Calibration methods for phased array radars

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ABSTRACT

For successful beam shaping and scanning in phased array radars, it is essential to precisely set the amplitude and phase of each element channel. However, considerable amplitude and phase differences among the channels can occur due to the different RF hardware connected to each element. Also, the phase and amplitude characteristics of most RF devices depend on frequency and temperature and usually drift in time. In order to equalize the phase and amplitude effects of the channels, phased array radars need to be calibrated periodically.

In the literature, various phased array calibration methods are discussed. However, the specifics of these methods are usually not covered. Here, we describe four of the most commonly used calibration methods in detail: near-field scanning probe, peripheral fixed probes, calibration lines, and mutual coupling. Each calibration method is described step by step and relevant formulas are given. The advantages and disadvantages of each method are also discussed.

Keywords: calibration, phased array, radar, antenna, mutual coupling

1. INTRODUCTION

Due to their ability to rapidly scan their beams, phased array antennas are commonly preferred over reflector antennas in modern radars. This electronic beam scanning is achieved by means of adjusting the phase of the signal received by each antenna element such that the signals become in-phase for the specific beam scan angle desired. On the other hand, the amplitudes of the element channels relative to each other determine the shape of the antenna pattern. Unfortunately, in practice, the actual relative phase and amplitude values of the element channels deviate considerably from the desired values. These undesired phase shifts and amplitude attenuations are caused by various RF hardware such as antennas, phase shifters, attenuators, amplifiers, dividers, combiners, switches, connectors, transmission lines, coaxial cables, and waveguides. It is important to note that any RF component that is commonly used by all element channels cannot cause any relative phase/amplitude shifts.

For a phased array radar to perform as desired, it is essential to calibrate the radar by measuring and equalizing the phase and amplitude effects of all element channels. Furthermore, these relative phase/amplitude shifts due to RF devices often depend on frequency and temperature and usually drift in time (i.e., due to aging or temperature changes). Thus, calibration should be repeated at various temperatures and frequencies (unless it is designed to operate at a specific frequency only). In addition, the calibration procedure needs to be repeated periodically to compensate for the drifts occurring in time.

Although various calibration methods for phased array radars have been introduced in the literature[1-19], a comprehensive description of the most basic and commonly used methods is lacking. In this paper, we first discuss calibration procedure in general. We then describe four basic calibration methods in detail. These methods are: near-field scanning probe[1, 2], peripheral fixed probes[1, 2, 3, 4, 5], calibration lines[6, 7, 8], and mutual coupling[9, 10, 11, 12, 13, 14, 15]. The near-field scanning probe method is usually preferred for in-factory (offline) calibration whereas the peripheral fixed probes and calibration lines methods are more suitable for periodic in-field (online) calibration. The mutual coupling method can be used for both in-factory and in-field calibration. Several other calibration methods have been invented (such as phase toggling[4, 6, 16, 17, 18] and orthogonal codes[19]) but they involve complex algorithms and are designed mostly for specific radar systems so they are not commonly used.

We describe each of the four aforementioned calibration methods step by step and provide the analytical relations needed to understand and implement them. We also discuss the advantages and disadvantages of each method for different phased array radar systems.

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2. CALIBRATION PROCEDURE

The basic steps of calibrating a phased array radar can be summarized as follows:

1. The phase/amplitude differences among the channels are measured in the factory using an appropriate method.

2. The measurements are repeated for transmit and receive modes.

3. The measurements are repeated at different frequencies and temperatures that the radar is required to operate at.

4. If phase shifters and attenuators are used (i.e., analog beamforming), the calibration procedure should be repeated for each phase and amplitude step.

5. The calibration should be repeated in the field periodically to compensate for the phase/amplitude shifts that occur in time due to aging or replacement of parts.

For calibration, it is not necessary to measure the actual phase/amplitude responses (the phase/amplitude shift of output relative to input) of each channel. If the input signals are equal, then calibration can be done by simply measuring the output signals relative to each other. If the input signals are not equal, then the outputs should first be normalized (divided by the inputs) before comparing them to each other.

Step 3 is necessary because the phase/amplitude shifts of most RF devices depend on the temperature and frequency and the behavior of each channel would be different. Although channel effects can be measured and equalized at different operating frequencies, for radars that use FM coded waveforms, the frequency changes too fast to compensate with phase shifters that provide constant phase shift regardless of frequency. On the other hand, the phase shifts provided by switched delay line or True Time Delay (TTD) devices change with frequency allowing the waveform to propagate undistorted. If constant phase shifters are used in a wideband FM radar, the frequency responses of the channels should be kept as similar to each other as possible. This can be achieved by using RF devices whose frequency responses are similar and by equalizing the path lengths of each channel. If the path lengths are different, phase shifter compensation would be useful only at a specific frequency and not for the other frequencies in the bandwidth.

Step 4 is necessary because the amplitude/phase shifts induced by attenuators and phase shifters vary with their amplitude and phase settings, respectively. Ideally, the attenuator and phase shifter steps need to be calibrated for all combinations. For example, if there are N phase steps and M attenuator steps, calibration should be repeated $N \times M$ times due to the fact that the impedance mismatch (return loss) between the attenuator and phase shifter might depend on the phase and amplitude settings. However, if very high accuracy is not required, it might be sufficient to calibrate the phase shifters and attenuators individually which requires only $N+M$ calibration steps. Also, even though phase shifters do not cause much attenuation, the attenuators can cause considerable phase shifts so both phase and amplitude should be measured for each attenuator setting.

It is sometimes mentioned, in the literature, that the calibration should be repeated for all beam scan angles instead of all phase shifter settings. For large arrays and for high-bit phase shifters, beam scan angle calibration takes much less time; however, scan angle calibration is much less reliable than phase shifter calibration due to the fact that a phase shifter step that, in-theory, is not used for beam scanning might, in practice, have to be used to equalize the phase shifts of the channels. Finally, it should be noted that Step 3 is required only for Analog Beam Forming (ABF) systems. It does not apply to radar systems that employ full Digital Beam Forming (DBF) which do not require phase shifters or attenuators. So, the factory calibration procedure can be completed much more quickly for full DBF systems.

After all the measurements mentioned above are made, the measured complex values are stored as a table in the radar software (calibration coefficients). The phase and amplitude values can be stored as complex numbers (i.e., real and imaginary) or in two separate tables for amplitude and phase. For ABF systems, the amplitude coefficients should be divided by the smallest coefficient to normalize and lower their values as much as possible. That way, the extra attenuations to be applied to equalize channel responses during radar operation could be minimized. It should be noted that all values should be larger than 1 as they represent attenuation amounts. Unlike amplitude values, there is no need to normalize the phase shifts. During radar operation in the field, the phase/amplitude shift of each channel is compensated using the appropriate value from the calibration coefficients table based on the current phase shifter and attenuator settings as well as the frequency and temperature. In ABF systems, this is achieved by applying extra attenuations and phase shifts. In full DBF systems, the complex calibration coefficients can be applied digitally by the processor.

The amplitude/phase shifts of RF components usually drift in time due to aging, so it is very important to periodically re-calibrate phased array radars in the field and update the calibration coefficients. In addition, when a failed component (such as a T/R module) is replaced with a new one, it is necessary to repeat calibration before resuming operation.

Finally, we note that, although the main purpose of calibration is to equalize phase/amplitude shifts of element channels, calibration measurements can also be used for other purposes such as indirect antenna pattern measurements (via Fourier Transform of sampled aperture distribution[20]) and in detecting failed components (from the high attenuation of the corresponding channel relative to other channels).

Next, the four aforementioned calibration methods are described in detail.

3. NEAR-FIELD SCANNING PROBE METHOD

In this method, a test antenna (probe) is scanned across the antenna array to directly measure the relative phase and amplitude of each antenna element (Figure 1). Using a near-field scanning probe, an array can be precisely and directly (i.e. without previous calibration) calibrated. However, it is a time consuming method that requires a complex setup involving automated precise probe movement. Therefore, this method is most suitable for initial factory calibration of phased array radars rather than periodic in-field calibration.

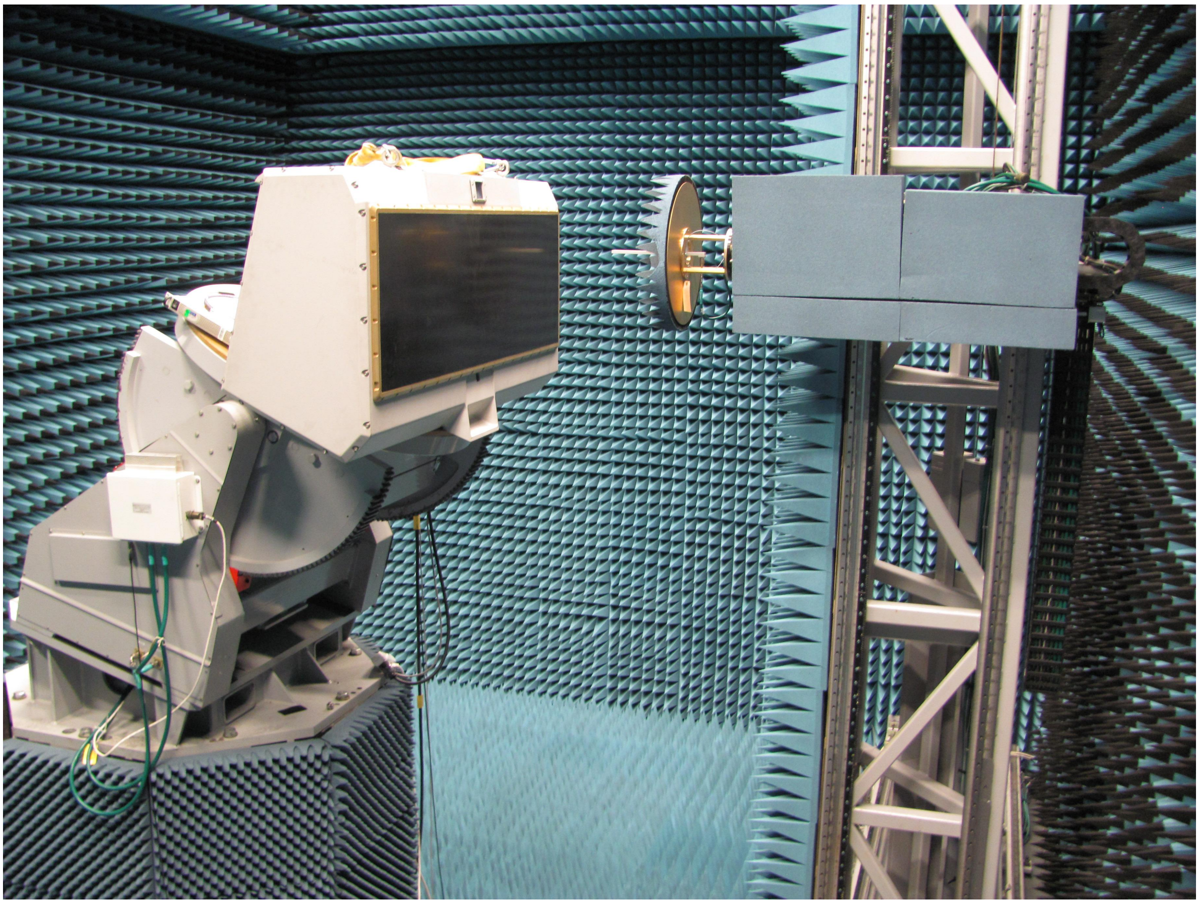

Figure 1. Measurement of a prototype phased array radar at the ASELSAN near-field range using a scanning probe.

In transmit calibration, the radar transmits a test signal from each element one by one and the received signal is measured with the probe which is consecutively kept at the near-field of each antenna element. In receive calibration, a signal is transmitted from the probe to each antenna element and the signal received by the radar receiver is recorded. First, the obtained values are normalized by the corresponding amplitude and phase settings of phase shifters and attenuators, respectively. Then, the measured signals for each channel are compared to each other cancelling the effects of the probe, probe-antenna couplings and the transmitted signals. Finally, the obtained ratios are stored as calibration coefficients for future use in the field.

Since the signals are transmitted to each channel (from the transmitter and probe) at different times, they (especially their phases) would not be identical. Therefore, the amplitude and phase of the transmitted signal should be measured and used to normalize the received signals. In other words, the received signals should be measured relative to the transmitted signals. For transmit calibration, this can be readily achieved by connecting Port 1 of a network analyzer to the input of the transmit module and Port 2 to the probe receiver and by measuring the complex S_{21} parameter.

For receive calibration, the measurements are usually made at the digital receiver before which signals are mixed with the local oscillator (LO) signal to shift the frequency to IF or baseband. So, the phase of the received signal depends not only on the shift induced by the receiver channel, but also on the phase difference between the probe and LO signal which should be kept constant so that the measured phases correspond only to the channel effects. This can be achieved simply by generating the LO signal from the transmitter signal so that they are synchronized.

For calibration, it is sufficient to take one measurement across each element. Furthermore, it is not necessary to keep the probe precisely in front of each antenna element. It is sufficient to keep the distance between two measurements equal to the separation of antenna elements. In that case, even if the probe is somewhat offset from the antenna positions, the amount of offsets (and therefore couplings) will be the same for all measurements and calibration can be done. In order to obtain the far-field antenna pattern from the near-field measurements, the near-field pattern should be sampled as densely as possible; therefore, the distance between measurements should be kept lower than necessary for calibration.

3.1 Technique

Using the terminology shown in Figure 2, the analytics of this technique can be described as follows:

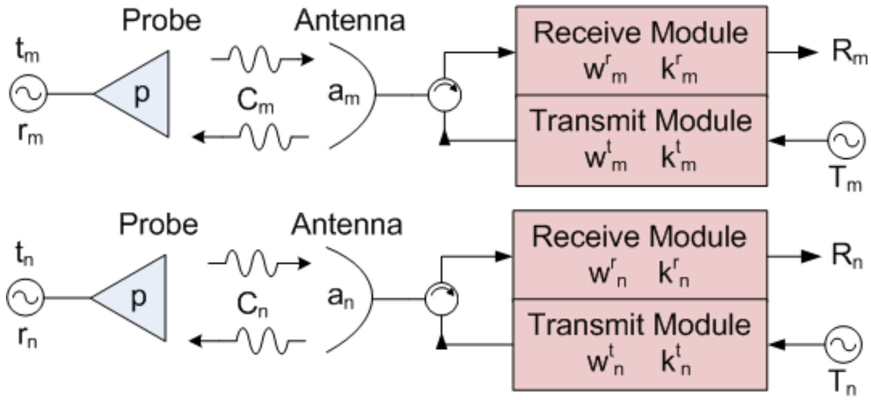

Figure 2. Calibration of a phased array radar using a near-field scanning probe.

$$R_m = t_m\, p\, C_m\, a_m\, w^r{}_m\, k^r{}_m$$
$$r_m = T_m\, k^t{}_m\, w^t{}_m\, a_m\, C_m\, p$$

R_m	the signal transmitted from the probe and received by the m[th] receive module	(measured)
r_m	the signal transmitted from the m[th] transmit module and received by the probe	(measured)
t_m	the signal transmitted from the probe to the m[th] antenna element	(known)
T_m	the signal transmitted from the m[th] transmitter	(known)
$w^r{}_m$	the phase/amplitude setting of the m[th] receive channel	(known)
$w^t{}_m$	the phase/amplitude setting of the m[th] transmit channel	(known)
p	losses due to the probe antenna and channel	(unknown)
a_m	losses due to the antenna elements	(unknown)
C_m	the amount of coupling between the probe and the m[th] antenna element	(unknown)
$k^t{}_m$	phase/amplitude effects of the m[th] transmit module	(unknown)
$k^r{}_m$	phase/amplitude effects of the m[th] receive module	(unknown)

The information needed for receive and transmit calibration: $(a_m\, k^r_m) / (a_n\, k^r_n)$ and $(a_m\, k^t_m) / (a_n\, k^t_n)$

If the distance and angle between the probe and the elements are kept constant and the elements are identical, the coupling between the probe and elements is constant: $C_m = C_n$

Since the calibration is repeated for all phase shifter and attenuator settings, the measured signals should be divided by the corresponding phase/amplitude settings (w^r and w^t). Then, the errors due to non-ideal phase shifters and attenuators would be included in the channel effects (k^r and k^t).

As explained earlier, for receive calibration, if the amplitude and phase of the LO signal relative to the transmitter signal is kept constant, the measured signals would not be effected by the changes in the transmitted signal. Here, for simplicity, we do not include the LO signal and assume that all transmitted signals are identical: $t_m = t_n$ and $T_m = T_n$

The calibration coefficients are given by the ratios of the signals measured from channels (m) and (n) normalized by their corresponding phase/amplitude settings:

$$S^r_m = R_m / w^r_m = t\, p\, C\, a_m\, k^r_m \qquad S^t_m = r_m / w^t_m = T\, p\, C\, a_m\, k^t_m$$
$$S^r_n = R_n / w^r_n = t\, p\, C\, a_n\, k^r_n \qquad S^t_n = r_n / w^t_n = T\, p\, C\, a_n\, k^t_n$$

Receive calibration coefficients: $K^r_m = S^r_m / S^r_n = a_m\, k^r_m / a_n\, k^r_{\mathrm{n}}$

Transmit calibration coefficients: $K^t_m = S^t_m / S^t_n = a_m\, k^t_m / a_n\, k^t_n$

If the nth channel is taken as the reference channel, the above complex ratios are stored as factory calibration coefficients for the mth channel. During radar operation in the field, the signals transmitted to or received from each element channel are divided by the corresponding calibration coefficient. For full DBF systems, the corrections for each channel (K^r and K^t) can be applied digitally. For ABF systems, corrections should be applied via phase shifters and attenuators. As a result, the undesired phase/amplitude shifts among the elements are corrected; and, as desired, the difference in the two channels would be caused only by the difference in the phase/amplitude settings of the channels:

$(R_m / K^r_m) / R_n = w^r_m / w^r_n$

3.2 Advantages

- Allows reliable calibration of phased array antennas without prior calibration.
- The calibration accounts for all adverse effects (mutual coupling, scattering, antenna losses).
- The test probe effects and couplings (between probe and antennas) cancel out.
- The antenna far-field pattern can be estimated from the near-field measurements.

3.3 Disadvantages

- The test setup is complex and costly.
- Not suitable for in-the field calibration.
- It is required to very precisely move the probe in front of each element.
- Takes a very long time for large antennas with many elements.

4. PERIPHERAL FIXED PROBES METHOD

In the peripheral fixed probes method, several probe antennas are placed at the periphery of the phased array antenna. Unlike the scanning probe method, the coupling (both amplitude and phase) between each probe and each antenna element is going to be different. For large arrays, the difference in coupling magnitudes leads to a wide dynamic range which is usually mitigated by using multiple test probes placed around the periphery of (or even embedded inside) the antenna array.

As we shall see next, for in-field calibration, it is not sufficient to compare the peripheral probe signals measured in the factory with the signals measured later in the field. Since the mutual couplings are different, the peripheral fixed probes method is useful only if the mutual coupling amounts were previously measured or only if the phased array antenna was previously calibrated in the factory using the scanning probe method. The peripheral fixed probes method can be applied in two different ways: by calculating or by canceling the mutual couplings. Both methods require prior calibration with a scanning probe. The steps of the method can be summarized as follows:

1) The phased array antenna is calibrated in the factory using a near-field scanning probe.
2) Measurements using the peripheral fixed probes are made in the factory to calculate the couplings.
3) Afterwards, the phased array radar can be periodically calibrated in the field using the peripheral probes.

4.1 Technique

The analytics of the method are shown in Table 1 which is based on the terminology given in Figure 3. For simplicity, a single probe is used and only the couplings and channel effects are shown. The transmitted signals are assumed identical, the antenna losses are included in the channel effects, and the phase/amplitude settings are assumed to be accounted for as discussed in the previous section.

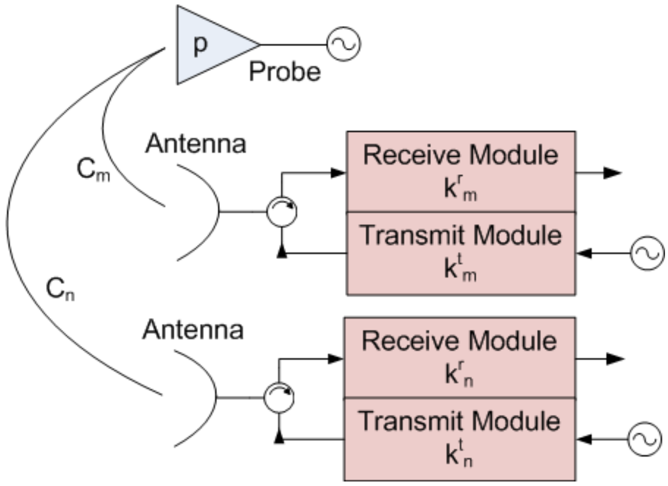

Figure 3. Calibration of a phased array radar using a peripheral fixed probe.

In Table 1, the phase/amplitude changes that occur in time are shown by the symbol ('). Equations are shown only for receive calibration but the analysis for transmit calibration is very similar (the k^r's are replaced with k^t's). Also, it is assumed that the shifts caused by both the elements and the probe(s) can change in time (e.g. due to aging or change in temperature). For receive calibration, the $(k^{r\prime}_m / k^{r\prime}_n)$ ratios need to be known.

Table 1. The steps of the peripheral fixed probes method for receive calibration.

Step	Method	Location	Measured channel m	Measured channel n	Calculated
1	Scanning probe	in-factory	$p_s.C.k^r_m$	$p_s.C.k^r_n$	k^r_m / k^r_n
2	Fixed probe	in-factory	$p.C_m.k^r_m$	$p.C_n.k^r_n$	$(C_m / C_n).(k^r_m / k^r_n) \rightarrow C_m / C_n$
3	Fixed probe	in-field	$p'.C_m.\, k^{r\prime}_m$	$p'.C_n.\, k^{r\prime}_n$	$(C_m/C_n).(k^{r\prime}_m / k^{r\prime}_n) \rightarrow k^{r\prime}_m / k^{r\prime}_n$

It can be seen from Step 2 of Table 1 that, unlike the case with scanning probe, the ratio of peripheral probe measurements includes the ratio of coupling coefficients between the probe and elements (C_m / C_n); so the ratio of amplitude/phase shifts (k^r_m / k^r_n) cannot be obtained because we would not be able to isolate the channel effects from the coupling effects. These coupling ratios can be directly measured in the factory by transmitting from the peripheral probe and connecting the same receive module to each antenna element. Alternatively, (C_m / C_n) can be obtained by combining the measurements made with a scanning probe (Step 1) and the peripheral probes (Step 2). Step 1 actually achieves factory calibration, whereas Step 2 (combined with Step 1) achieves the measurement of couplings which then allows future in-field calibration (Step 3). We note that, even if the probe characteristics do not change in time ($p' = p$), the array cannot be calibrated with peripheral probes without initially knowing the coupling ratios.

Another way to obtain the in-field calibration coefficients $(k^{r\prime}_m / k^{r\prime}_n)$ is to cancel the coupling coefficients by taking the ratio of the measurements of the same element in the factory (Step 2) and in the field (Step 3). The changes in the test antenna can be removed by dividing the ratio of an element with the ratio of another one. Finally, the initial differences among elements are removed using the factory calibration coefficients (obtained using a scanning probe) and the remaining ratios represent the current differences among elements (field calibration coefficients). This alternative approach can be shown as follows:

$D = k^{r}_{m} / k^{r}_{n}$ (scanning probe measurements)	factory calibration coefficients
$A = (p'.C_m.\ k^{r\prime}_{m}) / (p.C_m.k^{r}_{m}) = (k^{r\prime}_{m} / k^{r}_{m}).(p' / p)$	changes in time for mth channel
$B = (p'.C_n.\ k^{r\prime}_{n}) / (p.C_n.k^{r}_{n}) = (k^{r\prime}_{n} / k^{r}_{n}).(p' / p)$	changes in time for nth channel
$A/B = (k^{r\prime}_{m} / k^{r}_{m}) / (k^{r\prime}_{n} / k^{r}_{n}) = (k^{r\prime}_{m} / k^{r\prime}_{n}) / (k^{r}_{m} / k^{r}_{n})$	ratio of factory coefficients to field coefficients
$(A/B) \times D = k^{r\prime}_{m} / k^{r\prime}_{n}$	field calibration coefficients

Usually multiple peripheral probes are used to overcome the dynamic range problem and the antenna elements are measured using the nearest probe. In that case, the differences in measurements by different probes would be due to three factors (probes, couplings, and channels). If the probe effects do not change in time, then the method described above can be used for calibration. The following equations show how two measurements with two different peripheral probes can be calibrated relative to each other:

Table 2. The steps of the fixed probe method for receive calibration.

Step	**Method**	**Measured** element m	**Measured** element n	**Calculated**
1	Scanning probe (in-factory)	$p_s.C.k^{r}_{m}$	$p_s.C.k^{r}_{n}$	k^{r}_{m} / k^{r}_{n}
2	Fixed probe (in-factory)	$p_1.C_m.k^{r}_{m}$	$p_2.C_n.k^{r}_{n}$	$(p_1 / p_2).(C_m / C_n).(k^{r}_{m} / k^{r}_{n}) \rightarrow (p_1 / p_2).(C_m / C_n)$
3	Fixed probe (in-field)	$p_1.C_m.\ k^{r\prime}_{m}$	$p_2.C_n.\ k^{r\prime}_{n}$	$(p_1 / p_2).(C_m/C_n).(k^{r\prime}_{m} / k^{r\prime}_{n}) \rightarrow k^{r\prime}_{m} / k^{r\prime}_{n}$

However, if the probe effects do change in time, they would not cancel. A better approach would be to select a specific element and measure it with both probes. That way the two separate sets of elements, which are calibrated using two different probes, can be related to each other using their common element.

4.2 Advantages

- It is not necessary to move the probe precisely across each element.
- It allows periodic in-field calibration with little extra hardware.
- The probe effects do not affect the results even if they change in time.

4.3 Disadvantages

- The aperture size increases.
- It requires either prior measurement of couplings or in-factory calibration using scanning probe.
- In large phased arrays, the magnitudes of couplings between the peripheral probes and the antenna elements would span a wide dynamic range.

5. CALIBRATION LINES METHOD

Using transmission lines connected to each antenna element is a very common method for the periodic in-field calibration of small phased array radars. These calibration lines sample the signals received and transmitted by the antenna elements. The measured signals are then used to calculate the phase/amplitude differences among the element channels.

To successfully calibrate a phased array radar using this method, the phase shifts and amplitude losses caused by the transmission lines and the couplers that connect them should be equal or already known. If the tranmission lines are built using the same material and have the same radius and length, their effects would be very similar. In addition, the amplitude losses and phase shifts caused by the couplers that connect the calibration lines to antenna elements need to be measured and equalized. If these are accomplished, calibration lines can be used to calibrate the element channels. Nevertheless, the effects of different antenna elements cannot be equalized using calibration lines which are connected behind the antennas. So, for successful in-field calibration, the antenna elements, the calibration lines, and the couplers need to be calibrated in the factory first. Although these three components can each be measured separately in the factory, it would be much more accurate if they are measured simultaneously while connected to each other (and to the other components of the radar). This can be done using a scanning probe in the factory. In addition, for periodic in-field calibration, it should be assumed that the characteristics of the antenna elements, transmission lines, and couplers do not change in time. Since these components are passive, this is a reasonable assumption. However, if one of these components fails and is replaced, factory calibration should be repeated.

5.1 Technique

The analytics of the method can be explained as follows using the terminology in Figure 4.

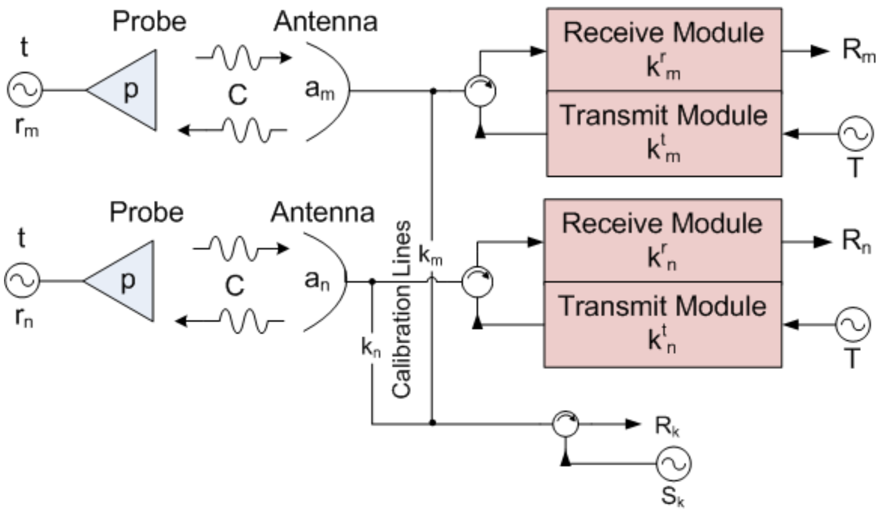

Figure 4. Calibration of a phased array radar using calibration transmission lines.

The letters in the above figure that were not previously defined are described below:

S_k : calibration signals transmitted through the calibration lines
R_k : signals received via the calibration lines
k_m : phase/amplitude effect of the mth calibration line (including the coupler)

As before, we assume the phase/amplitude settings are accounted for and the transmitted signals are identical. We also assume that the antenna and calibration line effects (a) and (k) do not change in time but the channel effects (k^r) and (k^t) can change in time.

The information needed for receive and transmit calibration: ($a_m\, k^r_m$ / $a_n\, k^r_n$) and ($a_m\, k^t_m$ / $a_n\, k^t_n$)

The steps of the calibration lines method are as follows:

1) In-factory calibration using the scanning probe method (factory calibration coefficients)

Transmit	Receive
$r_m = T\, k^t_m\, a_m\, C\, p$	$R_m = t\, p\, C\, a_m\, k^r_m$
$r_n = T\, k^t_n\, a_n\, C\, p$	$R_n = t\, p\, C\, a_n\, k^r_n$

$F^t_{mn} = r_m / r_n = (a_m\, k^t_m) / (a_n\, k^t_n)$ $\quad F^r_{mn} = R_m / R_n = (a_m\, k^r_m) / (a_n\, k^r_n)$

As shown earlier, using a scanning field probe, the array can be calibrated. However, this calibration would not be valid in the field if the channel effects change in time.

2) Calibration line measurements in the factory

Transmit	Receive
$R_{km} = T\, k^t_m\, k_m$	$R_m = S_k\, k_m\, k^r_m$
$R_{kn} = T\, k^t_n\, k_n$	$R_n = S_k\, k_n\, k^r_n$

$K^t_{mn} = R_{km} / R_{kn} = (k_m\, k^t_m) / (k_n\, k^t_n)$ $\quad K^r_{mn} = R_m / R_n = (k_m\, k^r_m) / (k_n\, k^r_n)$

For transmit calibration, Steps 1 and 2 can be done simultaneously by using the same transmitter signal. For receive calibration, Steps 1 and 2 should be done sequentially.

3) Calculation of (a / k) ratios (adjustment coefficients)

After these two steps, the ratios of the antenna effects to calibration line effects (*a / k*) can be calculated:

$AK_{mn} = (F^{t}_{mn} / K^{t}_{mn}) = (F^{r}_{mn} / K^{r}_{mn}) = (a_m / k_m) / (a_n / k_n)$

Here we assume that these ratios (AK) are identical for transmit and receive. This is valid if the ratio of coupler effects for channels (m) and (n) is similar for transmit and receive. If this is not the case, the (AK) ratios should be calculated separately for both transmit and receive. These (AK) ratios are assumed to stay constant in time and are stored in the radar software as adjustment coefficients.

These adjustment coefficients should be calculated at different frequencies (if necessary) and temperatures. The factory calibration should also be repeated whenever an antenna element, calibration line, or coupler malfunctions and is changed with a new one.

4) In-field calibration coefficients

The changes in the amplitude/phase effects of the transmit and receive modules that occur in time are shown with (').

Transmit	Receive
$R'_{km} = T\, k^{t\prime}_{m}\, k_m$	$R'_{m} = S_k\, k_m\, k^{r\prime}_{m}$
$R'_{kn} = T\, k^{t\prime}_{n}\, k_n$	$R'_{n} = S_k\, k_n\, k^{r\prime}_{n}$
$K^{t\prime}_{mn} = R'_{km} / R'_{kn} = (k_m\, k^{t\prime}_{m}) / (k_n\, k^{t\prime}_{n})$	$K^{r\prime}_{mn} = R_m / R_n = (k_m\, k^{r\prime}_{m}) / (k_n\, k^{r\prime}_{n})$
$F^{t}_{mn} = K^{t\prime}_{mn} \times AK_{mn} = (a_m\, k^{t\prime}_{m}) / (a_n\, k^{t\prime}_{n})$	$F^{r}_{mn} = K^{r\prime}_{mn} \times AK_{mn} = (a_m\, k^{r\prime}_{m}) / (a_n\, k^{r\prime}_{n})$

These complex ratios (F^{t}_{mn} and F^{r}_{mn}) should be calculated at different frequencies, temperatures, and phase/amplitude settings and are recorded in the radar software as in-field calibration coefficients. They are updated during radar operation as necessary by taking measurements from the calibration lines.

5) In-field calibration

During normal radar operation, the transmitted signals are divided by the complex field coefficients equalizing the amplitude/phase effects of the TR modules and antennas. The corrections are applied via phase shifters and attenuators in analog systems or by means of complex division in digital systems.

Transmit	Receive
$r_m = T\, k^{t\prime}_{m}\, a_m$	$R_m = t\, a_m\, k^{r\prime}_{m}$
$r_n = T\, k^{t\prime}_{n}\, a_n$	$R_n = t\, a_n\, k^{r\prime}_{n}$
$r_m / F^{t}_{mn} = r_n$	$R_m / F^{r}_{mn} = R_n$
(the two transmit channels are equalized)	(the two receive channels are equalized)

5.2 Advantages

- Direct sampling of phases and amplitudes allows precise calibration.
- Suitable for periodic in-field calibration.
- Does not increase the size of the aperture.

5.3 Disadvantages

- Requires extra hardware behind antennas (high cost for large arrays).
- Requires prior in-factory calibration.
- Requires re-calibration in the factory if the characteristics of a transmission line, coupler, or antenna element change in time (i.e., due to aging or replacement).

6. MUTUAL COUPLING METHOD

This method, first proposed by Aumann, Fenn, and Willwerth (1989)[10], is based on the idea that the mutual coupling among the array elements can be used to measure the phase/amplitude differences among the elements by transmitting from an element and receiving from another. It should be emphasized that the aim of mutual coupling calibration is not to correct the errors due to mutual coupling and scattering, but to take advantage of the mutual coupling to measure and compensate the phase/amplitude shifts due to the RF hardware. In fact, the effects of mutual coupling and scattering are usually much lower than the errors due to the RF hardware.

It is a very practical calibration method for phased array antennas as it allows periodic in-field calibration without requiring initial in-factory calibration. However, in order to take advantage of it, several requirements should be met:

- Radar should be able to simultaneously transmit with one element and receive with another.
- All other elements should be able to be switched off.
- The mutual couplings among the elements should be identical.
- The mutual coupling amplitudes should not be too high or too low.

In a full DBF system, there is a separate receive channel for each element, so the on/off switches are not required. For ABF systems, an on/off switch for each element is required so that the signals received from each element are isolated. In addition, the combiner in the beamformer should be separate from the divider used to distribute the transmitter signal. For mutual couplings to be identical, the distances between the elements should be uniform and the element patterns in the aperture plane should be isotropic (or at least symmetric in the row and column directions). For large phased array antennas, this is usually the case. In small arrays, it might be necessary to add a couple rows of dummy elements along the periphery to have uniform mutual couplings.

The amplitude of mutual coupling between two neighbor elements depends on the antenna element pattern and the distance between the elements and it is usually between -15 dB and -25 dB[9, 12]. For mutual coupling calibration to be successful, the amount of mutual coupling should be high enough to be detected but low enough not to saturate the receiving element. This can be adjusted by changing either the element type or the distance between elements but it is usually not possible to change these parameters; so, the best way to obtain the ideal signal strength would be to adjust the transmitted power. In any case, the mutual couplings should be kept as low as possible to keep its adverse effects on radar operation to a minimum. So, the ideal solution would be to choose an antenna type with a low directivity in the aperture plain and to use high transmitter power during calibration to obtain a detectable amount of mutual coupling.

6.1 Technique

The mutual coupling method can be explained as follows using the terminology in Figure 5.

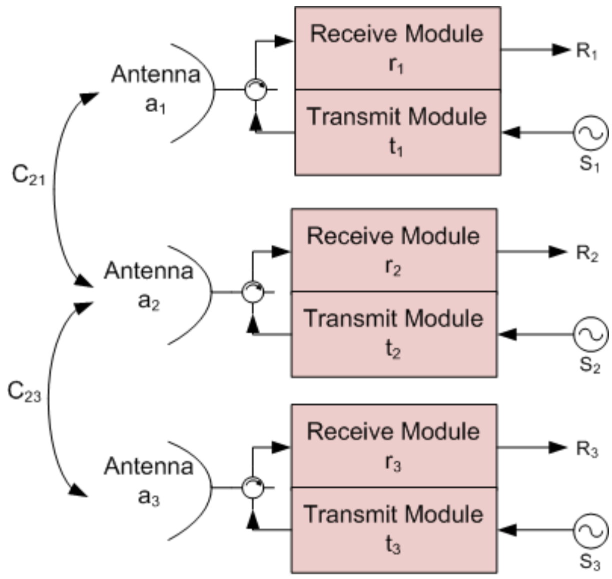

Figure 5. Transmit and receive calibration of a phased array radar using the mutual coupling method.

$$R_{nm} = S_n.t_n.a_n.C_{nm}.a_m.r_m$$

R_{nm}	signal transmitted by element n and received by element m	(measured)
S_n	signal transmitted through the nth transmit module	(known)
C_{nm}	the amount of mutual coupling between elements n and m	(unknown)
a_n	phase/amplitude shifts due to nth antenna element	(unknown)
t_n	phase/amplitude shifts due to nth transmit module	(unknown)
r_m	phase/amplitude shifts due to nth receive module	(unknown)

If the distance between elements are uniform and their patterns isotropic in the aperture plane: $C_{nm} = C$
If we keep the transmitted signals and the phase/amplitude settings constant or normalize them: $S_n = S$

Receive

For receive calibration of elements (1) and (3), we transmit from element (2) (which has same amount of mutual coupling with both elements) and receive from elements (1) and (3). Taking the ratio of these two measurements cancels out the effects of antenna element (2) and its transmit module and provides the ratio of phase/amplitude shifts due antenna elements (1) and (3) and their respective receive modules. This ratio gives the calibration coefficient to equalize receive channels of elements (1) and (3).

$R_{21} = S_2.t_2.a_2.C.a_1.r_1$
$R_{23} = S_2.t_2.a_2.C.a_3.r_3$

$K^r_{13} = R_{21} / R_{23} = (r_1.a_1) / (r_3.a_3)$

Transmit

For transmit calibration of elements (1) and (3), we transmit consecutively from elements (1) and (3) and measure the two signals received by element (2). Once again, taking the ratio of these two measurements cancels out the effects of antenna element (2) and its receive module and provides the ratio of phase/amplitude shifts due channels (1) and (3). This ratio gives the calibration coefficient to equalize transmit channels of elements (1) and (3).

$R_{12} = S_1.t_1.a_1.C.a_2.r_2$
$R_{32} = S_3.t_3.a_3.C.a_2.r_2$

$K^t_{13} = R_{12} / R_{32} = (t_1.a_1) / (t_3.a_3)$

The transmit and receive calibration coefficients obtained (K^r_{13} and K^t_{13}) are then used during radar operation to equalize the responses of channels (1) and (3) to each other. If we apply this procedure to the other elements of a linear array, all odd numbered elements can be calibrated relative to each other. Similarly, all even numbered elements can be calibrated relative to each other (Figure 6).

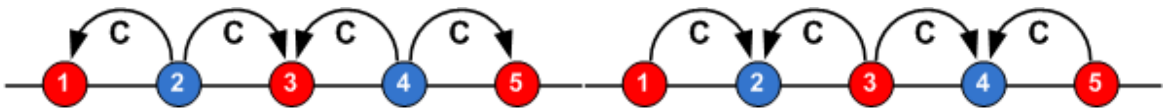

Figure 6. Calibration of a linear array using the mutual coupling method for receive (left side) and transmit (right side). The arrows represent the direction of signal and the odd (even) elements that are calibrated relative to each other are shown by red (blue) color.

6.2 Calibration of even and odd elements:

It is also possible to calibrate the even and odd elements of a linear array relative to each other. This is illustrated in Figure 7.

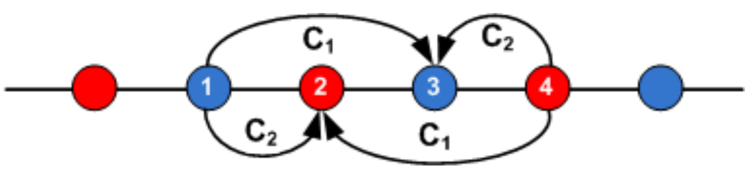

Figure 7. Mutual coupling calibration of odd (blue) and even (red) elements of a linear array relative to each other.

Two odd (blue) elements and two even (red) elements are chosen. One of each color transmits (1 and 4) and the other two receive (2 and 3). Signals received by each receiver from both transmitters are then measured:

$R_{13} = t_1.C_1.r_3$
$R_{12} = t_1.C_2.r_2$
$R_{43} = t_4.C_2.r_3$
$R_{42} = t_4.C_1.r_2$

Using these measurements, even and odd elements can be calibrated relative to each other:

$(R_{13}.R_{12}) / (R_{43}.R_{42}) = (t_1 / t_4)^2$
$(R_{13}.R_{43}) / (R_{12}.R_{42}) = (r_3 / r_2)^2$

In addition, the mutual coupling ratios, although not necessary, can be calculated:

$(R_{13}.R_{42}) / (R_{12}.R_{43}) = (C_1 / C_2)^2$

6.3 Calibration of 2D arrays

The mutual coupling technique was extended to 2D arrays by Shipley and Woods (2000)[13]. The application of mutual coupling method to a 2D array depends on the array geometry (i.e., hexagonal, triangular, rectangular). In a hexagonal (i.e., equilateral triangular) array, all elements can easily be calibrated relative to each other. This is demonstrated in Figure 8. First the red dots, then the blue dots are calibrated relative to each other using the black dot in the middle as the common transmitter or receiver. Then the red and blue dots can easily be calibrated relative to each other by means of their common element (shown in purple).

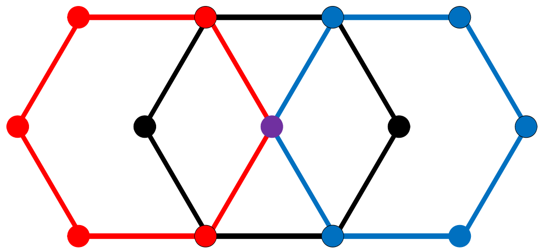

Figure 8. Calibration of a hexagonal array using the mutual coupling method. For each reference element, six elements around it can be calibrated.

The calibration of a triangular or square array (Figures 9 and 10) is similar to the calibration of linear array. First, the odd (red) and even (blue) elements are calibrated relative to each other. By transmitting or receiving from each blue (red) element, four red (blue) elements around it can be calibrated. With the choice of transmit/receive pairs shown in the right panels of Figures 9 and 10, the same equations given above for the linear array can be used to calibrate the two halves of the triangular or square array relative to each other.

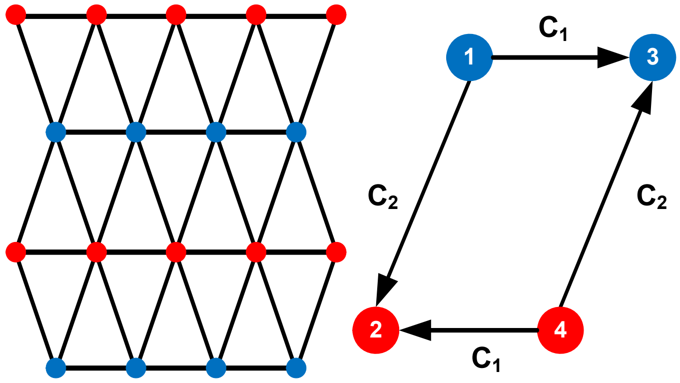

Figure 9. Calibration of a triangular array using the mutual coupling method. In the right figure, elements (1) and (4) transmit whereas elements (2) and (3) receive. This allows calibration of red and blue elements relative to each other.

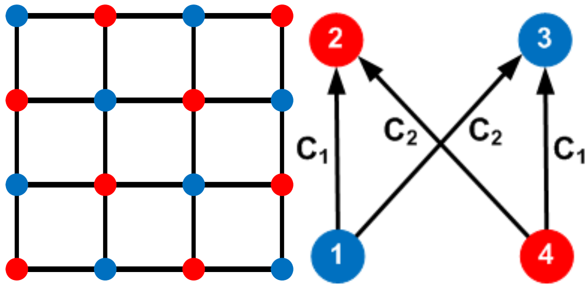

Figure 10. Calibration of a square array using the mutual coupling method. In the right figure, elements (1) and (4) transmit whereas elements (2) and (3) receive. This allows calibration of red and blue elements relative to each other.

Calibration of a rectangular array is a bit more complicated. As shown in Figure 11, only a quarter of the array elements can be directly calibrated relative to each other. This results in four different subarrays that need to be calibrated relative to each other. This can be achieved by using four neighbor elements and choosing three different transmit/receive pairs from the six possible combinations. Three such transmit/receive choices are shown in Figure 11. The first combination achieves receive calibration of elements (2) and (3) and transmit calibration of elements (1) and (4). The second combination achieves receive calibration of elements (1) and (4) and transmit calibration of elements (2) and (3). The third combination achieves receive calibration of elements (1) and (2) and transmit calibration of elements (3) and (4). Alternatively, full calibration can also be achieved by applying the linear array method to two rows and one column or two columns and one row.

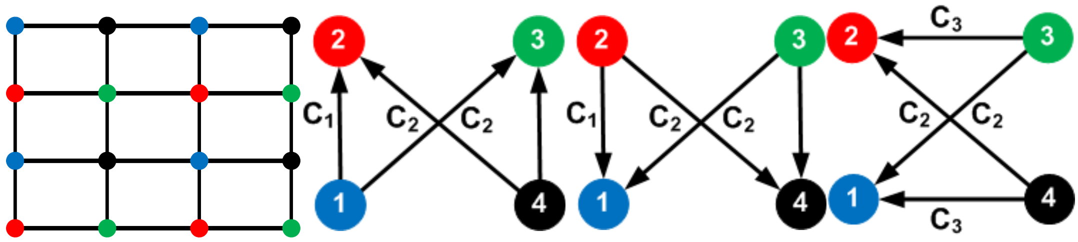

Figure 11. Calibration of a rectangular array using the mutual coupling method. Three different transmit/receive combinations are necessary to calibrate each quarter of elements relative to each other.

To summarize, mutual coupling calibration consists of the following steps:

- Calibration of one half (or quarter) of the array
- Calibration of the other half of the array
- Calibration of the two halves relative to each other
- Repetition of calibration for transmit and receive

6.4 Detection and avoidance of faulty elements:

As mentioned earlier, for mutual coupling calibration to be successful, the mutual coupling amounts should be very similar which requires that the distances between elements are uniform. If the position of an element is offset from its ideal position the calibration of all other elements involving that element would be incorrect. In other words, since the calibration is done in series, the error involving a single element propagates to other elements. This is also true if any RF component connected to an element is malfunctioning (i.e., fails to transmit or receive signals or highly attenuates them). Thus, if calibration is done using the mutual coupling method, a smart calibration algorithm that detects and avoids the faulty (malfunctioning or offset) elements should be used. Such an algorithm was proposed by Neidman, Shavit, and Bronshtein (2009)[15]. The algorithm first detects the faulty element channels. The position errors can be detected by locating the elements with unexpectedly high or low amplitude ratios. For example, an unexpectedly high $|R_{21}|$ / $|R_{23}|$ ratio indicates that the position of element (2) is shifted towards element (1). On the other hand, the malfunctioning element channels can be found from the fact that such elements transmits/receives no (or very low) signal. However, as each measurement involves two elements, two measurements involving the same element should give zero (or very low) signal to locate the faulty element. For example, if both $|R_{32}|$ and $|R_{34}|$ are zero or very low then it is most likely that element channel (3) is faulty. It is also possible but much less likely that element (3) works fine and both elements (2) and (4) are faulty. By making extra measurements with elements (2) and (4) (e.g., R_{12} and R_{54}), it can be verified that element (3), not (2) and (4), is faulty.

After the faulty elements are located, they should be bypassed during mutual coupling calibration. For example, if a faulty element is encountered during the calibration of a row, calibration can continue using a few elements from the row above (or below) as illustrated in Figure 12. In the figure, elements Red-2 and Red-3 are calibrated using element Blue-3, and elements Red-3 and Red-4 are calibrated using element Blue-4. Similarly, Blue-2 and Blue-3 are calibrated using Red-2, Blue-3 and Blue-4 are calibrated using Red-3, and Blue-4 and Blue-5 are calibrated using Red-4.

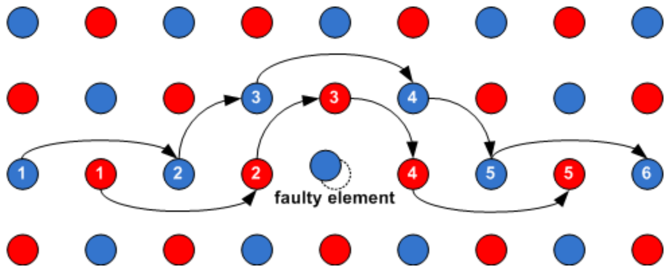

Figure 12. An illustration of how to bypass faulty elements during mutual coupling calibration.

6.5 Advantages

- No additional hardware is required (except on/off switches).
- Allows periodic in-field calibration without any in-factory calibration.
- Very convenient for large arrays in contrast to other methods.
- Coupling dynamic range can be easily optimized (unlike peripheral probes method).

6.6 Disadvantages

- Requires on/off switches and separate channels for simultaneous transmit and receive.
- Element spacing (and patterns) in row and column directions should be uniform (symmetric).
- Requires dummy elements at the periphery for small arrays.
- Requires smart algorithm to detect and avoid faulty elements.

7. DISCUSSION

It can be concluded that the best calibration method depends on the specifications of the phased array radar system. Among the four methods studied, the scanning probe and mutual coupling methods allow direct measurements of amplitude/phase shifts of both the antenna and RF hardware. Thus, these two methods can be used for factory calibration. Due to the physical movement of the probe, the scanning probe method takes much longer than the mutual coupling method, but it is more accurate, allows derivation of antenna far-field pattern and can be applied to any phased array radar system as opposed to the mutual coupling method which has several prerequisites. However, the mutual coupling method can be used for both in-field and in-factory calibrations, whereas the scanning probe method is feasible only for in-factory calibration. The other two methods studied, calibration lines and peripheral fixed probes, allow only for the re-calibration of a radar that was previously calibrated in-factory. Thus, these two methods are best suited for periodic in-field calibration.

In general, the mutual coupling method, which achieves direct calibration, has a small dynamic range, and requires no extra hardware, is the most convenient in-field calibration method, especially for large phased array antennas with many elements. But it does not apply to all radar systems as mentioned before. On the other hand, the peripheral fixed probes and calibration lines methods can be better options for small arrays with few elements or for radars that do not meet the requirements of mutual coupling method. If the cost or the space behind the aperture is an issue, the peripheral probes method, which requires less hardware, would be a better choice; whereas, if accuracy or aperture size is an issue, then the calibration lines method, which has no dynamic range issue and does not increase aperture size, would be a better option.

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