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APPLICATION OF HEURISTIC SATELLITE PLAN SYNTHESIS ALGORITHMS TO REQUIREMENTS OF THE WARC-88 ALLOTMENT PLAN

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Abstract

Creation of an Allotment Plan for the Fixed Satellite Service at the 1988 Space WARC represented a complex satellite plan synthesis problem, involving a large number of planned and existing systems. Solutions to this problem at WARC-88 required the use of both automated and manual procedures to develop an acceptable set of system positions. Development of an Allotment Plan may also be attempted through solution of an optimization problem, known as the Satellite Location Problem (SLP). Three automated heuristic procedures, developed specifically to solve SLP, are presented. The heuristics are then applied to two specific WARC-88 scenarios. Solutions resulting from the fully automated heuristics are then compared with solutions obtained at WARC-88 through a combination of both automated and manual planning efforts.

1.0 Introduction

The creation of an Allotment Plan for frequency bands allocated to the Fixed Satellite Service at the 1988 Space World Administrative Radio Conference demonstrated many of the difficulties inherent to the satellite system plan synthesis problem.[1] A workable Allotment Plan was achieved only after substantial effort on the part of an international panel of experts, who performed manual adjustment of the satellite positions supplied by an initial plan configuration obtained through significant computational effort.

The general form of the satellite plan synthesis problem might be stated as follows: given constraints imposed by physical system limitations (such as the extent of the service arc available to each satellite system) and technical considerations (such as protection criteria imposed by allowable single-entry or aggregate carrier-to-interference ratios), determine orbital positions for all satellites considered that (1) allow the necessary constraints to be satisfied and (2) are optimal or quasi-optimal with respect to some specified objective function. Objectives that may be considered include minimization of the total arc occupied by the satellites considered[4], or minimization of deviations of satellite positions from desired locations.[10]

The satellite plan synthesis problem increases in complexity with an increasing number of systems to be considered; further complexities are introduced if the systems under consideration evidence a substantial degree of inhomogeneity in operating parameters. Development of an Allotment Plan for the Fixed Satellite Service took into account more than 200 systems; substantial inhomogeneity existed between many of the systems considered, particularly with respect to satellite power levels. Thus, development of the Allotment Plan represented a satellite plan synthesis problem of formidable complexity.

It has been recognized that the satellite plan synthesis problem is, in actuality, a two-stage problem.[4, 8, 10, 13] The primary, or "master" component of the problem is that of determining a satellite ordering that will result in the most advantageous set of satellite positions. The secondary, or "sub" problem, is that of actually determining satellite locations, given the ordering found in the first stage. The number of possible satellite orderings to be considered can be substantial. In certain areas of the geostationary orbit, where the same orbital location is within the service arc limitations of a large number of national service areas, the satellite plan synthesis problem becomes combinatorially explosive.

The combinatorial complexity of determining a satellite ordering precludes direct application of standard optimization techniques. Instead, a number of heuristic approaches to the problem have been developed. One such procedure is the use of the

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"evolutional model," developed by Ito, et al,[4] extended by Mizuno et al,[8] and described in detail in two additional papers.[5, 6] This procedure derives an ordering for the satellites considered by employing a user-selected "launch sequence," in which satellites are placed into position one at a time, in the order and location that produces the most advantageous constellation of the satellites that have been "launched." This procedure was implemented in the ORBIT software package utilized in the development of the initial configuration of the Allotment Plan at the 1988 Space WARC. Examination of the technique demonstrates that, for "n" satellites, n complete satellite orderings are assessed.

The heuristics developed by Gonsalvez,[3] Gonsalvez et al,[2] and Reilly and co-authors[10, 11, 13,14] offer examination of a substantially increased number of satellite orderings - particularly for large numbers of satellite systems - and thus may permit the examination of a larger portion of the feasible solution space for the satellite plan synthesis problem posed by the data utilized in the development of the WARC-88 Allotment Plan. This paper demonstrates application of these heuristic satellite plan synthesis procedures to the WARC-88 Allotment Plan data, and examines the quality of solutions that result.

2.0 Development of the WARC-88 Allotment Plan

The Second Session of the World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and the Planning of Space Services Utilizing It (WARC-88) was tasked with the development of an Allotment Plan for the Fixed Satellite Service in the frequency bands

4500 to 4800 MHz, and
6725 to 7025 MHz

and

10.70 to 10.95 GHz, 11.20 to 11.45 GHz, and
12.75 to 13.25 GHz.

Each national Allotment consisted of:

- a nominal orbital position
- a bandwidth of 800 MHz (up-link and down-link) in the above frequency bands
- a service area for national coverage
- generalized parameters
- a predetermined arc (PDA)

In addition to national allotments, "existing systems" were also to be included in the Allotment Plan. For purposes of planning, existing systems were defined as those satellite systems operating in all or part of the above frequency bands,

- which were recorded in the Master International Frequency Register, or
- for which the coordination procedure had been initiated, or
- for which information relating to advance publication was received by the International Frequency Registration Board (IFRB) before 8 August 1985.

A total of 238 systems were considered in development of the Allotment Plan; of these, 184 were national allotments, while 54 were existing systems. Among existing systems, 30 systems were designated for operation in the 10/11 and/or 13 GHz portions of the spectrum, while the remaining 24 were designated for the 4 and/or 6 GHZ frequencies. Allotted systems were required to be considered in both the C- and Ku-band frequencies simultaneously. Multiple national allotments were required, in some cases, to provide adequate coverage to the geographic extent of the national service area. Some service arcs were also restricted, in order to ensure that acceptable elevation angles would be associated with the orbital position given to the national allotment. Substantial differences in technical parameters (particularly, satellite EIRP) also existed between many allotted systems and the existing systems. Creation of a successful Allotment Plan entailed deriving a set of orbital positions for all networks that allowed a target aggregate carrier-to-interference ratio (C/I) of 26 dB to be achieved for all planned systems in both C- and Ku-bands. Thus, the development of an acceptable Allotment Plan represented a problem of formidable complexity.

The ORBIT software package, originally designed in Japan and residing on the IFRB computer system, was used to develop a preliminary set of satellite positions for allotted networks. (Orbital locations for existing systems were input as fixed positions to the software.) Difficulties arose with this preliminary plan, however, in that aggregate C/I's achieved were not satisfactory in all cases. An international panel of experts was assembled from Conference delegates, and was tasked with the objective of improving this preliminary plan. It was determined by the Conference that a viable approach to development of a Plan would be the creation of a "Part A" plan, including allotted systems only, in which all systems would meet an agreed-upon aggregate interference criterion, followed by the addition of existing systems as "Part B" of the Plan. An improved plan was eventually derived by manually relocating a number of systems, relative to their original positions as derived by the software, and supplying the new locations as fixed inputs to the computer program. Existing systems and their associated parameter values were then added, requiring further manual repositioning of allotted systems. Eventually, an Allotment Plan was developed that contained both planned and existing systems and that was accepted by the Conference. However, the Plan was derived only after considerable effort on the part of the panel of experts to improve results obtained from the planning software utilized at the Conference.

The complexity of the allotment planning problem presents a substantial challenge to automated satellite plan synthesis procedures. In the following section, procedures are presented which display promise in solution of plan synthesis problems of this level of complexity; in a subsequent section, results of application of the procedure to requirements of the WARC-88 Allotment Plan are presented.

3.0 Problem and Solution Procedures

3.1 The Satellite Location Problem

The satellite plan synthesis problem addressed here is referred to as the satellite location problem (SLP). SLP solutions seek to provide each satellite with a location in its service arc and single-entry interference protection at a level that is also intended to provide adequate aggregate interference protection. It is assumed also that a desired location is specified for each satellite. The objective is to produce a plan (set of satellite locations) that minimizes the sum of absolute differences between locations prescribed for the satellites and desired locations. SLP is a very difficult problem to solve to optimality, as shown formally by Reilly and Mata.[12]

Mount-Campbell et al. have suggested that SLP be viewed as two problems: the problem of ordering the satellites in the geostationary orbit (GSO) and the problem of determining locations for the satellites given an ordering.[9] A mixed-integer programming (MIP) formulation for SLP[13] that exploits the two-problem view of SLP suggested by Mount-Campbell et al. is shown below. In this formulation, satellites are assigned to positions in an ordering of satellites. The satellite positions are located along the GSO, and each satellite is allotted the location of the position to which it is assigned. The order of the positions is fixed, and different satellite orderings are considered by assigning the satellites to different positions. The following parameters and decision variables are used in the MIP model for SLP:

Parameters:

n = the number of satellites and the number of satellite positions.

E_i = the easternmost location for satellite i (in degrees longitude) that satisfies a stated minimum elevation angle requirement, $i=1, 2, \ldots, n$.

W_i = the westernmost location for satellite i (in degrees longitude) that satisfies a stated minimum elevation angle requirement, $i=1, 2, \ldots, n$.

D_i = the desired location for satellite i in degrees longitude, $i=1, 2, \ldots, n$.

Δ_{ih} = the minimum required angular separation (in degrees) between satellites i and h that guarantees that a specified single-entry (pairwise) interference requirement is met, $i=1, 2, \ldots, n-1$; $h=i+1, i+2, \ldots, n$.

Decision Variables:

y_j = the location allotted to satellite position j in degrees longitude, $j=1, 2, \ldots, n$.

y_j^+ = westward difference in longitude between the jth satellite position and the desired location of the satellite in the jth position in degrees, $j=1, 2, \ldots, n$.

y_j^- = eastward difference in longitude between the jth satellite position and the desired location of the satellite in the jth position in degrees, $j=1, 2, \ldots, n$.

x_{ij} = {1 if satellite i is assigned to satellite position j;
{0 otherwise;
$i=1, 2, \ldots, n$; $j=1, 2, \ldots, n$.

With these parameter and variable definitions, SLP can be formulated as follows:

Minimize

$$z = \sum_{j=1}^{n} (y_j^+ + y_j^-) \qquad (1)$$

Subject to

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad j=1, 2, \ldots, n \qquad (2)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i=1, 2, \ldots, n \qquad (3)$$

$$y_j - y_j^+ + y_j^- = \sum_{i=1}^{n} D_i' x_{ij} \qquad j=1, 2, \ldots, n \qquad (4)$$

$$y_{j+k} - y_j \ge \Delta_{ih} (x_{ij} - (1 - x_{h,\,j+k})) \qquad (5)$$

$$h = 1, 2, \ldots, n, \quad i=1, 2, \ldots, n$$
$$j = 1, 2, \ldots, n-1, \quad k=1, 2, \ldots, n-j$$

$$y_j \ge \sum_{i=1}^{n} E_i' x_{ij} \qquad j=1, 2, \ldots, n \qquad (6)$$

$$y_j \le \sum_{i=1}^{n} W_i' x_{ij} \qquad j=1, 2, \ldots, n \qquad (7)$$

$$y_j^+, y_j^- \ge 0 \qquad j=1, 2, \ldots, n \qquad (8)$$

$$x_{ij} \in \{0, 1\} \quad i=1, 2, \ldots, n, \quad j=1, 2, \ldots, n \qquad (9)$$

where E_i', W_i', and D_i', are the results of (piecewise) linear transformations of E_i, W_i, and D_i, respectively, that yield $0 \le E_i' \le W_i' \le D_i'$, $i=1, 2, \ldots, n$, and thereby allow the decision variables y_j to have only nonnegative values.

The objective function (1) totals the absolute deviations between prescribed and desired locations of satellites. Constraints (2) and (3) collectively assign the satellites to the satellite positions; exactly one satellite is assigned to each satellite position. The deviation between each satellite's prescribed location and its desired location is determined by constraints (4). Required orbital separations are enforced by constraints (5). These constraints also guarantee that the satellite positions remain in the proper order. Constraints (6) and (7) guarantee that the location allotted to each satellite lies in the satellite's service arc. Finally, constraints (8) and (9) enforce nonnegativity and integrality restrictions on the continuous and integer variables, respectively.

This model enforces a minimum required orbital separation, Δ_{ih}, for each pair of satellites i and h.[7, 15] These separation values are calculated to ensure that a specified single-entry C/I is satisfied at each of the test points that define the satellites' service areas, regardless of the locations allotted to satellites i and h. However, there is more concern with aggregate interference - the interference from all unwanted signals simultaneously. Consequently, solutions to this model are analyzed by calculating all interferences to determine to what extent the aggregate C/I requirement is met.

For an n-satellite SLP, there are 3n continuous variables, and $(n^4 - n^3 + 10n)/2$ structural constraints.

3.2 Description of Heuristic Solution Methods

Three heuristic procedures that are designed to find solutions to SLP have been developed at The Ohio State University. Each of these procedures is outlined here, and references to more complete descriptions of the methods are given.

OSU-SLOT (Orbit Spectrum Utilization - Satellite Location and Ordering Technique) is a greedy procedure for SLP that was originally intended to order satellites only.[13, 14] However, it has been observed, even for some large SLP examples, that OSU-SLOT not only successfully orders the satellites but that it also finds feasible solutions to SLP.

OSU-SLOT begins by accepting as input the SLP parameters defined in section 3.1. Next, a feasibility/desirability matrix, F, is constructed. F contains an element for each possible pairing of a satellite with a discrete orbital location. For each candidate longitude-satellite combination, an entry is made in F to indicate the proximity of that longitude to that satellite's desired location. The procedure identifies the satellite with the fewest (remaining) feasible candidate longitudes; that satellite is next to receive the feasible candidate longitude nearest its desired location. The procedure then uses the orbital separation matrix (Δ) to modify the entries in F to reflect which locations are no longer available to the remaining satellites. The procedure repeats this process until all satellites are ordered or until it is no longer possible to find ordering positions for the remaining satellites.

If OSU-SLOT orders all satellites, then the result constitutes both a feasible ordering and a set of orbital locations - hence a solution to SLP. If any satellite is not accommodated, however, then the required orbital separations are reduced by a common factor and the procedure is repeated; this reduction is performed as many times as needed to accommodate all satellites. Any reduction of required orbital separations implies that the solution associated with the complete satellite ordering may not satisfy the single-entry interference criterion in all cases. The extent to which aggregate interference limitations are violated depends upon the number of times that the orbital separations were reduced.

The discrete candidate orbital locations considered by OSU-SLOT are equally spaced at 0.1° intervals. Therefore, OSU-SLOT is often attempting to solve a problem that is actually more difficult than SLP, where it is assumed that each satellite can occupy *any* longitude in its service arc. The observed execution times for OSU-SLOT on 183-satellite SLP examples are under 2 CPU seconds on an IBM 3081-D, (which has an approximate speed of 4.5 million instructions per second) when no adjustment to orbital separation is made.[13]

OSU-TOLS (S-L-O-T reversed) is a second heuristic that often finds a feasible solution to SLP very quickly.[14] The procedure differs from OSU-SLOT only in that OSU-TOLS attempts to place satellites at the feasible location farthest away from, rather than closest to, their desired locations. The rationale for such an approach is that C/I's may be improved if some satellites with extensive service arcs are relatively isolated from satellites that they would interfere with, or from which they would receive interference. Computation times are similar to those described for OSU-SLOT.

OSU-STARS (Synthesis Technique for Allotting Resources to Satellites) is an extended version[13] of the earlier k-permutation algorithm devised by Gonsalvez[2] that is documented in Gonsalvez et al.,[3] and Reilly et al.[10, 11] It differs from the earlier version of the algorithm in two respects. It is capable of finding solutions to synthesis problems in which the satellites' service arcs completely encircle the Earth, by constructing interdependent subproblems with at most m satellites, where we require $m \leq 100$. The procedure also disregards some satellite orderings that are not anticipated to yield an improved solution.

Once an ordering of satellites is specified, the MIP model for SLP reduces to a linear program [3], one of the easier types of optimization problems to solve. When this linear program has been solved for some satellite ordering, the quality of the solution associated with an alternative ordering can be assessed using standard results from duality theory and sensitivity analysis for linear programming.

Since there are n! possible orderings of n satellites, enumerating all possible satellite orderings is impractical. OSU-STARS begins with an ordering found by OSU-SLOT, OSU-TOLS, or an alternative method, and searches for improved orderings that differ from the incumbent ordering in no more than k adjacent positions, where $2 \leq k_{min} \leq k \leq k_{max}$, and k_{min} and k_{max} are user-specified parameters. Computation times for OSU-STARS will depend, in part, on these parameter values.

Beginning with the k easternmost satellites, the satellites are permuted k at a time until no group of k adjacent satellites that can provide an improved solution remains to be examined. Then, if $k < k_{max}$, k is incremented and the process is repeated; otherwise, the method terminates. In each iteration of the search for an improved satellite ordering for the same value of k, the search is restricted to those positions in the ordering that lie between the easternmost and westernmost positions affected by successful reorderings during the last search with the given value of k.

OSU-STARS can test a considerably larger set of satellite orderings than some other proposed procedures. For example, the ORBIT procedure utilized at WARC-88 examines exactly 100 complete satellite orderings for a 100-satellite synthesis problem; OSU-STARS considers at least 100, 388, 1704, and 8880 complete satellite orderings with $m = 50$ and $k_{max} = 2, 3, 4,$ and 5 respectively. However, ORBIT does consider $(n(n-1) - 2)/2$ partial orderings of the satellites in arriving at a fixed satellite ordering (4949 partial orderings for a 100-satellite problem). Additionally, OSU-STARS reports every improved solution it finds, each corresponding to a different satellite ordering. ORBIT reports a single final solution, determined from a single complete ordering.

An additional difference between all of the procedures described above and the ORBIT program has to do with the computationally intensive calculation of interferences. ORBIT calculates both single-entry and aggregate interferences; OSU-SLOT, OSU-TOLS and OSU-STARS calculate no interferences during execution. Instead, the orbital separation constraints are relied upon to continually enforce the single-entry interference protection requirements, and thereby eventually meet the required aggregate carrier-to-interference ratio.

4.0 Applications of Heuristics to WARC-88 Data

4.1 WARC-88 Data Description

The data sets utilized for creation of the WARC-88 Allotment Plan were organized in four distinct scenarios:

1. Ku-band planned allotments plus existing systems, containing 203 satellites; 255 links.
2. Ku-band planned allotments only, containing 184 satellites; 226 two-way links.
3. C-band planned allotments plus exisiting systems, containing 201 satellites; 247 links.
4. C-band planned allotments only, containing 184 satellites; 226 two-way links.

We define a link as a single communications path, either from a ground station to a satellite (uplink) or from a satellite to a ground station (downlink). A total link includes both uplink and downlink; links for planned allotments are all total links. Certain existing systems have links that may be one-way, either uplink or downlink, in the band of interest. These systems may, for example, uplink in the Ku or C allotment planning band, and downlink in a different band.

Scenarios contain both global and per beam data. Global data, which is used for all beams of a particular scenario (unless overridden for an individual beam), includes a global single-entry target C/I (32 dB), a global earth station antenna sidelobe slope (25), the minimum satellite half-power beamwidth (0.8° for Ku-band, 1.6° for C-band), spacecraft and earth station antenna efficiencies (0.55 and 0.70, respectively), and an option to include the effects of rain attenuation, up to a maximum attenuation of 8 dB (rain effects were included in development of the Allotment Plan). Further details of parameter values selected for allotment planning appear in the WARC-88 Final Acts.[1]

The set of data associated with each beam represented in a scenario includes a beam identifier, a satellite identifier to identify multiple beams associated with the same satellite, a minimum elevation angle to be achieved, western and eastern service arc limitations prescribed by the minimum elevation angle or by other constraints, earth station transmit and receive antenna sidelobe characteristics, a system-specific target single-entry C/I criterion (generally, 32 dB), and uplink and downlink frequencies. (The frequencies 13 GHz and 11.2 GHz for Ku-band and 6.875 GHz and 4.65 GHz for C-band represent the midpoints of the appropriate allotment planning bands. If one link of a particular existing system beam is unused, the corresponding link frequency is assigned an artificial value outside the frequencies considered for allotment planning. These values were selected as 15 GHz for the uplink and 12 GHz for the downlink.) Also specified for each beam are earth station transmit and receive gains (these values were calculated to correspond to earth station antenna diameters of 3 m for Ku-band frequencies, and 7 m for C-band), a target aggregate C/I (generally, 26 dB), earth station and satellite receive system noise temperatures, uplink and downlink target carrier-to-noise (C/N) ratios (23 and 17 dB, respectively), satellite antenna specification, earth station and satellite maximum and minimum transmit powers, power (EIRP) calculation option, and a planned/existing system identifier.

In addition to the technical parameters described above, the geographical area to be served by each beam is defined by test points - latitude/longitude pairs at or near the beam's edge. The number of test points, up to a maximum of ten, may vary for each beam.

In conjunction with the four scenarios described above, a master file of elliptical beams was utilized. Satellite antennas were assumed to generate elliptical beams that covered their corresponding service areas with adequate power; thus a minimum-area ellipse was calculated for each integer longitude contained within the service arc associated with each beam. Also included in this file were rain attenuation values associated with each test point at each uplink and downlink frequency. In applying heuristics to obtain the results presented in the next section, only worst-case (maximum uplink attenuation, maximum downlink attenuation, over all test points) rain fades were used.

4.2 Results of Heuristics on WARC-88 Scenarios

The heuristic algorithms presented in section 3.2 were applied to two of the scenarios presented in section 4.1: the scenario consisting of Ku-band planned allotments plus existing systems (Scenario 1) and Ku-band planned allotments only (Scenario 2). Resulting satellite positions, along with the appropriate scenario files, were then input to the version of the ORBIT software utilized at WARC-88, which functions as a single-entry and aggregate interference analysis program if input satellite positions are supplied.

In application of two heuristics (OSU-SLOT, OSU-TOLS), Scenario 1 was treated in a manner that was intended to present the greatest challenge to the performance of the algorithms - i.e., algorithms were applied to planned and existing systems simultaneously, rather than applied to planned systems first followed by manual insertion of existing systems, as was done at WARC-88.

Aggregate C/I results from satellite positions obtained by OSU-SLOT for Scenario 1 are presented in Figure 1, along with the corresponding results from analysis of WARC-88 positions for the same systems. It should be pointed out that the results obtained first required modification of the matrix of required satellite separations used by OSU-SLOT. Recall that required orbital separations are those calculated to ensure that a specified single-entry interference criterion is met by all pairs of systems; the matrix calculated for Scenario 1 contained several inordinately large separations resulting primarily from the interaction of existing systems with planned systems. The matrix was modified by replacing each required separation value with the minimum of that value and the corresponding separation provided by the positions of the WARC-88 Plan. The modification was required as a result of application of the algorithms to both planned and existing systems at the same time.

Figure 1 illustrates that the solution found by OSU-SLOT displays some interesting properties. First, the minimum aggregate C/I achieved by any system (14.86 dB) is well above that found in analysis of the WARC-88 positions (2.11 dB). (It should be noted that the WARC-88 solution did not seek to achieve the target C/I ratio for existing systems.) The plot of the percentage of systems achieving or exceeding a given C/I value for OSU-SLOT seems to demonstrate that improvement in the very worst aggregate interference situations is traded for some degradation of C/I values in the range 20.0 - 36.0 dB. However, the same percentage of systems achieve an aggregate C/I of 20 dB or greater. The OSU-SLOT solution also displays higher aggregate C/I values for approximately twenty percent of systems, in the range 36.0 - 67.0 dB. Perhaps most significantly, the OSU-SLOT solution represents a fully automated solution achieved in a few CPU seconds, versus a solution achieved through both automated and manual means with significantly greater computational time and effort. Additionally, the OSU-SLOT algorithm was applied to the <u>entire</u> scenario - allotment systems plus existing systems - eliminating the effort necessary to derive a two-part solution.

Aggregate interference results from analysis of positions derived by OSU-TOLS for Scenario 1 are illustrated in Figure 2. Once again, results of an analysis of the corresponding WARC-88 positions are presented for comparison. The same modifications to the matrix of required separations that were performed in the application of OSU-SLOT were also performed for OSU-TOLS. As was true for OSU-SLOT, the worst aggregate C/I value achieved for OSU-TOLS positions (8.97 dB) is significantly greater than that found in aggregate interference analysis of the WARC-88 positioning. Once again, it appears that improved worst aggregate C/I values are obtained at the cost of some degradation of C/I values in the range 25.0 - 38.0 dB. However, approximately 90 percent of systems in <u>both</u> solutions achieve aggregate C/I values of 25 dB or greater; in view of the fact that the target aggregate C/I for all systems was 26 dB, we may say that OSU-TOLS has produced a solution that is at least comparable in quality to the WARC-88 solution for Scenario 1. The OSU-TOLS solution also represents a solution achieved after significantly less computational time than that expended to develop the WARC-88 solution; also, no manual repositioning of systems was required. OSU-TOLS was also applicable to allotment systems and existing systems combined as a single scenario; two-part solution development was not necessary.

Finally, OSU-STARS was applied to Scenario 1, using as an input ordering the WARC-88 Plan positions for Scenario 1 systems. Results of aggregate interference analysis of the resulting positions, and those obtained for the WARC-88 positions, are presented in Figure 3. OSU-STARS performs very few repositionings when applied to the WARC-88 satellite locations; aggregate interference results differ only slightly, for C/I values above 30 dB. These results illustrate clearly the difficulty of the allotment planning problem encountered at WARC-88; the fact that OSU-STARS did not significantly alter the WARC-88 Plan positions seems to indicate that little room for modification exists under constraints imposed by the input data. Recall that OSU-STARS will permute satellites only if the permutation results in an improved positioning with respect to satellites' desired locations; in cases where service arcs are severely restricted, OSU-STARS is severely limited in its ability to search for improved satellite orderings. The results presented in Figure 3 also indicate that the international panel of experts who developed WARC-88 satellite positions through manual repositioning performed a task of considerable difficulty.

Two heuristics, OSU-SLOT and OSU-TOLS, were applied to Scenario 2 - the scenario containing Ku-band planned allotment systems only. As was done for Scenario 1, systems were analyzed with respect to aggregate interference using the ORBIT software. For purposes of comparison, two additional sets of satellite positions were also analyzed. The first was the set of satellite positions for Ku-band planned allotments only, contained in the WARC-88 Allotment Plan. The second set of positions represented a draft Plan for allotment systems only, <u>prior</u> to the addition of existing systems. This set of positions was derived by applying the ORBIT software as a plan synthesis algorithm to requirements data, accompanied by manual adjustment of the resulting positions for the purpose of achieving improved aggregate C/I ratios. In fact, both sets of positions are the result of application of the ORBIT software and manual repositioning; the two sets of positions differ in that final WARC-88 plan positions reflect additional adjustments to allotment system positions made for accommodation of existing systems.

Results of aggregate interference analysis for Scenario 2 positions derived by OSU-SLOT are presented in Figure 4, along with aggregate interference analysis results for WARC-88 final positions and draft plan positions. The results indicate that OSU-SLOT was able to achieve comparable performance with the WARC-88 Plan, for Scenario 2; in fact, the minimum aggregate C/I (24.64 dB) achieved over all systems as positioned by OSU-SLOT represents a slight improvement over the minimum aggregate C/I value achieved over all Ku-band allotment systems as positioned by the WARC-88 Plan (23.05 dB). Approximately 97% of systems achieve aggregate C/I values above a target value of 26 dB as positioned by the WARC-88 Plan; approximately 94% of systems positioned by OSU-SLOT achieve or exceed this figure. Aggregate C/I values for systems as positioned by OSU-SLOT are lower than those achieved for the WARC-88 positioning in the range 25 - 38 dB. Above 38 dB, however, values for the OSU-SLOT positioning tend to exceed those for the WARC-88 positioning. It appears that a similar tradeoff to that seen earlier for Scenario 1 occurs: improvement in the very lowest C/I values is traded for some degradation in mid-range C/I values.

Since draft Plan positions are very similar to final WARC-88 positions of allotment systems, a similar comparison in performance is observed when analysis results for systems as positioned by OSU-SLOT are compared with results obtained for the draft plan positioning. The minimum aggregate C/I value observed for the draft plan positioning was 26.07 dB, which was achieved after manual repositioning of ORBIT-derived positions; with use of OSU-SLOT alone, 94% of all aggregate C/I values meet or exceed the target value of 26 dB. Also, in the range 40.0-54.0 dB, aggregate C/I results for the OSU-SLOT positioning exceed aggregate C/I values achieved by the draft Plan for allotment systems. It should also be emphasized that the OSU-SLOT positioning was achieved automatically, in a few CPU seconds, requiring significantly less manual and computational effort than that required to develop either of the two comparative sets of system positions.

Figure 5 presents the outcome of aggregate interference analysis of systems as positioned by OSU-TOLS. Once again, results for WARC-88 Plan positions for Ku-band, allotment systems are also presented, as are results for systems as positioned in the draft Plan. OSU-TOLS was able to obtain a set of satellite positions for Scenario 2 that actually offers a slight improvement in aggregate interference results over those obtained with both sets of positions utilized for comparison, in the range of 26.0-40.0 dB. A particularly interesting comparison may be made between OSU-TOLS results and draft Plan results. Recall that the draft Plan, for allotment systems only, was achieved by the ORBIT software accompanied by manual repositioning of systems. OSU-TOLS results exceed the target aggregate C/I value of 26 dB for all systems, and exceed those achieved by the draft Plan for approximately 65% of all systems; these results were obtained through the application of OSU-TOLS as an automated procedure, with no additional manual manipulation of system positions required.

The results achieved by OSU-SLOT and OSU-TOLS, for Scenario 2 in particular, seem to indicate that alternative satellite orderings may have a significant effect on the quality of solutions to the satellite synthesis problem that may be achieved by a completely automated procedure; a significant portion of manual repositionings required to develop draft and final Plans were, in fact, reorderings as well. The quality of solutions achieved for Scenario 2 (Ku-band planned allotment systems only) versus those achieved for Scenario 1 (Ku-band allotments, plus existing systems) also indicates the impact that inhomogeneity in technical parameter values may have upon the difficulty of achieving a satisfactory solution to the satellite plan synthesis problem.

5.0 Summary and Conclusions

The satellite plan synthesis problem is one of formidable complexity, particularly when a large number of satellite systems must be considered and substantial inhomogeneity is present in system specifications. The development of an Allotment Plan for the Fixed Satellite Service at the 1988 World Administrative Radio Conference presented an extraordinary degree of difficulty; more than 200 satellites were considered, consisting of both planned systems and a substantial number of existing systems, with widely differing technical parameters. In order to develop the Allotment Plan, an international panel of experts performed extensive manual readjustment of positions found for planned systems by Conference computer software; this formed Part A of the Plan. Part B, consisting of positions for existing systems, was then added. After additional manual modifications of satellite positions, a full set of satellite positions for the Allotment Plan was developed.

The satellite plan synthesis problem has been recognized as a two-stage problem - first, of ordering the satellites within the GSO; then, of determining satisfactory satellite locations. A mixed-integer programming formulation of the Satellite Location Problem (SLP) has been presented, which captures the two-stage nature of the satellite plan synthesis process. Three heuristics were presented, which were developed to exploit the specialized structure of the SLP: OSU-SLOT, OSU-TOLS, and OSU-STARS. While OSU-SLOT and OSU-TOLS were specifically developed to attack the satellite ordering problem, they also may provide solutions to SLP. OSU-STARS is a k-permutation algorithm, accepting an input satellite ordering derived by OSU-SLOT, OSU-TOLS, or an alternative method, which permutes satellite positions k at a time in search of improved satellite orderings. It is possible that the variety of satellite orderings examined by the heuristics allow for greater exploration of the solution space for SLP than some alternative procedures that have been utilized in the past for this problem.

The heuristics were applied to two WARC-88 scenarios. For Scenario 1, consisting of Ku-band planned allotments and existing systems, aggregate interference analysis demonstrates that OSU-SLOT provides satellite systems with positions resulting in significant improvement of worst aggregate C/I values, when compared to analysis results obtained for the same systems as positioned in the WARC-88 Plan (where C/I objectives for existing systems were not considered in the solution). However, as might be expected, the improvement is apparently traded for some degradation of C/I values for other systems. The positioning derived by OSU-TOLS for Scenario 1 systems provides results much closer to those obtained with WARC-88 positions, while still exhibiting substantial improvement of the very worst C/I values. It must be noted that OSU-SLOT and OSU-TOLS were applied to both planned and existing systems simultaneously, rather than in a Plan A/Plan B sequence; both algorithms were applied to the entire scenario, eliminating the effort required to develop a two-part plan. It is also emphasized that OSU-SLOT and OSU-TOLS achieved solutions automatically (i.e., without additional manual repositioning) in a matter of a few CPU seconds.

Application of OSU-STARS to the satellite ordering and positioning provided by the WARC-88 Plan for Scenario 1 systems produced little change to aggregate interference results obtained, suggesting that little room for modification of the input positions existed under constraints imposed by the input data - particularly constraints imposed by service arc restrictions.

Two of the heuristics, OSU-SLOT and OSU-TOLS, were also applied to a second WARC-88 scenario - that containing Ku-band planned allotment systems only (Scenario 2). Results obtained through aggregate interference analysis of the configuration provided by each heuristic were compared with those obtained from WARC-88 positions, with positions for existing systems removed, and with those corresponding to satellite positions provided by ORBIT, utilized as a satellite plan synthesis algorithm, and accompanied by additional manual manipulation. For Scenario 2, OSU-SLOT provides positions that result in aggregate interference performance comparable to that associated with both configurations. The OSU-TOLS solution for Scenario 2 resulted in improved aggregate C/I performance over that obtained for the WARC-88 positioning and the draft Plan positioning, without the necessity of manual manipulation of system positions. Both heuristics obtained their respective solutions with comparatively little computational time and effort.

It is possible that either the OSU-SLOT or OSU-TOLS positioning derived for Scenario 2 could be utilized very effectively in a Plan A/Plan B approach to development of a set of satellite positions that also includes existing systems. As positioned by OSU-TOLS, all Ku-band allotment systems achieve the target aggregate C/I value of 26 dB; it is probable that little manual readjustment would be required to achieve the same result for the OSU-SLOT configuration. In any case, the repeated manual adjustments to positions for allotment systems that were required for the development of Part A of the Plan at the Conference would not be required for the OSU-TOLS or OSU-SLOT solutions. Alternatively, manual adjustment could be applied to the OSU-SLOT or OSU-TOLS configuration obtained for planned and existing systems simultaneously.

The allotment planning problem addressed at the 1988 World Administrative Radio Conference represented a satellite plan synthesis problem of such complexity that it is unlikely that a completely automated satellite plan synthesis procedure could have produced a solution that was completely satisfactory in all respects. However, the heuristics presented in this paper demonstrate significant promise in applications to problems of this level of difficulty. Thus, these algorithms are potential tools for future satellite communications planning efforts to find solutions to problems that will only increase in complexity.

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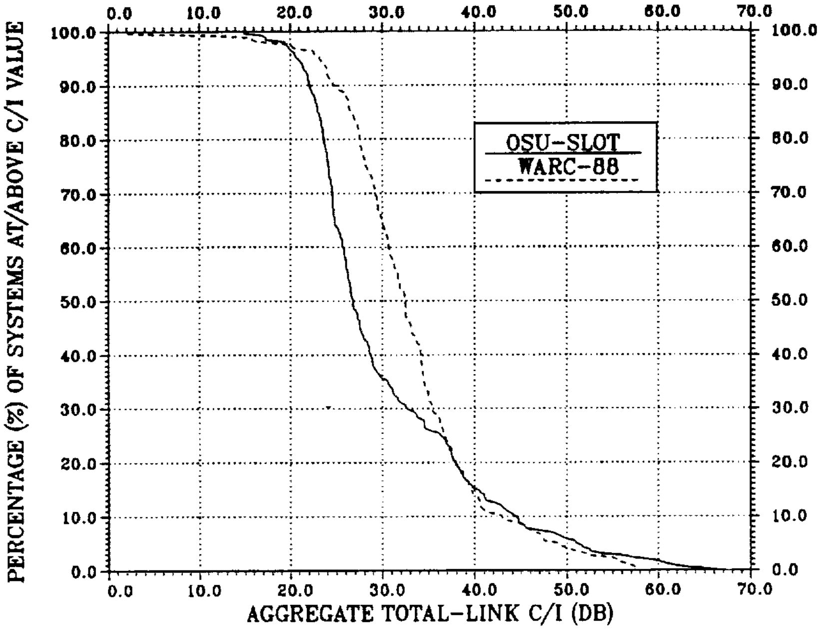

FIGURE 1 - AGGREGATE INTERFERENCE ANALYSIS RESULTS, SCENARIO 1 (OSU-SLOT)

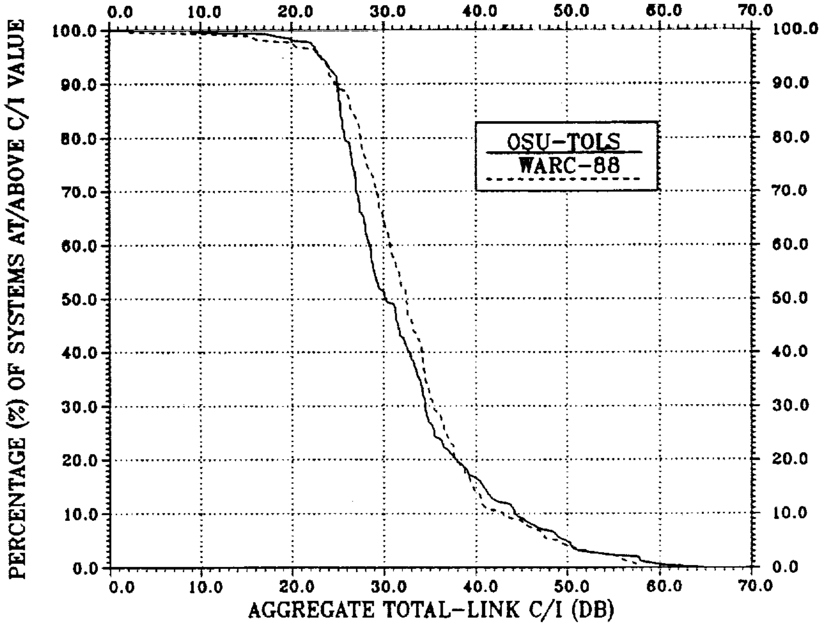

FIGURE 2 - AGGREGATE INTERFERENCE ANALYSIS RESULTS, SCENARIO 1 (OSU-TOLS)

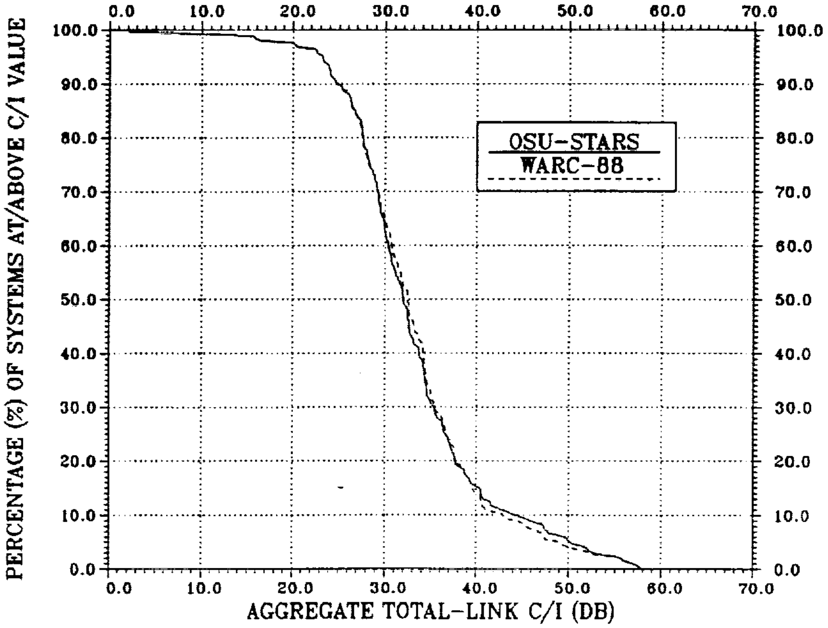

FIGURE 3 - AGGREGATE INTERFERENCE ANALYSIS RESULTS, SCENARIO 1 (OSU-STARS)

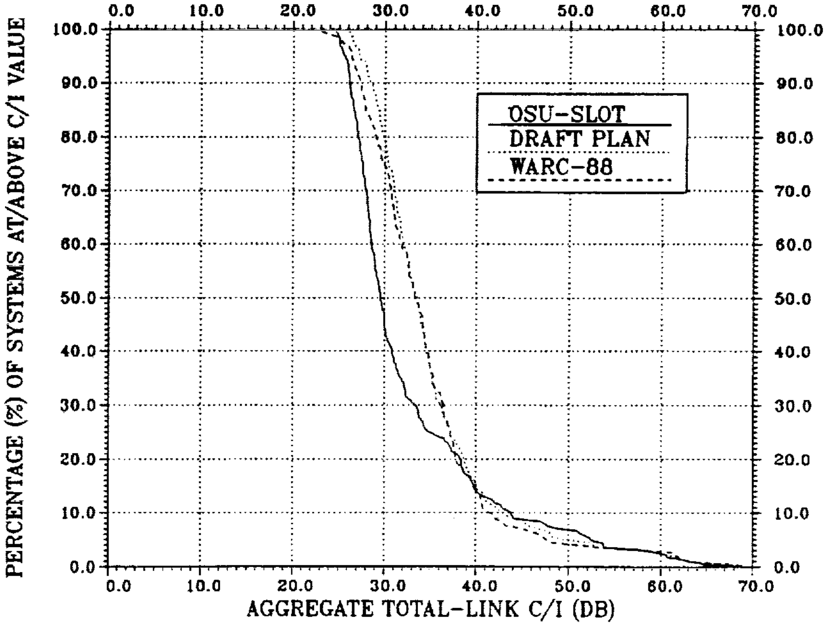

FIGURE 4 - AGGREGATE INTERFERENCE ANALYSIS RESULTS, SCENARIO 2 (OSU-SLOT)

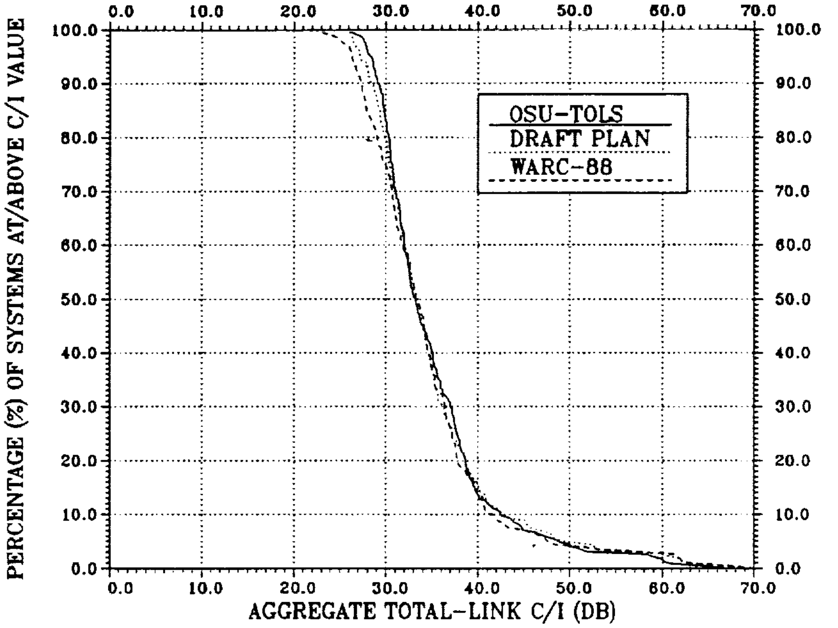

FIGURE 5 - AGGREGATE INTERFERENCE ANALYSIS RESULTS, SCENARIO 2 (OSU-TOLS)

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15. Supplementary Notes

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16. Abstract

Creation of an Allotment Plan for the Fixed Satellite Service at the 1988 Space WARC represented a complex satellite plan synthesis problem, involving a large number of planned and existing systems. Solutions to this problem at WARC-88 required the use of both automated and manual procedures to develop an acceptable set of system positions. Development of an Allotment Plan may also be attempted through solution of an optimization problem, known as the Satellite Location Problem (SLP). Three automated heuristic procedures, developed specifically to solve SLP, are presented. The heuristics are then applied to two specific WARC-88 scenarios. Solutions resulting from the fully automated heuristics are then compared with solutions obtained at WARC-88 through a combination of both automated and manual planning efforts.

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