Wideband Multifunction Array Architectures using Wavelength-Scaled Radiating Elements

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\textbf{Abstract} – There has been a significant increase in developing multifunction wideband arrays to consolidate the large number of narrowband reflector antennas on US Navy ships. However, the use of conventional methods results in a need for an extremely large number of radiating elements to populate these arrays resulting in a complex and costly multifunction array. We propose architectures that use wavelength-scaled arrays in combination with asymmetrical distribution of arrays to reduce the number of radiating elements by more than a factor of two as well as ease bandwidth requirements. Additionally, a combination of rectangular and square apertures is used, where possible to help further reduce the number of simultaneous beams from any section of the full array. These proposed architectures are capable of providing eight different beams from a single wideband multifunction array.

\section{I. INTRODUCTION}

Existing Navy ships use separate antennas for each function resulting in a proliferation of a large number of antennas to meet the numerous functional requirements. There is a significant interest to develop wideband multifunction arrays to reduce the number of separate antennas [1]. However, the number of radiating elements needed to avoid grating lobes at the highest frequency becomes prohibitively large resulting in a complex and costly multifunction array. At the US Naval Research Laboratory, there has been some effort to reduce the number of elements using wavelength scaled arrays [2-4], but the proposed methods have been limited to symmetric (square) arrays or the wavelength scaling factor has been fixed to two, limiting the flexibility of the derived architectures.

The proposed architectures overcome these limitations by using wavelength scaled elements in combination with an asymmetrical distribution of arrays, used for multiple functions, over the largest aperture. This technique reduces the number of radiating elements and hence the cost and complexity of the multifunction arrays. The proposed approach also reduces the number of simultaneous beams from any given part of the aperture, resulting in the use of realizable beamformers [5], and minimizes the bandwidth requirement for both the radiating elements as well as the electronics behind the element.

To illustrate the advantages of the proposed architectures, we will present notional designs for a US Navy aircraft carrier to meet the requirements for satellite communications (SatCom) downlink or receive functions. However, the technique discussed here can be applied to other types of applications. These designs will show how the total number of elements, the maximum number of beams formed from any part of the array aperture as well as the maximum bandwidth of the radiating elements can all be reduced using the proposed architectures. The reduction in the number of radiating elements will result in lower cost and complexity of the multifunction array while a reduction in the number of beams from any part of the aperture will allow the use of realizable chipset beamformers [5].

\section{II. ANTENNA ARCHITECTURES}

A US Navy aircraft carrier uses many satellite communications links including [6]:

- Satellite TV links at both C- and Ku-bands
- Commercial satellite links at C- and Ku-bands
- Military satellite links at UHF-, X- and Ka-bands
- Meteorology and Oceanography (MetOc) satellite links at L- and S-bands

A link is needed to set up a direct path of communication between a shipboard antenna and a satellite. The proposed architectures will provide all of these downlinks except the UHF link. Incorporating a UHF link into the wideband array will result in an impractically large area requirement for the array’s small radiating elements. Thus, it is better to use a separate antenna just for the UHF system. Table 1 lists the frequencies for the eight downlinks that the proposed architectures will provide as well as a notional antenna aperture size needed to satisfy typical directivity requirements for aircraft carrier SatCom applications. The largest aperture size of 25.6 m\textsuperscript{2} is needed by the C-band downlink.
Table 1 Notional Specifications of SatCom Functions Needed on an Aircraft Carrier

<table>
<thead>
<tr>
<th>System</th>
<th>Downlink Frequency (GHz)</th>
<th>Notional Directivity (dB)</th>
<th>Notional Aperture Area (m²)</th>
<th>Maximum Interelement Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>3.7 – 4.2 (C)</td>
<td>47.0</td>
<td>25.6</td>
<td>35.7 × 35.7</td>
</tr>
<tr>
<td></td>
<td>10.7 – 12.75 (Ku)</td>
<td>49.0</td>
<td>5.2</td>
<td>11.8 × 11.8</td>
</tr>
<tr>
<td>TV</td>
<td>4.08 – 4.127 (C)</td>
<td>41.0</td>
<td>5.3</td>
<td>36.3 × 36.3</td>
</tr>
<tr>
<td></td>
<td>12.224 (Ku)</td>
<td>43.0</td>
<td>1.0</td>
<td>12.3 × 12.3</td>
</tr>
<tr>
<td>Military</td>
<td>20.2 – 21.2 (Ka)</td>
<td>52.0</td>
<td>2.9</td>
<td>7.1 × 7.1</td>
</tr>
<tr>
<td></td>
<td>7.25 – 7.75 (X)</td>
<td>46.0</td>
<td>5.2</td>
<td>19.4 × 19.4</td>
</tr>
<tr>
<td>MetOc</td>
<td>1.684 – 1.71 (L)</td>
<td>32.0</td>
<td>3.9</td>
<td>87.7 × 87.7</td>
</tr>
<tr>
<td></td>
<td>2.205 – 2.2535 (S)</td>
<td>34.0</td>
<td>3.6</td>
<td>66.6 × 66.6</td>
</tr>
</tbody>
</table>

For a planar array whose elements are arranged in a rectangular lattice, the maximum interelement spacing for grating-lobe free operation in the two orthogonal planes should be half wavelength at the highest frequency for wide scan angles, or

\[ d_x = d_y = \frac{\lambda}{2} \times \frac{c}{f_H} = \frac{\lambda_H}{2} \]  

where \( c \) is the speed of light (\( = 3 \times 10^8 \) m/s), \( f_H \) is the highest frequency of operation, and \( d_x \) and \( d_y \) represent the maximum interelement spacing in the two orthogonal planes of the array. Table 1 also lists this maximum interelement spacing allowed for each function to ensure that the antenna pattern has grating-lobe free operation over that bandwidth of operation. For example, to operate over the commercial C-band (3.7 – 4.2 GHz), the interelement spacing can be at most 35.7 mm. A smaller interelement spacing will also satisfy the grating-lobe free operation, but more elements will be needed to satisfy the directivity requirements.

A single wideband array designed to operate at all the frequencies listed in Table 1 needs a radiating element that can work from the lowest frequency of 1.684 GHz to the highest frequency of 21.2 GHz. Using Eq. (1), the maximum interelement spacing (calculated from the highest frequency of 21.2 GHz) is \( d_x = d_y = 7.1 \) mm. The bandwidth requirement of this element will be 12.6:1 (\( = \frac{21.2}{1.684} \)). If these 7.1 × 7.1 (mm²) sized elements were used to fill the 25.6 m² C-band aperture, almost 510,000 elements will be needed!!! Such a large number of elements will make this multifunction array so complex and costly as to be impractical. An example of an array using this conventional architecture is shown in Fig. 1. In this architecture, each of the 510,000 elements will be channelized eight ways to generate eight simultaneous beams to satisfy the eight link requirement. Thus the output of each element will need to feed eight separate beamformers, or in other words, the output of each element will feed eight phase shifters, eight attenuators, etc. This extremely large number of components needed to build up this multi-beam architecture further illustrates the complexity and the resulting high cost of a conventional wideband multifunction array.

To reduce the number of elements, we decided to adopt the approach of wavelength scaled radiating elements, previously discussed by Cantrell [2] and demonstrated by Kindt [3-4]. Direct implementation of their approaches was not viable as they had a constraint of equal beamwidth at all frequencies, which is not the case for the SatCom functions considered here. In this paper, we discuss how these approaches were modified to meet the requirements for the SatCom application.

From Table 1, it is observed that the interelement spacing needed at Ka-band (20.2 – 21.2 GHz) is approximately 1/3 the interelement spacing needed at Ku-band (10.7 – 12.75 GHz). Similarly, the interelement spacing needed at Ku-band is about 1/3 the interelement spacing needed at commercial C-band (3.7 – 4.2 GHz). Thus, an array with interelement spacing designed for Ku-band can provide grating-lobe free operation at all frequencies below 12.75 GHz. Likewise, an array designed with interelement spacing at C-band will provide grating-lobe free operation at all frequencies below 4.2 GHz. Following
the method discussed in [3-4] strictly, we must maintain symmetry in the array aperture by placing the array ("core") with the smallest interelement spacing (for the highest frequency) at one corner of the multifunction aperture followed by forming a layer or array around this core of the next larger interelement spacing and finally the outermost layer or array will have the largest interelement spacing. This architecture is shown in Fig. 2.

Figure 2 shows the interelement spacing for the different sections of the array aperture. The core has the elements with the smallest interelement spacing of \( x = \frac{11.8 \text{ mm}}{2} = 5.9 \text{ mm} \) (from Table 1), followed by the second perimeter having interelement spacing of \( 2x \). Finally the outermost region will have interelement spacing of \( 6x \). Note that the interelement spacing is assumed to be the same in the two orthogonal directions per Kindt [3-4]. The value of 5.9 mm was chosen over the maximum allowed interelement spacing of 7.1 mm for Ka-band because we wanted to maintain the interelement spacings of the different regions to be integer multiples of the interelement spacing in the core per Kindt [3-4].

If the core has an interelement spacing of 7.1 mm, then a multiple of two will make the interelement spacing of the next layer equal to 14.2 mm, which is greater than the required interelement spacing of 11.8 mm. Using 14.2 mm will result in grating-lobe formation at frequencies greater than 10.6 GHz (Ku-band). On the other hand, using the smallest whole number ratio of two between the interelement spacing of the middle layer and the outer layer will result in interelement spacing of \( 2 \times 2 \times 7.1 \text{ mm} = 28.8 \text{ mm} \), which is smaller than the needed 35.7 mm. There will be no grating-lobe if 35.7 mm is used, but filling an aperture with smaller than needed elements will result in a larger number of elements to satisfy the directivity requirements. To avoid these issues, the interelement spacing of 11.8 mm was chosen as the basis with the core area having a spacing reduced by half (i.e. 5.9 mm) and the outermost layer having a spacing that is three times as large (i.e. 35.4 mm).

Since the area required to satisfy the directivity of TV Ku-band function is smaller than the area of the Ka-band, it is better to use a portion of the Ka-band array region for TV Ku-band. If the entire Ka-band array were to be used for the TV-Ku function then more directivity than needed will be obtained (providing design margin), and at the same time more phase shifters, attenuators and other beamforming components will also be needed making the system unnecessarily complex and costly. A similar reasoning allowed the L- and S-band arrays to be smaller than the X/Ku/TV-C-band arrays.

Using the wavelength-scaled approach allowed us to reduce the number of elements for this multifunction array significantly. The number of elements needed for the architecture shown in Fig. 2 is only 116,110 compared to the 510,000 elements needed in the architecture in Fig. 1. This is a 77% decrease in the number of radiating elements needed. However, one of the difficulties in implementing this architecture is that the radiating elements in the core region still need a bandwidth of 12.6:1, which is very difficult to obtain. Another issue is that the core of this architecture needs to form eight links (or beams) simultaneously. At present there are no simple and cost-effective beamforming techniques capable of forming eight simultaneous beams at element spacing of 5.9 mm! Emergent beamforming technology is capable of providing a maximum of four simultaneous beams [5]. Still another drawback is the fact that the low frequency links at L- and S-bands, which are able to provide grating-lobe free operation even at much larger interelement spacings of 87.7 mm and 66.6 mm, respectively, are forced to use smaller elements and interelement spacings of 5.9 mm and 11.8 mm. This significantly increases the number of elements needed and thus the number of components at these frequencies, thereby increasing the cost and complexity of the array. At the same time, there is a large portion of the array that supports only one link (at C-band), while a small corner of the array is forced to provide eight links!!
Our approach overcomes all these limitations while still using the wavelength-scaled elements to reduce the total number of radiating elements. From Table 1, the required interelement spacing for L-, S- and TV C-bands to provide grating-lobe free operation is larger than the interelement spacing needed for commercial C-band. So, L-, S- and TV C-bands can use the same interelement spacing as commercial C-band and still provide grating-lobe free operation. Thus, by breaking the symmetry of the C-band aperture and dispersing the low frequency arrays (L-, S- and TV-C bands) over the commercial C-band aperture, it is possible to reduce the number of links needed from any region of the full aperture. Figure 3 shows this architecture. Comparing Figs. 2 and 3, the maximum number of links needed from any section of the array is reduced from eight to only five!! In additional, the largest bandwidth requirement from any region of the array is reduced to only 5.7 \((\frac{2.12}{3.7}) : 1\) from 12.6:1. Designing radiating elements to operate over a bandwidth of 5.7:1 is feasible while designs to obtain bandwidth of 12.6:1 are difficult. As the wavelength scaling of the elements has not changed, no more elements are needed as we move from the architecture in Fig. 2 to the architecture in Fig. 3.

It turns out that with this change, the width of this new area is now as large as the area needed by the TV Ku-band array to satisfy its directivity requirement. Also, since the interelement spacing of 2x is less than 12.3 mm, which is the required spacing by the TV Ku-band for grating-lobe free operation, this area with the larger interelement spacing can be used to provide the TV Ku-band function. This change allows a further reduction in the maximum number of links needed from any section of the aperture from five to only four without any increase in the number of elements. This new architecture now allows us to use current beamforming techniques to support the beamforming requirements of this multifunction array. Additionally, fewer components will now be necessary to implement the beamformer at TV Ku-band. Any reduction in the number of components means a cost reduction and is thus desirable.

The southwest corner of the full aperture in Fig. 4 provides only one link — the commercial C-band link. By separating both the Ka-band and TV Ku-band array regions from the X- and Ku-band array regions as shown in Fig. 5, it is possible to reduce the maximum number of links needed from any region of the aperture to only three, which may reduce the cost and complexity while improving the performance of the beamformer. However, this architecture results in an increase in the total number of elements from 116,110 to 135,260 (about a 16% increase). So Architecture 2 should be chosen if a smaller number of elements are more important, and Architecture 3 should be chosen if a smaller number of links from any region is more important.
Fig. 5 Architecture of a Multifunction Aperture (Architecture 3) for an Aircraft Carrier using the Proposed Approach with Rearranged Square/Rectangular Array Regions, $x = 5.9$ mm

III. SUMMARY

In this paper, we presented new architectures for a wideband multifunction array for satellite communication downlink used on an aircraft carrier. The proposed architectures used wavelength-scaled radiating elements to reduce the number of elements significantly. In addition, a combination of rectangular and square apertures was used where possible to help further reduce the number of links. The individual apertures were dispersed over the largest aperture to reduce the number of simultaneous links from any given region of the aperture. An added advantage of this proposed method is the reduction in bandwidth requirement for the radiating elements.

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REFERENCE