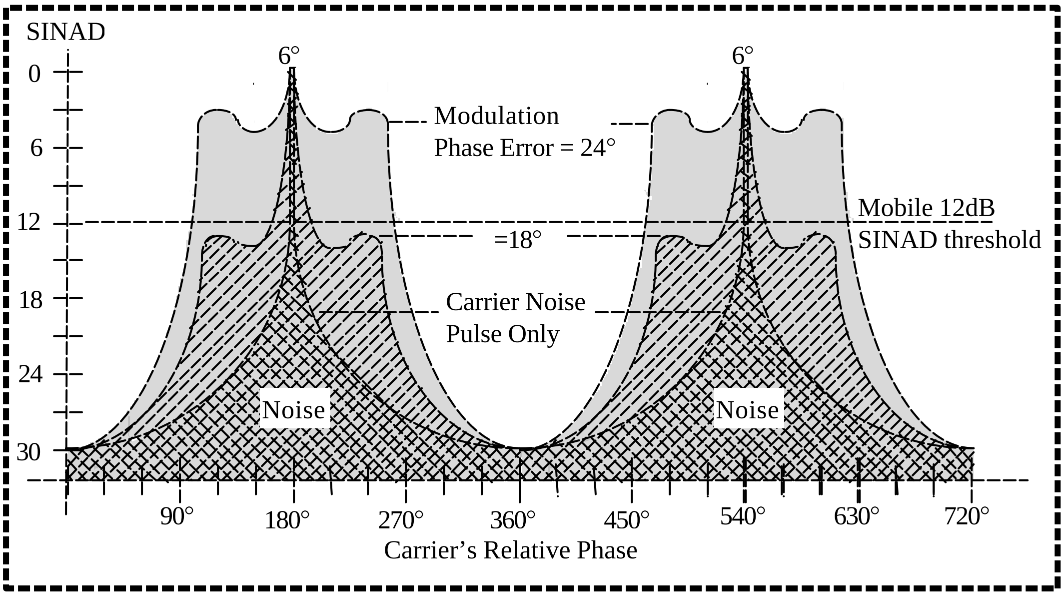

Fig 11 Receiver noise and distortion profiles produced by two 5.0µV signals with 18° & 24° modulation phase error

Shown in fig 11 and displayed in SINAD form related to the noise pulse obtained by two 5µV equal signals, are the distortion profiles for audio modulation phase errors of 18° and 24°. The distortion is most noticeable adjacent to the carrier anti-phase conditions.

Distortion increases rapidly as phase differentials increase, producing severe distortion throughout the complete carrier beat cycle as shown in fig 12 below.

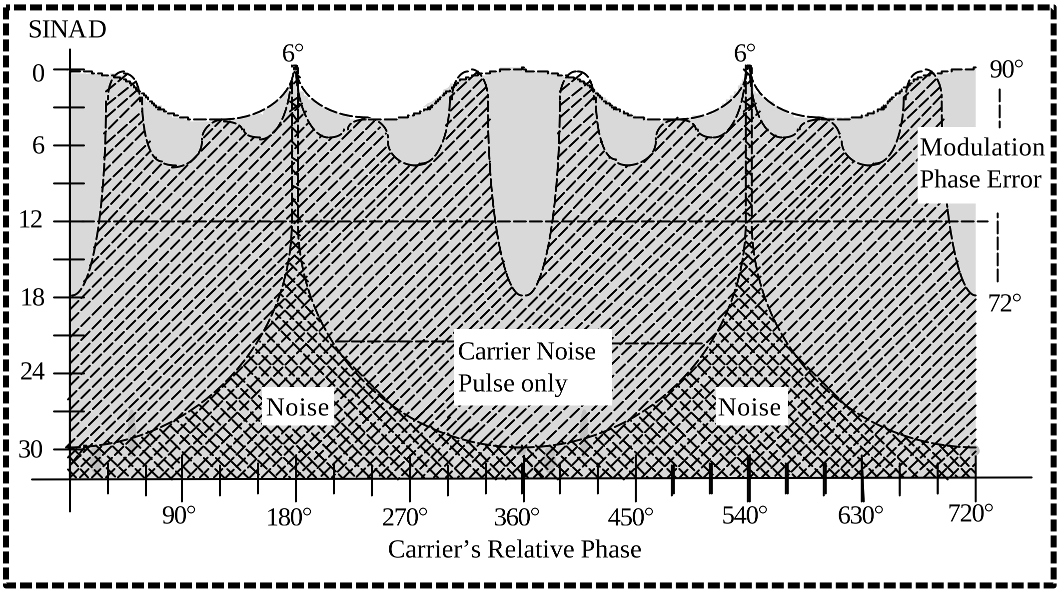

Fig 12 Receiver noise and distortion profiles produced by two 5.0µV signals with 72° & 90° modulation phase error

As can be seen, only some 70° phase differential is necessary to produce a complete carrier beat cycle with a SINAD figure well below the accepted minimum 12dB. The situation is thus rapidly reached when communication is totally lost, never mind just unacceptably distorted.

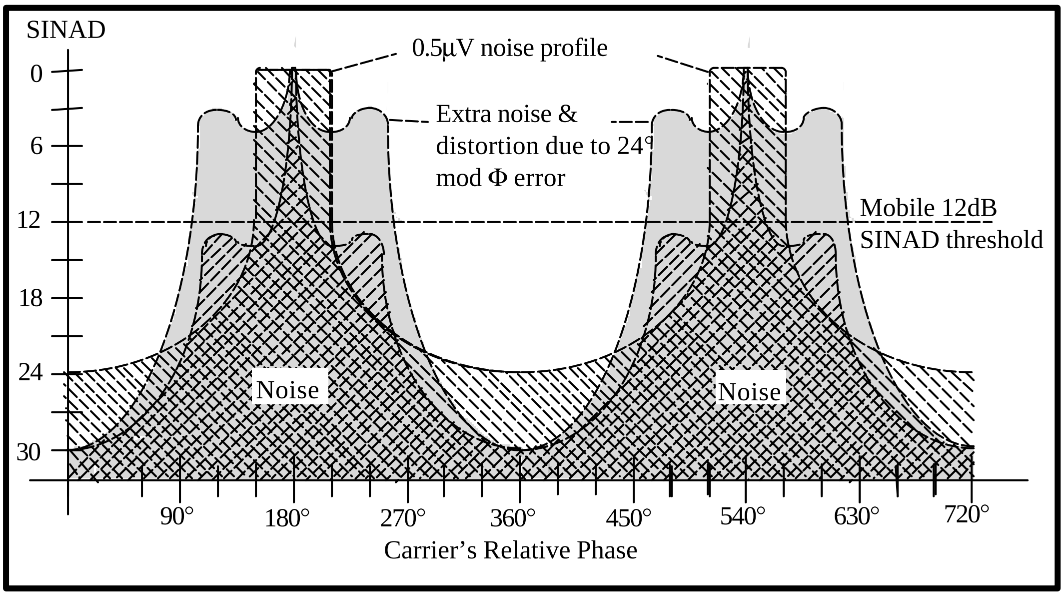

Fig 13. Receiver noise & distortion profile produced by two 0.5µV signals with 18° and 24° audio modulation phase error.

As Fig 13 shows, the effect of a modulation phase error of some 24° produces more than double the period of distortion that a 20 dB drop in carrier level from 5µV to 0.5µV would produce!

This is not such a bad a situation as at first it seems, since a carrier level differential of only 3dB produces correspondingly lower possible levels of distortion.

Typically, with carrier differential levels of 3 dB, it requires some 70° of phase error to even approach the 12 dB SINAD figure with distortion anywhere in the beat cycle. Further investigations have revealed that since the distortion is essentially harmonically related, once the fundamental frequency exceeds the mid frequency point of the mobile audio pass-band, the distortion is rapidly attenuated by the high frequency falling response and becomes less noticeable. This allows some latitude to gradually increasing phase errors at frequencies above the mid-system response and appears to hold true until phase errors exceed 60° at the upper end of the band. Larger errors than this apparently produce sidebands of amplitude and phase discrepancy sufficient to cause carrier noise pulses once again due to effective side-band signal cancellations.

Obviously if the phase errors can be restricted to less than 20° then simulcast systems are certain to produce the best quality speech. However, it isn't just sufficient to adjust system to 20° maximum differential, it must be set up to much lower initially to allow for environmental, ageing and vehicular motion effects. Using modern test equipment and suitable corrective networks, it has been found that a 10° phase differential across the band is both a practical proposition for field commissioning and produces eminently acceptable results.

Specifying a phase differential of ± 5° will allow for environmental changes before the onset of noticeable speech distortion. In practice many systems have been set up with as little as 5° total phase differential over the lower half of the pass-band resulting in even better long-term performance.

Phase and Delay relationship

Throughout this document reference has generally been made to phase matching, avoiding reference to delay. The reason for this is that distortion is directly related to phase error; also, the intertwined relationship between phase and delay, yet simple, is an area of so much confusion. A full appreciation of the methods necessary to achieve accurate matching, requires a thorough, but basic understanding of this relationship. It is suggested that readers wishing to compliment the following brief explanation and further clarify their understanding of phase and delay should study explanations in various theory text books (3) (4).

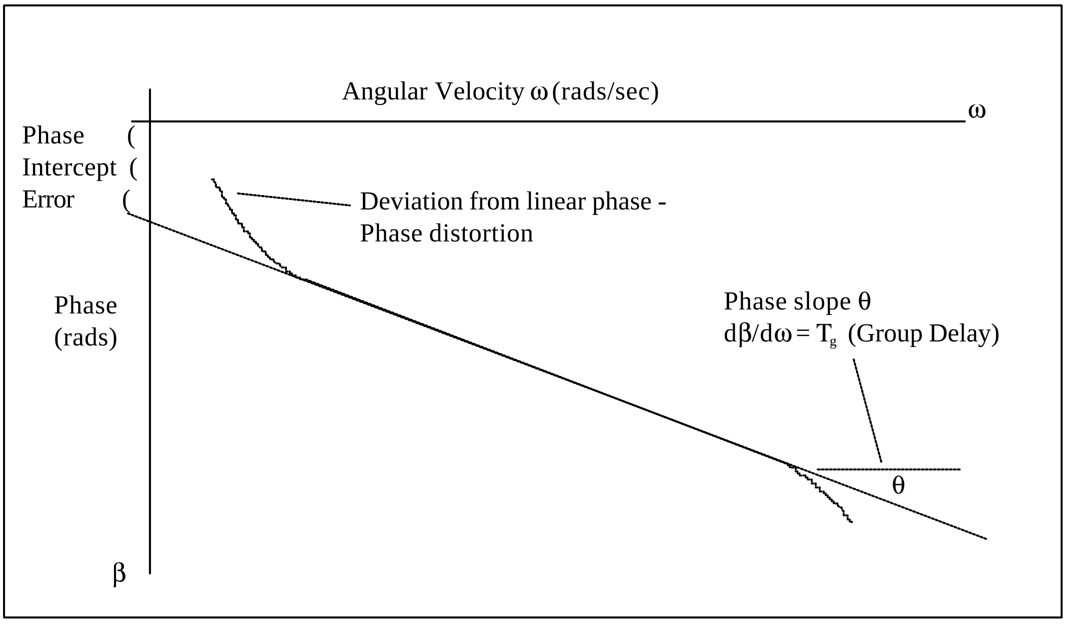

Fig 14 Typical Transmission Circuit Phase Characteristic

If typical transmission circuit's phase characteristic as shown in fig 14 is examined, it can be seen that the characteristic has three distinct regions:

a) A nominally linear central portion, the slope of which can be equated to the nominal propagation delay of the circuit

b) Distorted band edges, where increased propagation delay through the transmission filters results in greater phase slope.

c) Phase intercept error which is the phase at notional zero frequency.

It is the latter phase intercept which can cause so much problem, since unless it passes through the origin, the **phase delay** β/ω, will not be the same as the propagation or **group delay** $d\beta/d\omega$. Examination of two phase characteristics, as depicted in fig 15, shows that both circuits have identical shape and slope, but have different intercept errors. Since group delay is defined as the slope, $d\beta/d\omega$, of the phase characteristic, the nominal bulk or group delay characteristic will be the same for both. However, phase delay, β/ω, will not be the same.

It should be clear from this fact, that a match achieved simply by adjustment of group delay characteristics may show a very good match, but will usually still leave quite unacceptably wide phase differences between the two circuits.

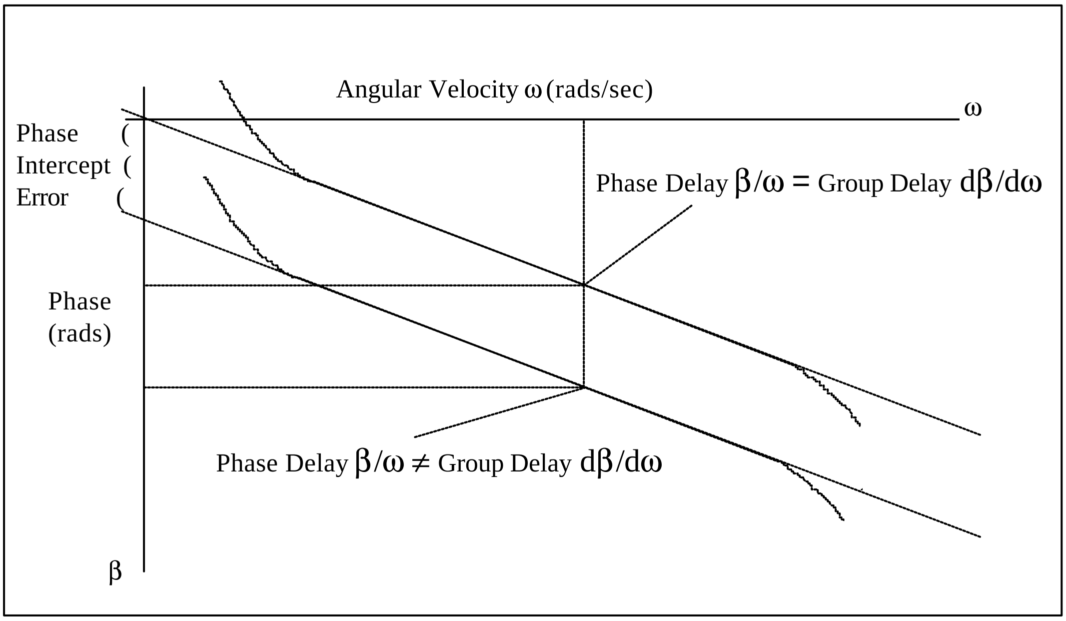

Fig 15 Phase Characteristics showing phase delay & group delay

The requirements therefore for matching two different communication circuits' phase characteristics will be circuitry to adjust: -

1. Phase or group delay distortion, (synonymous with group delay distortion)

2. Bulk or propagation delay, (synonymous with bulk or propagation delay)

3. Phase Intercept error, (the factor which make phase delay **not** the same as group delay)

With control over these three characteristics independently of each other, it is fairly simple to achieve the necessary match.

The "Mechanics" of matching the phase characteristic

In practice, the method of matching the phase distortion of two circuits requires a three-point approach, and is illustrated by the matching of the "A" to the "B" characteristic depicted in fig 16.

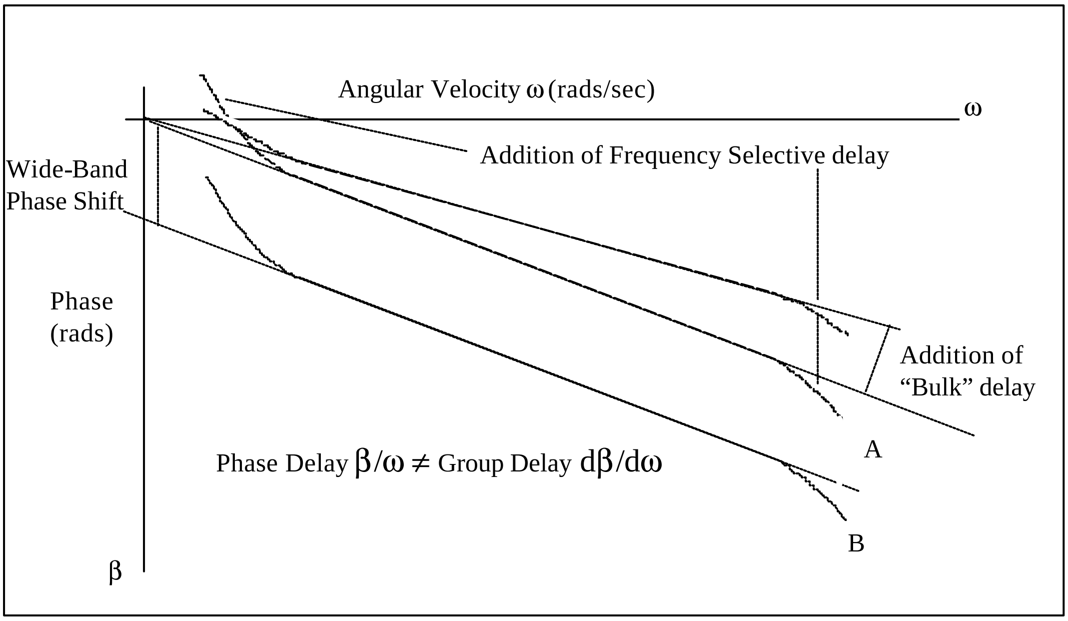

Fig 16 Phase Characteristics showing matching requirements

1. The addition of delay selectively applied over the band edge distorted sections of the phase characteristic "A". This action effectively increases the slope of the phase characteristic over the affected band of frequencies. Often, this will need to be repeated a number of times to different areas of the characteristic before a reasonable match between the shape of the two circuits is obtained.
2. Wide-band, non-frequency selective delay is added to the "A" circuit thereby bringing the two characteristics to exactly the same slope.

3. Finally, the phase intercept of the “A” or "B" characteristic is changed using wide-band phase shifting networks to eliminate the static phase error between the two circuits and bring the two circuits to almost perfect coherence.

For speech only systems, it is only necessary to make the phase intercept the same. However, circuits carrying medium speed FFSK data require both the phase intercept to be zero and the mid-band phase distortion minimised to reduce their effect upon the noise performance of the data decoder. This may be achieved by the use of more frequency selective delay sections tuned over the required areas of the middle part of the band.

Practical applications to systems

All simulcast systems should incorporate a phase delay correction module, Simoco 3513 535 15002 or similar, into the feed for each transmitter to cater for the necessary optimisation adjustments. This module provides amplitude-frequency correction networks, a digital programmable delay line, seven, all-pass frequency selective delay networks and a wide-band low ripple phase-shifting network. Use of this module allows acceptable matching to be effected between the majority of common interconnecting circuits, including wire lines.

For 1200-baud data applications it is necessary to correct the overall distortion characteristics that generally will be at an unacceptable level to permit data to be carried uncorrupted. The addition of a CT40136/201 data correction module will be required in the common transmit and possibly the receive circuit too to permit correction of the characteristic. This module provides a similar range of adjustments as the phase delay correction module, with the omission of the programmable delay, and is adjusted to flatten the overall characteristic.

Phase-Locking

The use of wire line circuits or analogue multiplex circuits can cause operational problems, due to line reversals and the un-synchronised modulation and demodulation that cause a continuously variable phase relationship between ends. Whilst it is possible to obtain frequency locked multiplex equipments, most exhibits a phase shift, if, even momentarily, lock is lost. Such phase-shift changes negate optimisation adjustments made to match the circuit phase intercepts, and will lead to distortion. Digitally derived multiplexing circuits do not suffer from this variability of the end-to-end phase due to frequency shifting.

A special stand-alone phase-locking system comprising encoder 3513 530 20011 and corresponding decoders 3513 530 40001, have been developed to exploit operation of simulcast systems on both landline and multiplex circuits. These modules are able to eliminate the dynamically varying phase relationship between the source and destination of analogue multiplex circuits. As a bonus, the system also compensate for wire line reversals too, one of the common features of most wire line circuits.

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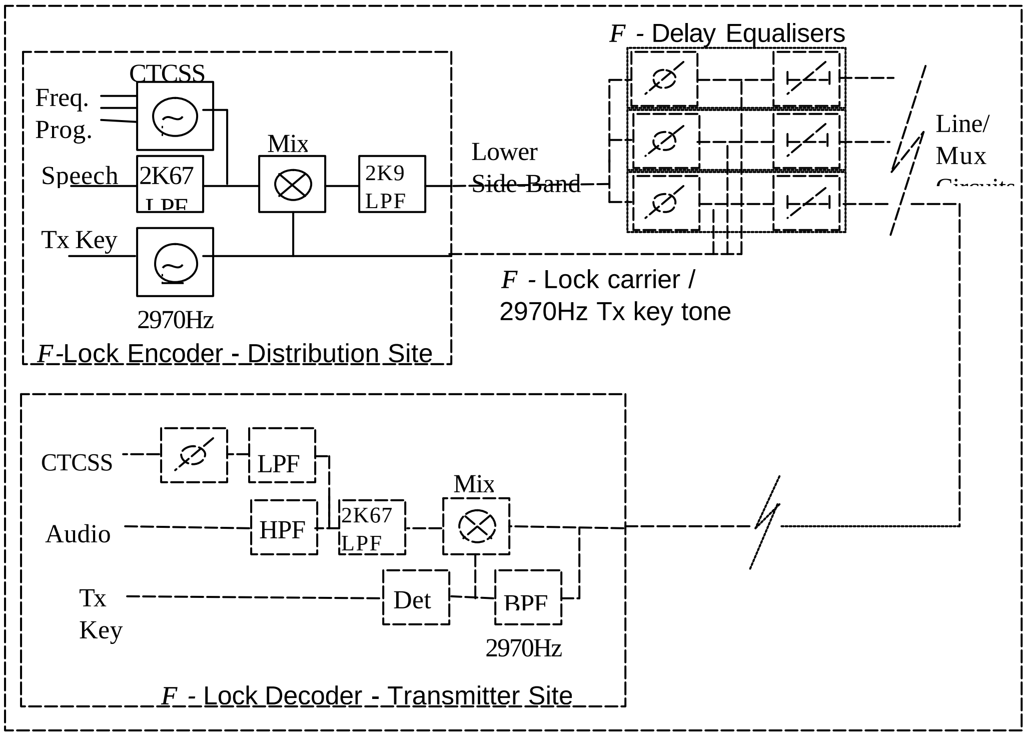

Fig 17 Block Diagram of Phase-locking System

The block schematic of the phase locking system, fig 17, shows that in the encoder, speech or other modulating signal is mixed with a higher frequency carrier - the 2970Hz key-tone. The products of the balanced modulator are filtered to leave only the lower side band, which is an inverted simile of the original audio. The carrier is chosen to be just a low enough frequency to pass over a normal interconnecting circuit. After correction for differences in phase distortion, the carrier is re-combined with the side band, and distributed to all remote sites.

At each radio site, side band and carrier are separated by filtering and applied to a second balanced mixer in the decoder. The output of this decoder process is again filtered to remove the upper sideband, leaving the lower, or original, erect audio. Since the lower side-band is the difference between the two input components, any frequency translation error, or varying phase error, affecting the circuit interconnecting the two locations, affects both components equally and the difference between the two components remains the same.

In this manner, the lower-side-band output will be a true phase locked replica of the original input and all sites will be phase locked together.
The same technique is employed to distribute phase-locked CTCSS tones from a centrally generated source. Sub-audio tones, normally unable to be

transmitted down wire lines or normal voice circuits due to their low frequency and circuit band pass restrictions, will, when mixed with the high frequency carrier, be translated to higher frequencies passing readily down such circuits. Recovery by similar means to the speech at the remote transmitters results in the output to the transmitter of the original low frequency CTCSS tones now phase-locked with each other. Final adjustment for static phase differences between sites by a 0° - 360° phase-shifting network permits these CTCSS tones to be matched to within the ± 5° required to minimise distortion at the mobile.

Practicalities of on-site adjustments

Previous sections of this paper have outlined the means whereby the various system parameters may be controlled or adjusted. What are yet to be covered are the practical aspects of adjusting these parameters in the real world environment.

Previously it has been mentioned that the practical limits of phase matching in the optimising process is about ± 5°. Adjusting to accuracies of this order used to be a major hurdle. The adoption of audio frequency network analysers to facilitate the matching of characteristics has resulted in huge benefits:

The ability to display amplitude, phase and group delay characteristics in near real-time

Inbuilt memory to effect storage of past results to compare with current,

Inbuilt computational capability to effect analysis of results

High accuracy

After more than 10 years experience using a variety of suitable network analysers, there is absolutely no doubt of the validity of the original decision to use such instruments. Unfortunately however, the majority of these instruments are very expensive and very heavy for field use.

Network Analysers found suitable:

Hewlet Packard	3577A & 4194A
Anritsu	MS420, 560 & 3401

Field Optimisation Procedures

Procedures for optimising systems in the field involve consideration of a further set of requirements, quite apart from the adjustments to eliminate variations between equipments and all the different connection circuit characteristics.

The aim of the equalisation procedure is to obtain coherence of all contributing modulation side bands in the overlap area. The obvious way to ensure that all sources of phase and amplitude variation are considered is to sample signals from the base-stations "off-air". Unfortunately, the seemingly obvious way to achieve this, that of installing a monitor receiver in the overlap area and comparing the results of a sweep analysis from one site with another introduces it’s own problems.

In most systems the location of overlaps is most unlikely to coincide with either the distribution hub or one of the transmitter sites for the system. Indeed there are usually a number of areas of overlap and not just one!

All is not lost however, as the equalisation point may be assumed to be at an imaginary position, for instance any one of the transmitter sites, or, more conveniently, the central distribution node provided a monitoring signal could be received from all radiating sites at this point. Adjustment for coherence at the monitoring location, followed finally by a correction added to each site for the propagation time between the monitoring position and each site will move the locus of optimisation into the actual overlap area.

A very basic minimum requirement of any system is the reception of a signal at each site from each of its neighbours. In this way one site may be adjusted relative to its neighbours. Another possibility is that of groups of sites, each group with at least one site in common with the adjacent group, whereupon each group’s sites can be adjusted as an entity and the groups adjusted one to another. Without the basic prerequisite of receiving all sites in a group at a common point, it will be impossible to set up the system.

However, the simplest and most convenient of system arrangements is that shown in fig 18: a central distribution node containing all the equalisation modules, surrounded by sites all able to be received by a monitor receiver at the same site. Such system topology minimises both the commissioning and maintenance requirements; it also provides the simplest arrangement for explain in detail of the field equalisation procedure.

Detailed procedure for setting up a simple system

Firstly a monitor receiver is set up at the adjustment site enabling the off-air comparison of each transmitter output to be made. Many readers will undoubtedly recognize that this procedure can create it's own complications, since co-locating a receiver on mobile frequency with similar frequency transmitters, is likely to produce some problems. Indeed, past experience shows that often this is where theory and practice can diverge dramatically. Such have been the severity of problems on some systems, the only way acceptable measurements and adjustments have been made, has been by working throughout the night into the early hours of the morning! Providing such basic problems are overcome, the network analyser output is used to modulate the system via the common distribution point. The output from the monitor receiver, when applied to the measurement port of the analyser then permits the instrument to record the required characteristic of the system when set to sweep the normal pass-band range of the system.

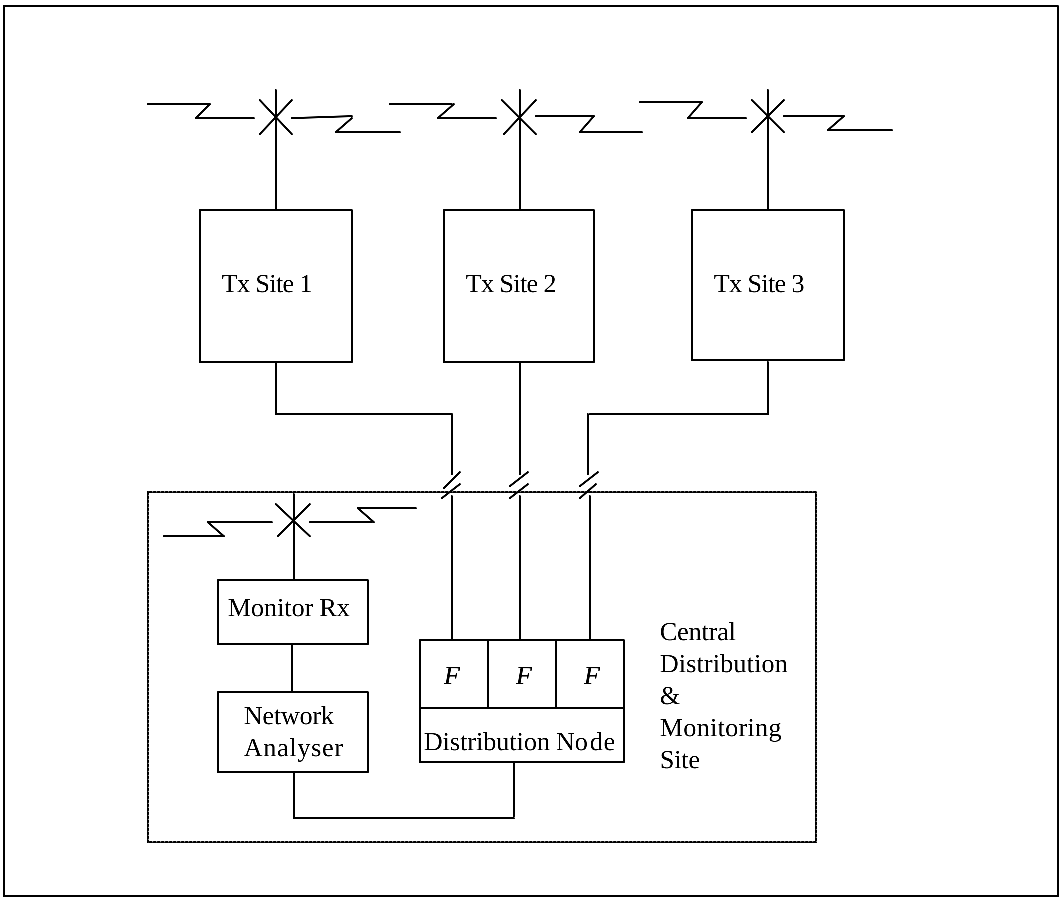

Fig 18 Most convenient system topology for optimisation

A quick scan of the parameters amplitude and delay for all sites is invaluable. It will show up major irregularities as well as showing which circuit has the greatest phase distortion and therefore which circuit for use as the reference characteristic for delay/phase adjustments. These results are obtained by sequentially arranging to inhibit all but one site, assessing each circuit's basic characteristics in turn storing the result, comparing the stored result with the next circuit and retaining the worst characteristic in store.

As mentioned before, it is necessary to be able to receive a signal from all transmitter sites at the monitor receiver location. t is often impossible to receive all sites of a system at one point and in the worst case it may be necessary to resort to monitoring of each site separately at it's nearest neighbour. Such a system will also require each transmitter's phase delay equalisation equipment to be also co-located with each transmitter. Optimisation of such systems is made sequentially between each site and it's neighbour and vastly increases commissioning times and makes procedures for maintenance much more cumbersome.

The order in which matching adjustments are made is very important, since adjustments to match amplitude responses will always affect the phase responses too, but not necessarily vice-versa.

Amplitude characteristic matching

Initial optimisation adjustments must always be made to amplitude and level characteristics, since changes affecting the frequency responses in particular will always result in corresponding changes to the phase characteristics. Since the optimisation requirements for simulcast systems are to minimise differentials, all adjustments should be made with this primary objective in mind. In the case of amplitude frequency characteristics however, some optimisation of the basic characteristic may also be conveniently attempted though this should not compromise the minimisation of differentials.

Careful manipulation of the analyser output level and comparison between different sites allows basic operating points for limiters and compressors to be checked for accurate matching. Since there are always these elements of audio processing within FM/PM transmitters, it is particularly important when making amplitude frequency response measurements to adjust the analyser output to a level below limiting / compressor operation. Failure to observe this will almost certainly result in invalidation of the amplitude-frequency response adjustments due to operation of limiters masking the actual frequency response.

Phase Delay matching

Once the amplitude characteristics are matched to the required accuracy, the crucial adjustments to phase may be tackled. Care has been taken previously to avoid mention of group delay matching and consequential confusion. However, since delay is a convenient way of expressing very large phase differences the matching of widely differing phase characteristics is often more readily achieved in two stages; one of coarse group delay matching, followed by a second stage of fine phase comparison.

Since it is obviously impossible to remove delay from circuits, unless previously it were added, it is important that the site which displays the highest delay distortion at the band edges is used as the reference to which all circuits are matched. This is where results of preliminary comprehensive assessments of all circuits are so useful. It is also often most helpful if some delay, say 1mS, is initially added to all sites using the delay module. This permits minor reductions in delay if the reference circuit ends up actually having less nominal delay than other circuits.

By arranging for storage and display of the reference circuit's group delay characteristic on one trace of the instrument and the current site being adjusted on the second channel, the basic reference characteristic may be directly compared with the actual circuit to be adjusted. Careful adjustment of the phase delay equaliser's all-pass networks permits the addition of delay over specific sectors of the audio pass band to attain a rough match of distortion characteristics. Final matching of the two group delay shapes will almost certainly require some re-adjustment of wide -band or "bulk" delay.

With the group delay matching adjustments resulting in generally less than ± 180° residual phase differential, the measurement procedure may revert to differential phase for fine adjustment of the phase distortion, phase slope and phase intercept. Careful adjustment must now be made to bring the final differential, at least over the lower half of the pass-band, to less than ± 5°.

Repeating this procedure for all sites in turn will ensure that there is less than 10° residual phase differential between any two sites at the location of the monitoring receiver.

Placement of the locus of equalisation

The previous adjustments should have ensured that the outputs from the various transmitters are matched at the measurement location. However, signals arriving at the measurement location from the other sites have actually left each transmitter site slightly earlier than from a local transmitter. For each mile of separation between sites the radio signal takes 5.4µS (3.3µS for each km). By adding to each circuit, the equivalent time in µS that each signal takes to reach the monitor site, all signals can be arranged to radiate synchronously.

Fig 19 below is a hypothetical system with 8 sites, two of which, C & G, cannot be received at the central node site A. In this case sites B & F become “Tandem” node “mini” systems, equipped with equalisation for sites B/C & F/G in their own right. Either system centred on site B or F could become the reference as both sites C & G have two circuits in tandem.

System optimisation / equalisation will start with site B being equalised to site C at location B, treating site B as a terminal node with the monitor receiver and network analyser connected as in fig 17.

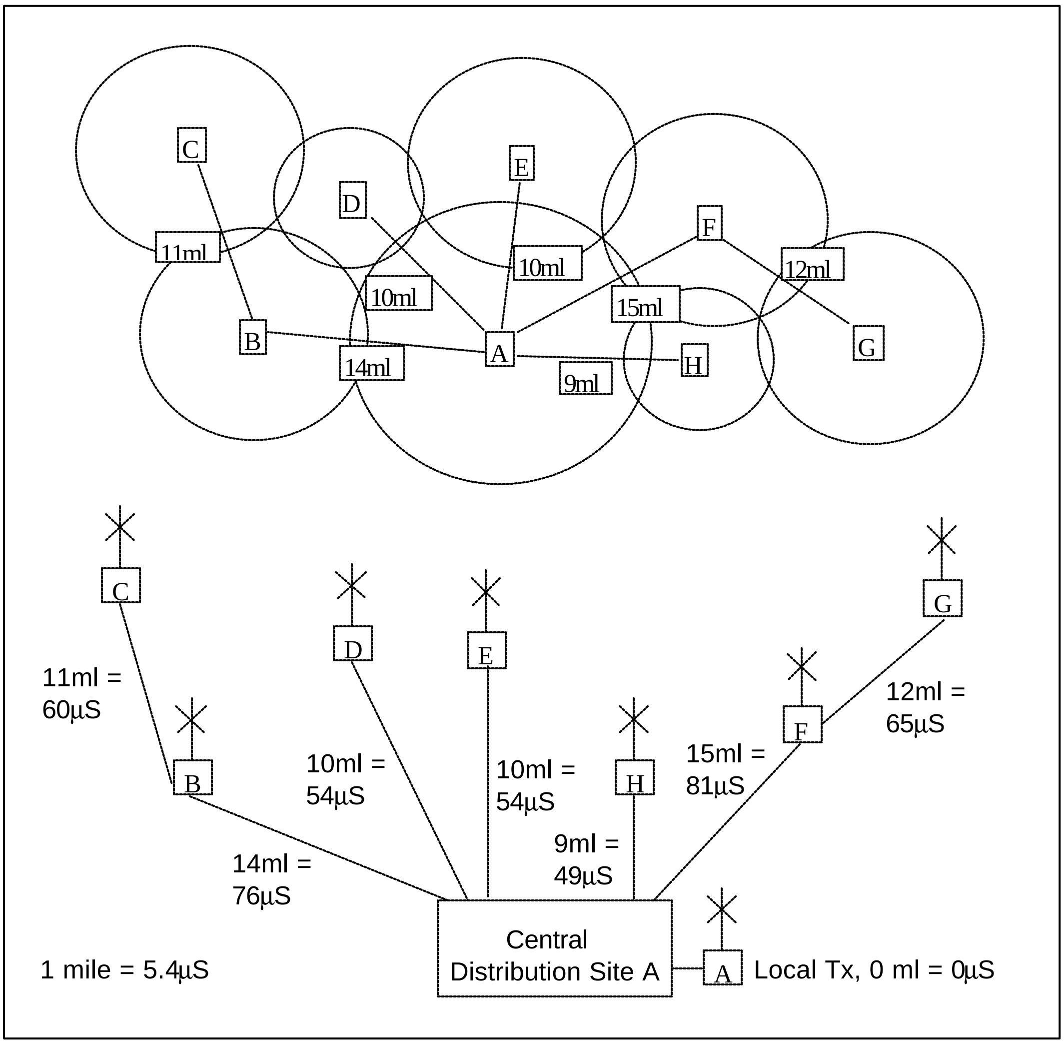

Fig 20 Propagation delay equalisation - hypothetical system

After matching of the distortion characteristics and obtaining coherence at site B, site B local transmitter finally has 60µS added to it’s circuit to place the point of optimum equalisation mid way between sites B & C.

The same procedure is repeated for sites F & G with site F equalised to site G at location F. Finally site F has 65µS added to the local transmitter F to place the optimisation point mid way between sites F & G.

In all probability site F will become the reference for the rest of the system due to the slightly longer length of lines to F & G sites.

Re-linking the nodes at B & F for tandem working allows the main node equalisation / optimisation to proceed using, say, site F as reference. Once all sites have been made to have the same basic characteristic, the feed to each site, including sites B & F, will have the propagation delays added as follows:

A = 0µS; B = 76µS; D = 54µS; E = 54µS; F = 81µS; H = 49µS

This latter procedure will place all the points of optimum equalisation along the equi-distant loci between the sites concerned.

If the area, or areas of equi-signal do not coincide with these loci, then the added propagation times will need adjustment accordingly. For instance, if the point of equalisation between sites A & D is not mid-way between sites - quite likely with an in-fill site - then to move the equalisation point closer to site D requires delay to be added to D or subtracted from A. The amount of delay is determined by measuring the distance towards site D from the mid-point to the actual over-lap area and **doubling** the distance before calculating the extra delay required. The reason for the doubling is that for every half mile of movement, the path difference is 1 mile, half a mile more from site A and half a mile less from site D!

However, great care needs to be exercised in making such adjustments, since changing the delay to site D for instance, will alter the position of optimum equalisation between D and **all** of sites A, B C & E! In practice some compromise will have to be made, since although in all probability the points of equalisation between site D and it's adjacent sites will also be closer to D, they will not be the same change in distance as with the more dominant site A.

The effect of vehicular movement upon optimisation

When any two sites are adjusted to radiate their intelligence at exactly the same instant, a line bisecting the area between the sites can represent the optimum equalisation locus. With propagation of radio signals taking approximately 5.4µS for each mile, varying the distances from each of the contributing sites to the mobile's position will upset equalisation. In practice, each mile of additional path differential from the optimisation locus introduces an additional phase error of approximately 5° at 1250 Hz and therefore some 4 miles of path difference would use up all the theoretical phasing tolerance. The following diagram Fig 20 shows this diagrammatically

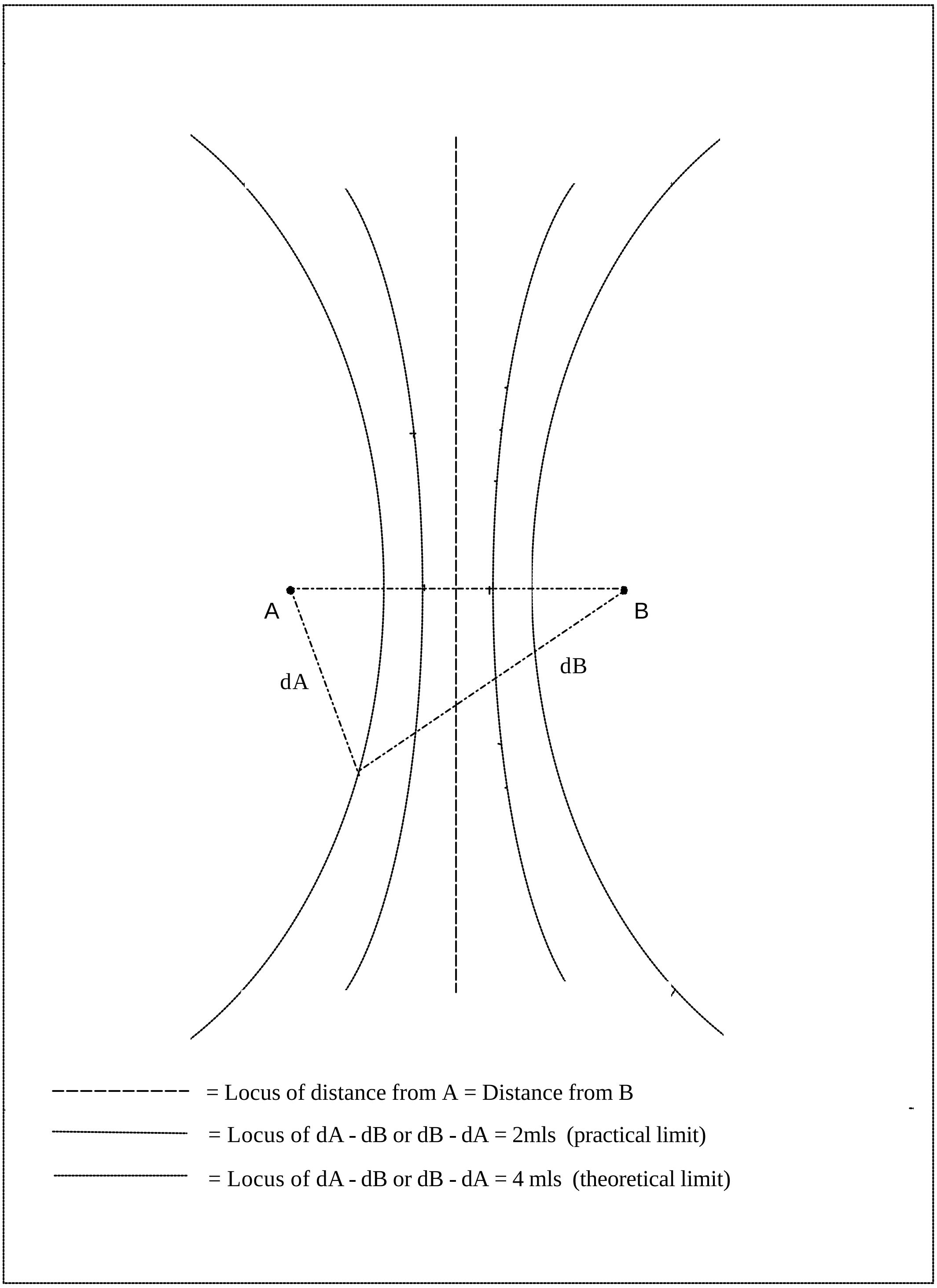

Fig 20 Optimisation Loci for two stations 10 miles apart

In practice therefore, equalisation limits can be only reasonably maintained between the two dotted loci corresponding to path differentials of about 2 miles. This allows for the optimisation match between sites to be a practical ± 5° and permits mobiles to operate within this area without noticeable distortion if the contributing carriers are equal in level.

Hopefully it will now be appreciated that areas of non-capture or equi-signal, outside the theoretical limits of equalisation defined by the solid loci, are likely to suffer distortion of speech peaks. Even those areas of equi-signal overlap occurring between the practical optimisation loci and the theoretical loci are likely to suffer some degree of distortion. The importance of ensuring that the primary overlap area is identified and agreed with the end user cannot be stressed too strongly, since for optimum system operation the locus of optimal equalisation must be correctly located.

It all really comes back to what was iterated earlier: simulcast systems need careful planning and the rewards for short cuts can be unsatisfactory systems.

Maintenance of system parameters

A system set up well at the time of field commissioning is a major hurdle overcome. However, since systems of this type are usually required to operate for many years with the minimum of attention and the highest reliability, it is essential to consider the maintenance aspects.

Apart from equipment reliability, there are two primary considerations involved in the maintenance aspects of simulcast systems. These are:

Maintenance of carrier offsets:

Maintenance of optimisation characteristics

The first factor resolves down to the differential stability of the primary carrier generation reference as mentioned previously. If the differences set on commissioning drift too far, communication may become difficult in the areas of true equi-signal. Whilst excessive carrier drift is unlikely to prevent operation of a system or require the system to be taken down, it can be a time-consuming task re-setting station carrier differential. As such stable sources are employed; the absolute carrier frequencies are most unlikely to have drifted far enough to cause any contravention of statutory licensing requirements. However, even with rubidium standards the differentials will almost certainly need periodic checking, albeit at fairly protracted intervals.

Checking and re-adjustment of carrier offsets at 6-monthly intervals is usually considered acceptable, even so, UHF applications do push the crystal technology close to the limit. It is important to realise that frequent re-netting back to an accurate off-air standard will usually mean that more adjustment will be necessary than if only the differentials are kept in step. The smaller the changes that need to be introduced the more stable the general operating conditions of the oscillator become and the less adjustments the next time. So, **do not** re-adjust un-necessarily, you will only be defeating the ultimate object - long term stability. Crystals almost always improve with age, and ultimately, maybe 5 years down the line, the need for any adjustments may extend to 12 months or more even at UHF.

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Virtual maintenance free operation can be achieved by using the technique of automatic drift control or synchronisation of the frequency sources from off-air references. Such systems, using the GPS (Ground Positioning Satellite) system today rather than Rugby, are, as previously noted, able to provide synchronous operation or quasi-synchronous operation with clearly defined off-sets which never should need re-adjustment.

Even with standard ovenised crystals, there are ways of increasing stability and reliability. As previously mentioned, climatic conditions within the confines of even large simulcast systems can generally be considered similar, provided the sites physical conditions are also similar. Constructional and location differences between sites can have adverse effects upon all aspects of system stability. This may be minimised by careful use of environmental controls at sites to restrict temperature fluctuations. If site conditions can be regulated to within the range 50-80°F (10-25°C), the possible differences between sites can be no greater than 30°F (15°C) and are generally much less. Not only will such measures enhance the performance of the frequency reference oscillators but also general stability of the equalisation networks and the various components of the audio circuits will all benefit from the effect of long-term environmental stability. This approach is considered one of the most cost-effective means of enhancing the long-term stability of any system.

Automatic Delay Equalisation

As described, simulcast optimisation adjustments are all about minimising differentials. The required result is achieved by exercising the system one circuit at a time, comparing the results and making adjustments to circuit and site parameters. Achievement of this automatically is generally a complex matter, particularly if overall distortion characteristics are part of the change.

Before the regular use of digitally derived circuits with their stable distortion characteristics, it was a very complex matter to provide a system that would measure the circuit characteristic and both equalise and optimise the match between circuits.

Today however, the use of digital networks by both the public network providers and even private network providers has resulted in all such circuits on a network having near identical amplitude and phase distortion characteristics. Differences between digital circuits are generally only in electrical length due to propagation delay differences over different path lengths.

Such circuits do suffer from dynamic variability of electrical length. This is due to either automatic re-routing due to network management, or to flexible buffering within network nodes. This latter characteristic is somewhat insidious since it is introduced to minimise the loss of data due to slightly

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different clock rate for incoming and out-going data and results in a continuously changing delay.

To combat these problems a **D**ynamic **A**utomatic **D**elay **S**ystem (DADS) has been developed. This operates as an overlay on the system and controls the delay cards via a data bus in response to periodic “off-air” measurements of delay. Unfortunately, this system can suffer badly from external interference to the off-air measurements that generally render the result under such conditions invalid. This being said, there are a number of successful applications of this system in current use, though all have suffered at one time or another from interference induced errors.

Further problems in the implementation of this type of system are that it is both intrusive in it’s testing and it requires the central node to be linked to a monitor receiver capable of picking up **all** transmitters on the system. This can seriously restrict its application. To combat these shortcomings, a new system employing the GPS system has been developed.

The GPS based system “marks” the originating transmission at the start of each 1-second pulse generated from the local GPS receiver. It then compares the received “mark” at the transmitter site with the same I PPS received by that site’s GPS receiver. The calculated delay is then used by the local controller to ensure all sites are buffered out to the same overall delay. The system allows the actual delays to each site to be tailored to account for over-laps not being at mid points between sites. Additional circuitry at each site can provide synchronously locked synthesisers producing the transmitter RF reference frequency and, if required, a synthesiser producing the CTCSS frequency for outgoing transmissions. Whilst not cheap, this system will produce a near “plug-and-play” QS system requiring the minimum of maintenance and setting up.

It should be remembered, that with a well-planned system, the greatest portion of the area covered by radio communication would be essentially single site operation. Areas that can be affected by carrier beats or distorted audio will normally be small in total area and usually made up of many very small and localised pockets. As such, even if systems drift out of adjustment occasionally, most of the time this fact will not be noticed, particularly if the system is planned to place overlap areas outside major conurbations and communication areas. Often the errors will even self correct before it is noticed there was a problem. This is particularly true for variations due to environmental reasons and is good cause for such diurnal changes to be basically ignored. Only when simulcast systems are poorly planned initially, use unsuitable equipment or are inadequately optimised will they really perform badly. Even systems with very low levels of signal in the overlap areas can, with detailed attention to the phasing optimisation, provide intelligible, if somewhat noisy communication.

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The correct choice of equipment

As should be now apparent, the choice of equipment and competence of system supplier can have a marked effect upon ultimate performance of any simulcast system. It is essential that consideration of the specialist application of simulcasting be taken in the design of equipment and systems. This is unlikely unless manufacturers and suppliers have proven experience and expertise in simulcasting techniques.

Summary

It should now be very clear that there are a number of important steps necessary for achieving the best performance from any single frequency simulcast system.

1. Careful planning and selection of site locations thereby ensuring:

   : Non too large distances between sites,
   : Adequate signal levels in overlap areas
   : Short sectors over which equalisation may be maintained.

2. Control of the site conditions

   : To ensure a respectable degree of environmental stability.
   : To provide optimum stability from frequency sources
   : To minimise changes in equaliser and transmitters

3. Control of carrier frequencies

   : Use of really high performance high stability sources
   : Adjust offsets within optimum settings
   : Use drift controlled/ synchronised sources if possible

4. Control of circuit characteristics

   : Use of identical purpose designed equipments
   : Ensure accurate matching of basic circuit characteristics.
   : Use phase-locking system to control variable phase on analogue multiplex circuits and lines
   : Use automatic delay correction equipment when digital interconnection circuits are involved

Following these basic rules will result in simulcast systems that perform as well as they possibly can and with which anyone can be proud to be associated!

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