Layout and Cabling Considerations for a Large Communications Antenna Array

R. T. Logan, Jr.
Communications Systems Research Section

In this article, layout considerations for a large deep space communications antenna array are discussed. A novel fractal geometry for the antenna layout is described that provides optimal packing of antenna elements, efficient cable routing, and logical division of the array into identical sub-arrays.

I. Introduction

Phased arrays of many small antennas have been proposed as alternatives to large antenna structures for communications and navigation support of deep-space missions. Large arrays of antennas have been constructed previously for radio astronomy applications, but the considerations pertaining to a telemetry receiving array are fundamentally different. In a radio-astronomy array, the requirement for high angular resolution motivates a large inter-element spacing. However, the design goal for a communications array is to maximize the total gain, which increases with the number and size of the elements, but does not depend on the physical dimensions of the array. To keep construction costs low, the land area and cable requirements should be minimized. Therefore, the densest packing of the antenna elements is desired for a communications array.

In this article, the design constraints for a hypothetical communications array will be defined. A novel fractal array geometry that satisfies all of the design constraints will be presented and then compared to a conventional square-grid layout geometry. The fractal layout geometry may also be advantageous to other types of phased-array antenna systems, including printed-circuit microwave and millimeter-wave antenna arrays.

II. Design Constraints

Throughout this article, the following design constraints will be assumed to illustrate the layout and cabling considerations of a large communications array:

(1) No shadowing of adjacent antenna elements is permitted over the entire tracking range of 360 deg in azimuth, to an angle $\alpha = 10$ deg above horizontal.

(2) The most dense packing of antenna elements without shadowing is desired to minimize the physical size and cabling requirements of the array.

(3) The whole array should be divisible into independent, identically shaped subarrays, so that the correlator/combiner hardware and software are not subarray-dependent.

(4) The array will be operated from a single, centralized control facility, so that all antenna cables must be routed to this facility.

The analysis presented below addresses each of these questions in turn.

III. Shadowing

It is assumed that the antennas are all pointed toward a distant source such as a spacecraft, and that the received wave front is nearly planar when it reaches the antenna array. The shadowing of adjacent antennas will determine the lowest tracking elevation angle, as sketched in Fig. 1.

When all antennas point in the same direction, the minimum distance required between them is determined by the diameter, D, of the antennas, and the minimum required tracking elevation angle, α, from horizontal: $L_{min} = D/\sin\alpha$.

IV. Packing

From the results of the previous section, each antenna must be located a distance L_{min} away from any other antenna to avoid shadowing. This is guaranteed if each antenna element occupies an effective circular area of diameter $L_{eff} = L_{min}$ that does not overlap any other element. For the telemetry-receiving application, the gain of the array depends only on the sum of the collecting areas of the individual antenna elements. Another consideration is to minimize the amount of cable needed to connect the antennas to the central control facility. From these considerations, the optimum antenna layout is simply the most dense packing arrangement for circles of area $A_{eff} = \pi\left(\frac{L_{eff}}{2}\right)^2$

From mathematics or solid-state physics, it is known that the most dense packing arrangement of spheres is the hexagonal close-packed (hcp) arrangement, illustrated in Fig. 2. In the hcp arrangement, the land area required by each antenna is equal to the area of the hexagon inscribed around each circle, as shown in Fig. 3. The area of this hexagon is $0.866L_{eff}^2$. If a square-packing arrangement is used, each antenna requires a square area of L_{eff}^2. Obviously, other less-dense packing arrangements require yet more area. Since the hcp packing arrangement is the densest possible, the cable lengths between antennas will be minimized in this arrangement.

V. Layout

For maximum configuration flexibility, it is desirable to break the large array into smaller sub-arrays that may be used independently or arrayed together to synthesize various size apertures. The sub-arrays should have equal numbers of elements and be identically shaped to allow maximum flexibility and compatibility of the sub-arrays with the correlator/combiner, monitor and control, and receiver subsystems. To conserve the amount of land and cabling required for the array, the sub-arrays should interlock perfectly so that no space is wasted between sub-arrays.

It was noted in the previous section that the closest arrangement of circles is the hcp, so that each antenna occupies a hexagonal unit cell of area $0.866L_{eff}^2$. Given the sub-array considerations outlined above, the layout of the array can be cast as a tiling problem, in which the hexagonal unit cells must be arranged in some larger sub-array shape that is perfectly interlocking with itself. At first glance, a larger hexagonal shape is a possible candidate for the sub-arrays, since the hexagon interlocks perfectly with other adjacent hexagons, as seen from Fig. 3. However, "it is a widespread source of irritation that hexagons put together do not quite make up a bigger hexagon" [1], i.e., it is impossible to construct identical hexagonal sub-arrays from the single-antenna hexagonal unit cells.

A fractal object called the Gosper snowflake [2,3] solves the problem of interlocking sub-arrays while maintaining the hcp arrangement. The Gosper snowflake is formed from a recursive tiling of hexagons. Starting with a single hexagon, the first-order Gosper snowflake is created by breaking up each face into segments of equal length, such that the original area of the hexagon is preserved. The first-order transformation is equivalent to grouping seven hexagons together, as depicted in Fig. 3. The second-order transformation groups seven of the first-order objects together, as in Fig. 4. The third-order transformation groups seven second-order objects together as in Fig. 5.

The second-order Gosper snowflake is a fractal object that retains its basic shape after subsequent transformations. Note that the general shapes of the second-order and third-order snowflakes in Figs. 4 and 5 are similar, although the perimeter becomes more complex. This is a distinguishing feature of a fractal object.

Clearly, in the Gosper snowflake, the hcp structure is maintained, so that the closest possible packing of antennas is achieved. But more importantly, Nth-order Gosper snowflakes interlock perfectly to form another Gosper snowflake of order $N+1$. These two properties together solve the problems of most efficient packing and division of the array into identical sub-arrays.

VI. Cable Layout Considerations

In this large array structure composed of hundreds, or even thousands, of individual antenna elements, the cable routing scheme deserves careful consideration, since it determines not only the amount of cable required, but the installation technique. To motivate the discussion of the cabling scheme, a set of reasonable requirements on the signal distribution scheme is assumed. The details of the signal distribution and combining hardware are not the subject of this article, but for the purposes of this analysis, it is assumed that each antenna will require (1) a fiber-optic cable, containing multiple fibers for RF signals, frequency references, and monitor/control data and (2) a power cable. Optical fiber for RF and digital signals and wires for ac power can be contained in the same cable, since the optical fiber is immune to electromagnetic interference.

The basic requirements for the cabling scheme are assumed to be

(1) Minimize the cable lengths.

(2) Minimize the number of cable varieties used throughout the array.

(3) Route all individual fiber-optic antenna cables to a central signal-processing location at the center of the array.

(4) Minimize cable installation and maintenance costs.

(5) Minimize environmental perturbations experienced by the cables.

Costs, attenuation, and differential phases between elements are minimized when the lengths of the individual cable runs are minimized. It is desirable to use as few types of cable as possible throughout the array, since the unit cost of cable is lower when purchased in large quantities. Routing all antenna cables directly to the central processing facility saves construction costs and facilitates operation of the array. Finally, the cables should be protected from extreme environmental perturbations, to minimize phase shifts due to thermal expansion.

The least expensive installation technique for fiber-optic cable is direct burial with a tractor-pulled cable plow. Also, the thermal stability of direct-buried cable is excellent, with peak-to-peak variations in the ground temperature at DSS 15 at Goldstone at a depth of 1.5 m measured to be less than 0.1 deg C daily, over several months,[1] compared to variations on the order of 40 deg C at the surface. Also, commercial direct burial fiber-optic cable has a mean-time-to-failure (MTTF) of approximately 100 yr. For these reasons, direct-burial of the fiber-optic cable is far superior to above-ground cable trays or underground conduits in terms of installation cost, stability, and MTTF. However, direct burial by plowing typically requires that cables not cross each other, to avoid snagging a previously buried cable with the plow. Therefore, in a large antenna array, the cable layout must be carefully planned to avoid crossing of cables.

Applying the reasoning used in the packing scheme to the cabling problem, the Gosper snowflake layout offers a naturally centralized cabling scheme with no crossing of cables for arrays as large as 343 elements. The basic element of the cabling scheme is a star that connects six outer elements of the first-order Gosper snowflake to the central element, as shown in Fig. 6. The seven cables from the individual antenna elements are spliced to a larger trunk cable at the central antenna site of the first-order snowflake. Then, each of the six first-order elements in the second-order snowflake is connected using a similar star-shaped structure, as illustrated in Fig. 7. This scheme can be repeated for the third-order snowflake, as in Fig. 8, in which 343 elements are connected to the center of the array without crossing of cables. For a snowflake of order 4 or larger, the trunk cables connecting the third-order snowflakes to the center cannot be straight runs if cable crossing is to be avoided.

Each of the fiber cables in Fig. 6 contains N fibers, where N is determined by the signal and monitor and control requirements for a single antenna. The 49-element second-order sub-array cabling scheme proceeds in a similar fashion, as in Fig. 7, but each of these fibers contains $7N$ fibers. Finally, for the 343-element array of Fig. 8, the largest cables contain $49N$ fibers each. An attractive feature of this cabling scheme over a daisy-chaining scheme is that only three types of fiber are required for the entire array: N-fiber cable, $7N$-fiber cable, and $49N$-fiber cable.

Note that none of the cables in any of these arrays crosses another. This is a subtle, yet extremely important, characteristic of this cable-routing scheme, since it provides for the possibility of direct burial of the cables using a tractor-pulled cable plow. The installation could proceed with the tractor plowing in all the N-fiber cable, then switching reels to the $7N$-fiber cable, and finally the $49N$ cables—never crossing trenches.

The distance between centers of adjacent $(n-1)$st-order elements composing an nth-order transformation is

[1] M. Calhoun, P. Kuhnle, and J. Law, "Environmental Effects on the Stability of Optical Fibers Used for Reference Frequency Distribution," presented at the 39th Annual Meeting of the Institute of Environmental Sciences, Las Vegas, Nevada, May 2–7, 1993.

$7^{(n-1)/2}\ L_{eff}$. Thus, the centers of adjacent 7-element first-order snowflakes in the second-order snowflake of Fig. 7 are separated by $7^{1/2}\ L_{eff}$, and the centers of adjacent 49-element second-order snowflake sub-arrays of Fig. 8 are separated by $7L_{eff} = 7^{(3-1)/2}\ L_{eff}$.

With this formula, the length of any of the fiber cable runs can be calculated as a function of L_{eff}, which depends on the diameter of a single antenna element, as discussed previously. Let the N-fiber cable used within a first-order snowflake be defined as type 1, the $7N$-fiber cable used in the second-order array as type 2, etc. By inspection of Fig. 8, for a 343-element array there are

(1) 49 first-order (7-element) snowflakes, each requiring 6 type-1 cables of length L_{eff}, for a total of $294L_{eff}$ m of type-1 cable

(2) 7 second-order (49-element) snowflakes, each requiring 6 type-2 cables of length $7^{1/2}\ L_{eff}$, for a total of $111.12L_{eff}$ m of type-2 cable

(3) 1 third-order (343-element) snowflake, requiring 6 type-3 cables, each of length $7L_{eff}$, for a total of $42L_{eff}$ m of type-3 cable.

From these numbers, the total length of the buried cable required is $L_{cable} = 447.12L_{eff}$ m. The total fiber length contained in those cables is $L_{fiber} = (294L_{eff}N) + (111.12L_{eff}7N) + (42L_{eff}49N) = 3129.84NL_{eff}$ m.

For comparison, consider a hypothetical array of $M = 343$ antennas laid out in a regular square grid pattern, separated by the minimum distance derived previously: $L_{eff} = D/\sin\alpha$, where D is the diameter of the antennas, and α is the minimum elevation angle to be tracked above the horizon. The grid will have sides of length $L_{side} = (M^{1/2} - 1)L_{eff}$. Assume that the cables are buried in trenches, with a central cable trench running the length of the square array through the center, and horizontal trenches perpendicular to the central trench for each row. There will be $M^{1/2} + 1$ trenches, each of length $M^{1/2}\ L_{eff}$. The total trench length is thus $L_{trench} = (M + M^{1/2})L_{eff} = 361.52L_{eff}$ m. The total length of cable required to run individual cables in the trenches from each antenna to the center of this square array is well approximated by $L_{cable} = \left((M^{3/2})/2\right) L_{eff}$ for $M > 50$. Thus, for the square grid array with $M = 343$, $L_{cable} = 3176.22L_{eff}$ m. In this scheme, all of the cables contain N fibers, so that $L_{fiber} = 3176.22NL_{eff}$ m.

By this estimate, the fractal array uses less optical fiber to connect all of the antennas to the center. But the more significant feature of the fractal array layout is that the optical fibers from many antennas are combined into larger cable assemblies, like the branching of a tree. Thus, by the above estimate, the fractal array layout requires substantially less total *cable* length than the square array, for which each antenna requires a separate cable assembly that may only contain a few optical fibers. This can significantly influence the cost of a large array, since much of the cost of an optical fiber cable assembly is for the outer jacket materials, and the costs of installing a 100-fiber cable assembly or a 1-fiber cable assembly are essentially equal. Finally, the fractal geometry permits installation of the cables using a plow pulled by a tractor, at roughly 1/100 the cost of digging trenches, laying conduits, and pulling the cables through them.

VII. Conclusions

The layout and cabling problems of a large deep space telemetry-receiving antenna array were investigated. It is concluded that the antenna elements should be arranged in the hexagonal-close-pack configuration, and that the sub-arrays should have the shape of a Gosper snowflake. This arrangement provides the most dense packing without shadowing, so it requires the least amount of land and shortest cable runs. Also, the Gosper snowflake provides perfectly interlocking, identically shaped sub-arrays and enables a cabling scheme that does not require any crossing of cable trenches. This greatly simplifies construction, since all cables may be installed at a uniform depth using a tractor-pulled cable plow. This antenna layout and cabling scheme may also be generally useful for other types of phased-array antenna systems, including integrated printed-circuit microwave and millimeter-wave arrays.

This work was performed while the author was a member of the design team for the JPL Small Aperture Arraying task, headed by George M. Resch. The team produced a design and cost model for the synthesis of a large communications aperture using small antennas for the DSN.

References

[1] B. Mandelbrot, *Fractal Geometry of Nature*, chap. 6, New York: Freeman, 1977.

[2] M. Gardner, "Mathematical Games," *Scientific American*, vol. 235, pp. 124–133, 1976.

[3] L. Cook, "Fractal Fiber Optics," *Applied Optics*, vol. 30, no. 36, pp. 5220–5222, December 20, 1991.

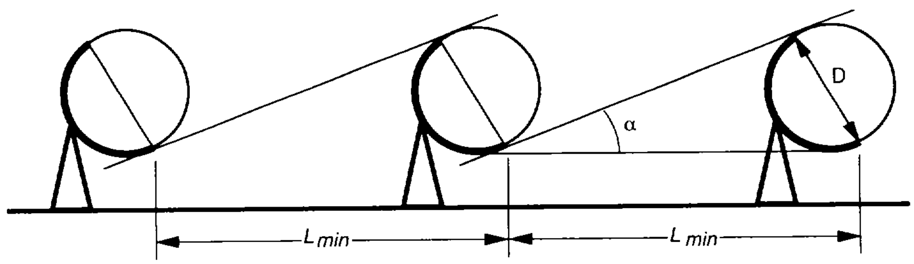

Fig. 1. Shadowing of adjacent antennas.

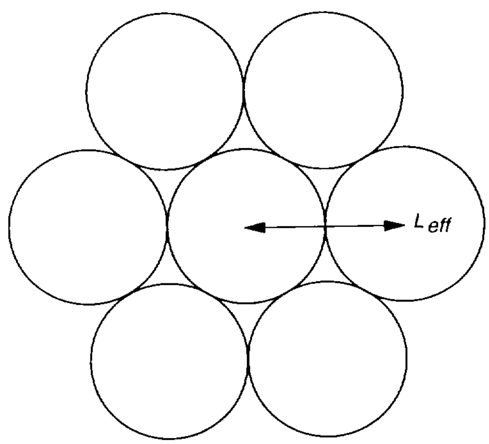

Fig. 2. Hexagonal close-packed structure.

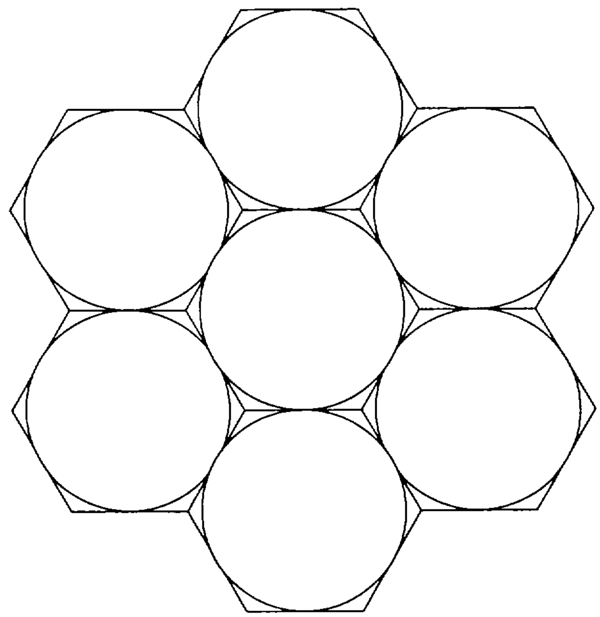

Fig. 3. Area required for hexagonal close-packed array.

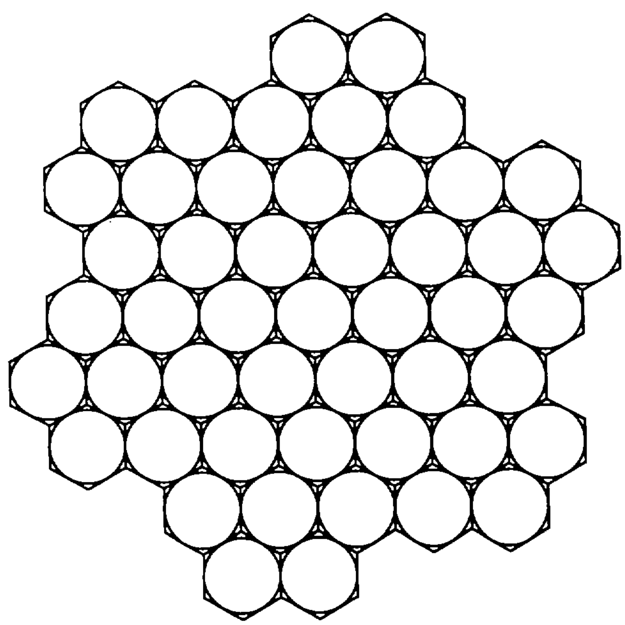

Fig. 4. Second-order Gosper snowflake, containing 49 elements.

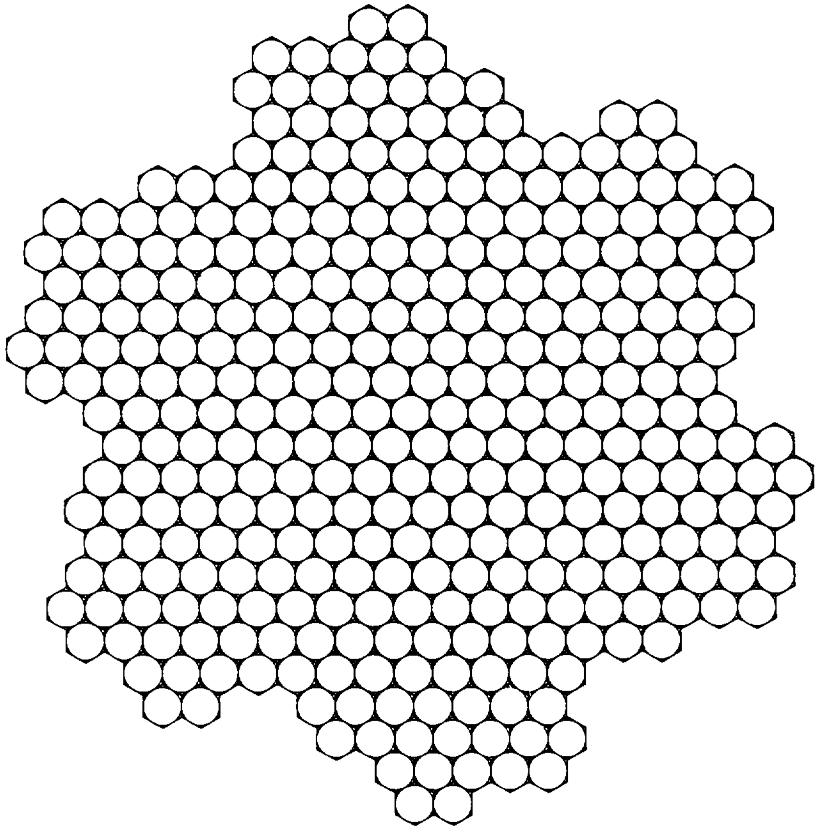

Fig. 5. Third-order Gosper snowflake, containing 343 elements.

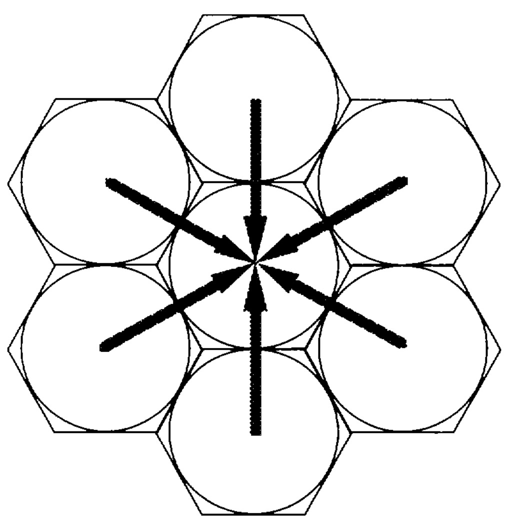

Fig. 6. Cabling scheme for first-order Gosper snowflake array.

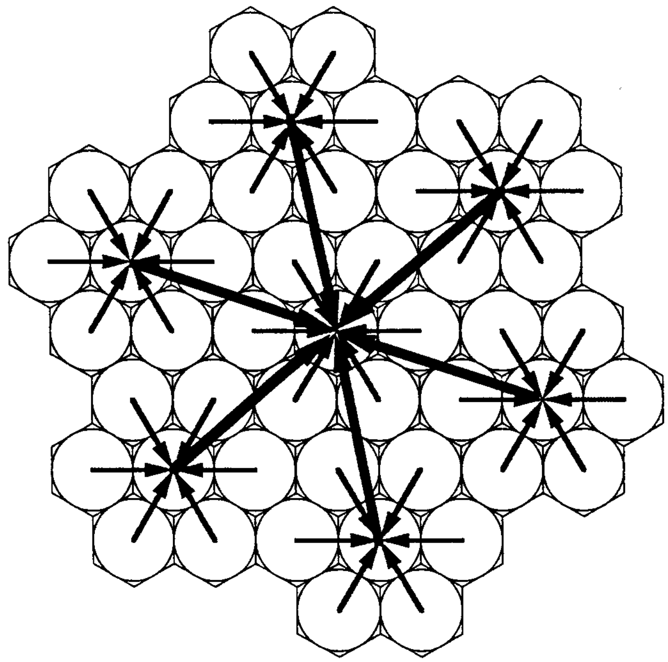

Fig. 7. Cabling scheme for second-order Gosper snowflake array.

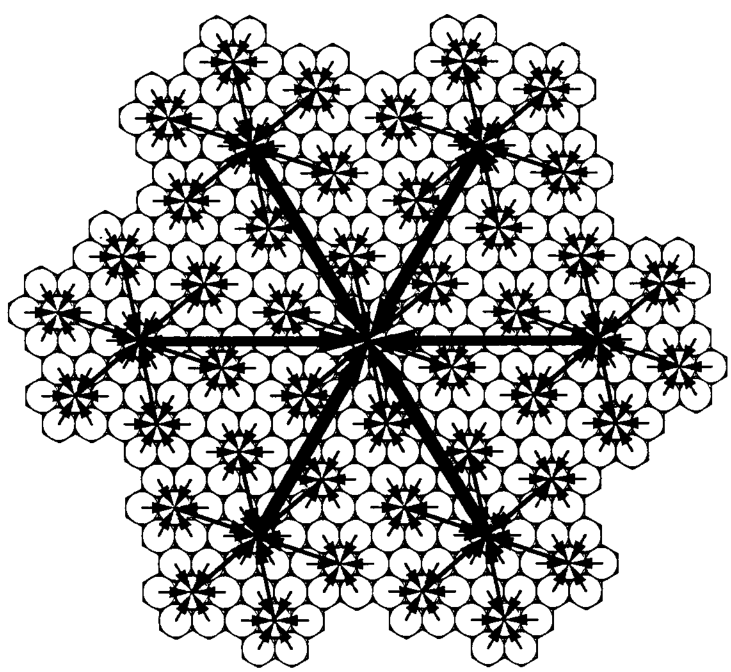

Fig. 8. Cabling scheme for third-order Gosper snowflake array.