Reliability Analysis for Phased Array Radar Systems

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Abstract—Phased array radar systems are used by the military for tracking targets and providing weapon engagement support. Each radar system consists of multiple antenna modules arranged in a 2-dimensional grid. An n-by-n antenna array radar system can operate with up to a given number of antenna module failures, with acceptable degraded performance, as long as the failed antennas are not adjacent to each other. In this paper, an improved RBD (Reliability Block Diagram) configuration is proposed to analyze the reliability for phased radar systems. Other reliability metrics such as point availability and mean availability also are evaluated.

Keywords—phased array radar system; k-out-of-n system; adjacent failures

I. INTRODUCTION

Phased array radar systems are used in both military and civilian applications. The military radar networks are crucial for national security. The nation’s weather radar networks are vital for severe weather detection and forecasting. Therefore, the reliability and availability of a radar network are very important. By studying the reliability performance, cost-efficient maintenance decisions can be made. The number of spare parts can also be determined in a scientific way according to the availability requirement. In this paper, the reliability and availability of a phased array radar system are studied. Because of the unusual definition of failures, a traditional RBD cannot be used to calculate the reliability of a phased array radar system. An improved RBD will be presented in this paper to solve this issue.

This paper is organized as follows: in Section II, the definition of failures will be given; Section III will discuss the analytical solution for the reliability and its limitations; in Section IV, simulation solutions will be presented using the improved RDB configuration. Finally, conclusions will be drawn at the end of the paper.

II. SYSTEM FAILURE DEFINITION OF PHASED ARRAY RADAR SYSTEMS

Like other complex systems, a phased array radar system has many different failure modes. In this paper, only the antenna module failure is considered. Antenna modules are arranged in a 2-dimensional grid. For example, the antenna module grid for an 8-by-8 array radar system is given in Fig. 1.

Usually, for an n-by-n phased array radar system, system failure is defined by the following two conditions. When either of them occurs, it is defined as a system failure:

- If the number of failed antenna modules is greater than a given number of k. Usually k is less than or equal to n,
- If there are adjacent failed antenna modules.

For the layout given in Fig. 1(a), assume it can have a maximum of 8 failures. If the modules in Fig. 1(a) in the circles failed, the radar still can work in an acceptable way. The definition of adjacent failures is illustrated in Fig. 1(b). The two antenna modules that are in the same ellipse are said to be adjacent. Failures that are next to each other, whether in a horizontal, vertical or diagonal way, are called “adjacent failures.”

If the failure were defined only by the first condition, the reliability for a phased-array radar system could easily be calculated by treating it as a standard k-out-of-n (success) system [1, 2]. Here, n is the total number of modules; k is the required number of functional modules. The 8-by-8 array example given in Fig. 1, for example, can be treated as a 56-out-of-64 system. However, with the second failure condition, the reliability can not be calculated by simply using the standard k-out-of-n method. Instead, the standard k-out-of-n method can provide an upper bound for the system reliability. There is a special case, for a 2-by-2 array where the allowed number of failed elements is 2, in which these two failure conditions are the same. In this case only, the reliability can be calculated using the standard k-out-of-n method. For other arrays, this method cannot be applied directly.

III. ANALYTICAL SOLUTIONS

Failure data were collected from the field and entered into Weibull++, a software package from ReliaSoft. The 2-parameter Weibull distribution is used to model the data. The probability density function of a Weibull distribution is:
\[ f(t) = \frac{\beta}{\eta} \left( \frac{t}{\eta} \right)^{\beta-1} e^{-\left( \frac{t}{\eta} \right)^\beta} \]  

(1)

where \( \beta \) is the shape parameter and \( \eta \) is the scale parameter.

The failure and suspension times are in hours. Fig. 2 shows the Weibull probability plot.

A. Reliability for a 3-by-3 Phased Array Radar System

In this paper, all of the antenna modules are assumed to be identical and independent. According to the failure definitions described in section II, the reliability of a 3-by-3 phased array radar system can be calculated as:

\[ R_{sys}(t) = R(t)^9 + 9(1 - R(t))R(t)^8 \]

\[ + 16(1 - R(t))^2R(t)^7 + 8(1 - R(t))^3R(t)^6 \]

where \( R(t) \) is the individual antenna reliability and \( R_{sys}(t) \) is the system reliability.

The system reliability plot is given in Fig. 3.

As the size of the array increases and as other properties, such as repair time and cost, part availability and repair crew availability, come under consideration, obtaining the analytical solutions for the reliability and the availability becomes more difficult or even impossible. Therefore, simulation is an attractive alternative. With today’s computing speed, a standard PC is capable of the quick analysis of a phased array radar system. In section IV, simulation solutions for the 3-by-3 phased array radar system will be given. The comparison between simulation and analytical solutions for the system reliability shows that simulation can provide accurate results.

IV. SIMULATION SOLUTION WITH IMPROVED RBD

In order to use simulation, the phased array radar system should be modeled using an RBD. The two basic RBD configurations are serial and parallel configurations. RBDs for any complex systems are built based on these two basic configurations. Recall the two conditions in the failure definition for phased array radar systems; the first condition can be modeled by a standard \( k \)-out-of-\( n \) RBD, where \( n \) is total number of items in parallel and \( k \) is the required number of functional items required to make the system work. We will now illustrate how to model the second condition, the prohibition of adjacent failures, using the traditional \( k \)-out-of-\( n \) configuration.

Fig. 4 illustrates how to model the adjacent failures using a \( k \)-out-of-\( n \) RBD configuration. It can be seen that for an array of any size, it can be decomposed into many 2-by-2 arrays. For each 2-by-2 array, the adjacent failure requirement can be modeled by a \( 3 \)-out-of-\( 4 \) configuration.

The first failure requirement can be modeled directly by a \( k \)-out-of-\( n \) configuration. The second requirement, which is illustrated in Fig. 1(b), can be modeled by the method given in Fig. 4. The system reliability of a phased array radar system can be modeled by combining these approaches. However, one may notice that the same component is used multiple times in Fig. 4. For example, component 5 is used by all four \( 3 \)-out-of-\( 4 \) RBDs. In order to model a component with multiple copies in an RBD, the concept of a mirror block is proposed [2].

Definition of Mirror Block: A mirror block is one that appears multiple times in an RBD diagram, but is essentially the same block each time it appears.

Although a block appears multiple times in a diagram by using mirror block, the reliability of the system is not underestimated since all the mirror blocks with the same source are counted as a whole. When the source block is failed, all its associated mirror blocks will be down. With the above idea, a 3-by-3 phased array radar system can be modeled using the RBD given in Fig. 5.
Figure 5. Improved RBD for a 3-by-3 phased array radar system.

The part before the 6-out-of-9 (6/9) node in Fig. 5 is for the first condition in the failure definition; the part after it is for the second (adjacent) failure condition. A block with a black square at its upper right corner is a mirror block. The name of a mirror block indicates which original block it represents.

Using BlockSim, another software package from ReliaSoft, the reliability of the example used in section III can be obtained through simulation. It is shown in Fig. 6.

Figure 6. Simulation and analytical reliability results.

In Fig. 6, the points are the analytical results and the line represents the simulation results for the reliability. These match very well. It took only about 3 seconds for a standard PC to obtain the above simulation results. The simulation settings in BlockSim are: seed = 1, time = 8760 hours; number of simulations = 1000. Please keep in mind that when the system is becoming more complex, simulation convergence criteria should be used to determine the number of runs. Longer simulation time will be expected.

In the above analysis, it was assumed that the antenna module is not repairable or replaceable. If we assume that whenever an antenna module fails, it can be replaced, then the availability of the phased array radar system can be analyzed. Assume the replacement duration is a normally distribution random number with mean of 40 and standard deviation of 10. The point availability within a five-year operation period is given in Fig. 7.

Figure 7. Simulated point availability for a five year operation.

If the costs, such as repair cost and part cost, are considered, the total cost due to antenna module failures can be estimated through simulation. Assume a cost of $5,000 per antenna, and that each replacement of a failed antenna will bring additional $1,000 miscellaneous cost. The total expected cost for antenna replacements is given in Table I.

<table>
<thead>
<tr>
<th>Block Name</th>
<th>Misc Cost</th>
<th>Part Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>$5,493</td>
<td>$27,465</td>
<td>$32,958</td>
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<tr>
<td>E2</td>
<td>$5,484</td>
<td>$27,420</td>
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<td>E3</td>
<td>$5,528</td>
<td>$27,640</td>
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<td>E4</td>
<td>$5,519</td>
<td>$27,595</td>
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</tr>
<tr>
<td>E5</td>
<td>$5,523</td>
<td>$27,615</td>
<td>$33,138</td>
</tr>
<tr>
<td>E6</td>
<td>$5,497</td>
<td>$27,485</td>
<td>$32,982</td>
</tr>
<tr>
<td>E7</td>
<td>$5,516</td>
<td>$27,580</td>
<td>$33,096</td>
</tr>
<tr>
<td>E8</td>
<td>$5,501</td>
<td>$27,505</td>
<td>$33,006</td>
</tr>
<tr>
<td>E9</td>
<td>$5,497</td>
<td>$27,485</td>
<td>$32,982</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$49,558</strong></td>
<td><strong>$247,790</strong></td>
<td><strong>$297,348</strong></td>
</tr>
</tbody>
</table>

The cost is calculated based on the simulated number of failures of each antenna module. From Table I, it can be seen that the total cost for each antenna element is about $33,000. Dividing this by $6,000, the expected number of replacements of each module is about 5.5. So for each module, we need to have at least 6 spare modules during a 5-year operation period.

V. CONCLUSIONS

In this paper, the reliability and availability of phased array radar systems are analyzed using analytical and simulation methods. With the size of the array increasing, it becomes impossible to get the analytical solutions. In order to apply the
simulation method, an improved RBD is proposed. The mirror block concept is introduced. By comparing the analytical and simulation results for a 3-by-3 phased array radar system, it can be seen that the simulation results are accurate. In addition to the reliability results, simulation can provide much more useful information, such as the expected total cost and the expected number of repairs.

REFERENCES
