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A DIVERSITY COMBINING ANTENNA ARRAY FOR LAND MOBILE SATELLITE COMMUNICATIONS

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Abstract

A unified approach to adaptive antenna array design and transceiver signal processing architectures is proposed for the user segment of the Land Mobile Satellite communications service. This novel technique is described here in its conceptual form, and compared with steered antenna array configurations currently favoured for this class of mobile communication system.

The proposed system employs established diversity combining techniques previously developed for mobile terrestrial radio. It is suggested that a diversity based receiver architecture would allow the coherent recombination of the multipath signal energy present at the mobile terminal site, and thereby enhance system performance for a given link budget. Further, it is recommended that this processing can be most simply achieved if a pilot-based modulation format is utilised, and near instantaneous adaptation to the multipath energy if feedforward signal regeneration techniques are employed in the receiver.

1.0: Introduction

Communications to mobiles is becoming an increasingly important factor in business, search and rescue, and recreation. Developments such as Cellular radio and wide area paging networks provide a service suitable for populated regions, however in sparsely populated areas it becomes uneconomical to install these systems on the grounds of the considerable infrastructure costs. A satellite communication service administered by the International Maritime Satellite Organisation (INMARSAT) has provided a communication service for ships and nautical platforms since the early 1980's. In 1983 plans were disclosed by INMARSAT to extend this service to include both terrestrial and aeronautical mobile platforms, thereby providing a mobile communication service for regions where no terrestrial based network previously existed. Besides INMARSAT, individual countries are also developing their own satellite communication network for mobile platforms, however negotiations are being held to ensure a global standardisation of access technique[1]. For example, the NASA[2] MSAT-X and Canadian[3] MSAT programs.

Land Mobile Satellite (LMS) is the generic name associated with this new class of mobile communication service. This service is primarily targeted to bridge and complement terrestrial based cellular mobile telephone networks and private mobile radio systems by extending the coverage area to include rural and sparsely populated areas. For example, in Australia and Canada there are vast open spaces which would be virtually impossible to adequately cover using terrestrial based links. Thus, potential users of this satellite service would include the trucking industry and air ambulance fleets, where roaming beyond the range of terrestrial based systems is required. Also, in addition to providing a communication service with extensive global coverage, new data message services will be provided by the LMS networks.

.The viability of a satellite based maritime radio communications service has already been established, however the propagation characteristics of the land mobile satellite radio channel are vastly different to those of its nautical counterpart. The effective utilisation of this new communication channel now presents communication system designers with an interesting and demanding challenge.

2.0: Land Mobile Satellite Communication Networks

Global mobile communication services such as maritime, aeronautical and land mobile are most effectively provided by using satellites transponders. Although INMARSAT commenced service as a maritime organisation, it was recognised from its inception that technically there was much in common between providing services to ships at sea, or to aircraft and land mobile terminals. Initially land mobile terminals will be vehicular mounted, and many of the system operators will employ the INMARSAT standard-C transmission format originally developed for maritime operation. It is expected that portable terminals will quickly evolve for both voice and data communications, and personal communications by satellite become a reality. The limited L-band frequency allocation to this service and the over-riding need for cost efficient commercial systems has driven system integrators to carefully utilise existing and developing ground and space segment technologies.

The long range and limited radiated power of the satellites together with the modest allocation of radio spectrum given to these services necessitates efficient use of both bandwidth and power. Further to this, the modulation format selected must be tolerant of the restrictive propagation characteristics of the mobile radio channel if intelligible and reliable communications are to be provided. To this end, significant advances in both analogue and digital modulation techniques have been made for this, and the closely related field of terrestrial mobile communications. For example, the development of amplitude companded single sideband (ACSSB), and digital modulation schemes employing linear predictive vocoders. However, further gains using such techniques are now unlikely, and hence research is now being directed towards mobile antenna technology.

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As a precursor to the discussion on present generation mobile satellite antenna technology and the new receiver architecture being proposed here, it is first necessary to review the propagation characteristics of the mobile satellite radio channel. In addition, the fundamental architecture of the mobile terminal is considered and the basic specification of the mobile antenna system derived.

2.1: Propagation Characteristics

The propagation characteristics of the signal path between a mobile terminal and a satellite provides some of the worst propagation conditions encountered in the field of radio communication. There are a number of effects ranging from ionospheric scintillation to multipath, and also, significant attenuation losses associated with roadside vegetation. For economic and technical reasons satellite systems are designed with minimum propagation margin consistent with desired performance objectives.

Numerous propagation studies have described the fading and shadowing characteristics of the land mobile satellite radio channel. This has been analysed both theoretically[4] and with real-time[5,6] channel sounding techniques using signals transmitted from operational satellite platforms and pseudo sources (eg. helicopters and balloons). Results have been presented for both UHF (800-900MHz) and L-band (1.5GHz) systems for a radio receiver operating in urban, suburban and rural terrain.

It is generally agreed that the received signal envelope consists of two components, the direct line of sight signal, and a scattered or multipath contribution. Land mobile satellite systems tend to rely upon a line of sight path between the transmitter and receiver, however the signal arriving at the receiver is usually the composite of a number of scattered waves as illustrated in figure 1. Hence, as the mobile moves through this signal environment, the dominant scatters and reflectors change, as do the electrical path lengths of the waves. The received signal is therefore subject to random amplitude and phase fluctuations. In addition the line of sight component is subjected to shadowing, or blockages caused by man-made or natural features, as well as foliage attenuation. It can be shown that the multipath signal envelope at the receiver, with no direct line of sight components, has a Rayleigh type distribution. In addition, the received signal phase, the rate of change of phase and the rate of change of the envelope can be approximated by a Gaussian process.

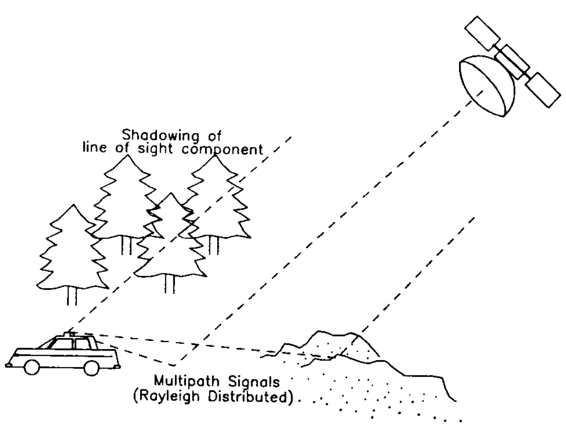

Figure 1: Signal Reception at the Land Mobile Satellite Terminal.

When there is a direct line of sight path, with little or no shadowing and only minor multipath contributions, the received signal can be described by a Rician distribution. Typically, the ratio of the line of sight component to that of the multipath signals is approximately 10dB. For a received signal experiencing only light shadowing, say in a rural environment (6dB variation), the received envelope can be modelled as the sum of log-normal and Rayleigh random processes. When heavy shadowing (12dB variation) is experienced the received envelope distribution tends towards a Rayleigh function. It has been shown that suburban area propagation conditions are similar to those experienced in rural regions with heavy shadowing. Measurements have also shown that large variations in received signal strength exist for changing elevation angle, and that considerable doppler frequency offsets are present for all operating conditions.

Comparing the propagation characteristics of the land mobile satellite channel with that of terrestrial mobile radio[7] reveals some very striking similarities. Although terrestrial systems do not rely upon a line of sight component for operation, the received envelope at the mobile has identical amplitude variations to those described for the land mobile satellite channel when the line of sight path is obscured. However, since the average power level at the mobile terminal is considerably less in the case of satellite communications, the relative magnitudes of the distributions are different. This synergy is important, since signal processing techniques previously developed for terrestrial mobile radio can also be applied to land mobile satellite systems.

2.2: Land Mobile Satellite Transceiver

The minimum performance of analogue or continuous data links is usually defined for a specific threshold value of carrier to spectral noise density (C/N_o) at the receiver output. The link availability is determined by the percentage of time that this threshold value is likely to be exceeded, and the *link budget* provides an indication of the achievable performance of the system.

The INMARSAT 'Strawman' specification[1] assumes a mobile terminal with a G/T of approximately -12dBK, and an EIRP of 24dBW. This will provide an overall C/N_o of approximately 45dBHz for direct line of sight (unfaded) operation. On the basis of subjective performance tests, this figure of C/N_o provides acceptable speech performance when ACSSB modulation is employed. This rudimentary specification can be achieved by employing a 4-element array antenna with an on-beam gain of approximately 12dBi, assuming a receiver system noise temperature of 250K and 1dB implementation loss. Further it is assumed that tracking of the satellites is accomplished by mechanical means.

The importance of the antenna system to a successful land mobile terminal design cannot be over-emphasised. Currently both mechanical and electronically steered antenna systems are being considered in detail.

2.3: Present Trends in LMS Antenna Design

Numerous antenna beam steering techniques employing various antenna array topologies are now being proposed for the user segment of the land mobile satellite service. The stringent link budget specification of this channel can be maintained by tracking the satellite with the antenna, assuming line of sight operation. When the space segment is fully deployed, all the satellites will share the same L-band frequencies, hence for a typical operational scenario two or more satellites may be visible at the land mobile receiver site. The narrow beam formed by the array will therefore be used to mitigate the effects of mutual satellite interference, as well as greatly enhancing multipath discrimination. Since the relative geometry between the various transmitter and receiver terminals is constantly changing, these interference suppression techniques must be adaptive in order to provide robust performance in a range of system configurations.

Antenna array systems proposed to date for the land mobile satellite service employ either a mechanically steered platform[8], or, a fully electronically steered array[9,10]. The latter technique has been implemented in the form of a phase weighted array and a parasitically steered structure, and these systems generally have switched beam patterns. The mechanical systems tend to employ a monopulse tracking system, whereas the other systems cited use a sequential lobing tracking and acquisition technique. Further to these closed loop control schemes, a flux gate compass open loop controller provides pointing information whenever the line of sight path to the satellite is lost due to shadowing.

2.4: An Alternative Approach to LMS Antenna Design

Currently none of the antenna array systems under development for the land mobile satellite service fully exploit all the information available at the array aperture. The output of each element in the antenna array, such as that illustrated in figure 2, contains all the essential geometrical information required to implement an optimum closed loop adaptive beam steering control system. Adaptive antenna arrays[11] have attracted much interest and investigation, primarily because of their ability to automatically steer radiation pattern nulls (reduction in sensitivity) towards sources of interference.

The basic operation of the array can be explained as follows. Consider a wavefront generated by a narrowband source of wavelength λ arriving at an N element uniform linear array from a direction θ_k as indicated in figure 2. The conventional beamformer is a network which can delay the phases of individual signals causing the components of a wave arriving from a particular location to either add coherently, or non-coherently. Now taking the first element in the array as the phase reference and letting d equal the array spacing, the relative phase shift of the received signal at the n^{th} element can be expressed as:

$$\Psi_{nk} = \frac{2\pi d(n-1)}{\lambda} \sin\theta_k \qquad (1)$$

Assuming constant envelope modulation of the source at θ_k, the signal at the output of each of the antenna elements can be expressed as:

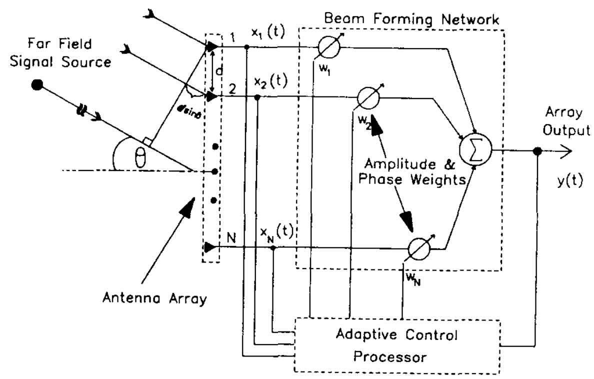

Figure 2: An Adaptive Antenna Array.

$$x_{nk}(t) = e^{j(\omega t + \Psi_{nk})} \qquad (2)$$

And the total array output in direction θ_k as:

$$y_k(t) = \sum_{n=1}^{N} w_n e^{j(\omega t + \Psi_{nk})} \qquad (3)$$

Where w_n represents the value of the complex weight applied to the output of the n^{th} element. Thus it can be seen that by suitable choice of w_n the array output can equal zero for certain θ_k. This corresponds to a radiation pattern null. Likewise for the case of interest, the weighting network can be optimised to provide maximum gain in a specific direction.

The heart of the adaptive capability of the array lies with the ability of the control algorithm to adjust the array beam pattern in response to the signal information present at each of the individual antenna outputs. Established techniques, such as, the *Least Mean Square* algorithm of Widrow[12] can be applied since a coherent reference is readily available if a pilot-based analogue modulation scheme is employed. At the mobile terminal site it is recognised that significant multipath energy will be present, the effects of which can be mitigated to a large extent by employing this classical implementation of an adaptive antenna array. The *anti-multipath spatial filtering* capabilities of an adaptive antenna array is illustrated in figure 3 for a spread spectrum communications system. Here, the radiation pattern of a 7 element linear adaptive antenna array, with $\lambda/2$ spacing, operating in a multipath signal environment is given. It is assumed that the line of sight component arrives from 45° off the array boresight, and the multipath contributions impinge on the array from 10°, -25° and -45°. For simplicity all signal contributions at the array aperture have equal magnitudes, and the multipath signals are delayed by 200, 400 and 600 time units with respect to the line of sight component. It can be seen that as adaptation takes place the sensitivity of the array towards the line of sight source is greatly enhanced, whilst the gain response towards the multipath signals has decreased. As steady state is acquired, deep nulls are formed in the direction of the multipath components.

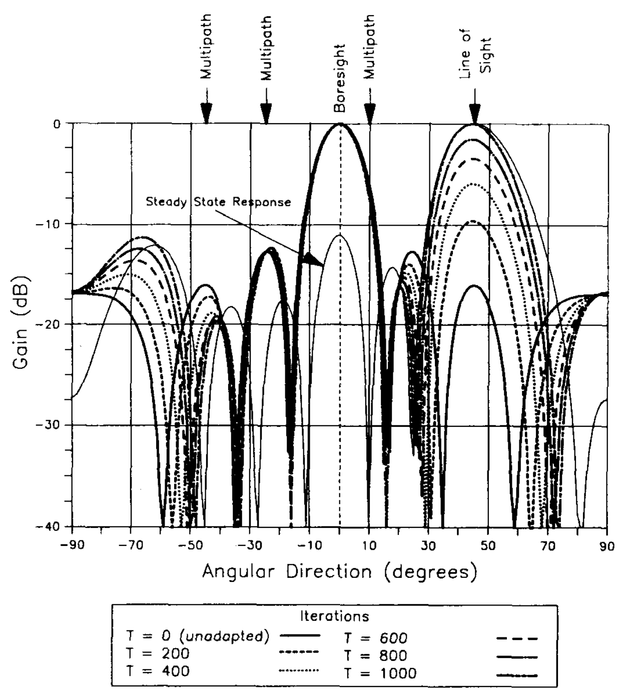

Figure 3: Adaptation of Radiation Pattern of the *Anti-Multipath* Array.

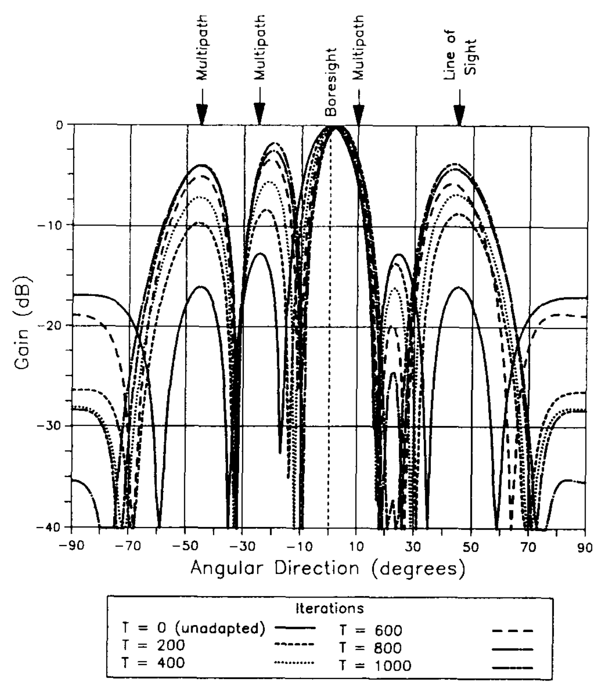

Figure 4: Adaptation of Radiation Pattern of the *Multipath Combining Array.*

This has been accomplished by generating a reference signal which has a high correlation with the line of sight component, and a low correlation with the multipath contributions. Hence at the output of the array the multipath energy present has been significantly reduced by an adaptive amplitude and phase weighting process.

However, of particular interest here, is the development of an array signal processing architecture which will provide coherent recombination of the multipath signals. This class of receiver should greatly enhance the performance of land mobile satellite systems, particularly when the line of sight path is obscured by shadowing. Beach[13] has previously demonstrated that an adaptive antenna array can be simultaneously sensitive to multiple spread spectrum signal sources impinging on an array from random directions. This was achieved by generating a binary reference sequence with a high correlation with each of the wanted signals, and using this to control the response of the array. A similar approach has been adopted to control the response of the *multipath combining array* shown in figure 4. The operational scenario is identical to that described above for the anti-multipath array, however here, adaptive control has been achieved using a reference signal which has a high correlation not only with the line of sight component, but also with the multipath signals. It can be seen that as adaptation occurs the sensitivity of the array to both the line of sight and multipath signals is maximised. The beam steering operations of the two adaptive array techniques are illustrated in figure 5. For a situation where the line of sight path has been obscured, the classical beamforming technique can only provide reception via the strongest multipath reflection. However, the proposed antenna system can exploit the presence of all the multipath signals as shown.

In order to provide the coherent recombination of the multipath energy, an array signal processing architecture which is capable of responding to the real-time variations of the multipath signals is required. The adaptation rate of a feedback controlled adaptive array is too slow to exploit the dynamic characteristics of the multipath signals present at the mobile terminal site. Typically, the adaptation rate of these systems is in the order of 10's of milliseconds. However, for narrow-band systems, real-time adaptive co-phasing can be very effectively implemented using a technique previously developed for terrestrial land mobile radio systems. This technique is known as *Diversity Combining*[14]. The real time co-phasing of the received signals is achieved by using a signal processing technique known as *Feedforward Signal Regeneration*[15].

3.0: Diversity Systems and Techniques

Diversity reception requires the provision of two or more signals each carrying the same message, but having independent fading statistics, i.e. uncorrelated. Proper combination of these signals will result in a reduction of the severity of fading and will generally provide greatly enhanced reception. Although time, polarisation, frequency and space diversity can be used to provide uncorrelated fading signals, the ease of implementation, with no demands for additional radio spectrum, make space diversity an appropriate choice for mobile radio. It has been shown elsewhere[16] that two antennas separated by $\lambda/2$, where λ is the wavelength of the RF carrier, can provide uncorrelated fading signals at the land mobile satellite terminal site.

Each of the received signals contributes a branch

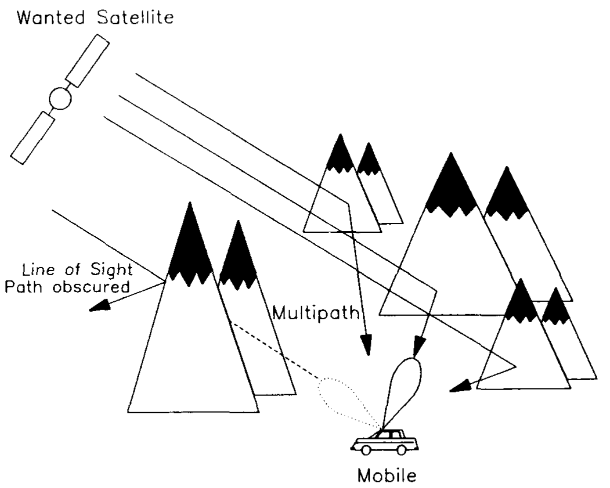

Figure 5a: Classical Beamsteering. Signal Reception via Single Multipath Reflection when Line of Sight Path is Obscured.

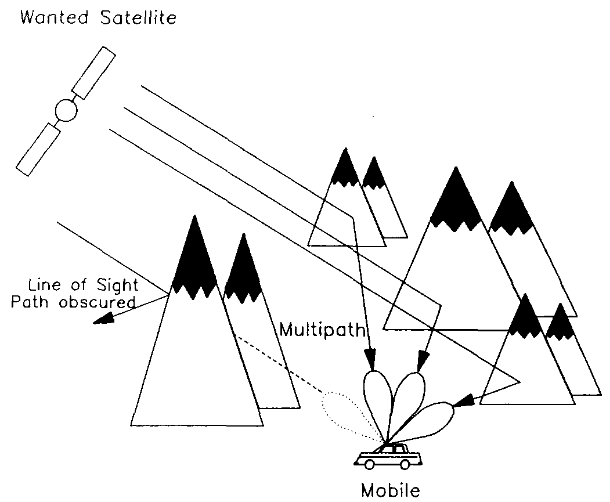

Figure 5b: Signal Reception via Coherent Recombination of Multipath Signal Energy.

to the diversity combiner which processes them to give an output signal with improved signal to noise ratio (SNR) and greatly reduced multipath effects. The diversity order, M, is determined by the number of branches or array elements used, and this depends on the degree of signal enhancement required. The space diversity receiver is usually designed to co-phase the multiple wanted signals and thus achieve coherent combining of the wanted signal energy, whilst providing incoherent combining of interference and noise.

3.1 Space Diversity Combining Schemes

Three principal types of space diversity combining techniques have been considered for terrestrial land mobile radio systems. These schemes are also applicable to the land mobile satellite scenario. *Switched* or *Selection* diversity employs M receivers with independent fading envelopes. At any given time instant the receiver with the highest SNR is alone connected to the output port. This can be shown to improve the average SNR as the order of diversity, M, is increased. However, at low SNR excessive switching between diversity branches will reduce the diversity advantage, and also the overall antenna system gain is less than that of other diversity systems considered below.

In contrast to selection diversity, the M received signals are co-phased, weighted and then summed together in a *Maximal-ratio* combining scheme. This configuration suggests that the combiner output will provide the coherent addition of the wanted signals from all branches, while the noise signals are added incoherently. This will result in a combined signal with a better SNR than that of the individual branches. However, in order to obtain the correct weighting factors for the maximal ratio combiner some additional instrumentation is required. This is in direct contrast to the relative simplicity, and almost equivalent performance, of *Equal-gain* combining. In this case the weighting factors all have unit magnitude.

The improvement in average SNR for increasing number of diversity branches is illustrated in figure 6 for each of the combining strategies considered above. The results presented here assume that the multiple received signals fade independently. Practically this may not be the case, and the effects of partially correlated fading signals on the performance of diversity systems has been estimated by several workers, notably Jakes[14]. It is generally agreed that the performance of diversity systems degrades with increasing fading envelope correlation. However, the diversity advantage appears to hold for correlation coefficients as high as 0.8, with a loss of only 4dB and 3dB in the effective diversity gain for selection diversity and maximal-ratio combining respectively for a two branch system.

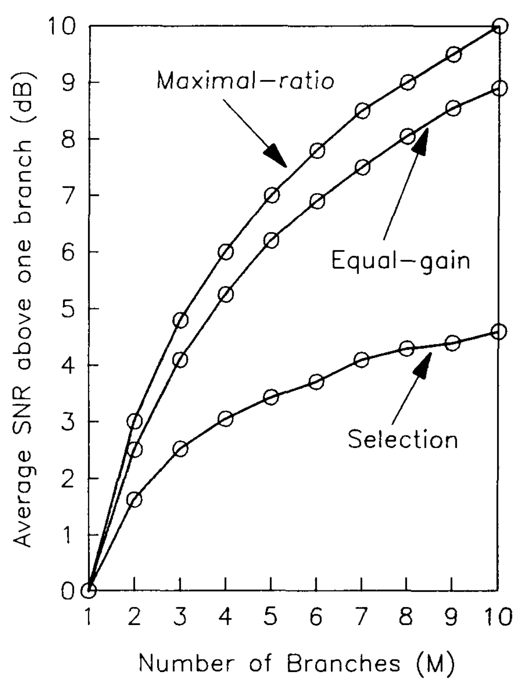

Figure 6: Diversity Improvement in Average SNR for Independently Fading Branches.

3.2: Diversity Improvement in Rician and Rayleigh Fading Environments

In Rician fading environments, where the direct line of sight component is significantly large, equal-gain performance approaches that of maximal-ratio combining, whereas the improvement through selection diversity is less pronounced. Correlated fading has been found to deteriorate the performance of all diversity systems and maximal ratio combining continues to offer the best performance advantage.

The effectiveness of space diversity can be assessed in a number of ways. Most important, as far as mobile radio is concerned, is the capability to increase the reliability of transmission for a given link budget. Diversity has been shown to reduce both the average fade duration by a factor proportional to the number of diversity branches employed, and the percentage of time that the received signal is below unusable levels. Thus, link availability can be enhanced to include areas where Rayleigh fading is dominant.

3.3: Co-phasing in Diversity Systems

Several methods of coherently combining the received signals from an antenna array have been developed over the past years. In RF combining, where a single receiver is used, a variable phase shifter is introduced into the RF path and controlled by a voltage derived from the relative phase between the RF signals. The disadvantage of this approach is the difficulty of implementing an analogue 360° phase shifter. In practice quantised phase shifters have been used, however, these are found to oscillate about their optimum value. This architecture implies feedback control of the RF phase shifters as described previously in section 2.4. Also, the use of RF phase shifters prior to RF amplification further increases implementation losses. For example, overall noise figure and intermodulation performance. This can be overcome by employing the appropriate weighting at a suitable IF frequency (*predetection combining*), or at audio frequencies (*postdetection combining*).

The real time co-phasing requirements of the optimum diversity combiner can most effectively be implemented by employing a technique known as *Feedforward Signal Regeneration*[15] (FFSR). McGeehan[17] has demonstrated the feasibility of this technique for correcting the restrictive propagation characteristics of a single sideband (SSB) terrestrial mobile radio channel. A pilot-tone is transmitted with the information signal, and this is used to provide the receiver with a real-time profile of the channel. This is then subsequently used to remove the unwanted perturbations present on the wanted signal. A much simplified implementation of this technique for the co-phasing of M diversity branches in a LMS receiver is illustrated in figure 7. The pilot and its associated phase and amplitude variations are filtered by F_1, and this control signal is then used to remove the random variations from the received signals by selecting the difference term at the mixer output as shown. Since the output signal in each branch is locked in both frequency and phase to a common reference, the co-phasing requirement of the diversity combiner is thus achieved. Delay is included in the signal path to compensate for the phase delay in the control path. This technique has been shown to provide multipath correction for signals with a fade rate of >150Hz.

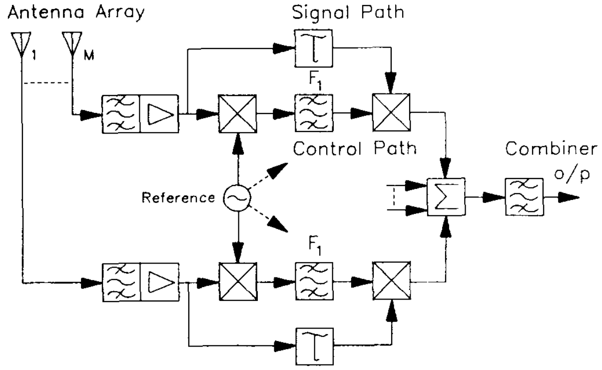

Figure 7: Co-phasing Diversity Combiner.

4.0: FFSR Based Diversity Combiner for LMS Networks

The foregoing discussion has demonstrated that a multi-channel space diversity receiver can enhance the C/N_o ratio of a LMS receiver for line of sight operation. This significant result has several important ramifications on the overall system specification. For example, the stringent link budget specification quoted previously can be relaxed, possibly allowing for a reduction in the transmit power of the space segment. Conversely, the current specification of the space segment EIRP can be maintained and the link availability in sub-urban and urban areas greatly enhanced. This result is based on the fact that line of sight operation is no longer necessary since the multipath signal reflections can now be exploited.

Certain modulation formats will facilitate the economic implementation of a FFSR based diversity terminal. Kanso[18] has demonstrated a dual branch system for mobile radio which utilises FFSR for the diversity co-phasing process. This system employed *Transparent Tone In-Band* (TTIB) SSB modulation, and recent developments at Bristol University have produced an elegant digital implementation of the FFSR technique based on the Texas TMS320 family of digital signal processors.

4.1: Equivalence with Classical Beam Steering Techniques

The space diversity receiver must also provide interference rejection to combat the effects of mutual satellite interference. An interesting analogy can be drawn between the diversity combining architecture, and the classical adaptive antenna array described in section 2.4. The feedforward and feedback co-phasing techniques of the respective receiver architectures both optimise the reception of the wanted signal energy in the presence of interference. This is achieved by implementing an adaptive control process which maximises the correlation[13] between a local reference and the array output. Assuming that the wanted and mutual satellite communication channels are uncorrelated, the space diversity receiver can then provide the necessary mutual satellite interference rejection.

The paper so far has concentrated on issues concerning the receive function, however the mobile terminal must also provide an up-link communications channel at L-band to the satellite. In order to minimise the EIRP of the terminal and to reduce mutual terminal interference in the space segment, a retro-directive beam on transmit must be formed towards the active satellite. The beam steering parameters can be derived from the down-link signal energy present at the array aperture as described in section 2.4. Although the phase relationship between a diversity combining array and a classical adaptive array architecture have hitherto been overlooked, it should be possible to extract the necessary beam steering parameters from the FFSR control loop. However, at present it is considered that the highly dynamic multipath reflections cannot be exploited for the transmit function. It is therefore suggested that the up-link retro-directive beam is formed using a beamformer similar to that shown in figure 2, and deriving the adaptive weights for the transmit operation from the phase conjugate of the average value of the receive weighting function.

4.2: Implementation Issues

A four branch space diversity combiner for a LMS mobile terminal is at present under development at Bristol University. The basic transceiver architecture is illustrated in figure 8. The four element planar array consists of patch (printed circuit) antennas fabricated from RT-Duriod 5880 substrate. The individual patches have been optimised for the reception of a circularly polarised wave at 1545MHz, and have a bandwidth of 30MHz with a VSWR of better than 1:2. It is recognised that patch antennas are

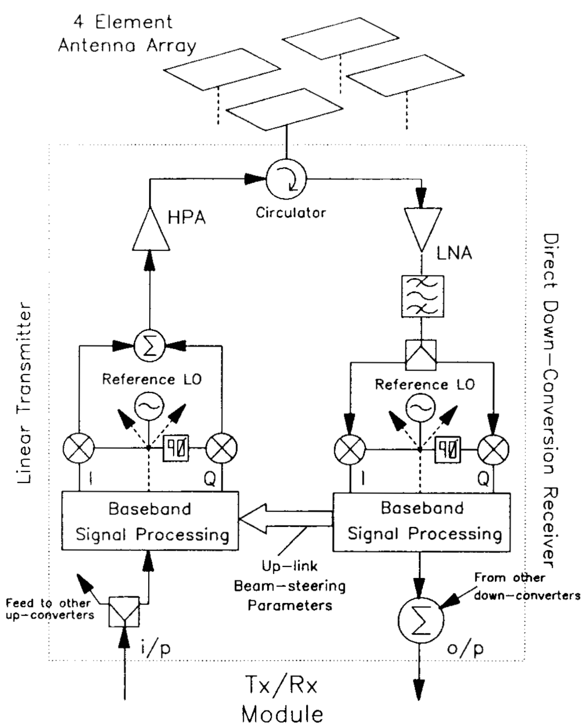

Figure 8: The LMS Diversity Transceiver.

inherently narrowband, and various techniques are currently being investigated to enable full duplex operation of the transceiver from a single transmit/receiver antenna array. This includes the use of feedline parasitics, and coupled structures for the dual excitation of the dominant TEM modes. The patch antenna array is suitable for vehicular mounting since low profile structures are readily attainable, and also the technology is amenable to low cost mass production.

The receive and transmit paths are isolated using a microstrip circulator as shown. The receiver chain employs a direct down-conversion[19] architecture, thus avoiding the need for bulky and expensive IF stages, and a linear transmitter[20] is proposed for the up-link. The receiver will require a low noise, high gain, RF amplifier (LNA) prior to down-conversion. This has been implemented using a cascade of GaAs Fet devices and silicon monolithic amplifiers. The price of small signal, low noise, GaAs Fet devices has now fallen to below $5. Mini-circuits SRA2000 double balanced mixers are currently being employed in the quadrature down-conversion mixing stage, however these devices are rèlatively expensive (approx $20). Hence, various microstrip mixer techniques using hot carrier diodes are currently under investigation. A fully integrated and low-cost[21], LNA, bandpass filter, and quadrature down-conversion stage is envisaged. Control of the down-conversion mixing, and the FFSR co-phasing process, have already been implemented using digital signal processing (DSP) techniques at baseband on a Texas TMS320C25 processor for SSB mobile radio systems operating at 150 and 900MHz. The integration of this hardware in a 1.5GHz mobile transceiver is seen as a relatively simple task.

Linear Modulation (LM) is implied in the transceiver architecture described above, hence a transmitter having low out of band emissions is required. Currently the poor availability and high price (>$500) of high power linear (Class A) L-band power transistors has forced designers to seek alternative techniques. Class C power devices can be linearised by employing *Cartesian Loop Feedback*[17], and this can show dramatic improvement in the suppression of spurii, even when compared with class A or AB operation. Thus, the high power linear GaAs Fet devices, previously required for the LMS antenna configurations described in section 2.3, can be replaced by relatively cheap (<$35), and readily available, silicon class C devices. Up-link beam steering is implemented at baseband as shown in figure 8, and each patch antenna is separately driven by a medium power (≃10W) linear power amplifier. Further, the use of class C linearisation techniques greatly enhances power efficiency, when compared with class A operation.

5.0: Conclusion

The importance of the antenna system cannot be over-emphasised, and must be considered in detail before the final specification of modulation format for the land mobile satellite service. Certain modulation schemes, such as the scheme cited above, will facilitate the successful ergonomic design of the land mobile terminal antenna system. In addition, this modulation format provides excellent voice and data communications, and is also very spectrum efficient.

The proposed system employs a space diversity antenna array with dynamic multipath tracking, and has been shown to greatly enhance link availability when the line of sight path is obscured by shadowing. It has been shown that the co-phasing of the multipath signals can be implemented using a FFSR signal processing architecture, which exploits the presence of a pilot-tone within the communications channel. On transmit, a retro-directive beam is formed towards the active satellite. Further to this, the economic viability of such a transceiver has been considered.

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