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Advances in Network Sciences via Collaborative Multi-Disciplinary Research

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Abstract - Network Science is the scientific exploration of the shared fundamental properties underlying different types of networks and their interactions. Two large research alliances, the International Technology Alliance in Network Sciences and the Network Science Collaborative Technology Alliance, have brought together researchers from many diverse disciplines to create fundamental advances in network science. In this paper, we discuss some of the advances made by the scientists in these two research alliances, and some of the lessons learnt as fundamental scientific advances are translated to real networks via military and commercial transitions. Since both of the alliances themselves are complex networks, some of the lessons learnt from management of these networks are also discussed briefly in this paper.

Keywords: Network Science, Research Alliances.

1 Introduction

Network science [1] is the branch of scientific exploration that strives to find the properties shared across different types of networks, whether arising in computer communications, Internet of Things, Intelligence Surveillance and Reconnaissance, social communities, information networks, genetic replication, business processes and other areas. These properties include the common principles and models underlying the structure, behavior, design, and control of networks, their interactions, and their coevolution. Today, no single type of network exists in isolation, but is deeply intertwined with others upon which it depends and which depend on it. The exploration of networks and their interactions across a wide variety of application domains requires researchers from many different disciplines to work together to identify these properties. This knowledge can eventually lead to the design of better architectures and software for operations, analysis, control, and management of individual networks as well as composite systems combining multiple types of network. While at first glance the networks from disparate disciplines may appear very different, our research has shown that i) they indeed share significant properties, and ii) exploiting understanding of systems where multiple networks interact advances beyond what can be achieved when each is considered alone.

Two large multi-disciplinary alliances are performing such cross-disciplinary research in network science. These are the US/UK International Technology Alliance in Network and Information Sciences (ITA) established in 2006, and the Network Science Collaborative Technology Alliance (NS CTA) established in 2009. The alliances have established scientific goals as well as pragmatic goals for their explorations in network science. The scientific goals include discovering the fundamental principles that apply across a wide variety of types of networks, exploiting insights gained from one type of network to another type to accelerate understanding of different types of networks, and understanding how intertwined networks impact one another's behavior, properties, and evolution. The pragmatic goals include creating new software, systems and tools for modeling, analyzing, designing, controlling, operating, and managing systems with different types of networks. The ITA focuses on coalition networks, i.e., a federation of networks from two or more countries/organizations (whether from similar or disparate disciplines), while the NS CTA explores systems where multiple types of networks interact.

In this paper, we summarize the scientific and pragmatic advances made by the two alliances, both working alone as well as in collaboration with each other. After briefly providing an overview and background of the two alliances in Section 2, we review the scientific and pragmatic accomplishments of the two programs in Section 3, which also includes results that have come out from collaboration between these two programs. Finally Section 4 discusses the lessons learnt from the management and operations of these programs, with the final conclusions in Section 5.

2 Overview of the Research Alliances

Both the NS CTA and ITA were sponsored by the US Army Research Laboratory (ARL), with the ITA being co-sponsored by the UK Ministry of Defence (MoD) Defence Science and Technology Laboratory (DSTL). In this section, we give a brief history of the two alliances.

2.1 ITA Background

The ITA program is an alliance between 27 research institutions in the US and the UK. The program involves ARL, DSTL, 8 universities in the United Kingdom, 8 universities in the United States, 4 industrial research laboratories in the UK, and 5 industrial laboratories in the US. The alliance is led by IBM. The UK universities participating in the ITA are Cranfield University, Imperial College London, Royal Holloway University of London, University of Aberdeen, University of Cambridge, Cardiff University, University of Southampton and University of York. The US universities participating in ITA are Carnegie Mellon University, City University of New York, Columbia University, Pennsylvania State University, Rensselaer Polytechnic Institute, University of California Los Angeles, University of Maryland, and University of Massachusetts at Amherst. The industrial partners in the UK are IBM, Logica CMG, Siemens Roke Manor Research, and Systems Engineering & Assessment. The US industrial partners are IBM, Raytheon BBN Technologies, Boeing, Honeywell, and Applied Research Associates.

During the first five years of its existence, the alliance focused on four technical areas: (i) network theory, (ii) security across systems of systems, (iii) sensor information fusion and processing, and (iv) and distributed coalition planning and decision making. As the program evolved in order to address the changing requirements of coalition operations, the scope in the last five years was redefined to address technical research in the two areas of (v) Coalition Interoperable Secure & Hybrid Networks and (vi) Distributed Coalition Information Processing for Decision Making. At a very coarse level, the two new areas could be viewed as a pair-wise merge of the scope of the previous activities with some changes in scope.

The alliance has been active since May 2006, and scheduled to operate till May 2016 exploring fundamental research topics in coalition operations as defined by these technical areas.

2.2 NS CTA Background

The NS CTA is a collaborative research alliance between ARL, other government agencies, and a consortium of 18 US universities and industry research organizations. Its purpose is to perform foundational multi-disciplinary research in network science, potentially resulting in greatly enhanced soldier performance and in greatly enhanced speed and precision for complex military operations. The consortium is led by Raytheon BBN Technologies and also includes ArtisTech, Carnegie Mellon University, City University of New York, IBM, Northeastern University, Northwestern University, University of Notre Dame, Pennsylvania State University, Rensselaer Polytechnic Institute, University of California Davis, University of California Riverside, University of California Santa Barbara, University of Delaware, University of Illinois at Urbana-Champaign, University of Massachusetts at Amherst, University of Minnesota, and University of Southern California.

The NS CTA program began in September, 2009, and in 2014 entered its second 5-year phase, which ends in September 2019. The research program is structured as five interdisciplinary technical areas, each of which unites alliance expertise in social/cognitive networks, information networks, and communication networks. These areas are Co-evolution and Dynamics of Inter-genre Networks (Co-EDIN); Information Processing Across Networks for Decision-Making (IPAN); Quality of Information for Semantically-Adaptive Networks (QoI-SAN); Trust, Influencing, Modeling, and Enhancing Human Performance (TIME); and the Science of Multi-genre Network Experimentation (Exp).

3 Research Accomplishments

Both research alliances have made significant advances in the state of the art of network science, with a significant number of technical papers in leading journals and conferences, with some of the scientific output transitioning into military programs with a higher technology readiness as well as commercial products. Some of the key research outputs from the different programs are identified below.

3.1 ITA Scientific Accomplishments

While there have been many scientific accomplishments from the work of the ITA research alliance, we can categorize some of the more significant ones as the following:

Insights into fundamental limits and properties of mobile network structures: ITA researchers developed a variety of models characterizing scaling properties of mobile ad-hoc hybrid networks. These models determine the fundamental communication capacity of opportunistic and cooperative communications [2], scaling properties of network coding [3] [4], and performance characterization of multi-path communications [5]. A pragmatic output was a universal mobility modeling framework [6].

Energy Efficiency Techniques: The alliance invented a variety of approaches to improve battery power consumption and energy efficiency in ad-hoc networks. The approaches include distributed beam forming using cooperative communications [7], estimation of network transmission efficiency [8], and techniques for improving duty cycling behavior in networks [9].

Coalition Communications Interoperability: The alliance created techniques for efficient data ferrying in coalition networks [10], new paradigms for inter-domain routing [11], and algorithms for efficient gateway placement in dynamic coalition networks [12] along with other techniques for coalition operations [13].

Network Tomography: ITA researchers developed the scientific principles underlying monitoring of dynamically changing coalition networks with minimum overhead. The insights can be used to instrument and observe a variety of networks with minimum possible probing [14].

Mobile Micro clouds: The ITA program developed the concept of mobile micro cloud, an approach to create a dynamic cloud at the coalition edge, and analyzed approaches for mapping distributed applications onto hybrid coalition networks. It has created new techniques for distributing streaming and transaction oriented applications, analyzing their performance, and improving the effectiveness of distributed applications [15].

Cryptography applications in Coalition Contexts: The ITA has made fundamental advances in making cryptographic techniques applicable in the context of coalition networks. These include the adaptation of threshold cryptography for mobile ad-hoc networks [16], development of new identity-based encryption paradigms, and efficient implementation-friendly reformulation of fully homomorphic encryption algorithms.

Policy based Security Management: ITA researchers developed new paradigms for security management using a policy-based approach, creating new frameworks for policy negotiation, policy refinement, and policy analysis [17]. They applied them to create constructs like self-managing cells, and manage coalition information flows. The work resulted in various transitions such as the Army multi-modal signature database [18].

Trust and Risk Framework: The ITA program developed the basic formulations to characterize trust and risk using different adversary models, and showed how applications of control theory to risks can create new frameworks for managing risk [19]. The trust and risk framework has influenced the direction the NS CTA.

Quality of Information (QoI): The ITA pioneered the concept of QoI, and created the framework, algorithms, and various use-cases surrounding the use of QoI in ISR and sensor networks [20]. The concept had a significant impact on community, including starting the I2QS workshop and being a major thrust in the NS CTA program (see below).

Mission-Aware Information Networking: The ITA developed a variety of techniques to adapt the network to meet the requirements of a mission, including approaches for mission-aware network configuration, matching assets to missions, optimal coverage problems, and approaches for dynamically identifying information sources [21]. One of the key transition outputs was a Sensor Asset Matching tool for matching missions to assets available in the field to perform that task [22].

Sensor Information Processing Algorithms: ITA researchers have developed a variety of sensor information processing algorithms including approaches for autonomic identification of misbehaving sensors, ontology-based information processing to map sensor information into higher level analysis, and obfuscation of information [23].

Distributed Relational Algebra: ITA researchers created a model to represent sensor information flows as distributed databases, and created the principles that allowed them to create a distributed dynamic federated database [24]. The work resulted in the transition activity of the Gaian database which has had multiple transitions to other programs in UK MoD and US Army.

Advances in Human Agent Cooperation: The ITA made significant advances in the use of intelligent agents to assist humans in coalition tasks. Some of the specific use-cases were the use of agents to identify how successful human teams operate, the development of the ACT-R framework, and advances in creating a human-agent cooperation framework [25].

Controlled English: The ITA program made several advances in using a limited subset of English to improve the usability of computing systems by soldiers in the field in a variety of contexts, including mission planning, asset allocation, and policy specifications [26]. Controlled English led to several transition activities [27].

3.2 NS CTA Scientific Accomplishments

Scientific highlights to date from the NS CTA research program include:

Analysis of group structure in networks: NS CTA research has developed and extended powerful mathematical techniques for representation of groups, based on hypergraphs & simplicial complexes. These discipline-agnostic abstract models have proven highly effective in disparate practical domains, such as multi-channel, multi-radio broadcast [28] [29] and analysis of social collaborations [30].

Modeling and analysis of time-evolving and composite networks: The alliance developed new analytical and algorithmic methods for studying various aspects of time-evolving networks such as the development of temporal graph theory [31], phase transition phenomena in intermittent networks [32], diffusion processes in dynamic networks [33], and fast algorithms for temporal community detection [34].

Controllability and novel observability of layered networks: The NS CTA program has created provably effective and efficient algorithms for identifying the minimal sets of nodes required to drive a network, or a specified subset of network nodes, to a desired state. Our initial approach [35] required strong restrictive assumptions, such as linearity, but this pioneering work is now being actively extended [36]. The NS CTA has developed techniques for unbiased estimation of structural properties of complex networks and uncovered inherent limitations to the estimation of some of these properties. [37]

New measure of network capacity: The alliance was the first to show that QoI-aware (Quality of Information) processing & resource allocation achieve fundamentally different, and superior, results than existing optimization formulations. The NS CTA defined the Operational Information Content Sum Capacity (OICC-S) of a network, as the maximum QoI sum across the network, achieved by the set of information attributes most useful for decision making. The alliance then discovered algorithms for optimum rate allocation to maximize the output sum QoI and achieve OICC-S for various conditions, and demonstrated that such solutions differ from solutions that provide maximum throughput, making QoI-awareness necessary in resource allocation [38].

Symptotic analysis for accurate scalability of real-world networks: The alliance formulated an effective methodology for sensitivity analysis of network scalability that considers QoI and network dynamics for large but non-asymptotic (i.e., finite) size networks [39]. This non-asymptotic analysis of real-world wireless networks captures protocol overhead, congestion bottlenecks, traffic heterogeneity, and other real-world concerns. The NS CTA introduced the definition of "symptotic scalability", and a metric called "change impact value" (CIV) for comparing the impact of underlying system parameters on network scalability.

Fact-finding and uncertainty management across multi-genre networks: NS CTA research has generated new principles and effective methods for fact-finding, i.e., extracting reliable information from sources whose reliability is generally unknown, which established analytic foundations that allow the fact-finder to rigorously assess the reliability of its conclusions. The new analytic framework is used to extend the fact-finding system, Apollo, in several major ways, including the analysis of non-independent claims, the analysis of non-independent sources, accommodating time-varying state, fact-finding with polarized sources, conflict resolution, and handling uncertain links [40] [41].

Construction and mining of text-rich heterogeneous multi-genre networks: Network reconstruction and mining of text data is a challenge due to the noisiness of the data and their potential untrustworthiness. To cope with this challenge, NS CTA researchers have created techniques that exploit knowledge about human behavior and about other known structures to extract and exploit latent semantic structures. This research has generated multiple effective methods for (i) phrase mining and construction of high-quality, semi-structured, multi-genre networks from unstructured, noisy text data, (ii) multi-dimensional summarization and knowledge discovery within heterogeneous socio-informational networks [42][43].

Distributed query processing and problem solving in socio-information networks: This line of research seeks to answer multiple questions: What information is needed based on user requests and the need to enhance situational understanding? How can network manipulations enhance information processing over multi-genre networks? How can synthesized knowledge be formed over distributed computing resources? What are optimal ways of displaying information to users? NS CTA research has developed effective methods for search and recommendation over socio-information networks, especially on collaborative networks that are composed of information repositories and human experts who cooperate with each other and use the repositories to complete specific tasks [44].

Social consensus via committed minorities: The alliance discovered that existence of committed individuals [45] or zealots [46] leads to accelerated spread of opinions at tipping points of minority density, which depends on individual properties of nodes [47], the number of competing opinions [48][49], the model of spread [50], and the network structure [51]. These results can be used to predict and influence the spread of opinions in social communities.

Measuring and enhancing human trust in decision making contexts: NS-CTA researchers have investigated behavioral trust [52] in information provided by networked sources (human and automated systems), developed an extended notion of structural balance to model trust [53], and are conducting experiments via a complete agent simulation system with an extensible architecture [54]. Experiments are also being conducted to assess the role of perceived information credibility on decision-making.

Exploitation of social network structure for routing and cache placement in mobile communication networks: Unpredictable node mobility, low node density and lack of global information make it challenging to achieve effective data forwarding in mobile networks. The NS CTA's cross-disciplinary research created algorithms for routing in Disruption Tolerant Networks (DTNs) and cache placement in Mobile Ad hoc Networks (MANETs) that exploit knowledge of the structure of social and information networks to significantly improve performance and efficiency over traditional approaches [55] [56] [57].

3.3 Joint ITA and NS CTA Achievements

As the ITA predated the formation of the NS CTA, some of the ideas pioneered by ITA research had a significant influence on the direction of the NS CTA. Two such ideas were the concept of Quality of Information, which started out in the ITA and became a key theme in NS CTA research, and the concept of trust and risk, on which some foundational work was done in the ITA, and which was adopted as a major cross-disciplinary theme of the NS CTA program.

As the two programs became active, there was significant cooperation between researchers belonging to the two groups. Some examples of significant collaboration are the following:

Joint Experimentation Facility: Both the ITA and NS CTA programs focus on conducting experiments in order to verify and validate the outputs of the fundamental research activity. As a result, both alliances had developed an experimentation framework around the assets and methodologies developed within the two programs. In 2014, the two alliances decided to bring their experimentation capabilities together, and to establish a joint experimentation facility which was made available to researchers from both alliances. The experimentation facility includes a cloud-based service available to researchers to store, modify, and rerun experiments and demonstrations as a collection of packaged virtual machines. This facility enables a researcher in one organization to jointly run experiments and share results with researchers in another organization using the cloud as an enabling mechanism. The experimentation facility also includes migration of research tools (supporting, e.g., traffic generation, analysis, and visualization) between research tasks and across both programs. Such migration entails enhanced documentation and carefully designed "shim" layers and interfaces to allow ready interoperability of tools from disparate research efforts within integrated experiments. The concepts and technology from this joint effort have also been used to extend capabilities in the ARL Open Campus and the ARL Network Science Research Laboratory (NSRL), and to enhance the availability of ARL research resources across the alliances.

ITA Mobile Micro-cloud and NS CTA Apollo: Joint ITA and NS CTA collaboration is enabling the truth finder system, Apollo, developed in the NS CTA, to run in the micro-cloud, developed in the ITA [15]. Apollo analyzes social network data to build models that classify different sources based on their credibility. The micro-cloud platform provides compute capability at the edge. The goal of this collaboration is to enable real-time classification at the edge and evaluation of models based on information that is available at the edge of tactical networks.

4 Lessons Learnt

Since both alliance programs are fairly large complex networks in their own right, there were several lessons learnt from the operations of these networks themselves. The lessons learnt primarily deal with two classes of challenges: i) taking network science research from the academic domain to the domain of transition and commercialization; ii) bridging the intellectual and "cultural" barriers to successful scientific collaboration across traditionally separate disciplines.

4.1 Lessons: Research Transitions

There were two different paths for transition from the base research programs like that of ITA and NS CTA to a level of more maturity. One path tried to apply the ideas into programs of record, which typically have a higher technology readiness level (TRL) than does basic research (TRL 1-2). The other path tried to incorporate the research ideas into a commercial context to create a commercial product which could then be provided to society at large, or provided to the military. This second path was not anticipated by any member of the ITA alliance at its inception, and discovery of this model of transition was serendipitous.

Looking at transition successes, some of the most successful transitions of the ITA research technologies were policy algorithms, micro-cloud technology, sensor information fabric, and distributed dynamic databases. Not all of the ITA scientific accomplishments made it to field deployment in military or to a successful commercial product, although several made it into transitions as defined by incorporation into applied research programs with a higher TRL value. The focus in the NS CTA on foundational mathematical principles achieved some unanticipated rapid transitions: for example, techniques based on simplicial complex representation of group structures proved applicable to multicast routing algorithms in MANETs. Based on this limited sample, one hypothesis is that there are two qualitatively distinct paths to effective transition: crafting research technologies directly inspired by the challenges of a specific potential tool (supported by in-house resources for system maturation) and creating highly technology-agnostic mathematic techniques inspired by foundational issues (supported by proactive awareness of potential techniques by more application-oriented programs).

In all these transition approaches, some of the differences between the scope of theoretical network science and practical network science became very clear. For example, looking at the transition efforts in policy based technologies, several key differences between scientific work and transition work stand out. In our investigations, we explored a variety of cutting edge topics such as policy negotiations for coalitions [58] and policy supersession [59]. While these resulted in several interesting algorithms, the transition needs for policies tended to be relatively simpler, e.g., trying to manage fine-grain access control in databases [18], where negotiation and supersession were not required, but other simpler analysis algorithms developed in the very early phases of the program were sufficient. Thus, only a small fraction of the algorithms developed made it to the transition. While the complex algorithms had many interesting aspects, the challenges envisioned were ahead in time-frame for the people on the ground.

A similar discrepancy exists in the ability to transition work related to micro-cloud technology. Micro-cloud was one of the most successful commercial transitions from the ITA program, as ideas resulting from ITA research were incorporated into the concept of enterprise containers [60] announced by IBM as a cornerstone of its hybrid cloud strategy. The commercialization route in IBM required significant effort in maturing the technology and supporting complex business scenarios. However, several of the advanced algorithms in the ITA research mapping application graphs onto underlying systems were not incorporated, and a much smaller subset of simpler algorithms resulting from the research were used in the commercial version.

Our speculation is that the reason for only a small subset of algorithms to transition is due to the Pareto distribution of problems that arise in practice. A set of small algorithms can address a large suite of problems in practice, but the exact set of problems that will be encountered in the field is not known at the time of basic research. As a result, basic research explorations result in several paths of investigation that may not intersect with real transition opportunities over a brief time period. However, over a longer period, the probability of such an transition increases.

Within scientific research disciplines, we often end up making assumptions in analyzing networks that may not be valid in real networks. As an ITA example, several key algorithms in network tomography make the assumption that network metrics are additive. However, in a real network, network metrics are frequently not additive, and even simple metrics that ought to be additive, such as link delays, cannot be summed together to get the final results due to the fact that network topology is often partially known. These assumptions are needed for tractability in analysis. Unfortunately, the real world sometimes does not care for tractability. Nevertheless, ideal assumptions can sometimes lead to workable heuristics, an option we are exploring with tomography results currently. Similar issues arose in NS CTA research, where, for example, early results on network controllability assumed linear responses to control actions on a network component: an assumption that is rarely true in real networks. In each case, several of the algorithms that were provably correct in scientific investigations were hard to apply in practical network management considerations but suggested promising new lines of research.

4.2 Lessons: Multi-disciplinary Research

Strikingly, both programs observed a similar trajectory in the challenges, evolution, and eventual success in performing productive multi-disciplinary research. Both the ITA and NS CTA were explicitly designed with a requirement for multi-disciplinary collaboration. All participating researchers embarked on their work in the program with a strong commitment to working together across organizational and disciplinary boundaries. In practice, however, initial successes in cross-discipline collaboration proved somewhat sporadic, often facilitated more by pre-existing informal personal relations than by explicit research planning. Human social and cognitive factors proved as critical for realizing multi-discipline research as the formal scientific content of the research questions addressed.

Recognizing the importance of social relations and individual familiarity across researchers in different disciplines, both programs cultivated several explicit mechanisms to facilitate such connectivity. Some were formal; for example, careful review of proposed research topics and proposals to ensure inherently multi-disciplinary technical challenges and clearly multi-disciplinary research teams. But these formal requirements and metrics are translated into practice by a variety of approaches for facilitating informal interactions between researchers and research groups: regular technical working meetings (called “bootcamps”) that bring together all of a program’s researchers and, on occasion, both programs’ researchers; webcast seminars to allow researchers to become aware of the research being done in other areas and to become familiar with other terminology and approaches; and, critically, integrated experimentation in which tools, data, and methods from across the programs came together to advance the range of research questions and approaches that every researcher could explore. Collocation of researchers, e.g., via short-term and long-term extended visits (“rotations”), is critical to cross-disciplinary cross-organizational collaboration, particularly since web-based collaboration tools are still less effective than face-to-face interactions. The ARL Open Campus concept seeks to facilitate such rotations from the larger S&T community [61].

There are no painless paths to enabling productive, truly multi-disciplinary research. Not all researchers are comfortable working across disciplines, and certainly not all research requires that. Some researchers will decide that a multi-disciplinary program is simply not their most scientifically productive environment. But, in both ITA and NS CTA, we continually observed a positive feedback phenomenon that expands multi-disciplinary research within and beyond the programs: as the researchers see for themselves that new ideas, new results, and new avenues for exploration and publication do indeed arise when they work across disciplines, they discover new research opportunities that expand their own scientific horizons.

5 Conclusion

The two research alliances discussed in this brief overview have created a highly productive approach to multi-disciplinary research in network science, where researchers from many backgrounds and both programs successfully collaborate on fundamental research.

More broadly, in the decade that has passed since the landmark NCR report on network science [1], that nascent field has evolved dramatically. One can now confidently state, based on extensive and well-cited research publications, that network science can create both significant results in its own right and valuable contributions to traditional disciplines. In today’s world of intimately intertwined networks, network science is becoming a crucial tool in both research and practice.

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References

[1] National Research Council Committee on Network Science for Future Army Applications, "*Network Science*." The National Academies Press, 2005.

[2] Z. Ding et al., "On the application of cooperative transmission to secrecy communications," *IEEE JSAC*, vol 30, no. 2 (2012): pp. 359-368.

[3] J. Liu et al., (2007, May). "Bounds on the gain of network coding and broadcasting in wireless networks", *IEEE INFOCOM 2007*, Anchorage, AK, USA, May 2007, pp. 724-732.

[4] Z. Ding et al., "On the study of network coding with diversity." *IEEE Trans. Wireless Communications,* vol. 8 no. 3, pp. 1247-1259. March 2009.

[5] Y. Chen et al., "A measurement-based study of multipath TCP performance over wireless networks," *Proceedings of the 2013 ACM conference on Internet Measurement*, pp. 455-468.

[6] A. Medina et al., "On the universal generation of mobility models." *IEEE MASCOTS*, 2010, pp. 444-446.

[7] Z. Ding et al., "Distributed beamforming and power allocation for cooperative networks," *IEEE Trans. on Wireless Communications*, 7, no. 5 (2008): 1817-1822.

[8] M. Zafer et al., "Cooperative transmit-power estimation under wireless fading." *Proc. of the 9th ACM symposium on Mobile ad hoc networking and computing*, pp. 381-390. ACM, 2008.

[9] P. Basu et al., "Opportunistic forwarding in wireless networks with duty cycling," *Proc. of the third ACM workshop on Challenged networks*, 2008, pp. 19-26.

[10] H. Liu et al., "Dynamic control of data ferries under partial observations." *IEEE Wireless Communications and Networking Conference* (WCNC), 2010, pp. 1-6.

[11] S. Lee et al., "InterMR: Inter-MANET routing in heterogeneous MANETs." *IEEE 7th Conference on mobile ad hoc and sensor systems*, Nov 2010, pp. 372-381.

[12] Y. Song et al., "Optimal Optimal gateway selection in multi-domain wireless networks: a potential game perspective", *ACM 17th annual international conference on Mobile computing and networking*, Sept. 2011, pp. 325-336.

[13] S. Calo et al., "Technologies for federation and interoperation of coalition networks," *SPIE FUSION*, 2009.

[14] L. Ma et al., "Efficient identification of additive link metrics via network tomography." *IEEE ICDCS*, 2013, pp. 581-590.

[15] S. Wang et al.,"Mobile Micro-Cloud: Application Classification, Mapping, and Deployment." *Proc. of Annual Fall Meeting of ITA (AMITA),* September 2013.

[16] R. Gennaro et al., "Strongly-resilient and non-interactive hierarchical key-agreement in MANETs." *Computer Security-ESORICS*, Heidelberg, Germany, 2008, pp. 49-65.

[17] M. Beigi et al., "Policy Technologies for Federation and Interoperation of Coalition Networks." *Network Science for Military Coalition Operations: Information Exchange and Interaction,* 2010, pp. 103.

[18] K. Bennett et al., "Fine-grained policy control in US Army Research Laboratory (ARL) multimodal signatures database," *SPIE Defense+Security Conference*, 2014.

[19] J. Clark et al., "Risk based access control with uncertain and time-dependent sensitivity." *IEE Security and Cryptography (SECRYPT)*, 2010, pp. 1-9.

[20] C. Bisdikian et al., "Building principles for a quality of information specification for sensor information.*" IEEE FUSION 2009*, pp. 1370-1377.

[21] M. Gomez et al., "An ontology-centric approach to sensor-mission assignment." *Knowledge Engineering: Practice and Patterns*, 2008, pp. 347-363.

[22] T. Pham et al., "Sensor and Information Fusion for Actionable Intelligence, U. at the Tactical Edge," NATO IST/SET-126 Symposium on Information Fusion (Hard and Soft) for ISR, Norfolk, VA, May 2015.

[23] C. Bisdikian et al., "Trust and obfuscation principles for quality of information in emerging pervasive environments." *IEEE PERCOM Workshop*, 2012,pp.44-49.

[24] G. Bent et al., "A dynamic distributed federated database." *Second Annual Conference of International Technology Alliance*, 2008.

[25] K. Sycara et al., "Agent support for policy-driven collaborative mission planning." *The Computer Journal*, 2009.

[26] P. Xue et al., "Controlled English for Effective Communication during Coalition Operations," *The 18th International Command and Control Research and Technology Symposium*, Alexandria, VA, June 2013.

[27] D. Braines et al., "Enabling CoIST Users: D2D at the Network Edge," Proc. FUSION 2014, Salamanca, Spain, Jul 2014.

[28] S. Dabideen et al., "Exploiting Frequency Groups for Broadcasting in Multi-Channel Multi-Radio Networks," *IEEE MILCOM 2014*, October, 2014.

[29] W. Ren et al., "Broadcasting in Multi-Radio Multi-Channel Wireless Networks using Simplicial Complexes," *IEEE Trans. on Wireless Communications*, August, 2013.

[30] T. Moore et al., “Analyzing Collaboration Networks Using Simplicial Complexes: A Case Study,” *IEEE International Workshop on Network Science for Communication Networks, (NetSciCom)*, March 2012.

[31] P. Basu et al., "To Sample or To Smash? Estimating reachability in large time-varying graphs" , *Proc. SIAM Data Mining (SDM '14)*, April 2014.

[32] P. Basu et al., "Percolation Phenomena in Networks under Random Dynamics", *COMSNETS 2012*, January 2012.

[33] D. Figueiredo et al., "Characterizing continuous time random walks on time varying graphs,” *SIGMETRICS 2012*, pp. 307-318, 2012.

[34] M. Araujo et al., "Com2: Fast Automatic Discovery of Temporal ('Comet') Communities,” *Proc. PAKDD '14*, May 2014.

[35] Y.-Y. Liu et al., “Controllability of complex network,” *Nature* 473, pp. 167-173, May 2011.

[36] J. Gao et al., “Target Control of Complex Networks,” *Nature Communications*, November 2014.

[37] F. Murai et al., “On Set Size Distribution Estimation and the Characterization of Large Networks via Sampling,” *IEEE JSAC special issue on Network Science,* vol. 31, no. 6, June 2013.

[38] E. Ciftcioglu et al., “Operational information content sum capacity: From theory to practice,” *Computer Networks,* 75 pp. 1-17, 2014.

[39] R. Ramanathan et al., "Symptotics: A Framework for Analyzing Real-World Wireless Networks," *Proc. ACM PE-WASUN*, Cyprus, 2012.

[40] D. Wang et al., *Social Sensing: Building Reliable Systems on Unreliable Data*, Morgan Kaufmann, 2015.

[41] D. Wang et al., "Using humans as sensors: an estimation-theoretic perspective," *Proc. IPSN'14*, pp. 35-46, 2014.

[42] A. El-Kishky et al., "Scalable Topical Phrase Mining from Text Corpora,” *Proc. of The VLDB Endowment* vol. 8 no. 3, pp. 305 - 316, 2015.

[43] F. Tao et al., "NewsNetExplorer: Automatic Construction and Exploration of News Information Networks,” *Proc. of 2014 ACM SIGMOD*, June 2014.

[44] H. Sun et al., "Analyzing expert behaviors in collaborative networks,” *Proc. ACM SIGKDD,* pp. 1486-1495, 2014.

[45] J. Xie et al., "Social consensus through the influence of committed minorities," *Physical Review E* 84(1) 011130, July 2011.

[46] G. Verma et al., "The impact of competing zealots on opinion dynamics," *Physica A: Statistical Mechanics and its Applications*, 395, 310-331, 2014.

[47] A. M. Thompson et al., "Propensity and stickiness in the naming game: Tipping fractions of minorities," *Physical Review E* 90(4):042809, Oct. 2014.

[48] J. Xie et al., "Evolution of opinions on social networks in the presence of competing committed groups," *PLoS ONE* 7(3), 2012.

[49] A. Waagen et al., "Effect of zealotry in high-dimensional opinion dynamics models," *Physical Review E* 91, no. 2, 2015: 022811.

[50] P. Singh et al., "Threshold-limited spreading in social networks with multiple initiators," *Nature Scientific Reports* 3 2330, July 2013.

[51] W. Zhang et al., "Opinion Dynamics and Influencing on Random Geometric Graphs," *Nature Scientific Reports* article 5568, July 4, 2014.

[52] S. Adali et al., "Measuring behavioral trust in social networks," 2010 *IEEE International Conference on Intelligence and Security Informatics (ISI)*, pp. 150-152.

[53] Y. Qian and S Adali, "Foundations of Trust and Distrust in Networks: Extended Structural Balance Theory," *ACM Transactions on the Web (TWEB)* 8 (3), June 2014.

[54] K. Chan and S. Adali, "An agent based model for trust and information sharing in networked systems," 2012 *IEEE CogSIMA*, pp. 88-95.

[55] E. Bulut et al., “Exploiting Friendship Relations for Efficient Routing in Mobile Social Networks,” *IEEE Trans. Parallel and Distributed Systems*, Vol 23 No 12, pp. 2254-2265, December 2012.

[56] W. Gao et al., “On Exploiting Transient Social Contact Patterns for Data Forwarding in Delay Tolerant Networks”, *IEEE Trans. Mobile Computing*, February 2013.

[57] X. Zhuo et al., “Social-Based Cooperative Caching in DTNs: A Contact Duration Aware Approach,” *IEEE MASS 2011*, pp. 92-101, October 2011.

[58] C. Brodie et al., "The coalition policy management portal for policy authoring, verification, and deployment." *IEEE POLICY,* 2008, pp. 247-249.

[59] K. Grueneberg et al., "Policy Supersession in a Coalition ISR Network." *IEEE POLICY*, 2011, pp.178-179.

[60] IBM Corporation, "IBM Cloud Makes Hybrid a Reality for the Enterprise", 23 Feb 2015, http://www-03.ibm.com/press/us/en/pressrelease/46136.wss.

[61] United States Army Research Laboratory, “Open Campus,” http://www.arl.army.mil/opencampus/.