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14. ABSTRACT While the US has been at war for the past 16 years, our adversaries have heavily invested in the defense of their sovereign territory and hegemonic interests. The result of these efforts is that of a contested and degraded environment whereby US military access is in question. If swift action is not taken to address this A2/AD threat, the ten-year period between 2025-2035 could see a shift in world powers as we know them. It is therefore essential that US efforts focus on developing a C4ISR construct that can operate within the confines of the projected enemy environment of the future. Leveraging emerging breakthroughs in algorithm design, specifically that of ant colony optimization coupled with an adaptive ad-hoc multi-nodal mesh network provides both the robustness and flexibility required to counter the adversaries contested and degraded operating environment. This new technology will create a paradigm shift in the way wars are fought from the tactical realm where every asset is a sensor-shooter, to the operational realm whereby units operate in a distributed control fashion on simplified mission orders inside carved out spaces of access.					
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FUTURE WAR PAPER

Preparing for the Near Peer:

The Adaptive Ad-hoc Mesh Network

**SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF OPERATIONAL STUDIES**

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While the US has been at war for the past 16 years, our adversaries have heavily invested in the defense of their sovereign territory and hegemonic interests. Both China and Russia continue to develop a robust multi-domain defensive construct with emerging powers, the likes of Iran and Syria not far behind. The result of these efforts is that of a contested and degraded environment whereby US military access is in question. If swift action is not taken to address this anti-access/area-denial (A2/AD) threat, the ten-year period between 2025-2035 could see a shift in world powers as we know them. In November 2015, Lt Gen (ret) Deptula testified to Congress regarding A2/AD environments, advocating that in order to render this environment ineffective, the US must “actively pursue and invest in options...to counter the increasingly advanced anti-access strategies...our adversaries are likely to employ.”¹ Given that the ability to gain access is paramount, it is therefore essential that US efforts focus on developing an adaptive multi-nodal network of command, control, computers, communications, intelligence, surveillance, and reconnaissance (C4ISR) that can operate within the confines of the projected enemy environment of the future.

The description of the problem will be discussed first, analyzing A2/AD and its sub-components to synthesize the root of the problem. Emerging technology theory will then be detailed beginning with the evolution of Moore’s Law and its effect on encryption followed by the self-imposed constraints to the electro-magnetic spectrum (EMS). Next, adaptive ad-hoc mesh networks will be described in detail to include how they differ from current data-link technologies. Specific attention will be given to the algorithm known as ant colony optimization, which seeks to exploit the capability found in the common ant to forage for food using a path of least resistance. This will culminate with a discussion of the operational impact that such a

system will have on the future fight to include the potential for doctrinal changes across the joint force.

Analysis of the Problem

The moment adversaries placed barriers between themselves, they introduced A2/AD into armed conflict. As weaponry advanced to destroy or circumvent these barriers, the defenses also evolved. Today, the US finds itself facing adversaries that have extended their barriers so far and made them so robust, that it will take the whole of the joint force arsenal to penetrate them without specific offsets in technology. These potential adversaries will continue advancing these barriers until they are assured that the US and its allies are unable to affect their interests. Attempting to tackle A2/AD without a basic understanding of the root of the problem is mere patchwork. It is therefore necessary to break A2/AD down to its specific components.

Anti-Access

Anti-access is defined as the strategies aimed at preventing US forces from entering into a theater of operations.² Robert Haddick in his book *Fire on the Water: China, America, and the Future of the Pacific*, refers to this technique as “salami slicing.”³ This process entails leveraging all instruments of power as well as the growing proliferation of national and commercial satellite services to apply steady pressure and increased presence around the disputed territory, while building up a military power for its defense.⁴ This “robust defensive power” concept is harmonious with what Scobell describes in his book *China’s Use of Military Force*, hinging on a dissuasion strategy.⁵ China, along with other emerging powers, is leveraging comparatively low cost weapons systems to include long-range anti-ship, anti-satellite, and ballistic missiles as well as surface-to-air systems in an effort to dissuade and deter US and allied interests, while securing

their own.⁶ Assuming the joint force is capable of entering this theater, the problem-set is only amplified by the highly contested operational environment.

Area Denial

Area denial is defined as a localized contested environment whereby an adversarial country seeks to prevent freedom of action within areas under their direct control.⁷ In the air domain, this constitutes robust integrated air defense systems that incorporate such surface-to-air missile (SAM) systems as the S-400 with a range up to 215 NM as well as a multitude of spectral jammers degrading laser, GPS, and radar capability.⁸ To put this into perspective, the premier airborne command and control (C2) platform, the E-3 AWACS, has an operational radar range of 173 NM, making it a prime target for the S-400.⁹ The land domain will see similar degradation due to adversarial jamming capability along with short to medium range surface-to-surface missiles, anti-personnel mines, and ballistic missiles targeting dispersal areas. More importantly, land components will fight in absence of air superiority, a devastating concept not experienced by the US in the last few decades of conflict. Submarines and maritime mines aside, the sea domain is at no less risk with the advent of the DF-21 anti-ship missile. Dubbed the “carrier killer,” the DF-21 has a range of 917 NM, capable of sinking carrier-sized vessels from extreme distances.¹⁰ By themselves, these defeat mechanisms within the AD environment have the potential to neutralize a technologically advanced aggressor; coupling this with the fact that these systems are either mobile or stored in hardened deeply buried bunkers adds exponential difficulty.

The Heart of the A2/AD Problem

A2/AD is generally described as a singular entity without compartmentalizing each root concept, however; doing so, enables a synthesis of the true nature of the problem. A specific

platform can certainly be developed to gain access and strike within this contested construct. Modern stealth technology was created with this intent in mind, but without situational awareness of the fluid battlespace, a singular platform will not solve the larger problem. Weaponry too has shown some capability with the continuous advancements in precision guided munitions as well as low observable long-range air-to-surface missiles such as the Joint Air to Surface Standoff Munition (JASSM). However, this too will fall to the same fate as the stealth platform without real-time targeting capability. Emerging missile technology such as hypersonic weapons capable of traveling 1,000 miles in 17 seconds seek to close the gap from target receipt to target prosecution but they first require targetable coordinates.¹¹ The lynchpin assets that have provided this battlespace situational awareness and C2 in the past such as the AWACS, JSTARS, and Aegis Combat System equipped vessels will be at a standoff distance outside of their maximum effective radar range or otherwise put into high risk situations for limited gain. The heart of the problem therefore resides in the inability to gain battlespace awareness without risking high demand, low-density platforms, a problem that emerging technology will amplify but may also ameliorate.

Emerging Technology

As computer technology advances, Moore's law will become invalid, as the number of transistors on a microchip will be unable to sustain exponential increases every 2-2.5 years.¹² However, where Moore's Law tapers off, parallel computing will pave the way for quantum computing and artificial intelligence.¹³ These offsets in computing technology will force those who transmit and receive secure data to rethink their business models. "Data at rest," or data that is not generated and immediately transmitted will be vulnerable to attack and encryption as we know it will be obsolete. The communications network that is required for the future fight must

look to leverage both existing and emerging technology while working within the confines of a diminishing EMS.

A US Senate report illustrates that the Federal Communication's Commission (FCC) recorded a bandwidth usage of over 10,000 MHz in 2011, a 555% increase since the year 2000.¹⁴ In November 2014, the FCC sold "six blocks of airwaves," to commercial buyers totaling 65 MHz at a price of \$34B, nearly doubling the money earned from the last sale in 2008.¹⁵ The billion-dollar industry created by the selling of bandwidth is saturating the EMS, degrading the military's communications capability prior to the enemy lifting a finger. Per the "Satellite Communications Strategic Report," 2026 should see an increase in High Throughput Satellites, Ku-band for maritime coverage, and a wideband MILSATCOM replenishment strategy.¹⁶ What this means is that as the reduction continues within the EMS due to the selling of bandwidth to the commercial sector, its use for military purposes is expected to increase. It is essential to plan to this conflicting paradigm and one way is through the development of a C4ISR construct comprised of an adaptive ad-hoc mesh network.

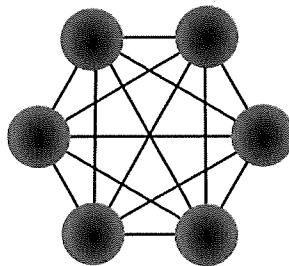
Adaptive Ad-Hoc Mesh Networks

Prior to addressing what an adaptive ad-hoc mesh network is, it will help to describe what it is not. An adaptive ad-hoc mesh network is not the tactical data link of today. The current system, Link 16, is considered a "nodelessness" system, meaning that it contains no central net control station like its predecessor Link 11.¹⁷ Instead, Link 16 uses dedicated time slots for each asset to broadcast within, providing a more robust system by not relying on a central node to both receive and broadcast information.¹⁸ The drawback however, is that Link 16 requires a network time reference (NTR) to start the entire system.¹⁹ An NTR is analogous to a master clock by which other assets must align with, in order to operate within the data link. Deny either

the establishment of an NTR or an asset from synchronizing their terminal and the entire link architecture is defeated. This process creates a vulnerability that is all too feasible in the contested and degraded environment of the future.

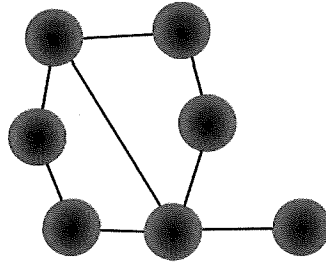
Mitigating this risk requires an overhaul of our entire data link architecture into that of a wireless mesh network. A wireless mesh network is “infrastructureless,” comprised of numerous transmitters and routers that have the ability to connect to each other, sending and receiving data, in absence of a central authority.²⁰ Adding the term “ad-hoc” means that the connections are not prior planned, occurring at random based on location and information needed, individual nodes arrive and depart whenever they choose.²¹ These systems can automatically reconfigure their bandwidth, storage, and processing rate making them resistant to adversary interference.²² In addition, the dynamic connections made between each node creates an infinite number of routes throughout the network, increasing its robustness as shutting the system down requires the enemy to neutralize every single node in the network.²³ Figure 1 illustrates the complexity of a full mesh network, where every node interacts with the other nodes, creating this redundancy.

Figure 1. Full Mesh Network



While this network is an ideal setup, the adversary has a vote and should they decide to degrade or deny elements of the network, a partial mesh network as seen in Figure 2 possesses a strength far exceeding the current centralized control model.

Figure 2. Partial Mesh Network



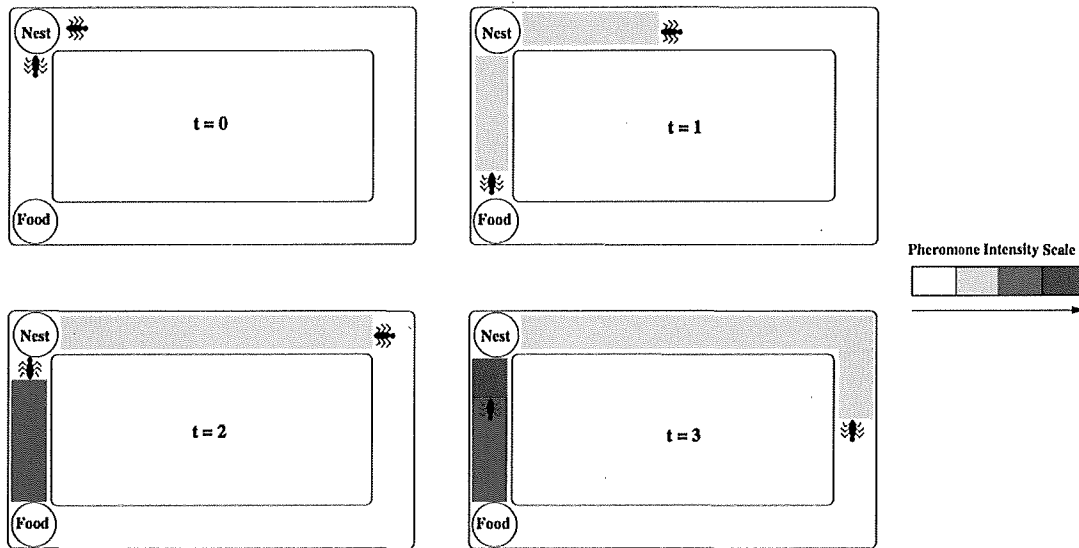
If each node is some form of joint asset, even a partial network can affect numerous nodes as the assets transmit data to each other, fusing pieces of the battlespace together as they transit in and out of the theater. In addition to the organic strength of a mesh network, the fact that these nodes are constantly on the move makes them even more difficult to find, fix, and target while increasing their area of influence. However, this infrastructure-less architecture is not the only advantage of an ad-hoc mesh network, it is the algorithms within the network that truly make it revolutionary. The “adaptive” element of this technology is replicated from nature and more specifically, from the foraging ability found among the common ant.

Ant Colony Optimization and Swarm Intelligence

Ants have the unique ability to find the most direct path between their nest and a food source using pheromone secretions. Pheromones are chemicals secreted by a particular species, which trigger social responses in other members of that species. Ant colonies use pheromones primarily for navigation to and from food sources. Assuming two ants leave their nest by two different directions en route to the same food source, the ant that returns first will leave the strongest pheromone concentration, as it will have been released more recently than the ant that has yet to return. These pheromones act as a beacon to other ants and the stronger the concentration the more they are drawn. As other ants join the trail, they leave their own

pheromones further increasing the concentration and enforcing the route. Figure 3 provides a pictorial representation of this phenomenon.

Figure 3. Direct Path Phenomenon of Ants²⁴



This direct path phenomenon has multiple benefits. First, it is both self-organized and highly distributed, lacking a central control element.²⁵ Second, there is no single point of failure, making the system highly robust as each ant is unimportant by itself but the quantity increases the quality.²⁶ Lastly, the process is inherently adaptive as ant behavior is not deterministic; some ants will still venture out on their own, allowing the system to adapt as the environment changes.²⁷

Modifying this natural phenomenon to the digital world is done by creating a software algorithm consisting of a colony of artificial ants and a matrix of synthetic pheromones in a process known as ant colony optimization (ACO). When these agents communicate indirectly through local change in the environment, this is called stigmergy.²⁸ The elements that are changed in the environment and sensed by other agents are called stigmergic variables and it is through these variables that the adaptive algorithm is built.²⁹ While the technical details are

beyond the scope of this paper, the “digital ants” within the algorithm have the ability to seek out paths of least resistance within an environment and provide a synthetic pheromone trail for other ant bots to follow. The net result is what is known as swarm intelligence whereby otherwise heavy computing power is spread among a number of minimalist units that self-organize to create the greater effort.³⁰ The possible uses of this technology are endless, whether part of the data link architecture of a theater asset or injected into the environment as self-contained micro-air vehicles. These units do not require any centralized control nor a preprogrammed notion of the greater task, they operate in a simple and localized stochastic manner, leveraging stigmergic variables to find avenues of least resistance.³¹ In the contested and degraded environment of the future joint fight, this adaptive ad-hoc mesh network has the potential to change the operational level of war.

The Operational Impact

The application of this technology to the joint fight cannot be overstated, considering the potential for massive C4ISR degradation from adversarial actions. Assets with the ability to pass tailored packets of information between one another regardless of the degradation to the EMS environment will provide an asymmetric advantage over an adversary, and have a profound impact on the way in which future wars will be fought. Incorporating this technology in the future fight will create a modification to the operational level of war for the joint force.

Information collection and dissemination will be redefined; moving away from time-slot based generic data dumps to the entire force, to one that is tailored to a specific platform and mission. Each asset will be equipped with a system that cannot only talk to all other systems but can learn and adapt from neighboring systems. The immediate result will be a unity of information flow between all operating systems within the localized joint fight, enabling multi-

domain tactics, techniques, and procedures to progress more rapidly as the fight endures. While this change is organic to the new technology, other changes will take a considerable amount of planning and forethought.

Every Asset a Sensor-Shooter

Rational thought would suggest that if assets are being provided tailored unimpeded intelligence about the enemy, they should have the capability to provide an effect. One benefit to the mass data dump of information in previous conflicts is that it provides the warfighter with overall situational awareness (SA) of the battlespace. This process enables a unity of effort whereby assets can act per the overall scheme of maneuver. While this option is arguably the better way to fight a campaign, complete unimpeded SA is not realistic in the future A2/AD environment and augmenting wide-area intelligence will be required. In a similar fashion to the algorithm itself, assets may now have to rely on operating in a simple and localized manner whereby the quantity of numerous localized fights make up for the quality of a massive coordinated strike. What this leads to is the theory that all assets should become sensor-shooter platforms, a paradigm shift in the way task and function specific combat systems are both created and employed.

Attack in Depth

The concept of attack in depth emerges because of the transition to a sensor-shooter fleet whereby assets with varying capabilities are spaced in a manner that offers the greatest effect with the least risk. Platforms capable of penetrating into the enemy environment will provide the deep strike, supported by older generation assets as well as assets that have previously lacked kinetic strike capability, leveraging standoff munitions. Equipping support assets with kinetic capability is neither a new nor novel idea as we have seen this performed throughout history,

beginning with the earliest uses of aviation to the most recent use of unmanned aerial vehicles, both of which were otherwise conceived as reconnaissance platforms. While a KC-10 Extender might appear to be an odd choice to launch a standoff munition, the target rich environment of a near peer will warrant all assets within the battlespace to be equipped with such capability. In addition, the localized manner with which information is received will require all assets to act in a distributed and decentralized fashion.

Distributed Control

As the environment becomes more degraded and assets find themselves segregated within their respective mesh networks, there will be a shift in how objectives are achieved. The current model begins with a strategy and its associated means and circumstances, linking them down to the tactical tasks via campaigns goals, intermediate goals, and major operations. The environment of the future will call for a looser coupling in some areas between strategy and tactics. Command will remain centralized but control will be distributed across the battlespace with execution taking place in a decentralized manner via an idea first consummated by Gerhard von Scharnhorst known as “Auftragstaktik,” or mission orders.³²

Mission Orders

Mission orders will achieve flexibility within the campaign plan to ensure that objectives are being completed in an environment where reach back to a higher echelon may be impossible for extended time periods. These mission orders can range from basic tactical tasks to operational standing orders with an emphasis on simplicity. One example of a tactical task would be to destroy all DF-21 “carrier killer” missiles within the first 10 days of conflict, regardless of their location. Commanders at the upper echelon can be assured that irrespective of the degraded status of communications to the lower echelons, any DF-21 missile that the joint force can find

will be destroyed without hesitation. After the 10-day window, the intelligence that trickles in throughout this period can be assessed to determine follow-on operations.

At the operational level, mission orders could look to leverage the ACO algorithms to seek out paths of least resistance within the enemy's defensive construct and exploit these gaps. These exploitations must be immediate and with the assets collocated within the particular mesh network, to gain maximum effect. Time will not be afforded to the aggressor who must ask permission from higher headquarters, as the gaps will be fleeting. Instead, those assets who can communicate with one another must organize a strike to breakthrough and exploit. This concept is no different from the evolution seen within the German military as they perfected their "stormtroop" tactics in WWI and leveraged mobility in WWII to create a breakthrough and operational exploitation that knocked the allies on their heels. In this case, simple direction carried the day whereby every unit understood four basic rules: move as far forward as you can; if not the lead trace, follow the unit in front of you; if under fire take cover and attempt to neutralize the threat; if not engaged, roll-out and assist the engaged unit, attacking from the flank or rear. This simplified command and control construct created a coordinated action for a given situation maximizing tempo and cohesion. It is reasonable to think that simple rules of this nature can be applied to future conflict. Whether the action is performed by man, pre-programmed in machines, or a combination of both, such rules would enable the entire battlefield to be affected in absence of centralized control and unrestricted battlespace awareness. In addition to the operational level impact, it is conceivable that the evolution of adaptive ad-hoc mesh networks will also create doctrinal changes across the joint force that must be adopted to maximize its effectiveness.

Doctrinal Evolution

As changes occur within the operational level of war, doctrinal procedures must also evolve. The intent is not to dictate these doctrinal changes as they will likely emerge as the new paradigm is set in motion, instead this section will address some likely changes.

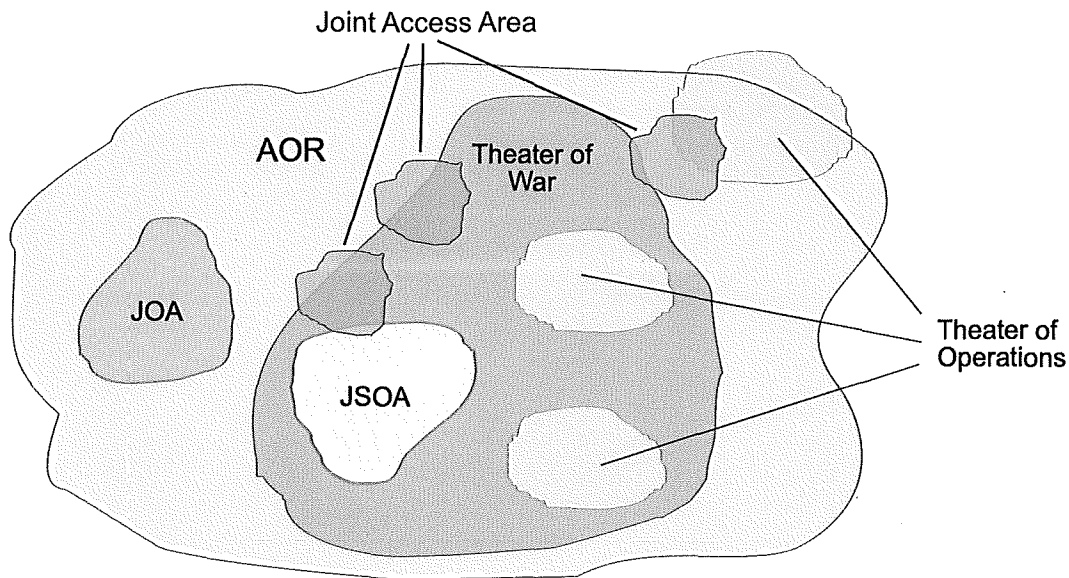
Joint Tasking Order

To provide up-to-date battlefield intelligence for airmen striking targets in Iraq, General Chuck Horner instituted the 72-hour air tasking order (ATO) cycle.³³ While the intent was to ensure that new targeting information was updated every three days, the process is reaching its 30-year anniversary and is woefully outdated given current technology. This archaic process must be cut down and reshaped to allow for streamlined execution in the fight of the future. Mission orders, as previously addressed, should find their way into this document, ensuring all persons are operating within the same constraints. In addition, the centralized command, distributed control, and decentralized execution concept may find that tasking orders of the future begin as commander guidance and build as they disseminate down to the lower echelons rather than a completed document created at the highest level. The idea of a simple joint tasking order (JTO) developed by the commanding general and passed down through each organization could become the new standard whereby the localized operational commanders in the field develop the actual objectives based on their respective C4ISR connectivity. Incorporating the JTO concept with that of the varying levels of access afforded to the operational level commanders using adaptive ad-hoc mesh networks could potentially create an addition to the operational areas within a theater.

Joint Access Area

Joint Publication 3-0 *Joint Operations* lists five operational areas within a theater beginning with the area of responsibility as the largest, nested inside of which is the theater of war as well as joint operations areas, joint special operations areas, and the various theaters of operation.³⁴ The importance of these distinctions is that they dictate command authority as well as supporting/supported relationships. While it is not anticipated that the future fight will remove any of these areas, it is conceivable that with the ACO algorithm, a joint access area (JAA) will emerge through either attrition of enemy defenses or unidentified gaps in their coverage. A JAA is an evolving area of access that is created through a sequence of events in which the enemy defenses have been overcome either temporarily or permanently, thereby creating a shared battlespace capable of being exploited by the joint force. The ability to exploit these specific sections will require the establishment of a joint access area (JAA) whereby a single commander oversees this location and can thereby manage asset requirements. This concept builds on that of mission orders as the commander in charge of the JAA will generally be of a lower rank than those commanding the other five operating areas and will be forced to act swiftly to exploit the available access. The JAA commander must have a clear idea of what the higher echelon expects as tempo will be paramount and real time communication to higher headquarters may be impossible. The assets that the JAA commander has at their disposal will be those within the nodal architecture as tasked through the JTO. Once the joint force commander becomes aware of a JAA, exploiting it should become the main effort, and necessary assets must be allocated to achieve a breakthrough. Figure 4 shows an overlay of all six of the operational areas within a theater in order to understand their relationships and the necessity of both deconfliction and asset allocation.

Figure 4. Modified Operational Areas within a Theater³⁵



Conclusion

To remain a credible threat in wars of the future, the way forward must include a continued investment in a common architecture of C4ISR, capable of adapting and surviving in a contested and degraded environment. Retrofitting old platforms with new technology will be essential, as will the building of new systems capable of sustaining their functionality inside the degraded environment. Additional research in platform specific capabilities, weapons technology, and force structure will also be needed to defeat the adversary of the future.

The description of the problem was first discussed by analyzing A2/AD in its sub-components to synthesize the root of the problem. Emerging technology theory was then detailed beginning with the premise that where Moore's Law tapers off, it will give rise to parallel and quantum computing, putting encryption as we know it at risk within the confines of an ever-deteriorating EMS. In an effort to mitigate this risk, the concept of adaptive ad-hoc mesh networks was described in detail to include how it differs from current data-link technology. Specific attention was given to the algorithm known as ant colony optimization and its ability to

find the path of least resistance, enabling connectivity in an otherwise degraded environment.

The culmination of the discussion drew out the operational impact that such a system would have on the future fight to include the potential for doctrinal changes across the joint force. The foreseeable threat of future A2/AD environments draws attention to a significant gap in the ability to gain access. An adaptive ad-hoc mesh network, where no one node is critical, capable of autonomously adjusting to the contested and degraded environment is an essential requirement to ensure that US access remains unimpeded.

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²³ DeFilippa, Take Mesh Networks Seriously.

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²⁵ Ducatelle, Ad Hoc Wireless Multi-hop Networks, 59.

²⁶ Ducatelle, Ad Hoc Wireless Multi-hop Networks, 59.

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