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## Developing a Viable Approach for Effective Tiered Systems

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***“How do you get information from the Air Force down to a Marine Corps unit down on the ground that’s trying to assault an objective? How do you get a Navy fire control mission onto an Army target?...Now what you see is people really working hard on getting networks linked up so that information can flow across traditional boundaries...And what we’re really trying to do is unlock all the combat potential that we have, that we bring to a joint task force, and be able to use it in non-traditional ways.”***

*Admiral Dennis C. Blair, CINCUSPACOM  
KB(X), USS Coronado, 23 June 2001  
[on the topic of JTF WARNET]*



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## Developing a Viable Approach for Effective Tiered Systems

### Executive Summary

Tremendous learning opportunities exist for understanding how to realize net-centric operations. The ability to share information to and from the tactical edge will allow operators to work in more dispersed environments while taking decisive, collective actions. However, to realize this vision, significant S&T issues must be resolved. Possibilities of net-behavior must be better understood in order to shape future DoD net-centric systems technologies and operation concepts, to define with stability the defense industry after next, and — centrally — to develop the future tactics, techniques, and procedures that will enable net-centric advantages to be effected at the tactical, operational, and ultimately strategic levels. Near-term success will be realized by proceeding with scenario-driven, experimentally-based tiered systems development and demonstration activities that are co-evolved in small development cells staffed with cohesive teams of Service Lab technologists and Operational/Tactical war fighters who are chartered to work collaboratively for four to five consecutive years. Topical focus for each cell should be provided by a net-centric overarching theme. Examples include coherent horizontal networking, or realistic sensor integration toward real-time actionable information. Within 18 to 48 months each cell should provide: (1) experimental distributed tiered systems capabilities (hardware and software) for war fighter experimentation and evaluation; and (2) elucidation of methodologies for tiered systems developments that will enable wide further prototyping.

**Background.** As the 21<sup>st</sup> century progresses, one of the major factors impacting world security will be immense overpopulation pressures in the most volatile parts of the world. Along with this will be inexorable demands on basic resources such as food, water, chemical feedstocks, and energy, and a general degradation of the environment. As conflicts may increase in number, scope, and severity, the U.S. military will be called upon to project power and to respond, using the resources at hand, when and where needed.

**Tiered Systems.** From the perspective of sustainable military forces, it will be imperative for the DoD to have the ready ability to harness many operationally relevant aggregate capabilities using only those resources that may be available wherever action is required. These disparate resources must then be linked into a single, closely-knit, ad hoc entity, a “tiered system.” Tiered system elements will generally include mission-dependent subsets of cross-service hardware and software: configurable mobile networks, sensors, effectors (cueing agents, weapons, etc.), platforms, command and control, and authorized individuals.

**Recommendation.** Initiate an objective, focused, tiered systems R&D endeavor to develop, experiment with, assess, and “red-team” the new and complex distributed tiered systems that are now possible, in order to expedite development of militarily-relevant tiered systems-of-systems that are needed for conducting irregular and distributed missions as noted in QDR 2006. Technical instantiation should be via one or more affordable tiered systems experimental test beds, cells that bridge simulation with field environments and span from individual system hardware elements through fully integrated tiered systems capability. Each cell should proceed as a rigorous, integrated simulation and experimental activity analogous to the fielding of a significant physics proof-of-principle experiment, and with a commensurate resource envelope: \$10-15M/year for four to five consecutive years, with appropriate contiguous staffing throughout.

**Example Cells.** Example cells are scoped in this report. A Reference Implementation Cell would provide hands-on environments for testing prototype tactical edge applications, service-oriented architecture, middleware, communication services, networking, and radio subnets, and for evaluating how they work together. Examples of co-evolutionary experimental test bed cells include those for maritime defense awareness of non-cooperative targets; urban contaminant transport (weapons of mass destruction (WMD) aerosols; liquid natural gas explosion; etc); and tactically-oriented intelligence, surveillance, and reconnaissance (ISR) for ship-to-objective maneuvers (STOM) across expeditionary littoral spaces.

**Summary.** Effective tiered systems-of-systems may be developed in the near-term via a suite of small, interactive, scenario-driven, experimental test beds that each involve, at minimum, all basic assets necessary for an operational tiered system.

# 1 Overview

## 1.1 Context: Sustainable Military Forces

1.1.1 As the 21<sup>st</sup> century progresses, one of the major factors impacting world security will be extreme overpopulation pressures in the most volatile parts of the world. Along with this will be immense demands on basic resources such as food, water, chemical feedstocks, and energy, and a general degradation of the environment. As conflicts may increase in number, scope, and severity, the U.S. military will be called upon to respond, using fewer and more expensive capabilities.

1.1.2 The future military will most likely be under pressure to fight and project power using the resources at hand in the most economic way possible. For instance, no longer will the U.S. Navy have the luxury of unlimited physical resources being transported 12,000 miles as needed to the theater of operations. This leads to a new concept that we introduce here, the idea of sustainable U.S. military forces (SMF).

1.1.3 From the perspective of SMF, it will be imperative for the U.S. military to have the ready ability to harness many operationally relevant aggregate elements that may be available wherever one is on the globe at the onset of an engagement, and to link these disparate elements that are possibly under different commands into a single, closely-knit, ad hoc entity, a “tiered system.” To accomplish this requires an objective, focused, tiered systems research endeavor to develop, experiment with, assess, and “red-team” these new and complex distributed systems-of-systems, in ways that consistently encompass individual system hardware elements through integrated systems capability.

## 1.2 Analysis: Effective Tiered Systems

1.2.1 A key enabler for forefront SMF is the idea of a tiered system. The Defense Science Board (DSB) Task Force on Future Strategic Strike Forces, co-chaired by ADM D. Blair, USN (Ret), and Gen M. Carns, USAF (Ret), published a report in 2004 (Blair et al. 2004, referred to here as the Blair DSB report). This report operationally defines a tiered system with the observation that “in order to achieve the most leverage from individual systems, we recommend an integrated, multi-tier intelligence system encompassing space and air-based sensors linked to close-in and intrusive lower tiers. For the ISR system needed for future strategic strike to come to fruition, it is essential that the leadership view the multi-tiers as ‘a system.’... The lower tiers are not only the critical source of intelligence, they can also serve as a key cueing device for other sensors.” The Blair DSB report centrally recommends that tiered systems be developed for the near, middle, and long term to improve tactical ISR and ultimately to support strategic strike needs in the long-term (30-year) time frame.

1.2.2 The Blair DSB report further envisions the need for a C3ISR test bed “employing surrogate and prototype sensors, with appropriate attention on how the sensors would be deployed. This test bed would also be used to (1) develop concepts of operation and algorithms for multi-tiered architecture(s), (2) refine sensor exploitation, and (3) assess sensor communications.” The gravity of the present deficiencies in current and planned capabilities leads the Blair DSB report to recommend that “a C3ISR test bed (a virtual

and distributed test range) essential to support the spiral development of the C3ISR architecture required for future strategic strike... will need approximately \$1.5 billion....”

1.2.3 On the subject of present deficiencies in surveillance and reconnaissance persistence, penetration and identification, battle damage assessment, and data processing, exploitation, and dissemination, the Blair DSB report observes that “the laws of physics... seriously limit [assets] to penetrate foliage, track individuals, identify WMD components, defeat camouflage, and identify decoys. Dealing with these surveillance and reconnaissance challenges will require lower tiers of close-in and intrusive sensors.” The report then makes specific recommendations for development of “technologies and systems for networked close-in sensors (air and ground) and tagging, tracking, and locating invasive sensors; networks to self-form, infil and exfil data; and sensors of various types to manage power and gather information.... The technologies developed should be fielded and demonstrated in the C3ISR test bed so that the effectiveness and interoperability of each tier of the C3ISR architecture may be assessed.”

1.2.4 A central concern of the Blair DSB report is that even as the DoD becomes more dependent on networked C3ISR, “no dedicated ‘red team’ effort exists which concerns itself with camouflage, concealment, and deception; ...vulnerabilities; and tactics which might be used by adversary against our emerging C3ISR system” (Blair et al. 2004). We share this concern.

### 1.3 Recommendations: RIC and ETB

1.3.1 For the present study, we used as basis the tiered systems operational view of the Blair DSB report. Tiered systems elements, aggregates of existing and novel cross-service hardware and software, will thus generally include mission-dependent subsets of ad hoc configurable networks, sensors, effectors (cueing agents, weapons, etc.), platforms, command and control, and authorized individuals.

1.3.2 This report agrees with all technical essentials of the tiered systems development needs outlined in the Blair DSB report, briefly synopsisized above. However, prior to embarking on a comprehensive test bed activity as envisioned in the Blair DSB report, we recommend beginning with two focused integration cell initiatives to address two key deficiencies that are currently impeding effective tiered systems developments: seamless horizontal networking, and sensor integration. The first initiative, a Reference Implementation Cell (RIC), would provide an environment to host and evaluate prototype tactical edge applications, service-oriented architecture (SOA), middleware, communication services, networking, and radio subnets. The second, a co-evolutionary cell made up of Operational/Tactical war fighters along with Service Lab technologists, would focus on coherent development of tiered systems. The central goal of this experimental test bed (ETB) would be to elucidate tiered systems developmental methodologies; products would include integrated tiered systems hardware for war fighter experimentation. Each ETB should proceed as a rigorous, integrated simulation and experimental sensors exploitation and integration activity, analogous to the fielding of a major physics proof-of-principle experiment, and with a commensurate resource envelope: \$10-15 million/year for four to five consecutive years.

## 2 Study Objectives and Context: Technical Flexibility on a Global Scale

### 2.1 Future Security Environment and the Idea of Sustainable Forces

2.1.1 The present climate of security, which is very different from that in which most of us historically have been “schooled” (Woolsey 2006), requires consideration of a spectrum of adversaries, as illustrated in Fig. 2.1, after Blair et al. (2004).

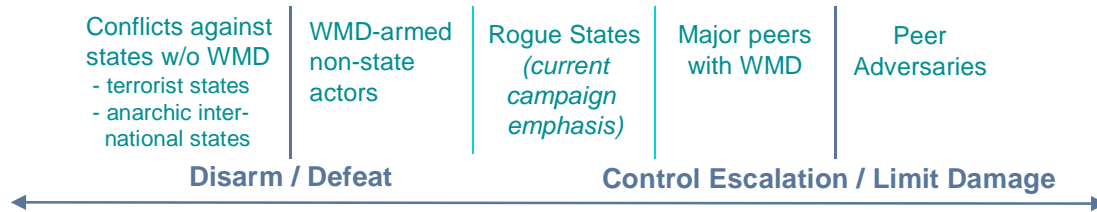


Figure 2.1. The Current Spectrum of Adversaries

2.1.2 In the past, and even today, strategic strike capabilities have focused on addressing an offshore, bureaucratically predictable peer adversary over whom the U.S. was technologically dominant: “it was the Pentagon who drove the electronics, for the Cold War” (Woolsey 2006). However, recent and ongoing uncertainties redefine emphasis for near-, mid-, and long-term planning. In the 10-20 year range, will there be more terrorism or less terrorism? Will a peer adversary re-emerge by 2030? What new technologies will be available to the U.S. military? How can we best deflect terrorism and the emergence of a peer adversary, through our future actions?

2.1.3 Evolving views of power projection, in the context of the “long war” that the military must now fight, are noted in the 2006 Quadrennial Defense Review (QDR 2006). An illustration is CNO ADM Mullen’s “very different image of sea power.” Along with his goal of 313 ships (e.g., Cavas 2006), ADM Mullen’s vision of sea power includes, according to Barnard (2006), “‘doctors and nurses healing the sick’ and mechanics repairing a city’s lost infrastructure. He points to the work of U.S. forces that sped to the scene of the December 2004 tsunami, providing relief to tens of thousands in Indonesia, ‘a country that as a whole didn’t feel very kindly toward Americans.’ After U.S. forces left, a poll indicated the sentiment ‘had just about reversed.’ There is not enough military or economic power in the world to bring about that kind of change that fast. ADM Mullen wants naval forces to ‘have a lot of impact in a positive way... and create relationships which hopefully will lead to reason in tense times.’”

2.1.4 Moreover, the world environment itself may be approaching an era of change. According to many, global warming is “happening.... Ice shelves are collapsing, glaciers are retreating. For politicians, the message from science is clearer than ever: global warming is real and it is changing the world. Now deal with it” (New Scientist 2006). If true, this significant message is one that would extend well beyond the realm of politics. For example, technical experts predict that within a 10 to 20 year (mid-term) timeframe, the U.S. will be surrounded by a very different ocean. “The newest study of the Arctic ice



cap [found] it faded [in the summer of 2005] to its smallest size ever recorded.... [In this context,]...Canada's aim is not only to tighten control of its territory, but also to establish a strong posture in future talks over the Northwest Passage, a long-sought shortcut from Europe to Asia.... Bill Graham, the defense minister, said, 'I don't see the Northwest Passage as something for another 20 years, but at the rate of present global warming, we know that it will be within 20 years and we have to get ahead now'" (Krauss et al. 2005). For the U.S., even this one result of global warming, the appearance of a new transcontinental coastline to the north that would provide a viable Northwest Passage — and an alternate major shipping route to the Panama Canal — would have profound effects on national security.

2.1.5 As the 21<sup>st</sup> century progresses, a major factor affecting world security will be immense overpopulation pressures in the most volatile parts of the world. Along with this will be increased demands on basic resources such as food, water, chemical feedstocks, and energy, and a general degradation of the environment. As conflicts may increase in number, scope, and severity in the coming century, the U.S. military will be called upon to respond, and with fewer and more expensive resources. Moore's Law may no longer be relied upon to drive the reduction in size and cost of electronic hardware (Borsuk and Coffey 2003), and broad questions loom about the vitality of the U.S. innovation pipeline (Coffey et al. 2005). The future military will most likely be under pressure to fight and project power using the resources at hand in the most economic way possible. For instance, no longer may there be the luxury of unlimited physical resources of any and all kinds being transported 12,000 miles as needed to a theater of operations. This leads to a new concept that we introduce here, the idea of Sustainable Military Forces (SMF) (Hardy 2006). SMF provides a perspective from which to consider the U.S. military's forefront capability needs for the next 10 to 30 years.

2.1.6 In this regard, according to the Blair DSB report, two key planning questions are:

- (1) What types of targets must the U.S. be able to strike effectively in 2030?
- (2) How will the targeting tasks differ between the two categories of
  - (a) rapidly terminating a conflict with a rogue, and
  - (b) degrading a great power's projection capabilities?

## 2.2 Network-Centric Warfare and Capability-Based Planning

2.2.1 Network-centric warfare (NCW), an activity in which each service of the U.S. military is now implementing a thrust, is a concept for transformation that was first elucidated in the mid 1990s by ADM Cebrowski (e.g., Cebrowski and Gartska 1998). NCW divides military assets into nodes and networks, where nodes may be thought of as platforms that are connected by networks for data sharing and input. "Designing NCW system-of-systems poses formidable challenges for the acquisitions bureaucracy and the defense industries" (Dombrowski et al. 2002). "TRLs [technology readiness levels] are not a measure of design validity" (TRA 2005); in the case of systems-of-systems, this can lead to ramifications within the defense industries that range from straightforward but rigorously difficult questions about what to build / what to accept, through intricate issues of contractual fair process. Dombrowski et al. (2002) raise serious concerns in this

regard. For transformation to proceed, it is crucial to be successful here, since “military transformation begins at the level of ‘system-of-systems.’” Dombrowski et al. (2002) note, specifically, that “for Naval transformation to succeed, the Navy must rally.... It is... troubling that no one — *neither the contractors, the Navy laboratories, nor the Navy systems commands* — appears to be systematically thinking through the large scale system-of-systems architecture questions facing the NCW Navy....[e.g.,] ‘What, if any, systems-design problems are inherent in overlaying an expeditionary grid over existing and proposed space-based sensor systems?’” They advise that “the best way to implement NCW would be to return to the well-known ‘lack of bias’ trajectory as soon as possible, while suitable organizations still exist with core competencies to proceed with system-of systems integration.”

2.2.2 The DoD has embraced capabilities-based planning (CBP) as a concept-led framework that would be effective against whatever threats may emerge, from the time of the 2001 Quadrennial Defense Review: “A capabilities-based model — *one that focuses more on how an adversary might fight than who the adversary might be, and where a war might occur* — broadens the strategic perspective” (QDR 2001). CBP will enable emerging technologies to be employed in new ways into strategic, operational, and tactical operational concepts, with scenarios serving as context. Further, “when CBP is properly implemented, one of the key benefits lies in its ability to help take focus away from single-service stovepipes” (Subcommittee on Non-Atomic Military R&D 2004). CBP thus is a suitable engine for furthering NCW. A downside is that “the absence of a traditional security threat to the U.S. from a ‘peer competitor’ may allow the civilian national security agenda to be dominated by pork-barrel concerns that will not drive the services toward long-term doctrinal innovation” (Dombrowski et al. 2002). However, when coupled with the concept of forefront sustainable military forces, CBP may provide an open framework for objective NCW planning that is also practically useful.

2.2.3 We therefore suggest that next levels of research in the areas of NCW and Operations other than War (OTW) should proceed as scenario-driven (NATO 2001), experimentally-based development and demonstration activities that are co-evolved by means of small development cells staffed with integrated teams of Service Lab technologists and Operational/Tactical war fighters who are chartered to work collaboratively together for four to five consecutive years. Topical focus for each such cell should be provided by one or a few NCW overarching questions derived out of ongoing research areas towards NCW deployment, such as seamless horizontal networking, or effective sensor fusion. There presently exist tremendous learning opportunities to understand how to realize net-centric operations. It is envisioned that the ability to share information to and from the tactical edge will allow operators to work in more dispersed environments while taking decisive, collective actions. Possibilities of net-behavior must be better understood in order to shape future NCW systems technologies and concepts of operations, to define with stability the defense industry after next, and — centrally — to develop the future tactics, techniques, and procedures that will enable NCW advantages to be realized at the tactical, operational and strategic levels.

## 2.3 Future Strategic Strike and the Concept of Tiered Systems

2.3.1 The Blair DSB report, defining strategic strike as “military operation to decisively alter an adversary’s basic course of action within a relatively compact period of time,” observes that “a very wide range of forces operating from either within the U.S. or overseas can be used in executing strategic strike. These forces include traditional longer-range assets, and in-theater special operations forces (SOF). Newer information operations capabilities could also be used as part of a strategic strike mission. All of these military assets need to be integrated together.”

2.3.2 “Improved ISR is the single most important pacing factor in the future achievement of effective strategic strike. Success in making effective strategic strikes requires both innovative new sensor packages and improved means for bringing together and fusing the information provided by sensors, operatives on the ground, and HUMINT in a timely fashion” (Blair et al. 2004).

2.3.3 A key enabler for improved ISR (and thus Future Strategic Strike) is the concept of a tiered system. The Blair DSB report operationally describes a tiered system (as defined, e.g., in Coffey and Montgomery [2002]) with the observation that “...in order to achieve the most leverage from individual systems, we recommend an integrated, multi-tier intelligence system encompassing space and air-based sensors linked to close-in and intrusive lower tiers. For the ISR system needed for future strategic strike to come to fruition, it is essential that the leadership view the multi-tiers as ‘a system.’... The lower tiers are not only the critical source of intelligence, they can also serve as a key cueing device for other sensors.” The DSB report centrally recommends that tiered systems be developed for the near, middle, and long term to improve tactical ISR and ultimately to support strategic strike needs in the long-term (30-year) timeframe.

2.3.4 We note that an additional problem with weapons data links (WDLs) required for strike is that we have multiple WDLs. This creates a problem on platforms such as the F/A-18 where WDL pods are required, instead of additional weapons. Better integration of sensor/weapon data links would enable more munitions/platform and more effective use of these stores in a network-centric approach as compared with a limited point-to-point capability.

2.3.5 The tiered systems concept developed by Blair, and adopted in this report, is illustrated in Fig. 2.3.1 (Blair et al. 2004, Fig. 3.1), with possible specific transformational activities indicated in the figure caption. Following the Blair tiered systems C3ISR operational view, tiered systems elements, and aggregates of existing and novel cross-service hardware and software, will generally include mission-dependent subsets of ad hoc configurable networks, sensors, effectors (cueing agents, weapons, etc.), platforms, command and control, and authorized individuals.

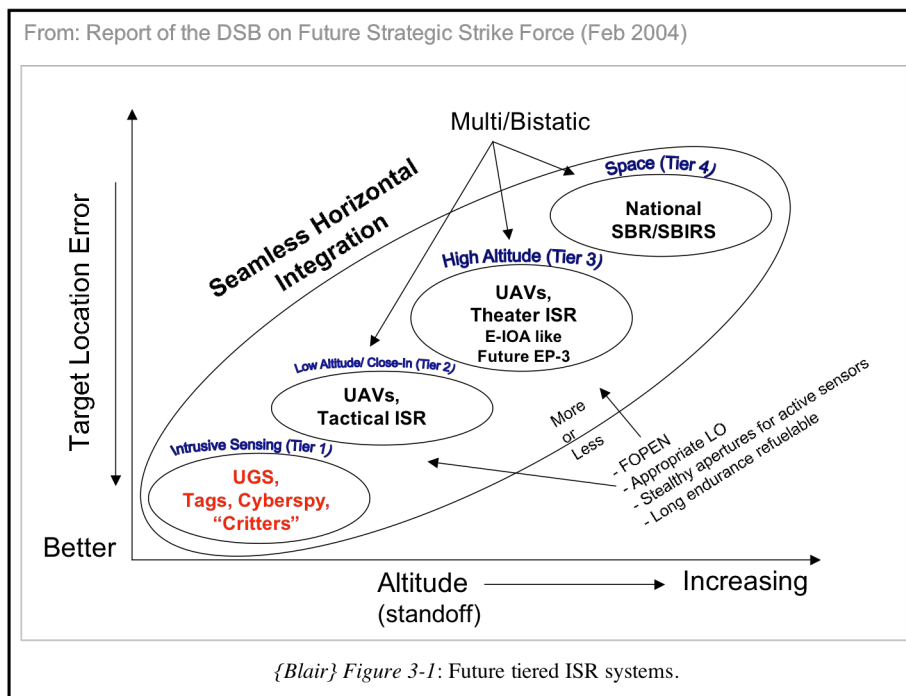


Figure 2.3.1. Future tiered ISR systems (Blair et al. 2004), where: Tier 4 could include Operationally Responsive Space assets such as TacSAT (Hurley et al. 2003); Tier 3 could include high-altitude expendable UAVs; Tier 2 could include affordable expendables such as the Dragon Eye small UAV (Foch et al. 2000); and Tiers 1 and 2 could include experimental Distributed Autonomous Systems (Montgomery 2000; Dahlburg et al. 2005).

2.3.6 Distributed Autonomous Systems (DAS) (Montgomery 2000; Dahlburg et al. 2003, 2004, 2005) are particularly promising areas of research towards Tiers 1 and 2 intrusive sensing and effecting capabilities. Distributed integrated sensor systems will have broad applications in urban search and rescue, fleet and land mine countermeasures, anti-missile defense, and persistent surveillance. Future DAS technologies include heterogeneous smart sensor and communication networks that self-adapt to provide superior situational awareness, effectors that autonomously acquire, engage, and deter threats, alternative power sources that enable long-time operation of distributed networks for back clearing and border patrol, sensor platform mobilities that range from adaptive slewing through extremes of flying and hopping for autonomous deployments, coordination of groupings of ground, underwater, or air platforms for force protection and strike, and flocking behaviors of small inexpensive systems such as expendable air platforms for wide-coverage delivery of close-in jamming devices. Distributed, autonomously configurable tiered systems will maximize available manpower, increase situational awareness, enable new mission capabilities, enhance cognitive readiness, and remove personnel from unnecessary harm while improving survivability of components. DAS at all Tiers will be required for the most significant capabilities toward conducting irregular and distributed missions as noted in the QDR of 2006 (QDR 2006).

## 2.4 Recommended Development Path: Tiered Systems Test Bed

2.4.1 Challenges confront the development and fielding of a robust NCW Tiered System that go well beyond the information technology and engineering problems of assured, web-enabled communications. World-class subject area expertise is required in each field (scenario) being incorporated. Among other consequences, this means that the hardware and software process of installing a new application portal or gateway to the overall tiered system must be made simple enough that the application experts can prepare, install, monitor, and update their components as the system evolves. The process of system operation must also be made simple, with general, easy-to-use, standardized interfaces and acceptable latencies at every stage of development and deployment.

2.4.2 These systems also differ radically from what currently exists in that many of the data repositories and sensors to be tapped are controlled by different “jurisdictions” that may not be in a position to or willing to surrender control. Therefore the overall system must process data queries that need to be serviced with a priority appropriate to the evolving situation — including those that originate from jurisdictions external to the system. In many cases, the jurisdictional priority adjudication must be virtually immediate, and may be concomitant with allocation of communication resources within the net to ensure optimal availability of data needed and/or desired elsewhere while at the same time not impacting local operations. Much of this process will have to be totally automatic. In this regard, e.g., a dual connection to all local assets is recommended for efficiency, to ensure local autonomy and to guarantee back-up communications paths in case of outages from natural or malicious sources.

2.4.3 From the perspective of forefront Sustainable Military Forces, it will be imperative for the U.S. military to have the ready ability to harness the many operationally relevant aggregate elements that may be conveniently available wherever one is on the globe at the onset of an engagement, and enable these possibly ad hoc elements to work together as a distributed but cohesive fighting machine. To accomplish this requires an objective, focused tiered systems test bed to research, experiment with, assess, and red-team these new and highly complex distributed system-of-systems, in ways that consistently integrate from individual elements through fully developed tiered systems resulting capability.

2.4.4 The Blair DSB report also envisions the need for a C3ISR test bed “employing surrogate and prototype sensors, with appropriate attention on how the sensors would be deployed. This test bed would also be used to (1) develop concepts of operation and algorithms for multi-tiered architecture(s), (2) refine sensor exploitation, and (3) assess sensor communications.” The gravity of the present deficiencies in current and planned capabilities leads the Blair DSB report to recommend that: “a C3ISR test bed (a virtual and distributed test range) essential to support the spiral development of the C3ISR architecture required for future strategic strike... will need approximately \$1.5 billion over the FYDP.” This test bed is illustrated in Fig. 2.4.1 (Blair et al. 2004, Fig. 4.2), with possible specific transformational activities indicated in the caption.

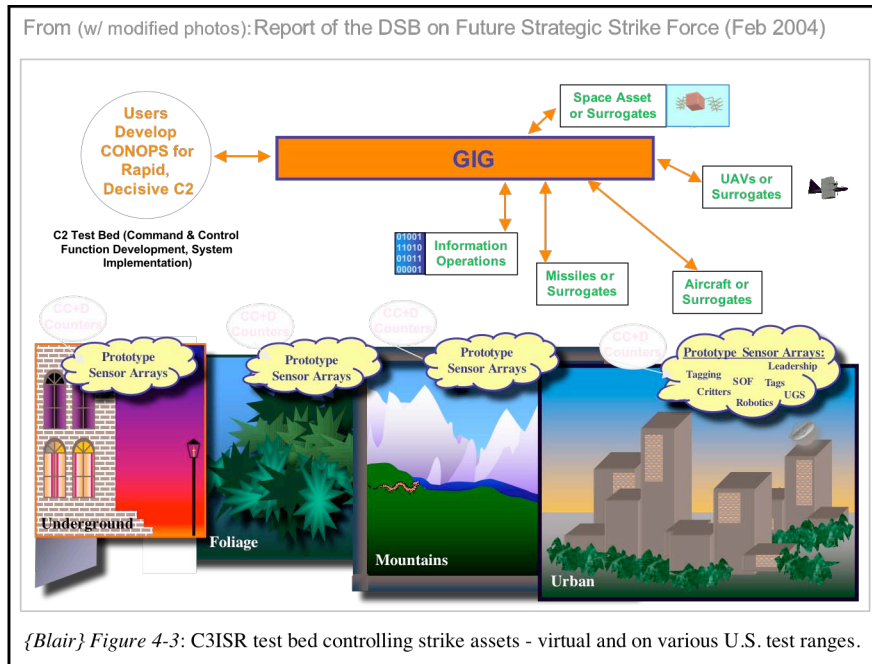


Figure 2.4.1. C3ISR virtual and test range test bed (from Blair et al. 2004). A near-term Experimental Test Bed (ETB) could be augmented by the GIG<sup>EF</sup> (Global Infrastructure Grid Evaluation Facility) (GIG<sup>EF</sup> 2006), the JVL (Joint Virtual Laboratory), a Reference Implementation Cell (RIC, per Section 6.2), and experiences gained/lessons learned from Joint Task Force WARNET (JTF WARNET 2006).

2.4.5 In the area of present deficiencies in surveillance and reconnaissance persistence, penetration and identification, battle damage assessment, and data processing, exploitation, dissemination, the Blair DSB report observed that “the laws of physics... seriously limit [space and airborne assets] to penetrate foliage, track individuals, identify WMD components, defeat camouflage, and identify decoys. Dealing with these surveillance and reconnaissance challenges will require lower tiers of close-in and intrusive sensors.”

2.4.6 The DSB report then makes specific recommendations for development of: “technologies and systems for networked close-in sensors (air and ground) and tagging, tracking, and locating invasive sensors; networks to self-form, infil and exfil data; and sensors of various types to manage power and gather information.... The technologies developed should be fielded and demonstrated in the C3ISR test bed so that the effectiveness and inoperability of each tier of the C3ISR architecture can be assessed. The Task Force estimates that this... will cost approximately \$3 billion over the FYDP” (Blair et al. 2004).

2.4.7 A central concern of the Blair DSB report is that even as the DoD becomes more dependent on networked C3ISR, “no dedicated ‘red team’ effort exists which concerns itself with camouflage, concealment, and deception; redout/blackout/electromagnetic pulse vulnerabilities; and tactics which might be used by adversary against our emerging C3ISR system.” **We share this concern.** An effective tiered systems test bed must have

an enfranchised red team to perform vulnerabilities assessments of ongoing activities, and to develop protective countermeasures for system core functions.

2.4.8 This report agrees with all technical essentials of the tiered systems development needs outlined in the Blair DSB report, briefly synopsized above. However, prior to embarking on a comprehensive test bed activity as envisioned in the Blair DSB report and illustrated in Fig. 2.4.1, we recommend beginning with two focused integration cell initiatives to address the key deficiencies that we find are currently impeding effective tiered systems developments, as discussed in Section 6: seamless horizontal networking, and cohesive sensor integration.

2.4.9 The process we use to derive the findings and recommendations of this report is the following. From a range of scenario parameters that span tactical military environments for which an aggregate of distributed assets with seamless networked connectivity — i.e., a tiered system — may be expected to provide significant advantage, we develop two specific scenarios that bound the landscape: (i) Contaminant Transport (CT) Urban Defense (Section 4); and (ii) Maritime Domain Expeditionary Maneuver Offense (Section 5). After describing paths toward specific tiered systems developments for each of the two example scenarios, we identify in Section 6 the essential elements of each and compare the state of development of the necessary collegial activities across these scenarios, to obtain a list of similarities and differences and an understanding of readiness status.

2.4.10 Section 6.2 describes the first of the two cells we recommend to address the major identified tiered system readiness issue, seamless horizontal networking: a Reference Implementation Cell (RIC) that would provide a hands-on R&D environment for testing prototype tactical edge applications, service oriented architecture (SOA), middleware, communication services, networking, and radio subnets, and for evaluating how they work together. Information assurance should be incorporated in the activities of the RIC from the outset and throughout, and with red-teaming also integral.

2.4.11 The second cell, a co-evolutionary cell made up of Operational/Tactical war fighters along with Service Lab technologists who would work together on scenario-specific tiered systems developments, is described in Section 6.3. The central goal of this experimental test bed (ETB) would be to elucidate tiered systems developmental methodologies from the focusing perspective of C3ISR, with emphasis on cohesive sensor integration. ETB products would include experimental distributed tiered systems capabilities (system-of-systems hardware and software) for war fighter experimentation and evaluation.

2.4.12 For success, we recommend that the ETB should proceed as a rigorous integrated simulation and experimental sensors exploitation and integration activity analogous to the fielding of a significant physics proof-of-principle experiment, and with a commensurate resource envelope; at a minimum, each such cell should be funded in the range of \$5 to \$15 million/year, and staffed contiguously, for each of four to five consecutive years. Section 7 summarizes the report findings and recommendations.

## 3 Tiered Systems Capabilities-Based Planning (CBP) Scenarios

### 3.1 Scenarios Overview

3.1.1 Much has been written about the implementation of capability-based scenarios for defense long-term planning (e.g., NATO 2001; Subcommittee on Non-Atomic Military R&D 2004). Our purpose here is straightforward: to use high-level aspects of capabilities-based planning (CBP) as a tool to shed light on tiered systems essential development needs. As there is no official government definition of the term, we take the definition from NSB (2005), i.e., “CBP is planning, under uncertainty, to provide capabilities suited for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice.” For the present purposes, the economic framework deemed most appropriate for planning is that derivable for forefront sustainable military forces.

3.1.2 From a range of scenario parameters that span tactical military environments for which an aggregate of distributed assets with seamless networked connectivity — i.e., a tiered system — may be expected to provide significant advantage, we here develop two specific scenarios that bound the landscape. Sections 4 and 5 lay out paths to the development of tiered systems specific for each of these two bounding scenarios. From the multi-year work-plans that are described for each, we will ask in Section 6: why can't we just put these tiered systems together now? Answers to this question will indicate sticking-points for further work. Key tiered systems needs that are common across the bounding scenarios will thus indicate broader areas for development that may be most fruitful to pursue next.

3.1.3 It is expected that tiered systems will be useful anywhere within the DoD sphere of influence. Geographically, they will be applicable in cluttered urban environments, wide land and air battlespaces, marine environments that stretch from the littorals to the deep ocean, and far into space. Temporally, they will be effective in situations that range from defense and extended reconnaissance through fast-paced, possibly repetitive offense maneuvers. They will be relevant to security actions that span detection through response. As a first cut to picking representative scenarios for specific focus, we considered threat detection scenarios in each of these temporal and geographical regions (Dahlburg et al. 2003; Dahlburg et al. 2004; Davidson et al. 2006; Hoffman 2006; Hurley 2005; Kiviat 2006; Lamb and Bevilacqua 2006), with incorporating threats that ranged from those observable via the electromagnetic spectrum (EO, IR, HSI, etc.) through those that need high-sensitivity WMD materials sensors for direct detection.

3.1.4 The complexity of component technologies and the wealth of application possibilities indicate that successful early tiered systems will likely be products of innovation from collaborative teams of military operators with applications-oriented scientists and engineers, who together will synthesize working knowledge of the art of the possible with an understanding of mission needs. Such teams will have the skill sets required to maximize good configuration decisions from the vast space of options that are theoretically possible.



3.1.5 Further, it is vitally important to enfranchise forefront DoD critical technologies (and technical expertise) into this development process from the beginning, for best long-term effect for the DoD. “The proper role for the government in R&D is to ensure the health of the prospecting phase R&D (basic and applied research and exploratory development) that is crucial for long-term economic growth and military power, but is not going to get done by the private sector (cf, e.g., Dombrowski et al. 2002, comments on conflict of interest with NCW system-of-systems). This role is so important to the long-term economic and military health of the nation that the government must be staffed with the world class scientists and engineers needed to carry out this responsibility. This responsibility cannot be carried out by functionaries or administrators whose jobs are simply to send public moneys to non-governmental entities. We have chosen the term “governance” quite deliberately in this regard. It should be carried out by government employees who are active members in the relevant scientific and technical communities and have the respect of their peers in those communities. The communities must accept the government’s scientists and engineers as scientific and technical peers in order for the required long-term planning and steadfast direction to occur and so that the required advocacy is in place both within and outside of the government. At one time, the federal government was staffed to carry out this function. It is not clear that this is true today, especially in the DoD sector, and this deficiency must be remedied. Excuses for not dealing with this matter — such as asserting that the government cannot hire or retain the required talent — are not acceptable since that is a problem that can be fixed. It is not an overstatement to say that the Nation’s long-term economic and military strength may be at stake.

3.1.6 A special situation exists for Defense R&D, where the beneficial effects of the free market do not apply due to the small market size and the specialized nature of warfare. In this case the United States Constitution implicitly assigns governance for the full spectrum (prospecting phase and mining phase) of R&D to the federal government (Coffey et al. 2005). For highly complex but potentially overwhelmingly advantageous new capabilities such as effective tiered systems, these observations particularly apply.

3.1.7 This is not to say that collaborations with academia, industry, and M&O (Management & Operating) contract laboratories such as the Department of Energy National Labs are to be avoided; rather, they should be encouraged in order to bring best ideas forward. However, the tiered systems development process should be government-led by technically expert honest brokers who have as their chief concern maximizing benefit for long-term U.S. defense without regard to corporate profit or personal gain. Centrally vesting DoD best technologies, and technologists, into the process will keep both the technologies and also the tiered systems products at the forefront.

3.1.8 With the above considerations in mind, the vast landscape of tiered systems development choices may be resolved to some extent by using forefront SMF as a lens to focus next tiered systems developments to the incorporation of new technologies (and associated technologists) that are relevant for the long term mission futures of the DoD, e.g., capabilities that are simultaneously at the technological edge, affordable, and practically sustainable.

3.1.9 Figure 3.1.1 shows an example DoD (NRL) current research in the topical area of networking. This figure illustrates how DoD focuses its grid networking research on pushing the forefronts in the areas of the field that are most important to defense — strategic high performance, and tactical mobility — while expecting from experience that the market will provide product capabilities that are also widely desired by commercial mainstream users without (much) DoD intervention or direction.

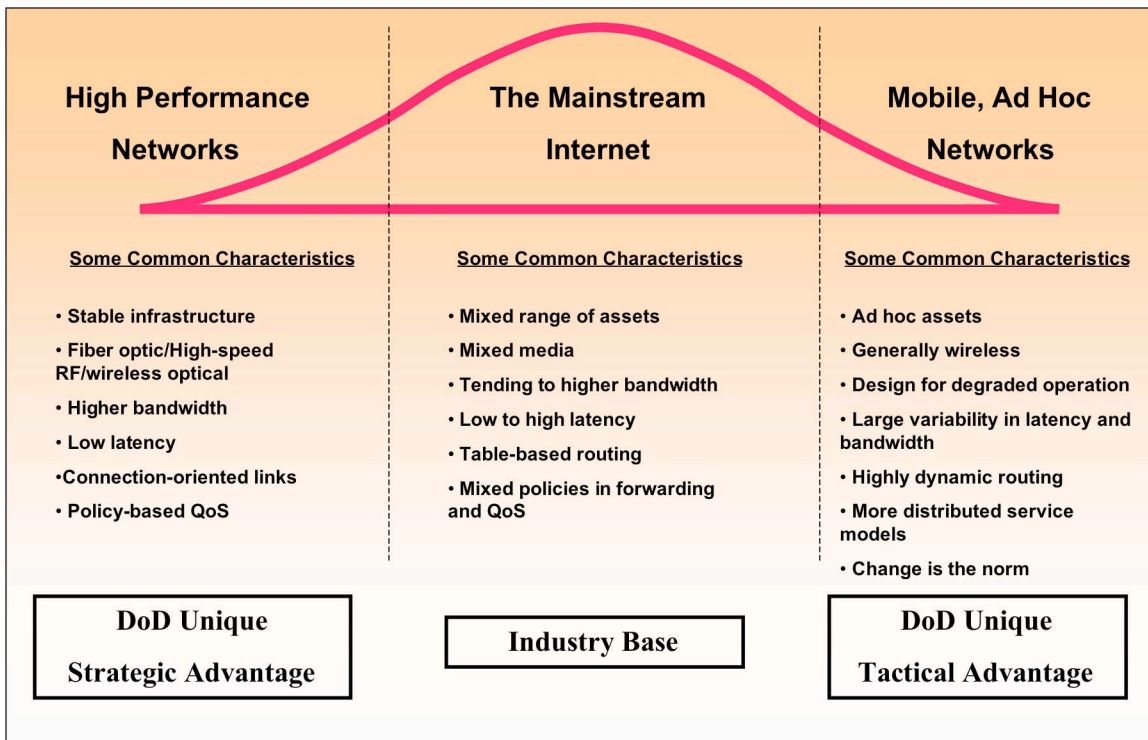


Figure 3.1.1. DoD evolves commercial technologies to support the GIG

3.1.10 Planning curves that are comparable to that in Fig. 3.1.1 may be generated for nearly every topical area of DoD-relevant research. A representative aggregate of DoD forefront critical technologies across disciplines and TRL levels derivable from such a perspective is shown in Figs. 3.1.2a and b. From the above discussion, all of the technologies listed in that figure should be incorporated into near-term tiered systems developments, to the extent possible. We find that an admixture of just two overarching scenarios enables this objective: contaminant transport urban defense (as connected schematically in Fig. 3.1.2a); and maritime domain expeditionary maneuver (in Fig. 3.1.2b). Thus we take these two broadly encompassing scenario tiered system developments as “typically” relevant, and with lessons learned from their analyses as to general applicability. Since these two topically and technologically very disparate scenarios share important subsets of tiered systems enabling technologies, they together illustrate generally the basic research that is needed to develop a tiered system (as compared with tiered system component technologies). In this regard we note central findings from the Welch et al. (2005) NAS report, “Assessment of DoD Basic Research”: “The basic research needs of the DoD are complex and do not end when specific

applications are identified... The need for ongoing discovery from basic research can, and usually does, continue through the applied research, system development, and system operation phases.”

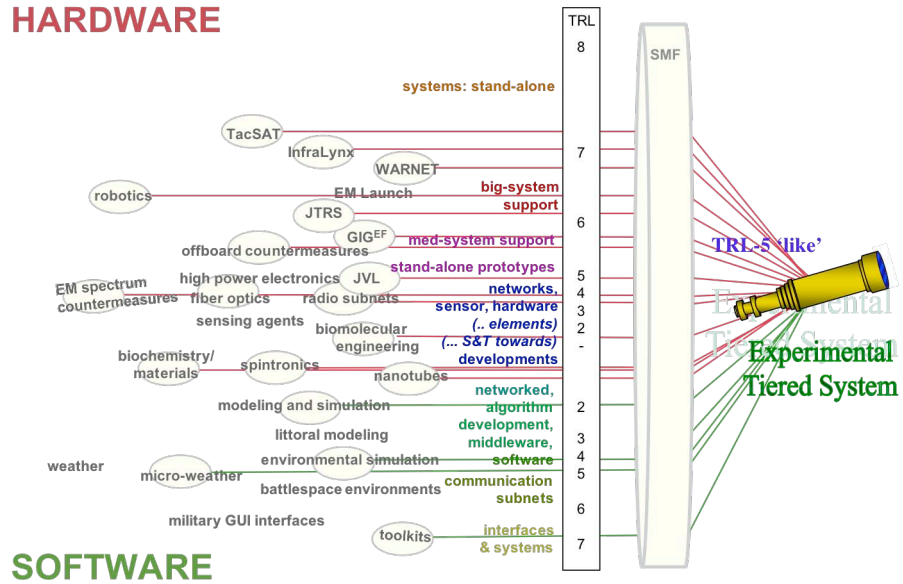


Figure 3.1.2a. DoD forefront critical technologies aggregated across disciplines and readiness levels (left). Lines to the right indicate the subset of these capabilities that may be integrated to develop a tiered system for Contaminant Transport Urban Defense.

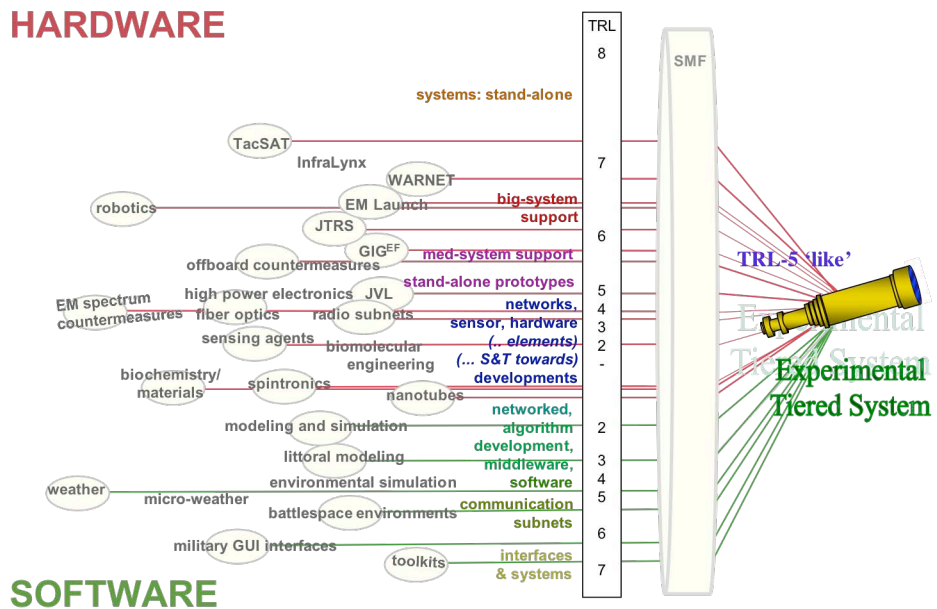


Figure 3.1.2b. DoD forefront critical technologies aggregated across disciplines and readiness levels (left). Lines to the right indicate the subset of these capabilities that may be integrated to develop a tiered system for Maritime Domain Expeditionary Maneuver.

## 3.2 Contaminant Transport Urban Defense, and Maritime Domain Expeditionary Maneuver

3.2.1 A comprehensive representation of DoD forefront critical technologies is required to achieve effective tiered systems for these two overarching scenarios in combination: contaminant transport urban defense, and maritime domain expeditionary warfare offense. By using these two scenarios as a basis from which to think about tiered systems developments, we thus will come to an understanding of most tiered systems near-term technical research needs. (We note that the scenario of maritime defense awareness of non-cooperative targets, as described elsewhere, is also very helpful in this regard.)

3.2.2 An overarching theme of the urban transport contaminant scenario is the ability to rapidly respond to a natural disaster or terrorist attack in a highly populated urban environment with unprepared civilians. Keys to successful emergency response are early warning, accurate forecasting, clear first responder guidance, reliable communications, and aftermath monitoring. In Section 4 we consider this scenario from the perspective of developing a tiered system that would address with robustness these key needs, to provide fast, coordinated response to a chemical, biological or nuclear attack. Such a system should be readily deployable, easy to use, and capable of cohesively incorporating sensor data from local through national Tiers. It should support accurate sensor placement optimization for defense planning, provide immediate sensor data fusion to locate covert contamination sources, and plan evacuation routes for crisis response. System components would include hardware (threat detection and environmental sensors; fixed and mobile sensor platforms; and networking: connectivity and computing); a planning tool that would replicate with fidelity all relevant process aspects of the developing tiered system and by means of data fusion from hardware and simulation predict the system first responder output with sufficient field accuracy for practical utility in the event of an emergency; and an information technology package to control routine operation of the system and govern system data gathering and display.

3.2.3 Maritime domain expeditionary warfare requires rapid mobility and persistent surveillance, two key attributes necessary for the future fighting force as described in the QDR 2006 (QDR 2006). Current capabilities are insufficient to achieve ISR that adequately support wide areas of coverage, speed, precision, and detail. However, ongoing technological advances in sensor development, signal processing, and communications currently enable the effective development of rapidly configurable, tiered systems that would cover the battlespace at varying resolution and respond in real time. In Section 5 we address the development of a tiered system that would provide a nearly complete set of ISR information required to plan and execute a tactical combined-arms maneuver through and across a littoral battlespace. This system would augment and rapidly update data obtained by existing space- and air-based assets. Similar to the urban tiered system overviewed above, system components would include hardware (ISR and environmental sensors; sensor platforms; and networking); a planning tool that would replicate with fidelity all relevant process aspects of the developing tiered system and provide accurate fused ISR data for operator evaluation; and an information technology package that would govern system operations, and would interface to system data gathering and display for various local and geographically-dispersed tiered system users.

## 4 Tiered System for Contaminant Transport in an Urban Environment

### 4.1 Concept Overview — Fixed and Mobile, Urban: Defense

4.1.1 Rapidly responding to a natural disaster or terrorist attack in any environment requires timely and accurate information that can enable tactical commanders and first responders to make appropriate decisions to warn and protect their troops, the public, and other emergency responders. A coordinated attack, as demonstrated in the U.S. on 9/11/2001 or in London in 2005, resulted in emergency response operations in multiple dispersed locations. A multiple location coordinated attack with chemical, biological, or radiological agents (CBR) will more severely limit emergency response since special training and equipment would be required to enter the area, deal with victims, and minimize the extent of damage. It is crucial to have early warning of the nature of the attack, and prediction tools that can generate rapid, accurate forecasts for effective emergency response decision making with continuing capability for aftermath monitoring. All of these depend on data from reliable and accurate sensor systems with processing and analysis occurring so quickly that the input data to the analysis is still current when the analysis is complete. In airborne CBR scenarios this generally means that data must be assimilated, processed, and displayed in seconds or less.

4.1.2 While the U.S. military has invested in technology to defend against a coordinated CBR attack, the investment has been directed toward defending the battlefield environment and with trained military personnel. A highly populated urban environment with unprepared civilians will significantly complicate the scenario, even for military facilities and personnel. Typical operational tools to predict, assess, and control damage are very limited in their capability because they are based on greatly simplified physics and engineering, slow computing, and land-based commercial communications liable to saturation or breakdown during any major incident, and with weak linkages, at best, to higher-tier assets. Military commanders and emergency managers coping with real incidents cannot afford to wait for accurate simulations, data post-processing, and discussions throughout the entire chain of command. In a chemical attack in an urban area, for example, every second of delay can cost 10 to 100 lives (Boris and Patnaik 2006).

4.1.3 In this section, we evaluate the urban contaminant transport scenario (Davidson et al. 2006) from the perspective of providing a high-level blueprint for developing an effective tiered system for Contaminant Transport (CT) Defense by means of an experimental test bed. Test bed activities would include: assessing current capabilities; networking together numerous sensor nodes; and developing a Planner for assessing key design issues, troubleshooting system operations, and researching future CT Defense emergency assessment tiered systems. This Planner would be a (planning) tool that would replicate with fidelity all relevant process aspects of the developing tiered system and, by means of data fusion from hardware and simulation, predict the system first responder output with sufficient field accuracy for practical utility in the event of an emergency. Key to ultimate CT Defense tiered system flexibility and extensibility would be designing

the infrastructure hardware and software to easily accept current sensor system formats, and to develop and enfranchise interface standards for the long term.

4.1.4 There are several reasons why the problem of contaminant transport (CT) in an urban environment makes an ideal multi-tier test bed subject scenario.

- (1) Because there are accidents and fires every day, this is a rapid-response application that would be guaranteed real-world use and therefore realistic testing, both military and civilian, without needs for a conflict or attack.
- (2) The wide range of relatively low-cost CBR sensor types already available and deployed means that implementing an effective local system in the near term is relatively low cost and low risk.
- (3) The range of existing assets under different jurisdictions provides the ideal framework for level-by-level expansion and testing of the tiered-system approach because the lower levels under local control allow a big gain over current technology.
- (4) A good defense can be the basis of a robust force projection and a flexible offense. Current CBR emergency assessment systems, both military and civilian, are poor with no integrated sensor fusion capabilities to speak of. Therefore, a big — and also quantifiable — improvement will be evident and easily made operational even over the currently fielded fixed-base CBR systems which require 5-15 minutes to process a single scenario. (Note that after 15 minutes in a focused chemical attack, three-quarters of the victims will already be dead or dying [Boris and Patnaik 2006].)
- (5) The system design would robustly apply to other scenarios of comparable relevance and importance, e.g., escape path prediction for a possible liquid natural gas (LNG) tanker detonation, using networked environmental sensors to determine the likelihood of explosion propagation as a function of local temperature, wind conditions, etc.

## 4.2 CT Defense Problem Statement

4.2.1 A coordinated CBR attack in an urban environment will greatly overstress the current capabilities of first responders. The difficulties of detecting and responding to a release of CBR materials are exacerbated in the urban “canyon” where topographical variations affect the dispersion of the particles, droplets, or gases, and can inhibit radio communications and geolocating. The effect of each attack will vary with weather conditions as well as population density (rush hour or non-work day) and type of population (untrained civilian to well-trained responders). It may not even be clear for some time whether the crisis arises from an attack or an industrial or transportation accident. The keys to successful emergency response in all cases will be early warning, accurate forecasting, clear first responder guidance, reliable communications, and aftermath monitoring.

4.2.2 While much work has been done toward a response to a CBR attack, most has been focused on relatively flat battlefield scenarios with trained personnel. The existing prediction and forecasting models do not account for the urban environment and untrained civilian population. In fact, current common-use operational CBR and airborne contaminant emergency assessment tools, developed for long-range transport and dispersion (T&D) predictions, ignore details of the urban environment. Because their

focus has been on long-range (and long-time) T&D, these tools were not designed for the speed and detail required for emergency response within the first few minutes in an area with obstructive physical clutter. T&D modeling techniques require a detailed characterization of the contaminant source, information that will not be readily available in the first moments of an incident. In order to respond in a timely manner, data from emplaced sensors and anecdotal reports must be integrated and a coherent response formulated. Sensor data and other reports may be available from a wide range of autonomous assets, some not in direct control by the incident commander. Conventional tools do not assimilate sensor data, but require substantial, often time-intensive operator input and interpretation.

4.2.3 Currently available chemical and biological sensors span a wide range of accuracy and reliability. While advances in sensor technology are making these tools more available, accurate, and reliable, the job of understanding collective implementation is just beginning. Building a sensor network compounds most of the problems seen in a single sensor. For instance, a false alarm on a single sensor operated alone may affect a small group of people or a building. Sensor networks, which cover large areas and are meant to protect large numbers of people, affect a great deal more. If false information is propagated through a sensor network, many people could be incorrectly warned to initiate emergency procedures. Accurately detecting and warning of a threat in a networked environment is paramount. Some good news is that the analysis of information on a sensor network can provide additional information that will help to eliminate the propagation of false alarms and improve the sensitivity and selectivity of the overall system. Using integrated sensor data from orthogonal sensors is one way to reduce the risk of a false detection. Taking into consideration environmental factors and knowledge of individual sensors, such as sensor health, will also help to discriminate between false alarms and real alarms. By augmenting this sensor information with accurate predictive modeling — which includes all information available for reducing false alarms — informed decisions can be made.

### 4.3 Tiered System Example Available Technologies

4.3.1 For the purposes of this study, NRL has evaluated the possible development of a tiered system test-bed environment for enabling rapid coordinated response to a CBR attack in an urban environment. The backbone of the approach should be a rapidly deployable, easy-to-use, emergency assessment/site protection system capable of incorporating local sensor data and issuing rapid assessment and response recommendations for a wide range of threats. As part of this approach, an early warning sensor detection system combined with a validated, predictive evaluation tool should be built to provide first responders with a plan of action for response. With an iterative development process the prediction capability should then be used to recommend a sensor dispersion pattern. Field experiments using simulants would be conducted to verify and update the software, with inclusion of weather, sensor, and anecdotal data obtained via network from a variety of distributed sources. The system would need to be developed around a reliable wireless network-based communications capability for collecting sensor data and distributing first responder guidance, and with long-lived

portable power options where required (Swider-Lyons 2006). The end result should be an experimental, fully functional leave behind capability for operational use that is at least at a TRL-5 or -6 level of capability. The system should support accurate sensor placement optimization for defense planning, provide immediate sensor data fusion to locate covert contamination sources, and weight other defense options for crisis response.

4.3.2 For this thought experiment, we centrally use NRL technologies since the relevant subject matter experts, as study participants, are readily available to provide subsystems cost and TRL estimates. Further, NRL technologies — U.S. Government developed and owned — may be discussed in this document without consideration of proprietary issues. Thus, we envision as core to the development of a near-term CT Defense possible tiered system these existing NRL capabilities: the lap-top based CT-Analyst® software (Boris 2002; Boris and Patnaik 2006); InfraLynx mobile, secure, wireless communications technology (U.S. Patent App, 2003); the Virtual Mission Operation Center (VMOC) *Spydr* collaborative engine (Medina 2006); chemical agent detection sensors; portable bio-sensors; environmental meteorological sensors; and, as may be required, the operationally responsive space asset, TacSat (Hurley et al. 2003). Additional sensors and systems could be acquired through broad collaboration with other U.S. laboratories, industry, and academia.

4.3.3 An existing tool, the NRL CT-Analyst® standalone (laptop) system has the functionality needed to serve as the core of an emergency CT Defense assessment toolset. The CT-Analyst assesses airborne contaminant threats for bases, facilities, and cities where the terrain and building geometry are complex and the winds fluctuate. It is 1000 times faster than other existing systems, with capabilities that include unknown source location backtrack using multiple sensor inputs, sensor coverage, and escape routes display functions. Full, 3D, building aerodynamics computations using the validated FAST3D-CT model provide a database of the detailed airflow over the entire area in Dispersion Nomographs™ format (Boris 2002). CT-Analyst recalls results from this database with 3D accuracy instantly. The detailed database also provides accurate predictions for detailed scenario analysis, risk assessment, and sensor placement. The CT-Analyst graphical user interface can be learned in 1-2 hrs, and operates on most ruggedized laptop systems. The CT-Analyst airborne contaminant transport-processing core has been available since before 9/11 and now sees “operational” use in the Missile Defense Agency’s current PEGEM 5.0 system release, in the commercial, ruggedized DGI COBRA system, and with the FBI. A number of the important features relevant to a CT Defense emergency assessment system are unique and well tested. Figure 4.3.1 (right) shows a completed CT-Analyst backtrack isolating two different sources from sensor readings fused with reports in the downtown area of a major city.

4.3.4 For system networking, we envision that a capability such as CT-Analyst would be integrated with a communication capability such as the NRL’s InfraLynx®. This dynamically reconfigurable wireless network would be able to make use of sensor assets as they become available to the incident commander from other layers in a tiered system. InfraLynx is a broad spectrum, fully interoperable, rapidly deployable communications infrastructure packaged in a secure, mobile headquarters (Hummer, van, or small truck).



It provides high assurance telephony, network, and radio connectivity with building blocks of technology that enable flexible architectures that can scale seamlessly from support of a Federal-level event down to a coordinated state/local rescue and recovery effort. The technology is designed to be mobile in the event that a headquarters must be replaced during a crisis or moved rapidly to a new area in response to an incipient need. The mobile, secure, wireless InfraLynx communications technology is at a high technology readiness level (TRL-8) and is being used in a number of operational systems fielded for military and civilian use. Figure 4.3.1 (left) shows the InfraLynx being loaded into a C117 for long-distance deployment. It is to be an important component of the DHS Pre-positioned Equipment Program to seamlessly integrate and transmit the output of multiple types of wireless monitoring equipment from an incident site to the command center. InfraLynx emerged from the lessons learned from the terrorist attacks on the Pentagon and World Trade Center on 9/11. In less than 24 hours, the first InfraLynx was trucked to New York City in response to FEMA's agency-wide request for communications support for the relief efforts in New York. InfraLynx in its current form has been used in nineteen events since its first operational deployment to the 2002 Winter Olympics in Salt Lake City, Utah. The most recent deployment was to New Orleans and the surrounding region in 2005, in response to Hurricane Katrina.

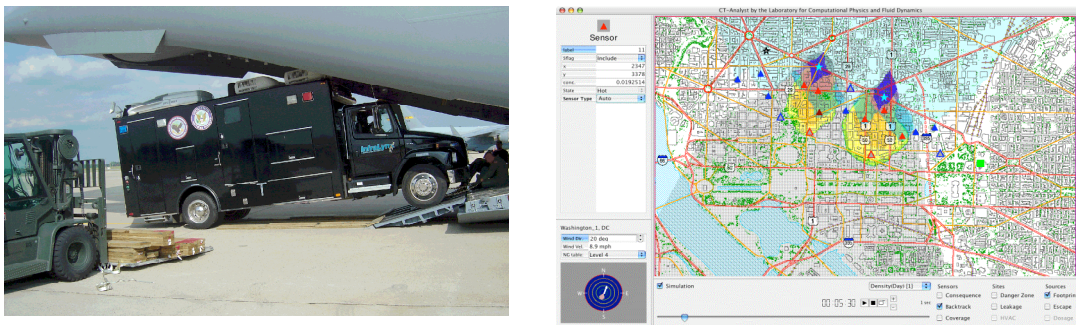


Figure 4.3.1. Left: SJFHG-N InfraLynx being loaded into a C117 for long-distance deployment. Right: CT-Analyst performs sensor fusion and integrated emergency assessment. Sensor readings are used in backtrack operation to locate two distinct sources. Sensors (red = contaminant, blue = clean air) localize sources to a diamond region, allowing evacuation routes (purple lines) to be computed and displayed.

4.3.5 A primary technical challenge is the sensor concentrator and associated collaborative tool. Appreciable work is ongoing in this area, with high-performance computing and advanced web services providing good design solutions. The concentrator hardware goal needs to be a small, all-weather package that can be distributed with a group of several close or co-located sensors, to screen the varied outputs automatically for possible false alarms and to increase selectivity and sensitivity before transmitting the full fledged alarms and warning flags to central sites for overall emergency assessment. The NRL VMOC *Spydr* is a web enabled collaborative engine that allows access to a multitude of sensor data. In this architecture, sensors provide data to local servers called sensor concentrators. Each concentrator stores, processes, and fuses the data, then sends a formatted message to the VMOC *Spydr* alerting it of new data, the type of data, and a hyperlink to the data. The VMOC *Spydr* catalogues the message and alerts users via subscription filters of this new data. Users seamlessly access and collaborate with the

data using tools such as work folders, web maps, chat, and forums. On their end, users only need an internet connection and a browser to access the system. The VMOC *Spydr* system, under development for nearly two years, is sufficiently matured that architecture testing is in process. Figure 4.3.2 illustrates VMOC *Spydr* modes of operation.

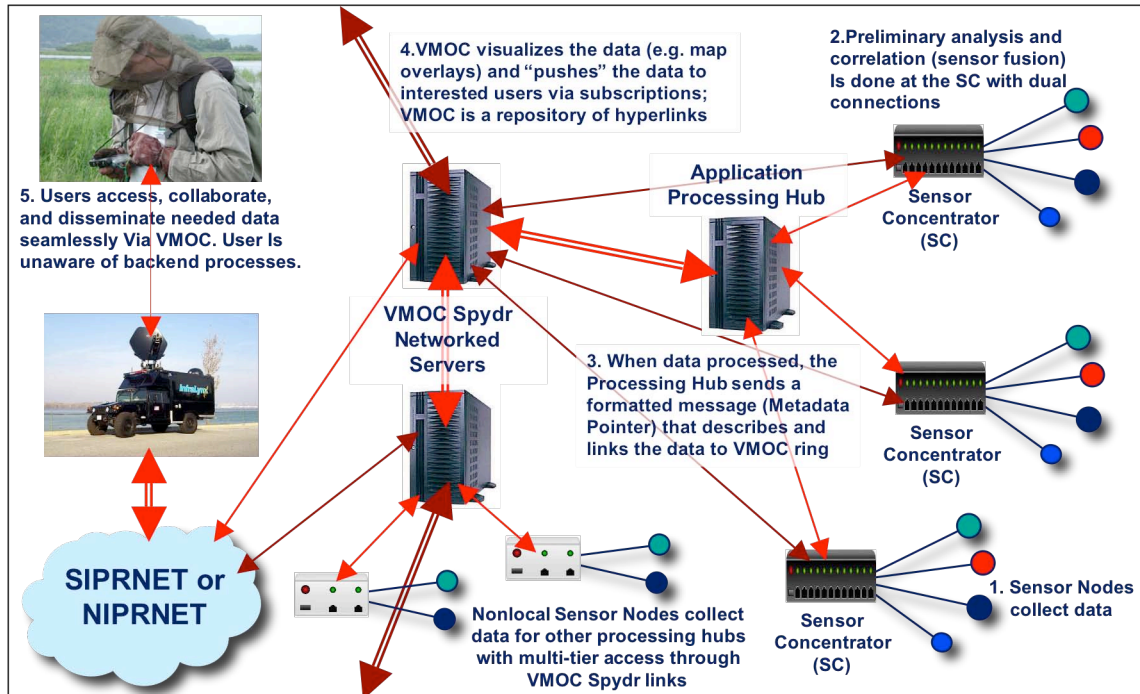


Figure 4.3.2. NRL VMOC *Spydr* tiered system architecture for realistic, multi-application, multi-level environments

4.3.6 A broad range of other sensor and sensor fusion capabilities exist, which could readily be folded into a tiered CT Defense assessment system. For example, Microsensor Systems, Inc., produces several chemical warfare agent detection products designed to provide quick, accurate detection of harmful chemical warfare agents and toxic industrial chemicals while minimizing false positives. They offer both handheld portable and fixed-site installed instruments that employ surface acoustic wave (SAW)-technology devices or the new chemiresistor technology. (These technologies are well understood by subject matter experts within the DoD: both were developed and originally patented by NRL.) As example technology in the area of bio-defense, Research International, Inc., produces a portable, multianalyte bioassay system based on a fluorometric assay (also developed by NRL) for monitoring toxins, viruses, bacteria, spores, fungi, and other diverse agents. Another available bio-defense capability is NRL's Silent Guardian (Stenger et al. 2005). In November 2004, the OSD tasked the USAF Surgeon General, the JPEO for Chemical and Biological Defense, and the NRL to take a newly developed NRL protocol for gene-based pathogen identification into full operation for bio-surveillance in the National Capital Region. During the Silent Guardian Project, nasal wash specimens were collected from patients presenting fever and cold symptoms at six military clinics in the DC area, and transported to NRL for analysis. The procedure for analysis included replication of the pathogen genes and reading the genetic code using a two-dimensional array of

complementary genes. The gene arrays were designed to detect both common respiratory pathogens and Category A Bioterrorism agents. This successful project is the first documented application of DNA microarray technology to operational, broad-spectrum pathogen identification in an urban population (Stenger and Lin 2006).

## 4.4 Technical Challenges

4.4.1 Even with above-described, readily available capabilities, numerous challenges in communication technology, hardware integration, and sensor net architecture would need to be surmounted to develop a rapid-response CT Defense assessment system. These include the following.

- (a) Develop a self-consistent, realistic methodology to support selection of a reliable, cost-effective sensor suite, and placement or deployment of the sensor platforms.
- (b) Develop on-the-move configuration optimization for mobile and rapidly deployed sensors.
- (c) Develop an adaptive, distributed multi-sensor concentrator to evaluate sensor outputs and provide sensor fusion as needed.
- (d) Extend the software tools to incorporate data from multiple sensor types for varied threats (e.g. standoff sensors, information from assets outside the Tiers 1 & 2 circles).
- (e) Demonstrate seamless transition from fixed to mobile headquarters during a crisis.

4.4.2 A primary developmental challenge is a comprehensive test-bed Planner. This emulation planning tool should replicate with fidelity all relevant process aspects of the developing CT Defense tiered system, and predict accurately the expected CT-Analyst first-responder output. In addition to the currently-simulated transport of possible contaminants through the urban geometry as discussed in Section 4.2, the Planner would need to model the tiered system itself: all individual sensors (inputs and outputs, by means of possibly empirical “synthetic sensors”); the system network (latency, bandwidth, effects of noise); and sensor concentrator inputs and expected fused information outputs (accounting for sensor location and other errors, relevant environmental conditions such as heat, cold, wind, rain, etc., and possible network bottlenecks). This tool would enable the CT Defense tiered system researchers to rapidly and accurately assess the key design issues 4.4.1 (a) and (b) for particular situations and geographies, to troubleshoot tiered system operations — e.g., for issue 4.4.1 (e), and to research, develop and ultimately tune future CT Defense assessment systems and the advanced CONOPS they will enable. In short, a Planner is needed to provide the tiered system “glue”: for design of the system; for replication with fidelity of all relevant process aspects of the developing tiered system; for providing accurate fused data from system experimentation and also simulation (via synthetic fusion); and for red-teaming.

## 4.5 Tiered System Development Example Plan

4.5.1 The tiered system CT Defense assessment activity should begin with the establishment of a hardware/software experimental test bed to allow iterative hardware in the loop testing and software development upgrades. The architecture would need to be

scalable to permit integration of an arbitrary number of real and simulated weather and hazard sensors. Simulation models of the generic classes of sensors would be assembled for tradeoff studies to aid in choosing reliable, cost-effective sensor suites for the field, and would begin to be integrated into the comprehensive test-bed software emulator Planner that would simulate all aspects of the developing tiered system. In the second year, the team would integrate additional (e.g., Colton et al. 2006; Wert 2006a; Wert 2006b) and existing sensors into the architecture through the sensor concentrators installed in a selected primary demonstration region, and the Planner would be advanced to a stage of validation (where verification is ensuring that the equations programmed are solved with accuracy; and validation is ensuring that the integrated emulator produces physical results when operated as intended). During the third year, the tiered hardware system would be used in an operational environment as a research tool, to investigate sensor adjudication strategies in a network, to develop improved concentrator protocols and algorithms, to reduce instances of false alarm, and to develop and test metrics for system evaluation. Further, it would be used by the test bed team and by other Operators for developing minimum-latency procedures for response, for improving crisis management and force protection in current and planned systems, for sensor placement optimization at fixed and mobile sites in the region, and for extending to rapidly deployed, mobile tiered nodes. It is envisioned that design of the developmental system could be frozen as early as the end of the third funding year, and up to three replicated systems could be assembled at that time for wider testing. During the fourth year these pre-prototype replicas would be evaluated in different locations to verify operational suitability. The results of such tests would support transition to fieldable production systems. Depending on priority and different levels of initial acceptable performance, this overall schedule could be advanced by one or even two years.

4.5.2 For purposes of realism, and to develop cost and time estimates, we envision that the experimental tiered system test bed year-by-year activity set that is sketched below would occur at an existing secure, high-tech DoD laboratory facility with expertise in all phases of the technology, such as NRL (instead of at a green site). As this is to be a prototypical tiered system, those aspects would then be extended first to the NRL environs and then the Washington DC metro area by accepting sensor feeds from agent detectors and meteorological sensors already in place but operated by other agencies outside the jurisdiction of the test bed.

4.5.3 **Year 1:** approximately \$12.6M

*Goal:* To prove the viability and main advantages of the CT Defense assessment system and to design the necessary missing components to ensure the success of the program.

*Major Milestone:* Experimental setup.

1. Establish the overall test bed hardware and operational software architecture from existing hardware and software subsystems and components.
2. Conduct experiments to verify functionality and interoperability of components and systems.

A central hardware focus of the first year effort would be to ensure the connection of vendor sensor equipment to the distributable concentrators and thus to the CT-Analyst processing hub via wireless communication links. Some available sensors

- provide wireless capabilities, but no standard interfaces currently exist. The experiment/demonstration would be a simulated event using an extant breadboard system to simulate the planned primary defense region. The simulated fixed and mobile sensor inputs would be initialized using a pre-computed detailed release scenario to evaluate what the sensors would be expected to see and when. These first experiments would allow preparation for the follow-on field experiments testing the tiered systems communication and analysis components, in collaboration with Reference Implementation Cell activities as feasible (Section 6.2).
3. Conduct software development for incorporating multi-vendor sensor data.  
A simple and flexible hardware/software sensor concentrator is needed to automatically convert inputs from a number of disparate Tiers 1 and higher sensor inputs into a format for direct assimilation by CT-Analyst and the VMOC *Spydr*. Vendor-specific analysis packages (where available) would need to be modified to provide a uniform output.
  4. Develop the CT Defense Tiered System Planner to initial operational status.  
The Planner would be based initially from: CT-Analyst and associated hydrodynamics and other codes that underpin that capability; sensor point and environment models; and models of the networks. At first operation, it would include synthetic sensors (models, possibly empirical, of inputs and outputs) for each individual sensor in the system; a model of the system network that would predict with fidelity finite-network effects such as latency, bandwidth, and noise; and a model of the synthetic sensor concentrator (that would provide as output the expected local sensor data outputs, while taking as input the network-modified data outputs of all of the individual synthetic sensors in the system, and also accounting for sensor location errors — particularly for mobile and higher Tier sensors — and relevant environmental conditions such as heat, cold, wind, rain, etc.). Planner activities would also include development towards the ability to rapidly generate Dispersion Nomographs<sup>TM</sup> (Obenschain and Patnaik 2006).
  5. Empirically and with the software tools available, assess the impact of sensor placement and distribution on system performance, and conduct initial experiments to validate the Planner.
  6. Investigate the effect of sensor fusion on prediction performance by combining CB point detection sensors with other data and information derived from a broader tiered system of local, regional, and operationally responsive space capabilities such as the TacSat (Hurley et al. 2003) or other assets as necessary. (Cost estimates for space assets are not included here.) It is envisioned that the NRL VMOC *Spydr* would be employed as primary coordinating capability for any such assets.  
In addition to the critical Tier 1 and the possibility of sensor data from higher Tiers, the inputs would include weather reports, accident reports, and medical reports from hospitals and veterinarian clinics, zoo animal behavior monitors, etc.
  7. Select a field site for in-situ field experiments based on DoD priorities, local participation, and local capabilities available for piggyback.
  8. Assess existing sensor systems available for in-situ experiments; identify and obtain additional sensor components as necessary.

#### 4.5.4 **Year 2:** approximately \$9.2M

*Goal: Assess CT Defense emergency assessment system in an operational setting.*

*Major Milestones: Install pre-prototype hardware at a CONUS military facility; in-situ experiment with agent simulant.*

1. Install pre-prototype sensor net at military base with concentrator(s).

The field activity would focus on taking the selected complement of disparate sensors, made wireless compatible, to the field to augment capabilities possibly already in place and under control of local authorities. The plan would be to install several concentrators (small, standalone computers collecting data from the relevant sensor packages under their control) and field the concentrator outputs to the operations center via robust wireless links.

2. Perform in-situ field experiments with the Planner and tiered system hardware.

The hardware would be taken to the field and connected to a subset of the local hardware and information systems sufficient to test and demonstrate the integration. Beyond these initial installation efforts, the project would be to develop information for a general database for selecting and evaluating equipment suites in which all selected sensors, regardless of wireless interface capabilities, would communicate via a mesh network. The in-situ experiments would be designed so that moving sensors (e.g., in fire trucks or police cars) would appear to report what they are sensing at the actual current locations of the sensors. In this way, first responders could be directed on the streets realistically in response to what their sensors would be telling them in a real event. Some of the in-situ sensor tests would be verified by use of accepted CBR test methods, such as utilizing grab samples and analyzing these samples by gas chromatography/mass spectrometry (GC/MS), proofing that would confirm the effectiveness and response of the lowest tier sensor system.

3. Continue analysis of the impact of sensor placement and distribution.

4. Continue analysis of incorporating additional sensors, including stand-off and line-of-sight detectors, and other data.

5. Demonstrate VMOC *Spydr* with the InfraLynx system, including the ability to conduct distributed searches in the sensor concentrator, and sensor tasking.

6. Continue development and validation of the Planner, and incorporate into the collaborative environment of the VMOC *Spydr*.

7. Complete development of the ability to rapidly generate Dispersion Nomographs.<sup>TM</sup>

#### 4.5.5 **Year 3:** approximately \$8.4M

*Goals: Transition the CT Defense emergency assessment system to Operator use and test with hardware in the loop. Verify analytical and experimental sensor results.*

*Major Milestone: Field trial of the CT Defense emergency assessment system in a mock emergency response experiment with contaminant simulant and various sensors.*

1. Transition to trial operation.

Operate the CT Defense system in situ with connections to local assets in place. Monitor the system for 24/7 reliability and the incidence of false alarms. Consult with the local officials to make modifications as needed to reduce manning costs and improve responsiveness for their particular environments. Conduct a full

- operational field trial where the detailed Planner is compared to the various sensor readings for validation relevant to the primary defense location, and CT-Analyst is used in situ and in tempo to backtrack to the source location as a basis for building ventilation shutdown and evacuation opportunities as if for a real event.
2. Expand system; test operational concept; spiral in new technology.  
As experience is gained, expand the region spanned by the capabilities. The central analysis engine would have been designed to handle many more concentrators and thus sensor suites than the experimental test bed would provide. Therefore, local assets from an extended coverage region would be connected as piggyback feeds from existing systems so that alternate analysis approaches would not be disabled as their data is incorporated into the assessment system. This would also be testing the multi-tiered system aspects of the implementation.
  3. Continue to analyze sensor effectiveness in an effort to ascertain the optimal set of sensor data necessary to provide timely, accurate, and effective response. Incorporate modifications as necessary.
  4. Freeze design of developmental hardware and software user interfaces. Assemble a leave-behind pre-prototype for continued operational experiments. Fabricate/assemble additional pre-prototype system replicas, in preparation for experimentation at different locations in year four.
  5. Determine location(s) for additional field tests and begin test preparations.

4.5.6 **Year 4:** approximately \$6.7M

*Goal: Technology transition for operational use and production.*

*Milestone: Validated leave-behind at several locales.*

1. Conduct field experiments at additional locations.
2. Develop and provide transition plan.

## 4.6 Recommended Demonstration Test Site

4.6.1 As outlined above, it is envisioned that the tiered CT Defense emergency assessment system would initially be stood up at a secure technology forefront site such as the NRL, with a combination of simulated and hardware-in-the-loop sensors. This choice would greatly reduce the cost of the first two years of the effort through lowered personnel costs and accessibility with local management control. Initial software and communications integration would be performed during the first year on an existing breadboard system already at NRL, and with additional Reference Implementation Cell experimentation throughout to advance and harden the network capabilities for various envisioned situations. This approach would provide a base protection demonstration early in the project and give the test bed team an effective hardware breadboard to integrate and troubleshoot before going into the field, without the need for travel. At the end of the second year, a tiered CT Defense emergency assessment system could be ready for operational testing by external Operators such as local emergency response authorities, with some fixed and mobile sensors. San Diego and/or Norfolk would be good possible locales because they encompass extensive rural and compact urban domains containing important military bases and complex terrain. Other U.S. cities could be Seattle, Houston, or Chicago.

## 5 Tiered System for Maritime Domain Expeditionary Maneuver

### 5.1 Concept Overview — Fast-paced, Multi-environment: Offense

5.1.1 Regardless of theater, the rapid tempo required for expeditionary warfare mission success often depends on the time-critical intelligence that enables tactical decisions. Information must be collected over a wide area and transmitted back to operational commanders who can then project power when and where needed. Ongoing technological advancements in sensor development, signal processing, and communications now allow the realization of rapidly configurable, tiered sensor systems that cover the battlespace at varying resolution and are responsive in real time. Development of this capability requires a collection of experiments centered on a Ship-to-Object Maneuver (STOM) scenario with the goal of integrating sensors and networks that are presently at various levels of maturity.

5.1.2 Here we describe the development path for a tactically-oriented tiered system designed specifically to obtain the intelligence required to plan and execute a STOM mission through and across a littoral battlespace, and to provide that information to mission operatives in near-real time. This tiered system would include the novel networking of primarily existing sensor technology deployed, for the first time, on unmanned air vehicles (UAVs). These sensors would be networked to each other, to one or more sensor concentrators (e.g., VMOC *Spydr* [Medina 2006]; also see Fig. 4.3.2), and thence to an evaluation server (e.g., a VMOC *Spydr* Server) where a STOM Tiered System Planner would reside along with auxiliary data analysis algorithms and database management and sophisticated visualization software. The Planner would replicate with fidelity all relevant process aspects of the developing tiered system and provide accurate fused ISR data for operator evaluation. Sensor data could be accessed by mission operatives both from the concentrators and the evaluation server, at varying degrees of processing (closer to raw data from the concentrators, and closer to actionable intelligence from the server). The tiered system described in this section would provide, overall, a nearly complete set of ISR information required to plan and execute a STOM mission. Further, it would incorporate, augment, and rapidly update data provided by existing space- and air-based assets. In terms of management structure, a small cohesive cell — an experimental test bed — would be effective, to develop this tiered system to a TRL-5 (or -6) integrated degree of readiness.

### 5.2. Maritime Domain Expeditionary Maneuver Problem Statement

5.2.1 Complicated littoral environments are a challenge to the execution of Expeditionary Warfare and associated concepts such as Seabasing, STOM, and Riverine Operations. STOM operations, in particular, require Marine Corps forces to thrust ashore at multiple points in order to concentrate forces at the decisive place and time and in sufficient strength. This requires a more rapid tempo over a wider area than traditional operations.



Threats to tempo include entrenched defenses, mines, large tidal cycles, high civilian populations, dynamic ocean currents, and rapidly changing weather conditions. Superior tempo is first achieved and then sustained through utilizing a comprehensive ISR network, and then projecting forces ashore where the threat is minimized and at a pace that disrupts enemy response.

5.2.2 A comprehensive ISR network must be in place to support all STOM phases including planning, rehearsals, and the execution of multiple concurrent operations. A key use of battlespace intelligence is to facilitate operational maneuver and precision engagement. The planning and execution of STOM requires rapidly (time-scales of tens of minutes to hours) updated information on bathymetry, water depth, bottom type, beach trafficability, and water column clarity. Other tactically relevant information includes the locations of mines and waterborne obstacles/objects, both natural and man-made. The suitability of the assault lanes and littoral penetration points depend upon detailed knowledge of beach gradients, obstacles, tide and surf, water depths, contour of the sea bottom, routes of egress from the beaches, soil trafficability, and beach defenses. Although there is an increased use of unmanned underwater vehicles (UUV), SEAL and EOD teams still are required to survey the coastal zone to gather much of this information. By their nature, manual surveys are limited in the spatial and temporal coverage to the location and time in which they were conducted. The bottom line is that the widest area of coverage, speed, precision, and detail necessary to support STOM continues as an important warfighter capability gap. Remote sensing technology and sensors deployed on UAVs offer the potential for providing the needed increased spatial and temporal coverage in a covert framework. A tiered system will allow the overlap of complementary sensors and capabilities.

5.2.3 The distributed components of the tiered system we envision for STOM would rapidly assemble, reconstitute and re-deploy as the situation dictates. In order to clear an assault lane, for example, a UAV-based hyperspectral imager would measure water optical properties and determine they are suitable for a UAV-based mine countermeasures (MCM) LIDAR. The imager UAV would pass that information to the LIDAR UAV, which then would begin searching only the areas where there is a higher probability of detection, thus freeing other MCM assets to search in other areas. Upon mine detection, the LIDAR UAV would pass the information to a pre-positioned UUV for mine marking or neutralization. As a result, MCM and obstacle clearing operations would be able to cover the area in minimal time. This means that — equipped with a tiered system such as envisioned here — the amphibious assault force as a whole would spend less time offshore the littoral penetration area (LPA).

5.2.4 Rapid mobility and persistent surveillance are two of the required capabilities for the future fighting force as described in National Defense Strategy 2005 (NDS 2005) and the Quadrennial Defense Review 2006 (QDR 2006). Expeditionary warfare and the STOM mission in particular highlight the need for these capabilities. A tiered sensor system enables rapid mobility by minimizing the time to engage the enemy, clear an area, or respond decisively to changing conditions. A tiered system for STOM also answers the

call for persistent surveillance through systems that can penetrate and loiter in denied areas. Exercised development of a tiered system to support effective STOM will provide capability directly for a wide range of significant missions with comparable needs.

### 5.3 Tiered System Example Available Technologies

5.3.1 A number of sensor and system technologies with relevance to the STOM intelligence problem are now reaching levels of maturity that allow for their exploitation within an integrated, tiered sensor system, and that will enable reduced time spent in the LPA. These include the Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS), NRL Interferometric SAR (NiSAR), Sandia National Laboratory MiniSAR (Sletten 2006), WARHORSE (visible) and IRONHORSE (SWIR) hyperspectral imagers, and the NRL Passive Millimeter Wave Interferometer (PMI). Note: as in Section 4, we here centrally use NRL technologies since the relevant subject matter experts, as study participants, are readily available to provide subsystems cost and TRL estimates. Further, NRL technologies — US Government developed and owned — may be discussed in this document without consideration of proprietary issues.

5.3.2 Through the use of these example complementary technologies, a significant portion of the electromagnetic spectrum would be cohesively exploited in support of expeditionary warfare. We illustrate this by considering environmental conditions, mine countermeasures, and problems of noise with low probability of detection radars.

5.3.3 Environmental Conditions: STOM doctrine requires the capability to maneuver over the horizon from blue water through the beach exit. A tiered ISR system that can measure key environmental parameters in near-real time will aid decision-making, maneuver flexibility, and therefore maximize operational tempo. A major conclusion of the Expeditionary Warfare Integrated Product is that proximity of the ships to the objective, and weather conditions, are the main influences on the time to build-up to the desired force level (e.g., Higgins et al. 2004). For example, the Expeditionary Fighting Vehicle (EFV) is a keystone of STOM and is designed to safely navigate from offshore attack positions through the coastal ocean to the shoreline. Nonetheless, it is still subject to environmental limitations that include sea state, ocean currents, mudflat extent, and porosity. Operation of the EFV also requires knowledge of the bathymetry to properly transition from planning hull to tracked vehicle. Therefore, successful STOM operations require timely knowledge of the environment. In order to gather information about the environment, synthetic aperture radar (SAR), hyperspectral, and passive microwave imagery use different portions of the electromagnetic spectrum and rely upon different physical processes. Together they provide a more complete assessment of the key environmental parameters necessary to support STOM. Radar scatters off the ocean surface, providing information on wave size, currents, and surfzone, and is sensitive to exploitable bathymetric effects. Hyperspectral sensors collect visible and near-IR radiation reflected and emitted from the surface of objects. Visible light, however, is the only portion of the electromagnetic spectrum that penetrates into the water column. A hyperspectral sensor that is highly sensitive in the blue-green (such as the NRL PHILLS [Bowles 2006]) can measure tactically relevant information such as sea bottom type,

underwater obstacles, and diver visibility, while estimating bathymetry. The spectral resolution also has environmental application on land such as terrain categorization, foliage cover, sediment type and soil moisture.

5.3.4 Mine Countermeasures: If mines cannot be avoided or are inadvertently encountered, the amphibious force must breach the minefield without tactically significant disruption of the operational tempo. Although SEALs, EOD teams and marine mammals play active roles in MCM, initial cueing and change detection can more efficiently be done using remote sensing. An ISR capability is required to identify the location and extent of the mine threat, thus determining probable areas to avoid and minimizing exposure during breaching or clearing operations. Hyperspectral techniques that focus on the capability of blue-green light to penetrate into the water column are being developed for the MCM mission. The exploitation of hyperspectral sensors will support remote detection, classification, identification, marking, and monitoring of mines and obstacles at sea and ashore. PHILLS in particular is designed to be highly sensitive in the blue-green, which makes it applicable to MCM.

5.3.5 Low Probability of Detection Radar: The proliferation of low probability of detection (LPD) radars in the littoral creates new challenges for the Electronic Warfare community. The high noise environment, combined with waveforms and modulation techniques designed to minimize detection, require systems with increased discrimination and threshold sensitivity. Once a signal is detected, it must then be geo-located to be truly actionable intelligence. A sensor such as the NRL Passive Millimeter Wave Interferometer (Twarog 2006) uses phase differences between multiple elements to discriminate signals of interest from the background with a sensitivity not possible in single antenna systems. Not only would this raise the signal-to-noise ratio for signal detection, but it also enables small angular resolution for target detection.

5.3.6 An ISR tiered system developed around these sensors would be applicable to all phases of the STOM operation from planning through execution. As a visible hyperspectral instrument with high sensitivity in the blue-green (where water is transmissive) and sub-meter resolution from aircraft altitudes, PHILLS can measure parameters such as sea bottom type, terrain type, and foliage coverage, and set a baseline for change detection. The imagery can also be used to derive bathymetry (beyond the surf zone), soil moisture, and trafficability needed to select assault lanes and egress routes. Further, PHILLS can be used for in-water mine and obstacle detection, in addition to the high-resolution refinement of measurements obtained by space-borne hyperspectral assets. The MiniSAR offers 6-inch resolution for target ID and tracking as well as MASINT exploitation. NiSAR is a flexible radar that supports arbitrary waveforms, polarimetric and interferometric modes, and is readily modifiable to operate in several radar bands. PMI uses a passive millimeter wave thinned array imaging system (interferometer) for geolocation of SIGINT and potential imaging of non-transmitting systems day or night and even under conditions of poor optical visibility (i.e., fog, dust, etc.). Hyperspectral imaging takes advantage of the subtle differences in the reflected spectrum of objects to detect targets that may be difficult to find due to camouflage, concealment, and deception techniques. The WARHORSE (visible) and IRONHORSE

(SWIR) hyperspectral imagers are tactical ISR sensors that have already been deployed operationally on larger tactical (or strategic) UAV platforms in the following framework:

- Intelligence and information systems that allow for full integration with national, theater, and joint/multinational organizations;
- Dissemination systems that link widely dispersed forces afloat and forces on or closing with the landing force (LF) objectives;
- Architecture determination;
- Determination of covert vs overt communication links; and
- Connecting tactical collection assets to theater and national assets and databases.

5.3.7 The sensors described above are inherently suitable for configuration in a tiered system. Together they would address many of the documented ISR and METOC (meteorological and oceanographic) capability gaps pertinent to all phases of STOM. Their modes of operation are readily reconfigurable and offer differing levels of covertness. Tables 5.3.1 through 5.3.7 provide an overview of how this suite of sensors is applicable to STOM intelligence gap requirements. The intelligence gap requirements are taken from the STOM Concept of Operations document and divided into separate phases from pre-D-day intelligence preparation of the battlespace through targeting and damage assessment. For all requirements we also list candidate sensors with potential to fulfill the requirement.

<b>Table 5.3.1 Pre-D-day Intelligence Preparation of the Battlespace (IPB)</b>	
Intelligence Requirement	Candidate sensor
Hydrographic survey	UUV SONAR, SAR, HSI
Topographic surveys	SAR
Terrain categorization	Visible/IR HSI
Determination of potential Littoral Penetration Points (landing sites)	Visible/IR HSI, SAR
Ground slope and conditions in HLZs	SAR
Bridge capacity	Visible/IR HSI, SAR
Order of Battle	Visible/IR HSI, SAR, PmmW
SIGINT Collection	PmmW
Track enemy movements	Visible/IR HSI, SAR, PmmW
Targets identification	Visible/IR HSI, SAR, PmmW
Determination of enemy intentions	Visible/IR HSI, SAR, PmmW
Prepare the LPPs (Mine and Obstacle clearance)	Visible HSI, SAR
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.2 Mine Countermeasures and Obstacles</b>	
Intelligence Requirement	Candidate sensor
Mine and obstacle identification (locations and types)	Visible HSI, SAR
Mine and obstacle marking	Visible HSI, SAR
Mine and obstacle clearing and neutralizing	Visible HSI, SAR
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.3 Beach Reconnaissance</b>	
Intelligence Requirement	Candidate sensor
Beach gradients	SAR
Obstacles (natural and manmade)	Visible/IR HSI, SAR
Tide	Visible/IR HSI, SAR
Surf	Visible/IR HSI, SAR
Water depths and contours	Visible/IR HSI, SAR
Egress routes	Visible/IR HSI, SAR
Soil trafficability	Visible/IR HSI, SAR
Suitability of selected LPPs for the surface assault.	Visible/IR HSI, SAR
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.4 Identification of Defenses Ashore</b>	
Intelligence Requirement	Candidate sensor
Defenses in the LPA (beach, drop zone (DZ), and landing zone (LZ))	Visible/IR HSI, SAR
Gun emplacements	Visible/IR HSI, SAR
Observation and control posts	Visible/IR HSI, SAR
Other enemy capabilities that could impede advancement	Visible/IR HSI, SAR, PmmW
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.5 Meteorological and Oceanographic Information</b>	
Intelligence Requirement	Candidate sensor
Bathymetry	LIDAR, Visible HSI, SAR
Tidal constituents	VIS/NIR
Winds, surface	LIDAR, SAR
Winds, aloft	LIDAR
Atmospheric Visibility	LIDAR, Visible/IR HSI
Diver Visibility	Visible HSI
Precipitation rates	SAR, LIDAR
Ocean currents (Surface and subsurface)	SAR, VNIR, SWIR, LWIR
Sea state & wave characterization	SAR
Surf zone characterization	SAR
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.6 Electronic Countermeasures</b>	
Intelligence Requirement	Candidate sensor
SIGINT collections on enemy communications and electronic facilities	PmmW
Facilities are neutralized, destroyed, or marked for exploitation	PmmW
Protective measures to mitigate any hostile electronic warfare threat.	
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

<b>Table 5.3.7 Real Time Support to Targeting &amp; Battle Damage Assessment</b>	
Intelligence Requirement	Candidate sensor
Target types, locations, and movement	Visible/IR HSI, SAR, PmmW
Assessment of possible collateral damage	Visible/IR HSI, SAR
Assess the effectiveness of targeting	Visible/IR HSI, SAR
<i>HSI = Hyperspectral Imager; SAR = Synthetic Aperture Radar; PmmW = Passive millimeter Wave</i>	

5.3.8 Tables 5.3.1 through 5.3.7 illustrate unambiguously that a well-placed sensor suite consisting of visible/IR hyperspectral sensors, IR thermal camera, SAR, and a profiling LIDAR system can provide nearly complete ISR to support all phases of a tactical STOM mission. The CONOPS we envision for utilization of these sensors in a tiered networked system is to deploy as many of the sensors as possible on agile UAV platforms. The hyperspectral sensors (PHILLS, WARHORSE, IRONHORSE), and the MiniSAR (once it becomes available) are candidates for small, tactical-scale UAVs. Due to the larger size of the interferometer baselines, NiSAR and PMI are suitable for larger, high-altitude systems (or, depending on circumstance, a TacSat). Through the use of these complementary technologies, a significant portion of the electromagnetic spectrum would be exploited in support of expeditionary warfare. The sensors would be linked to each other and to a few small sensor concentrator UAVs that would hover in appropriate relay positions (e.g. for STOM, primarily over the offshore fleet). Raw sensor data would be sub-processed and compressed aboard the sensor platforms, then linked to the concentrator-UAVs. From there the data would be available for direct read by troops accessing, e.g., the VMOC *Spydr* website, and would also be linked or transmitted to the evaluation server where database management systems would be populated, and analyses would proceed to higher levels (sensor data converted to ISR and METOC data via the Planner and associated tools, and fused as appropriate with incoming data from other space and air-based assets). The entire tiered system operation, including the flight plans for the sensor UAVs, and mode of operation of the sensors themselves, would be directed via the evaluation server. Such command and control information would be uplinked to the concentrator-UAVs and out to the sensor UAVs as required.

5.3.9 It is envisioned that the tiered system communications would be provided by a high-bandwidth backbone that is hybrid across the IR through the RF bands. Such a network would provide a seamless broadband capability to deliver the most important and urgent information at all times, and would support tens of gigabits per second (in the IR, at 1550 nm) whenever and wherever possible (Gilbraith et al. 2006). When operating in the IR, this network would exhibit extremely low probability of detection and intercept due to small footprint at the receivers and to the non-detectability of the wavelengths with the naked eye, night vision goggles, and other detectors. Transmission through the atmosphere and channels with small and large particles is very good at 1550 nm. The wavelength is susceptible to cumulous clouds and moderate to heavy fog, however, and does require line-of-sight propagation architectures. Concentrator-UAVs located directly over the offshore fleet and possibly elsewhere strategically through the battlespace would provide relays for the links; an architecture that would exploit routers that search seamlessly for the highest bandwidth available (from IR through RF) would mitigate propagation shortcomings. Economies of topography and power for the hybrid system are anticipated to be significant. Technical challenges to a fielded hybrid capability include matching specific upper and lower data rate requirements by the router to those available from each propagation band, and providing requisite error corrective methods for the variable environmental conditions.

## 5.4 Tiered System Development Example Plan

5.4.1 A four-year progression is envisioned for the experimental development of this expeditionary tiered system. *Note: as in Section 4, indicated cost figures below are “ballpark” estimates only.*

5.4.2 **Year 1:** approximately \$6.8M

*Goal: Assemble a tiered sensor test bed focused on the STOM mission and design the necessary missing components.*

*Major Milestone: Experimental setup and component integration.*

1. Assemble the overall test bed hardware and software and integrate existing sensors to obtain complementary information motivated by STOM intelligence requirements, providing tactical situational awareness and an environmental assessment.
2. Develop algorithms to extract the ISR and METOC information from the sensor data.  
Algorithms currently exist to extract, from the suite of sensors, all of the information listed in the STOM requirements tables. However, they are at varying levels of maturity and sophistication. Also, with regard to METOC, only R&D retrieval algorithms exist, and they need to be operationalized. Capability gaps within algorithms will be identified; this will guide future work.
3. Conduct experiments to verify functionality and interoperability of components and systems. Two experiments are envisioned:  
Experiment 1A uses airborne platforms to carry sensor payloads that are ultimately intended for UAVs. The majority of the data will be collected for post-mission processing, except where the capability for real-time downlink presently exists. This experiment would also include an extensive ground-truth data collection campaign so that the performance of the sensors and algorithms could be evaluated.  
Experiment 1B address the problems and capability gaps (in both sensors and algorithms) elucidated by Experiment 1A. This ensures that subsequent experiments focus on relevant sensor data and associated algorithm development.
4. Identify candidate UAV platforms, and modify payload designs for UAV integration.
5. Design and begin build of the IR/RF Router; begin development of error-corrective coding for the hybrid system.
6. Develop the overarching STOM Tiered System Planner to initial operational status, and perform simulated scenario exercises with the VMOC *Spydr* to test data formats.
7. Select test sites for in-situ experiments in following years and begin test planning.

5.4.3 **Year 2:** approximately \$8.5M

*Goal: Assess STOM ISR sensor test bed in operational setting.*

*Major Milestone: Conduct simulated exercises across the suite of networked sensors.*

1. Expand the capabilities of the sensors that were demonstrated in the first experiment with an emphasis on data downlink and inter-platform communications. Test algorithms that extract intelligence requirements from sensor data with the goal of ultimately sending the processed information to the collection node.
2. Demonstrate VMOC *Spydr* with the developing network, including the ability to conduct distributed searches in the sensor concentrator, and sensor tasking.

3. Continue development of STOM Tiered System Planner; compare predictions with experimental results.
4. Conduct in-situ field tests of subassemblies to elucidate allocation of bandwidth, effectiveness of network protocols, and node hierarchy, and to assess effectiveness of sensor combinations in STOM environment.
5. Continue payload hardware development for UAV integration.
6. Design/build/test hybrid comms terminals.
7. Continue test planning for field experiments.

#### 5.4.4 **Year 3:** approximately \$9.8M

*Goal: Prepare for operational field experiments with UAVs.*

*Major Milestone: Full integration of hardware on UAV platforms.*

1. Increase autonomy of the sensors and test the associated requirements for power, communications, navigation, and networking. Test real-time downlink of mission information and dynamic retasking capabilities. Incorporate database and visualization tools for exploitation of sensor data. Distributed environmental sensors will be networked together into a Littoral METOC Sensor Suite (LIMSS).
2. Continue development of STOM Tiered System Planner; provide reliability measures for fused data.
3. Integrate sensors, the hybrid communication capabilities, and the VMOC *Spydr* sensor concentrators, to UAV platforms.
4. Continue test planning for field experiments.

#### 5.4.5 **Year 4:** approximately \$7.7M

*Goal: Conduct field experiments in an operational setting and prepare for technology transition.*

*Major Milestone: Validated operation of mobile STOM ISR suite.*

1. Participate in a field experiment at an expeditionary warfare training facility.
2. Develop and implement transition plan.

### 5.5 Recommended Demonstration Test Site

5.5.1 As discussed in Section 4, the test bed should be initially set up at a secure technology site such as NRL, with a combination of simulated and hardware in-the-loop sensors. For in-situ field experiments, Everett, WA — a location with conditions analogous to a relevant operational scenario — would be a good candidate. In Year 4, the system should be ready for participation in a test at an expeditionary warfare training area.



## 6 Tiered Systems Essential Elements, and Development Path Forward

### 6.1 Comparison between Scenarios: Elements and Activities

6.1.1 In Sections 4 and 5 we described paths to the development of tiered systems that are specific to each of the two bounding scenarios considered here: contaminant transport urban defense; and maritime domain expeditionary warfare offense. The multi-year work-plans laid out in those sections provide straightforward answers to the question: why can't we just put these tiered systems together now?

6.1.2 Consideration of the tiered system experimental test bed activities (Sections 4 and 5) indicates that to develop a tiered system one needs readily to hand:

**(1) HARDWARE:**

sensors; sensor platforms; networking; connectivity, and also computing;

**(2) PLANNING TOOL:**

for design of the system; for replication with fidelity of all relevant process aspects of the developing tiered system; for providing accurate fused data from system experimentation and also simulation (via synthetic fusion); and for red-teaming;

**(3) IT PACKAGE:**

for controlling the routine operation of the system, and for governing system data gathering and display (for the local site, and also for collaboratory operation); and

**(4) EXPERIMENTAL TEST BED - SPECIFIC TOOLS**

development diagnostics; data outputs for understanding system operation, for tuning; for red-teaming at every level; etc.

6.1.3 Most of the elements listed above exist, or would be easy to procure by direct application of resources. However, tiered systems could not at present be built from these elements in a stand-alone sense. Two key functional deficiencies that prohibit immediate tiered system prototyping are:

(i) seamless horizontal networking, for on-demand physical linking of aggregate hardware and software components into an operational tiered system “machine;” and

(ii) sensor integration, for on-demand manipulation of data gathered by individual tiered system sensor components into cohesive, actionable information.

6.1.4 These two aspects are dramatically shared across the bounding scenarios. Each represents significant stand-alone development, while at the same time the two aspects are conceptually linked as related system-of-systems integration activities.

6.1.5 We agree with the observation of Dombrowski et al. (2002) that “the bedrock of systems integration is familiarity with the technical state of the art in the wide range of disciplines that contribute to the components of the system.” Since networking integration involves a plethora of technical activities that are quite distinct from those needed to integrate sensor data, it is possible to study each in parallel prior to embarking

on a comprehensive test bed activity as discussed in the Blair DSB report (2004). For problem tractability, we recommend this approach: begin with two focused integration cells to address the two key deficiencies that are currently impeding broad tiered systems developments. The first, a Reference Implementation Cell (RIC), would provide an environment to host and evaluate prototype tactical edge applications, SOA, middleware, communication services, networking, and radio subnets, and for evaluating how these elements may work together. The second, a co-evolutionary cell made up of Operational/Tactical war fighters along with Service Lab technologists would focus on coherent development of tiered systems. The central goal of the experimental test bed (ETB) would be to elucidate tiered systems developmental methodologies; products would include integrated tiered systems hardware for war fighter experimentation.

6.1.6 Each cell, the RIC and the ETB, should be multi-disciplinary and have multi-institutional representation. There is no doubt the sociology of these cells will be a challenge. On the one hand, strong technical components will be required. These will involve a number of research disciplines and associated theory, simulation, and experimental expertise. For the work to be truly cutting-edge, each will bring a required degree of intellectual independence. On the other hand, setting priorities and direction will be essential, for the reason that each cell must be a coordinated, goal driven activity. Cell governance structure will thus need to effectively balance the processes of coming to the best possible technical judgments when evaluating individual tiered systems component options, with the technical and broader implementation decisions that will apply across the tiered system.

6.1.7 We next consider each of these cells individually.

## 6.2 Recommended Approach for Seamless Horizontal Networking: Reference Implementation Cell (RIC) for GIG Tactical Edge Networks

6.2.1 The Joint Global Information Grid (GIG) Tactical Edge Networks (TEN) initiative is a Navy-led Joint effort that will identify applications and related network services and protocols to support multi-mission warfare requirements into the 2015 time frame. This effort will focus on the tactical edge firsthand then build out using a spiral engineering approach. Engineering spirals, and Navy mission baseline threads (anti-submarine warfare, suppression of enemy defenses, etc.), have been identified that transform the current overall architecture while allowing the TEN concept to complement existing legacy tiered and other systems; see Fig. 6.2.1 for an example of a TEN future activity. To further this and other comparable objectives, there is a profound need for a Reference Implementation Cell for evaluating prototype GIG TEN applications and capabilities.

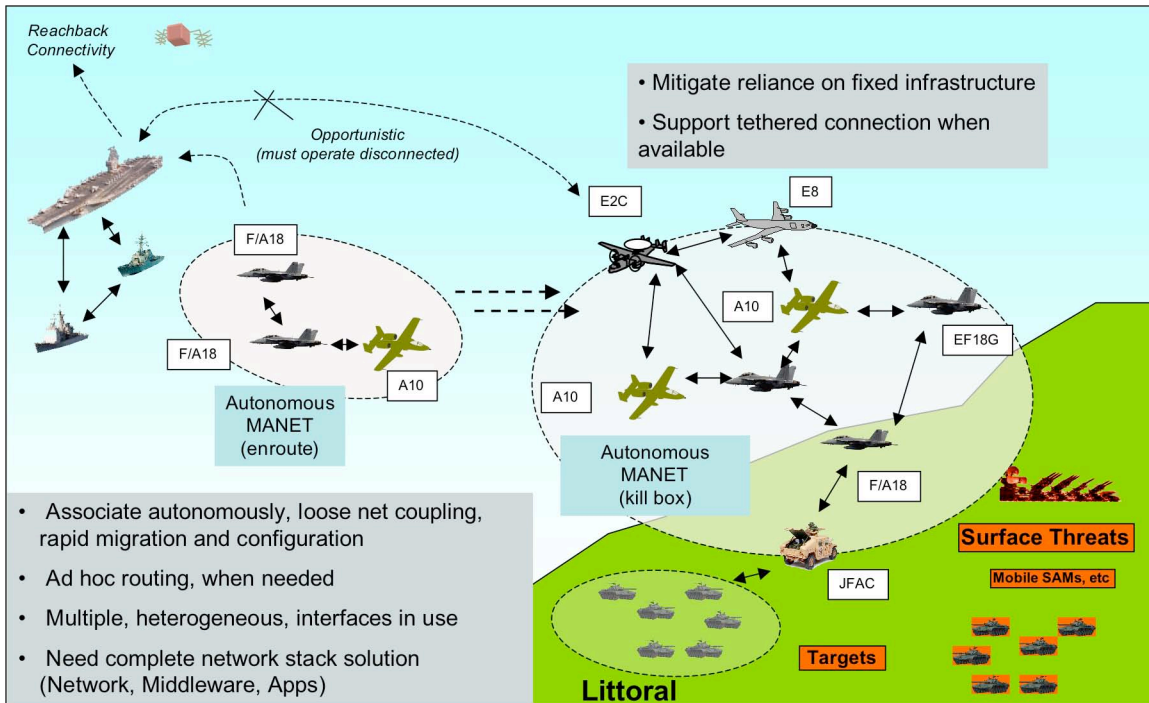


Figure 6.2.1. Tactical Edge Network (TEN) Example

6.2.2 A major current problem is illustrated in Fig. 6.2.2. Presently, simple queries from the tactical level, such as a request for around-the-corner information, will most often be routed through overhead assets. This action triggers extensive — and essentially unnecessary — bandwidth utilization.

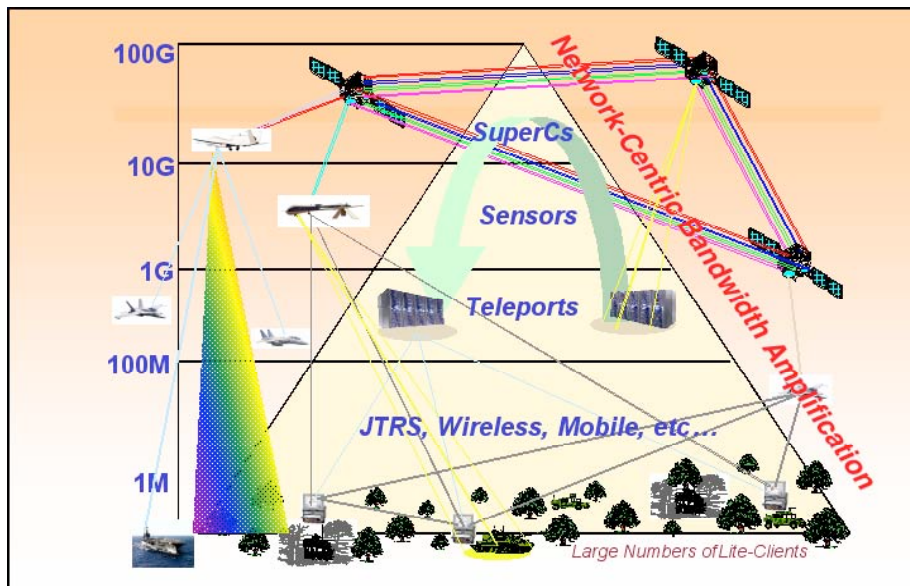


Figure 6.2.2. Network-Centric Bandwidth Amplification

6.2.3 JTF WARNET (JTF WARNET 2006), a Joint activity with NRL technical leadership, addressed this issue with goals to provide: tactical connectivity using JTRS surrogates and existing legacy communication capabilities; interface and translation among Service tactical C2 systems for direct, horizontal, tactical, secure, joint interoperability; system management of network and application performance and networking components; and CONOPS and tactics, techniques and procedures (TTPs) for new joint capabilities. Deployable JTF WARNET operational prototypes are planned as ongoing from FY04 through FY11.

6.2.4 Lessons learned from JTF WARNET (short version) include:

- Fielding an operational capability quickly does not reduce the number of steps required. You still have to do testing in a controlled environment before you take it to the field.
- It takes a lot of effort to support a fielded capability in terms of training, logistics, web pages, and a help desk.
- Since FY03 it has been hard to do joint exercises with the operational components. They have been too involved in real world events.

6.2.5 We need to find innovative ways to get the war fighter to experiment with emerging capabilities. It is envisioned that a cell such as the RIC would further this goal. The RIC would build from the current GIG<sup>EF</sup> and Joint Virtual Laboratory (JVL) to provide a hands-on R&D environment for testing tactical edge applications, service-oriented architectures (e.g., Figure 6.2.3), middleware, communication services, networking, and radio subnets, and for evaluating how they work together. The model is for government to work cooperatively with industry to enable access to the DoD technology base and fix deficiencies and performance issues in products while they are still in development. The RIC would provide an environment where information assurance, sensors, weapon systems, electronic warfare, and across-the-board re-teaming would be integrated as a part of a shared infrastructure supporting NCW. It would help with the identification of “holes” in the technology base, and work with sponsors to fill these with appropriate S&T investments. Finally, it would help the Services with CONOPS and TTPs associated with new and perhaps transformational capabilities.

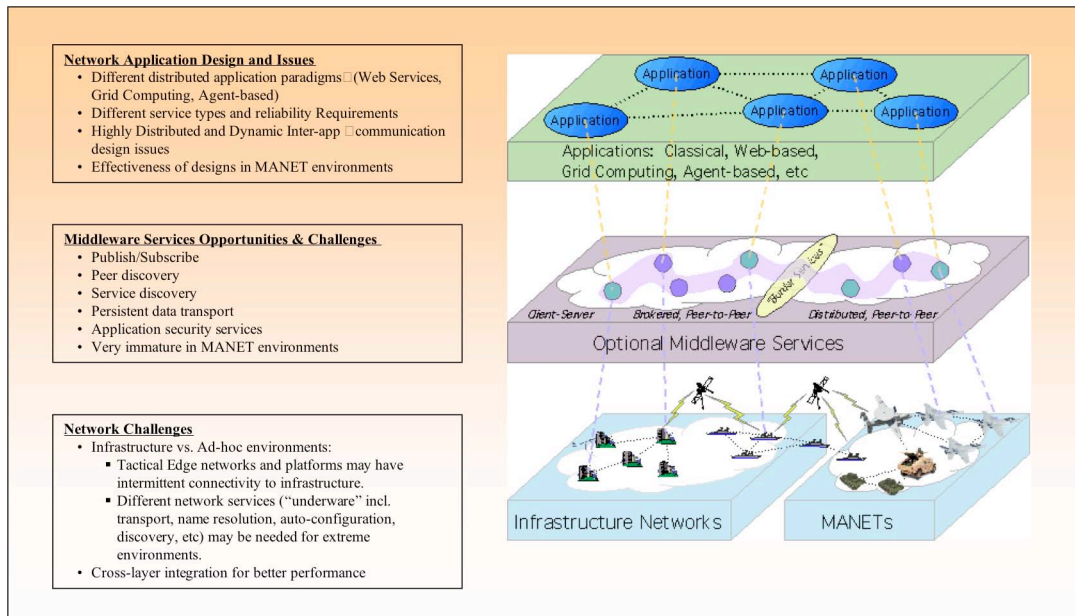


Figure 6.2.3. Service-Oriented Architecture (SOA) to the Tactical Edge

6.2.6 NRL would be an ideal site at which to host RIC, in that there is significant participation in both the GIG<sup>EF</sup> and the JVL already on board, and also considerable ongoing research in wide areas of networking and communications. DoD is embarked upon a substantial investment in the Telecommunication Infrastructure. RIC will help ensure that these programs deliver the necessary interoperable, high performance services that will enable the war fighter to “use the right platform to place the right weapon on the right target at the right time” (Cole 2006).

### 6.3 Recommended Approach for Cohesive Sensor Integration: Experimental Tiered System Development Test Bed (ETB)

*“Learn by doing.” JAM*

6.3.1 To develop effective tiered systems it is necessary to begin from the right end. We believe that this is starting from within small interactive test beds that involve, at minimum, all of the basic assets necessary for an operational tiered system. These cells should be staffed with integrated teams of Service Lab technologists and Operational/Tactical war fighters who are chartered to work collaboratively together for at least four consecutive years, with resources adequate to address major system issues such as cohesive sensor fusion across sensor systems and networks. Topical focus for each such cell should be CBP scenario-driven and directly relevant to one or a few NCW overarching research areas towards NCW deployment. Each ETB should produce the following as products: one or more experimental (TRL-5-like) tiered systems for war fighter testing at each phase of development; and elucidation of “how to” and “lessons learned” per activities for developing effective tiered systems.

6.3.2 The tiered systems central research problem may be thought of as similar to the diagnosis of a major illness exhibiting broad symptoms. The patient wanders from specialist to specialist, printed copies of test results (data) in hand, but it is only when synthesis occurs in some dedicated specialist's office and a complicated diagnosis is made that the data will become actionable information. A close analogy is a large number of sensors trained on a particular geographic area. The sensors may all be focused on a particular physical space; they may return timely data to one or more locations as specified; and they may even be straightforwardly integrated into a single hardware network to facilitate the data transfer. However, the methodology for making the “diagnosis” from the sensor data remains trial-and-error science. We hypothesize that this tiered systems integration problem should be treated from a new system-of-systems R&D activity perspective. Such a shift would enable the motivation for genuine development towards the necessarily new kind of systems integration.

6.3.3 “Platform systems integration and system-of-systems integration are not the same task, and it is not even clear that developing skill at one helps very much in developing skill at the other” (Dombrowski et al. 2002). With this in mind, the ETB product of elucidation, noted above, should be provided with due regard to what college courses a student should take, to become expert in tiered systems R&D.

6.3.4 Specific near-term ETBs, such as those exemplified in this report for CT Urban Defense or for Maritime Domain Expeditionary Maneuver, should generally be developed from the needs list provided in 6.1.2. However, they should systematically leverage the RIC for networking hardware, forego system design options for the Planning Tool (at early times), and work on collaboratory tools only after developing capabilities for routine system operation and across-platforms data gathering and display.

6.3.5 Regarding the time required for these tiered systems developments: instrumenting, integrating, and pulling reliable results from an experiment in a high-tech laboratory, for which that laboratory was not intended, can be achieved in short order (e.g., 18 months) if much of the equipment is already on the floor, with validated calibration software for that equipment already in place, and for experiments that are quantitatively if not qualitatively similar to those for which the laboratory was built. A tiered systems laboratory could be developed and populated as an R&D environment comparable in capability, flexibility, and sophistication to a successful proof-of-principle experiments laboratory, and with comparable TRL-3 deliverables in about 18 months (as indicated in Table 6.3.1 below). Robust (TRL-4 to TRL-5) tiered systems deliverables may then be pulled from such an environment in relatively short time frames.

Table 6.3.1. Goals and Milestones for Tiered Systems Example Solutions in Sections 4 and 5.

<b>Months</b>	<b>Goals</b>	<b>Major Milestones</b>
<b>Tiered System for Contaminant Transport in an Urban Environment (see also Sec. 4)</b>		
0-12	Prove viability, main advantages of the CT Defense assessment system; design necessary missing components.	Experimental setup.
12-24	Assess CT Defense emergency assessment system in an operational setting.	Install pre-prototype hardware at a CONUS military facility; in-situ experiment with agent simulant.
24-36	Transition the CT Defense emergency assessment system to Operator use. Test w/ hardware in the loop. Verify analytical, experimental sensor results.	Field trial of system in a mock emergency response experiment with simulant, various sensors.
36-42+	Technology transition for operational use, production.	Validated leave-behind systems at several locales.
<b>Tiered System for Maritime Domain Expeditionary Maneuver (see also Sec. 5)</b>		
0-12	Assemble a tiered sensor experimental test bed focused on the STOM mission, and design the necessary missing components.	Experimental setup and component integration.
12-24	Assess STOM ISR sensor test bed in operational setting.	Conduct simulated exercises across the suite of networked sensors.
24-36	Prepare for operational field experiments, with UAVs.	Full integration of hardware on UAV platforms.
36-42+	Conduct field experiments in an operational setting and prepare for technology transition.	Validated operation of mobile STOM ISR suite. Develop and implement transition plan.

## 7 Summary: Findings and Recommendations

### 7.1 Findings: Seamless Horizontal Networking, and Sensor Integration

7.1.1 In summary, two key findings emerge from the scenario-based representative tiered systems development paths that are examined in this report:

Finding 1: There is a profound need for seamless, reliable, and trustworthy horizontal networking, for tiered system-of-systems.

Finding 2: Realistic sensor integration is a key — and central — missing element for tiered systems further developments. Methodologies and specific integration and validation technologies are required for next steps.

### 7.2 Recommendations: RIC and ETB

7.2.1 This report's major recommendations are:

Recommendation 1: Building off of the current GIG<sup>EF</sup> and JVL, develop a Reference Implementation Cell (RIC) to provide an environment that will host prototype tactical edge applications, service-oriented architecture, middleware, communication services, networking, and radio subnets, and for evaluating how these prototype Global Infrastructure Grid Tactical Edge Network applications and capabilities work together.

Recommendation 2: Develop one (or more) affordable tiered systems experimental test bed(s) (ETB) that will emphasize sensor integration methodologies and technologies. The ETB will leverage the controlled environment of the RIC, and provide a scientifically viable bridge between simulation environments and field demonstrations and span from individual system elements through fully integrated tiered systems capability. For success, the ETB should proceed as a rigorous, integrated, simulation and experimental sensors exploitation and integration activity analogous to the fielding of a significant physics proof-of-principle experiment, and with a commensurate resource envelope; at a minimum, each such cell should be funded in the range of \$5-15 million/year for four (4) consecutive years.

Recommendation 3: Foster a culture that welcomes red-teaming, which “concerns itself with camouflage, concealment, and deception;... vulnerabilities; and tactics which might be used by adversary against our emerging C3ISR system” (Blair et al. 2004). For the RIC, information assurance should be incorporated in the activities from the outset and designed in throughout, and with red-teaming also integral. For each ETB, a red team should be called in at each major milestone to devise and implement tests of the effects of all likely degradation sources, malicious and natural, on the tiered system performance. Red-team results should be used for calibration, further design, and lessons-learned.

7.2.2 The ETB with the RIC should provide (in 3-5 years): (1) experimental distributed tiered systems capabilities (hardware and software) for war fighter experimentation and evaluation; and (2) elucidation of methodologies for tiered systems developments that will enable wide, successful prototyping of tiered systems.

7.2.3 On the topic of where to site the next levels of focused NCW system-of-systems activities, Dombrowski et al. (2002) noted that “it may very well be that to get the level



of systems integration they require, DoD or the Navy will need to create a new organization with system-of-systems integration responsibilities.... This... should probably report to the Secretary of Defense or the Secretary of the Navy if it is to have the authority necessary to make integration a priority.... If DoD or even the Navy itself creates a new acquisition[-focused] organization for system-of-systems integration, in all likelihood technical and professional assistance from a private sector contractor will be required.... Our initial judgment is... an FFRDC or organization of that kind....”

7.2.4 We suggest that — per ability, interest, and appropriateness — the in-house defense Naval Research Laboratory would be unambiguously well suited for siting the tiered system-of-systems activities as discussed in this report, ranging from development through constructive red-teaming that makes sure the technological promise can be realized. The broad and deep expertise base resident at the Laboratory, reviewed recently in, e.g., DeYoung et al. (2006) (the successful package that nominated NRL for the 2005 New York Council of the Navy League Roosevelts Gold Medal for Science), would provide an ideal environment for tiered systems developments encompassed in the Reference Implementation Cell; in one or more Experimental Test Bed co-evolutionary cells of war fighters with technologists that would focus on coherent development of tiered systems; and in follow-on coordinated tiered systems research, development, and experimentation.

7.2.5 This recommended course of action would significantly further the development of militarily-relevant distributed tiered systems-of-systems that are needed for conducting irregular and distributed missions as noted in the 2006 Quadrennial Defense Review (QDR 2006). Distributed tiered systems will provide the ready ability for the U.S. military to harness together the many operationally relevant aggregate elements that may be available wherever one is on the globe at the onset of an engagement, and effect that these ad hoc elements work together as a distributed but cohesive single system. In the long term, heterogeneous tiered systems that may be assembled flexibly at will, with rapid tempo, and to significant extent, will enable the breadth of operations required for forefront sustainable military forces.

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## A1. Statement of Work: DoD Office of Force Transformation

### **NRL SOW: Developing a Viable Approach for Optimally Tiered Systems: a Study**

#### **Purpose:**

The Naval Research Laboratory (NRL) will develop a methodology for generating and verifying rule sets from which optimally tiered systems architectures may be derived. For the purpose of this study, a tiered system is defined to be a mission-dependent aggregate of existing and novel cross-service hardware and software that responds to the war fighter as a synthesized, integrated single entity, i.e., as a new kind of machine. System elements would include mission-dependent subsets of ad hoc configurable networks, sensors, effectors (cueing agents, weapons, etc.), platforms, command and control, and authorized individuals.

#### **Approach:**

NRL will first define a small number (3 or 4) of specific tiered systems examples that span relevant aspects of urban, land and air, maritime coastal, and open air missions. For each of these envisioned physical examples, details about the system will be described, including specifics about available element technologies, necessary systems engineering and integration, and possible concepts of operation. NRL will then generalize from these field “thought” examples, to an approach for the development of the “rule sets,” plus identify an associated simulation test bed that would be required to model across — or a priori derive — all of the example tiered systems.

#### **Impact:**

The study is expected to define a methodology that will lead to specific guidance for an architectural framework and rule sets that underpin the effective development and prototyping of a myriad of tiered systems now within reach. Such tiered systems are expected to provide significantly enhanced battlespace management for situations that range from those requiring long term awareness to those that need rapid, coordinated, time-critical response to unpredictable simultaneous events.

#### **Deliverables:**

The result of the study will be a report that:

1. Describes a suite of possible tiered systems and associated concepts of operation;
2. Using these potential real-world examples as a basis, describes a methodology for developing the rule sets that are hypothesized to underpin all of the examples;
3. Discusses the requirements for a tiered systems simulation test bed that would implement these rule sets to generate, optimize, and train users for new kinds of tiered systems.

## A2. List of Terms and Acronyms

ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vehicle
BDA	Battle Damage Assessment
C2	Command and Control
C2ISR	Command, Control, Intelligence, Surveillance, and Reconnaissance
C3	Command, Control, and Communications
C3I	Command, Control, Communications, Intelligence
C3ISR	Command, Control, Communications, Intelligence, Surveillance and Reconnaissance
C4ISR	Command, Control, Communications, and Computers, Intelligence, Surveillance, and Reconnaissance
CONOPS	CONcept of OPERATIONs
CBP	Capability-Based Planning
CT	Contaminant Transport
DAS	Distributed Autonomous Systems
DoD	Department of Defense
DOE	Department Of Energy
DSB	Defense Science Board
DUSD	Deputy Under Secretary of Defense
EO	Electro-Optical
EOD	Explosives Ordnance Disposal
ETB	Experimental Test Bed
EW	Electronic Warfare
FRET	Fluorescence Resonance Energy Transfer
FYDP	Future Years Defense Plan
GIG	Global Information Grid
GIG-BE	GIG-Bandwidth Expansion
GIG <sup>EF</sup>	GIG-Evaluation Facility
GMTI	Ground Moving Target Indicator
GNCST	Global Strike Force – Network-Centric Surveillance and Targeting
GPS	Global Positioning System
HFI	Horizontal Fusion Initiative
HSI	Hyper-Spectral Imagery
HUMINT	HUMAN INTelligence
IED	Improvised Explosive Device
IO	Information Operations
IR	InfraRed
ISR	Intelligence, Surveillance, Reconnaissance
IT	Information Technology
JPEO	Joint Program Executive Office
JTF WARNET	Joint Task Force Wide-Area Relay NETWORK
JTRS	Joint Tactical Radio System
JVL	Joint Virtual Laboratory
LIDAR	LIght Detection And Ranging
LIMSS	Littoral METOC Sensor Suite
LNG	Liquid Natural Gas
LPA	Littoral Penetration Area
MANET	Mobile Ad hoc NETWORK

MCM	Mine Counter-Measures
METOC	METeorological and OCEanographic
MLRS	Multiple Launch Rocket System
NCES	Network-Centric Enterprise Services
NCW	Network-Centric Warfare
NRL	Naval Research Laboratory
OFT	Office of Force Transformation
OSD	Office of the Secretary of Defense
OTW	Operations other than War
QDR	Quadrennial Defense Review
QoS	Quality of Service
R&D	Research & Development
RIC	Reference Implementation Cell
RF	Radio Frequency
S&T	Science & Technology
SAR	Synthetic Aperture Radar
SATCOM	SATellite COMmunications
SEAL	SEa, Air, Land
SIGINT	SIGnals INTelligence
SMF	Sustainable Military Forces
SOA	Service-Oriented Architecture
SOCOM	Special Operations Command
SOF	Special Operations Forces
SR	Surveillance, Reconnaissance
STOM	Ship-To-Objective Maneuver
T&D	Transport & Dispersion
TBP	Threat Based Planning
TEN	Tactical Edge Network
TPED	Task, Process, Exploit, Disseminate
TPPU	Task, Post, Process, Use
TTPs	Tactics, Techniques, and Procedures
UAV	Unmanned Aerial Vehicles
UGS	Unattended Ground Sensors
UHF	Ultra-High Frequency
UXO	Unexploded Ordnance
VMOC	Virtual Mission Operation Center
WDL	Weapons Data Link
WMD	Weapons of Mass Destruction