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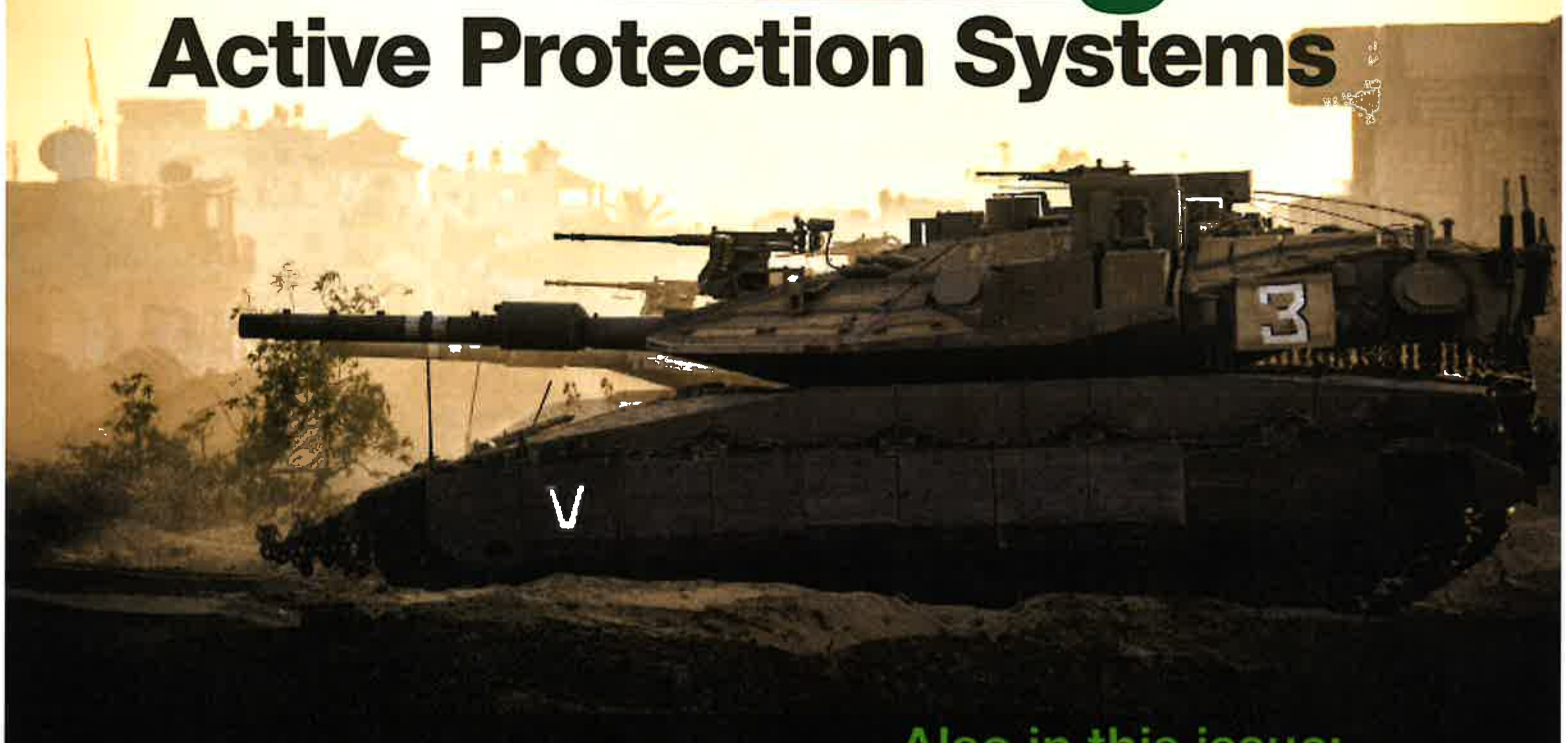


Also in this issue:

55th Annual AOC International Symposium and Convention Guide

Thinking Through Collaborative EW Part 3 – Distributed Jammers and Array “Gain”

EW 101: Upgrades to Acquisition Radars (Cont.)

Thinking Through Collaborative Electronic Warfare

Part 3 – Distributed Jammers and Array "Gain"

Dr. John A. Kosinski and Dr. Phil Mumford

Collaborative EW – multiple systems working together for increased effectiveness – is the way of the future. As we explore collaborative EW, we need to be careful in bounding expectations as to what can and cannot be achieved. The importance of this point cannot be understated as some simplistic views of collaborative EW are actually too simplistic. In this article, we will clear up some misconceptions that might creep back into the envelope analyses. We will discuss some potentially confusing terms that are used with multiple meanings, and some aspects of arrays as necessary ground work for considering collaborative EW.

A QUICK REVIEW

In our first installment, we established two important points:

a) Conservation of energy is absolute.
b) One cannot just use simple properties of idealized plane waves for "back-of-the-envelope" reasoning about complicated electromagnetic (EM) fields generated by multiple sources.

In our second installment, we established two additional points:

a) Antenna "gain" is not the same as the thing we call "gain" in any other part of an EW system.
b) Antenna "gain" does not increase the total power level of the propagating signal.

"LOSS" – ANOTHER WORD WITH MULTIPLE DEFINITIONS

We noted last time that the word "gain" has different meanings in the different contexts of electronic systems and antennas/arrays. The same is also true for the word "loss" as seen in **Table 1.** We need to make sure that there is no

TABLE 1 – IMPORTANT DEFINITIONS [1]

TERM	DEFINITION
Loss	[COMMUNICATIONS] See transmission loss. [ENGINEERING] Power that is dissipated in a device or system without doing useful work. Also known as internal loss.
Internal Loss	See loss.
Dissipation	[PHYSICS] Any loss of energy, generally by conversion into heat; quantitatively, the rate at which this loss occurs. Also known as energy dissipation.
Energy Dissipation	See dissipation.
Transmission Loss	[COMMUNICATIONS] 1. The ratio of power at one point in a transmission system to the power at a point farther along the line; usually expressed in decibels. 2. The actual power that is lost in transmitting a signal from one point to another through a medium or along a line. Also known as loss.
Array	[ELECTRONICS] A group of components such as antennas, reflectors, or directors arranged to provide a desired variation of radiation transmission or reception with direction.

confusion going in to the "back-of-the-envelope" calculations.

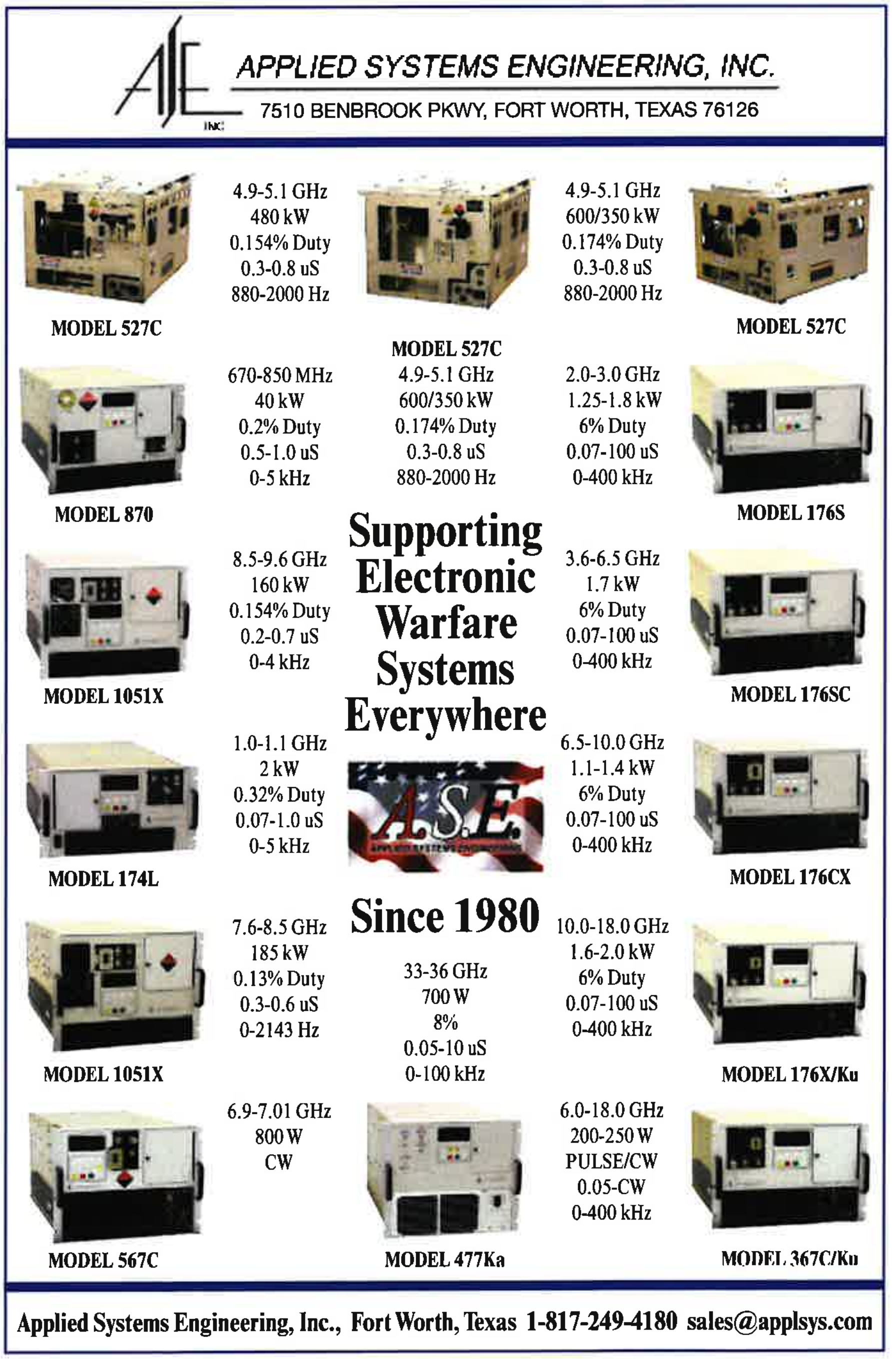
In one usage, the word "loss" refers to energy dissipation, usually through the conversion of electrical or mechanical energy to heat. This energy is lost both to the intended user and to anyone else that might want to use it. In RF propagation, we have absorption of energy by the heating of water vapor and other molecules present in the atmosphere. This absorption varies with frequency and exhibits pronounced peaks at the resonance frequencies of the various molecules.

TABLE 2 – FORMS OF THE "SPREADING LOSS"

"SPREADING LOSS"	UNITS
$LS = (4\pi/c)^2 \times (R \times f)^2$	any consistent set
$LS(dB) = 32 + 20 \log(f) + 20 \log(R)$	f in MHz, R in km

In the context of RF and other links, the term "loss" is also used to describe energy that is *not* dissipated, but simply goes elsewhere and is not captured for use at the receiving end of the link. For simplicity, this loss is sometimes referred to as "spreading loss," which can be misleading as there is more to it than just "spreading." This type of loss overall is more properly referred to as *"link loss"* or better yet *"link leakage."* The leakage can be eliminated by a combination of more fully directing the energy toward the intended receiver, and narrowing the beam or increasing the receive antenna capture area.

Some common equations for "spreading loss" are shown in **Table 2.** As expected, the "spreading loss" equations depend on the distance between the transmitter and the receiver, since a spherical wave front "spreads out" with distance. But notice that there is also frequency dependence. How can "spreading out," which is a purely geometric effect, depend on frequency? The answer is that it can't, and it doesn't. The actual "spreading" depends only on distance. What depends on frequency is the capture area of the receive antenna. The effective area of the receive antenna is larger for longer wavelengths (lower frequencies) and smaller for shorter wavelengths (higher frequencies). Note that the critical pointing (or actually *mis*-pointing) loss is obscured by the way the antenna gain terms are written without indicating any angular dependence. The gain values achieved in practice depend on how the antenna patterns are aligned relative to the axis connecting the jammer and its target, and this will be a significant effect for arbitrary groups of jamming assets attempting to work together. Overall, the phenomenology is this: the jammer antenna gain helps establish the initial power flow density in the direction of the target; this is diminished by spherical spreading; the reduced power flow density at the target is captured over an effective area that depends on the gain of the targeted antenna along the direction from which it is receiving the jamming signal; power transfer is larger when both antenna patterns align for maximum gain along the axis between



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the antennas; power transfer is maximized when the jammer has sufficient gain for the jamming signal to be fully captured by the targeted antenna.

"GAIN" AND "ACTIVE ANTENNAS"

We noted last time that the radiating element in an antenna is a passive component that acts as a transducer. What then is an "active antenna?" An active antenna is essentially one or more passive radiating elements with integrated amplification. The active antenna therefore provides both types of gain. Because these are two different things, they should be broken out separately for phenomenological clarity in any back-of-the-envelope reasoning.

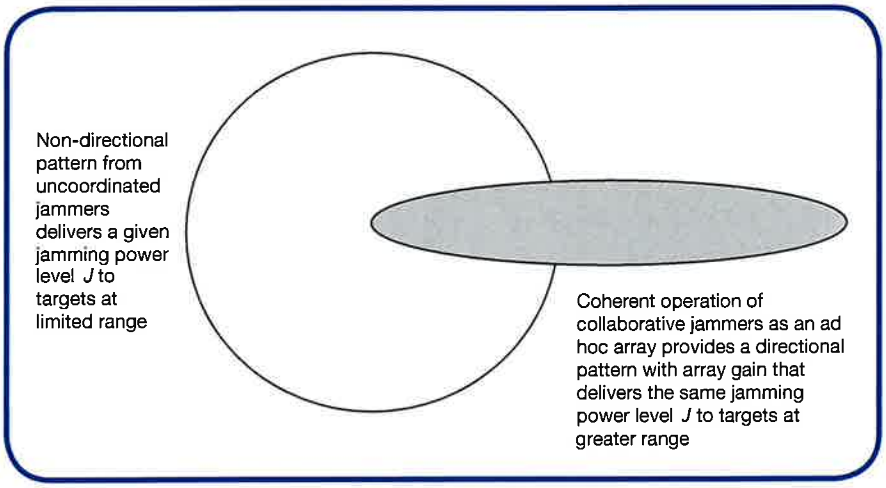

Figure 1. An over-simplified concept of collaborative EW. An omnidirectional radiation pattern is transformed into a highly directional radiation pattern without regard to the details of the collaborating systems and how this is accomplished. The visual presentation infers that collaborative EW will enable jamming from greater range.

AD HOC ARRAYS OF COLLABORATIVE EMITTERS

A basic premise of collaborative EW is that multiple systems can work together for greater effect. We agree with that premise, but care must be taken in thinking through the meaning of "greater" and the types of effects that can be achieved. An overly simplistic assumption we have heard repeatedly is illustrated in **Figure 1.**

The collaborating EW systems form an ad hoc array that generates a directional beam with "gain," and therefore the jamming power delivered to a distant target will be increased by the amount of "gain" associated with the ad hoc array factor. Can things really be that simple? In general, no. Things are only that simple for limited special cases that have no guarantee of being useful.

Figure 2 shows a simple linear antenna array. This example embodies two explicit characteristics that help define an "array." Firstly, the elements are arranged in a regular geometric pattern, and secondly, the element patterns are identical. But there is also an implicit characteristic that cannot be ignored: *as seen from the target, the array needs to look like a point source*. This appears in many antenna texts as an assumption of parallel rays emanating from the array elements, and this is equivalent to the superposition of identically-directed plane waves at the target. With regard to phenomenological clarity for thinking through novel problems, it is critical to understand that this is a useful fiction and not actually true! The assumption of parallel rays/identically-directed plane waves greatly simplifies the mathematics involved in analyzing an array. But, it is only *approximately* true for closely-spaced array elements observed at long range, and clearly cannot be *precisely* true for *any* set of spatially separated points. We are emphasizing this point because it plays directly into the "field-stacking" confusion we discussed in an earlier article.

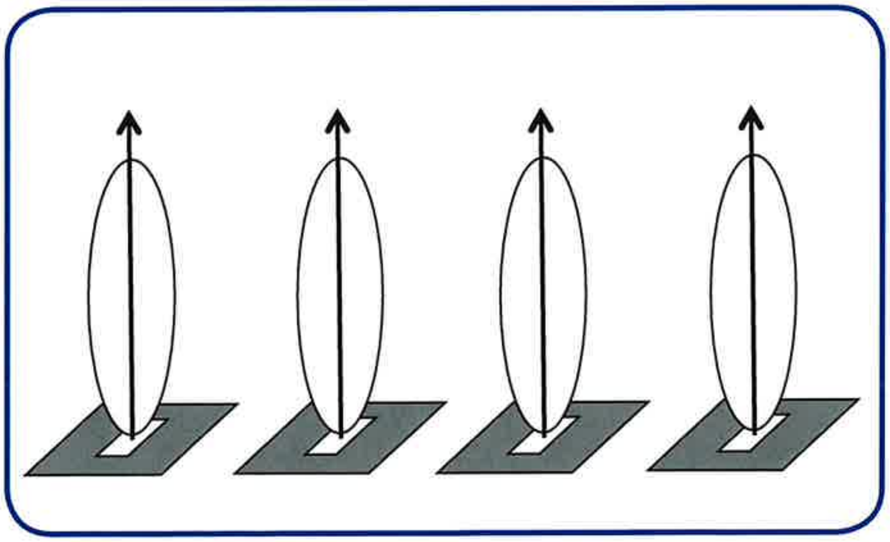

Figure 2. Example of an antenna array composed of identical radiating elements *placed in a* regular geometric arrangement. *Here we have illustrated a simple linear array of directional antennas shown as dark gray patches with slots. The outward directed radiation patterns are shown as light gray ovals.*

The overall pattern of an array, such as that in Figure 2, can be found simply. The Pattern Replication Theorem establishes the overall pattern as the product of one copy of the element pattern and an array factor which is also a pattern with directional "gain." The array factor is calculated assuming all of the elements are isotropic radiators. It can be calculated for any geometry, but is much simpler for regular arrays. The *shape* of the array factor pattern can be obtained by assuming "field-stacking" of signals radiated by the various elements. Note however, the *magnitudes* of the element, array, and/or total patterns are always constrained by conservation of energy – the total radiated power found by integration over the pattern cannot exceed the specified

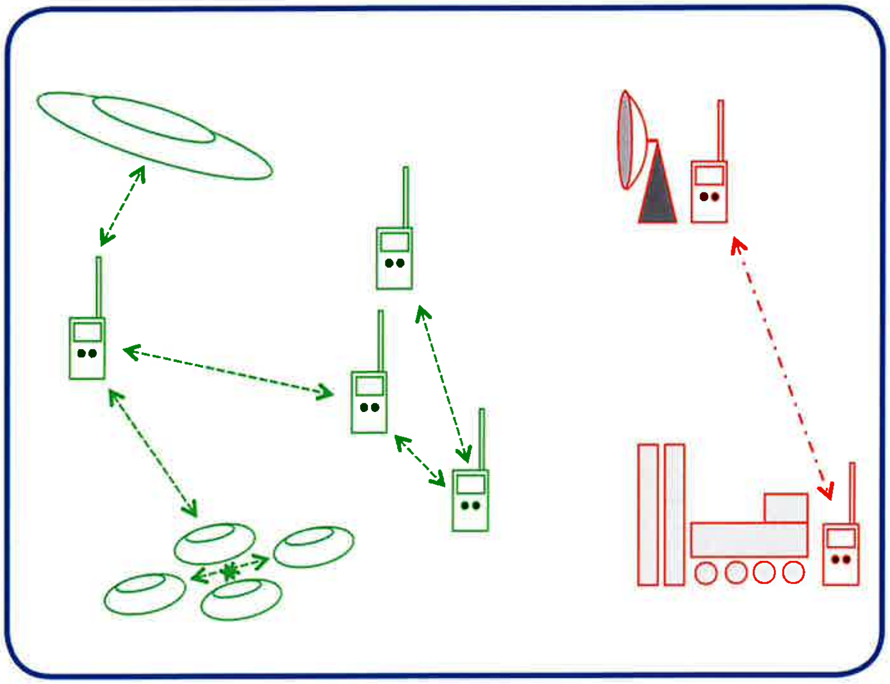

Figure 3a. Practical collaborative EW. A heterogeneous collection of RF transmitters in an arbitrary and dynamic configuration work together against a heterogeneous collection of sensors, weapons, and communications systems. We illustrate a notional large body airborne support jammer at standoff range, numerous mobile ground units, and a flight of advanced tactical aircraft (illustrated in green) engaging a radar, TEL, and associated comms, showing the notional comms links (illustrated In red).

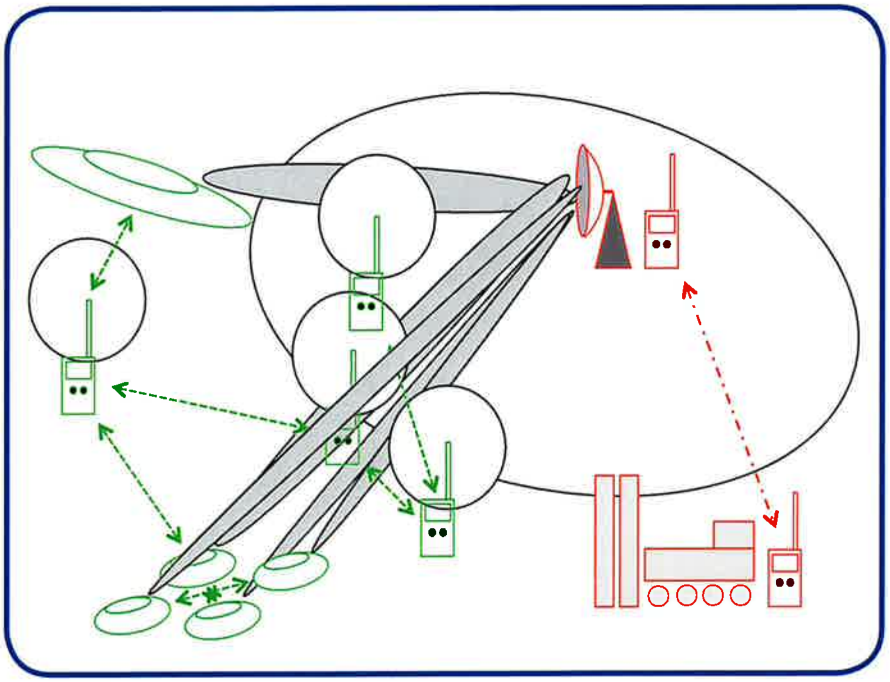

Figure 3b. Practical collaborative EW. The overlay shows the nominal antenna patterns for the heterogeneous collection of RF transmitters in high bands (dark gray) and low bands (light gray). The point of note is that we have different radiating elements placed in an irregular geometric arrangement.

power radiated by the single element or array of elements.

A naive presumption for collaborative EW is that the "gain" of the array factor is available to increase the power delivered by an arbitrary configuration of jammers. This presumption is incorrect. Consider what we actually have in most practical collaborative EW scenarios as illustrated in **Figure 3,** where a heterogeneous assortment of assets with different and differently-oriented antenna patterns are found in an irregular geometric arrangement.

The Pattern Replication Theorem is not applicable in this type of scenario! That theorem is specific to the case of identical radiation patterns for all elements in the array. Not only do the patterns need to have the same shape for this theorem, but they need to have the same orientation and polarization.

What about a swarm of identical assets? In theory, this could be done with tight coordination and very precise (i.e., very expensive) position, navigation, and timing. But the array behavior will be different than that normally expected of arrays for another reason – the element spacing.

Figure 4 shows the array factors for a two-element array excited with equal amplitude and phase with half-wavelength spacing and full-wavelength spacing. The half-wave spacing produces only the desired main lobes, whereas the full-wavelength spacing introduces two undesired grating lobes. Arrays are typically designed with element spacing of half-wavelength or less in order to avoid these grating lobes. More and more grating lobes are introduced as the spacing is further increased. Considering the case of radar wavelengths on the order of 1 cm and airborne platforms on the order of 1 m length/wingspan, the array elements will have spacing greater than 100 wavelengths with a correspondingly large number of grating lobes. The situation is even more extreme for larger platforms spaced by tens of kilometers.

EFFECTIVE ISOTROPIC RADIATED POWER

Figure 5 shows one final area where some confusion exists.

The Effective Isotropic Radiated Power (EIRP), also referred to as Equivalent Isotropically Radiated Power, is a useful metric for comparing options to achieve a given level of link performance. It is correctly described as the transmit power level of an isotropic source that would deliver the same amount of power as a different transmitter combined with

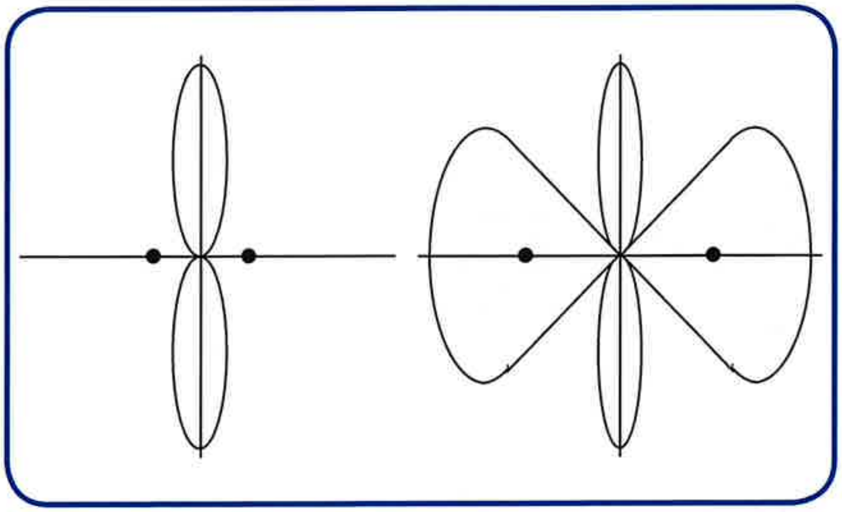

Figure 4. Array factors for a two-element array excited with equal amplitude and phase (left) with half-wavelength spacing and (right) full-wavelength spacing illustrating the presence of grating lobes as the spacing is increased. More and more grating lobes are introduced as the spacing is further increased.

a directional antenna, *to a specified location in space.* It is *not* "...the output power when a signal is concentrated into a smaller area by the antenna." In decibel form, EIRP = $P_T + G_T$ where P_T is the actual transmitted power and G_T is the transmit antenna gain *in the direction of interest.* Quite often, EIRP is calculated based on the maximum transmit antenna gain, but this is only correct if the antenna is pointed directly in the direction of interest. The directional dependence is not explicit in the simplified engineering expression, but can be a significant factor for collaborative EW, where we expect to have multiple jammers and multiple targets scattered throughout the battlespace.

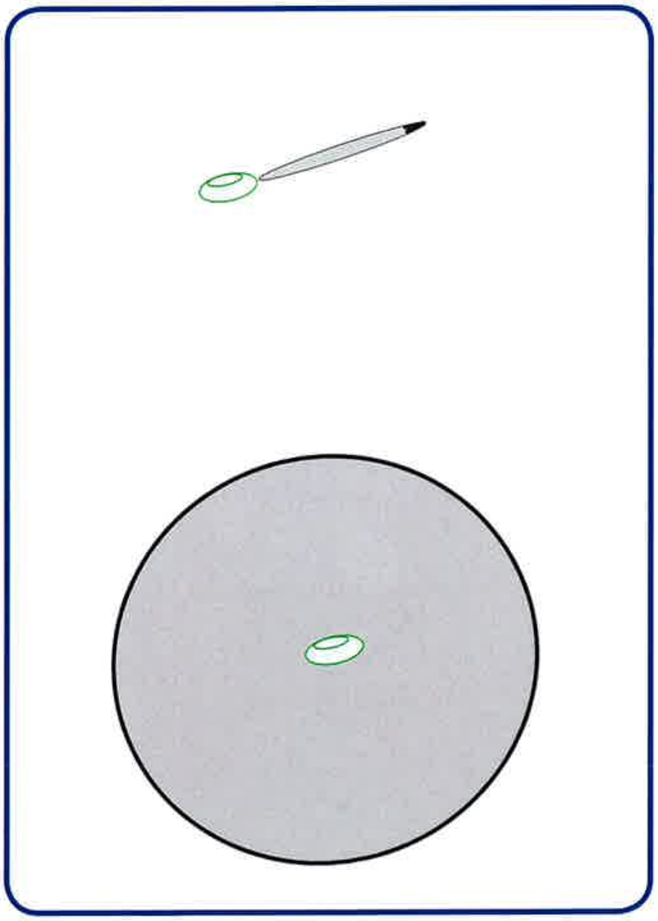

Figure 5. Illustration of transmitted jammer power density using a directional antenna (top) as compared to that of the Effective Isotropic Radiated Power (bottom, also known as Equivalent Isotropically Radiated Power).

POINTS TO REMEMBER FOR THE BACK-OF-THE-ENVELOPE

There is a saying, "If you live long enough, you will see everything." We have seen the various misconceptions discussed in these articles in print, in briefings, and elsewhere. Our hope is to not see them again.

So, what do we need to remember when making back-of-the-envelope calculations for collaborative EW? Here are the important points:

1) Be on the lookout for technical terms like "gain" and "loss" that have different meanings in different contexts. Always be aware of the context.
2) A heterogeneous assortment of collaborative EW assets scattered about the battlespace and an "array" are two different things. And, where an array can be formed, the elements will not be closely-spaced and the pattern will include a large number of grating lobes. The desirable behavior of a closely-spaced array (array factor "gain" and no grating lobes) should not be expected from something that is not.

MORE TO CONSIDER

We have spent a fair amount of time trying to dispel these misconceptions. In a sense, we have been trying to clarify *what not to expect* from collaborative EW. So what should we expect? We will tackle this next time.

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REFERENCES

[1] McGraw-Hill Dictionary of Scientific and Technical Terms, Fourth Edition, McGraw-Hill Book Company, New York, 1989, ISBN-0-07-045270-9.w