RESEARCH STATEMENT

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My research endeavors span the areas of disruption-tolerant networking, network measurement, and system modeling, with the common thread between those being network resilience and survivability research. This is a long-established, yet constantly evolving field, with substantial future implications as networked systems play increasingly pivotal roles both for the Navy/DoD as well as for the public at large. My research in this domain has leveraged a tri-pronged approach of graph theory, system simulation and modeling, and validation via testbed implementation.

Background and Current Work

Tactical networking is an application of resilient and survivable networks that includes worst-case-scenario challenges, and therefore fascinating research problems. In addition to conventional causes of disruption such as mobility, channel errors, and episodic disconnection, tactical networks must address intelligent adversaries who may jam or infiltrate the network itself. Addressing these challenges is a long-term focus area for Navy and Marine Corps research.

We find a rich body of prior work in the domain of Fault Tolerance, with early references dating back to the 1830s, and modern literature from the 1950s [1]. Much of this prior art was developed in reference to the long-haul telephone network. However, fault tolerance only addresses the problem of random, individual, component failure, and we must look beyond this to correlated and dependent failures, as well as malicious attacks, to address the challenges of tactical networking. This expanded scope gives us the field of network survivability, with the further additions of graceful-degradation and recovery encompassed by the topic of resilience. In order for these concepts to have real-world benefit, it is necessary to understand and apply their general principles to complex systems. I describe my efforts in this field in the sections following.

Disruption-Tolerant Networking

Over the past decade, my research has sought to both advance the state of the art in network protocols for challenged environments, as well as lower the barriers to adoption of such. The latter is especially important in this field because the basic principles of delay- and disruption-tolerance tend to be at odds with the accepted paradigms of ubiquitous IP networking (end-to-end connectivity). The former has direct application to forward-deployed military tactical networks.

As an example, I led the development of the Airborne Network Telemetry Protocol (ANTP) suite (network, routing, and transport) designed for highly-dynamic airborne tactical networks. This particular application was to operate independently of the airborne vehicle flight systems resulting in highly constrained in terms of weight, physical profile, and power, which resulted in limited radio range and frequent channel fading. We showed that traditional IP network (including MANET) routing could not be expected to converge in this environment due to the short contact durations involved in these networks of high-speed airborne nodes, and therefore designed a network stack designed around opportunistic message exchange and localized decision-making [2, 3]. At the same time we minimized barriers to retrofitting existing systems with these new protocols by designing a gateway to translate between our protocols and the existing IP stack (IP to AeroNP, and TCP/UDP to AeroTP) [4]. The work completed on this USAF-funded project included multiple design iterations with ns-3 simulations to evaluate the effects of various design options, and eventual implementation of a proof-of-concept of the protocol suite for testbed deployment and field tests.

The ANTP project was very applied and focused on the sponsor requirements, which included research problems that led to interesting results. Elements of the system design were influenced by the DTNRG Bundling Protocol [5], however ANTP differs significantly in that instead of forming an overlay on top of IP (or other opaquely-layered network protocols), our stack is tightly vertically integrated in order to use cross-layer feedback to improve channel utilization and efficiency. We mitigate the effects of very high mobility by taking the position and velocity of the aircraft and its neighbors into account when making local routing decisions, and snooping on the TDMA wireless channel to perform congestion avoidance and hop-by-hop custody transfer. The result is a routing protocol (AeroRP) that outperforms traditional MANET and DTN routing protocols, especially as node-density increases [6]. At the transport layer we find that tightly-coupled closed-loop end-to-end control is too slow to adapt to the dynamic network environment, so we use open-loop control in combination with custody transfer, along with a network layer that provides hop-by-hop acknowledgements and congestion control. This allows us to achieve congestion-control and error-control, limit overhead, and keep up with the changing network conditions [7].

More recently my research has involved building on the lessons learned in the aeronautical networking environment and applying them to traditional DTN routing protocols designed for use with RFC5050-compliant bundling protocol implementations. LT Kevin Killeen's thesis compares several such protocols [8]. Although he has graduated, he is continuing to collaborate with me on a conference paper based on this work. We have also made significant progress in reducing barriers to adopting the Bundling Protocol in vehicular networks [9]. As in the aeronautical networking case, this again takes the form of gateways, however network- and transport-layer translation alone are insufficient in this case, due to application-layer (and user-layer) assumptions about end-to-end delay [10]. To mitigate this we have extended our gateway architecture to include the application layer, as well as creating a plugin-architecture to support community extensibility. I advised LT Lance Alt's research on this subject, and his thesis describes our architecture in detail [11]. I am currently advising Mr. Michael Monahan's thesis research on evaluating the technical readiness of several Bundling Protocol implementations, which is a question of interest to several sponsors. Aspects of my DTN research have been funded by the USMC, SPAWAR, and the NRP.

Network Measurement and Analysis

The study of network resilience and survivability is heavily dependent on accurate network measurement and analysis, across a spectrum of domains. Some of these include measuring network topology to predict its survivability; traffic analysis to understand its EO matrix as well as application diversity; quantifying the *normal* state and behavior of the network in order to measure and compare its divergence from the norm in the face of a variety of attacks and challenges; and comparing the effectiveness of countermeasures. While conceptually it is only necessary to be a consumer of network measurements gathered by others, in practice finding good measurement data is a difficult problem even for a subject as generic as the Internet, and generally unavailable for niche network domains such as tactical and highly-mobile networks. This has resulted in increasing involvement in network measurement research on my part over a number of years.

While studying Path Diversification [12] for my dissertation it became apparent that the router-level topologies which were readily available at the time did not adequately reflect the physical-layer diversity that underlaid them.[1] We therefore compiled physical-layer maps from original sources and made them available to the research community [14], followed by a number of analyses aimed at quantifying the available

[1]This work predated the Internet Topology Zoo [13].

diversity present in these network graphs [15, 16] and understanding the relationships between varying graph types (router, physical, railroad, interstate-highway, etc.) [17]. This NSF-funded work culminated in the development of new metrics for quantifying the expected survivability of a particular network graph [18].

More recently I led a directed study for a dual math/computer-science major on graph reduction methods, in which we revisited a number of previously proposed methods and evaluated their performance on new data sets. We ultimately developed two novel graph reduction methods that outperform the existing state-of-the-art [19]. Elements of this work were recently accepted for publication [20]. In this work we investigated router-level topology data sets based on IPv4 data, but with the exponential increase in IPv6 traffic share, it becomes increasingly critical to understand and quantify the evolution of the Internet from a predominantly IPv4 topology, to a hybrid V4/V6 topology, further motivating prior collaborative research to improve the fidelity of IPv6 router-level topology data sets [21].

System Modeling

Many systems are not available for direct experimentation at scale (interdomain-routing on the Internet for example), thus requiring testbed deployment or simulation approaches. These two tools have the potential for high-fidelity, high-throughput (in terms of test scenarios), and low cost (choose two). Due to the complexity of the systems involved in resilient and survivable networks, a robust simulation and testbed strategy is a necessary component of a successful research program. In addition, many simulators and testbeds are only designed to test communication networks that are working as intended, i.e., the tools do not include the capability to introduce outages, failures, and challenges into the communication environment. This has led me to modify tools and develop new models, as well as being involved in large-scale specialized testbed deployments in support of simulating and testing resilient and survivable networks.

Simulation is a logical first step in the testing and validation process for new protocols and mechanisms, allowing for arbitrary levels of abstraction to isolate and analyze specific effects. In this vein I have made extensive use of custom MATLAB simulations for graph-theoretic and static failure analysis [22, 23]. While transient analysis of network behavior is also possible in MATLAB I have taken the approach of modifying the ns-2, and later ns-3 simulators to support challenge modeling [24, 25], as well as contributing several well-known and novel protocol models to these simulators [26, 27, 28]. The majority of this work was funded by the US Air Force with the objective of developing network protocols for highly-dynamic airborne environments [27]. This work has been uniquely challenging because it incorporated not only high-mobility but also tight resource constraints in terms of power, spectrum, and antenna properties. I have also made extensive use of the ONE simulator, which lacks some fidelity due to extracting away layers two and three of the network, but is one of the few simulators specifically designed to enable DTN routing simulation and has been particularly useful in modeling military asset movement and exercises, such as the Bold Alligator exercises examined by LT Kevin Killeen in thesis work I advised [8].

Network Resilience and Survivability – A Research Agenda

For network resilience to occur, resilience principles must be applied at every layer of networked systems; however the routing and transport layers have a particularly large effect on these objectives and it is on these layers that I intend to focus my efforts. This includes the necessary measurement and instrumentation to quantify the survivability of these layers.

In the course of my research I have observed that it is especially difficult for organizations to adopt resilient and survivable networks, especially when those networks don't adhere to the "always on" connectivity model of traditional IP. This elevates the importance of integration methods if existing networks' resilience is to be improved. In all of these cases, the systems involved are highly complex and simulation will be an invaluable tool to study a wide range of approaches in a systematic manner, as well as cross-validating measurement and implementation results.

In the future, my research will also look at resilience and survivability in the context of emerging networking topics such as software-defined networking. Any time system complexity is increased, new failure modes are introduced, and with the DOD/DON's interest in these systems it will be important to understand the critical failure points. I am excited by the opportunity to pursue these research directions at an institution where the outcomes are so directly applicable.

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