COMPUTATIONAL ASPECTS IN ANALYZING THE EFFICIENT UTILIZATION OF THE RF *TRANSMISSION HYPERSPACE*

Andrew L. Drozd[†], Chilukuri K. Mohan[*], Pramod K. Varshney[*] and Donald D. Weiner[*]

Abstract

New approaches for enhancing spectrum utilization and frequency management for large, complex systems have recently been investigated. These approaches enable the effective and efficient joint utilization of all orthogonal electromagnetic (EM) transmission resources, including, but not limited to time, frequency, geographic space, modulation/code, and polarization. This multi-dimensional environment is hereafter referred to as the *Transmission Hyperspace* (*TH*), a term intended to convey the notion of a multi-dimensional resource space (with n *degrees of freedom* expressed as an *n-tuple*) in which each dimension allows orthogonality amongst users. The challenges to the modeling and solution of large-scale *TH*-based problems are presented in the context of assigning the n-tuple dimensions in near real time. Also described are the key aspects of the multi-dimensional *Transmission Hyperspace* and approaches for efficient spectrum management, the results of which are expected to garner several orders of magnitude improvement in RF resource utilization and therefore, aggregate information throughput.

INTRODUCTION

EM propagation at RF frequencies is currently governed by a one-dimensional "real estate" approach to the allocation of frequency bands, where the licensee has specific legal right to transmit within a band. The entire spectrum from 3 kHz to 30 GHz is currently allocated in this fashion. Unfortunately, this "set-it-and-forget-it" management scheme is straining under the immense pressure of exponentially increasing demand by burgeoning numbers of various types of wireless devices, spanning commercial and military applications all the way from short range home networks and cordless phones to the global communications grid. Given the finite nature of the RF frequency spectrum, it is desired that alternative approaches to the management of the resource be explored.

One approach involves exploiting optimization and orthogonality schemes that allow for multiple users to operate without interference. These schemes leverage several techniques in unison such as time slicing, frequency division multiplexing, use of smart directional antennas, application of new spread spectrum codes, and polarization diversity. Conceivable approaches to a system for joint optimization of the multiple orthogonalizing transmission parameters show that no two (or more) users are transmitting at the same time, even though they may be using the same frequency in the same space with the same spread spectrum code. Similar illustrations include the case of a spatially orthogonalized system in terms of transmit beam patterns that do not overlap and cross-polarized waves in ideal cases.

The *Transmission Hyperspace* (*TH*) concept takes advantage of optimization and orthogonality schemes to permit multiple users to operate without interference. The concept applies operations research theory and multiobjective joint optimization algorithms assisted by knowledge base technologies, novel frequency- and time-domain interference rejection models, and waveform diversity techniques to analyze dimensional "synergy" and "prioritize" the *TH* cell dimensions. This includes the limited application of joint time-frequency transforms.

One of the challenges being faced in the design and implementation of this concept is that of ensuring computational efficiency. The *TH* paradigm includes an electromagnetic interference monitor/analyzer that effectively determines the RF links and signal strengths in the presence of ambient interference, and then computes the various environmental interactions to assist in assigning and managing the RF resource space.

[†] ANDRO Computational Solutions, LLC, Beeches Technical Campus, Rome, NY USA, *adrozd@androcs.com*.

[*] Syracuse University, EECS Dept. Syracuse, NY USA, *mohan@ecs.syr.edu, varshney@ecs.syr.edu*, *ddweiner@ecs.syr.edu*.

THE TRANSMISSION HYPERSPACE

The *TH* concept can be imagined as an electromagnetically occupied volume bounded in all dimensions (time, space, frequency, code/modulation, polarization, etc.), or a "cube" (in more than three dimensions), as shown in Figure 1. Here, the cube is constantly changing with "cells" of signals that have applied for, received, used, and returned their transmission coordinates. When one wants to transmit, one asks for the coordinates, then transmits and goes off the air. Someone else then fills in or occupies that cell and the new or current user gets another cell the next time through the cycle. Using this approach, it can be shown that unused spectrum changes in *time* and *space.*

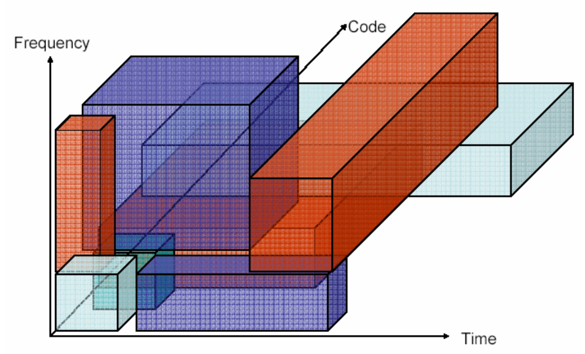

Figure 1: Geometric Representation of the *TH* Concept (Constrained to 3-D).

Currently, there are no known technological approaches to RF transmission in spectrum management that consider all of these dimensions jointly, and certainly none that consider them in the context of a system optimization problem.

Furthermore, these approaches have taken into account existing spectrum policies and ideas being pursued in government, academia, and industry, the subset of which includes the obvious solutions such as: a single centralized global broker of *TH* cells, multiple distributed and coordinated local brokers of *TH* cells for local users, ad-hoc "mesh" networking, fixed assignment, and hybrid approaches.

Multiobjective Optimization Approaches

There are a number of possible approaches to achieving multiobjective joint optimization. Statistical optimization is one approach. Linear and nonlinear optimization, meta-heuristics, constraint satisfaction, and multidisciplinary optimization are yet others. Potential solutions to the multiobjective joint optimization problem are founded in the industrial engineering, operations research, and geoscience disciplines.

An important distinction between *multiobjective* and *joint* optimization should be made before proceeding here. First, multiobjective joint optimization refers to a procedure for determining the "best fit" of decision variables that satisfy a given cost or objective function in an optimal way. In general, the basis of this approach is the application of mathematical algorithms founded in operations research theory; in this case, to arrive at techniques for improving spectrum efficiency utilizing flexible and adaptive communications technologies—the overall objective. For example, one can optimally assign the multiple dimensions of an electromagnetic signal or waveform in a *joint* manner to ensure that multiple objectives are met, such as maximizing RF point-to-point connectivity and availability, improving signal-to-interference-plus-noise ratio (SINR) or the interference rejection capacity of systems, and optimizing the mobility of systems in the overall spectrum management scheme while reducing power consumption, latency, and operational cost. Other potential approaches include methods to extend the frequency agility of software defined radios to provide a wider set of capabilities for dynamic spectrum management as a function of the RF resource space assignments.

Hence, given a set of dimensions, what can be expected as the dimensions are iteratively varied to arrive at an optimal assignment? Furthermore, how does changing one dimension affect all other dimensions? The application of joint optimization schemes will help answer these questions. Also, given the placement of one or more transmitters in a "spectral environment," how can radio channel assignments and efficient solutions of network design problems be optimized? The knowledge to be gained here will lead to the identification of ways to optimize the RF communications process for real world situations.

Let us further consider the multiobjective problem. Research in the domain of data analysis and knowledge discovery in multivariate databases has demonstrated the applicability of information systems for geophysical databases to support collaborative research tasks—which exemplifies a type of multiobjective problem. Novel indexing and abstraction techniques have been studied for efficient search and monitoring of massive data sets. This includes the optimization of complex spatial-temporal queries and rules using knowledge-based data mining (i.e., intelligent searching for patterns in data, cataloguing and retrieval of information, data management, and query optimization). Implementations based on mass-storage systems and an intelligent front-end have been investigated using Supercomputer testbeds for parallel search and computationally-intensive functions.

Why be concerned with ensuring computational efficiency in this case? The answer lies in our desire to implement new technologies that can automatically *sense, analyze, interpret, and decide* (SAID) about the nature of the EM environment in real time both efficiently and accurately—a challenging goal indeed! This is key to effectively designing a real time environmental monitoring and analysis system that can collect a wealth of environmental data and performs subsequent decision making on the multi-dimensional data to arrive at a *best-fit* solution to a given RF communications or multi-spectral sensors problem.

The present problem is one of optimization that requires assigning user requests to regions in the RF resource space as the requests are applied for and processed. Clearly, latency or long delays in processing requests and/or responding must be minimized in this case; otherwise, the purpose of having a high-throughput, rapid-response communications system would be defeated. So the main question is: *how do we achieve computational efficiency "on the fly" for the present problem?*

It is noted that the "spectrum management" of many of today's RF communications systems and information networks mainly involves the management of a smaller subset of the resource space dimensions; namely, time, frequency, and code and to some extent, geo-position. Typically, this invokes such techniques as Frequency-Division Multiple Access (FDMA), Time-Division Multiple Access (TDMA), and Code-Division Multiple Access (CDMA) including the use of Global Positioning System (GPS) coordinates.

The *TH* approach extends the current methods for achieving the goals of spectrum management by applying multiobjective joint optimization to the broader set of multiple dimensions of the RF resource space. One can view the application of optimization schemes for the present problem in terms of sets of intersecting parallel lines that are nearly orthogonalized with respect to each other as Figure 2 roughly illustrates.

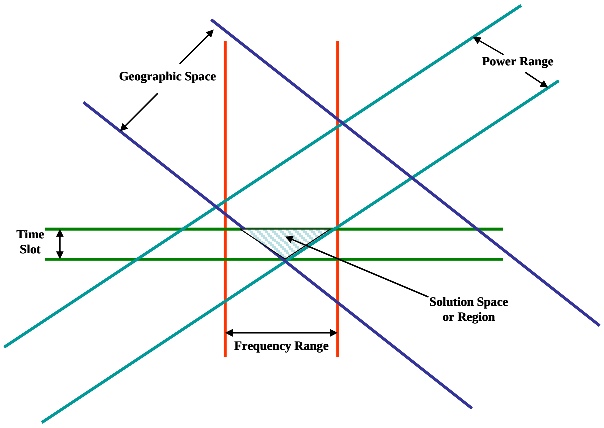

Figure 2: Generalization of the Approach for Arriving at an Optimized Solution for the Multi-Dimensional RF Resource Space.

The "assignment" of the parallel lines is somewhat arbitrary in this illustration. True or perfect mutual orthogonalization among the dimensions is not necessarily implied or enforced here for practical purposes. Each set of parallel lines represents a range for a given RF resource space dimension e.g., frequency range, time span, geographic space or region (say, for mobile transceivers), range of code/modulation diversity, and so on.

The shaded region formed by the intersection of the lines in Figure 2 represents the joint optimum solution to the multi-dimensional RF resource space problem. Of course, this is an oversimplification of the approach in that the actual process of achieving the desired result is much more involved and can be quite computationally rigorous depending on the approach (i.e., the mathematical algorithms and computational methods) utilized. Another concern is the potential computational expense involved in iterating over the problem space as well computing the EM figures of merit that will be used as part of the forward reasoning and downstream decision making process in arriving at interference-free operational states over all time slots, that is, to the extent practical. These additional aspects are further addressed later.

In any case, the optimization task bears a close resemblance to the NP-complete bin-packing problem [1], and can hence be explored with algorithmic approaches that have been used successfully for similar assignment problems. These include: iterative improvement techniques, simulated annealing [2], Tabu Search [3], and evolutionary algorithms [4-8].

These algorithms and approaches have largely been applied to the task of optimizing a single function, although multiobjective evolutionary algorithms have also been explored in recent years. In addition, other approaches have been suggested for multiobjective optimization, attempting to explore Pareto-optimal solutions. These include the use of weighted sum techniques, multilevel programming, homotopy techniques, goal programming, and normal-boundary intersection (NBI) [9, 10].

Unfortunately, algorithms such as NBI have very high computational requirements, making their use in real time response-critical situations impractical. Also, most existing multiobjective optimization algorithms follow a "de novo" approach whenever problem data change even a little. Nonetheless, efficient multiobjective optimization algorithms that rely on an incremental approach, reusing or modifying previously discovered solutions when small changes occur in the problem data offer a potentially useful solution. Research needs to be performed to make such algorithms more computationally efficient.

However, our purpose here is not to delve into the subtle details of these various algorithmic approaches, nor to cover the advantages and limitations of each approach. Suffice it to say that the optimization schemes mentioned above, as well as other approaches, are being studied to arrive at robust and computationally efficient ways of determining optimal solutions for various classes of *physical layer* to *network layer* RF communications and multisensor problems.

Instead, we shift our focus here on the use of efficient computer modeling and simulation techniques to analyze the "spectrum management" problem for a large number of *TH*-enable radiators, assuming some degree of optimization has already been achieved. This approach allows us to incrementally determine the efficacy (and efficiency) of the RF resource space approach involving many devices and starting with a reasonable subset of dimensions. The original goal was to develop a proven, computationally-efficient approach for determining how the RF links can be optimally formed in the presence of electromagnetic interference, to provide a basis for implementing a real time environmental monitor/analyzer component in the *TH* design.

Described below are several of the methods that currently exploit two or more dimensions of the RF resource space. The exploitation of the multi-dimensional characteristics of the RF resource space will be discussed in terms of a computer modeling and simulation approach applied to a representative communications grid problem involving multiple RF radio and antenna systems. The goal, of course, is to use several dimensions simultaneously and to maximize overall data throughput. This discussion is prefaced by a brief review of relevant topics pertaining to electromagnetic interference/compatibility (EMI/C) and spread spectrum systems.

Mutual Orthogonality and EMC

The successful implementation of the multiobjective joint optimization implies EMC between its many users. A user is said to be electromagnetically compatible provided it satisfies three criteria: (1) it does not cause interference with other users, (2) it is not susceptible to emissions from other users, and (3) it does not cause interference with itself. Central to the goal of EMC is the concept of orthogonality between the users as determined by how cells are assigned in the multi-dimensional RF resource space.

However, perfect orthogonality between users is unlikely to be achieved in typical real world applications. For example, in the spatial dimension it is possible to design the main beams of transmit and receive antennas such that they do not overlap in specified directions. However, all antenna patterns include sidelobes which do overlap. Analogous statements apply to frequency domain spectra. These overlaps can lead to severe interference when a high power emitter, such as a radar, is co-located near a highly sensitive digital receiver, such as a wireless device. In the polarization domain, orthogonality between users can be compromised by multiple reflections. As another example, the nonlinearities present in all electronic systems can generate unintended consequences for users of the RF resource space. Thus, a frequency hopping spread spectrum system produces a complicated pattern of harmonics, intermodulation products, and spurious responses that may cause problems for users in both nearby and distant frequency-domain cells of the RF resource space. In addition, the various domains of the resource space are all interrelated, as predicted by Maxwell's equations and Fourier analysis. Therefore, orthogonality in one domain can lead to undesired results in another. For example, shorter duration times for pulses in a time-division multiple access scheme causes wider frequency spectra that could be troublesome to some of the users.

In the present context, perfect orthogonality between users is referred to as strict orthogonality. Orthogonality that is intended, but not strictly achieved, is referred to as loose orthogonality. EMC applies automatically to those users for which strict orthogonality exists. On the other hand, EMC may or may not apply to those users for which there is loose orthogonality. Loose orthogonality is not necessarily to be avoided. In the following paragraphs a scheme is devised, which is briefly described where loose orthogonality is employed in order to increase the number of users in a CDMA direct sequence spread spectrum (DSSS) system.

CDMA DSSS Example

Consider a CDMA DSSS system for which all users have the same chip rate, R_c, data rate, R_b, and carrier frequency, f_o, but are assigned different spreading codes which are nearly orthogonal. The chip rate is chosen such that the power spectral density (psd) of each user fills the common frequency band centered at f_o having bandwidth, B_o. This scheme is illustrated in Figure 3a where all users have identical power spectral densities and a maximum processing gain given by $L_o = B_o/B_b$ where B_b is the data signal bandwidth. Because the codes are nearly orthogonal, a residual component due to each undesired signal exists at the correlator output of each receiver and limits the total number of users in the band to K_o such that a pre-specified probability of error, P_e, is achieved. Because each DSSS signal has the maximum possible processing gain, it might be conjectured that the number of DCMA DSSS users for the given frequency band and probability of error cannot exceed K_o.

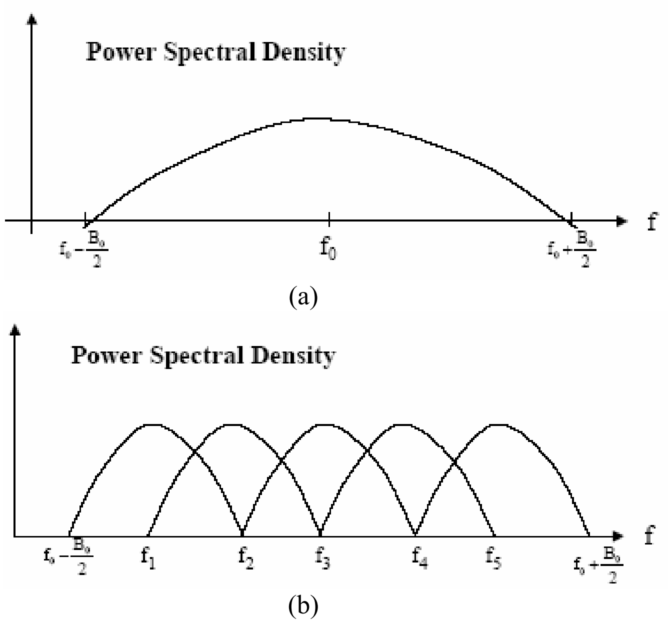

Figure 3: PSD of (a) Each CDMA DSSS System and (b) Subdivision of Original Frequency Band.

However, consider the scheme illustrated in Figure 3b where the original frequency band has been subdivided into 5 sub-bands. The center frequency bandwidth B_o has been subdivided into 5 sub-bands, where each sub-band is given by

$$f_1 = f_o - B_o/3, \qquad f_3 = f_o \qquad f_5 = f_o + B_o/3$$
$$f_2 = f_0 - B_o/6, \qquad f_4 = f_o + B_o/6 \qquad (1)$$

Let K_k, k = 1, 2,…, 5, denote the number of CDMA DSSS users in each sub-band where K_k is maximized such that the probability of error for each user does not exceed that of the scheme in Figure 3a. It has been shown both by analysis and computer simulation that the total number of users for the scheme of Figure 3b, given by

$$K = K_1 + K_2 + K_3 + K_4 + K_5 \qquad (2)$$

is approximately 20 percent larger than K_o. This result is partly explained by the loose orthogonality that exist between the overlapping sub-bands of Figure 3b (Note that the peak of one sub-band is placed at the null of the neighboring sub-band).

Also, the loose orthogonality of the spreading codes allows for more different codes of a fixed length to be generated that would be possible if strict orthogonality was enforced.

Nonetheless, loose orthogonality may result in EMI which reduces the quality of service (QoS) required by one or more users of the RF resource space. Consequently, the approaches for joint optimization of the multiple orthogonalizing transmission parameters should be constrained by EMC considerations. Assignments that are likely to cause unacceptable losses in QoS can then be removed from consideration.

For this purpose, users of the RF resource space having potential for undesired signal coupling can be identified. These can be divided into sets of emitter and receptor ports having specified coupling paths. It is assumed that one or more emitters can couple to a given receptor while a given emitter can couple to one or more receptors. Using the resource space dimensions, multidimensional profiles are established for each emitter and receptor port. These are used, along with characterizations of the coupling paths, to determine whether or not the power from unintentional users at each receptor port exceeds the susceptibility threshold for that port. Because of the complexity of the above approach, simple *rules of thumb* can be used to demonstrate the EMC constrained joint optimization procedure. These can then be refined so as to yield more accurate predictions.

These EMC considerations can be embedded in the system so that users who are assigned particular coordinates are not prevented from operating at acceptable levels of performance.

Exploiting Diversity and Applying Joint Transforms

The current *TH* concept incorporates the above considerations including the design of novel diverse waveforms to address the dilemma of increasing demand for improved performance of future communication and radar systems that will be co-located. Recent advances in hardware technology make it possible to design waveforms in real time that maximize signal-to-interference ratios, improve resolution, and increase information transfer.

For instance, temporal and spatial waveform diversity can support: reliable communications in realistic multipath environments, radar with multiple mission (tracking and imaging capability), interferometric radar and communications for better resolution and throughput, multistatic radar for improved discrimination, as well as integrated radar and communications in severe interference environments.

Also, joint time-frequency analysis (JTFA) has potential for the investigation of EMI/C problems in support of the *TH* approach. JTFA can be used to gain more insight and information than can be obtained from only a time-domain waveform or its frequency-domain counterpart. Time-frequency distributions are highly useful schemes for interference excision in spread spectrum communications systems, so their importance cannot be overlooked. Although JTFA is generally an effective approach, its applicability is limited in this case. In particular, the dimensionality would need to be extended to address solutions for joint optimization of an n-tuple space problem. This technique has not been fully exploited in the present concept design and is left for future research.

COMPUTER MODELING AND EMI ANALYSIS APPROACH

A computer model was generated for the case of 100 spatially fixed nodes (radio transceiver antennas) distributed uniformly over earth ground. This model was analyzed to assess the efficacy of selected optimization measures to enhance RF communications throughput and the potential for frequency reuse. Two ground propagation models were considered: (i) one based on a classical high-frequency ray tracing and diffraction formulation, which incorporates a lossy smooth earth model that accounts for signal fading as a function of frequency, distance, and surface propagation media effects [11, 12]; and (ii) an analytical model based on the Hata empirical formulation [13], which includes an average loss term to account for urban/terrain attenuation effects.

First, a baseline legacy system model was constructed consisting of a group of RF antenna systems each with identical transmitter and receiver operating characteristics and omni directional antenna patterns. All the antennas were tuned to 2.4 GHz in the model. Electromagnetic coupling was computed for all possible pairs of interactions over each time slice. A successful transmission was assumed when a message packet was sent and received between an intended pair of nodes. This was accomplished on the basis of a single node-pair intentionally communicating with each other during a given time slice in the legacy system case. In the legacy system, only one pair of transmit-receive antennas could operate interference free (simultaneous transmissions were not considered viable as this could lead to significant interference in the legacy case). The total number of time slots over all possible time slots based on single-pair interactions for the legacy system was computed to be 9,900.

The next step was to introduce several additional RF resource space dimensions into the problem; namely, power range, beamwidth, smart antenna beam directionality and limited frequency agility. The results of analyzing changes in these other dimensions of the problem were then compared to the legacy system results in order to compute the effective improvement in data throughput and frequency reuse. In the augmented problem, the 3-dB beamwidths for each antenna were specified to be 12.5 degrees each with a Gaussian beam distribution in azimuth and elevation along their (coincident) boresight direction. The transmit and receive beams were aligned with respect to each other and then coupling interactions were recomputed for antenna pairs over each possible time slice. This is illustrated in Figure 4. In this case, multiple antennas were allowed to transmit and receive simultaneously. Intended pairs (RF links) were established in the presence of ambient interference due to unintentional signals from other antennas in the model. In addition, power control was employed to set the transmit power levels to threshold the intended receiver based on a predefined +10 dB SINR value. Information was then accumulated on the number of interference-free RF links and time slots in order to arrive at a throughput enhancement figure of merit.

By comparing the number of interference-free time slots involving simultaneous transmissions to the total number of time slots in the legacy case, approximately a 22X+ improvement in frequency reuse over the legacy system was predicted (or more than 450 simultaneous transmissions can take place). This was based primarily on employing beam diversity, power control, and other geo-spatial diversity techniques. When frequency diversity is considered in addition to other control schemes, further improvement by nearly 38X+ over the legacy system was predicted. If modulation diversity as well as other waveform diversity schemes were to be employed, the improvement could be extended to nearly an order of magnitude above the legacy system.

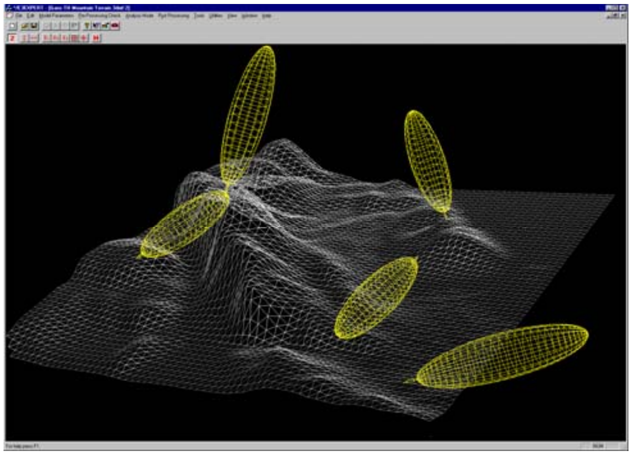

Figure 4: Earth Ground Computational Model Showing Spatial Beam Patterns.

Computational Optimization

Using only a subset of dimensions and assuming a relatively simple set of problem conditions, we observed that significant improvements in throughput and frequency reuse could be achieved by employing fairly straightforward diversity measures. These measures reflect the process of automatically optimizing certain parameters in the problem to improve communications performance, albeit, a number of simplified assumptions were made with regard to the availability of smart antenna technologies, stable broadband antenna performance, and so forth.

Perhaps an equally important result was that a viable approach had been demonstrated for efficiently computing EM coupling and associated figures of merit for decision making in near real time. For instance, on a PC with nearly 1 GB memory and a processor speed on the order of 2 GHz, it took well under a minute (and in most cases, just a few seconds) to analyze the 100-node configuration for interference and to verify what RF links were viable. The coupling models that were used to analyze the problem over the iteration sample space and matrix of possibilities were based on conservative, discrete, closed-form analytical formulations. Hence, it was not too surprising that the computation times were relatively short. Nonetheless, it is believed that a scenario-based and rule-driven number-crunching capability would be highly useful as part of a *TH*-enabled system approach for real time environmental monitoring and management.

It should also be mentioned that some numerical modeling was performed on limited segments of the model to resolve uncertainty areas in the predicted results and to gain additional insights into the physics underlying the interference problem. This involved the use of hybrid moment method (MoM) and uniform theory of diffraction (UTD) techniques to analyze certain localized, near-field effects. It goes without saying that relaying on a numerical solution as part of the *TH* system-level approach is impractical based on inherent limitations in today's computer technologies, but computational electromagnetics (CEM) can be used as an offline approach to studying methods for optimizing the problem.

One potential solution in overcoming the computational bottlenecks of CEM tools and techniques as part of a system-level *TH* approach in the future, will likely be to exploit novel parallel processing architectures and use of floating point gate array (FPGA) hardware. Indeed, upcoming multifunctional radio and sensor systems are already making more use of on-board memory and FPGA hardware to support distributed and accelerated space-time adaptive processing of data to meet real time performance goals.

ADDITIONAL CONSIDERATIONS

The above discussion on optimization for efficient utilization of the RF Transmission Hyperspace focused more on the methods to assign the dimensions of the RF resource space to meet a generalized set of performance objectives (e.g., maximizing frequency reuse). However, one can also exploit other aspects of the problem. For instance, methods to leverage the technology base in microelectronics with new waveforms and routing protocols—from the *medium access and control (MAC) layer* through the *network layer*—to construct an integrated system, can be leveraged to fully achieve the goals of multiobjective joint optimization and to assure point-to-point connectivity. The multiobjective optimization is aimed at assuring optimum information pathways or the best routing scheme using a centralized or a distributed *TH*-enabled resource management hub (broker), implemented in either a fixed or mobile network mode. The goal is to develop, integrate, and evaluate the technology to enable equipment to automatically select spectrum and operating modes to both minimize disruption of existing users and to ensure operation of information and sensor systems. This will require the development of new *appliqués* and an intelligent centralized or distributed architecture for legacy and future emitter systems for joint service utility. Both the enabling technologies and system concepts must be developed to provide assured military communications in support of worldwide, short notice deployments through the dynamic redistribution of allocated spectrum.

The initial implementation of the *TH* concept will likely be realized by enabling legacy and upcoming software defined radio systems in development, as well as emerging wideband technologies. In this scheme, the new *appliqué* and any necessary constraints (based on approved spectrum policies, protocols, case studies, and lessons learned) could be applied to a selected technology or device e.g., the Joint Tactical Radio System (JTRS) for managing the RF resource space and network routing schemes for fixed-frequency and frequency-agile systems, and for both static and mobile scenarios. The application of approved spectrum management policy constraints and protocols is critical to the automated decision-making process embedded within the *TH*-enabled technology.

CONCLUSION

This article described a new "spectrum management" paradigm that can be characterized as a *jointly optimized transmission space*. In this approach algorithmic techniques are used to mathematically perform joint optimization of frequency, time, space, code/modulation, polarization, and other signal dimensions to ensure orthogonality and allow for multiple users to operate without interference. This approach is embodied in the *Transmission Hyperspace* (*TH*) concept and is intended to be a unifying visionary solution to today's problem of achieving efficient spectrum management that leverages techniques for selectively maximizing desired RF communications links and by denying unwanted links in the presence of EM jamming environments. To accomplish this, a computationally-efficient method of analyzing the potentially large matrix of coupling interactions was developed and demonstrated that could provide a foundation for an embedded near real time environmental monitoring and interference analysis component. However, more research needs to be conducted to find ways of further optimizing the computational approach. This may involve investigations of how scalable CEM tools can be integrated within the system architecture. This is only one of the many challenges that are being addressed in the future.

The *TH* concept supports the notion of spectrum management for *systems of systems* of transmitters and receivers on virtually any scale. *TH*-enabled systems will lead to increased channel capacity, information throughput, and communications range as well as influence the generation of new policies and a more efficient methodology for spectrum management that could be applied at various levels of an overall communications network or multisensor grid.

Acknowledgements

The authors wish to acknowledge the support of Dr. Michael Gans of the Air Force Research Laboratory/IFGC, Rome Research Site and Dr. Alan Lindsey (formerly of AFRL/IFGC, RRS) for their support in various aspects of this research provided under Contract No. FA8750-04-C-0028.

References

[1] M. R. Garey and D. S. Johnson. Computers and Intractability: A Guide to the Theory of NP-Completeness. Freeman, New York, (1979).

[2] Kirkpatrick, S., C. D. Gelatt Jr., M. P. Vecchi, “Optimization by Simulated Annealing”, *Science*, 220, 4598, 671-680, 1983.

[3] Glover F., “Tabu Search: A Tutorial”, *Interfaces*, 20(4):74-94, (1990).

[4] D. E. Goldberg. Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley, Reading, Massachusetts, (1989).

[5] C. K. Mohan, A Framework for Evolutionary Operators, *International Journal of Smart Engineering System Design*, 1(3):1-38, (1998).

[6] D. B. Fogel (1995) “Evolutionary Computation: Toward a New Philosophy of Machine Intelligence,” IEEE Press, Piscataway, NJ.

[7] Rechenberg, I. (1973) “Evolutionsstrategie: Optimierung technischer Systeme nach Prinzipien der biologischen Evolution”, Stuttgart: Fromman-Holzboog.

[8] K. Veeramachaneni, T. Peram, C. Mohan and L. Osadciw, Optimization using Particle Swarms with Near Neighbor Interactions, in *Proc. Genetic and Evolutionary Computation Conference (GECCO)*, Chicago, July 2003.

[9] I. Das. Nonlinear Multicriteria Optimization and Robust Optimality. Ph.D. Thesis (1997), Dept. of Computational and Applied Mathematics, Rice University, Houston, TX 77251, USA.

[10] I. Das and J. E. Dennis. Normal-Boundary Intersection: An Alternate Approach for Generating Pareto-optimal Points in Multicriteria Optimization Problems. ICASE-NASA Tech. Report 96-62, July 1996.

[11] T. S. Rappaport, R. Muhamed, V. Kapoor & J. D. Gibson, Ed., "*The Mobile Communications Handbook*," CRC Press, FL, Chap. 22, pp. 357-365, 1996.

[12] T. S. Rappaport, “*Wireless Communications Principles & Practices*,” Prentice Hall, NJ, Chap. 3, pp. 119-120, 1996.

[13] “*Spectrum Planning Report: Investigation of Modified Hata Propagation Models*,” Spectrum Planning Team, Radio Frequency Planning Group and Australian Communications Authority, Document: SP 2/01, April 2001.