Spacecraft Multiple Array Communication System Performance Analysis

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Abstract—The Communication Systems Simulation Laboratory (CSSL) at the NASA Johnson Space Center is tasked to perform spacecraft and ground network communication system simulations, design validation, and performance verification. The CSSL has developed simulation tools that model spacecraft communication systems and the space and ground environment in which the tools operate. In this paper, a spacecraft communication system with multiple arrays is simulated. Multiple array combined technique is used to increase the radio frequency coverage and data rate performance. The technique is to achieve phase coherence among the phased arrays to combine the signals at the targeting receiver constructively. There are many technical challenges in spacecraft integration with a high transmit power communication system. The array combining technique can improve the communication system data rate and coverage performances without increasing the system transmit power requirements. Example simulation results indicate **significant performance improvement can be achieved with phase coherence implementation.**

Index Terms—Spacecraft communication, phased array, communication coverage, phase error.

I. INTRODUCTION

A dish antenna does not have gain reduction or loss when scanning beam to an off-boresight target. On the other hand, a phased array system does suffer gain reduction as the beam is pointed in an off-boresight direction. This gain degradation while scanning will reduce communication coverage, data rate, and link margin. To overcome the phased array gain degradation while scanning, the system design has to increase the array size with a larger number of elements, or raise the transmit power to meet the minimum effective isotropic radiated power (EIRP) at the required scanning angles. In either case, the greater the number of elements in the array design or the larger transmit power will increase both system complexity and cost [1,2]. There are many technical challenges in spacecraft integration with a high transmit power phased array system. To ease the integration of a phased array system to a power limited spacecraft, it is desirable to improve antenna performance without increasing the transmitter power or array number/size requirements.

A technically viable solution is to coherently combine the signals of multiple array apertures. The aperture combining technique can compensate for loss of array gain as the individual arrays steer off-boresight. As a result of the constructive interference among the combining arrays, the total gain increases significantly. For a specific design with an EIRP requirement, the size and/or number of phased array apertures, as well as

their element transmit power, can be reduced. NASA significantly implemented a similar technique to improve the performance of the Deep Space Ground Network communication systems [1-4].

In the spacecraft phased array system coverage applications, there are advantages to using multiple arrays with phase coherent combining. The combined arrays gain will increase as well as the coverage without increasing the element transmit power or array aperture area [5,6].

In this paper, performance improvements in communication coverage for a multiple array system are analyzed. The coherent combined signals are derived under the assumption of perfect phase coherent combining. To provide coherent combining, the radio frequency (RF) system must adjust and compensate the time difference or phase shift for each array on both receive and transmit [7,8,9].

II. MULTIPLE ARRAY COMBINING

The ideal coherent combination of subapertures is achieved when the time delay between array phase centers is exactly compensated by a true time delay. The array gain is increased by 6 dB, a factor of 4, but the overall noise is increased by 3 dB, a factor of 2. Thus, the overall figure of merit, in terms of antenna gain (G) and system noise temperature (T), at the receiver antenna G/T increases by 3 dB which is the ideal upper bound for combining two arrays [1,2].

III. PHASE ERROR ANALYSIS

The phase center is a virtual point. As the array phased center locations are generally determined with some small random errors, position uncertainties result in phase error. RF components, such as cables, mixers, filters, and amplifiers, etc., along the signal traveling path can also cause phase errors due to temperature variations in the space environment [3,4].

Digital phase shifters can only shift phase in quantized steps. The minimum phase step is determined by the number of bits, n, according to $\Phi_n = 2\pi/2^n$. The maximum quantization error is $\varepsilon = \pm\,\Phi_n\,/\,2$. Fig. 1 shows the phase error due to quantized steps for an N-bit phase shifter.

Phase errors in array combining will result in signal strength degradation. The combined signal strength of two arrays is a vector sum of the signals from the two arrays.

The array gain degradation relative to a perfect coherent combining for two arrays with a phase error is

$G_1 = |E_t|^2 / |E_{t0}|^2 = ¼\,(1+\cos\Phi)^2 + \sin^2\Phi$

which is plotted in Fig. 2 as a function of the phase error Φ. To limit the loss to less than 0.1 dB, the phase error must not exceed 17 deg for combining two arrays. From Fig. 2, the maximum phase uncertainty for a 4-bit phase shifter is 11.3 deg. Thus, a 4-bit phase shifter can meet this 0.1 dB gain degradation requirement for 2 array combining.
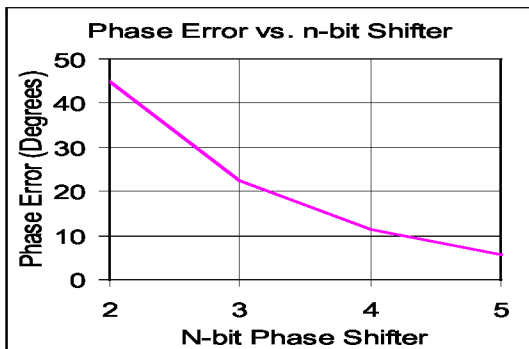

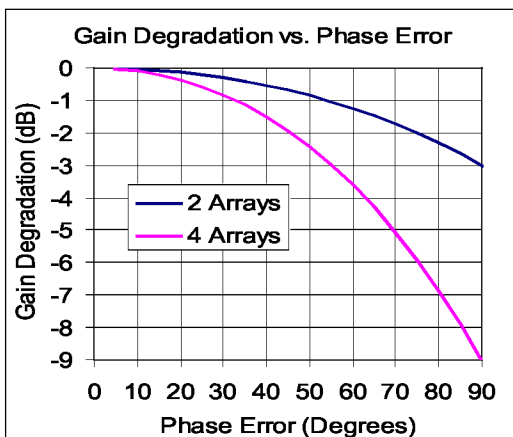Fig. 1. The phase error due to quantized steps for an N-bit phase shifter.

Fig. 2. Power loss due to phase error in 2 and 4 array combining.
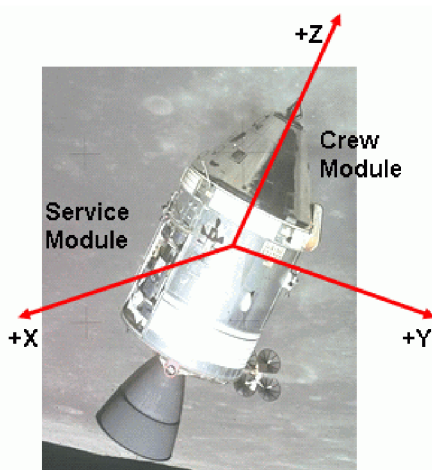

Fig. 3. The spacecraft coordinate system. The θ angle measures from the +Z axis (nose) and the Φ angle measures from the +X axis.

The array gain degradation relative to a perfect phase

coherent combining for four arrays with phase error is

$$G_l = |\mathbf{E}_t|^2 / |\mathbf{E}_{t0}|^2 = [(1+3\cos\Phi)^2 + \sin^2\Phi]/16$$

which is plotted in Fig. 2. To limit the loss to less than 0.2 dB, the phase error must not exceed 15 deg for combining four arrays. The maximum phase uncertainty for a 4-bit phase shifter is 11.3 deg, as shown in Fig. 2. A 4-bit phase shifter can meet this 0.2 dB gain degradation requirement for combining 4 arrays.

IV. SPACECRAFT ARRAY SYSTEM

An Apollo-like spacecraft is considered in this analysis. The spacecraft coordinate system is defined in standard spherical coordinates, as shown in Fig. 3. The θ angle measures from the +Z axis (nose) toward the −Z axis, and the Φ angle measures from the +X axis toward the +Y axis. A simple design to have full spherical coverage around the spacecraft could be to have 8 phased array antennas: 4 on the crew module (CM) and 4 on the service module (SM). The array antennas are separated by 90 deg from each other in Φ angle. A moderate ±45 deg scan for each of the 4 CM or 4 SM arrays will achieve full 360 deg coverage in circumference ($0° < \Phi < 360°$) around the spacecraft. Similarly, a moderate ±45 deg scan for 1 CM and 1 SM array will achieve full 180 deg coverage in the θ direction ($0° < \theta < 180°$) around the spacecraft. The 4 CM array antennas are to cover the upper hemisphere ($\theta < 90°$) of the spacecraft. The four SM array antennas are to cover the lower hemisphere ($\theta > 90°$) of the spacecraft.

A typical medium gain phased array antenna is simulated. Fig. 4 shows the array antenna pattern at a 0 deg scan angle [10,11]. The peak gain at the 0 deg scan angle is about 15 dBic. The 3-dB beamwidth is about 28 deg.

V. SIMULATED RESULTS

A. Single Array System

A phased array system is capable of beam scanning by applying appropriate phase separation among array elements. The phased array gain is always lower when scanning to off-normal positions. On the other hand, sidelobe gain levels increase when the array scans to off-boresight angles.
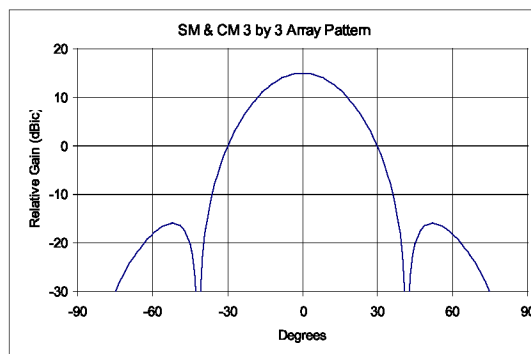

Fig. 4. The single array antenna pattern at a 0 deg scan angle.

The spacecraft phased array composite signal strength, shown in Fig. 5, is constructed through a composition of the 8 phased

array antennas pointed at various scan angles. Only one array is active with no aperture combining. As shown in Fig. 5, the 4 CM arrays will cover the upper hemisphere in the area $0° < \theta < 95°$. The 4 SM arrays will cover the lower hemisphere in the area $95° < \theta < 180°$.

The patterns clearly show the array gain loss while scanning the array off the normal direction. The composite array signal strength maps show valleys at $\Phi=60, 150, 240,$ and 330 deg for the arrays in the lower hemisphere $95° < \theta < 180°$. The signal strength level is about 10 dBic, which is -5 dB lower than the boresight gain level of 15 dBic at a 0 deg scan angle. The gain valleys are at $\Phi=0, 90, 180,$ and 270 deg for the arrays in the upper hemisphere $0° < \theta < 95°$. The gain level valleys also exist between arrays at around $\theta=95$ deg with 10 dBic.
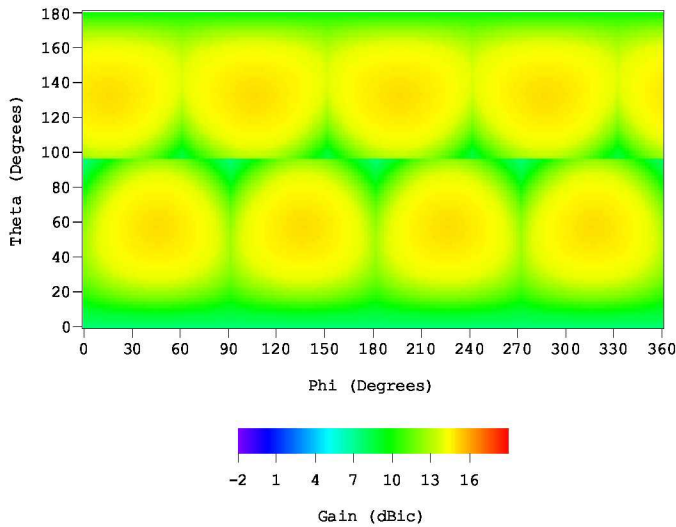
Fig. 5. Four CM and 4 SM array composite signal strength maps without signal combining.
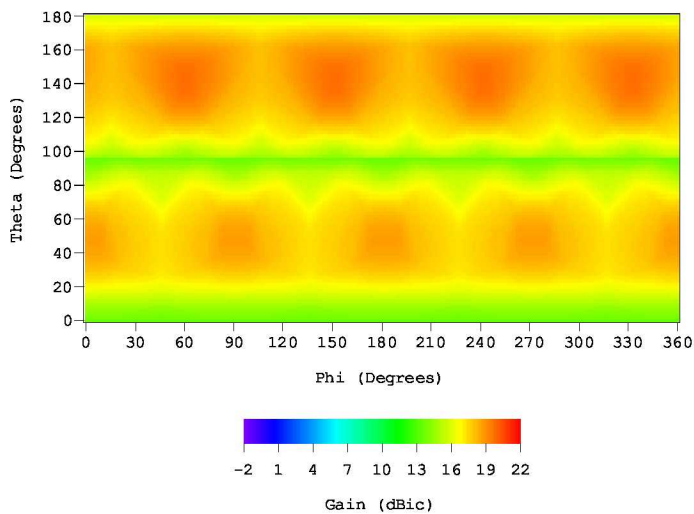
B. Multiple Array Combining

Fig. 6. Composite signal strength maps with two array combining (2 active CM or 2 active SM arrays).

Fig. 6 shows the composite array signal strength maps with 2 array signal combining. The peak signal levels shown at $\Phi=60,$

150, 240, and 330 deg in the lower hemisphere $95° < \theta < 180°$. These levels increase by 4.5 dB to 19.5 dBic from the single array maximum signal level of 15 dBic. The minimum signal levels are now at $\Phi=15, 105, 195,$ and 285 deg. Signal levels also increase to about 16 dBic, which is 6 dB higher than the 10 dBic for the single array without signal combining. Similar signal level improvement is also shown for the array in the upper hemisphere $0° < \theta < 95°$.

The minimum signal valleys are between the CM and the SM antennas at around $\theta=95$ deg. However, the signal levels at valleys are about 13.5 dBic, which is 3.5 dB higher than the 10 dBic for the single array without signal combining.

Fig. 7 shows the composite array signal strength maps with a total of 4 active arrays. Two active CM and 2 active SM arrays are used in the phase coherent signal combining. Peak signal levels for the 4 array combining increase by 6 dB to 21 dBic from the single array of 15 dBic. The previous signal valleys at around $\theta=95$ deg are eliminated with the 4 array combining. The only low signal level regions are in the spacecraft nose area, around $\theta=0$ deg, and in the spacecraft tail area, around $\theta=180$ deg.
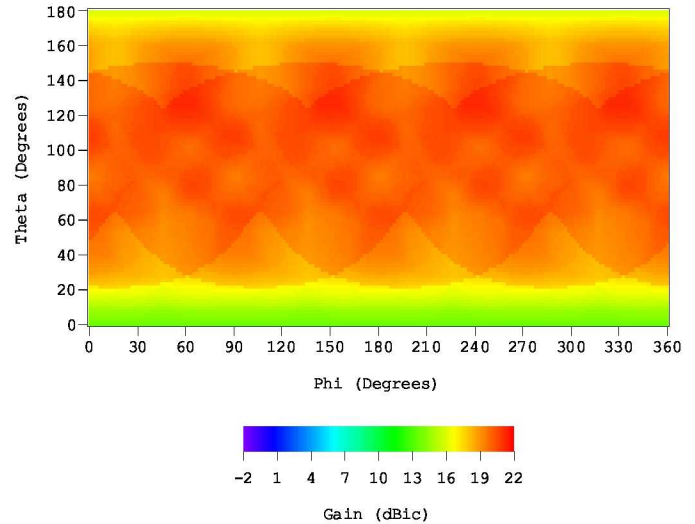
Fig. 7. Composite signal strength maps with 4 array combining (2 active CM and 2 active SM arrays).
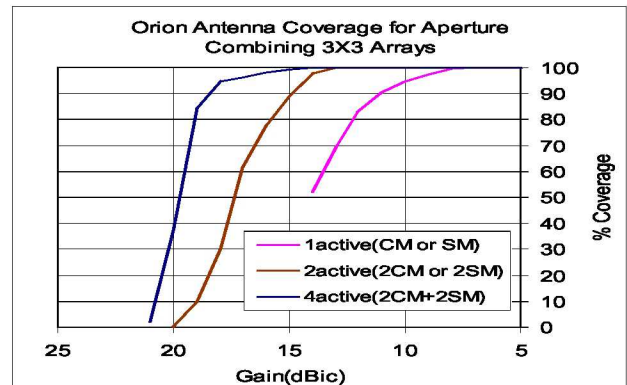
Fig. 8. Coverage performance improvement with 4 array signal combining implementation.

Fig. 8 shows the coverage performance improvement with aperture combining implementation for four combined arrays. At 90% spherical coverage, the gain level increases by 3.5 dB from 11 to 14.5 dB with 2 active CM or 2 active SM arrays combining implementation. The gain level increases by 7.5 dB from 11 to 18.5 dB with the 4 array aperture combining implementation. Two active CM and 2 active SM arrays were used in the 4 array signal combining.

TABLE I
COVERAGE PERFORMANCE IMPROVEMENT WITH ARRAY SIGNAL
COMBINING IMPLEMENTATION FOR SPACECRAFT MULTIPLE
ARRAY SYSTEM

No. of Sub-arrays	1 Active	2 Active	4 Active
Gain Level at 90% Coverage (dBic)	11	14.5	18.5
Data Rate at 90% Coverage (bit/s)	N	2.2N	5.6N

Table I summarizes the coverage and data rate performance improvement with 2 and 4 array combining implementation. The data rate increases 2.2 times in 90% coverage area with 2 array combining. The data rate increases 5.6 times in 90% coverage area with 4 array combining. The system implementation loss of signal combining is not included. The actual performance improvement will have to be adjusted to include vehicle structure multipath effects and system implementation loss.

VI. CONCLUSION

Multiple array signal combining enables a communication system to operate equivalent to a larger array with higher signal levels, higher data rate, and better RF coverage than a single array system. This paper explores the phase coherent combining technique to improve spacecraft multiple array communication system coverage and data rate performance without increasing transmit power or array element number and aperture size.

Signal strength maps are computed with array combining for RF coverage and data rate analysis. The computed results validate that significant improvement on signal strength and coverage can be achieved by phase coherent signal combining implementation. At 90% spherical coverage, the signal level increases by 3.5 dB with 2 array signal combining implementation. The system data rate can increase more than double in a 90% coverage area with 2 array signal combining. The signal level increases by 7.5 dB with the 4 array combining implementation. The system data rate can increase more than five times in a 90% coverage area with 4 array phase coherent combining.

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