TRANSMISSION IMPAIRMENT PARAMETERS IN MULTIPLE-BEAM SATELLITE COMMUNICATIONS SYSTEMS*

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ABSTRACT

This paper addresses transmission impairment mechanisms in multiple-beam satellite communications systems that use active phased arrays. The communications link and system aspects are assessed through measurements and analysis. Three link parameters that contribute to transmission impairment are investigated and their effects on the overall carrier-to-interference ratio are quantified. First are the intermodulation components that are generated at the non-linear amplifier outputs and contribute to well-formed interference in the array radiation pattern. Second is the bit-error ratio (BER) degradation due to the multi-carrier operation of the active array. Third is the co-channel interference caused by frequency re-use in the multiple-beam system.

INTRODUCTION

The requirement of satellite transmission over multiple spot beams is becoming the mainstay in newly developed satellite systems. In recent past, global, regional and zone coverage on the earth surface have been traditionally accomplished using multibeam reflector antennas that use a number of feed elements, or shaped reflectors that use a single feed. However, recent demands for large number of spot beams with high beam-to-beam isolation and the need for flexibility in steering the beams imposed new requirements on the communications system that are easier met with active phased arrays. The multiple spot beams are now more often generated using active phased arrays on board the satellite. The advances in monolithic microwave integrated circuits (MMIC) and digital technologies played a major role in realizing these arrays for satellite applications. On the other hand, the added requirements and active array characteristics introduce a set of transmission impairments in the satellite link that did not necessarily exist in the conventional satellite systems.

The development of active phased arrays for satellite communications has been reported in a number of papers, e.g. [1], [2], [3]. This included the use of MMIC components to realize the beam-forming matrix (BFM) that generates a number of beams simultaneously and independently. It also included the development of linearized high power amplifiers that are distributed across the array aperture to produce the required power efficiently. This paper addresses some of the transmission impairment mechanisms in such systems. The communications link and system aspects of the active phased array are assessed through measurements and analysis. Three link parameters and transmission impairment mechanisms are investigated and their effects on the overall carrier-to-interference ratio are quantified: the intermodulation components that are generated at the non-linear amplifier outputs, the bit-error ratio (BER) degradation due to the multi-carrier operation of the active array, and the co-channel interference caused by frequency re-use in multiple beam systems.

* Some of the results reported in this paper are based on work performed at Lockheed Martin Global Telecommunications/COMSAT Laboratories

INTERMODULATION COMPONENTS

The intermodulation components result from the amplifier non-linearity in the active phased array. The radiation of such components in the far field constitutes one element in the interference budget. The location of the intermodulation radiation is a function of the phased array geometry and carrier frequencies. The effects on the satellite system performance vary from being insignificant to being a major source of interference depending on the array parameters, amplifier characteristics and frequency allocations.

In some of the reported developments [2], the phased arrays were characterized for two-tone intermodulation patterns. The intermodulation products generated by a pair of carriers whose frequencies are f_1 and f_2 form distinctive beams with peak positions that are vector sums of the carriers' positions. If the frequency of the third order intermodulation product is defined by:

$$f_{third} = 2 * f_2 - f_1 \tag{1}$$

the direction of the intermodulation product beam can be predicted by:

$$\overline{k}_{third} = 2 * \overline{k}_2 - \overline{k}_1 \tag{2}$$

where, $\overline{k} = 2\pi \frac{d}{\lambda}(\sin\phi \sin\theta + \cos\phi \sin\theta)$ is the direction vector of the beam., d is the element spacing in the array and θ and φ are the conventional spherical polar angles of the beam. Similar equations can be written for the 5th and higher order intermodulation.

The far field intermodulation product radiation pattern of a conventional single beam antenna matches that of its linear radiation pattern. This holds true for both active as well as passive apertures. As a result, the far field carrier-to-intermodulation ratio can be predicted by the antenna's power amplifier characteristics. A multiple beam, active aperture phased array, on the other hand, produces intermodulation products whose radiation patterns are distinct from those of their originating carriers. As a result, far field carrier-to-intermodulation ratio characterization is a more challenging task for a multiple beam phased array. For this reason it is important to establish the non-linear far-field behavior of such antenna. In general, the far-field intermodulation performance will be dependent upon both the beam positions as well as the amplifier drive level.

BIT-ERROR RATIO MEASUREMENTS

The bit-error ratio is one of the measures of quality in digital systems. In an active phased array system, the degradation or increase of the BER is a function of the intermodulation performance and on the communication channel loading in the system, as well as other sources of noise and interference. The measurement results in the reported developments [2], [3] cover a wide variety of scenarios for transmission loading, amplifier operating points and channel interference levels. IF and RF loop back measurements were used for calibration purposes. IF loop back establishes the response of the modem, while RF loop back bypasses the phased array antenna and measures the effects of the rest of the setup. Broadband noise (500 MHz) was used to mimic the effect of transponder loading by large number of carriers.

The results of the measurements show that in a single beam system, or a non-active aperture antenna, operation in amplifier's non-linear region results in substantial intermodulation interference, which degrades the BER performance of the system. In a multiple beam system, the intermodulation products may be directed away from the beam carrying traffic. The reported BER measurements demonstrated the effectiveness of the active aperture, multiple beam phased arrays for communication purposes. In particular, it was shown that with judicious frequency and beam position assignments the system is capable of isolating intermodulation distortion to improve the overall communication link.

CO-CHANNEL BEAM INTERFERENCE

The co-channel interference is primarily a function of the antenna side-lobe performance and the frequency re-use assumptions. Careful design of the antenna patterns in order to produce low side-lobe levels or nulls at the locations where the same channel is re-used will reduce the level of interference. The allowable spacing between the beams that use the same frequency segment plays an important role in the co-channel interference calculations. Although narrower spacing allows for more frequency re-use and higher effective bandwidth, it also increases the number of interferers and thus limits the use of the channel for the given allocated power.

The co-channel interference is quantified or measured using the carrier-to-interference ratio (CIR), which is the ratio of the power levels of the desired signal and the aggregate interference. Multiple parameters affect the CIR, some of which are readily predictable from the system parameters (such as the total number of co-channel beams, and their separation), while the others need to be determined by statistical means (such as the antenna pointing error and user traffic).

The CIR for a multiple beam satellite communication system can be investigated in two categories: (1) Downlink interference (2) Uplink interference. The downlink CIR is measured at the user terminal and is a function of the payload antenna characteristics and the location of the user terminal within the beam. The uplink CIR is measured at the payload and is a function of the user traffic within all co-channel beams at a given time, as well as the user locations within the beam. Fig. 1 demonstrates the interference mechanisms for the uplink and downlink paths. The coverage area, in which frequency is reused among a cluster of beams is shown by the dotted line. The interfered beams (the receiving beam for downlink and the transmitting beam for uplink) and the interferers also identified in the figure. The different antenna patterns for the downlink correspond to the scanned radiation patterns that generate the interferer beams. The angular beam separation between the interferers and the interfered beam are shown as α , and β in the downlink case. While some system parameters (such as the total number of co-channel beams, beam separation, antenna patterns) are common to both uplink and downlink CIR, the inherent difference between the two mechanisms are observed by the influence of the statistical parameters such as the user location and traffic for the uplink at a given instant.

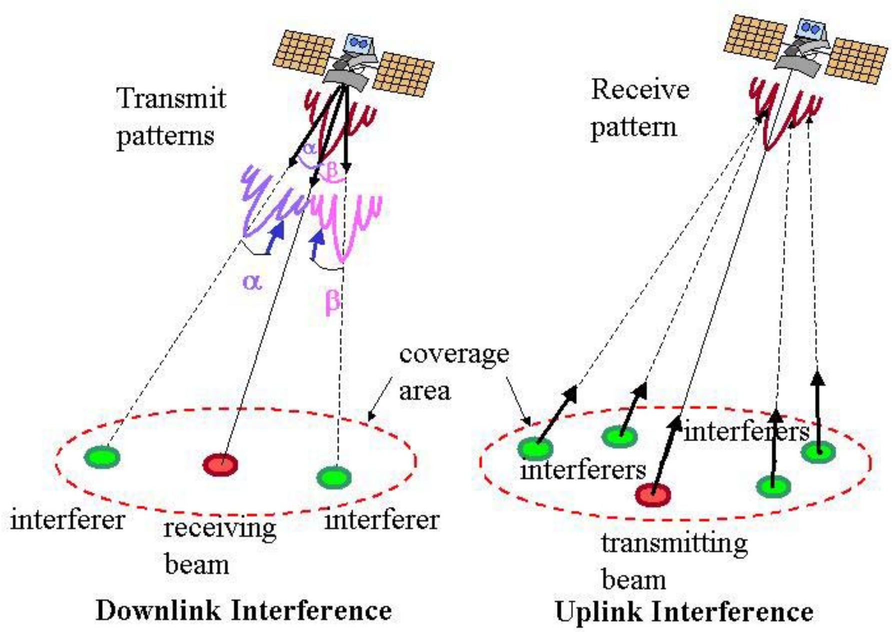

Fig. 1. Downlink and Uplink Interference Mechanism

A model to simulate the downlink and uplink CIR for a multiple beam satellite communications system was reported [4]. The multiple beam coverage is generated on earth based on the model inputs of the satellite location, the number of beams on earth, and the angular width of the beams at the half power level relative to the peak. Other input parameters to the model are the feed pattern to generate the beams, the frequency reuse factor, maximum power per beam, power per user, probability distribution functions for user traffic and user location. The model can be used to study a system with a large number of beams with identical far field patterns and individual look angles to satisfy a contiguous coverage on earth. Simulation results can be generated for different values of frequency reuse factors.

Simulations have shown that the CIR can be improved by optimizing the beam pattern, such that the pattern nulls coincide with the first and second tier of co-channel beams [4]. However, the optimized pattern is usually more sensitive to antenna pointing angle errors than the original pattern. Thus, the CIR enhancement is dependent on the accurate positioning of the pattern nulls at first and second tiers.

CONCLUSION

The system-level performance of active phased arrays, which employ distributed amplifiers across the array aperture can be assessed through measurements and computer simulation. The far-field intermodulation radiation follows certain patterns, which can be predicted using software tools that are verifiable by measurements. The BER degradation due to carrier suppression as a result of traffic loading exceeds the degradation that results from driving the desired channel at saturation or from adjacent channel or co-channel interference. The downlink and uplink co-channel interferences are functions of both deterministic parameters of the system, such as the total number of beams, antenna performance and frequency re-use scheme, as well as stochastic parameters, such as the traffic pattern, location and equipment pointing errors. While these effects can cause significant variations in the co-channel CIR, the system can be designed based on the worst-case predictions in order to offer higher levels of margin.

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