# Resource Management Architecture for Electronic Warfare Networks

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## ABSTRACT

*Distributed electronic attack and electronic support systems interact to complete a set of tasks and are of interest to the electronic warfare (EW) community. With the expanding operational threat space, the increasing complexity of emerging targets, and the increasing density of the electromagnetic environment, individual EW systems do not have sufficient resources to meet mission requirements. Moreover, current approaches to improve EW system interoperability and ensure Blue force communications constrain EW technique design and do not scale against emerging and future threats. Distributed and collaborative EW concepts offer potential relief to EW resource constraints by distributing sensing, communication, and engagement task management across multiple EW systems. While this vision offers many opportunities, its realization is currently limited by science and technology (S&T) gaps and incomplete functional requirements that prevent the precise definition of a distributed EW resource manager. In this article, we describe distributed EW use cases and associated functional requirements to motivate the need for a distributed resource manager architecture, and we identify the distributed resources to be managed. For future work, we suggest key focus areas and enabling technologies that can bridge the S&T gaps for the design of EW resource management.*

## INTRODUCTION

The objective of an electronic warfare (EW) system is to disrupt or degrade the adversary's radar or communications capabilities. By transmitting jamming techniques within range of adversary radio frequency (RF) receivers, an adversary's transmissions are not correctly received at the intended receiver. EW threats can be composed of a diverse range of RF standards and are densely packed across multiple octaves of the RF spectrum (e.g., high frequency, very high frequency, ultra-high frequency, super high frequency, and beyond). Wideband sensing, processing, and jamming must be considered to manage the scale of targets within the electronic battlespace. Supporting these wideband tasks is increasingly complex and challenging.

Wideband sensing typically results in nonideal samples of the RF threat environment because of inherent limitations of receiver linearity, sensitivity, dynamic range, scan duration, and time-sharing with jamming activity. To process this large amount of spectrum, a platform must digitize and analyze the spectrum of all signals with the limited digital resources available to it. However, because an EW platform's primary mission is to jam, and sensing is simply an enabler to provide situational awareness on jamming refinement opportunities and verification of effectiveness, a single-platform jammer seeks to minimize sensing time and maximize jamming time.

Wideband jamming is challenging because of transmitter linearity limitations and the reduction of jamming waveform power spectral density associated with increased spectrum coverage. To add to the aforementioned challenges, a single jammer platform has finite resources available to engage the various threats in a hostile environment. The main challenge with wideband jamming is power efficiency as the number of threats grows. The scale of threats and coverage required in many wideband scenarios requires more resources than a single EW platform has available. Threats are typically located at different spatial locations and use various frequencies, communications waveforms/protocols, transmit power levels, and timing schemes.

Distributing tasks across separate EW systems relieves the challenges posed by a single system, improving wideband sensing, processing, and jamming. EW systems must communicate with each other to share information and to advance their learning to improve awareness of the threat environment and inform enhanced engagement strategies. Through communication, a collection of jamming systems can function as an EW network. While EW networks are attractive in a dense or dynamic threat environment, the principal design trade-off is the increased overhead cost from the required interactions. Overhead comes from internode communication, data management, and processing, which use network resources. Managing resources effectively across a distributed EW network can limit this overhead.

The objective of this article is to ascertain which tasks must be managed across multiple jamming assets, identify goals for a resource management system, and provide high-level design choices for EW network resource management. Moreover, we highlight EW science and technology (S&T) topics that we believe require further investment to enhance capabilities for EW networks. We consider the complexity of resource management and why a solution is so difficult to create.

This article is organized as follows: First, we present the problem statement and use case scenario. Next, we report related work in resource management across wireless networks and then describe current research at APL that relates to EW resource management. We then consider the objectives of an EW network and resource management architecture. We describe the functionality of a resource manager architecture and detail an example scenario illustrating the functionality. Finally, we conclude with suggestions for future work for manifesting an EW network management system.

## PROBLEM STATEMENT

In support of APL's 2018–2020 fiscal year (FY) Precision Strike Mission Area strategy, multiple independent research and development (IRAD) projects and sponsor-funded projects investigated distributed EW use cases. Specifically, these projects focused on the benefit of distributed and autonomous EW approaches and the technology and operational gaps that must be solved to transition these capabilities to EW platforms to achieve the envisioned future of controlling the adversary's perception. The distributed management of EW platforms is a unique challenge that must leverage multiple disciplines and additional S&T investments before capabilities become operational on tactical platforms. The approaches and objectives presented in this article are platform agnostic.

There are compelling airborne, ground, and sea-based applications for EW networks. Figure 1 shows a diverse airborne EW network engaging naval and ground radar and surface-to-air missile assets. Figure 2 illustrates a scenario where an EW ground network's vehicles, body-worn systems, and a helicopter must interact to better engage existing cellular networks and adversary unmanned aerial vehicles. These scenarios show just two of many complex combinations of platforms and threats.

In the scenarios presented in Figures 1 and 2, the interactions among the various platforms have the potential to improve mission effectiveness over all the entities acting individually. The ability to share situational awareness and distribute jamming assignments across multiple platforms offers many operational advantages. These advantages include shared awareness of threat signals that may not be able to be received by all platforms, distribution of the signal processing load among platforms, assignment of sensing/jamming tasks to the platforms most likely to effectively execute the assignments, and reduction of the jammer transmit requirements on any single platform. For example, in Figure 1, fighters and stand-in jammers could provide electronic support information to the escort jammers to facilitate more efficient use of transmit resources (i.e., reduced frequency coverage requirements and/or more targeted jammer waveforms). In the ground-based scenario shown in Figure 2, the complex signal processing associated with sensing and jamming the cellular infrastructure might be assigned to the electronic countermeasure system on the helicopter or vehicle-mounted

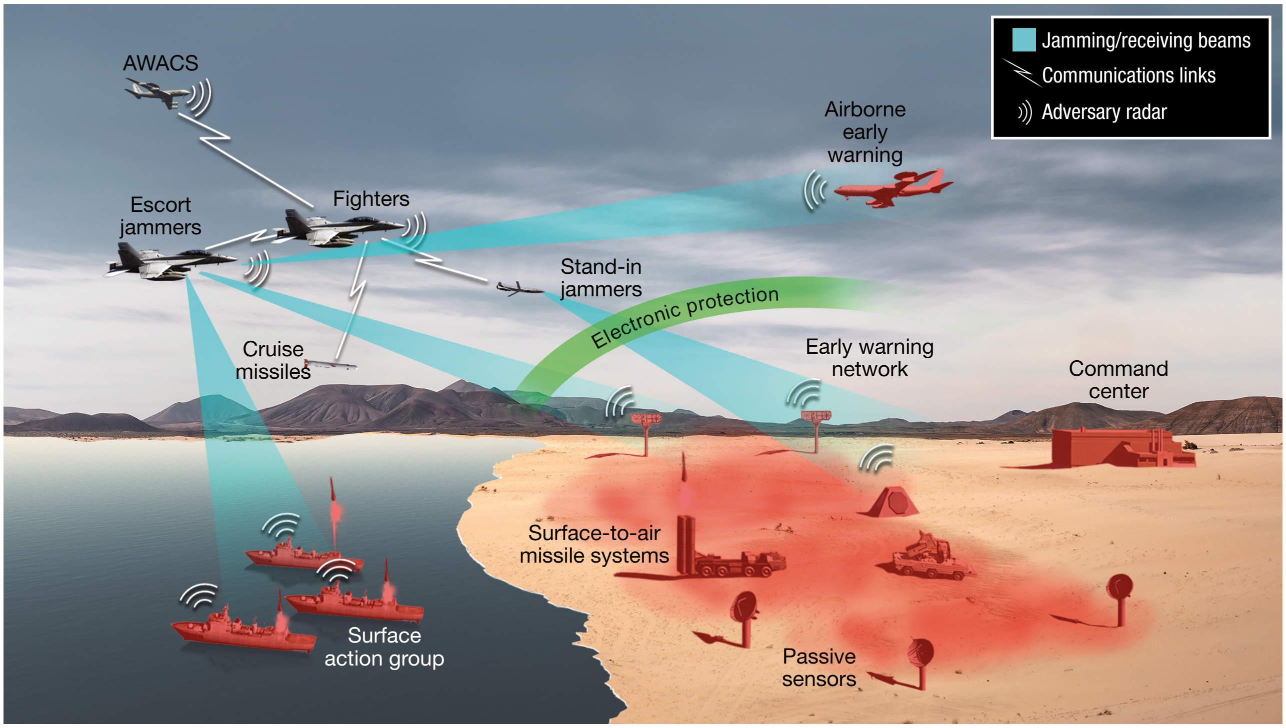


**Figure 1.** An airborne EW network. This diverse network engages naval and ground radar and surface-to-air missile assets. AWACS, airborne warning and control system.

systems since those systems have more processing resources than the systems worn by the soldiers. The final results of the processing could then be delivered to all the jammer platforms to enable more effective jamming of the cellular signaling.

EW networks are challenging to design and maintain. The variety of platforms and threats is limitless because EW network assets change dynamically, as does the threat space. Determining how to manage associations between platforms is also difficult. In this context, we consider how multiple systems interact by defining two ways to distribute and coordinate tasks: cooperative and collaborative. Each association describes a method to distribute and coordinate tasks among nodes. While a cooperative group of nodes could be tasked before a mission to jointly accomplish a given EW task, such as jamming the same threat at the same frequency, the collaborative group of nodes can dynamically work together to distribute the sensing, processing, communication, and engagement activities required to accomplish the task. Collaboration between nodes in an EW network to meet mission objectives is a higher-order instantiation of cooperation. Nodes can cooperate without collaborating, but the converse does not hold.

Future EW networks will use cooperative and collaborative techniques to improve wideband sensing, processing, and jamming capabilities. For example,

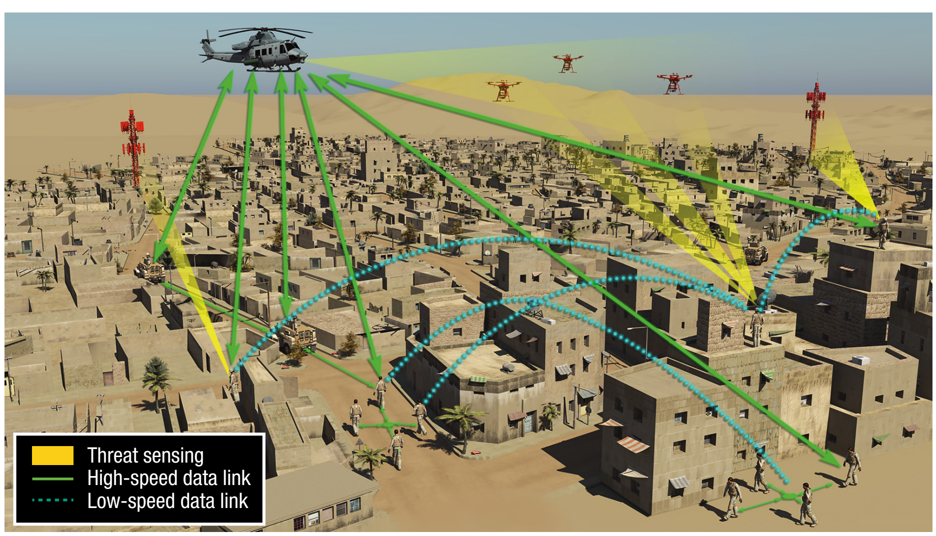


**Figure 2.** A ground EW network. In this scenario, vehicles, body-worn systems, and a helicopter must interact to better engage existing cellular networks and adversary unmanned aerial vehicles.

assigning different portions of the spectrum to different nodes reduces each node's collection requirement, or combining detection results may improve detection for targets with low signal-to-noise ratios. Coordinating sensing and jamming among nodes may allow staggering receive and transmit times on distributed platforms and avoid gaps in both. Jamming may be improved by coordinated jamming of smaller portions of the spectrum or using concurrent techniques to improve power spectral density. Coordinated processing increases signal processing capabilities by utilizing resources distributed across a network.

It is challenging to manage wideband sensing, jamming, and processing resources within an EW network that can adapt to a diverse set of scenarios. Understanding the resources available within a network of platforms and being able to allocate them in real time based on a dynamic threat environment, while simultaneously accounting for mission requirements and jammer-to-threat spatial considerations, is also a demanding task. Additionally, associations between EW systems have to be defined to distribute and coordinate platforms within an EW network. Effectively coordinating an EW network composed of multiple platforms targeting multiple threats requires a dedicated complex resource manager. A resource manager addresses the challenges in creating effective EW networks, as previously described in this section. A resource manager's tasks include requesting and parsing situational awareness data, establishing diverse communication links between all EW assets, and creating effective timelines to process and jam across assets. To assess the state of the topic area, we first looked at the literature on how network resources are managed. The following section details current topics related to resource management found in the literature.

## RELATED WORK

In this section, we not only highlight the gaps in current research on managing resources of distributed EW systems, but we also make an effort to apply concurrent research in other wireless network topics that may not be directly tied with EW. The research discussed could, with some effort, be leveraged to enhance EW network resource management, but as of this writing, the published literature does not offer a holistic solution for the EW resource management problem.

### Wireless Network Resource Management

The backbone of an EW network relies on the strength of the communication between each of the platforms. To that extent, the wireless communication between each of the platforms must be resilient to operational and environmental changes—such as platforms entering or exiting the network and information sharing between platforms. Because communication tasks are taxing to the platforms in the network, efficiencies in processing consumption and traffic overhead must be considered when developing a wireless network of distributed systems. Academic studies have focused on exploring resource management for distributed sensor networks, not EW networks. Nevertheless, we leveraged these studies to understand the resource management building blocks—even when the works may not provide a holistic solution to the EW application. Two aspects of resource management have been studied: platform traffic control and platform processing resource control. Traffic control aims to manage the number of messages transmitted between platforms in a network to minimize congestion and maximize bandwidth. Resource control aims to manage the processing capacity each platform provides.

Traffic control studies have focused on the small-world phenomenon to optimize network traffic. The small-world phenomenon is the principle that everything in a network is connected within "6 degrees of separation." Kumar et al. found that by leveraging this principle when routing traffic, a platform's energy consumption can be reduced by 8% and message exchanges by 40% over the standard broadcast method.[1] While this behavior may be desired for a resource manager, the platforms within an EW network need to be aware of events seen by other platforms' sensing awareness or capability awareness, and therefore this approach may not provide the full solution to minimizing traffic control. Another study explores using platform clusters[2] to handle the network congestion caused by a network where some platforms may share more information than others because of the rate of data updates, even when the processing is balanced across all platforms. While this solution might apply when the user application has a priori knowledge of each node's location, it does not address the clustering of EW platforms, as they change locations and apply associative convergence to enable distributed jamming. Other methods include traffic congestion detection within each platform[3] to self-correct and throttle platform throughput, as described by Wan, Eisenman, and Campbell. While throttling network congestion is important, their paper does not address EW messages that have to be delivered in real time to avoid mission failure.

Resource control studies have looked into ways to control platform utilization as a means of maximizing overall capacity. One way to maximize capacity, described by Kang, Zhang, and Nath, is to identify hot spots within the network caused by an event that is detected by several platforms and therefore transmitted as several copies across the platforms, decreasing overall capacity because of this redundancy.[4] The paper focuses on minimizing hot spots within the network; however, it fails to point out that for an EW resource manager, it may be important to highlight hot spots to determine adversary activity with added sensing awareness. Another study aims to balance traffic and resources using platforms that are active only during periods of a data surge and are dormant during quiet periods, therefore maximizing bandwidth and capacity and minimizing energy consumption.[5] However, this paper does not go into detail that an EW resource manager should focus on computational efficiency to engage the target waveforms and could have platforms act as listeners to compute more waveforms at the cost of processing delays. Another study looks into ranking the reliability of the data links between each of the platforms to the capacity of a network.[6] Platforms with lossy links or intermittent connections are ranked lower and therefore have less processing load in case the platform is dropped off the network; likewise, platforms are ranked higher, and thus contain more processing load, if their network link strength is stronger. While this approach may be desirable for some resource managers, to ensure threat coverage with the lossy link, an EW resource manager must also account for things the platform-provided sensing awareness is seeing that other platforms are not seeing. Simply dropping the rank of a platform because of the lossy link may lead to a loss in performance and therefore cause mission degradation.

### EW Network Resource Management

As the number and complexity of threats increase, collaborative and/or cooperative networked systems are a necessity for EW. Because a single jamming platform has limited resources, a network of EW systems working collaboratively can more efficiently and selectively disrupt adversarial assets. Dehnie, Ghanadan, and Guan investigate using a game theory framework to effectively allocate resources among a network of EW assets.[7] Ly and Liang discuss cooperative resource allocation in airborne applications,[8] and others have explored how collaborative target localization, classification, recognition, and tracking of multiple targets with techniques could be applied to ground-based networks.[9] Resource management in distributed sensor networks has been researched specifically for providing a framework capable of intelligent resource management based on decision fusion and congestion avoidance.[10] These functions, in addition to concepts discussed in the Wireless Network Resource Management section, can be applied to create a more robust and effective resource management architecture for EW networks.

All these related works detail enhanced functionality for a general resource management system. However, as mentioned, these efforts are simply building blocks that require further enhancement to encompass the requirements of an EW resource manager. The discussion above illustrates that a holistic solution for the EW resource management problem does not exist in the literature; therefore, this article aims to bring to light the requirements and capabilities that should be considered when developing an EW resource management system. Next, we look at current APL research that is helping bridge the gap in resource management and EW networking.

## CURRENT RESEARCH AT APL

Many disciplines, some outside of traditional EW domains, are required to create a holistic resource management system. APL researchers are focusing their efforts in some of these required disciplines. First, machine learning, an area of active APL research, needs to be incorporated into mission planning and resource management behaviors. Second, a holistic EW resource manager will rely on networking, another domain where APL has expertise, to transfer information to facilitate management and provide feedback between assets. This data transfer increases the networking demand typically supported by EW assets. APL is pursuing cognitive radio (CR) concepts to enable more opportunities to optimally meet this demand.

Resource management behaviors such as workload and task sharing, dynamic or fixed assignments, and centralized or decentralized infrastructures are currently at the forefront of APL research into designing successful resource management systems. Mission planning can be autonomous or discrete, where an autonomous network would create optimal strategies continuously to accomplish a set of tasks. In this context, mission planning is no longer a discrete behavioral ruleset of the tasks to be performed by each node. This new paradigm for mission planning requires more complicated and dynamic test and evaluation models and tools to verify EW network behavior and jamming effectiveness. APL has pursued machine learning approaches in several IRAD efforts, including the FY2018–2019 Feature-based Electronic Attack Trained Hypersurface Responses (FEATHR) and the FY2019–2020 Intelligent Learning Electronic Attack Maestro (IL'EA Maestro) projects, which are described in the article by Casterline et al., in this issue.

Networking is the backbone for dynamic and feedback features for managing EW assets. The overhead from resource management can be relieved by using CR concepts. CR allows multiple networks to coexist and can increase the number of de-conflicted communication opportunities, adding robustness to communications.[11] Embedding Blue force signals in existing networks also physically hides the signals, enhancing network security. Ongoing research at APL involves the Cognitive Opportunistic System Manager for Intelligent Communications (COSMIC), which coordinates these spectral opportunities found within and outside of existing networks to improve Blue force communications using CR. COSMIC considers opportunities across all technologies, frequencies, and resources to provide passive electronic protection and increased dissemination of information for EW networks. How to create networks and access these opportunities is critical. Cognitive Interweave Access Operator (CIAO) is a set of MAC layer protocols that use CR access for EW networks. CIAO optimizes interference control, perception, throughput, and delays for EW networks. To provide efficient communication in-band with EW waveforms, simultaneous jamming with communication techniques must be considered. An example of simultaneous communication and jamming is the FY2020 IRAD project Interwoven Jamming with Opportunistic Communications (IJWOC), which combines EW waveforms with CR communications in the same waveform by using the interweave paradigm from CR. Multipurpose waveforms such as IJWOC improve resource utilization, reduce the overhead of internodal communication, and improve robustness and security for a network using CR.

APL researchers are pursuing machine learning and CR to help bridge the S&T gap that needs to be filled to realize a complete resource management solution. However, existing S&T gaps in other fields, as well as within EW resource management, need attention. Overall, there are too many options and possibilities when considering all technologies at all frequencies, missions for all applications, and assets at all positions. Because the associated challenges are so diverse and demanding, sponsors have yet to invest in finding solutions. Another obstacle that has precluded developing a prototype EW resource management solution is a lack of use cases. Moreover, given the number of stakeholders, there are logistical challenges to ensuring the necessary collaboration. The next section presents a resource management architecture that will abstract EW network resources and provide functional layers that will serve as the foundation for future EW resource managers.

## EW RESOURCE MANAGEMENT

Managing EW network resources is complex because there are many design choices across several S&T topics. For example, should resource management be centralized or distributed? Should the management of resources and the associations between nodes be dynamic or should it be done before the mission starts? What should the hierarchal design be for nodes in the network? Is information sensed by the network stored at central locations or across nodes in the network? Additionally, resource management needs to consider and balance EW network priorities that solve wideband sensing, jamming, and processing. These design options and priorities are likely application dependent, so general solutions are not ideal. What is needed is an EW resource manager framework that can be tailored for specific applications and implementations. Based on insight from resource management and related work, current research underway at APL, and various applications across the history of EW development at APL, we developed an extensible framework to characterize the salient features of an EW network resource manager. This architecture can be used to design application-specific resource managers and group research topics into layers that require further development.

### Priorities and Conceptual Architecture

A resource manager must consider an EW network's priorities and needs to satisfy wideband EW challenges. The EW priorities, described in more detail below, include sensing and capability awareness, jamming and computational efficiency, and coordination of associations between nodes.

- **Sensing awareness:** An EW network must be aware of actual and potential threats, existing technological infrastructure, and Blue force node information that will update and enhance a situational awareness database (SAD). Sharing this situational awareness information among nodes can enhance jamming effectiveness against adaptive, noise-resistant, or directional threats while avoiding the electronic attack of nonthreats. How the information is stored and spread is up to the implementation and is not considered in the architecture.

- **Capability awareness:** If each node in an EW network shares its resource availability, this self-aware network can distribute tasks and assignments based on resources to improve load-balancing efficiency.

- **Jamming efficiency:** Coordinated jamming by multiple EW systems improves the ratio of jammer power to signal power against multiple threats within the battlespace. Additionally, distributed collaboration can mitigate the negative effects of destructive interference produced by uncoordinated EW systems that are part of the network.

- **Jamming effectiveness:** Effectiveness is the determination of whether jamming creates the desired outcome. This could include denial of service, lowering signal intelligence, and degrading performance. It is target and mission specific with sensing awareness required to provide jamming feedback.

- **Computational efficiency:** Complex and wideband processing tasks can be distributed to multiple nodes for faster execution. This distribution of tasks and data also provides information on the threat environment and performance of jamming techniques.

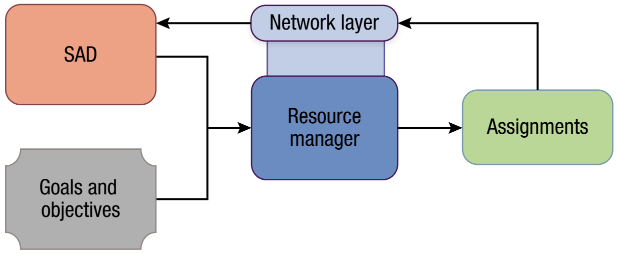


**Figure 3.** Resource management architecture's inputs and outputs. The backbone of the resource management architecture, the network layer moves information to and from nodes and the resource manager and adopts the OSI model to allow for flexible design when creating connections between EW platforms.

- **Associative convergence:** The EW network must determine association decisions to establish how nodes will interact to promote the other network goals. Associations between nodes include distributive, collaborative, and cooperative relationships. Creating these associations requires neighbor lists and network design considerations.

To begin addressing how to manage EW priorities and resources, we focus on the design of a conceptual resource management architecture. This architecture will characterize and standardize functions for EW resource management similar to how the Open System Interconnection (OSI) model does for network design.[12] The architecture will break down this complex problem into multiple layers to go from inputs to outputs. In the OSI model, the inputs and outputs are information. However, in this resource management architecture, the inputs are goals and objectives and situational awareness. The output consists of assignments to EW nodes. The inputs and outputs of a resource management system are shown in Figure 3. The backbone of the resource management architecture is a network layer that moves information to and from nodes and the resource manager. The network layer adopts the OSI model to allow for flexible design when creating connections between EW platforms. The following section describes Figure 3 in more detail.

## Architecture Inputs and Outputs

As shown in Figure 3, the first input is the EW network goals and objectives. The goals and objectives are high-level operational mission objectives given to the resource manager to accomplish. Goals could include degrade all RF communication, disrupt certain radars, disrupt certain communications and simultaneously enable Blue force communication, maintain Blue force communication in an RF-denied environment, or create a false radar image.

Another key input to a resource manager is a SAD that fuses incoming data from the network into a set of compressed information to provide an overview of the area of operations (AO) and key information a resource manager requires to distribute available resources. These data may come from smaller databases at each node or from a centralized database populated by nodes. Situational awareness metrics of interest include but are not limited to the number of nodes, each node's health, current tasking and capability, spectrum information on the threat environment, and battle damage assessments. A resource manager would poll the SAD to inform distributed sensing, communication, and engagement behavior. All information that feeds the SAD must be disseminated through the network.

The network layer is based on the OSI model and can be changed depending on the scenario and EW assets. This layer includes the physical, medium access control, and network layers to enable communications. The specific implementation depends on the application and scenario and will need to adapt to the environment. The network layer manages internodal communication and communication between a resource manager and the nodes. The network layer also helps coordinate communication across the layers shown in Figure 4. The communication link must be robust and adaptable to an ever-changing environment. To know what capacity the network has available to complete its objectives, as well as its limits, all resources from the network must be considered. How the resource management architecture organizes functional layers to go from inputs to outputs is detailed in the following section.

The resource management architecture takes in goals, objectives, and feedback from a SAD to create assignments for nodes in the EW network. These are the outputs of an EW resource manager and include transmit and receive assignments as well as direction on node movements and computation requests. Transmit and receive assignments correspond to sensing, jamming, and internode communication. All these assignments

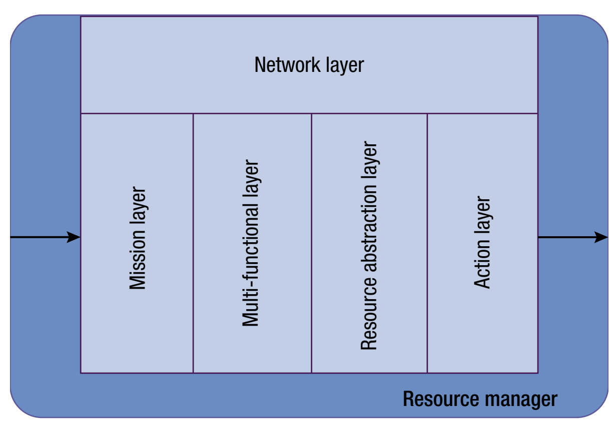


**Figure 4.** An overview of a resource manager architecture and the layers within it. The resource manager's operation is decomposed into the abstraction layers shown here.

require a notion of a timeline that can necessitate accuracies found in typical threat technologies, some of which demand real-time segments down to the microsecond or nanosecond level. Supporting a very disciplined, real-time timeline between assignments increases the complexity of assignment management. To balance the network's priorities and accomplish the mission goals, a resource manager must perform functions such as threat and resource analysis, engagement and arithmetic task creation, and coordination of association decisions. Arithmetic task creation would distribute mathematic operations based on execution costs across multiple tasks and nodes. These functions are topics of ongoing research and are beyond the scope of this article.

## RESOURCE MANAGER ARCHITECTURE

A resource manager must oversee the task of meeting the mission goals and objectives given the situation and resources available. In this section, we present an overview of a notional resource manager whose operation is decomposed into several abstraction layers, as shown in Figure 4. High-level descriptions of each layer are discussed in this section, from top to bottom, and a use case example is discussed in a subsequent section to help the reader understand each layer's responsibility.

### Network Layer

The network layer maintains and manages communication with the nodes based on network assignments from the resource manager. This layer will backfill information to other layers as capabilities, nodes, and resources become available or removed through the ad hoc joining or leaving of nodes and resources. This backfilling provides the ability for layers such as the resource abstraction layer to understand the feasibility of executing a certain waveform or algorithm given reported data from the nodes.

The network layer is directly connected to all layers in the resource manager. This ensures that up-to-date information is provided and shared among all layers in the resource manager and the SAD. Communication at all levels will allow the system to make the most informed decision it possibly can when given an ever-changing RF and threat environment.

### Mission Layer

The mission layer translates mission goals and objectives into tasks. These tasks will vary based on mission needs, potential outcomes, and hardware availability. The primary function of this layer is to translate human-readable requests into a more machine-readable format for the multifunctional layer by splitting the requests into objects that can be tangibly compared with one another to derive resource requirements.

The mission layer is tied to the SAD and will poll the database for information such as battle status, Blue force spectrum usage, and active threats. These data must be fused and disseminated from all nodes. Research on how to combine redundant data and simplify data structures is required to lower the overhead at multiple stages of the network. Using this information, the mission layer will determine the eligibility and priority of a task.

### Multifunctional Layer

The multifunctional layer translates the tasks provided by the mission layer into resource requirements. The multifunctional layer is aware of available waveforms, algorithms, and functions of the system, giving it the ability to compare available capabilities against the resources required and the resources available to best achieve mission success.

To determine the best capability to achieve mission goals, the multifunctional layer would need to implement a methodology that weighs the mission layer tasks against available capability (i.e., waveforms/algorithms) and the probability of success (i.e., a layered weighting system). The first weighting layer compares the mission layer tasks against available waveforms and algorithms. The weighted outputs are sorted based on the probability of success, complexity, and resource requirements of each potential solution. The second weighting layer takes the weighted potential solutions from the first layer and compares them against inputs passed from the SAD. The inputs from the SAD will determine the feasibility of using each potential output. While one solution from the first layer may have the highest probability of success, the reality may be that there is no feasible way to use that solution, given mission restrictions and the current battle status.

The output of the multifunctional layer is weighted tasks placed in order of most optimal to least optimal; this output is passed to the resource abstraction layer.

### Resource Abstraction Layer

The resource abstraction layer takes the tasks generated from the multifunctional layer and determines the optimal approach given the available resources. Typical resources found within this layer include instantaneous bandwidth, processing capabilities, number of band modules, energy/power, and system memory. Additionally, the number of jammers or disparate nodes should be considered to achieve geospatial superiority. The resource abstraction layer tracks the total current resource utilization by periodically polling the SAD to determine the status, capability, and location of nodes on the network. Based on the node's availability and capability, the resource abstraction layer decides on the optimal approach to meet the mission goal or objective and sends the commands to the respective nodes.

### Action Layer

The action layer executes the assignments given by the resource abstraction layer. The action layer contains four main parts:

1. **Receiving:** responsible for receiving any RF emissions
2. **Transmitting:** responsible for transmitting any RF emissions
3. **Processing:** responsible for executing any detection algorithms or generating required waveforms
4. **Positioning:** responsible for controlling and maintaining the movements of any nodes

The action layer outputs directly interface with the hardware of the nodes, providing direction for tasks such as determining which waveform to output and which power amplifier and antenna to use.

## EXAMPLE USAGE

In this section, we apply the resource manager to an example to provide context for the reader. Figure 5 represents an operation detached from the larger mission introduced in Figure 1. The mission illustrated in Figure 1 would be composed of potentially dozens of smaller operations, each with its own goals and objectives.

In this example, the mission goal is to jam the target early warning network so that the Blue force cruise missiles can reach their objective without being detected by the Red force. The fighter in this scenario has received mission information from a Blue force airborne early warning and control system (off-page) and is aware of the enemy early warning network. Upon entering the AO, the pilot chooses to begin disrupting the early warning network. The fighter in this scenario does not have

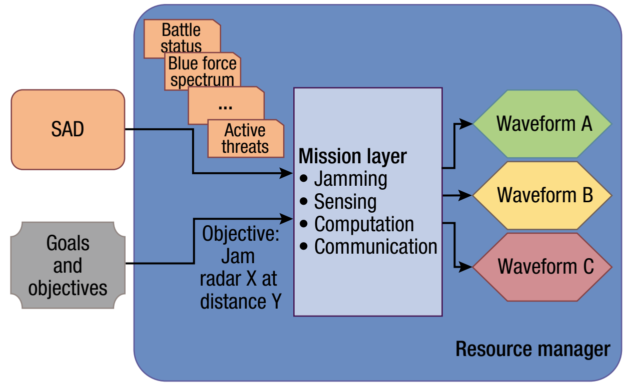


**Figure 6.** Overview of the mission layer and potential outputs. The SAD checks battle status to verify the authority to engage and then selects the jamming waveform among waveform A (most optimal), waveform B (optimal), or waveform C (less optimal),

antiradar electronic countermeasure and is relying on a stand-in jammer to provide cover for the flyover. To simplify the goals and objectives in this scenario, the pilot is asking the stand-in jammer to jam radar X at distance Y.

The host system, in this example the fighter, begins by invoking the resource manager with the user's request, which will poll the SAD to check battle status to verify the authority to engage and then select the jamming waveform among waveform A (most optimal), waveform B (optimal), or waveform C (less optimal), as shown in Figure 6. While all three waveforms are available options, their known effectiveness against the target radar provides the level of optimality. However, all three waveforms are distinct and have hardware and resource requirements:

- Waveform A (exceeds threshold) requires a sensing resource at frequency F1, significant processing resources to execute algorithm A1, and minimal transmit power P1 with a low duty cycle D1 at frequency F1 with a small bandwidth B1.
- Waveform B (achieves threshold) requires a sensing resource at F1 and moderate processing resources to execute algorithm A2, but more transmit power P2 with moderate duty cycle D2 at frequency F1 with a moderate bandwidth B2.
- Waveform C (acceptable) requires no sensing resource and minimal processing resources, but significant transmit power P3 (due to increased transmit bandwidth B3) and duty cycle D2 at frequency F1.

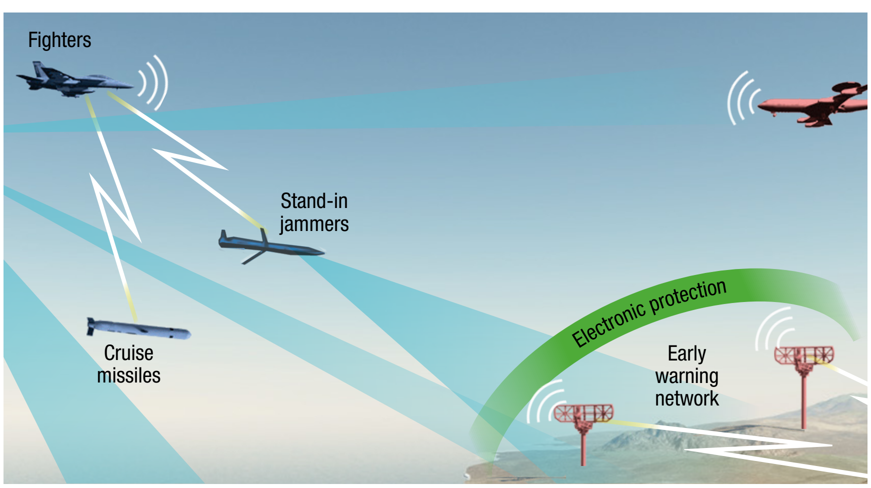


**Figure 5.** Example scenario. In this example, the mission goal is to jam the target early warning network so that the Blue force cruise missiles can reach their objective without being detected by the Red force.

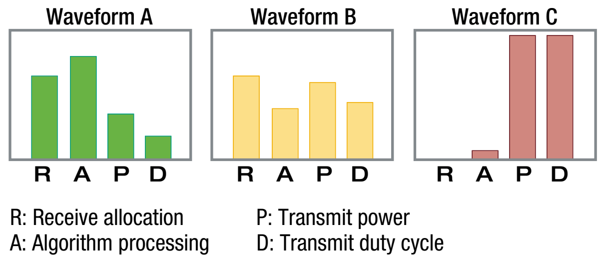


**Figure 7.** RAPD resource trade-offs between waveforms. In multiple target scenarios, RAPD outputs would be weighted against one another, the resources available, and the priority of the target to determine an optimal output that would satisfy mission needs.

Figure 7 shows the resource usage for receive allocation, algorithm processing, transmit power, and transmit duty cycle (RAPD) that can be considered when looking at trade-offs among resources. In multiple target scenarios, RAPD outputs would be weighted against one another, the resources available, and the priority of the target to determine an optimal output that would satisfy mission needs.

With the waveforms selected, the options are passed to the multifunctional layer. The multifunctional layer, represented in Figure 8, first takes the goal or objective provided and compares the available waveforms/algorithms to determine the best fit. This comparison accounts for the complexity required to generate a given waveform or run an algorithm and weights the outputs based on those criteria. The system is aware that at the current distance, waveform A will provide the most effect on a target, relating to a higher probability of successfully executing the goals and objectives, but also requires the most resources. Waveform B provides the next best performance with moderate resource requirements, and waveform C provides the least performance with minimal resource requirements.

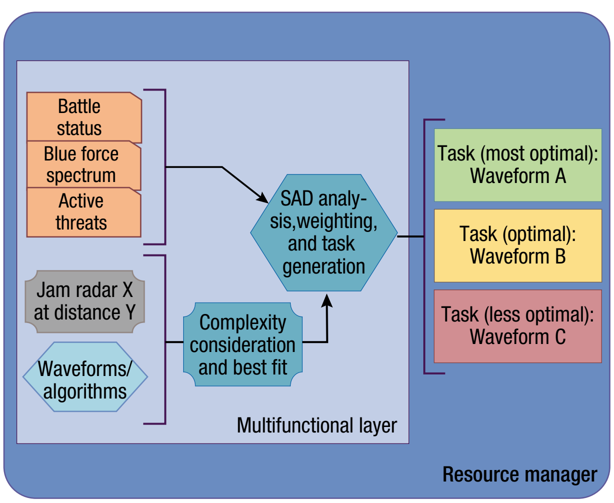


**Figure 8.** A demonstration of the multifunctional layer making decisions and weighting potential tasks. The multifunctional layer first takes the goal or objective provided and compares the available waveforms/algorithms to determine the best fit. It then compares the weighted outputs against the SAD inputs and again weights the outputs based on several criteria generated by mission requirements. Once the second round of weighting is complete, the multifunctional layer generates weighted tasks and passes them on to the resource abstraction layer.

Next, the multifunctional layer compares the weighted outputs against the SAD inputs and again weights the outputs based on several criteria generated by mission requirements, such as rules of engagement and spectrum use. Once the second round of weighting is complete, the multifunctional layer will generate weighted tasks and pass them on to the resource abstraction layer.

After weighting, it is determined that waveform A, despite being resource heavy, is the best path forward to achieve the objective to jam radar X at distance Y. As the resource abstraction layer is aware of the status, capability, and location of nodes on the network, it sees that a local node of the network, the stand-in jammer, has the resources available to execute the waveform A task. The resource abstraction layer then configures the action layer to execute waveform A (i.e., configure the sensing, processing, and transmit resources), as shown in Figure 9.

In this example, had the resources required to generate waveform A recently left the network (e.g., if the stand-in jammer was not in the AO), the network layer would have reported this to the multifunctional layer, and then the multifunctional layer would have used this information to weight the tasks differently, which may have resulted in an alternative outcome.

Finally, the action layer outputs a command to the node(s) to execute waveform A, and the targeted node(s)

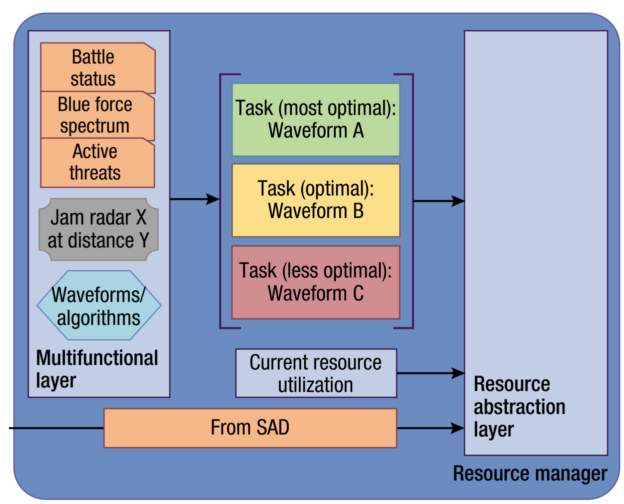


**Figure 9.** The resource abstraction layer taking all provided inputs to provide a final decision to the action layer. The layer configures the action layer to execute waveform A (i.e., configure the sensing, processing, and transmit resources).

respond by steering an antenna toward a given area in space (e.g., toward the early warning network), tuning to frequency F1 to receive RF, processing digitized RF (e.g., data) with algorithm A1, using the results to generate waveform A, and transmitting waveform A at frequency F1 at power P1. Afterward, the targeted node continues to report status to the SAD. These steps are illustrated in Figure 10.

In this example, the pilot would likely be unaware of the complex, behind-the-scenes set of functions. The ultimate goal is to instill confidence in the pilot so that when they set the objective of jam radar X at distance Y, the most optimal method of protection is automatically chosen by the system, so the pilot can concentrate on the multitude of other objectives required to complete the mission.

This is just one example; the mission objectives and goal do not always have to be jamming, nor do all nodes have to be stand-in jammers. Looking at the scenario in Figure 2, where there are many more assets with different capabilities, the resource manager's complexity grows considerably. As the number of EW assets in the AO grows, so does the importance and complexity of the resource manager—having an overarching coordinator in future scenarios will be not only valuable but necessary. It will be especially important when coordinating multiple tasks and objectives simultaneously over multiple diverse assets. This simple example illustrates the functionality of a resource manager architecture. The resource manager would be part of a larger multifunction EW network and needs to provide options for different mission types, goals, and objectives.

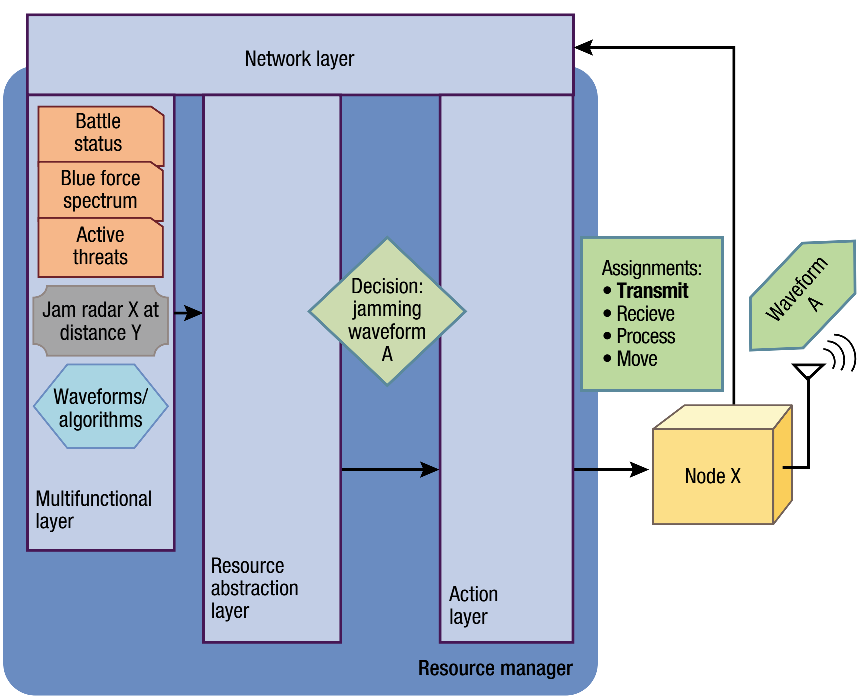


**Figure 10.** Using the SAD and objectives, the resource manager directs node X to broadcast waveform A to complete the objective.

## CONCLUSIONS AND FUTURE WORK

Distributed EW systems working together to collaboratively complete a task have the potential to improve threat sensing, jamming effectiveness, and resource management opportunities; however, achieving this vision requires implementing a resource management system that is not present in traditional EW systems. Furthermore, the breadth of S&T development still required and the number of applications leads to many options and paths forward. There is no general-purpose solution to EW resource management; instead, a resource management architecture is required. To divide and define these challenges, this article described the objectives, requirements, inputs, outputs, and layers of a resource management architecture to achieve distributed EW tasks.

System designers and researchers can use this architecture to implement distributed, collaborative functionality in their particular EW application. This article highlighted current academic research and research at APL that can be used to promote advanced concepts for EW networks and resource management. Each layer of the architecture has opportunities for growth and development in a variety of fields that will lead to better management of EW networks.

We believe APL can make major contributions to the important field of future distributed EW acquisition and operation, but a small APL team cannot do it alone. We are interested in collaborating across APL and with sponsors on related topics to advance this concept for the EW community. These collaborations would include finding more applications and use cases for resource management, bridging S&T gaps within the layers of the resource management architecture for those use cases, and prototyping resource managers for EW networks once the community of developers comes closer to a solution. We expect that resource management templates may become better defined—for example, based on the contributions of this article—but the challenge to apply resource management templates to the numerous possible scenarios will be ever changing and will require adaptation. Prioritized S&T gaps include the following:

- Resource management templates are not rapidly adapted to different scenarios and deployments.
- The role of machine learning in resource management is not well defined and requires more research.
- Data communications need assurance with multiple robust paths, especially in highly contested environments, and require innovation to stay competitive.
- Coordination and architecture of centralized and distributed control of autonomous agents is lacking integration with the EW research area.
- EW resource management has a low technical readiness level and requires prototype proof-of-concept demonstrations of both single and distributed EW scheduling algorithms.

## REFERENCES


[1]M. Kumar, K. K. Pattanaik, B. Yadav, and R. K. Verma, "Optimization of wireless sensor networks inspired by small world phenomenon," *2015 IEEE 10th Int. Conf. Ind. Inf. Syst. (ICIIS)*, Peradeniya, Sri Lanka, pp. 66–70, https://doi.org/10.1109/ICIINFS.2015.7398987.

[2]T. Irkhede and P. Jaini, "Cluster and traffic distribution protocol for energy consumption in wireless sensor network," *2013 Students Conf. Eng. Syst. (SCES)*, Allahabad, India, pp. 1–5, https://doi.org/10.1109/SCES.2013.6547535.

[3]C. Wan, S. Eisenman, and A. Campbell, "CODA: Congestion detection and avoidance in sensor networks," *Proc. First Int. Conf. Embedded Netw. Sensor Syst. (ACM SenSys '03)*, 2003, pp. 266–279, https://doi.org/10.1145/958491.958523.

[4]J. Kang, Y. Zhang, and B. Nath, "TARA: Topology-aware resource adaptation to alleviate congestion in sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 18, no. 7, pp. 919–931, Jul. 2007, https://doi.org/10.1109/TPDS.2007.1030.

[5]F. Ye, G. Zhong, J. Cheng, S. Lu, and L. Zhang, "PEAS: A robust energy conserving protocol for long-lived sensor networks," *Proc. 23rd Int. Conf. Distrib. Comput. Syst.*, , Providence, RI, 2003, pp. 28–37, https://doi.org/10.1109/ICDCS.2003.1203449.

[6]Y. Sankarasubramaniam, O. Akan, and I. Akyildiz, "ESRT: Event-to-sink reliable transport in wireless sensor networks," *Proc. 4th ACM Int. Symp. Mobile ad hoc Netw. Comput. (MobiHoc '03)*, 2003, pp. 177–188, https://doi.org/0.1145/778415.778437.

[7]S. Dehnie, R. Ghanadan, and K. Guan, "Resource allocation for networked electronic warfare," *2011 Mil. Comm. Conf. (MILCOM)*, Baltimore, MD, pp. 108–112, https://doi.org/10.1109/MILCOM.2011.6127442.

[8]H. Ly and Q. Liang, "Collaborative multi-target detection in radar sensor networks," *IEEE Mil. Comm. Conf. (MILCOM 2007)*, Orlando, FL, 2007, pp. 1–7, https://doi.org/10.1109/MILCOM.2007.4454836.

[9]M. Mears, "Cooperative electronic attack using unmanned air vehicles," *Proc. 2005 Amer. Contr. Conf.*, Portland, OR, vol. 5, pp. 3339–3347, https://doi.org/10.1109/ACC.2005.1470486.

[10]J. Zhang, E. Kulasekere, K. Premaratne, and P. Bauer, "Resource management of task oriented distributed sensor networks," *2001 IEEE Int. Symp. Circuits Syst. (ISCAS 2001)*, Sydney, Australia, pp. 513–516 vol. 2, https://doi.org/10.1109/ISCAS.2001.921360.

[11]A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: An information theoretic perspective," *Proc. IEEE*, vol. 97, no. 5, pp. 894–914, May 2009, https://doi.org/10.1109/JPROC.2009.2015717.

[12]J. Day and H. Zimmermann, "The OSI reference model," *Proc. IEEE*, vol. 71, no. 12, pp. 1334–1340, Dec. 1983, https://doi.org/10.1109/PROC.1983.12775.


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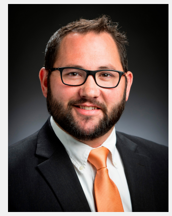

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