FREQUENCY ADDRESSABLE BEAMS FOR LAND MOBILE COMMUNICATIONS

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ABSTRACT

Satellites used for mobile communications need to serve large numbers of small, low cost terminals. The most important parameters affecting the capacity of such systems are the satellite EIRP and G/T and available bandwidth. Satellites using frequency addressed beams provide high EIRP and G/T with high-gain antenna beams that also permit frequency reuse over the composite coverage area. Frequency addressing is easy to implement and compatible with low cost terminals and offers higher capacity than alternative approaches.

INTRODUCTION

Communication satellites have served a variety of communications needs over the past two decades. During this time, satellite systems have become more tailored to the specific needs of the community being served. Although satellites are currently used to provide mobile communications, significant performance improvements are available with satellite designs which are better suited to the requirements of the mobile communications communities.

MOBILE COMMUNICATIONS CHARACTERISTICS

An efficient system architecture for land mobile communications by satellite must be responsive to the characteristics of the mobile communications environment. In general, mobile systems are characterized by a large mobile user population communicating to fixed points through a satellite and base stations (see Figure 1). The satellites for this service operate in two frequency bands: the allocations for satellite communication to and from the mobile users are at L-band,
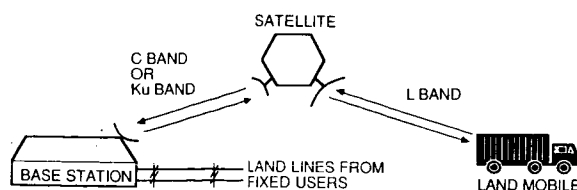

Fig. 1. Mobile satellite system

with the down- and uplink bands separated by approximately 100 MHz; the satellite-to-base station links are at C-band for the maritime mobile service, while use of Ku-band has been suggested for land mobile base station service. Furthermore, the traffic is of a point-to-point nature, and there is a scarcity of bandwidth to support the anticipated large community of mobile users, with the various services each allocated only a small portion of the frequency spectrum.

Mobile systems are further characterized by a geographically dispersed user population, each of whom has a low percentage use of the system. Hence, the economic viability of such systems requires a large subscriber base of users. The economics of the system also require low cost mobile terminals, not only since the number of users is large, but also to encourage further population growth.

Another characteristic of mobile systems is that any given signal is of a point-to-point nature (user to/from base station). Accordingly, there is little or no need for a broadcast capability to address all parties simultaneously. System characteristics are summarized in Table 1.

The characteristics described above clearly influence other aspects of such a system. Since the mobile user stations are limited in power and gain, it is of great advantage to achieve high gains for the spacecraft L-band antenna. And since traffic is of a point-to-point nature, the limited bandwidth allocation can be circumvented by frequency reuse in different geographic service regions.

A system design that most easily meets these requirements is one that uses multiple uplink and downlink high-gain beams over the coverage region of interest. The high gain supports the EIRP and G/T requirements, while the multiplicity of beams permits frequency reuse, thus increasing the available bandwidth.

Table 1. Mobile communications characteristics

Mobile users	Spacecraft
• Large population	• L-band links with users
• Geographically dispersed	• C- or Ku-band links with base stations
• Low duty cycle per user	
• Low cost terminal	
• Low gain antenna	Traffic (point-to-point)
Base Station	Bandwidth (limited allocations)
• Few in number	
• Intermediary role	

FIXED MULTIPLE BEAM SYSTEM

The EIRP advantage offered by multiple-beam systems is illustrated in Figure 2. A single beam over the entire coverage area is depicted in Figure 2a, while two-beam coverage of the same area is shown in Figure 2b. The single-beam coverage provides some reference EIRP over the full coverage region and over the full allocated bandwidth.

a) SINGLE-BEAM COVERAGE

b) TWO-BEAM COVERAGE

Fig. 2. Beam arangements

a) FOUR-BEAM COVERAGE
(TWO-FOLD SPECTRUM USE)

b) TWO-DIMENSIONAL MULTIBEAM
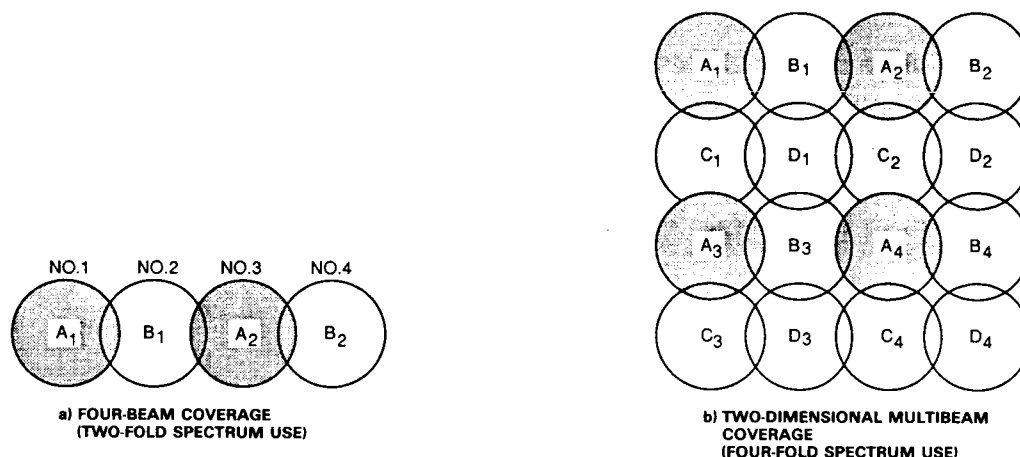COVERAGE
(FOUR-FOLD SPECTRUM USE)

Fig. 3. Beam arrangements with frequency reuse

For the two-beam system, the bandwidth is divided into two equal portions, A and B, and each portion is assigned to one of the two beams. Each beam covers half of the total coverage area and, thus, has 3 dB higher gain than a total coverage area beam. Normally in such systems, the bandwidth is divided into portions by filters, and the two filter outputs are routed to separate power amplifiers which, in turn, drive the separate transmit beams. The relevant figure of merit for this situation is EIRP/unit bandwidth. When the total transmit power is held constant with respect to the single-beam system, the two-beam system provides a 3 dB EIRP increase over the single-beam system. The G/T is also increased by the same factor.

In general, the total coverage can be divided into N beams, with a corresponding division of the bandwidth into N portions, to provide an EIRP increase (in dB) of 10 log (N). The G/T performance is also increased by the same factor of N. Ultimately, the value of N is limited by the aperture size required to form a beam of 1/Nth coverage size, as well as by the filters required to divide the bandwidth into N portions. High Q filters at L-band tend to be bulky. Alternatively, surface acoustic wave (SAW) filters can be used at some appropriate intermediate frequency (IF). In either approach, some portion of the allocated spectrum is lost to guardbands between the usable portions of the bandwidth.

The frequency reuse advantage offered by a one-dimensional multiple beam system is illustrated in Figure 3. In particular, Figure 3a shows a four-beam system. The frequency band is split into two subbands, A and B. The spatial isolation provided by beam 2 allows band A to be used in beams 1 and 3, while the spatial isolation provided by

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beam 3 allows band B to be used in beams 2 and 4. Thus, the one-dimensional four-beam system provides two uses of the frequency spectrum and the EIRP/unit bandwidth improvement is 3 dB.

The bandwidth increase associated with spatially isolated beams at L-band must be accompanied with additional bandwidth at C- or Ku-band for the links with the base stations.

The multibeam principle can be extended from a one-dimensional arrangement of multiple beams to a two-dimensional arrangement, as shown in Figure 3b. In this case, 16 beams are used to achieve four-fold use of the spectrum, with each quadrant of the coverage constituting a spectral use. Within each quadrant, the four beams are each associated with one of four portions of the quadrant, the four beams are each associated with one of four portions of the spectrum (A, B, C, and D). This arrangement permits spatial isolation of beams in both the azimuth and elevation planes. The 16-beam system offers a 6 dB bandwidth advantage and a 6 dB EIRP/unit bandwidth advantage over a single-beam system.

In general, for an N beam system with K spectral uses, the EIRP/unit bandwidth advantage is N/K, where

$$1 \leq K \leq N/2 \text{ for one-dimensional beam arrangements}$$
$$1 \leq K \leq N/4 \text{ for two dimensional beam arrangements}$$

The corresponding improvement in G/T for an N beam system with K spectral uses is simply equal to N, since it is not related to spacecraft power and grows as the number of beams is increased.

MULTIPLE BEAMS WITH DIRECT RADIATING ARRAYS

Using a direct radiating array antenna has distinct advantages over the reflector and feeds implementation for the mobile traffic application. For each beam the signals go through a beam forming network (BFN) that establishes the proper phase relationship at the inputs to the array elements. The multibeam composite BFN consists of an individual BFN for each beam, along with a hybrid summing network for each element. Since the composite BFN can have substantial loss, individual power amplifiers are used after the BFN. Each amplifier drives an azimuth array element, thus forming an active array. A similar arrangement of low-noise receivers is used before the receive BFN.

This configuration implies that all signals pass through all amplifiers. If a particular zone is lightly loaded, power can be re-allocated to other zones by means of base station uplink power control or by servicing more users in the other zones. This ability to re-allocate power dynamically provides additional system flexibility.

In an active array, it is desirable that all amplifiers operate at the same output backoff to achieve the best compromise between amplifier efficiency and linearity. When frequency reuse is not required and sidelobe performance is of no consequence, the active array amplifiers are equal in size and produce a uniform aperture distribution across the array. When frequency reuse is required, the sidelobe levels must be controlled, and a tapered aperture distribution must be used. To avoid the design and production costs of many amplifiers of different power levels, the unequal powers required for the array distribution are obtained by using hybrid-coupled dual
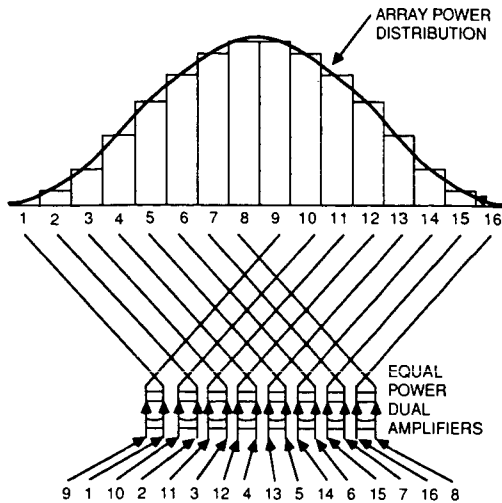
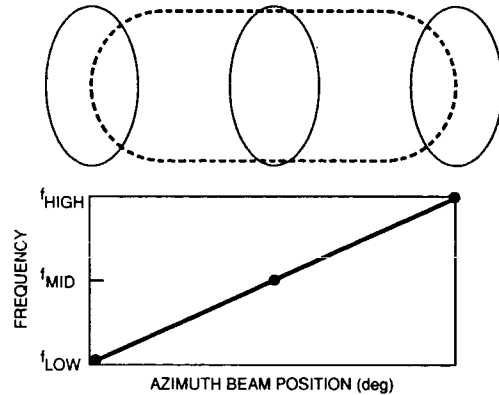Fig. 4. Equal power amplifiers in unequal power array

Fig. 5. Frequency address beam arrangements

amplifiers, as shown in Figure 4. In this arrangement, high and low power elements are paired in a systematic manner such that all pairs require the same total power. All amplifiers are then equal in power rating and operate at the same power level despite the unequal powers at their input and output hybrid ports.

The active array described in Figure 4 has the advantage of low risk from passive intermodulation products (PIMs), since the power is generated by a large number of amplifier pairs with each pair driving two or more array elements.

FREQUENCY ADDRESS MULTIPLE BEAM SYSTEMS

The frequency address system also uses a multitude of smaller beams to provide coverage over a large area. Like the fixed-beam system, this approach provides increased EIRP and G/T and allows multiple reuse of the frequency spectrum. However, the frequency address system enjoys certain other advantages which will soon become apparent.

In its simplest form, a frequency address system consists of a one-dimensional series of high-gain beams whose position within the coverage region is proportional to frequency. Such a beam arrangement is shown in Figure 5. High-gain beams at the left, middle, and right azimuth position of the coverage area correspond to frequencies at the low, middle, and high end of the allocated frequency spectrum. Since the beam position is a continuous function of frequency, there is actually a continuum of beam positions across the coverage region. This is an important distinction with respect to fixed multiple beam systems, where beam positions are restricted to discrete locations. The frequency address system enjoys the advantage of being able to place a beam peak at or very close to the user location in azimuth by proper frequency selection. At the azimuth beam peak, there is still gain variation in the elevation direction dependent upon the user location. When using uplink power control at the base station to radiate equal EIRPs to all users, the EIRP value is only about 0.7 dB below the peak, a significant advantage over the fixed beam approach.
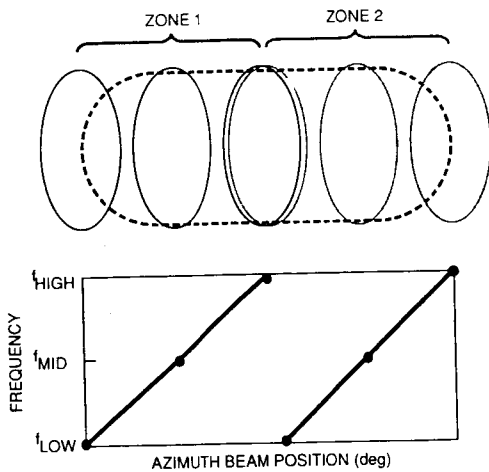
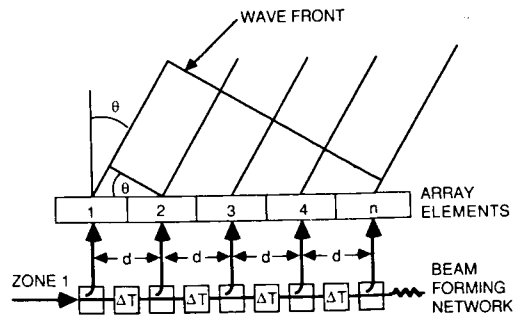Fig. 6. Frequency address with spectral reuse

Fig. 7. Frequency address implementation

The frequency address architecture also readily lends itself to frequency reuse, as shown in Figure 6. The total coverage region is divided into two zones, with the frequency address feature being replicated in each zone. Any beam in Zone 1 and its counterpart in Zone 2 are separated in angle by a zone width. In this gap, beams operate at other frequencies. This angular separation allows spatially isolated beams to reuse the frequency spectrum. To ensure satisfactory spatial isolation, the frequency address beam should be no larger than approximately half a zonewidth in azimuth.

A frequency address beam system is most easily realized by using an array antenna where the interelement phase shift is frequency dependent. This arrangement causes the beam direction to vary as a function of signal frequency.

The frequency dependent phase shifts for the antenna elements are generated in a beam forming network (BFN). This network consists of an alternating series of couplers and time-delay elements where each coupler is associated with an array element (see Figure 7).

The array interelement time delay (ΔT) yields a beam squint angle given by $\theta = \lambda/d \, (\Delta f) \, (\Delta T)$. Thus, the beam position angle, θ, is linearly related to the frequency of the signal.

For applications with relatively large bandwidths, the time delays can be realized in transmission line. For narrowband allocations, like those for mobile service, the time delays are best realized as resonant networks. Figure 8 shows a BFN made up of hybrid
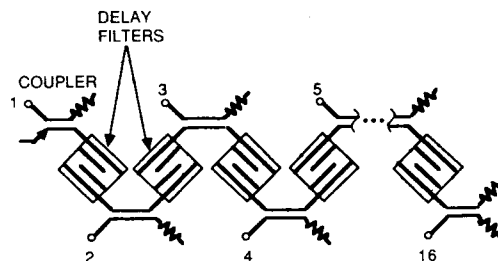

Fig. 8. Beam forming network

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couplers and two-pole interdigital filters as delay elements. This network is realizeable in TEM line to form a lightweight and compact BFN.

Multiple zones are used when reuse of the frequency spectrum is desired. In this case, the zones are normally adjacent and approximately equal in size. Multiple zones can also be used for multiple services, with each service segregated by frequency in the L-band spectrum. In this case, the zones need not be similar in size, and no constraints exist regarding zone overlap. It should be noted that the composite BFN for frequency addressable beams is simpler than for fixed beams because the number of zones is generally half the number of fixed beams required for the same frequency reuse.

Additional advantages are inherent to a frequency address system using an active array. First, all signals for all zones pass through all amplifiers with a prescribed set of relative phases. In each amplifier, intermodulation (IM) products are generated, and a large percentage of these, generated from signals in different zones, have distorted aperture phase distributions. As a result, some geographic IM dispersion takes place. A two-equal zone case provides about 2 dB reduction in IM levels over the regions of interest. Second, because of the hybrid-coupled amplifier arrangement, IM products generated within the amplifier pairs are geographically dispersed. The carrier-to-intermodulation ratio (C/IM) over the coverage region is improved by about 2 dB. This improvement is additive to the IM improvement from multizone operation of an active array.

In summary, the frequency address concept offers four key advantages over the fixed multiple-beam approach: increased EIRP and G/T; simpler implementation with fewer filters and less complex BFNs; increased flexibility through re-allocation of power between beams; and enhanced linearity performance through IM dispersal.

FREQUENCY ADDRESS FOR LAND MOBILE SERVICES

The benefits of the frequency addressable beam concept become even more evident when applied to an actual application such as land mobile service. The satellite for this system is designed to provide high-gain beams over the United States and Canada. In addition, it is desirable to reuse the L-band frequency spectrum, and a threefold spectral use was chosen in conjunction with an antenna aperture size of practical dimensions.

As shown in Figure 9, each zone is 3° wide in the azimuth direction and corresponds to one complete spectral use. At the intersection of two adjacent zones, the high frequency end of one zone coincides with the low frequency end of the other zone.

Since the zones are each 3° wide, frequency reuse occurs at 3° intervals. The interference between spatially isolated beams is kept within an acceptable level by selecting a tapered aperture distribution with low sidelobes. In particular, the cosine squared power distribution shown in Figure 4 is used, resulting in sidelobes at least 23 dB below the beam peak. Furthermore, the half-power beamwidth is selected to be 57% of the zone width, a factor which causes the half-power point of the pattern in one zone to coincide with the first null of the pattern of the same frequency signal in the adjacent zone. This arrangement, shown in Figure 10, results in a carrier-to-
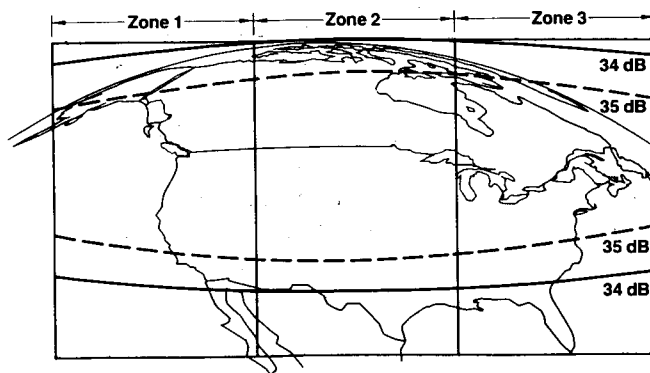
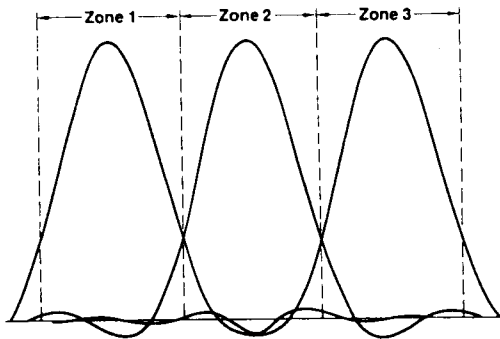Fig. 9. Antenna gain over coverage area
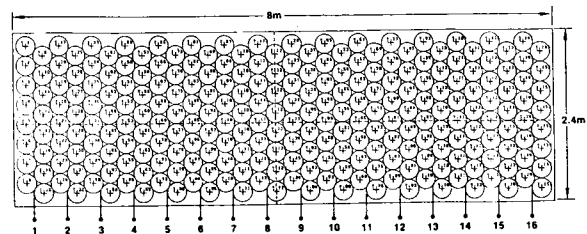

Fig. 10. Zonal frequency reuse

Fig. 11. Array antenna

interference ration (C/I) of 23 dB between adjacent zones. The effective achievable antenna gain over the coverage area resulting from the frequency address concept is shown in Figure 9. Note that a major portion of the service area is covered by the 35 dB gain contour.

These frequency address beams are generated by an antenna array 8 meters wide by 2.4 meters high. The array consists of a close packed arrangement of circularly polarized cup dipoles, as shown in Figure 11. The array has 32 columns. However, columns may be driven in pairs, so that only 16 drive points are required. Since the array is used for both transmit and receive beams, a diplexer is required at each drive point.

The threefold use of the frequency spectrum with a single array requires the use of a three-zone BFN, as shown in Figure 12. The corresponding outputs of the individual zone BFNs are combined in summing networks consisting of hybrid couplers to form single outputs for each antenna drive point.

As noted earlier, the risk of PIMs is much reduced compared to an offset fed dish antenna. The maximum RF power handled by any one diplexer is 12.5% of the total, while the maximum power in any one cup-dipole is 1.5% of the total radiated power. Since the direct radiating array has low coupling to the other spacecraft surfaces, there is little risk of PIMs there, either.

Additional flexibility in the allocation of frequencies can be obtained, with a modest increase in hardware complexity, by interweaving additional zones with the existing three, as shown in Figure 13.
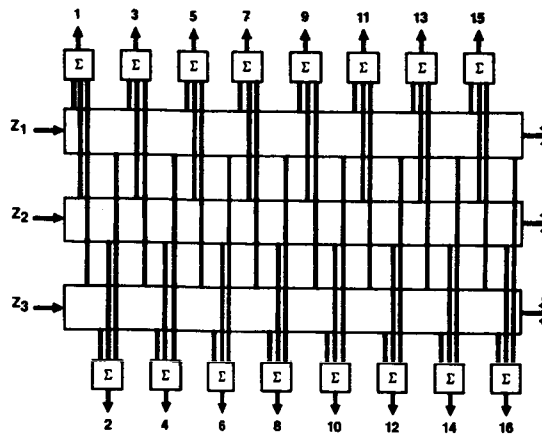
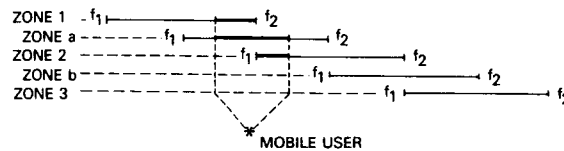Fig. 12. Three-zone beam forming network

Fig. 13. Overlapping zones

This does not change the amount of frequency reuse because of the spatial separation requirement between users of the same frequency. But virtually the whole frequency band is within reach of any one user rather than only half for the nonoverlapping-three-zones case.

The C/IM improvement due to frequency addressing, in conjunction with the active array and the use of hybrid coupled amplifiers, was evaluated through computer simulation. For the three-zone case it amounts to 5.1 dB. This improvement can be used to provide a higher C/IM value or can be used to operate the transmitters more efficiently at a reduced output backoff.

The frequency address system is realizable in a straightforward configuration. The three-zone system with three uses of the L-band spectrum requires a comparable amount of spectrum at Ku-band for links to the base stations. This is easily achieved by using three separate channels at Ku-band. These channels are converted to the assigned spectrum at L-band by use of three different local oscillator frequencies in the up- and downconverters. These repeater elements as well as the L-band elements previously discussed are shown in Figure 14.

The satellite configuration is shown in Figure 15 for both the stowed and deployed states. The outer portions of the L-band array are hinged so that it can be stowed compactly for launch. Small Ku-band arrays are provided about the L-band array for the links to the base station.
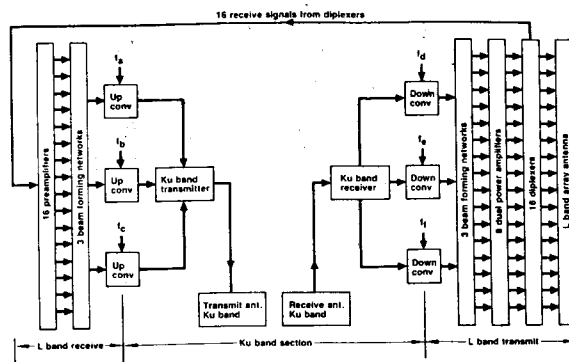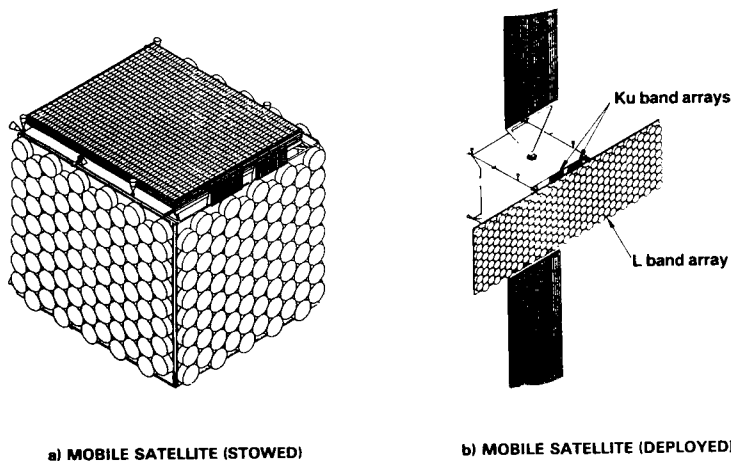
Fig. 14. Mobile satellite block diagram

a) MOBILE SATELLITE (STOWED)

b) MOBILE SATELLITE (DEPLOYED)

Fig. 15. Mobile satellite configuration

CONCLUSIONS

Frequency addressing provides the ability to achieve high satellite EIRP and G/T performance and permits reuse of the frequency spectrum to generate increased operating bandwidth. Its implementation is simpler than that of other multiple beam approaches and it offers improved linearity performance through IM dispersion, as well as improved flexibility in allocation of power among the beams. Furthermore, it has been shown that frequency addressing is well suited to the land mobile requirements for North America and that it can be implemented on a satellite in a straightforward manner.