A CROSS-LAYER NETWORK SUBSTRATE FOR THE BATTLEFIELD

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ABSTRACT

This paper describes the initial design and implementation of a cross-layer communications substrate for tactical networks. Traditional cross-layer strategies for MANETs often rely on the direct interaction between neighbor layers in the communications stack. We propose a different approach, where all lower layers (PHY, MAC and NET) directly interact with the overlying applications (or communications middleware). In this work, we discuss some of the requirements for cross-layer support in a tactical environment. We also introduce our proposed design for a cross-layer communications substrate for such environments, concluding the paper with a brief description of our current proof-of-concept implementation and future research proposal.

1. INTRODUCTION

Tactical networks are defined, for the purpose of this work, as mission-oriented mobile ad hoc networks (or MANETs) under policy and resource constraints. Although significant advances have been made in MANET technologies and protocols in recent years, most current implementations still rely on traditional layered networking models, with very limited (if any) state information exchanged between layers.

As opposed to their wired counterparts, tactical wireless networks are potentially highly dynamic, which often prohibits the traditional session-based hard QoS allocation. For instance, in wired networks the allocation of resources for different data flows can be established (or reserved) at admission time. In tactical networks such strategies are rarely applicable due to relatively frequent changes in network topology and link conditions.

In this paper we introduce a cross-layer network substrate specifically designed to operate as a supporting communications infrastructure for the battlefield. The target network environments are mobile ad hoc networks where policies and resource constraints require the dynamic prioritization and allocation of resources for mission success.

The networking substrate proposed in this work is different from traditional approaches in several aspects. It provides a common interface for applications (or an overlying communications middleware) to access information not only from the transport layer but also the routing and medium access layers.

It also provides a central coordination point that maintains state from all layers and can make selective decisions about optimization strategies, and it also allows for efficient data sharing between layers.

This paper will first introduce some of the requirements of the communications infrastructure for tactical environments. We will then provide a brief review of related work in cross-layer networks for ad hoc environments, and follow with the introduction of our proposal. Some of the core capabilities envisioned for the proposed design will be discussed and the paper will conclude with a brief discussion of a proof-of-concept framework implemented as part of this effort.

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2. COMMUNICATIONS NETWORKS FOR TACTICAL ENVIRONMENTS

The communications infrastructure is one of the most critical components in military combat operations. In general, the battlefield communications infrastructure is expected to be flexible enough to support highly dynamic environments, with constantly changing requirements and capabilities, and yet reliable, secure, and robust to multiple types of failures.

The communications environment is generally hybrid, with high capacity security networks linking operations center and back-haul networks, as well as highly dynamic and resource constrained ad hoc networks.

Mobile Ad hoc networks (MANET) are often located at the edge of the network, and they are characterized by dynamic (or mobile) hosts connecting to each other with no support of fixed infrastructure such as fixed communication towers, base stations, etc. Tactical networks might leverage, but not depend on, fixed network infrastructure to operate efficiently.

The lack of infrastructure implies battery operated portable devices that are usually constrained in computation and communication capabilities, as well as resource availability. Efficient and balanced resource utilization is paramount for the survivability of the network, and mission success. Tactical networks must also be able to quickly adapt to changes in operation goals or operation tempo. For instance, while monitoring the environment in the battlefield, the network should minimize resource utilization to maximize its lifetime. However, during combat, the network should prioritize performance in lieu of resource usage.

Robustness is certainly a major requirement in such environments. The communications infrastructure must survive arbitrary node or link losses, degrading gracefully as resources expire.

The lack of infrastructure in tactical networks poses yet another very important issue associated with monitoring and control requirements. The distributed nature of ad hoc networks in general, requires that coordination components either accommodate a fully distributed model or will enforce central (or zone-based) coordination based on resource negotiation. An important requirement for tactical networks is the capability to support policy distribution and enforcement at the local level (i.e. at each local node).

Such capability is important to ensure that local utilization of resources follow pre-defined network-wide constraints, ensuring that global (as well as local) policies are not indirectly violated.

3. RELATED WORK

Traditionally, cross-layer strategies for mobile ad-hoc networks are usually design to support variations of QoS protocols inherited from the wired networks. Most approaches are, in general, based on short term adaptation between neighboring protocol layers. The goal is to detect short term changes in channel conditions to notify upper layers about new QoS capabilities and constraints.

Applications, in this model, are generally expected to adjust data rates accordingly when notified by a neighboring layer that current service expectations are no longer available.

The actual adaptation and reporting between layers is generally done after local layer adaptations are no longer possible or cost effective Goldsmith (2002). For instance, changes in signal interference plus noise power ratio (SNIR) on ad hoc links tend to vary at a much faster rate (in the order of microseconds) than changes in topology, which are usually in the order of seconds. The different time scales at each layer usually imply that local adaptation within each layer generally occurs first (and more frequently) than adaptation between layers.

The dRSVP protocol (Mirhakkak et al., 2001) provides per-flow end-to-end bandwidth guarantees for requirements specified as a ‘range’ of acceptable values. Nodes in dRSVP exchange bandwidth reservation details through a signaling protocol and the flow is either allowed access or dropped if resource availability is (or becomes) insufficient. Once bandwidth resources are allocated, the application is responsible for enforcing the data rate, and for periodically refreshing its allocation state.

Signaling for short term resource reservation is also used by the SWAN Protocol (Ahn, 2002). SWAN, like dRSVP, is fully decentralized, however it is best-effort only and makes no assumptions about underlying QoS capabilities form the MAC layer.

The signaling in SWAN is intended for flow admission and the cross-layer nature of the protocol lies in the fact that MAC-level packet delay information is shared and used for estimating medium access contention. After a flow is admitted in SWAN, the protocol uses the packet's explicit congestion notification flag (ECN) to notify that requested services are no longer supported for that flow. Other cross-layer architectures that provide similar capabilities include Timely (Bharghavan et. al., 1999), Spine (Sivakumar et al., 1998) and CEDAR (Prasun, 1999).

4. THE CROSS-LAYER NETWORK SUBSTRATE

The main objective of the proposed cross-layer substrate is to allow for multi-layer information exchange coordination. The goal is to aggregate and expose information in all layers to all components so better decisions can be made for a given context. Consider for instance a common interface that would allow a communications middleware to selectively choose how to improve network capacity, for instance through topology control, MAC scheduling or alternative routing.

By coordinating control and feedback information from all layers into a single component, more effective coordination mechanisms may be devised to adopt different adaptation strategies for different contexts.

Figure 1 provides a schematic view of the proposed architecture. The 'Controller' component is essentially a coordination element that makes decisions about individual control commands based on communication requirements.

The controller has access to an aggregate view of all layers, maintained by the local node state monitor. This information includes, for instance, the list of neighbor nodes with associated link quality to each neighbor (PHY), details about route stability to each node (NET), and packet collision estimates (MAC).

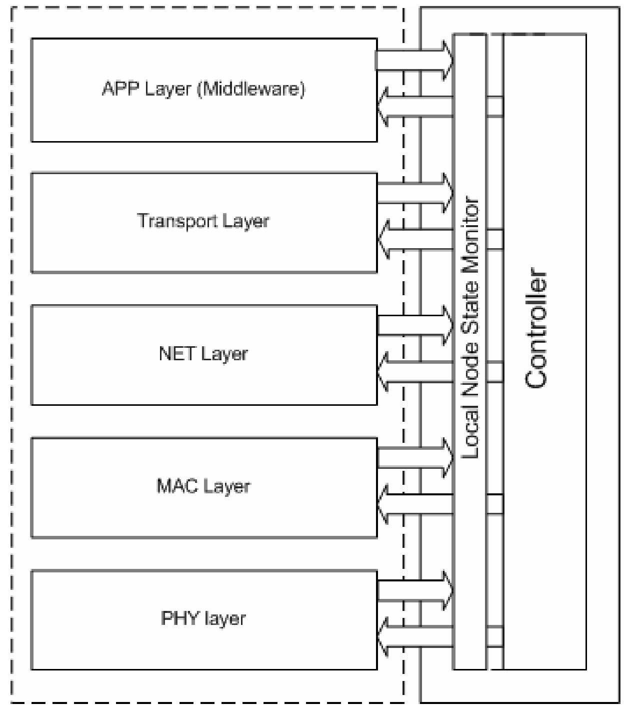

Figure 1. Cross-layer integration through a common controller component

Specific details about each layer depend on the actual protocol in use, and might not be necessarily be available in all implementations. For instance, for some reactive routing protocols, there might not be information available about redundant routes. The aggregate information structure maintained by the Local Node State Monitor is able to account for incomplete or missing data.

In order to support multiple protocols, a generalized architecture (Figure 2) is proposed where the main coordination controller essentially interacts with a layer-specific controller that interfaces to several possible implementations for each layer.

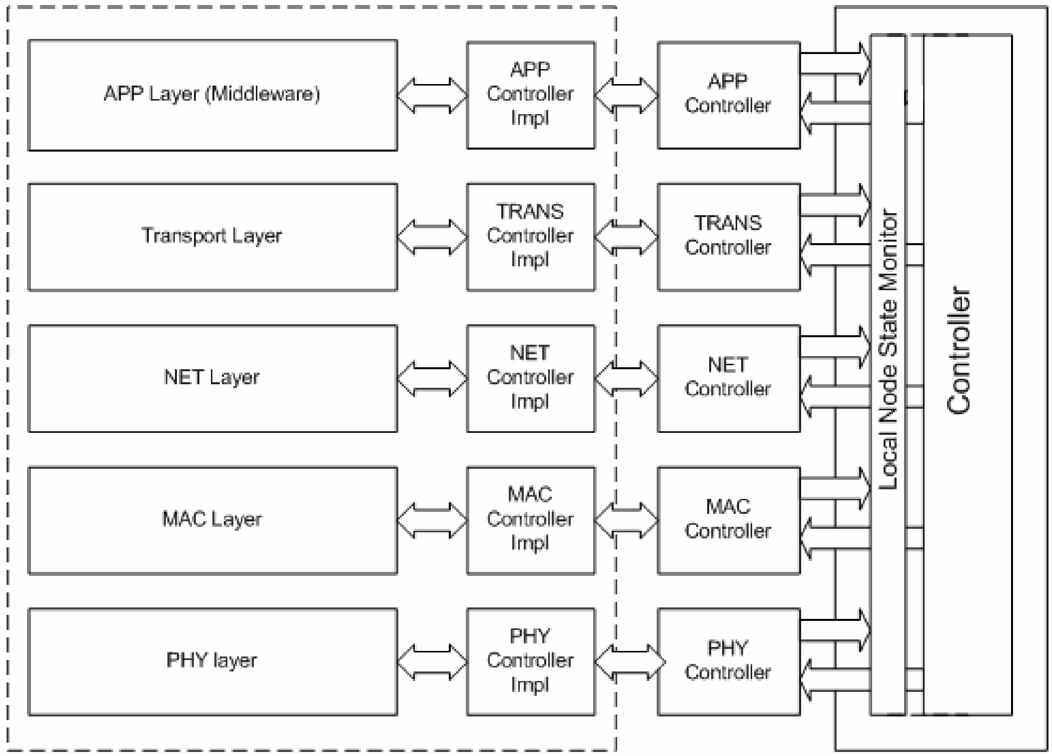

Figure 2. Cross-layer components with adaptable interfaces.

The network substrate is expected to support four core capabilities, which may be extended based on the choice of protocols for each layer. The following are the base capabilities expected for the cross-layer substrate.

4.1 Information sharing between middleware and network substrate

Sharing information between layers is possibly the most common goal of cross-layer strategies. Generally, lower layers essentially notify upper layers of changes in minimum QoS capabilities, while QoS requirements are often relayed in the reversed direction.

The middleware may benefit from lower-level information such as the set of neighbor nodes, the link quality and reliability to each neighbor, etc. to better schedule application requests based on current resource availability.

Information can also be exposed in the opposite direction, that is, from the middleware to the communications layer. Such information includes the communications profile of overlay applications (i.e. estimated bandwidth utilization, and traffic pattern) and is used by the communications layer to better allocate resources both at the Network and MAC levels. At the network level, for instance, the routing protocol will utilize different link weights based on the expected duration of the session (as reported by the middleware) for that specific traffic. Such weights will give preference to more stable links for longer sessions, while maintaining different routing criteria for other applications.

At the MAC level, packet scheduling will be modified to prioritize sessions based on application and flow requirements, even after flow admission.

4.2 Efficient Middleware-level information propagation

Route discovery and maintenance messages, for instance, are utilized to distribute application-specific state and control information, reducing the overall number of messages and bandwidth utilized for control.

Routing messages may also be utilized for service registration and discovery, following an approach previously proposed by Garcia-Macias J. and Torres D. (2005).

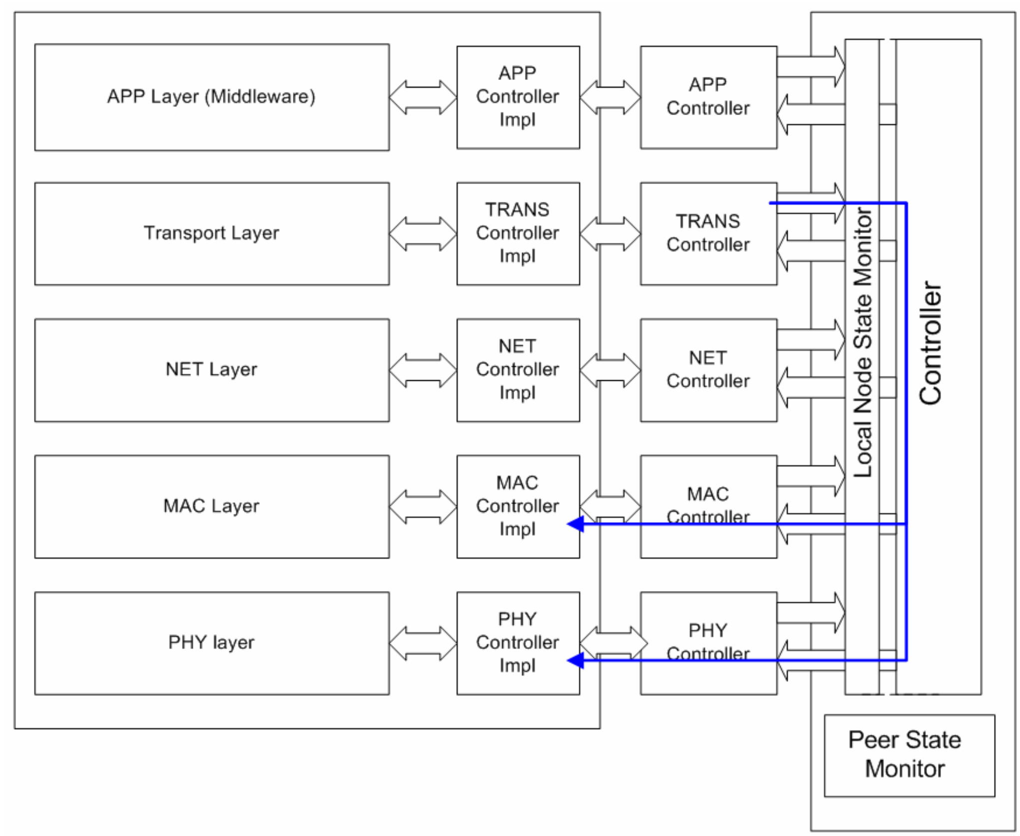

Figure 3. Routing layer or Middleware requirements coordinating wireless capacity (topology control and MAC scheduling)

4.3 Low-level adaptation based on middleware information

The transport, routing and MAC protocols are modified to take advantage of application-level information to better adapt to traffic requirements. For example, the middleware may start a data stream and provide the expected duration and priority of the flow which, within policy constraints, will be used by the routing layer for path selection and also by the MAC layer to prioritize packet scheduling.

4.4 Proactive resource manipulation to improve communications

This capability allows the middleware to proactively (and autonomously) manipulate network resources to enable or improve communications.

When mechanisms for topology control are available, the middleware can identify service degradation in the lower layers and adjust the topology accordingly.

Such mechanisms might include either re-positioning of mobile nodes (robotic nodes) to support immediate communication needs, or lower-level topology control mechanisms such as transmission power adjustment.

There are several topology control mechanisms for tactical networks. As part of this research, we are investigating topology control mechanisms for tactical environments.

In Granados, Montoya and Carvalho (2006), for example, a variation of the XTC algorithm for topology control is proposed for tactical networks with fast dynamics.

A subset of the proactive resource manipulation capabilities have been implemented and tested for specific scenarios with a limited number of nodes.

The paper provides a detailed description of these applications and validation of the added capabilities.

5. CURRENT IMPLEMENTATION

We have developed a proof-of-concept interface based on the optimized link state protocol for the Agile Computing Middleware (ACI) (Suri, Bradshaw, et al., 2003; Suri, Carvalho, et al. 2003)

ACI was developed in collaboration with ARL and AFRL for opportunistic resource allocation in tactical environments. The framework supports interfaces with a policy framework (KAoS – Bradshaw, 1997) and provides two access API's for applications, the Mockets (Suri et al., 2005; Tortonesi et al., 2006) and the FlexFeed API (Carvalho & Breedy, 2002; Carvalho et al. 2005).

Currently, the implementation provides a two-way interface between the middleware, transport and routing layers, with a one way (querying only) access to the medium access layer.

The Network layer in the current implementation uses an open-source version of the Optimized Link State Protocol (OLSR - Clausen and Jacquet, 2003) provided by OLSR.ORG.

OLSR utilizes the concept of multipoint relay nodes (MPR) to efficiently support flooding in the network, which is used to propagate changes in network topology and link state through the network. Topology updates are shared through a special message (TC Message).

Periodic broadcast messages (HELLO messages) are utilized by OLSR to discover and maintain topology information, ant to estimate link quality by tracking packet loss. The reference OLSR implementation has a modular structure that supports customized plugins for creating and handling generic messages.

A specialized plugin (ACI Plugin) was designed to support the interfaces with the Agile Computing Framework.

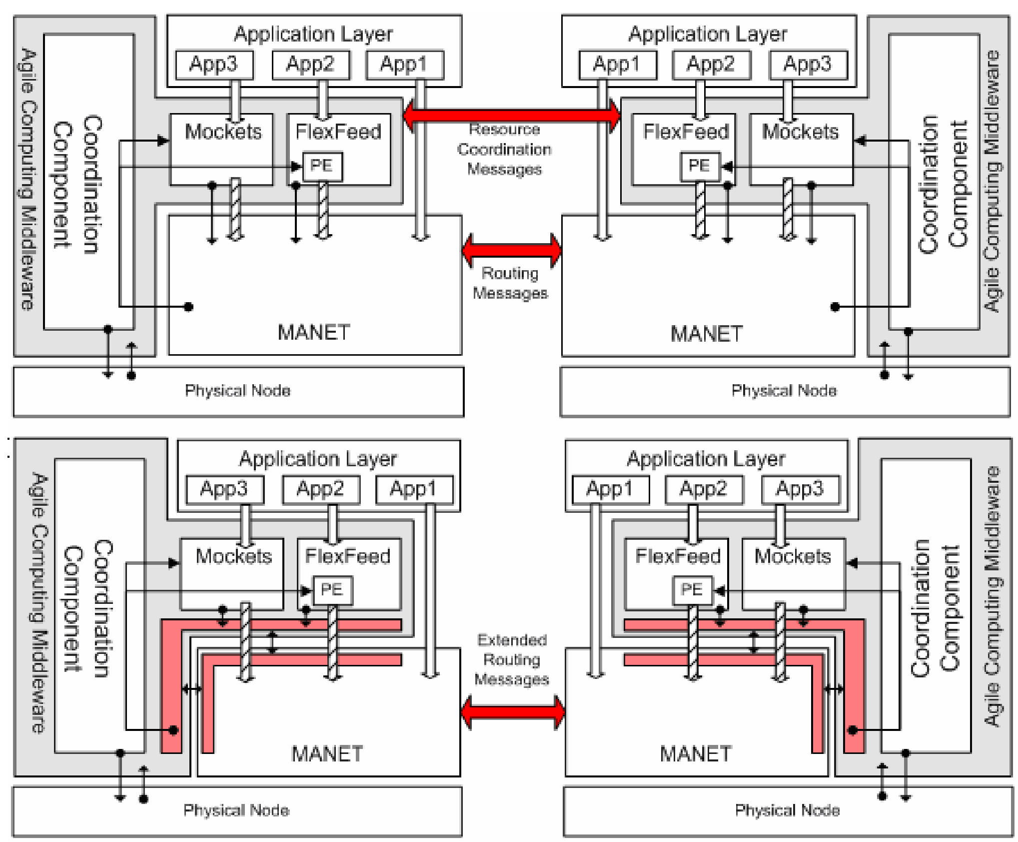

Figure 4. Integrating the current proof-of-concept implementation with eh Agile Computing Framework

All broadcast messages delivered to the plugin are automatically scheduled by OLSR to be appended to standard routing messages (Hello and TC). There is a maximum wait interval (timeout period), which is a function of the pre-defined HELLO interval. Several messages can be appended to protocol packets, as long as within size constraints.

Messages sent via the plugin are broadcasted to all nodes in the network. The broadcast, however, follows the same mechanism used for route maintenance and update, based on the TC message. If messages cannot be efficiently appended to the TC packet, they will be sent independently by OLSR.

Access to the ACI plugin (Figure 4) is done through a common interface that allows for message passing between the kernel and the plugin (OLSRMessageAdapter). The component maintains a local TCP connection to the ACI Plugin and exchanges information messages with the plugin via this connection, using a simple binary protocol.

6. CONCLUSIONS AND FUTURE WORK

This position-paper we have described some of the requirements for cross-layer strategies for tactical environments. We have also introduced a preliminary design of a cross-layer communications substrate aimed to address such requirements in mobile ad hoc networks.

The architectural design of the framework is such that it can easily support multiple interfaces and protocol implementation. A proof-of-concept implementation was designed for the Agile Computing Middleware.

The approach is, in principle, applicable to support applications in general or other communication middleware, however, several of the capabilities incorporated in our designed were envisioned to support (or complement) the Agile Computing Framework.

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