Reducing Quantization Lobes Through Different Rounding Methods

Peter A. Pawelski

Electrical Engineering Department

University of Massachusetts, Amherst MA

E-mail: ppawelski@umass.edu

***Abstract*—This paper describes a custom MATLAB application that utilizes algorithms to reduce quantization lobes levels in phased array patterns. There are extra functions in the program that allows the user to interact and further study the array patterns of any custom antenna element they upload from high frequency structure simulator (HFSS). Regarding quantization lobe level reduction, there are two main methods incorporated. The first method is the Two Dimensional Quantization (TDQ) method and the second is the Mean Phase Error to Zero (MPEZ). In the paper, the effects of each method at different scan angles are compared to if the number of phase shifter bits increases. These methods are capable of reducing the quantization lobe levels more than 6dB. Though a range of phase shifter bits are explored, the focus of improvement in this paper are patterns using two and three phase quantization bits.**

Keywords—Quantization Lobes, Two Dimensional Quantization, Mean Phase Error to Zero, Phase Shift Quantization

I. INTRODUCTION

While phased array antennas are good for steering narrow beams, phase shifter quantization is an impairment that may cause higher side lobes or quantization lobes. These quantization side lobes are undesirable since power is being directed in a direction outside of the focus, ultimately wasting power and picking up unwanted signals. In a phased array, when steering, each element is given a specific phase delay to help steer the beam. Due to the limited resolution of phase shifters, these specific phase delays can only be met by so much accuracy. The error in phase delay is what heavily contributes to quantization lobes [1]. A possible fix is to increase the number of bits for the phase shifters, but that is not always possible. Higher bit phase shifters

Custom MATLAB application was made specifically for this investigation. On startup of the application, the user is to import their HFSS antenna element pattern file and input information about their desired array geometry and beam steering. By default, the array geometry is 32x32 elements with λ*0.45 spacing, Azimuth and Elevation are 0° and 90° respectively and the number of phase quantization bits is 3. The element under test is from the paper *24 GHz Fixed Point Antenna Based on Starry Inc's Comet Antenna* by Pawelski [2]. The patch antenna directivity data was saved as a csv file on HFSS and imported to MATLAB. The single element directivity pattern can be seen in Figure 1 while the array directivity pattern based on the default specifications is in Figure 2.

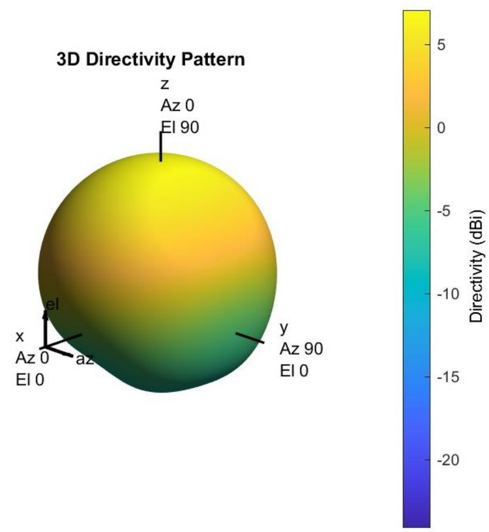

Fig. 1. Single Element Directivity Pattern of 24.5GHz Patch Antenna [2]

On this same application, there are eight main functions separated into tabs. These mains functions include displaying the array geometry, single element directivity pattern, array directivity pattern, an Azimuth cut, an Elevation Cut, the pattern in UV space, the grating lobes craters, and most importantly comparing side levels and quantization lobes between different phase bit rounding methods. While mainly the Quantization lobe function is used the most, the sub-functionalities of the other tabs are used in it.

While the functions work, it is difficult to implement and find scan angles with high quantization sidelobes and pointing errors. With this in mind, the paper focuses on a simple scan angle. There is also no amplitude weighting as to focus on fixing lobes using phase rounding.

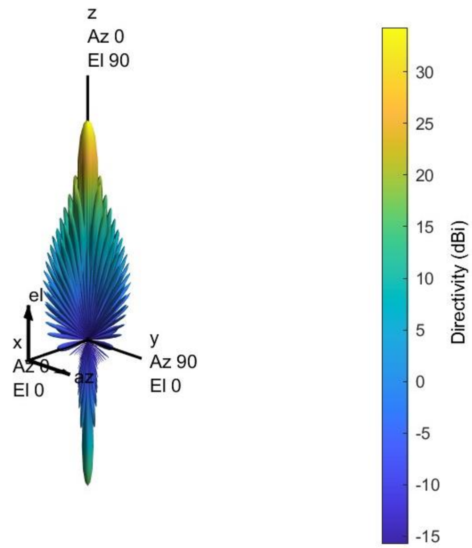

Fig. 2. Array Element Directivity Pattern using default specifications

II. QUANTIZATION REDUCTION METHODS

As mentioned before, the most important function to use in the MATLAB application is the one comparing side levels and quantization lobes between different phase bit rounding methods. This is under the eighth tab labelled 'Quantization Lobes' on the app. In this function, an Elevation cut is done using the azimuth inputted for the beam steering and the range of elevation as -90° to +90 °. There are also inputs on cycling through different numbers of phase shifter bits. At each bit, the peaks are recorded from each number of bits and compared to one another.

To understand how phase bit rounding is occurring here is to understand how to apply phase delay to each element in the array. The trick is to essentially make a matrix of complex value related to the weighting you wish to implement. This weight matrix is then applied to the array pattern. In this case, there is no amplitude weighting because this paper focuses on phase bit rounding performance. The phase of the complex values in the weight matrix is the phase intended to delay the individual elements. MATLAB has phase bit function inside of its Phased Array System Toolbox that creates this weighting matrix using phase values that are available from a phase shifter of a certain bits.

With understanding of the weighting matrix, now is to explain how phase bit rounding works with it. The next sections will explain how each element for phase bit round off is chosen but it all is applied to the weight matrix in a similar manner. Based on the number of phase bits, determines the size of each phase quantization level. If an element is rounded up, then the smallest quantization phase level is added to the phase of the element. The same logic can be said about rounding down. Since the weight matrix uses complex numbers, there are two main ways to apply the rounding. One can multiply the complex number with another complex number of amplitude 1 and desired phase change or convert the complex number to an angle, add or subtract the delay then convert back.

A. Phase Bit Increase Effects

For our easy example, the beam is steered to Elevation 70° and Azimuth 0°. An elevation cut from -90° to +90° is done at an Azimuth of 0°. The phase shifter bits is also incremented from 2 to 5. Figure 3 displays the Elevation cut using 2 phase shifter bits, while Figure 4 displays the same cut but using 5 phase shifter bits.

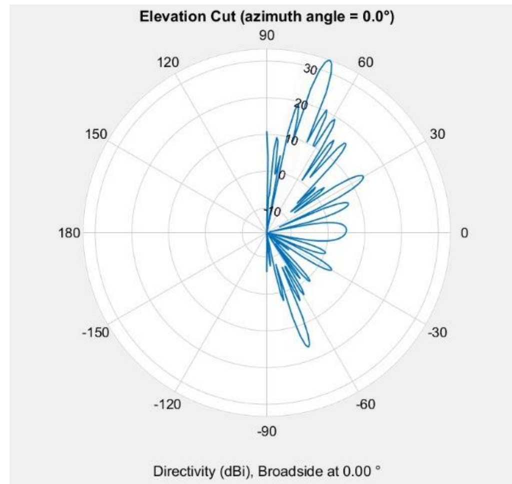

Fig. 3. Elevation -180°to+180° with Azimuth at 0°. Phase shift bits = 2 Directivity in dB versus peak number.

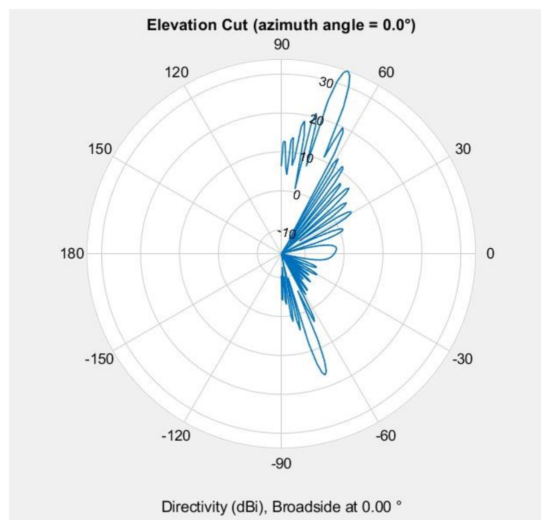

Fig. 4. Elevation -180°to+180° with Azimuth at 0°. Phase shift bits = 5 Directivity in dB

Only phase bits 2 and 5 were plotted for this section as to save space and to highlight the difference in side lobes and quantization lobes. Using two phase bits is also the easiest way to find quantization lobes in the pattern. Comparing Figures 3 and 4, there is a noticeable difference of around 7.5 dB between the side lobes at 0° Elevation. There also was a visible qunatization lobe difference between the two figures at 30°. This quantization lobe added almost 10 dB of directivity in that direction.

B. Two Dimensional Quantization Round Off

The TDQ method is a unique way of rounding up the phase shifter bits to achieve higher phase accuracy [3]. The paper mentions many configurations on how to round up the elements, however, this paper will only discuss a slightly different version of the first one. Figure 5 shows the base round off map used.

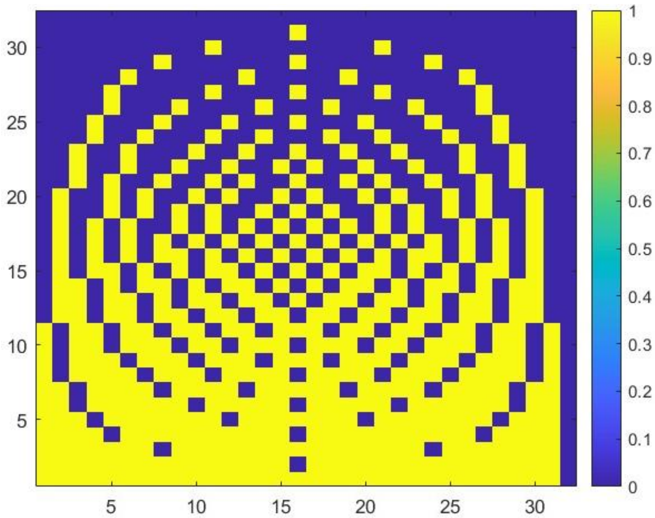

Fig. 5. Round up phase pattern similar to TDQ configuration 1 [3]

What makes the configuration pattern in Figure 5 different to the paper's pattern is how the 1' and 0's are ordered on the bottom third of the plot. The 0's should be more spread out, versus bunching up in the bottom of the right most column. This method is unqiue because of how the rounding occurs in a symetric manner. Having an arrangement like this in Figure 5 negatively affects the symmetry of the pattern, however it is symmetric enough for sufficient results.

Each point on figure 5 represents an element in the array. If there is a 1, then that element is rounded up to the next quantization phase level. If the phase overflows past 360° then it is kept at 360°. How this pattern was formed was creating an empty matrix the size of the array and selecting one minus the row number of elements in each row to be rounded up. The edge farthest from the direction of the beam will have zero elements and increase by one dimension towards the direction of the beam. Further explanation on this and to see how the elements were spread out can be seen in the code below:

```
for i = 1:M
    if i == 1
        continue
    end
    begin = M/i;
    step = begin;
    last = begin*(i-1);
    idxs = begin:step:last;
    idxs = round(idxs);
    tdqArrayMat(i,idxs) = 1;
end
```

Since the symmetry aspect is important for the pattern, to have an even number of elements in each direction. It is also preferable to have dimensions X and Y equal. Ideally, a circle array would be used, but a square array works as well. Laslty, there is a preffered criteria number of elements per dimension being a power of 2. This is because, the configuration is setup up in a way that averages the phase change in each dimenson to add extra resolution to the beam steering. In this case, since the array uses 32 or 2^5 for both dimesnions, the configuration allows for an extra $360/2^5$ or 11.25° phase difference[3].

Only one pattern needs to be applied in the easy example as the beam is steering only off the normal in the elevation direction. A second pattern rotated -90°or +90° can be applied to accommodate the azimuth angle component of the beam steering.

C. Mean Phase Error Zero

The MPEZ method is a popular method for rounding phase bits, however it is not reproducable. Since method uses randomness, the same exact pattern will be diffcult to achieve. However, some people use this to their advantage where, they run this method mutliple times and pick the best performance. This is common amonst all randomized rounding methods. How the method chooses to randomly choose and round up is based on the method itslef. For this method, random elements in the array are chosen to round up and the same number of ranomdly unselected elements will be rounded down. Overall across the array, the average change should be around 0 [1]. An example of a configuration I used for this method can be seen in figure 6 below.

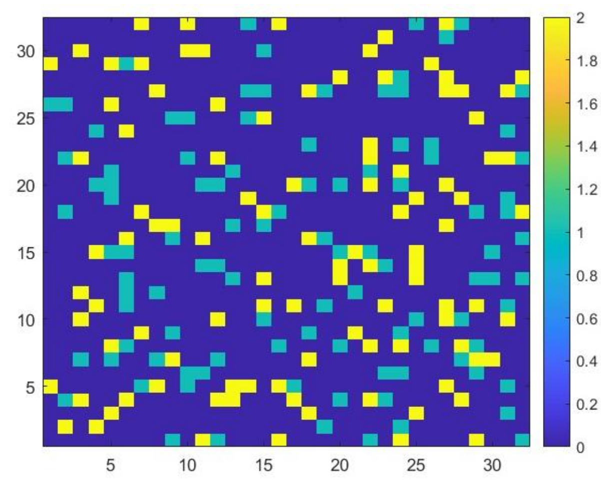

Fig. 6. Mean Phase Error Zero Method Round Up Configuration Example

What figure 6 is showing the elements affected by roundin up or down. The element was rounded down if it had a 1 and rounded up if it had a 2. A 0 meant no change was done to that element. The number of elements chosen to be rounded up was up in the air, so it was decided to use a fourth of elements for rounding up and down for phase bits less than 4 and half the elements for phase bits 4 and above. The reasoning behind this was because at lower phase bits, rounding up and down has a much larger change than with more phase bits.

How this method is supposed to be helpful is by affecting the average phase delay per row or column, similar to what was mentioned for the TDQ method. This method hopes using the power of ramdomization to make a rounding configuration that has better phase resolution. While this method is useful, it can take a long time and computation power to figure out the right pattern.

III. Method Implementation and Comparison

The MATLAB application is able to apply a simple phase shift bit increase, and the TDQ and MPEZ methods. Quantization lobes are not very problematic are phase bits higher than 4, this section will only sweep between 2 and 4 phase bits.

It is important to mention how the next figures are interpreted. The x-direction in the plot is related to the peak number in the pattern. Since the array is 32x32, then there are 31 peaks in both the x and y. The peaks number provides an idea on where in elevation the peak is occurring. There is a location value saved for each peak, but this way provides the same idea. Since we are comparing the same pattern each time, the peaks should be in similar order.

As mentioned in the beginning of the last section, as an elevation cut is performed, the peaks of each lobe are recorded and compared to one another. As seen in figure 7 below, here are how the peaks reduce as the phase bits are increased.

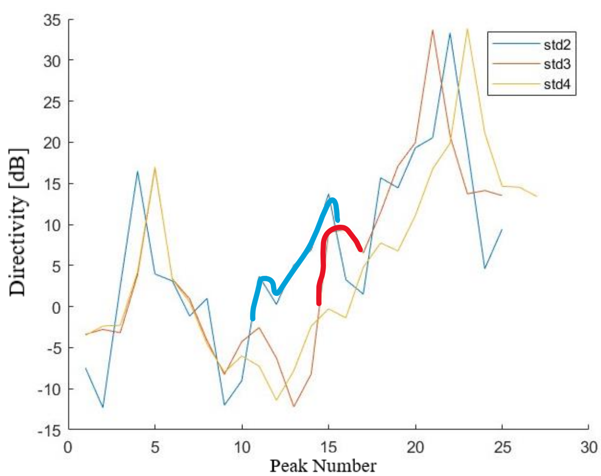

Fig. 7. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Using simple phase bit increase. Directivity in dB versus peak number.

In figure 7, the 2 phase bits line (blue) has noticeable leverage compared to the other lines. The leverage is outlined in blue to show where the quantization lobe is occurring. Same can be said about the 3 phase bit line (red) where it is below the blue line but above the yellow (4 phase shift bits). Essentially this acts as confirmation of how the quantization lobe will decrease as the number of phase shifts increases.

Next, as seen in Figure 8 below, the TDQ method is used.

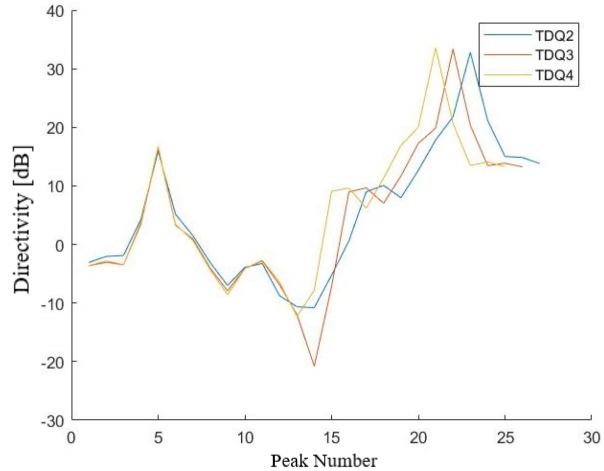

Fig. 8. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Using TDQ method. Directivity in dB versus peak number.

Looking at figure 8, doesn't seem to show much improvement as the phase shifter bits are increased, however there is noticeable improvement when comparing TDQ2 and TDQ3 to std2 and std3 in figure 7 as shown in figure 9 below.

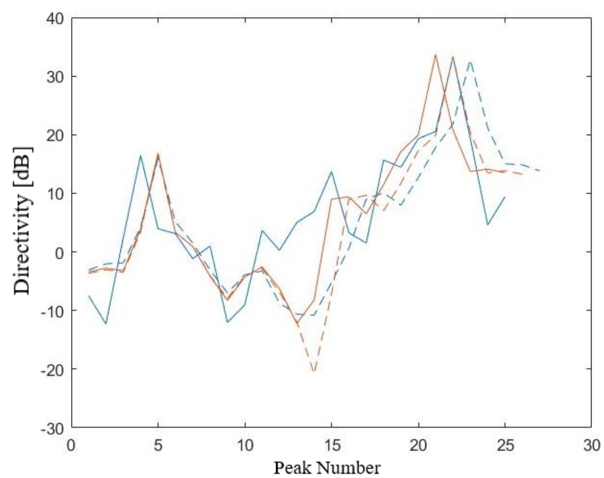

Fig. 9. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Comparing TDQ and simple method. Directivity in dB versus peak number.

Here in figure 9, it is evident that the TDQ method is properly reducing the quantization lobe mentioned in figure 7. The color scheme is kept the same for the phase bits however the solid line represents the data from figure 7 and the dashed for the figure 8. The 2 phase bit shifter using TDQ reduced the lobe up to ~15 dB and the 3 bit phase shifter reduced lobes by 10 dB at best.

Next, figure 10 displays how well the MPEZ method works. It is worth mentioning that it took a couple tries before achieving a plot where the quantization lobes were reduced. This is expected as randomization is used in this method.

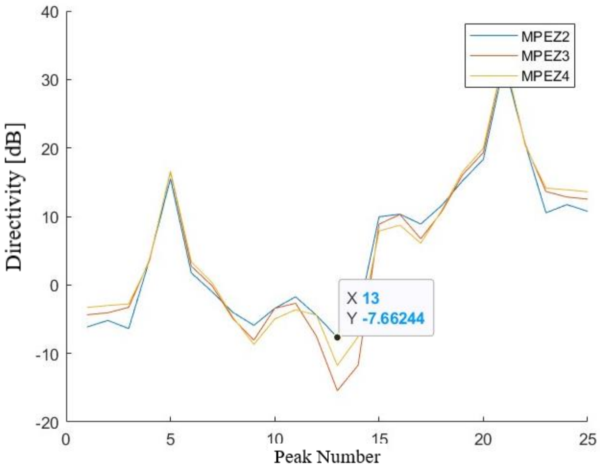

Fig. 10. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Using MPEZ method. Directivity in dB versus peak number.

Again, as in the TDQ method, there is not much improvement in the peaks of the pattern. However, it is visible that all phase shifter bits do not show much evidence of a quantization lobe. Phase shifter bits 2 and 3 between the simple method and the MPEZ method are compared in figure 11.

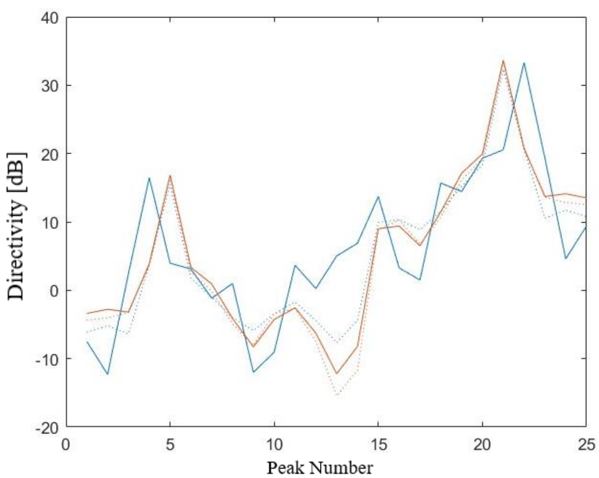

Fig. 11. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Comparing simple method and MPEZ method. Directivity in dB versus peak number.

Again, the phase bit rounding method has reduced the quantization lobe shown in figure 7. However, compared to the performance of the TDQ method, it is worse. For 2 phase bits, the MPEZ method reduced the quantization lobe by about 10 dB whole the 3 phase shifter bits reduced around ~2-3 dB. For clarification the color scheme is kept the same from figure 7, the solid lines are from the simple method and the dotted lines are from the MPEZ method. With more runs and time, there is a chance of generating better performance, but that is at a gamble.

IV. CONCLUSION

Combining all results together provides figure 12. Together the method performance can be seen. The TDQ method worked the best for phase shifter bits 2 and 3. Even though the MPEZ method did worse, it was the best at keeping the peaks in the same place. This is most likely because of the zero mean phase error. The elements that are rounded up push the peaks forward while the rounded down elements push them back. It is a tradeoff where we keep our same beam direction, but give up quantization lobe reduction.

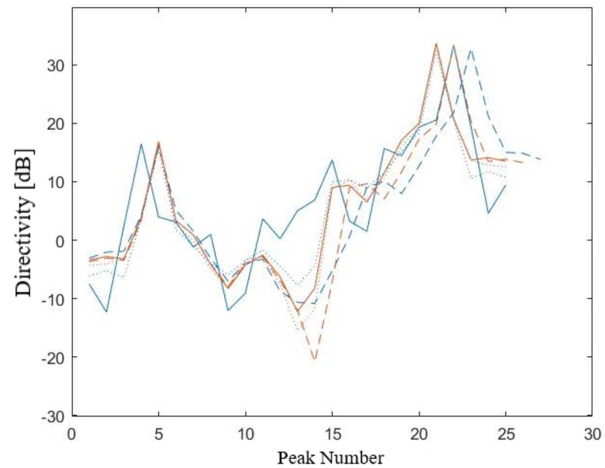

Fig. 12. Directivity Peaks in Elevation -180°to+180° with Azimuth at 0°. Comparing simple method MPEZ method and TDQ method. Directivity in dB versus peak number.

An interesting observation is how the 2 bit phase shifter rounding methods perform just as well as the 3 bit phase shifter simple method. Using these methods may have their constraints, but they show respectable improvement in the directivity pattern, without needing to increase the number of phase shift bits. This can save a lot of money while not sacrificing too much performance.

While the example was simple, this investigation can be built upon. What can be done for future use is scanning all angles and finding the highest quantization lobe. With this angle, then the methods can be put to further test. Alongside this, an amplitude taper can be entertained to further help reduce the quantization and side lobes.

Overall, the investigation has proved to be a success. The primary goal was to implement the phase bit rounding methods in a MATLAB application. With the time worked on it, this application is at industry standard. Regarding the main goal of reducing quantization lobes, the methods implemented indeed performed what was desired. Lastly, the aim of reducing quantization lobes by at least 3dB was achieved as the TDQ method reduced as high as ~15 dB and the MPEZ as high as ~10 dB.

[1] R. J. Mailloux, "Array Error Effect," in *Phased array antenna handbook*, 3rd ed, Boston, MA: Artech House, 2018, pp. 385–396

[2] P.Pawelski, "24 GHz Fixed Point Antenna Based on Starry Inc's Comet Antenna," *UMass Amherst ECE 687 Mock IEEE Paper*

[3] C. Hemmi, M. H. McCullough, and B. L. Ball, "Two-dimensional quantization method for phased-array scanning," *IEEE Antennas and Propagation* vol. 56, no. 5, pp. 43–59, 2014. doi:10.1109/map.2014.6971915