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Affordable Wideband Multifunction Phased Array Antenna Architectures Using Frequency Scaled Radiating Elements

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14. ABSTRACT

The existing Navy ships use a separate antenna for each function, resulting in proliferation of a large number of antennas on ships to meet the numerous functional requirements. Recently, wideband phased array antennas are being developed that can perform multiple functions simultaneously to reduce the number of antennas on ships. However, the number of radiating elements needed is prohibitively large, resulting in a complex and costly multifunction phased array antenna. This report discusses novel architectures that can consolidate many functions into a single wideband phased array antenna and at the same time reduce the total number of elements needed, thereby reducing the size, weight, power, and cost compared to a conventional wideband phased array architecture. Besides the number of elements, the number of simultaneous links and element bandwidth requirements are also optimized in an effort to optimize both cost and complexity.

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Contents

1. Introduction

Existing Navy ships use a separate antenna for each function resulting in a proliferation of a large number of antennas to meet the numerous functional requirements. Recently, there is a significant interest to develop multi-function arrays using a single wideband antenna [1]. However, the number of radiating elements needed to avoid grating lobes, at the highest frequency of this wideband antenna, becomes prohibitively large resulting in a complex and costly multi-function array. There is some effort to reduce the number of elements using wavelength scaled arrays [2, 3, 4]but the proposed methods are limited to symmetric and/or square arrays. In one case, the operating frequencies are chosen to be a factor of two apart, limiting the flexibility of the derived architectures.

The proposed approach overcomes these limitations, while still using wavelength scaled elements, (i.e. the inter-element spacing of the radiating elements in the array are scaled as a function of frequency), to reduce the number of radiating elements, and hence the cost and complexity of the multi-function arrays. Our approach also reduces the required number of beams (or links) from any given part of the aperture and minimizes the bandwidth requirement for both the radiating elements and the electronics behind them. To illustrate the advantages of the proposed approach, we will consider the aperture designs which meet the requirements for satellite communications (SatCom) on downlink for future Navy ships. A future study will consider these techniques for the uplink SatCom. We will consider two types of ships – the first one is an aircraft carrier and the second on is a surface combatant (e.g. destroyer, cruiser).

In what follows, we will discuss how by using a combination of wavelength scaled elements as well as asymmetrical distribution of the various function array apertures over the largest aperture, we are able to reduce the total number of elements in the aperture, the maximum number of beams formed from any part of the total array aperture as well as the maximum bandwidth of an arrray radiating element. The reduction in the total number of elements will result in lower cost and complexity of the multi-function array while a reduction in the number of beamf rom any part of the aperture will result in the use of realizable chipset beamformers [5] as well as a decrease in the required bandwidth of the array elements. We will look at the more complex case of an aircraft carrier before finishing the report with a surface combatant.

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2. Aircraft Carrier Antenna Architectures

Any future US Navy aircraft carrier class ship is expected to have the following link requirements. A link is needed to set up a direct path of communication between a shipboard antenna and a satellite. An aircraft carrier needs to have links for the following functions:

- TV-links at both C and Ku-bands
- Commercial links at C and Ku-bands
- Navy links at X and K-band, and
- Navy MetOc (Meteorological and Oceanographic) links at L and S-bands

Table 1 lists the frequencies of interest as well as the antenna aperture size required to satisfy typical directivity requirements. From Table 1 it can be seen that the C-band function requires the largest aperture size of 25.6m^2. All SatCom frequencies include a downlink at UHF frequency between 225 – 400 MHz. However, incorporating a UHF link into the wideband array will result in an impractically large requirement for the array radiating elements. Thus, it is better to use a separate antenna just for the UHF system.

Table 1: Specifications of SatCom functions needed on an aircraft carrier

System	**Downlink Frequency (GHz)**	**Directivity (dB)**	**Aperture Size (m^2)**	**Maximum Inter-Element Spacing (mm) $d_x \times d_y$**
Commercial	3.7-4.2 (C)	47.0	25.6	35.7×35.7
	10.7-12.75 (Ku)	49.0	5.2	11.8×11.8
TV	4.08-4.127 (C)	41.0	5.3	36.3×36.3
	12.224 (Ku)	43.0	1.0	12.3×12.3
Navy	20.2-21.2 (K)	52.0	2.9	7.1×7.1
	7.25-7.75 (X)	46.0	5.2	19.4×19.4
MetOc	1.684-1.71 (L)	32.0	3.9	87.7×87.7
	2.205-2.2535 (S)	34.0	3.6	66.6×66.6

For a rectangular lattice [6], the inter-element spacing for grating lobe free operation in the two orthogonal planes can be calculated using Eq. (1):

$$d_x = d_y = \frac{1}{2} \times \frac{c}{f_{highest}}$$

(1)

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

Eq. (1) above assumes that the radiating element is able to $\pm 90^o$. When the element scanning is limited to less than $\pm 90^o$, then Eq. (2) can be used to determine the inter-element spacing.

$$d_x = d_y = \frac{\frac{c}{f_{highest}}}{1 + \sin\theta}$$

(2)

In Eq. (2), θ is the maximum scan angle of the antenna. Limiting the scan requirements of the element allows the inter-element spacing to be greater than Eq. (1). Using larger elements to populate a given array size can help reduce the number of elements. The only disadvantage is that the array no longer has grating lobe free operation over $\pm 90^o$. For example, if elements with inter-element spacing of $35.7 \times 35.7\, mm^2$ at commercial C-band are used to populate a 25.6m^2 array then about 20,000 elements will be needed. However, now if the scan requirements of the element were limited to only 40° then using Eq. (2), the inter-element spacing will increase to $40.4 \times 40.4\, mm^2$ and this will help reduce the number of elements populating the array to ~15,000 which is almost a 25% reduction in the number of elements. However, in this report, we will only look at cases that use elements whose inter-element spacings are derived using Eq. (1).

If it is desired that a single aperture be designed to handle all the frequencies listed in Table 1, then the radiating element used in the aperture will need to work from the lowest frequency of 1.684 GHz to the highest frequency of 21.2 GHz. Using Eq. (1), the maximum inter-element spacing in this case will depend on the highest frequency, which is 21.2 GHz and will equal to $d_x = d_y = 7.1\ mm$. This element will need to operate over a bandwidth of 12.6:1 $(= \frac{21.2}{1.684} : 1)$. If elements of dimensions 7.1 $\times$ 7.1 (mm^2) were to be used to fill the largest array aperture of 25.6 m^2 required to satisfy the directivity of commercial C-band, then almost 510,000 elements will be needed!! Such a large number of elements will make this multi-function array so complex and costly, as to be impractical.

In a conventional architecture as illustrated in Fig. 1, an element is channelized for each link that needs to be formed. In this example, eight links are needed, 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 form this multi-beam architecture further illustrates the complexity and high cost of a conventional multi-function array with a very wide bandwidth (greater than 10:1).

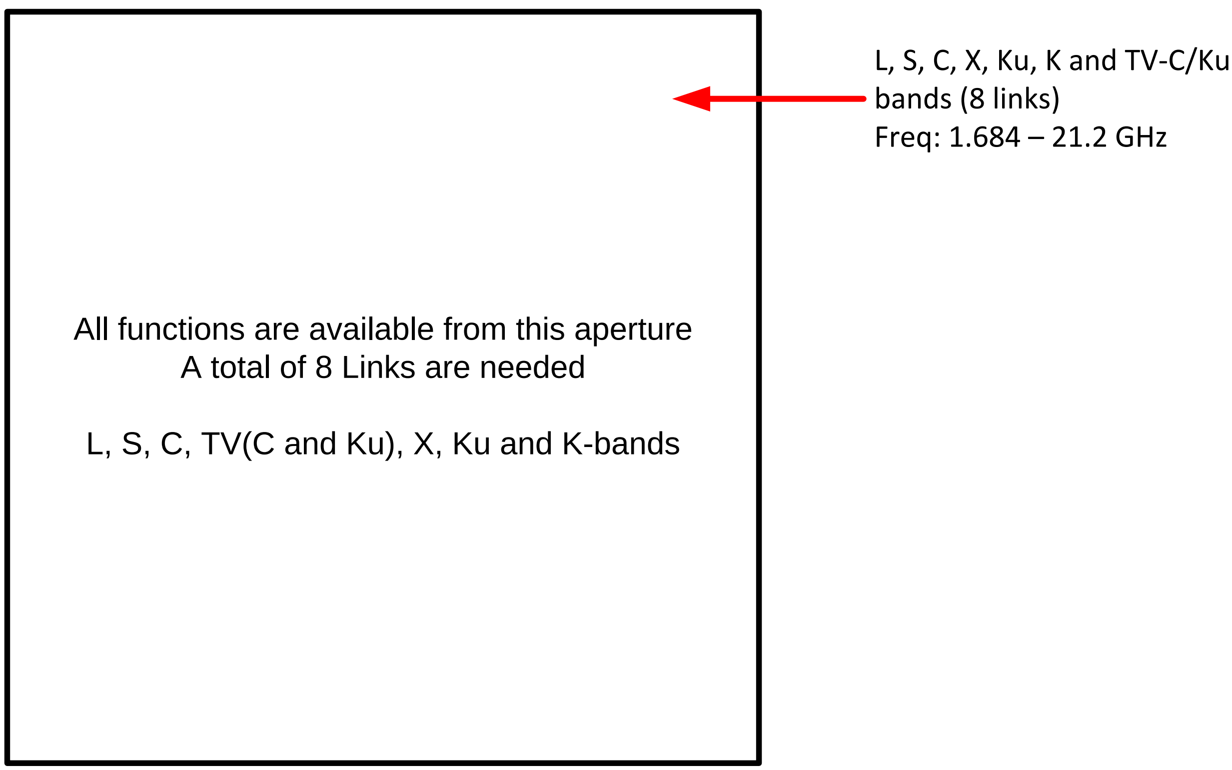

Figure 1: Architecture of a multi-function aperture using conventional methods

In an attempt to reduce the number of elements, we decided to adopt the approach of wavelength scaled radiating elements which has been previously discussed by Cantrell, and demonstrated by Kindt [2, 3]. However, these earlier methods could not be used directly because of the constraint that requires equal beamwidth at all frequencies, which is not the case for the functions considered here. However, we will first apply the procedure of wavelength scaling as used by Kindt and show how this approach can be modified for the problem at hand.

From Table 1, it can be observed that the inter-element spacing needed at K-band (20.2 – 21.2 GHz) is approximated ½ the size of the inter-element spacing needed at Ku-band (10.7 – 12.75 GHz). Similarly, the inter-element spacing needed at Ku-band is about $\frac{1}{3}$ the inter-element spacing needed at commercial C-band (3.7 – 4.2 GHz). The inter-element spacings needed at the other frequency bands lie somewhere between the two values. This means that an array with inter-element spacing designed for Ku-band can provide grating lobe free operation at all frequencies below 12.75 GHz. In a similar way, an array designed with inter-element spacing at C-band will provide grating lobe free operation at all frequencies below 4.2 GHz. Now, if we strictly follow the method discussed in Ref. [3, 4], we have to maintain symmetry in the array aperture. To maintain this symmetry we either put the array with the smallest inter-element spacing (for the highest frequency) at the center or at one corner of the multi-function aperture. In the example, shown in Fig. 2, we chose to place the array with the smallest inter-element spacing (also referred to as the core) in the south-east corner of the largest array (in this case the commercial C-band array). Next the array designed to have the next larger inter-element spacing forms a layer around the perimeter of the core. Finally the outer-most layer will have the largest inter-element spacing.

Figure 2 shows the inter-element spacings used for different sections of the array aperture. The core will have elements with the smallest inter-element spacing (i.e. $x \times x$) where from Table 1, $x = \frac{11.8mm}{2} = 5.9$ mm followed by the second perimeter having inter-element spacing of $2x \times 2x$. Finally, the outer-most region will have inter-element spacing of $6x \times 6x$. The value of 5.9mm is chosen over the maximum allowed inter-element spacing of 7.1mm for K-band because we want to keep whole number multiples between the inter-element spacings of the different regions as suggested by the designs in Ref. [3,4]. If the core has an inter-element spacing of 7.1mm, then with a multiple of two, the inter-element spacing of the next outer layer will need to be 14.2mm. This inter-element spacing will ensure no grating lobe formation for X-band and other lower frequencies. However, at Ku-band, this inter-element spacing is larger than the maximum allowed of 11.8mm for grating free lobe operation and hence will result in the formation of grating lobes. By the same argument, using whole number ratio of two between the inter-element spacing of the middle layer and the outer layer, the outer most layer will have an inter-element spacing of

$2 \times 2 \times 7.1$mm = 28.8mm, which is smaller than the needed 35.7 mm. A smaller inter-element spacing will result in the need for more elements to satisfy the directivity requirements. To avoid this, we decided to choose the inter-element spacing of 11.8mm of the middle layer as the basis. This means that now the inter-element spacing in the core will be half of 11.8 mm (i.e. 5.9 mm) while the inter-element spacing in the outer most layer will be three times 11.8 mm (i.e. 35.4 mm).

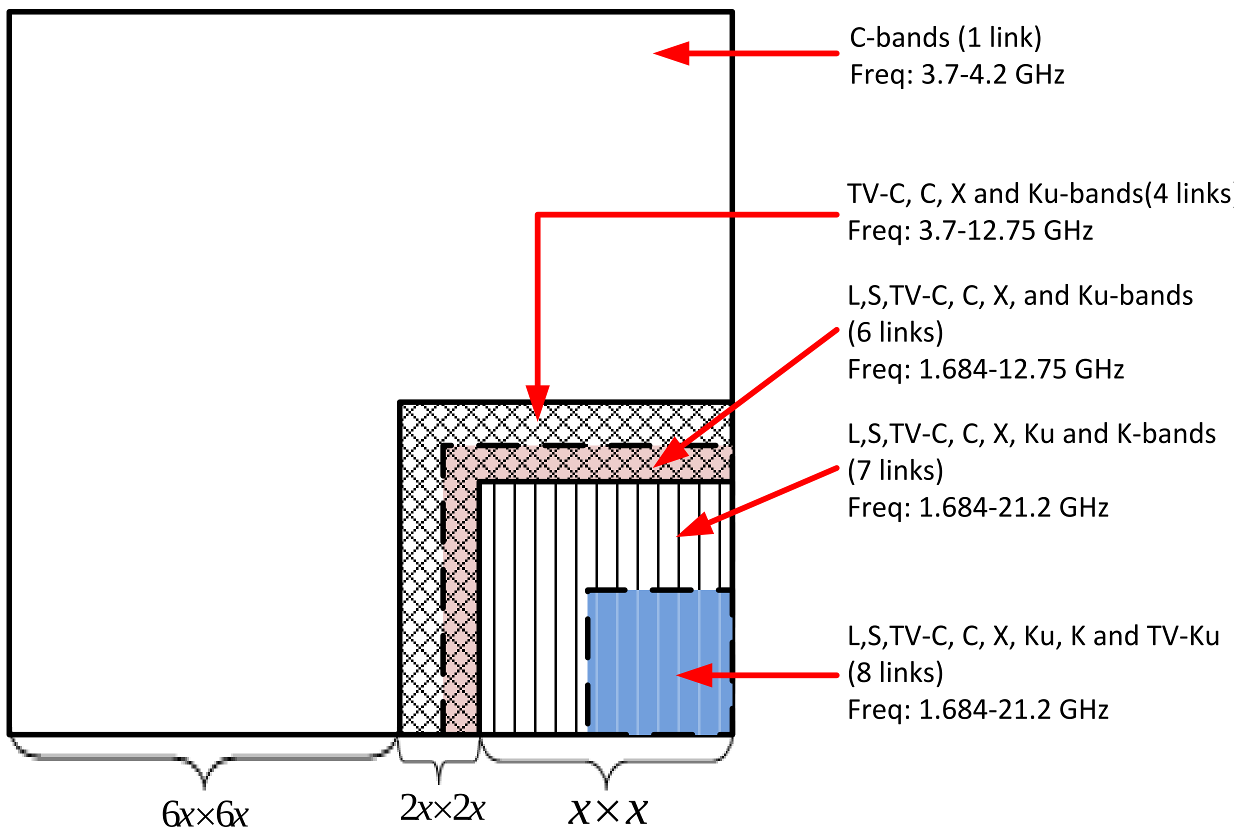

Figure 2: Architecture of a multi-function aperture using wavelength scaling per Kindt [3, 4] (x = 5.9 mm)

Since the core has the elements with the smallest inter-element spacing, reducing this spacing will result in a significant increase in the number of elements needed to satisfy the directivity requirement. To avoid this, we will also look at fractional ratios between the inter-element spacings of the different arrays. This will be discussed in more detail later in this section.

As an aside, an array with fractional ratios between the inter-element spacings has not yet been demonstrated and Kindt [3, 4] considered ratios of inter-element spacings to be powers of two to minimize the number of discontinuities. However, their numerical simulations actually indicated that the effect of discontinuities is insignificant strengthening the view of the authors that the discontinuities will be insignificant for non-integer ratios. In fact, in the architecture proposed by Cantrell [2], the inter layer ratios are all non-integers. More simulations should prove this insignificance, but a detailed discussion on the effect of discontinuities on the overall array pattern is not a part of this report.

Note, that since the area required to satisfy the directivity of TV Ku-band function is smaller than the area of the K-band ($x \times x$ region in Fig. 2), it is better to use only a portion of the K-band array region. If the entire region were to be used, then more directivity than needed will be obtained, which provides design margin, but at the same time more phase shifters, attenuators and other components would also be needed. This will make the system unnecessarily complex and costly. A similar reasoning can be used for the L- and S-band array regions which are smaller than the X/Ku/TV-C-band array regions.

By using the architecture where the inter-element spacings are wavelength scaled, it is possible to reduce the number of elements significantly. Using wavelength scaled architectures, as shown in Fig. 2; the total number of elements are reduced from 510,000 to only 116,110, which is almost a 77% decrease in the number of elements needed to form 8 beams. One of the difficulties in implementing this architecture is that the radiating elements in the core region need to have a bandwidth of 12.6:1, which is very difficult to achieve. Another issue is that the core of this architecture needs to be able to form eight links (or eight beams) simultaneously. At present there are no simple and cost effective beamforming techniques that are capable of forming eight simultaneous beams with very small element spacing (5.9 mm) needed for this design. Emergent beamforming technology is capable of providing a maximum of four simultaneous beams [5]. Still another point of concern is the fact that low frequency links at L- and S-bands which are able to provide grating lobe free operation even at large inter-element spacings (87.7 mm and 66.6 mm respectively) are forced to use much smaller elements and inter-element spacings. This significantly increases the number of elements needed at these frequencies and hence also increases the number of components needed, increasing the cost and complexity of the array. At the same time, there is a large portion of the array (C-band region) that supports only one link, while a small corner of the array is forces to provide eight links!!

Our approach overcomes these limitations, while still using wavelength scaled elements to reduce the total number of radiating elements. Our approach also reduces the required number of links from any given region of the aperture and at the same time reduces the bandwidth requirement for the radiating elements by judiciously dispersing the smaller apertures over the larger aperture, as will be discussed next.

From Table 1, we can see that for L- and S-bands as well as for the TV-C link, the inter-element spacing needed from grating-lobe free operation is larger than the inter-element spacing needed for commercial C-band. This means that the functions at these frequencies will be able to operate with grating lobe free operation with commercial C-band inter-element spacing. 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 region, it is possible to reduce the number of links needed from any region of the full aperture. This is shown in Fig. 3. Comparing Fig. 2 with Fig. 3, it is seen that now the maximum number of links needed from any section of the array is reduced from eight to only five! In addition, the largest bandwidth requirement from any region of the array is reduced to 5.7 ($=\frac{21.2}{3.7}$):1 from 12.6 ($=\frac{21.2}{1.684}$):1 for Fig. 2. Designing antenna elements to operate over a bandwidth of 5.7:1 is feasible but designs to obtain bandwidth of 12.6:1 are difficult. Since, the wavelength scaling of the elements is the same in the two architectures, no more elements than that in Fig. 2 are needed in Fig. 3.

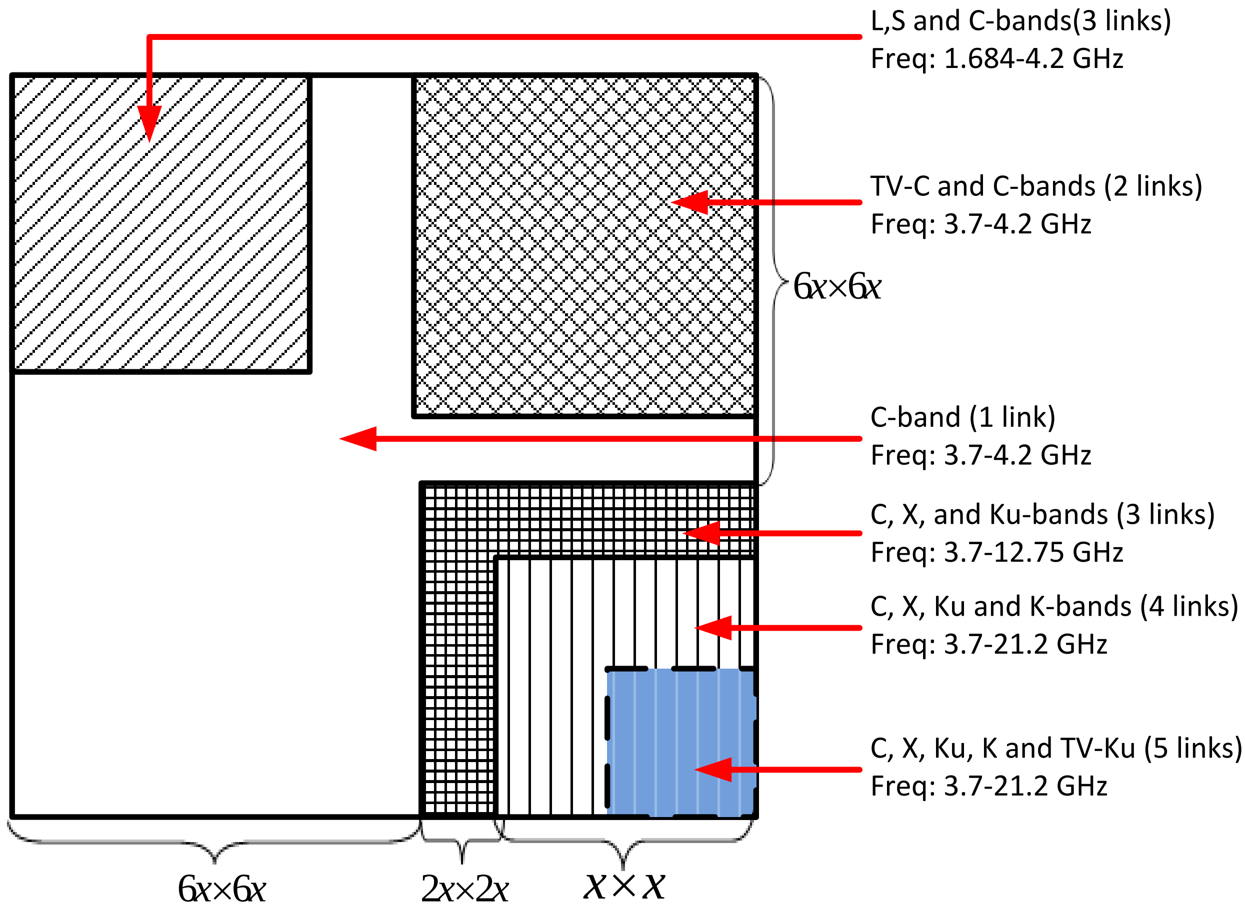

Figure 3: Architecture of a multi-function aperture (Architecture 1) for an aircraft carrier using the proposed approach with square shaped individual array regions, x = 5.9mm

So far, in all the architectures that have been considered, the arrays have had a square shape. A square shaped array has equal beamwidth in both the horizontal and vertical planes. For SatCom applications, for which this array is being designed, there is no requirement for the two orthogonal beamwidths to be equal. Hence, the arrays can be rectangular in shape. In Fig. 4, the array used for the X- and Ku-band functions is made longer in its width compared to its height. By making this alteration, the area with the inter-element spacing of $2x \times 2x$ is now at the side of the area with inter-element spacing of $x \times x$ (see Fig. 4). 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 array region to satisfy the directivity requirement. Also, the inter-element spacing of $2x$ is less than 12.3 mm is needed by the TV-Ku array for grating-lobe free operation. So, the area with the larger inter-element spacing can easily be used to provide the TV-Ku function. By making this change, it is now possible to further reduce the maximum number of links needed from any section of the aperture from five to four. As mentioned earlier, present beamforming techniques are available to support four simultaneous beams from a single region of the array [5]. Another benefit is the fact that fewer components will now be necessary to implement the beamformer at TV-Ku. In addition, the total number of elements needed for Architecture 2 is the same as that for Architecture 1.

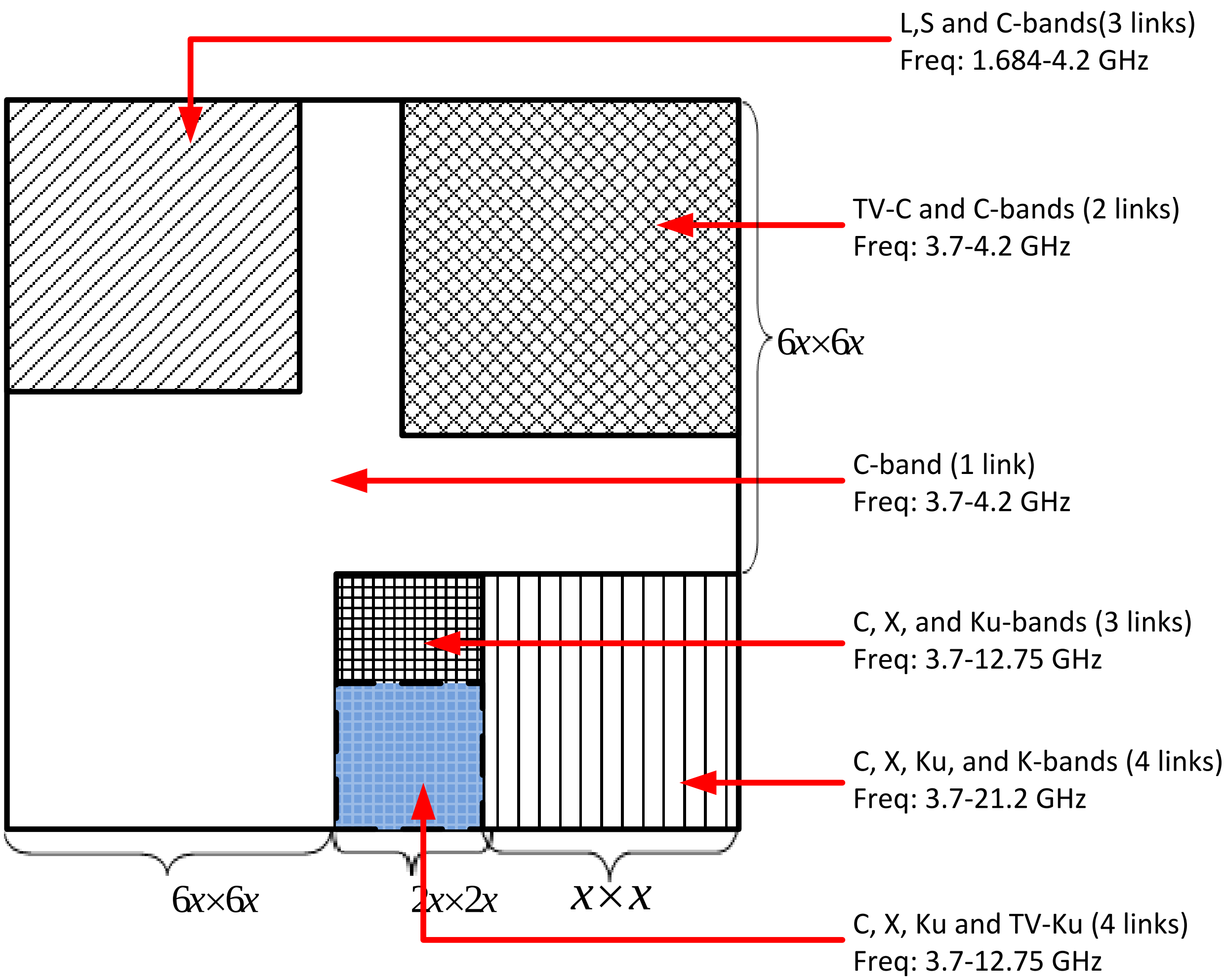

Figure 4: Architecture of a multi-function aperture (Architecture 2) for an aircraft carrier using the proposed approach using both square and rectangular individual array regions, x = 5.9mm

Finally, it is observed that the south-west corner of the C-band array in Fig. 4 provides only one link. By separating both the K-band and TV-Ku 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. 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 lower number of elements are more important and Architecture 3 should be chosen if a lower number of links from any region of the aperture is more important.

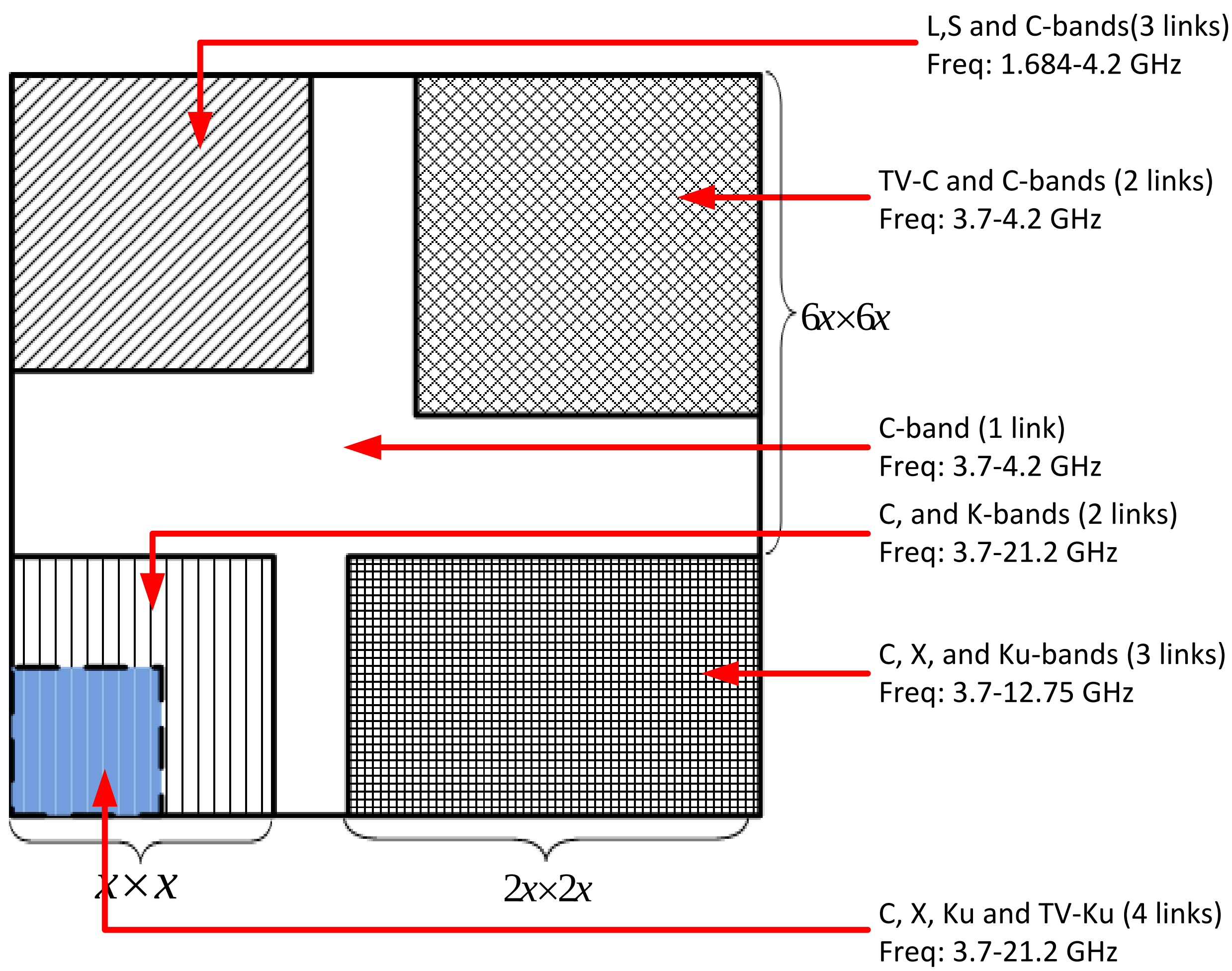

Figure 5: Architecture of a multi-function aperture (Architecture 3) for an aircraft carrier using the proposed approach with re-arranged individual square/rectangular array regions, x = 5.9mm

So far, we have worked within the constraint that the ratios of the inter-element spacings between the different arrays is always a whole number. But as mentioned earlier, by removing this constraint, it is possible to reduce the number of elements further. In fact, if we take the architecture shown in Fig. 4 (Architecture 2) and change the ratios to those shown in Fig. 6, whereby the inter-element spacing of the elements in the core is $x \times x$ with x equal to 7.1mm, the inter-element spacing of the middle perimeter (i.e. the arrays providing the X-, Ku- and TV-Ku links) is $1.5x \times 1.5x$ and finally the inter-element spacing in the remaining largest array region is

$4.5x \times 4.5x$, then it is possible to reduce the total number of elements from 116,110 to 97,810 which is almost a 16% reduction in the total number of elements. This reduction in total number of elements comes from the fact that inter-element spacing for K-band array region (x) in increased from 5.9mm used in the architecture of Fig. 4 to 7.1mm used in the architecture shown in Fig. 6.

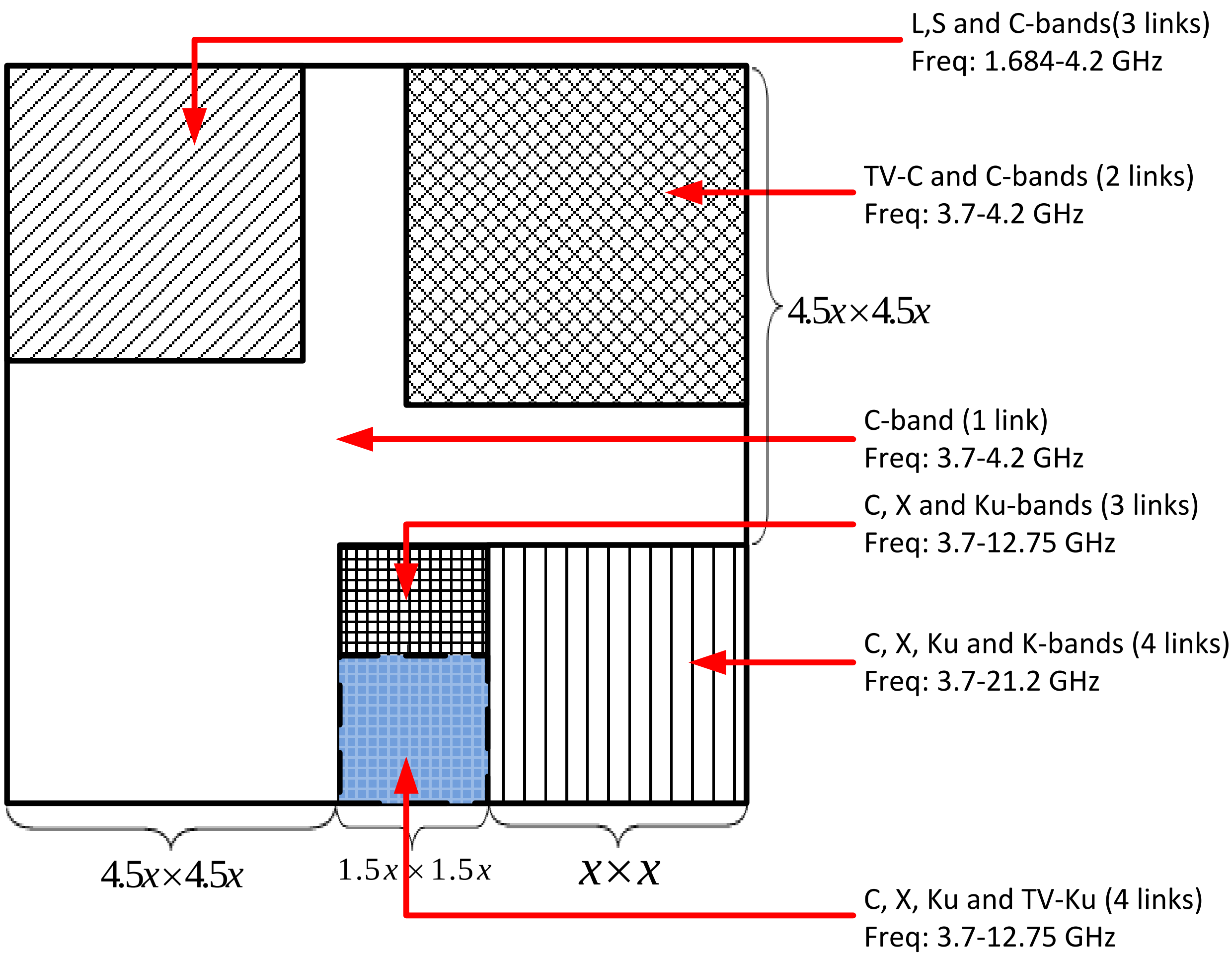

Figure 6: Architecture of a multi-function aperture for an aircraft carrier (Architecture 4) using array regions that have inter-element spacing of x, $1.5x$ and $4.5x$, x = 7.1mm

Table 2 shows the elements needed by C-, Ku- and K-band array regions with the inter-element spacings used for the architectures shown in Figs. 4 and 6. The other frequencies are not a concern since C, Ku and K-bands set the inter-element spacings. From Table 2, it is observed that by increasing the inter-element spacing in the K-band core region from 5.9mm to 7.1mm, it is possible to reduce the number of elements in the K-band array from 83,310 to 57,530. However, a smaller ratio for the middle and outer layers (i.e. $1.5x$ and $4.5x$ compared to $2x$ and $6x$) means that now the inter-element spacings of elements at Ku- and C-band is smaller than the respective maximum values of 11.8mm and 35.7mm, hence these arrays will need more elements to satisfy the directivity requirements of these links. Notice the increase in the number of elements from 16,280 to 20,000 for C-band and from 16,250 to 20,280 for Ku-band. In summary, finding the proper ratio of the inter-element spacings between the array regions is an optimization process and is chosen such that the total number of elements in the multi-function aperture is the smallest while at the same time the discontinuities between the interfaces of the array regions are not numerous. In this example, using the smaller ratios actually reduced the number of elements by almost 16%.

Table 2: Number of elements for different array regions based on chosen inter-element spacings

Array	Architecture 2 (x = 5.9mm)	Architecture 4 (x=7.1mm)
C-band	16,280	20,000
Ku-band	16,520	20,280
K-band	83,310	57,530
Total Elements	116,110	97,810

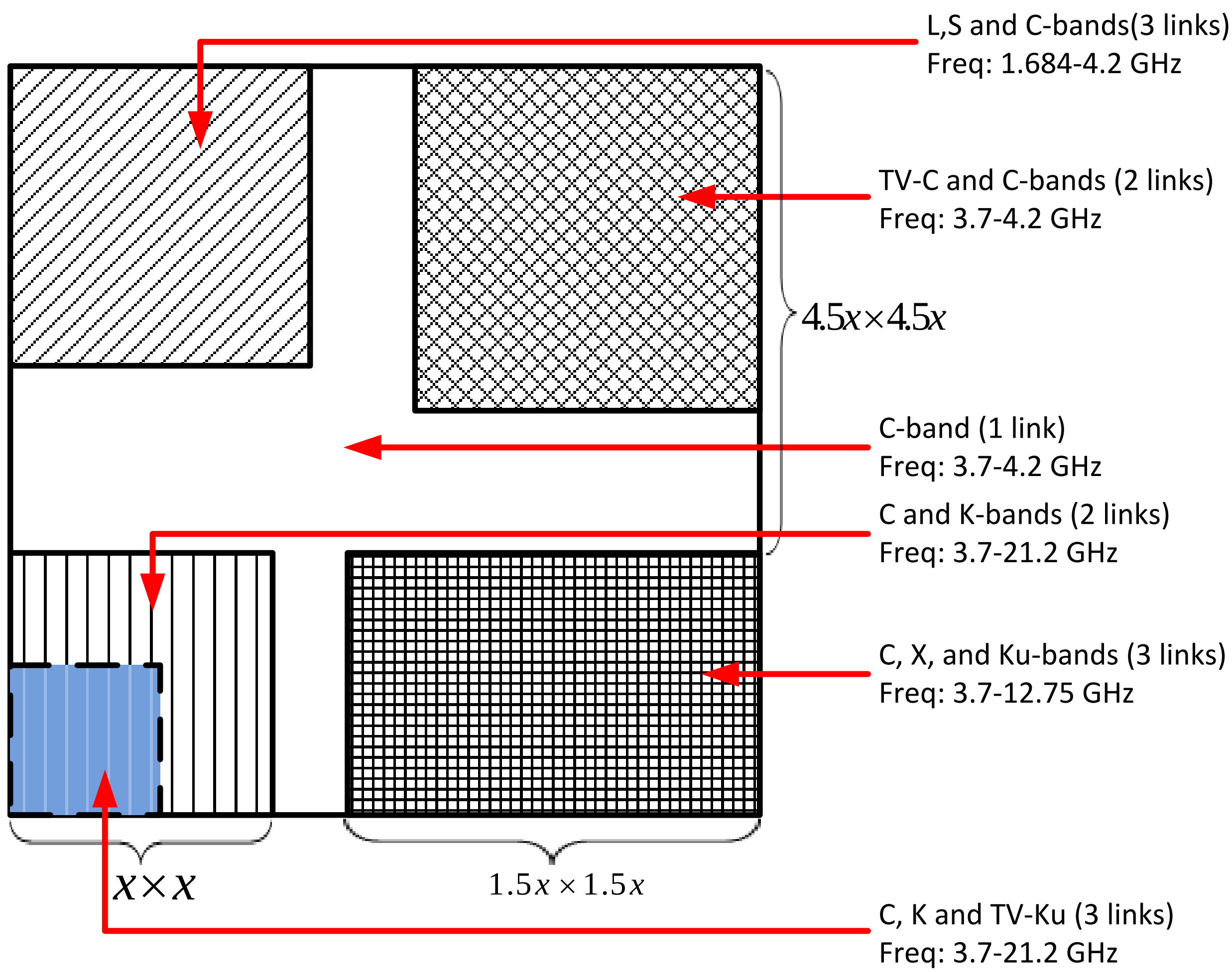

Figure 7: Architecture of a multi-function aperture for an aircraft carrier (Architecture 5) using array regions that have inter-element spacing of x, $1.5x$ and $4.5x$, x = 7.1mm

Finally, Fig. 7 shows a similar architecture to Fig. 5, except that now x = 7.1mm and the ratios are x, $1.5x$ and $4.5x$. In this architecture, the total number of elements is 120,530 which is a 23% increase over the number of elements in Architecture 4 (shown in Fig. 6) and a 3.8% increase over the number of elements needed in Architecture 2 (shown in Fig. 2). The highest number of links required by any region of the multi-band array is three. Therefore, this architecture needs to be considered only when the reduction of the number of links is more important that the reduction in the number of elements.

In summary, Fig. 6 represents an optimum architecture of a wideband multi-function array for SatCom downlink aboard an aircraft carrier. Here, we used wavelength scaled radiating elements, with scaling ratios of 1.5 and its multiples, to reduce the number of elements significantly. The individual apertures are dispersed over the largest aperture to reduce the number of simultaneous links from any given region of the aperture as well as to reduce the bandwidth requirement for the radiating elements. In addition, rectangular, instead of square apertures, are used where possible and advantageous in helping to reduce the number of links and the bandwidth requirement that any individual radiating element must support.

3. Surface Combatant Antenna Architectures

The surface combatant (e.g. destroyer, cruiser etc.) is another class of Navy ship that could benefit from the use of a wideband multi-function array for SatCom downlink. The specifications necessary to support these SatCom downlinks is similar but not exactly the same as what is needed for an aircraft carrier. Table 3 lists the specifications.

Table 3: Specifications for functions needed on a surface combat

System	Downlink Frequency (GHz)	Directivity (dB)	Aperture Size (m^2)	Maximum Inter-Element Spacing $d_x \times d_y$ (mm)
Commercial	10.7-12.75 (Ku)	49.0	5.2	11.8 × 11.8
TV-Links at C and Ku bands	4.08-4.127 (C)	41.0	5.3	36.3 × 36.3
	12.224 (Ku)	43.0	1.0	12.3 × 12.3
Navy	20.2-21.2 (K)	52.0	2.9	7.1 × 7.1
	7.25-7.75 (X)	46.0	5.2	19.4 × 19.4

The biggest difference between a surface combatant and aircraft carrier SatCom antenna architectures is the fact that the following functions are not necessary for a surface combatant:

(1) Commercial C-band
(2) MetOc L- and,
(3) MetOc S-band

The lowest downlink frequency (excluding UHF) then for the surface combatant is 4.08 GHz (for TV-C) and the highest is 21.2 GHz (K-band) which means that the largest bandwidth required from any region of the array would be 5.2:1. The maximum number of links is five. If all the elements were spaced at $\lambda/2$ at the highest frequency over the largest aperture of 5.2 m^2, then a total of

$\left(\frac{5.3m^2}{\left(0.5\times\frac{10^8}{21.2\ GHz}\right)}\right) \cong 106{,}000$ elements will be needed each requiring a bandwidth of 5.2:1. As mentioned earlier, by reducing scan requirements, it is possible to increase the inter-element spacing of the elements and thus reduce the total number of elements populating the array.

As before, it is possible to reduce the number of elements by using the concept of wavelength scaling. Figure 8 shows the layout. The core of this architecture will have elements with inter-element spacing of $x \times x$, where from Table 3 $x = \frac{11.8mm}{2} = 5.9$ mm. The value of 5.9mm is chosen over 7.1 mm because we want to keep whole number multiples between the inter-element spacings of the different regions as suggested by the designs in [3]. If the core has an inter-element spacing of 7.1 mm, then with a multiple of two, the inter-element spacing of the outer layer will be 14.2 mm. This inter-element spacing will ensure no grating lobe formation for C and X-bands. However, at Ku-band, this inter-element spacing is larger than the needed 11.8 mm and hence will result in grating lobe formation. To avoid this, we decided to choose 11.8mm as the basis inter-element spacing. Following this, it means that the inter-element spacing of the core will need to be 5.9 mm. However, using a smaller inter-element spacing in the core than the maximum allowed (7.1 mm) means that more elements will be needed to satisfy the directivity requirements.

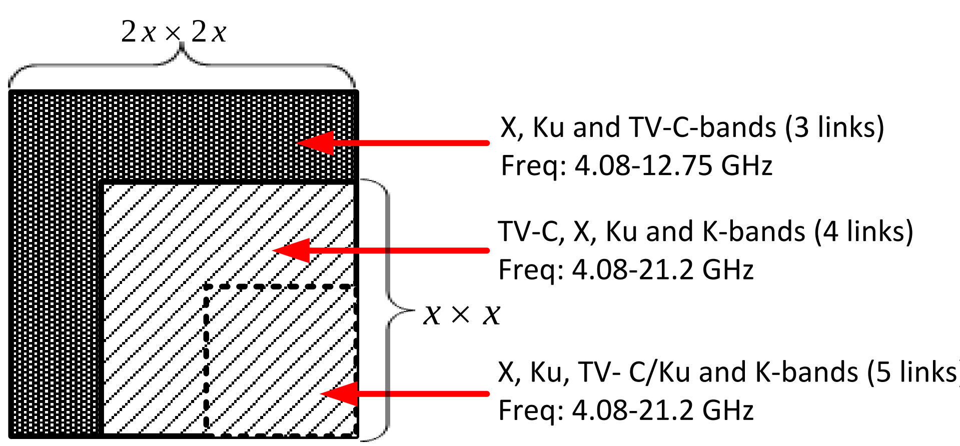

Figure 8: Architecture of a multi-function aperture for a surface combatant using wavelength scaling per Kindt [3], x = 5.9 mm

The bandwidth requirement for the elements in the core is $\left(\frac{21.2\ GHz}{4.08\ GHz}\right) = 5.2 : 1$ while the bandwidth requirement from the outer layer will only be $\left(\frac{12.75}{4.08}\right) = 3.125 : 1$. By using wavelength scaled approach (use inter-element spacing of 5.9 mm in the core region and inter-element spacing of 11.8 mm in the outer layer region), the total number of elements will be reduced from 106,000 to 100,600, which is only about a 5% savings in the total number of elements.

Once again, the maximum number of links needed is five, which is still a large number to currently realize. By moving away from square array regions, it is possible to reduce the number of links to four as shown in Fig. 9 without any increase in the number of elements since SatCom applications, for which this multi-function aperture was designed, do not require an equal beamwidth in the two orthogonal dimensions. It is possible to use rectangular arrays. The number of elements in the architectures shown in both Figs. 8 and 9 is equal to 100, 600.

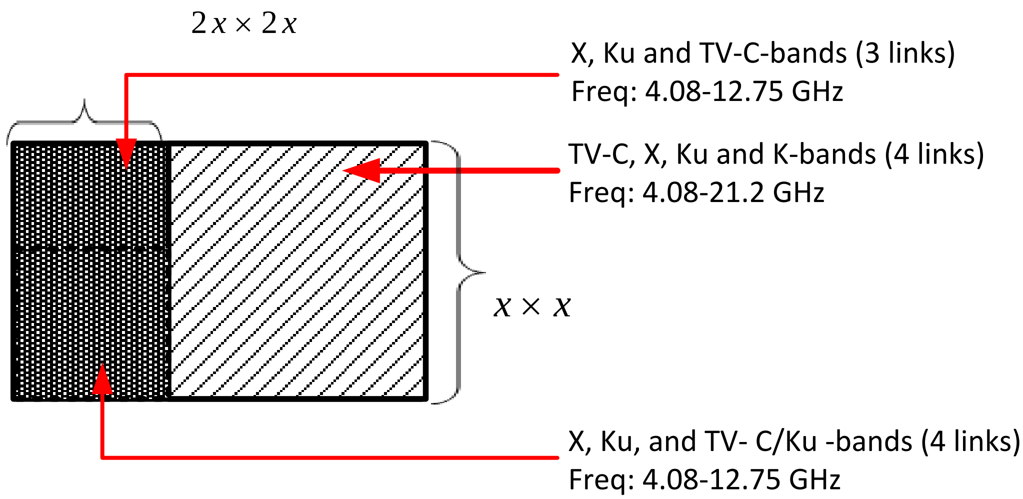

Figure 9: Architecture of a multi-function aperture (Architecture 1) for a surface combatant using square and rectangular array regions, x = 5.9mm

So far, we have only considered surface combatant architectures where the ratio between the inter-element spacing of the different array regions is a whole number. Next, we present an architecture where we have removed this constraint. This allows us to use the larger inter-element spacing of 7.1 mm at K-band and hence reduce the number of elements needed in the core array region to satisfy the directivity requirement. Now, the inter-element spacing for the outer array can be 1.5 times 7.1 mm (i.e. 10.65 × 10.65 mm) without generating grating-lobes at the highest frequency of 12.75 GHz. With these new inter-element spacings, the number of elements needed to satisfy the directivity is only 77,820 which result in 26.5 % fewer elements compared to the case where equal-sized elements were used over the entire array region and 22 % fewer elements when compared to the architecture shown in Fig. 8. Figure 10 shows the architecture with the new inter – element spacing.

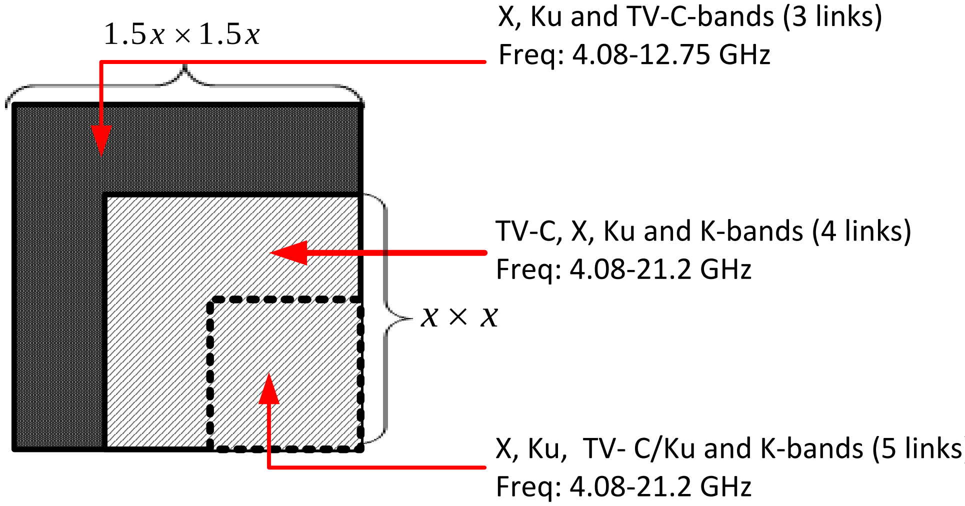

Figure 10: Architecture of a multi-function aperture (Architecture 2) for a surface combatant using square array regions with inter-element spacing of x and 1.5x, x = 7.1 mm

As before, the number of links needed from any section of the aperture can be reduced by creating rectangular array regions and hence moving the TV-Ku array out the K-band array. This is shown in Fig. 11. This can be done easily because the inter-element spacing needed by the TV-Ku band should be less than 12.3 mm and so 10.65 mm can be used. Moving from Architecture 2 to Architecture 3 reduces the number of links by one (from 5 to 4) without increasing the total number of elements or radiating element's bandwidth requirement.

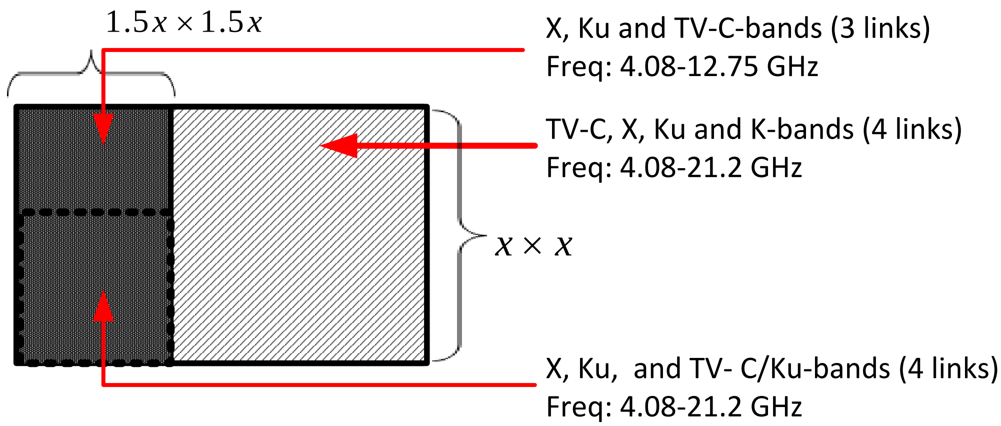

Figure 11: Architecture of a multi-function aperture (Architecture 3) for a surface combatant using square and rectangular array regions with inter-element spacings of x, and 1.5x, x = 7.1 mm

So in summary, Fig. 11 represents an optimum architecture of a wideband multi-function array for SatCom downlinks aboard a surface combatant. Here, we used wavelength scaled radiating elements, with scaling of 1.5 and its multiples to reduce the number of elements. The individual apertures were dispersed over the large aperture to reduce the number of simultaneous links from any given part of the aperture as well as to reduce the bandwidth requirement for the radiating elements. In addition, rectangular, instead of square regions were used where possible and advantageous.

4. Conclusions

Existing Navy ships use a separate antenna for each function resulting in a proliferation of a large number of antennas to meet the numerous functional requirements. Several organizations (including the Naval Research Laboratory) have developed wideband phased array antennas that can perform multiple functions simultaneously to reduce the number of antennas on ships. However, depending on the application, the number of radiating elements needed may be prohibitively large, resulting in an overly complex and costly multi-function phased array antenna. We have developed novel architectures based on a wavelength scaled approach that can consolidate many functions into a single wideband phased array antenna while reducing the total number of elements needed compared to conventional wideband phased array architectures. The design approach presented here also reduces the number of simultaneous beams needed from any part of the aperture and minimizes the bandwidth requirements for both the radiating elements and the electronics behind them by properly dispersion the functions over a large aperture, thus further reducing the size, weight, power and cost of the array.

Two architectures were developed to support SatCom systems on future Navy aircraft carriers and surface combatant ships. This study directly addresses requirements of the ongoing Office of Naval Research (ONR) Integrated Topside Program (InTop) to develop cost effective SatCom systems for future Navy ships. In addition, the techniques developed here can be used for other applications in designing architectures for affordable wideband multi-function phased arrays.

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