The Deep Space Network Large Array

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In recent years it has become evident that, if future science needs are to be met, the capacity of the telecommunications link between planetary spacecraft and the Earth must be increased by orders of magnitude. Both the number of spacecraft and higher data rates demand the increased capacity. Technologies to support the increased capacity include even larger antennas, optical receiving systems, or arrays of antennas. This article describes a large array of small antennas that would be implemented for a fraction of the cost of an equivalent 70-m aperture. Adding additional antennas can increase the sensitivity many fold over current capabilities. The array will consist of 400 parabolic reflector antennas, each of which will be 12 m in diameter. Each antenna will operate simultaneously at both X-band (8 to 8.8 GHz) and Ka-band (31 to 38 GHz) and will be configured with radio frequency (RF) electronics, including the feeds, low-noise amplifiers, and frequency converters, as well as the appropriate servo controls and drives. The array also includes the signal transmission and signal processing to enable the system to track from between 1 and 16 different signals. A significant feature of this system is that it will be done for relatively very low cost compared to the current antenna paradigms. This is made possible by the use of low-cost antenna reflector technology, the extensive use of monolithic microwave integrated circuits (MMICs), and, finally, by using commercially available equipment to the maximum extent possible. Cost can be further reduced by the acceptance of lower antenna element reliability. High system availability will be maintained by a design paradigm that provides for a marginal set of excess antenna elements for any particular tracking period. Thus, the same total system availability is achieved for lower element availability. The "plug-and-play" aspects of the assemblies will enhance maintainability and operability. The project plans include a modest start of 12 antennas at the U.S. longitude.

I. Introduction

The telecommunications link between the Earth and spacecraft engaged in solar system exploration includes the Deep Space Network (DSN). This network, consisting of large antennas located approximately equally spaced around the Earth, is responsible for the delivery of telemetry to scientists from a multiplicity of spacecraft currently on mission, as well as for those planned in the future. There is a cluster of antennas at each of the three longitudes that make up the DSN. Each cluster currently consists of one to three 34-m beam-waveguide antennas and one 70-m Cassegrainian antenna. These are located

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at Goldstone, California, U.S.A.; Madrid, Spain; and Canberra, Australia. Although the current DSN assets support existing mission scenarios, it has been suggested that future missions will desire both greatly increased data rates and higher capacity. The decision has to be made as to how best to support these needs by the ground system. The options typically considered include the construction of new large apertures, the development of even lower-noise receivers, the use of novel coding schemes, and the development of higher-power uplinks. Often, a combination of these is done to improve capability. These options are costly and result in a capability that is an incremental improvement in the overall capacity of the DSN. This article describes an alternate concept to the typical options: a large number of small antennas that are arrayed to produce a high effective area-to-noise temperature ratio, A_e/T, which is the figure of merit, or sensitivity, for ground systems.

The concept of using arrays to increase the sensitivity is not new for radio telescopes or to the DSN. What is new about this concept is the cost goals that have been identified to complete a project capable of replacing the downlink capacity of the 70-m antennas. The concept leverages the advances made in electronics, such as monolithic microwave integrated circuits (MMICs), cryogenics, and, in particular, the inexpensive fabrication of smaller reflector antennas. The result is that we expect to duplicate the downlink capability of a 70-m antenna for 1/10 to 1/5 of the cost of the 70-m antenna. This article describes the DSN Large Array System that is being considered for the future.

II. Requirements and the Prototype Array

In spite of the great promise of radio frequency (RF) arrays, significant uncertainties in cost and performance remain. Reducing these uncertainties is a prime consideration in the development of the array concept for the DSN in the coming year. One way to reduce these uncertainties is the development of breadboard hardware and a prototype array. The cost of a prototype will be significant; therefore, when completed, the prototype will form the basis of the first cluster of new apertures at the U.S. longitude.

The development of the array system has started with a significant level of system engineering. Currently, a requirements document[2] has been written that defines the main parameters and functional requirements. We will be considering operability, availability, maintainability, and scalability factors in the development of the array. With respect to scalability, once the size of the array elements is chosen, the number of them, i.e., the array size, can be increased as a function of time (and available funding) such that the critical figure of merit, A_e/T, can be improved to match any future requirements. This important aspect of arrays suggests that, for the Prototype Array, the array size need only be as large as required to minimize the uncertainties in cost, performance, and operations. Currently, we have chosen to focus on an array of size $N = 12$ for an element size of 12 m. This size provides us with a sample size large enough to test all aspects of the array, while providing a system that is roughly equivalent to the DSN 34-m antenna when completed. While the Goldstone Deep Space Communications Complex (GDSCC) is one obvious potential site for the prototype, other considerations suggest that an alternate site be identified for the prototype development. The final DSN configuration would be arrays of equal size at each longitude with potential for multiple sites to provide for spatial diversity to account for weather effects. The top-level requirements for the array of $N = 12$ elements are given in Table 1.

The rationale for the element size comes from the desire to minimize the total array cost. A cost model has been developed that relates the total array cost to the size of the antenna for a fixed A_e/T. Keeping in mind that, for the same A_e/T, a greater number of antennas is required as the antenna size becomes smaller, one can see that therefore the cost of electronics for each antenna will define the low end of the scale. As the antenna size becomes larger, the cost is dominated by the antenna manufacture. Figure 1 illustrates this effect and shows that, for the current state of technology, an antenna in the range

[2] M. J. Connally, *Prototype Array System Requirements*, DSMS 828-042 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 25, 2003.

Table 1. Proposed requirements for a DSN array size of *N* = 12.

Requirement	Value	
	X-band	Ka-band
Element size (diameter), m	12	12
Array size (N)	12	12
A/T, m^2/K	43.2	18.6
Sky coverage, deg		
Elevation	6–90	6–90
Azimuth	0–360+	0–360+
Tracking rate (max), deg/min	24	24
Slew rate (max), deg/min		
Elevation	48	48
Azimuth	48	48
RF frequency band, GHz	8.0–8.8	31–38
IF bandwidth, MHz	500	500
Signal processing bandwidth, MHz	100	100
Polarization	Dual circular polarization	Dual circular polarization
Array beams/cluster	16	16
Gain variation, dB	<0.2	<0.2
Phase noise, dBc/Hz		
1-Hz offset	−65.7	−65.7
10-Hz offset	−73.3	−73.3
100-Hz offset	−75.2	−75.2
1000-Hz offset	−75.2	−75.2
100,000-Hz offset	−75.2	−75.2
Allan deviation		
1-s integration	3.9×10^{-13}	3.0×10^{-13}
10-s integration	4.6×10^{-14}	3.0×10^{-14}
1000-s integration	4.5×10^{-15}	1.4×10^{-15}
3600-s integration	4.5×10^{-15}	1.4×10^{-15}

of from 8 to 15 m will provide minimum cost for a fixed G/T. In this figure, for example, the fixed G/T is provided by 100 × 12-m antennas, or equivalently by 12 × 34-m antennas. As mentioned earlier, we have chosen to develop a system based on 12-m antennas.

III. A Simple Comparison of Arrays and Single Apertures

To quantify the benefits of a large array, it is useful to have a comparison to current DSN antennas. The typical operating system noise temperature and efficiency at Ka-band (32 GHz) for the DSN 34-m antennas currently are $T_{op}(34\text{ m}) = 45$ K and $\eta(34\text{ m}) = 0.55$. By using an array element antenna of 12 m and a system temperature and efficiency of $T_{op}(12\text{ m}) = 40$ K and $\eta(12\text{ m}) = 0.55$, one can calculate the number of 12-m antennas, N, necessary to match the equivalent aperture for a single 34-m antenna. We can calculate N by relating the effective aperture to the physical aperture of the antennas.

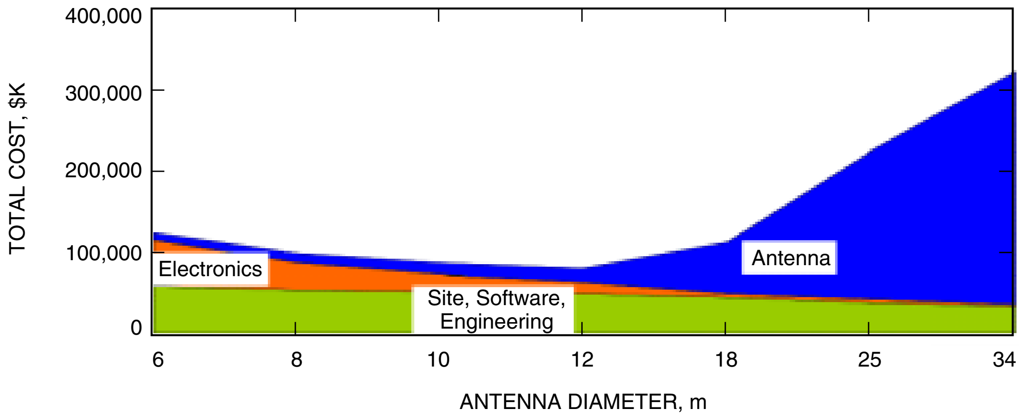

Fig. 1. Cost model of an array of 100 elements illustrating minimum cost at 12 m (cost of providing the *G/T* equivalent of 12 34-m antennas or 100 12-m antennas).

In particular, the effective area, A_e, and the physical area, A_p, of an antenna are related by the efficiency, η, by

$$A_e = A_p * \eta \tag{1}$$

To determine the size of array needed to be equivalent to the current 34-m antennas, we write

$$N \left(\frac{A_e(12\text{ m})}{T_{op}(12\text{ m})} \right) = \left(\frac{A_e(34\text{ m})}{T_{op}(34\text{ m})} \right) \tag{2}$$

$$N = \left(\frac{A_p(34\text{ m})}{A_p(12\text{ m})} \right) \left(\frac{T_{op}(12\text{ m})}{T_{op}(34\text{ m})} \right) \left(\frac{\eta_{34\mu}}{\eta_{12\mu}} \right) \tag{3}$$

Using the values above, we arrive at an array size of $N = 6.54$; however, we must choose an integer number for the array, so we choose $N = 7$. Finally, the total availability of each system must be the same. In the case of the single 34-m aperture, an availability of 0.95 is typical. For the 12-m array, the component elements may have a lower individual availability. The total system availability can be increased above the level of the individual elements by the addition of extra 12-m apertures. For our case, we find that 3 extra apertures are required to make up the difference.[3] Therefore, a rule of thumb for comparing this array to the equivalent capability of a 34-m antenna can be proposed. An array of 10×12-m apertures is equivalent to the current capability of a 34-m antenna. Similarly, an array of 40×12-m array will produce the same performance as the current 70-m antenna.

IV. Considerations for a Final DSN Array Size

It was suggested earlier that the prototype array would be an array of 12 elements located in a single location. The considerations in selection of this prototype size were limited to what were necessary to reduce risk with respect to the uncertainties in cost, performance, and operations. Here are discussed the considerations for choosing a final array size to support spacecraft operations through the year 2020. Again, in this context, the final size is fixed within a certain era. If implemented properly, an infrastructure

[3] V. Jamnejad to G. Resch, "Study of Probabilistic Availability of an Array," JPL Interoffice Memorandum 3327-92-069 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 9, 1992.

will exist after the initial construction phase that is capable of increasing the array size to meet any conceivable requirement. In practice, the limit is defined by available funding for any such project.

There are four main considerations to be made in determining a final array size. These considerations are as follows:

(1) Maintain the current downlink DSN capability, while systematically eliminating the large apertures currently in the DSN. Currently the DSN longitudes are populated with the following number of apertures:

   (a) Goldstone: 4×34 m; 1×70 m

   (b) Canberra: 2×34 m; 1×70 m

   (c) Madrid: 3×34 m; 1×70 m

   Given the simple metric of a 10×12-m array being equivalent to a 34-m antenna, and a 40×12-m array being equivalent to a 70-m antenna, we can suggest that to meet this consideration Goldstone should have an 80×12-m array, Canberra should have a 60×12-m array, and Madrid should have a 70×12-m array.

(2) Provide an array sized sufficiently large to enable tracking of all current and planned spacecraft at their maximum data rates for all phases of the mission, e.g., for a Mars mission at both maximum range and minimum range. In the case of existing spacecraft, the maximum data rates are limited by the onboard hardware. Future spacecraft could include much higher-data-rate hardware. Referring to Table 2, one can conclude that an array of 100×12 m antennas at each longitude will meet all current and planned future needs through 2015. The corollary to this conclusion is that future missions can be designed for even higher data rates until the array limits the communications link, after which a larger array would be necessary.

(3) Enable the DSN to track spacecraft in different parts of the sky at the same time. This suggests that there be a factor, A, which is dependent on the number of missions, the probability of needing to track two separate missions at the same time at the same longitude, the probability of this occurring when the involved missions are at their maximum ranges, and the number of antennas needed to guarantee maximum data rates for each involved mission. One note is that all spacecraft at a single location, e.g., Mars or Jupiter or Saturn, can be simultaneously tracked with a single array of 100×12 m antennas since all will be in the main beam of the array element antennas. The current estimate for the factor A is 4, suggesting a final array size of 400×12 m antennas.

(4) Reasonably match funding profiles for the largest size of array that is practical for the next 20 years. As the array size grows, the maximum data rate that can be supported in an end-to-end system becomes more limited. This is due to the available bandwidth for a particular RF channel, either in the X-band or Ka-band frequencies. Figure 2 illustrates this effect. The figure shows the maximum data rate that a link can support as a function of the Earth-to-spacecraft distance. Shown on the plot are curves for a 40×12-m and a 100×12-m array. Also shown on the chart for reference is a curve for the proposed optical communications demonstration planned for the Mars Telecommunications Orbiter (MTO). A 400×12-m RF array at Ka-band would be equivalent to the performance of the optical communications demonstrator.

Finally, when comparing the performance of a new capability to the current 70-m capability, one can consider changes in the frequency of operation. Specifically, since the array is configured for Ka-band whereas the 70-m antenna is configured only for X-band, there is a $\times 4$ factor for the capacity of the array as compared with the 70-m system. Therefore, a 400-element array will have $40\times$ the capacity of the current 70-m system.

Table 2. The array size to guarantee a mission can operate at the maximum data rate.

Mission	Location	Maximum[a] data rate (minimum range)	Minimum data rate (maximum range)	Data rate at all ranges with array	Array size guaranteeing maximum data rate	Year(s) of operation
MRO[b]	Mars	5.3 Mb/s	500 kb/s	5.3 Mb/s	75–100	2005–2010
MRO (extended mission)	Mars	5.3 Mb/s	500 kb/s	5.3 Mb/s	75–100	2010–2015
MTO	Mars	10.6 Mb/s	535 kb/s	10.6 Mb/s	100	Oct. 2009–Aug. 2020
MSL[c] (DTE)[d]	Mars	10 kb/s (34 m)	1 kb/s	8.5 kb/s (34 m)	<100	2009
Cassini (extended mission)	Saturn	165.9 kb/s	40 kb/s	165.9 kb/s	60–100	June 2008–June 2010
JIMO[e]	Jupiter	20 Mb/s	10 Mb/s	20 Mb/s	100	Apr. 2011–Mar. 2021
New Horizons	Pluto, Kuiper Belt	104 kb/s	10 b/s	104 kb/s	100	Oct. 2006–Mar. 2017
Solar Probe	Solar	62 kb/s	25 kb/s	62 (25) kb/s	100 (40)	May 2010–July 2017

[a] Circa May 2003.

[b] Mars Reconnaisance Orbiter.

[c] Mars Science Laboratory.

[d] Direct to Earth.

[e] Jupiter Icy Moons Orbiter.

V. Array System Description

The techniques used to phase up the elements of an array must account for variations in the atmosphere. For a telecommunications array, the placement of the individual elements is most efficient when the elements are tightly clustered. This improves the ability of the array combiner software to phase up on the weak sources. This is in contrast to a radio telescope array, which is more likely to include elements that are widely separated in order to increase resolution of the combined signal.

An architectural consideration for a telecommunications array is to create a widely separated set of clusters of many closely spaced elements. This concept is illustrated in Fig. 3. Each cluster is controlled by a cluster control center. Each cluster control center is connected in turn to an array control center. Such a system configuration enables both a certain amount of tolerance to local weather conditions and direct plane-of-sky measurement of the spacecraft for navigation purposes. While this architecture provides many advantages, one serious drawback is the added cost of the system due to the development of the facilities and the transport of the very wide bandwidth signals between the array clusters.

As described earlier, the architecture that the DSN currently is pursuing consists of a single cluster of closely spaced antennas at each of the three longitudes around the Earth. The initial cluster size would be 400 antennas. This is cost effective and also provides the initial infrastructure for an expansion that might eventually consist of multiple clusters. Each of the clusters includes the antennas, electronics, a signal combiner, the control and analysis software, and the infrastructure, including the control buildings, roads, fences, security system, and intra-array communications system.

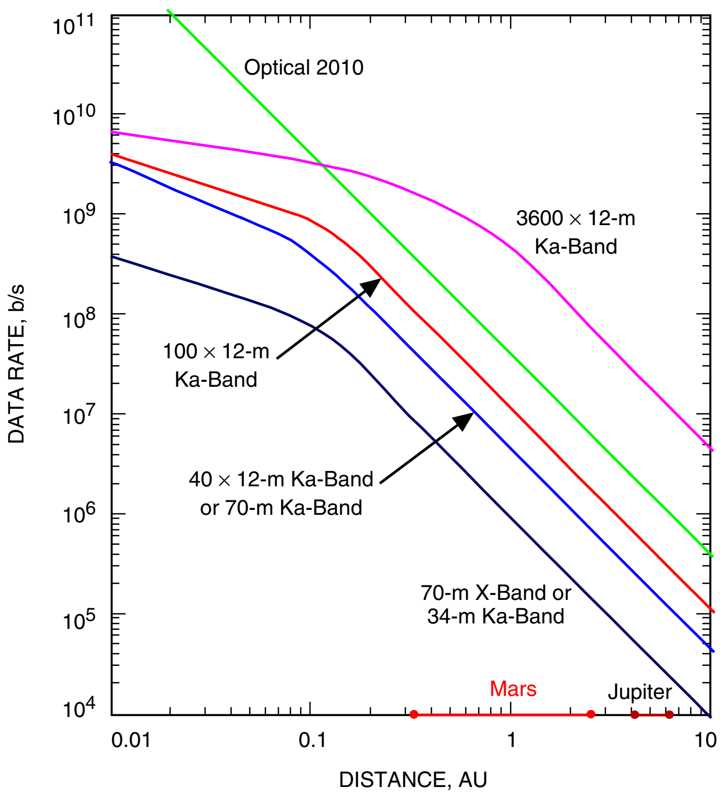

Fig. 2. Maximum data rate versus distance with 50-W DC at the spacecraft for various array sizes.

The array system consists of eight major subsystems, as shown in Fig. 4. These are the following:

(1) Antenna element, including the main and sub-reflectors, motors, drives, and servos

(2) Microwave, including feeds, optics, and low-noise amplifiers

(3) RF electronics, including the RF/intermediate frequency (IF) frequency converters and local oscillators

(4) Signal processing, including the signal conditioning, beam splitters, beam combiners, and correlator

(5) Monitor and control, including the software and hardware needed to control and monitor the array, and to interface it with the existing DSN equipment

(6) Frequency and timing, including the reference frequency generation, timing signal generation, and central local oscillator system

(7) Ground communications, including the fiber-optic cables between the antennas and the control building

(8) Facilities, including the control building, roads, power, heating and cooling, weather station, etc.

Current project activities include technology investigations and demonstrations in each of these areas with emphasis on minimizing the total system cost. Monolithic microwave integrated circuits (MMICs) will be used extensively to replace the larger bulky components in older systems. This lends itself to low-cost replication in great quantities. Furthermore, the development of reflector manufacturing techniques

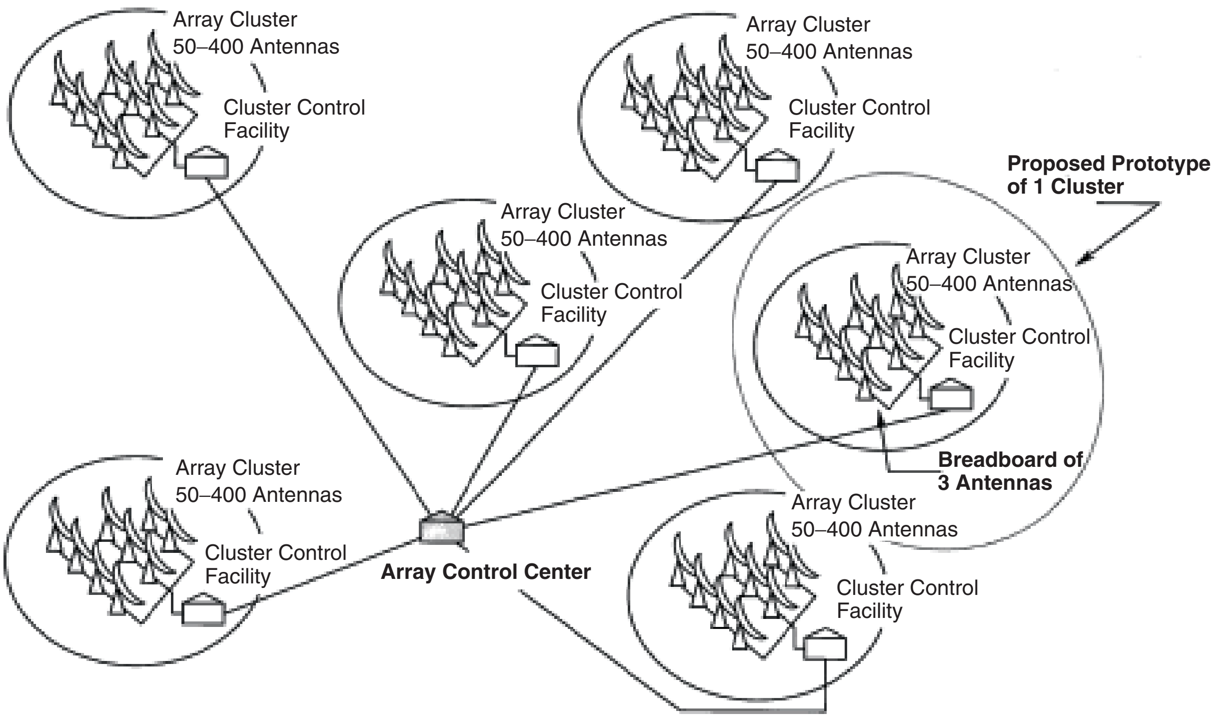

Fig. 3. Architecture of an array consisting of many clusters of antennas.

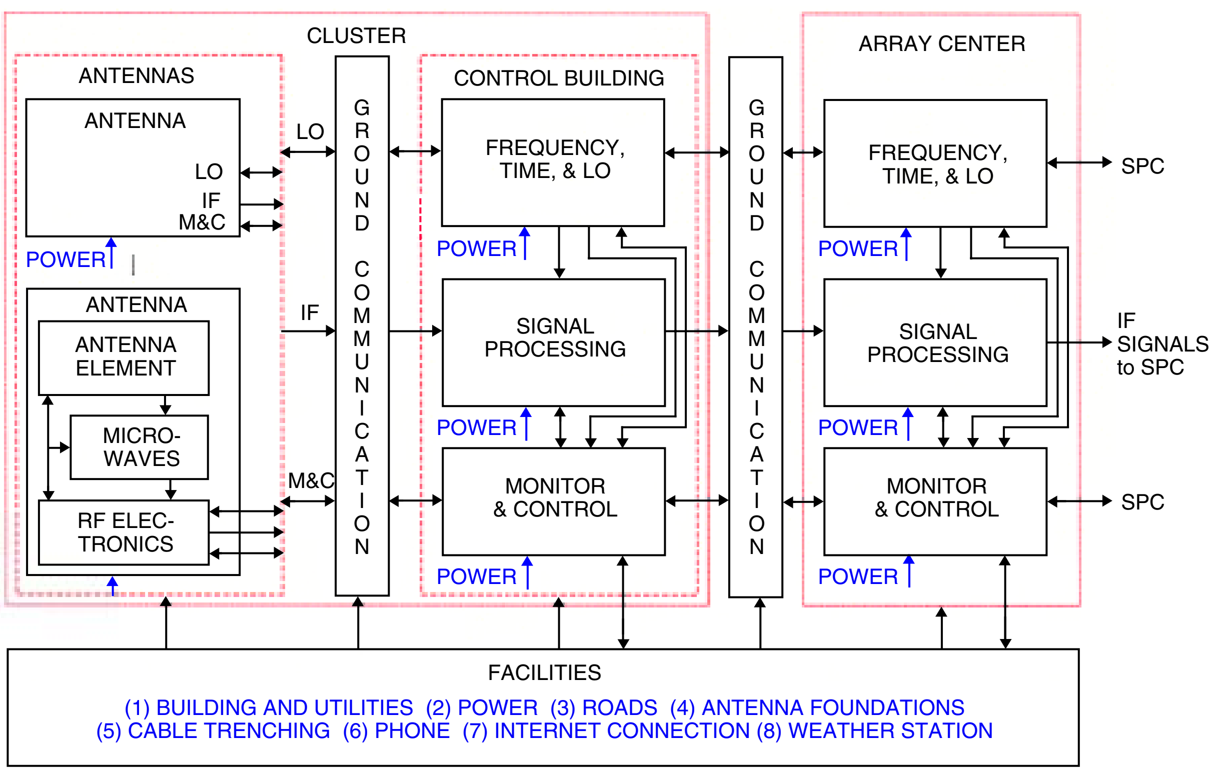

Fig. 4. Block diagram of the DSN array showing subsystems and interconnections.

is progressing to break the currently accepted rule of thumb for the cost of antennas as a function of the diameter. Currently costs are thought of as being approximately proportional to the antenna volume. This is given by cost = $D^{2.7}$. Our goal is to reduce the exponent from 2.7 to approaching 2.0, thus making the cost nearly proportional to the antenna area. We are making significant advances in antenna manufacture by the use of specially hydroformed aluminum reflectors. As a final note, we are designing the system in modular form, such that replacement components are "plug-n-play." The repair of failed components may depend on the cost to simply replace the components. We will investigate how best to implement this philosophy in the future.

VI. Operations Concept

The paradigm currently used by the DSN consists of providing a set of services with fixed performance. Spacecraft telecommunications system engineers design their systems to use these fixed services. The paradigm proposed in this array concept is for the system designers to request a particular A_e/T and an associated total system availability. Doing so allows the array scheduling system to allocate only those antennas required to meet the performance required in addition to the marginal extra antennas to meet the availability requirement. In this way, the number of multiple missions to be supported can be maximized. The projects and the DSN can negotiate performance as a function of cost and availability. A more detailed concept of operations has been developed recently that expands on these ideas [1].

VII. Summary

When implemented, the DSN Large Array described here will provide downlink capability 40 times greater than the current 70-m antenna system. However, the concept provides for an infrastructure that allows the array size to be expanded as required and is limited only by available funds. The cost goals are to do this for a fraction of the cost of the current large antennas. The initial prototype implementation of 12×12-m antennas will have developed the technologies, engineering, and infrastructure. This concept will ultimately be a replacement for the existing downlink capabilities of the DSN.

Reference

[1] D. S. Bagri and J. I. Statman, "Preliminary Concept of Operations for the Deep Space Array-Based Network," *The Interplanetary Network Progress Report*, vol. 42-157, Jet Propulsion Laboratory, Pasadena, California, pp. 1–13, May 15, 2004. http://ipnpr/progress_report/42-157/157L.pdf