Control Red Perception: Vision and Enabling Technologies

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ABSTRACT

Today's electronic warfare (EW) missions face increasingly agile, multimodal, highly integrated, and long-range threats. To help its sponsors accomplish their missions in the face of these threats, the Johns Hopkins University Applied Physics Laboratory (APL) Precision Strike Mission Area developed a vision for achieving information dominance and delivering overwhelming effects against our adversaries. This vision relies on using our EW systems in concert with other operational platforms and capabilities to control adversary, or Red, perception. Implementing this strategy requires revolutionary advancements in EW systems so that they operate in an intelligent, distributed, and collaborative manner. Investment in foundational technologies that enable these capabilities is a prerequisite to accomplishing the strategy and staying ahead of pacing threats. This article describes the technology gaps that must be filled to realize the vision of controlling Red perception and details recent APL independent research and development projects that are positioned to provide game-changing thought leadership and capability innovations to satisfy those gaps.

CONTROL RED PERCEPTION—MISSION, GAPS, AND STRATEGY

APL's Precision Strike Mission Area (PSMA) provides thought leadership, innovative capabilities, forward-looking system requirements, and practical solutions to enable its sponsors to achieve their electronic warfare (EW) mission objectives. Typical missions include an airborne electronic attack system providing EW support for a strike package of fighters; EW to support a maritime counter-C5ISR (command and control, communications, computing, combat, intelligence, surveillance, and reconnaissance) mission for safe passage of a carrier strike group; and EW support of ground troops by countering improvised explosive device and counter–unmanned aerial system threats. While each of these missions presents unique challenges for an EW system, some common challenges span the breadth of current EW capabilities. Adversary intelligence, surveillance, and reconnaissance (ISR) and weapons systems are rapidly evolving in terms of electronic protection features, waveform parameter agility, and the spectrum over which they can operate. The adversary's ability to leverage commercial off-the-shelf (COTS) systems and technologies has accelerated the fielding of threat systems that stress traditional Blue EW capabilities and tactics. These Red threat systems' agility challenges traditional sensing and identification techniques. The wide range of operating frequencies increases the probability that traditional receivers will miss out-of-band threat transmissions. Finally, because many threat systems are composed of COTS components, the radio frequency (RF) transmissions are able to blend in with other innocuous system transmissions, making it challenging to identify Red signaling within the RF spectrum.

The PSMA Control Red Perception vision, illustrated in Figure 1, seeks to achieve information dominance and deliver overwhelming EW effects against adversaries. By controlling the adversary's perception via manipulation of its sensors, real-world platforms such as aircraft or a carrier strike group could be concealed or could appear as other types of platforms or an overwhelming number of contacts.

A fundamental milestone that must be met before these capabilities can be realized is the development of collaborative EW concepts and technologies enabling distributed, disparate EW systems to work together to control Red perception. These collaborative EW concepts and technologies need to leverage the tactical use of space, airborne, ground, and/or sea-based platforms that adapt and learn from changes in the environment and deliver coordinated effects (i.e., collaborative use of military tactics, electronic support [ES], electronic attack [EA], decoys, and cyber effects). The objective of these coordinated effects is to fill current and projected EW capability gaps—and ultimately offer resilient, survivable strike options; provide an offensive sanctuary for strike platforms; and enable freedom of maneuver for Blue forces.

For the purposes of this article, the term *distributed* describes multiple disparate or similar platforms that play specific roles in achieving a given mission. The term *cooperative* describes distributed platforms working together to achieve a common task with predefined roles and rule sets that do not interfere with each other (such as a receiver and jammer blanking to conduct ES and EA). In contrast, *collaborative* implies that the participating EW systems can deviate from predefined roles and are therefore dynamic and able to work together and learn from each other to accomplish common task objectives.[1] In describing the Control Red Perception vision, we describe the advantages of distributed EW to motivate technical exploration of these concepts. In our role as a trusted agent for the Department of Defense, we understand the importance of system acquisition

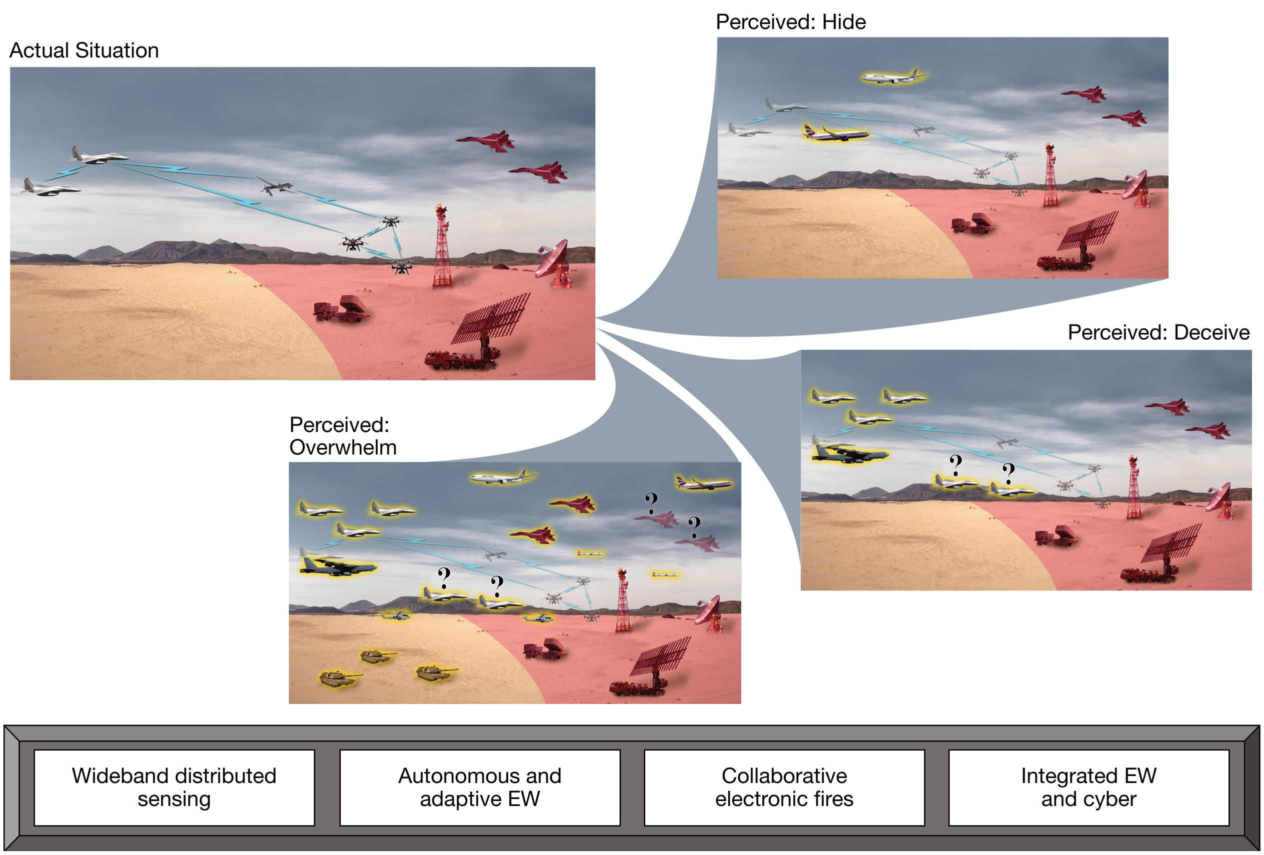

Figure 1. Control Red Perception effects and foundational capabilities. APL's PSMA Control Red Perception vision seeks to achieve information dominance and deliver overwhelming EW effects against adversaries. Manipulating the adversary's sensors could conceal real-world platforms or make them appear as other types or an overwhelming number of platforms. Underlying this vision are four foundational capabilities, shown at the bottom.

and operating costs in evaluating the benefit of these technologies, but we do not specifically consider costs in this article.

Embedded within cooperative and collaborative EW concepts are underlying technology gaps that must be satisfied to accomplish the Control Red Perception strategy. Maturation of the foundational capabilities, including wideband distributed sensing, autonomous and adaptive EW, collaborative electronic fires, and integrated EW and cyber (highlighted in Figure 1), will facilitate the development of collaborative EW concepts around sponsors' mission gaps and assessment of those concepts' operational utility. The remainder of this article describes the technical innovations required to enable the Control Red Perception strategy. We begin by describing the four foundational capabilities shown in Figure 1 and then offer some examples of enabling technologies that impact multiple foundational capabilities. Finally, we conclude with a summary of related proof-of-concept technology development being pursued through PSMA independent research and development (IRAD) projects.

FOUNDATIONAL CAPABILITIES TO CONTROL RED PERCEPTION

Wideband Distributed Sensing

Adversary EW/ISR and kinetic weapons systems are rapidly expanding the spectrum in which they operate, as well as the geographic areas and ranges at which detection and engagement occur. Traditional radar and communications systems that operate in very high frequency (VHF) or ultrahigh frequency (UHF), enabled by COTS technologies, have expanded into super high frequency (SHF) or extremely high frequency (EHF) bands.[2] Accurate and timely detection of Red threat emissions is a principal component of the Control Red Perception strategy as it both informs Blue's situational awareness and correspondingly closes the feedback loop that drives its tactical response and refines its countering EA jamming techniques. With emerging Red threat systems able to operate with agility over wide and often nontraditional frequency bands and at longer geographic distances, Blue sensors are forced to pursue novel approaches to sensing.

Simply increasing Blue systems' single-platform sensing bandwidths is often not a feasible solution to fill this capability gap. The ES capabilities of Blue systems are bounded by the integrated size, weight, and power (SWaP) constraints of the host platform sensors, including amplifiers and antennas. It is well known that receiver sensitivity is a function of the instantaneous bandwidth over which the signal detection and characterization analysis is performed. Instantaneous receiver bandwidth is often reduced to improve receiver sensitivity; however, to maintain wideband coverage, this approach requires increasing the number of narrowband channels to span the operational bandwidth (for a non-swept approach), which correspondingly grows the resulting single-platform SWaP requirement. Furthermore, narrowband processing may fail to detect important dynamic, bursty, or frequency-agile emissions that could inform jamming technique adjustments. Alternatively, trying to minimize processing by using wideband staring receivers creates susceptibility to Red EA or even unintended fratricide from Blue RF emissions.

Distributed sensing accomplished by multiple platforms at different spatial or geographically separated locations is one approach to relieve the aforementioned challenges of sensing wideband Red emissions. By distributing the ES functions across multiple narrowband receivers on separate platforms, the necessary receiver sensitivity over instantaneous bandwidths and the overall wideband operation can be maintained. Narrowband focused sensors may use cooperative or collaborative approaches to focus on specific regions of the spectrum or specific Red emissions. Raw detections or characterized signal information may be shared across platforms to improve overall situational awareness and better tactically allocate Blue ES capabilities.

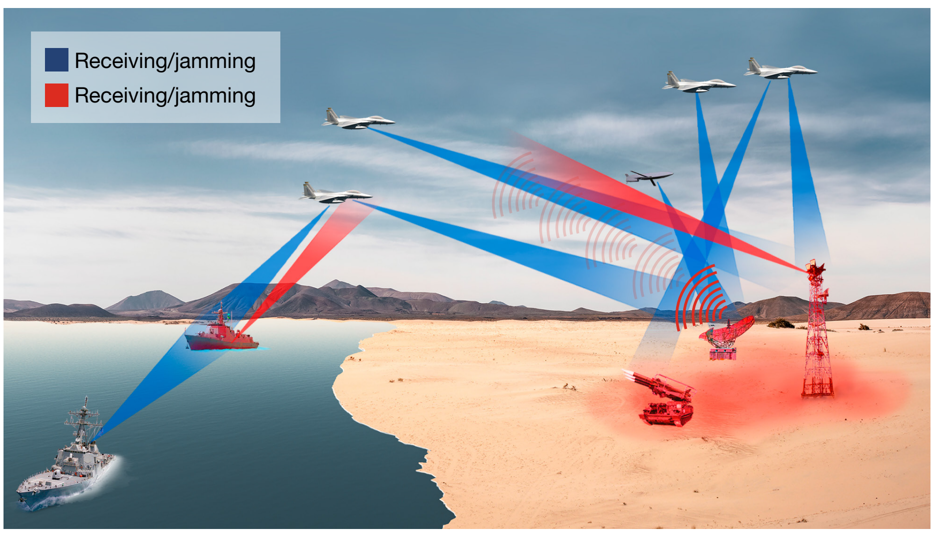

Figure 2. Wideband distributed sensing concept example. Shown is a notional example of multiple EW platforms sensing various Red threat sensors operating over a wide bandwidth while concurrently conducting an EA mission.

Depending on the specific sensor's capabilities, distributed sensing may also offer redundancy, allowing one platform to provide sensing for another if equipment fails or is rendered less effective because of targeted Red interference, for example. The ability to coordinate multiple spatially diverse sensors and platforms may also offer some inherent advantages to localizing a target emitter or characterizing an emitter's behavior before, during, and after EA.

Finally, whereas Blue EW systems involve both a receiver and a transmitter, geographic distribution of collaborative EW systems may provide opportunities to reduce single-platform EW receiver blanking windows yet increase aggregate receive time when performing high-powered EA techniques, thereby increasing total EA time and the probability of detection of Red emissions. To illustrate this concept, consider the notional scenario where three EW platforms are geographically separated and each jams the same threat 67% of the time and receives 33% of the time. Each single platform only observes the RF environment 33% of the time, resulting in Red emissions that are potentially not observed by Blue 67% of the time; however, collectively the three platforms are able to collaboratively observe the Red emissions 99% of the time. Figure 2 illustrates a notional example of multiple EW platforms sensing various Red threat sensors operating over a wide bandwidth while concurrently conducting an EA mission.

Autonomous and Adaptive EW

Wideband sensing of threats alone is insufficient to achieve situational awareness and to inform EW system actions aiming to control Red perception. Additional understanding and autonomous actions based on machine decision-making are required, typically encompassing the analysis of large volumes of information at machine speeds. The Control Red Perception strategy depends on successful application of intelligent agents to autonomous mission planning, in-mission resource management, in-mission EA technique refinement, on-the-fly adjustments to EW system tactics, and autonomous postmission analysis.

Current mission planning methods rely heavily on prior knowledge of the adversary's electronic order of battle—that is, the number of Blue EW platforms, their roles, their EW system capabilities, and EA techniques are planned based on the prior knowledge of Red systems, tactics, and disposition in the battlespace. This approach becomes brittle when faced with an agile adversary or when prior information and assumptions about Red's behavior and tactics are incorrect or incomplete. Controlling Red perception requires Blue adaptation of EW tactics with intelligent agents augmenting the mission planning process to optimize the EA technique, target, weapon, tactics, and platform combinations. Moreover, cooperative and collaborative multiplatform EW missions will require timing, frequency, and antenna pointing coordination across platforms, with precision and response times that are well beyond the capabilities of a human operator. As new information about Red behavior is learned or new threats are observed, intelligent agents can update EW decision-making processes and update future mission planning cycles.

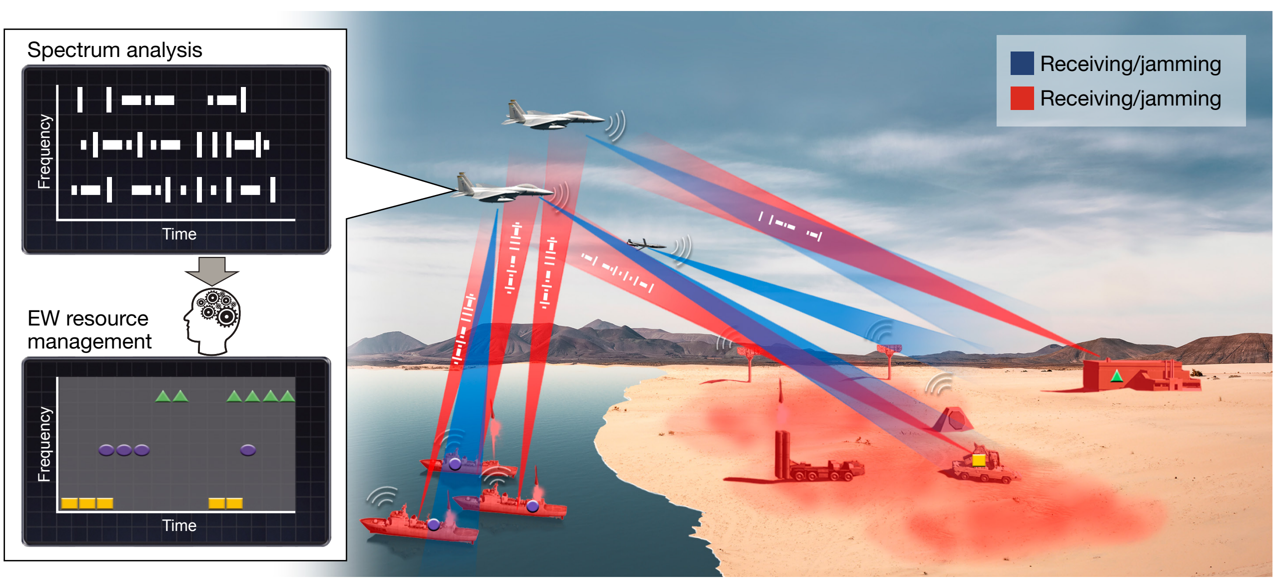

Figure 3. Autonomous and adaptive EW concept example. Shown is a single-platform autonomous resource management scenario, where received radar pulses are characterized and linked to specific Red threat systems. The spectrum analysis view shows received radar pulses from three unique threat systems. Once those threat systems are characterized, EW receiver and jamming resources are dynamically organized according to mission constraints and threat system behavior over time.

Another promising application for EW systems that learn is single-platform and multiplatform resource management. As previously discussed for wideband distributed sensing, high-powered EW systems on a single platform typically do not transmit simultaneously while sensing. Therefore, there are penalties associated with sensing the threat environment (e.g., the loss of EA duty cycle) and jamming the adversary (e.g., the loss of sensing time). Systems must be able to remotely determine, on appropriate timescales and with minimal human intervention, the presence, intent, and susceptibility of threat systems that are agile in frequency, timing, and mode changes. Correspondingly, EW system transmission and system resources must be continually balanced to sufficiently sense the threat environment to inform EA technique refinement. Figure 3 illustrates a single-platform autonomous resource management scenario, where received radar pulses are characterized and linked to specific Red threat systems. EW receiver and jamming resources are then dynamically organized according to mission constraints and threat system behavior. Furthermore, for distributed platform engagement concepts to control Red perception, selection of the best resource management controller strategy, whether distributed to all platforms or centralized to a single EW battle manager platform, is also an open research topic.

Future RF threat emitters, using increasingly complex agile waveforms, have driven changes in how EA techniques are employed. Current EA techniques are developed by subject-matter experts who analyze collected threat electronic intelligence and identify exploitation features. As emitters become more dynamic, the inherent latency of this human-in-the-loop waveform analysis will no longer be acceptable within operationally relevant timelines. Controlling Red perception requires near-real-time adaptation of EA technique and battlespace tactics to counter observed threats and present an effective countermeasure "perception" to Red. The perception imposed by Blue may be one Blue EW system versus one Red sensor, many Blue EW systems versus one Red sensor, or many collaborative Blue EW systems versus multiple collaborative Red sensors. Collaborative EW platforms must balance the ES and EA duties so that they can gather sufficient ES information about the threat environment to inform updated EA techniques to be automatically synthesized to achieve the desired operational effect. Finally, any previously unobserved threat emitters or behaviors must be automatically flagged for additional postmission characterization to inform future mission planning, resource management, and EA technique refinement.

Collaborative Electronic Fires

Similar to ES sensors, EA assets are challenged by adversary EW and weapons systems operating over wider frequency ranges, channel bandwidths, and geographic areas at longer ranges. Because of integrated platform SWaP limitations or other engineering trade-offs, individual EA systems may simply not have the capability to attack all frequencies in which Red emitters are operating or to otherwise operate in a tactically effective manner, hence limiting their effectiveness in EA. Furthermore, EA platforms have limited RF transmission power for jamming, so when they use traditional noise-based EA techniques to deny Red's ability to sense, the power spectral density on target frequencies decreases as the coverage bandwidth and stand-off range increases. Further, threat emitters that occupy large instantaneous channel bandwidths, or can operate instantaneously across large bandwidths, force traditional EA systems using noise-based techniques to cover large emitter bandwidths by spreading power, thus reducing power spectral density on target. When the jammer-to-signal power ratio (defined as the power of the jamming waveform at the target receiver divided by the received Red emission power at the target receiver) becomes too small, the jamming technique is no longer effective. This ultimately limits the range at which the EA system may operate from a target and still effectively jam. Hence, as Red emitters operate over wider bandwidths, single EA platforms must either decrease stand-off range or increase overall jamming RF power—neither of which may be effective for the mission, given the threat disposition of forces and defensive capabilities. Moreover, when a single EA platform has sufficient power to effectively operate over a given target bandwidth, it has limited ability to jam targets at multiple geographic locations; these targets may be operating at different frequencies, with different timing schedules, and using various waveforms and protocols. (See the article by Stevens et al., in this issue.)

Distributed EA using multiple platforms at different spatial locations is one approach to relieve the aforementioned challenges of attacking wideband Red emitters. Narrowband focused EW systems may use cooperative or collaborative approaches to focus EA energy and techniques on specific regions of the spectrum or specific Red emissions so that, in aggregate, all target frequencies are covered. Alternatively, multiple platforms may collaborate to focus their energy on the same select frequencies so that the resulting energy on a set of targets is higher than levels that a single platform could achieve, although this approach requires precise collaboration and comes with additional challenges in avoiding destructive interference between the transmitted jamming waveforms. Multiple platforms at different spatial locations may also selectively use different EA techniques that could potentially improve effectiveness. Further, distributing ES and EA tasks among multiple platforms may facilitate greater aggregate receiver-open times and EA-on times, increasing the probability that

ES will detect the threat signal and enabling higher jamming duty cycles that increase EA effectiveness. However, to accomplish this vision, reliable interplatform communications methods must be established to enable the interplatform exchange of messages on timescales that support collaborative ES and EA tasking. For example, if collaborative receivers and jammers distributed across platforms seek to assign and modify ES and EA tasking on microsecond scales, millisecond latency or millisecond timing precision is not tolerable. Finally, multiple platforms may collect electronic intelligence to be shared across platforms in near real time to improve overall situational awareness and enable the platforms to adapt techniques to improve effectiveness as well. We illustrate this example in Figure 4, where notional Blue airborne stand-in, stand-off, and fighter platforms are approaching a Red integrated air defense system and surface action group. In this distributed concept, the stand-in sensor senses target RF emissions and periodically passes this information via a data link to the two stand-off EW systems so that they can update their EA techniques and cover all Red threat systems.

Integrated EW and Cyber Fires

The final foundational capability of the Control Red Perception strategy is integrated electronic and cyber fires. In the broadest context of EW/cyber fires, any operation that achieves a cyber effect on a target and includes an RF component for sensing or effects delivery could be considered EW/cyber. Some example offensive cyber effects include, but are not limited to, deny, degrade, disrupt, or destroy target availability or provide deceptive information to a target. This integrated capability offers potential tactical benefits including

- increased persistence of effects (the delivered effects may continue after jamming ceases);
- decreased jamming duty cycle (increased persistence allows flexible jamming resource allocation);
- decreased jamming power (waveforms are not required to overpower the target but rather to elicit specific effects); and
- precision control of effects (the ability to use cyber effects to selectively choose targets and timing when effects should activate or deactivate).

Multiple technical research challenges must be addressed to enable these tactical benefits of integrated EW and cyber fires and, correspondingly, the Control Red Perception strategy. These challenges include developing remote, rapid, and autonomous vulnerability discovery tools; ensuring remote understanding of a target's state via sensing; developing the ability to

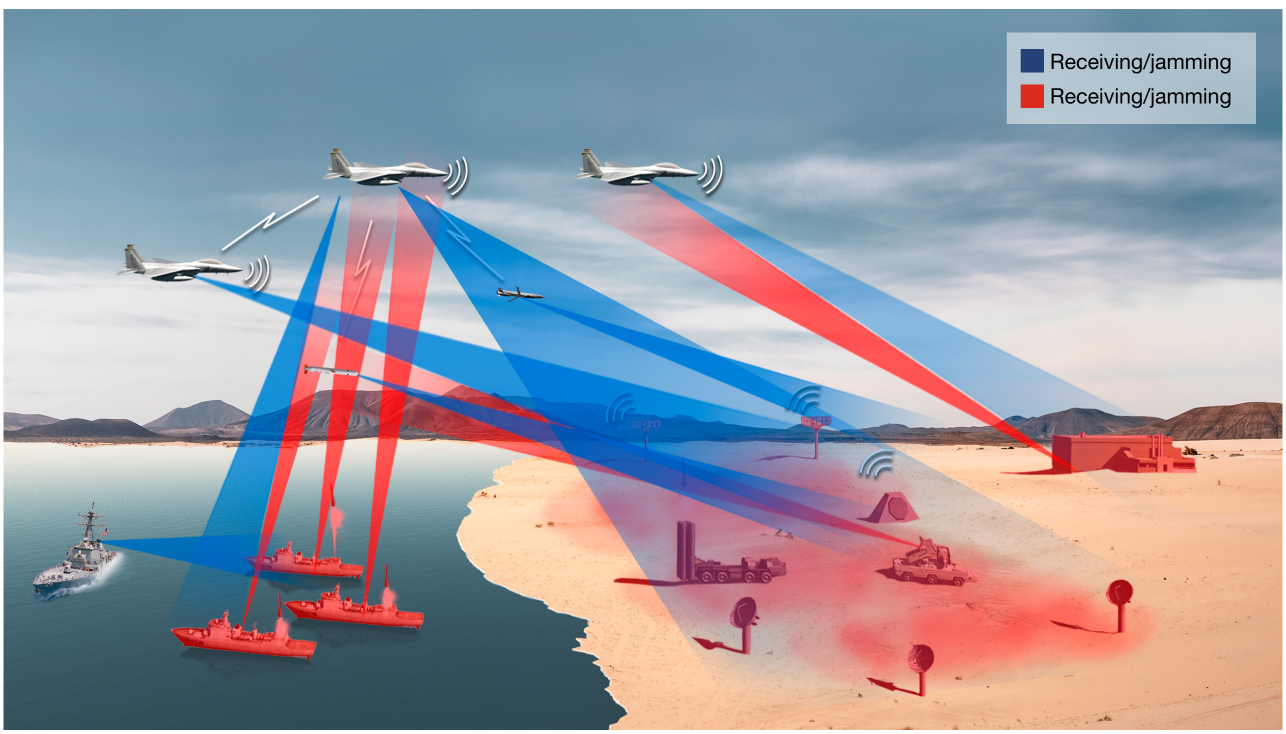

Figure 4. Collaborative electronic fires concept example. In this example, notional Blue airborne stand-in, stand-off, and fighter platforms are approaching a Red integrated air defense system and surface action group. In this distributed concept, the stand-in sensor senses target RF emissions and periodically passes this information via a data link to the two stand-off EW systems so that they can update their EA techniques and cover all Red threat systems.

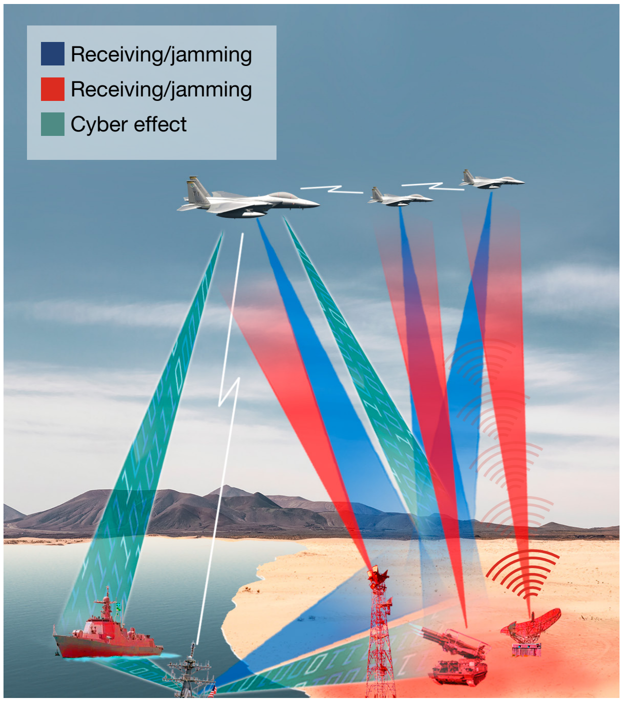

Figure 5. Integrated EW and cyber fires concept example. Distributed Blue platforms collaboratively perform ES and deliver EA and cyber effects against Red threat systems.

remotely verify effects via sensing; and developing universal cyber effects. Finally, these sensing and EA tasks may be accomplished more effectively from distributed platforms for the reasons previously described and also shown in Figure 5.

ENABLING CAPABILITIES TO CONTROL RED PERCEPTION

While the foundational capabilities are the focus of the Control Red Perception distributed EW concepts, underlying enabling capabilities are required to implement and evaluate the concepts. In this section, we describe those enabling capabilities and focus on the topics that require technical innovations to realize the Control Red Perception strategy.

Test and Evaluation Infrastructure

A wide variety of cooperative and collaborative EW concepts are emerging as part of the Control Red Perception vision. These concepts, although not yet technically mature, enable exploration of applications where, in aggregate, multiple participating EW platforms may be more effective than a single EW platform or multiple uncoordinated EW platforms conducting the mission. However, successful transition and integration of these concepts into platform capabilities for real-world mission applications will require a cost–benefit analysis of the associated costs, system functions, and operational utility. As an example, we revisit the scenario shown in Figure 4. It might seem intuitive that adding a second or third stand-in sensor to observe the Red threats may increase confidence in the observations and add potential redundancy to the overall ES picture by removing a single point of failure; however, the effectiveness and survivability gained by incorporating multiple platforms might not be worth the additional complexity and cost incurred. Furthermore, the improved performance of those collaborative EW concepts that show operational utility under ideal conditions may be dependent on situational awareness parameters such as platform position, timing alignment, and frequency alignment, which may be degraded, delayed, or simply unavailable. Test and evaluation infrastructure and methodologies must account for collaborative concepts and scenarios that incorporate intelligent agents and accurately account for nondeterministic, nonrepeatable, and nonideal platform and system behaviors.

As a trusted agent for many sponsors with EW platforms, subject-matter experts in PSMA will undoubtedly be asked to evaluate the cost–benefit of our own distributed EW concepts as well as those of government and industry. APL has a long history of evaluating the operational utility of EW capabilities in one-on-one scenarios. However, significant investment is required to develop, tailor, and apply modeling and simulation and hardware-in-the-loop capabilities to measure the degree to which a concept effectively controls Red perception in many-on-many cooperative and collaborative EW scenarios.

Distributed Communications

Distributed communication is a fundamental requirement to support most collaborative EW concepts and the aforementioned foundational capabilities because they require reliable and near-real-time information sharing across participating EW systems. Reliable communication enables collaborative EW platforms within Control Red Perception concepts to share resources, balance tasking, and update Blue platform situational awareness. We describe the basic characteristics of a distributed communications system, whether COTS or customized, to enable collaborative EW concepts that control Red perception.[1]

- **Operate in the presence of jamming**—The communications approach must be able to maintain an acceptable quality of service in the presence of Blue self-interference and intentional Red EA. Possible solutions could include operating communications that are out of band relative to the jamming or coordinated in time around jamming intervals, or using multiple, redundant communications paths.

- **Adaptable**—The communications approach must be able to support multiple communication paths and select the most reliable and effective path for the given scenario.
- **Scalable**—The communications approach must be able to scale such that multiple participating EW systems can securely enter and leave the network and correspondingly maintain information update schedules.
- **Distributed network management**—A centralized or distributed controller must manage participating EW systems' locations, tasking, and communication methods of distributed platforms. (See the article by Stevens et al., in this issue.) The network manager function is envisioned to be controlled by an intelligent agent capable of dynamically determining the optimal communication frequency, timing, and RF waveform based on location, threat environment, perceived reliability, and current tasking.
- **Distributed clock reference**—Participating EW systems in the network must synchronize clocks (within an established accuracy), either to a common reference or to each other's clocks, to align common timing schedules, sensing frequencies, and attack frequencies.
- **Secure**—The communications approach must implement basic security mechanisms to ensure confidentiality, data integrity, and authentication to prevent EW systems from malicious attack.

Software-Defined Miniature Systems

The previously described foundational capabilities can be prototyped and evaluated without specific regard to SWaP; however, mission application will typically require incorporation of capabilities into an EW system integrated on a platform that is inherently constrained in terms of SWaP. Technological advances in high-speed data converters and field-programmable gate arrays as well as aggressively scaled complementary metal–oxide–semiconductor (CMOS) fabrication for system-on-chip (SoC) solutions have enabled new devices such as RFSoC for novel considerations in a range of applications supporting the wideband, multichannel, multifunctional, miniaturized software-defined radio (SDR) concept. Prototypes of distributed EW concepts should account for the ease of porting to the eventual EW system. This includes prototyping capabilities using common SDR and SoC systems and selecting hardware and software, when possible, that avoids vendor lock-in (i.e., being unable to switch vendors because of compatibility, cost, contractual, or other challenges). For example, although the OpenVPX (VITA 65) and Sensor Open Systems Architecture (SOSA) standards are still maturing, developing systems according to these standards promises a number of interoperability and upgradability options.[3–5] Developing Control Red Perception concepts in a way that emulates the eventual target EW system as closely as possible facilitates porting and transitioning capabilities to a variety of distributed EW systems and platforms. Moreover, the prototyping of collaborative EW capabilities informs hardware baseline requirements for future EW system acquisition efforts so that capabilities are more easily integrated and adopted across the EW community.

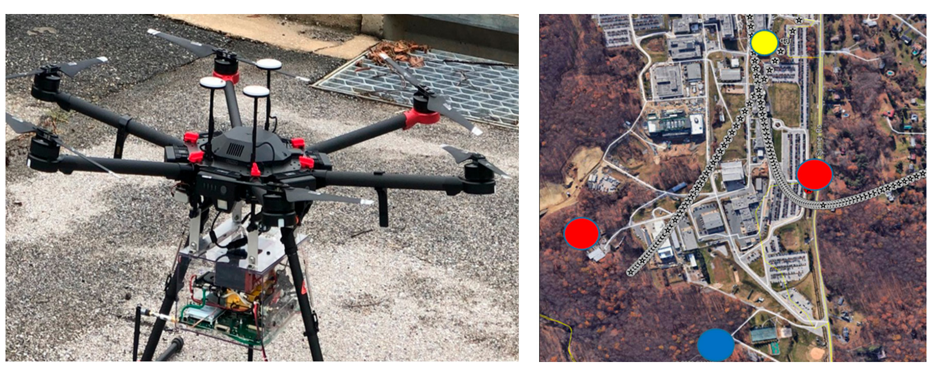

Figure 6. Prototype SDR sensor. Left, UAS with integrated ES payload. Right, Time-difference-of-arrival isochrones from two UASs. The Blue node is stationary, the Red node moved between two limited points, and the yellow node is the rooftop radar target.

RELATED PSMA IRAD PROJECTS

In this section we summarize recent PSMA-funded IRAD projects that are developing enabling technologies fundamental to the Control Red Perception strategy.

Distributed Sensing

PSMA staff members contributed to a joint cross-sector IRAD project with the Air and Missile Defense Mission Area to prototype a distributed sensing concept for an ISRT (intelligence, surveillance, reconnaissance, and targeting) demonstration using unmanned aerial systems (UASs). The team investigated topics such as anti-ship cruise missile raid defense of a strike group or enabling long-range Blue kill chains via off-board autonomous platforms. They hypothesized that a mission-tailored unmanned surface vehicle or UAS with relatively long endurance could provide needed over-the-horizon indications and warning and/or targeting for incoming anti-ship cruise missile raids, hence enabling EA engagement options. The team sought to develop this concept by examining the ES sensor and EA requirements and prototyping a set of low-SWaP sensors that flew on Level 1 UASs (weight between 2 and 20 lb and operating altitude <3,000 ft) and cooperatively determined the location of a target radar via time-difference-of-arrival measurements.[6]

The PSMA portion of the project focused on distributed sensing to complement the Air and Missile Defense Mission Area's investment in UAS platforms and an EA payload. The ability to find, fix, and target threat strike platforms from Blue surface ships before ordnance is launched is a challenging feat because of horizon limitations of surface ship sensors, as well as limited persistent (long-duration) airborne resources available to surface action groups. Recent improvements to high-sample-rate converters (analog to digital and digital to analog) and SoC technology have enabled the development of sensors that meet the SWaP requirements for persistent unmanned platforms. The rapid prototyping of an ES capability demonstrates the feasibility of the approach on SWaP-limited platforms. The team developed and demonstrated a dual-ES capability on two COTS SDRs and an integrated communications radio that shared detection information with the ground station and among ES nodes. Figure 6 shows the prototype SDR sensor integrated on a Matrice 600 drone (left) and a map of the demonstration layout (right).

Intelligent Agents for EW

Controlling Red perception using EW platforms often requires that decisions be made based on partial information with resources that are managed at machine speeds with little to no human intervention during an engagement timeline. As previously described, incorporating intelligent agents into EW systems could relieve technical and operational challenges the EW community faces. Recent PSMA-funded IRAD projects have applied state-of-the-art machine learning approaches to address some of these problems.

During fiscal years (FYs) 2019 and 2020, the Feature-based Electronic Attack Trained Hypersurface Responses (FEATHR) IRAD team applied supervised similarity learning to communications and radar signal baseband in-phase and quadrature (IQ) representations to modulation recognition and anomaly detection. Once trained, the agent was able to classify modulations and recognize anomalous signals. To train the agent and evaluate the approach, the team used the open-source RadioML2018 data set.[7] Each example is represented as a 1,024-length IQ vector sampled in time using floating points, and the data include multiple environmental distortions that are commonly observed in collected data. The data set was partitioned into two categories: (1) a supervised category of 22 known classes subdivided into an 80% training partition and a 20% evaluation partition, and (2) a category with two holdout classes (FM and 16 QAM withheld during training). The model trained on the 22 known modulations (i.e., excluding the two holdouts) and accurately recognized all 22. It also recognized that the two holdout class signals were anomalies relative to the training data set, and it accurately clustered the two observed anomaly signals. (See Casterline et al., in this issue, for a detailed description of the FEATHR IRAD project and demonstrated results.) Although this project only addressed a single machine learning approach demonstrated in laboratory settings, its results suggest that there is merit in further investigations into applying machine learning to EW tasks.

For the FY2019–2021 Intelligent Learning Electronic Attack Maestro (IL'EA Maestro) IRAD project, the team developed a method to apply model-based stochastic optimization coupled with approximate Bayesian inference to autonomous resource management. In contrast to standard off-the-shelf reinforcement learning algorithms, this approach allows system designers to incorporate significant domain knowledge (e.g., known characteristics of the adversary system) into the agent's design. Whereas with a standard reinforcement learning algorithm the agent must determine adversary RF emissions on its own if given enough training time on a simulator, building such knowledge into the system results in a lesser burden of learning. The net effect is that the system resource manager performance improves with the inclusion of this domain knowledge.

The long-term vision of the IL'EA Maestro project is to enable deployment of scalable, distributed, multiplatform approaches to autonomously manage sensing and jamming resources. In FY2021, the IL'EA Maestro team was focused on defining and evaluating centralized and distributed control methods for modeled distributed EW platforms with resource management agents. (See Casterline et al., in this issue, for a detailed description of the IL'EA Maestro approach and results.)

Collaborative EW Evaluation Infrastructure

Some of the Control Red Perception distributed EW concepts require multiple platforms to accomplish a task that otherwise could be accomplished by a single platform. Justifying a distributed approach requires a quantitative rationale for why it is advantageous, along with definition of associated performance and resource requirement trade-offs. Ensuring that EW evaluation infrastructure keeps pace as cooperative and collaborative EW concepts mature will enable robust assessment of advanced EW concepts. As of the writing of this article, PSMA teams are working on two FY2021 IRAD projects focused on defining and implementing test and evaluation infrastructure required to assess the operational value of Control Red Perception distributed EW concepts. These two projects are described in the subsequent Modeling and Simulation and Hardware Test and Evaluation subsections.

Modeling and Simulation

For one FY2021 PSMA IRAD project, A Search for Distributed EW Tactics (DEW-Tactics), a team is investigating how the resource-bounded operations involved in ES, electronic protection, and EA may be augmented or improved via the use of distributed sets of coordinated platforms, even in situations where such platforms are less capable when operating independently. The underlying hypothesis is that future EW engagements will be composed of scenarios involving multiple Red and Blue platforms. Thus, one-on-one interactions between Blue and Red will not be sufficient to adequately represent EW engagements at a mission level or to characterize the degree to which Red perception is controlled.

The DEW-Tactics researchers are developing tactics through modeling a suite of engagement scenarios where coordinated EW support is needed for success. The team selected the Advanced Framework for Simulation, Integration and Modeling tool (AFSIM) as an event-driven simulation framework. AFSIM allows mission-level engagement models to be dynamically executed while simulating flight dynamics, RF sensing, EA effects/reactions, and information transfer between platforms.[8] In early efforts, the DEW-Tactics team developed a simplified baseline scenario in AFSIM and charted a road map for supporting more complex scenarios. The team is currently working toward an external software interface for developing and evaluating control policies.

In the initial engagement scenarios considered, the team decomposed the problem of developing a control strategy for EW tactics that consider jammer alignment with the target, Blue jammer resource utilization, and jammer threat selection. The DEW-Tactics team seeks to establish a foundational AFSIM modeling and simulation capability that moves beyond scripted behavior so that they can begin evaluating the operational utility of distributed EW scenarios composed of dynamic platform interactions.

Hardware Test and Evaluation

Future collaborative EW systems will depend on adaptive, intelligent agent capabilities that make test and evaluation extremely difficult and costly on a traditional open-air range. PSMA has invested in development of a Small-scale, Broadband, Low-latency Environment (SaBLE) emulator to satisfy the immediate needs of the Control Red Perception vision to evaluate future EW systems and collaborative EW concepts. SaBLE is being designed to overcome current RF environment emulators' limited instantaneous bandwidth, limited ability to dynamically adapt RF channels during a scenario, and latencies in updating these RF links. SaBLE is meant to allow connected systems under test, such as sensors and EW systems, to provide the emulator with updates on platform motion, operating frequency, and antenna pattern. All these capabilities will dynamically update the RF links between the systems under test in the timescales necessary to evaluate the efficacy of future EW systems operating in an electromagnetic spectrum environment that dynamically changes based on the systems' behavior. SaBLE will use state-of-the-art COTS components configured in a scalable architecture to test collaborative EW concepts seeking to control Red perception.

Advanced EW/Cyber Concepts

In FY2020, the Platform Agnostic Remote Memory-Mapping Algorithm (PARMA) IRAD team researched controlling Red perception using a cyber capability by exploring the problem of shrinking a cyber payload. They sought to reduce the functions developed in the payload by leveraging required functions already on the target device without specific knowledge of the memory location of these resident functions. The objective was to reduce payload size and fragility to target software updates by allowing required library functions to be automatically identified and referenced in target systems.

Traditionally, device firmware images are statically analyzed to locate functions used within payloads. This approach's major shortcoming is its reliance on human analysts since not all firmware images have functions in the same memory locations. Although a cyber payload may successfully target one specific device with a specific firmware version, that payload probably will not function properly when targeting a device with a different firmware version. The PARMA team sought to accelerate vulnerability identification by researching methods for dynamically identifying library functions in firmware in real time.

Distributed Communications

The importance of distributed communications to enable multiplatform coordinated and collaborative EW concepts that control Red perception is described in the Enabling Capabilities to Control Red Perception section. The FY2020 Interwoven Jamming with Opportunistic Communications (IJWOC) IRAD team explored combining simultaneous physical layer cognitive radio access with EW techniques to schedule reliable sensing, communications, and jamming periods using a commercial communications protocol. Based on ES information to derive optimal times for multiplatform communication and jamming, the team demonstrated a proof-of-concept communications capability to operate in the presence of jamming with the flexibility to adapt communications, sensing, and jamming according to Red emissions. The FY2021 Cognitive Interweave Access Operator (CIAO) IRAD team built on IJWOC successes by creating novel physical and medium access control protocols for establishing collaborative EW networks, including creating power control protocols that limit Red perception.[9] Future work includes the Cognitive Opportunistic System Manager for Intelligent Communications (COSMIC) project, which will look at creating network decisions through use of machine learning to coordinate communication opportunities across available and existing communication links. COSMIC will support overall networking of EW and cyber capabilities to both control Red perception and increase communication opportunities by leveraging opportunities from multiple RF standards.

Software-Defined Miniature Systems

In an FY2020 IRAD project, a PSMA team developed and demonstrated a wideband, multichannel, multifunctional, miniaturized SDR architecture to enable the rapid development and evaluation of cooperative and collaborative EW concepts for low-SWaP applications such as high-speed projectiles. These SDR applications are foundational to mosaic warfare concepts, where a large number of small, expendable, SWaP-constrained systems with limited capabilities collaborate to control Red perception.[10] The ability to shrink sensing and signal processing capabilities into a miniature SDR form factor more easily supports integration into EW systems on SWaP-limited platforms. Moreover, as the aforementioned open standards and interfaces are more widely adopted across the Department of Defense, standard processes can be developed to make EW capabilities more portable across hardware platforms.[5]

CONCLUSION

The PSMA Control Red Perception strategy seeks to achieve information dominance and deliver overwhelming effects against adversaries. By developing coordinated and collaborative EW concepts to control Red perception and maturing foundational and enabling capabilities, PSMA seeks to fulfill traditional EW mission gaps and enable resilient, survivable strike options and offensive sanctuary for strike platforms. Multiple PSMA IRAD investments are positioned to realize technical innovations that contribute to the Control Red Perception strategy, but numerous follow-on research efforts are required to fully achieve the envisioned future. We believe future distributed EW concepts, acquisition requirements, prototyping, evaluation, and operations support are impactful areas to which APL can make major contributions. Indeed, controlling Red perception will require concurrence and adoption from the entire EW community and investment in technical innovations that bridge current capability gaps.

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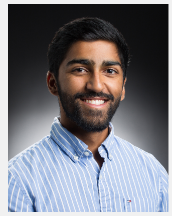

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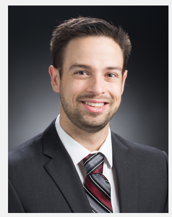

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