Multi-Agent Systems in Mobile Ad hoc Networks

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ABSTRACT

A number of technologies are evolving that will help formulate more adaptive and robust network architectures intended to operate in dynamic, mobile environments. One technology area, mobile ad hoc networking (MANET) enables self-organizing, multi-hop heterogeneous network routing services and organization. Such technology is important in future DoD networking, especially in the forward edge of the battlespace where self-organizing, robust networking is needed. A second technology area, Multi-Agent Systems (MAS) can enable autonomous, team-based problem solving under varying environmental conditions. Previous work done in MAS has assumed relatively benign wired network behavior and inter-agent communications characteristics that may not be well supported in MANET environments. In addition, the resource costs associated with performing inter-agent communications have a more profound impact in a mobile wireless environment. The combined operation of these technology areas, including cross-layer design considerations, has largely been unexplored to date. This paper describes ongoing research to improve the ability of these technologies to work in concert. An outline of various design and system architecture issues is first presented. We then describe models, agent systems, MANET protocols, and additional components that are being applied in our research. We present an analysis method to measure agent effectiveness and early evaluations of working prototypes within MANET environments. We conclude by outlining some open issues and areas of further work.

BACKGROUND AND MOTIVATION

Mobile Ad hoc Networking (MANET) technology is designed to provide effective dynamic Internet Protocol (IP) routing in network environments where "change is the norm". Change may be topological due to mobility or behavioral due to other wireless environmental effects (e.g., energy conservation, channel fading, etc) [CM99],[P01]. In addition, multi-agent system (MAS) technology is well suited for dynamic, distributed problem solving in which distributed software agents are able to both sense and act within complex environments [W02]. MAS-based architectures may be very valuable in the future forward battlespace to provide distributed teamwork-based solutions to complex problems. However, at present, MAS design and performance tradeoffs in disruptive and potentially mobile networks are largely unexplored.

PROBLEM SPACE

MANET is planned for future deployment in the forward edge of the battlespace. There has been some significant advancement in the development of MANET solutions in recent years, but much work remains to be done. Overall, there remains limited experience in using/adapting upper layer protocols and applications in these environments [B04]. Also more work is needed in developing and adapting multicast routing in these environments to better support group-oriented communications. Intelligent multi-agent systems are also of interest in future DoD systems. These

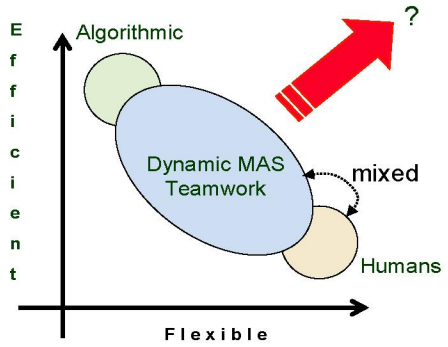

Figure 1: Dynamic MAS Benefits

systems are composed of autonomous or cooperating software entities; in the latter case these entities may be goal-driven and able to coordinate (communicate) as part of a team to reach the goals.

Figure 1 shows the potential benefit of MAS for more autonomous and flexible problem solving in complex environments. Some possible examples of future MAS applications include distributed command and control support software, network management, sensor networking, and mobile cooperative robotics. When considering MANET deployment in highly stressed networks, the design of distributed and cooperative agent-based systems is of interest. This is primarily due to the flexible problem solving approach offered by MAS, which provides a robust solution to address the challenges faced in MANET environments. Previous design work has assumed a benign wired network behavior; not MANET environments. In MANET environments peer agents experience increased topological dynamics, intermittent connectivity, and reduced reliability. The cost of interagent communications is also high; therefore communication resources in a wireless MANET should be utilized in the most effective means possible. For example, multi-party coordination and communication frameworks should be well supported.

Separately MAS and MANET encompass two challenging research areas. Our focus is to begin improving the performance capability of MAS applications running in MANET network environments. This includes the following subgoals:

- improve crosslayer design performance between MANET and MAS layers.
- investigate MAS design robustness in stressed network environments.
- develop and test new MANET network services and modeling where needed to support anticipated MAS operation.

ISSUES AND PROJECT APPROACH

Figure 2 represents an example of the architectural layering concept that we are targeting in this research effort. The goals are to identify and fill technology and protocol gaps that may exist in Figure 2 and improve any flawed design interactions between the layers. At the same time, we wish to maintain layered software and network protocol abstractions wherever possible.

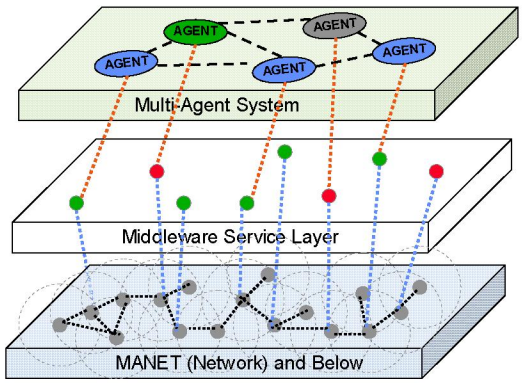

Figure 2: Layered Design Issues

At the MAS layer, we are interested in better multiagent designs to improve the potential for operation in MANET environments. In doing so, we are investigating the network service assumptions and robustness requirements at the agent layer. Special attention is being paid to interagent communication design including efficiency and flexibility of agent teamwork. An important issue is establishing measures of effectiveness applied to agent designs within these environments. At present, we are studying teamwork problem solving effectiveness vs. performance metrics such as increasing network size, mobility, and decreasing reliability.

Figure 2 also shows middleware as a potential design layer between MAS and MANET. Middleware plays a role as an important network design abstraction often used by network application designers, including designers of network agent software. Dynamic service discovery and other higher layer services are also often provided by a middleware layer. Examples of middleware systems include JXTA, Gnutella, and Peer-to-Peer Simplified (P2PS) [W05]. Despite their attractiveness as design abstractions, middleware frameworks are not an engineering panacea, especially in wireless environments. For example, middleware can take advantage of efficient network communication abstractions such as multicast but the present designs often assume static topology relationships or neighborhood subnet assumptions more consistent with wired network deployments. There are also robustness and efficiency tradeoffs between classes of middleware services that are unique to MANET

environment scenarios. Middleware or peer-to-peer layers also often provide some autonomous organization and identification independent of the underlying network addresses such as the Internet Protocol (IP) stack provides. We are interested in studying the potential functional redundancy and inefficiencies of such layered abstractions when operating in MANET environments. We envision an enhanced approach in which more efficient lower layer MANET network services (e.g., multicast) may be utilized by middleware when operating in stressed wireless ad hoc scenarios. This will maintain a degree of abstraction desired of middleware but will provide more efficient and effective cross-layer components for MANET use.

Figure 2 also shows the MANET layer as the bottom layer of the architecture providing ad hoc multiple-hop routing within a wireless network. The figure also depicts the fact that the scenario may be very heterogeneous between layers. For instance, some nodes may only provide network and possibly middleware services for other nodes that are operating as agent nodes. In other cases, a physical node may operate as an agent, middleware, and MANET node simultaneously.

As envisioned the MANET protocol layer is providing the following two main functions:

- Dynamic IP network routing
- Some network autoconfiguration support

The MANET dynamic IP routing is performing both unicast and multicast forwarding of data packets. We are presently looking at the application of MANET proactive unicast protocols in this environment. We expect MANET proactive to provide lower average delay between nodes and more predictable network overhead under stressed conditions. The dense many-to-many traffic patterns involved in interagent teamwork communications likely favor a more proactive approach but scaling a proactive approach can be challenging and future work in that area is needed. There is also nothing in our architecture concept to preclude the substitution of reactive protocols as well.

Because of the MAS teamwork model involving group communications, multicast MANET routing is also of particular interest. We are adapting ongoing work on Simplified Multicast Forwarding (SMF) protocol [MDC04] to our evaluation models. An effective MANET multicast routing capability will be important since interagent group communications and persistent sharing of team environment or plan information is called for by many interagent designs. Multicast may also be adjusted and optimized for more localized agent communication designs by changing scope range of the multicast dissemination.

MODELING APPROACH AND TOOLS

Due to analytical complexity, research of MANET systems is often done by simulation and sometimes via emulation. Researchers model the related dynamic network environments, network protocol stacks, applications, and node mobility within specialized simulation or emulation systems. In our work, we have extended some existing MANET test environments to include the introduction of non-abstracted agent software and middleware components.

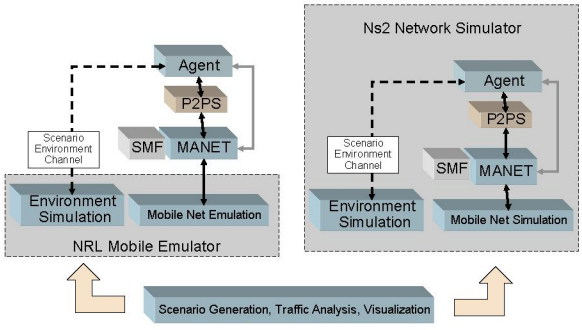

Figure 3: Example Modeling Approach

Figure 3 depicts part of the modeling approach and toolset we have developed. As shown, we use a cross platform prototype code development approach that results in the same software able to run in both simulation and emulation environments [CMW03]. The composite system under examination includes the agent software at the top layer, optional middleware, and then associated network stack and MANET protocols below. At the MANET layer, we have added the addition of SMF functionality providing an optional multicast routing capability within the MANET environment. Agents are useful in real world environments because they both sense and react to complex environments. To better support environmental modeling we have adapted an existing set of MANET tools to provide dynamic environment control and stimulus to the MAS simulations [D04]. In the past the environment

channel was normally used to control MANET node movement and position information in mobile simulations, but it is now also a channel that can provide local environmental information used by the agents (e.g., localized sensor stimulus, human input, etc). Once again the set of scenarios, traffic tools, and visualization tools equally apply to both simulation and emulation testing. In Figure 3, the optional middleware modeling layer is represented by the P2PS protocol layer [T05]. We have modified P2PS interface code to run in a portable way in the real world and within the ns2 simulation environment. Agents may use the middleware services or can optionally directly communicate through standard network and MANET-optimized network layers. We are also working on adding a multicast pipe capability to P2PS to be able to use the SMF MANET routing and possibly future additional reliable multicast transport services.

EARLY AD HOC MAS STUDY RESULTS

As we have discussed there are numerous design frameworks and approaches being developed for MAS and the application areas are varied. Because of the rich taxonomy of application areas for MAS this a "no one size fits all" design space. We have chosen to scope our investigation down to an area of team-based problem solving, with initial emphasis on the study of distributed role allocation algorithms and their effectiveness towards achieving team goals. We accomplished early work in adapting existing agent-basesd systems and frameworks including Machinett [MA], Control of Agent-Based System (CoABS) grid, and REPAST to enable early analysis and refinement of the algorithms prior to integration with MANET environments [AM03].

An example of our team-based problem solving scenario is the prey/predator pursuit problem. The prey/predator problem is a canonical example of agent teamwork in the literature and we are adapting this model to further study by including a MANET communications model. We have measured coordination (and hence teamwork) quality as a function of interactions between agents (messages and collisions) to accomplish the task of capturing the preys.

Figure 4 is an example visualization snapshot of an emulation scenario. Within figure 4, the icons of the soldiers represent predator and the monsters represent prey. The circle depicted around the prey represents the capture zone of the preys. In this example, it takes 4 predators to successfully capture a prey within the capture zone. Therefore agents are required to perform teamwork in order to satisfy the requirement of four complementary and unique roles being taken to capture the prey. The links between the predators represents the real-time network topology being calculated by the MANET routing protocol (in this case a variant of OLSR). The predators and preys are mobile within the scenario and the predators use the MANET to form a mobile network to allow for interagent coordination and communication. The agents support the dynamic allocation of roles and agent teamwork by communicating environmental state and or local intention across the MANET network.

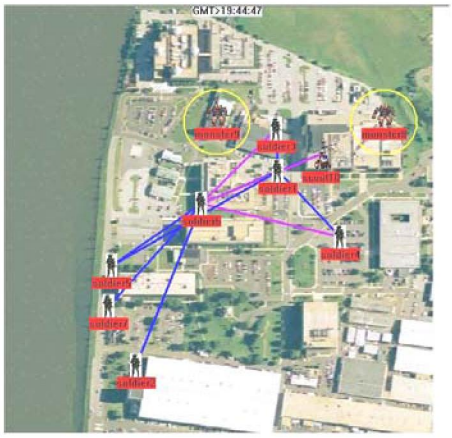

Figure 4: Emulation Visualization Snapshot

In early studies, we began by examining various role allocation algorithms in a more limited simulation environment (i.e., REPAST). We induced simulated message loss and limited communication range (to crudely represent facets of MANET) to examine performance of the various role allocation approaches [AMC05]. The initial results from those experiments showed that distributed coordination by sharing state among agents significantly outperformed algorithms based solely on communicating role switching with more localized and statistical methods. The interesting fact was that this advantage remained true with high network loss rates as well as when the system scaled in terms of numbers of agents.

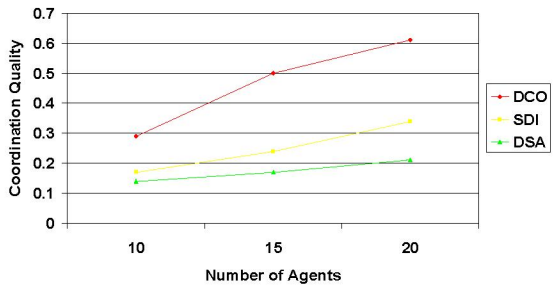

Figure 5: Role Allocation Simulations

We are now pursuing similar experiments within a more detailed emulation and simulation environment. The mobile topology, routing performance, contention, and congestion are being modeling with working protocol code and the wireless network environment and protocol stack will be more realistic. Figure 5 shows an early set of results demonstrating that the Distributed Constraint Optimization (DCO) based upon the Hungarian algorithm continues to outperform the more localized statistical role allocation methods[1] within the more detailed emulation environment.

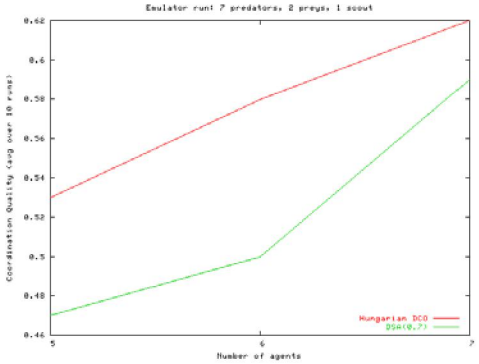

Figure 6: Early Simulation and Emulation Results

MANET MULTICAST PROGRESS AND AGENT USE

We have made significant recent progress in further developed and applying SMF for multicast routing within this project [MDC04]. New and improved relay set algorithms have been introduced into SMF and a simulation model has been completed and tested with larger networks than supported within the emulator. Some agent role allocation approaches and designs, such as the Hungarian algorithm variant, require significant interagent sharing of local environment information. These types of algorithms often find more optimal solutions to a complex problem because of the more accurate agent view. However, this is accomplished at the cost of increased inter-agent communications. SMF reduces network overhead by providing an efficient means of multicast forwarding within a dynamic, wireless network area making such solutions more viable within MANETs. We are presently exploring the tradeoffs between improved agent role allocation performance and the cost of this additional overhead in various scenarios. The example of Figure 6 uses SMF within the emulation experiment and shows that the additional network overhead is being utilized in an effective way. As mentioned, protocols like SMF can decrease the burden of overhead within the MANET operating area and make more effective agent communication possible. We plan to study this tradeoff more as the network and the MAS scale in size.

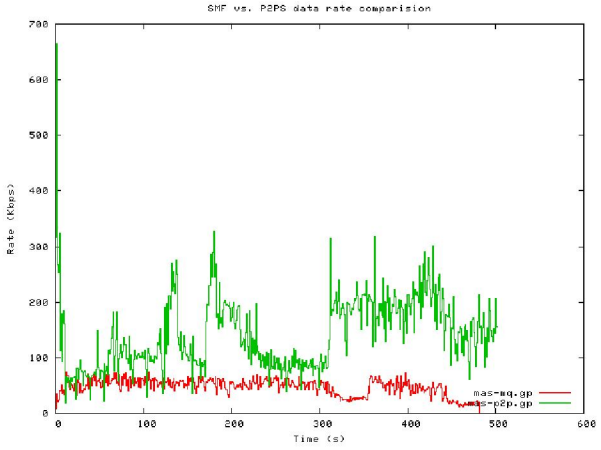

Figure 7: P2PS Middleware (unicast) vs. SMF pipes

Figure 7 shows some early analysis of network overhead with seven agents, two preys, and one scout. All nodes are mobile and the agents and scout use MANET protocols to dynamically route data within the changing topology. In one case, we use P2PS as a peer-to-peer protocol layer between agents. P2PS provides both unicast messaging pipes and service discovery for the MAS software. In the second case, we applied SMF as a mobile multicast forwarding directly between agents. This is more efficient as a team

[1] Distributed Stochastic Algorithm (DSA), Simple Distributed Improvement (SDI)

communication method and the curve represents the resulting savings in network overhead from using SMF vs. unicast P2PS. In future work, we hope to combine the use of SMF and P2PS so that the middleware can take advantage of efficient multicast forwarding when available in MANETs.

FUTURE WORK

Part of the challenge of studying MAS systems is to measure the effectiveness of performance. This is even more challenging within highly complex environments with competing goals. Using the outlined simulation and emulation test environments, future work will develop a set of more comprehensive tests and measures for a variety of agent teamwork scenarios beyond the present role allocation problems. Also, MANET environment variables can vary greatly and significantly affect the outcome of evaluation results. As a network environment degrades, there may be no one best answer, so in future work, we plan to investigate the possibility of agent adaptation to network conditions. As the network degrades in terms of delay, capacity, or connectivity the agent teams may adapt their distributed decision methods to better match network conditions.

CONCLUSION

In summery, we have presented some recent work being performed in the area of MAS and MANET technology research. The main scope of out work is studying team-based MAS problem solving using dynamic role allocation within the context of MANET environments. Early analysis has shown that MAS teamwork communications within MANET can be improved through better design between the layers. The use and adaptation of MANET multicast is one example. We have also discovered design problem with present middleware systems (e.g., JXTA[JX]) often used by agent to provide abstracted service discovery and communication services. Further improvements are being examined relating to MANET application scenarios.

We have developed and described a set of test tools including both simulation and emulation to further study detailed scenarios of combined MAS and MANET operation. An environment channel was developed to better control and exercise distributed MANET experiments and to provide agents with simulated external stimulus outside the network domain. We have adapted a lightweight middleware framework for study and we are examining services discovery and other features for possible interagent use in MANET. We have also adopted the SMF multicast routing prototype for MANET and we are applying this as a means for more efficient inter-agent group multicasting.

Presently, we are beginning detailed emulation and simulation studies involving prey/predator agent scenarios within both the MANET simulation and emulation environments. We plan to study the tradeoffs of various distributed role allocation approaches and the effectiveness of various MANET protocol enhancements on agent performance.

Early results confirm our initial hypothesis that classic MAS and middleware communication design assumptions may be invalid when applied in MANET environments. More recently, other researchers are examining related areas and have reported similar issues. and Additional research will be aimed towards better understanding the performance tradeoffs and improving designs in a variety of MAS scenarios and MANET environments.

We would like to acknowledge the contributions of other NRL scientists within the PROTEAN™ Research Group for their valuable input on this project. Justin Dean, Ian Downard, Brian Adamson, and Rick Jones all deserve acknowledgements.

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