Integrated Topside – Integration of Narrowband and Wideband Array Antennas for Shipboard Communications

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Abstract — The Integrated Topside (INTOP) Program is an Innovative Naval Prototype effort initiated by the Office of Naval Research (ONR) to develop wideband multifunction RF system technology that will enable increased functionality through the employment of shared hardware and software resources to execute the mission objectives. An Electronic Warfare/Information Operations/Communications (EW/IO/Comm) Advanced Development Model (ADM) is one of the prototypes being developed under the INTOP program. ONR is also developing low cost narrow band phased arrays as part of the High Throughput Networking Infrastructure (HTNI) program to support communications in the Common Data Link (CDL) frequency range. This paper explores the challenges and benefits that could be achieved through an integration of both technologies.

The INTOP EW/IO/Comm program effort functionality encompasses the existing CDL spectrum with broader frequency coverage. Both the narrowband CDL array and the wideband INTOP array provide multi-beam array technology. However, the INTOP array provides greater flexibility in beam forming, interference nulling, and frequency coverage. Depending on the specific requirement for the communications link support, the CDL array set (four per ship) may provide as many as eight receive beams when used individually, or four beams when used in an elevation diversity configuration to mitigate multipath and other atmospheric effects. The INTOP receive array set (4 per ship) has the potential to support as many as 16 communication links or as few as four, when supporting the most distant communication links. As a combined asset, the receive antenna capacity addresses the Navy projections for the number of links to support Intelligence, Surveillance, and Reconnaissance (ISR) platforms. The transmit array is sized to similarly support the required number of links. In addition to the combined link support, the integration of the two arrays provides redundancy, multipath mitigation, frequency diversity, the potential to employ spatial separation to achieve the desired number of links within the existing frequency constraints, and the ability to allocate receive assets to enhance the frequency management of the ship to prevent interference and contention.

Keywords—Multifunction, Common Data Link, resource allocation, phased array, AESA

1. INTRODUCTION

The Office of Naval Research established the INTOP Program to develop and demonstrate common RF apertures and supporting subsystems that are capable of performing diverse functions that support multiple warfare areas. INTOP is the evolution and technology maturation of two earlier efforts: Advanced Multi-Function Radio Frequency Concept (AMRFC) [1] [2] and Multi-Function Electronic Warfare (MFEW) [3]. The program is aligned to the Navy’s Product Line Architecture (PLA) for shipboard combat systems, a fusion with open architecture concepts that can systematically reduce cost, increase performance and minimize risk [4]. The objective is to increase the warfighting capability while reducing the number of single function RF systems required on Navy ships. Specifically, the INTOP EW/IO/Comm task has the purpose of designing, fabricating, and demonstrating an ADM system that supports Electronic Attack (EA), Information Operations (IO), and Line-Of-Sight Communications (LOS Comm) with a common set of RF apertures and associated subsystems. While the ADM, through the application of advanced multi-function component technology and open systems design, is applicable to a variety of ship classes, elements of the technology could apply to both aircraft and land vehicles to support the coordinated action of multiple system functions.

In addition, the ONR is pursuing developments to enhance the affordability of narrowband phased arrays for communications. The goal of this effort is to achieve a per element cost of less than $100 (including active electronics, cooling, mechanical, etc.) to remove cost as a barrier for widespread naval implementations. Developments in Monolithic Microwave Integrated Circuits (MMIC) have enabled this cost reduction. In conjunction, low cost radio architectures first developed under the ONR Modular Integrated Link Electronics System (MILES) program have been applied to reduce system cost, while providing comparable capabilities. This effort is nearing fruition with anticipated test results in late 2011 that will lead to advanced development and potential aircraft carrier deployment. Specifically, these arrays support the CDL systems operating at Ku band. Studies within the Navy have indicated that a least four CDL links are required, to various air platforms in the near term. Future projections expand this to as many as 24 links, based on the operational scenario.
The INTOP EW/IO/Comm ADM is currently in a design phase with options to build the ADM expected to be exercised in October 2011. Development and testing of the ADM will extend into late 2013. It is anticipated that the success of the ADM will lead to further development and deployment as part of a carrier installation plan in the latter part of this decade. It is also anticipated that a successful development will lead to the deployment on a variety of larger ships, cruisers and destroyers.

However, it is anticipated that given current development schedules, the narrowband communications arrays may be installed several years prior to the availability of the INTOP system. This paper discusses the coexistence and integration of the capabilities of both arrays into a cohesive set of resources to meet current and future communications requirements. The advantages of this integrated vision are presented in the remainder of this paper.

**2. DESIGNED CAPABILITIES BACKGROUND**

**2.1 INTOP Wideband System Design Capabilities**

A brief background of the capabilities being designed into the INTOP ADM is necessary to understand the scope of the effort. The foremost aspect of the INTOP EW/IO/Comm ADM is EA. The EA function places strong requirements on the capabilities of the transmission systems to provide sufficient power to effectively provide self defense capabilities for platforms with large radar cross sections. The capabilities required for the system must also include an interface with the shipboard Electronic Support Measures (ESM) system, the ability to process and track signals identified in ESM reports, determine appropriate responses and activate transmissions intending to deceive or disrupt a hostile emitter source (usually a radar system) with a minimum latency of response.

The IO function will be provided through interfaces to equipment that may have capabilities similar to the existing Ship's Signal Exploitation Equipment (SSEE) that provides a signal intelligence (SIGINT) capability. The SSEE is a signals exploitation system that provides ship commanders threat identification information. It allows the operators to monitor and analyze signals of interest within the Ship’s Signals Exploitation Space (SSES) aboard a variety of ship classes. The SSEE system’s capabilities to detect, identify, and locate targets near to and over the horizon contribute to a ship’s command and control (C2) capability and information warfare (IW) operations. [5]

Communications is the last major function of the INTOP system. The system design is to support CDL communications in both X and Ku bands as well as emerging network communications waveforms in Ku band. The communications requirements drive the need for the receive array Gain-to-System Noise Temperature Ratio (G/T) specifications, due to the need to receive relatively weak signals at long range. The required number of links that must be maintained forces a design that can support two high data rate X band CDL links, at least four Ku band CDL links and a Ku band networking waveform within each quadrant of array coverage. The primary focus of the ADM coverage is to address current bands of operation, while supporting concepts of dynamic spectrum access that will enable operation of communications at unconventional frequencies to optimize spectral performance. Additionally, the design supports spatial isolation using beam forming techniques to achieve concurrent spectral reuse.

While the design is currently in development, notional arrays can be envisioned as those illustrated in Figures 1 and 2, for the transmit and receive arrays, respectively. The transmit array is distinguished by sub-array segmentation that is intended to support the required number of beams with sufficient Equivalent Isotropic Radiated Power (EIRP). The receive array also supports sub-array segmentation, but is distinguished by the implementation of virtual arrays via independent channels implemented at each element. In Figure 2, four channels of beamforming electronics are represented as virtual arrays, while sub-array segmentation to the quarter array, or “quadrant” level is also displayed.

**2.2 HTNI Narrowband System Design Capabilities**

The ONR narrowband arrays are designed to support Ku band CDL communications with growth towards supporting a future networking waveform operating at approximately the same frequencies as Ku band CDL. The focus of the HTNI program has been to minimize the cost per element of the array as well as the whole system.

The receive array configuration, shown in Figure 3a, comprises two individual arrays that each support four...
channels per array. To increase performance without increasing the number of elements, the concept of antenna elevation diversity support is implemented as a means of reducing the overall antenna G/T requirements associated with the system. In this technique, one beam is used from each vertically separated array. The resulting signal is coherently combined before demodulation to maximize the signal to noise present at the demodulator input. The technique has been shown to mitigate multipath losses, since the arrays' vertical separation is intended to insure that when one array is experiencing a multipath null the other will experience a strong signal. It is also possible to treat each of the four beams from each sub-array individually, resulting in eight receive beams. In addition to vertical combing, the receive array architecture takes advantage of orthogonal combining of receive arrays. This technique maintains a receive antenna G/T as orthogonal arrays scan off boresight and allow for a smooth handoff between adjacent array faces.

Figure 4 - Ku Band CDL radio architecture.

Figure 3b illustrates the transmit array. In this case, single beam transmit arrays are co-located in one package to provide four simultaneous transmit beams. This architecture was selected since it minimizes cost by allowing for maximum efficiency in the transmit chain and reducing complexity.

The narrowband CDL array system also employs a unique radio architecture. Figure 4 illustrates the general architecture overview. There are a total of 32 receive beams (each with its own receiver) and 16 transmit beams (each with its own transmitter (not shown)) thus, making the radio component of the system a potential cost driver. The radio architecture builds upon the MILES program concept, where the radio system had been separated into components with clearly defined interfaces. This approach allows for RF signals to be digitized at the array and enables digital vertical combining before demodulation. Furthermore, an initial soft decision demodulation occurs at the arrays to reduce the amount of digital data being sent to the equipment located below decks. By separating the components, the cost of the electronics required is distributed. The portion of the processing being performed behind the arrays was reduced to vertical combining and soft decision demodulation. The remainder of the intensive signal processing (orthogonal combining, forward error correction, cryptography, and mux/demux) occurs below decks after the links have been combined.

3. INTEGRATED CONCEPT

Proposed installation diagrams for an aircraft carrier implementation allocate space, approximately half way up the island, for the narrowband arrays. The INTOP arrays are conceived as being installed just below the flight deck in the space allocated to the current AN/SLQ-32 EW system. INTOP provides for the shared allocation of resources coordinated through the Resource Allocation Manager (RAM) [3]. Incorporating the narrow Ku band arrays involves integration of not only the hardware, but also the appropriate control structure. If these arrays are fielded on aircraft carriers prior to an INTOP installation, they may be integrated into the ship architecture as a standalone communications system, in a manner similar to current installations of reflector antennas. When integrated with the INTOP architecture, the available hardware and interfaces will become part of the INTOP construct of resource allocation. To accomplish this, the INTOP system will "wrap" existing interfaces with hardware and/or software adapters.

As shown in Figure 5, the INTOP Resource Allocation architecture is not a single monolithic Resource Allocation Manager (RAM) component. Instead, resource allocation is a hierarchical distributed process between the combat system, Virtual Resource Controllers (VRCs), the Low-Level RAM (LLRAM), and Low-Level Resource Controllers (LLRC). A VRC is responsible for receiving tasking commands from the combat system and obtaining the appropriate resources from the INTOP LLRAM to execute the tasking. A VRC is also responsible for evaluating available resources and advertising the available
capabilities of its virtual system to the combat system. The LLRAM is responsible for the dynamic allocation of resources between RF functions. The LLRAM performs allocation based on requests from VRCs and based on an overall system priority doctrine. A LLRC will control one or more resources that are available for allocation. A LLRC provides adaptation of its resources to the INTOP control and resource allocation infrastructure. A LLRC will advertise the capabilities of its resources. It will perform setup of its resources for new allocations and activate them at the appropriate time [6].

As such, combining the hardware resources of existing and new installations into the INTOP architecture will require definition of the software interface for a LLRC and appropriate instantiations in the VRC and LLRAM. The hardware integration will involve additional switching infrastructure including the logic governing how transitions are achieved between the assets. However, since coordination is needed to achieve array hand-off within both the INTOP and HTNI systems individually, this existing framework could be leveraged for the integration of the two systems.

4. ADVANTAGES AND USE CASES

The following section describes various cases where advantages can be achieved from the combined interoperability of the two sets of arrays (narrowband and wideband). The rational for each case addresses a variety of potential benefits that may be achieved in areas such as total system cost, added capability or extension of an existing capability.

4.1 Extended Range and Multipath Mitigation

The requirements for the INTOP receive array are driven by communications with long-range air terminals in a strong multipath environment. By incorporating the narrow Ku band arrays as receive antennas, the need for a full replication of this capability becomes unnecessary. In particular, the narrow Ku band arrays incorporate elevation diversity techniques that have shown promise in mitigating the effects of a multipath environment. Therefore, engineering trade studies can be performed to optimize the resources for the intended mission requirements. Specifically, the long range communications requirements could be met exclusively with the lower cost narrow Ku band arrays, while near to mid-range requirements may appropriately be serviced with a reduced-size INTOP receive array. This would achieve the complete mission goal, while reducing the cost and size of the INTOP receive array. A notional division of missions may be similar to those illustrated in Figure 6. In this figure the outer coverage circle represents the mission area of the narrow Ku band arrays, while the inner circle expresses the main mission area of the INTOP arrays.

For both mission coverage areas, it is assumed that the INTOP transmitter array would provide sufficient power and array segmentation capability to support the combination of communications links established with both sets of receive arrays; however, the HTNI transmit array configuration shown in Figure 3b, could provide augmentation.

4.2 Support for Fly-over

During missions where an aircraft is sent from a base to a forward location, the aircraft may fly over the ship. This means that the communications system would have to establish a relatively short-range communications link at or near zenith. While it would be feasible to point the high gain narrowband asset to (or near) the zenith to establish the link, in the integrated concept, the INTOP receive array can establish the link and maintain it out to a defined cross-over range with transition to the narrowband array for the extended range. The same transmitter array can be used to support the entire range. Conversely, an aircraft coming...
Currently, there are frequencies allocated for CDL use. The number of reflector antennas installed on the ship limits the number of CDL links currently supported. In addition, there exists a realistic limit, considering deck/superstructure space, to the number of reflector antennas that can be installed. Employment of phased arrays greatly expands the number of communications links that can be supported within the available installation footprint. The design for the narrowband array has the potential to support four to eight communications full range links in each quadrant of spatial coverage. Similarly, the INTOP receive arrays are being designed to support a minimum of four communications links in each quadrant. The one distinction is that the receive array has the potential to support as many as 16 links through partitioning to the quarter sub-array and four virtual receive arrays. Considering the combined receive array capacity, the constraints include installation of an appropriate quantity of modems to support the number of links, the capacity of the transmitter array and the amount of bandwidth available in the CDL-assigned frequency band.

The INTOP arrays will have the capability to adaptively form beams and create nulls. These features provide the potential for spectrum reuse through spatial separation. To support the number of aircraft links desired in the future, the spatial separation capability might provide a viable method for spectrum efficiency.

4.3 Increased Support for Communications Links

The number of reflector antennas installed on the ship limits the number of CDL links currently supported. In addition, there exists a realistic limit, considering deck/superstructure space, to the number of reflector antennas that can be installed. Employment of phased arrays greatly expands the number of communications links that can be supported within the available installation footprint. The design for the narrowband array has the potential to support four to eight communications full range links in each quadrant of spatial coverage. Similarly, the INTOP receive arrays are being designed to support a minimum of four communications links in each quadrant. The one distinction is that the receive array has the potential to support as many as 16 links through partitioning to the quarter sub-array and four virtual receive arrays. Considering the combined receive array capacity, the constraints include installation of an appropriate quantity of modems to support the number of links, the capacity of the transmitter array and the amount of bandwidth available in the CDL-assigned frequency band.

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4.4 Legacy X Band CDL Support

Currently, there are frequencies allocated for CDL use within X and Ku bands. Depending upon the aircraft equipment installation, the air data terminal may only support X band CDL links. While the Navy has only a limited number of platforms that employ X band CDL links, partly to interoperate with other military or coalition assets, support may continue to be required. The narrowband CDL arrays support only Ku band CDL links. The wide operational bandwidth of the INTOP arrays supports CDL links in both X and Ku bands.

4.5 Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) is an active area of research, and by necessity may be a key enabler for the US Government’s broadband plan that seeks to enable greater exploitation by commercial enterprises of existing Government spectrum allocations. Access to spectrum not currently in use places greater demands on radio technology and the algorithms used to ensure link discovery. The Defense Advanced Research Projects Agency (DARPA) neXt Generation program (XG) and Wireless Network After Next (WNAN) programs have both demonstrated the potential for DSA. Fielding of this technology has occurred on a limited basis. If this technology becomes mainstream and is implemented on aircraft for CDL or network waveforms in the X and Ku bands, the INTOP array can support these new operations with DSA-enabled radios. Upgrades to the filtering and radio equipment might be necessary, but the array apertures would remain unchanged.

4.6 Azimuth Hand-off Capability

Both the HNTI and INTOP arrays provide one quadrant of azimuth coverage, with built in overlap capabilities. Conceptually, four arrays would be needed to provide the full coverage. Since an aircraft involved in a mission may have a path that requires more than a 90˚ operational area, the potential for contention exists if array assets of a particular quadrant are fully utilized. Without an integrated implementation, a determination would have to be made based on the priority of each link in order to support the aircraft traversing in azimuth. However, the integrated concept provides a far greater number of links before a contention case would be reached. Utilizing the integrated concept, the traversing platform could be handed-off to whichever array resource was available and support the necessary requirements of the link.

4.7 Redundancy During Maintenance

Each array may have periods when an outage is required to support maintenance. Utilizing the integrated assets of the narrowband and the INTOP arrays, the basic capability of supporting Ku band CDL links can still be supported (with only some degradation in the number of links). Procedures would be developed to ensure that maintenance on the INTOP array would not occur during conditions when the EW and IO functions were critical, as the narrowband array could not support the full range of capabilities required for those functions. Similarly, if the mission for the most distant CDL link requires the narrowband arrays, maintenance could be delayed in instances where the INTOP arrays could not provide the same level of support.

4.8 Battle Damage Redundancy

Although controlled maintenance actions could be planned based on the ongoing missions, array damage occurring during battle will diminish the overall capabilities of the integrated system. However, the integrated system would still have the capability to support a significant number of
CDL links. The degree of lost functionality would be based on the damage to the particular array.

4.9 Scalability

Scalability can be considered in two ways. The first is simply scaling the integrated arrays to be larger or smaller based on the platform. In this case, larger platforms may have larger arrays and support a corresponding increase in capabilities. The INTOP arrays are designed to have modular building blocks for the creation of the full array. If larger arrays are required, more modules can be added to the INTOP array with minimal changes to the underlying control structure of the arrays.

The second type of scaling is based on the functional requirements associated with the ship platform. For example, an installation on an aircraft carrier would consider the number of CDL links required and the EW and IO defense requirements for the carrier. For a smaller ship class, such as a destroyer, the CDL link requirements may be far less, so the strategy may be to use the narrowband array exclusively for the CDL links and the INTOP array exclusively for the EW and IO functions. This form of scaling would enable each array to be optimized to satisfy its functional requirements and the functional relationship of the integrated arrays would be different than a simple scaling in size.

4.10 Bi-directional Ship-to-Ship Communications

CDL links are normally configured such that different parts of the band are used to transmit and receive. The air data terminal is usually configured to transmit to the ship in the operating band below 15 GHz and receive in the band above 15 GHz. The converse holds for the ships. The nature of both the narrowband and INTOP arrays allows for either band to be used for transmit or receive. For communications with air platforms, the standard ship-to-aircraft configuration would apply. However, ship-to-ship communications (using CDL) would require one ship to operate like the aircraft. In communications with multiple ships, coordination could be performed to configure a ship to act as either end of the CDL link. This capability would enable high-speed data links with ships within line of sight and thus reducing the satellite communications load.

5. CONCLUSION

This paper describes the capabilities of a narrowband phased array being developed for CDL and network waveforms in the Ku band. It further describes the capabilities of the wideband INTOP array that is being developed to support CDL communications in Ku and X bands and capabilities that would support EW and IO functions. The focus of the paper has been on the communications capabilities that would be supported by the INTOP arrays and a concept that integrates the operation of the narrowband arrays with the INTOP arrays. Many new capabilities are envisioned for the combined system concept. This is particularly relevant, since the narrowband arrays are closer to being fielded than the INTOP arrays, which are currently in the design phase. As such, the narrowband arrays will most likely be installed on ships by the time the INTOP system is available. Integrating the capabilities of both arrays would enable a variety of new features, increase efficiency of communications resources, and provide expanded communications capacity.

New features that would not be possible with the narrowband arrays can be considered. First among these is greater spectrum access, such that Ku and X bands (traditionally used for CDL) can both be supported with the ability to support future DSA capabilities. Frequency reuse, implemented via beamforming techniques, represents another potential feature that may support more links within the same frequency constraints. Finally, greater equipment redundancy will be available with the integrated concept and providing much higher operational availability.

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