VERTICAL COMMUNICATION IN MULTIMEDIA MULTI-TIER TACTICAL NETWORKS

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ABSTRACT

We propose a lightweight proactive routing protocol, called Adaptive Multi-tier Routing (AMR), for vertical traffic in tactical networks. By adopting an asymmetric tree-like network topology, AMR minimizes the control overhead in the network as well as the computational complexity on intermediate nodes. Such tree topology provides both network connectivity and traffic distribution information. By routing via the tree topology, AMR automatically adapts to the network mobility and traffic dynamics. Using different routing trees for distinct traffic classes, AMR can provide service differentiation at the network layer. Simulation results show that the proposed routing protocol provides reliable data delivery, reacts dynamically to network changes and provides network layer service differentiation with low overhead.

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1. INTRODUCTION

Improving mobility and survivability has been the Army's prime objective for many years. Part of this objective is the ability of the Force to be operational upon landing anywhere in the world, to support battle planning and execution on-the-move, and to provide multimedia services involved in the military forces command and control. The communication systems that support the Force will be a heterogeneous mix of ad-hoc wireless personal area networks (PAN), local area networks (LANs) and wide area networks (WANs) supported by terrestrial, airborne and satellite links. Such heterogeneous systems form a multi-tier network architecture as shown in Figure 1. At the lowest tier, there are robotic sensors and dismounted soldiers with low bandwidth devices and limited range of up to a few hundred meters. The next tier is the maneuver network with wide area network coverage of up to 1 kilometer. The next level above the maneuver network is the airborne network, which includes manned and unmanned aircraft and aerostats. The top tier is the space layer that includes satellites. Depending on the individual application, some of the tiers may be absent in specific deployments. To communicate across different tiers, some of the nodes in the network may be equipped with multiple communication devices. We define these multi-homed nodes as the Inter-tier Access Points (IAP).

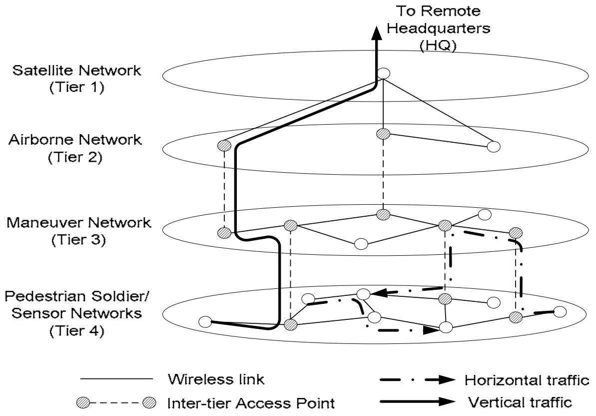

Figure 1: Communication in a Multi-tier Network

In the literature, communication between peer mobile users has been studied extensively under the category of mobile ad hoc routing [3]. The proposed ad hoc routing protocols adopt either a flat or hierarchical network architecture. In flat routing protocols [5, 6], the network is generally assumed to be homogeneous i.e., all nodes in the network share the same random access wireless channel. To reduce the overhead of flat ad hoc network architecture as well as provide better network scalability, a hierarchical (or multi-tier) architecture was proposed using either logical [7] or physical backbones [8, 9]. However, all existing ad hoc routing protocols focus on supporting the "horizontal" traffic (shown by the dash-dot arrows in Figure 1), where traffic originates and ends within the same network tier.

In tactical networks, however, large amounts of traffic occur between the units in the battlefield and the commanders located at the remote headquarters. Data collection applications in sensor networks or unmanned vehicle deployments are only some of such examples. Such operations involve extensive cross-tier traffic between the mobile units with limited communication devices and the headquarters with high communication capability, crossing multiple wireless networks. On one hand, the command and control traffic flows from the commanders or control panels, via the upper network tiers, to the soldiers or units, in the lower tier. On the other hand, the information converges from the mobile units in the lower tier to the commander in the upper tier. In contrast to the commonly studied "horizontal" traffic in ad hoc networking, we define the converging cross tier traffic as "vertical" traffic (shown by the solid arrow in Figure 1). Clearly, "vertical" traffic flows demonstrate an asymmetric distribution. As a result, routing protocols designed for "horizontal" traffic in ad hoc networks are not suitable for "vertical" communication. To support both "horizontal" and "vertical" traffic in a mesh wireless LANs, a flat on-demand routing protocol is proposed in [10]. Using the wireless LAN access points (AP) as the virtual destination of the "vertical" flows, the authors treat "vertical" traffic the same as the "horizontal" traffic. However, such virtual destination approach is only valid in the mesh wireless LANs where only two network tiers (wireless and wired) exist.

In this paper, we propose a novel lightweight proactive protocol named Adaptive Multi-tier Routing (AMR) for "vertical" traffic in multi-tier tactical networks. To adapt to traffic and topology changes, AMR chooses a route with minimum end-to-end delay between the mobile nodes (MN) and the headquarters (HQ). We observe that the end-to-end delay of each candidate route consists of the node processing delay, the node queuing delay and the radio propagation delay. Thus, the end-to-end delay represents the aggregated weights of the traffic load and the processing capability of the heterogeneous intermediate nodes along the route as well as the length of the candidate route. AMR minimizes the routing overhead by adopting an asymmetric network topology for mesh networks. The route information is updated by periodically broadcasting beacon packets from the HQ which is the root of the tree (see Figure 2). The uplink traffic (from MNs to HQ) is routed to the root of the tree (HQ) via the parent of each forwarding node in the tree. The downlink (from HQ to MNs) routes at each MN are automatically updated by its uplink traffic. By using different priority beacons and maintaining distinct routing trees for different traffic classes, AMR can provide service differentiation at the network layer.

We have implemented our protocol in OPNET Modeler [4]. The simulation results show using a MAC protocol that provides service differentiation, AMR can provide service differentiation at the network layer. The proposed protocol results in a system with the following features: 1) robust in face of link failures, 2) adaptive to nodes' mobility and traffic dynamics, 3) easy scalability, and 4) low overhead.

The rest of the paper is organized in the following way. The AMR protocol is presented in Section 2. Simulation results are presented in Section 3, and Section 4 concludes the paper.

2. ADAPTIVE MULTI-TIER ROUTING PROTOCOL

Integrating a highly dynamic communication infrastructure that supports the seamless flow of multimedia services across heterogeneous terrestrial and space based platforms is a challenging task. We propose a novel lightweight adaptive proactive routing protocol called Adaptive Multi-tier Routing (AMR) for routing vertical traffic in such a multi-tier network. The AMR protocol optimizes the network utilization by maintaining a load adaptive tree topology for the entire network. The route information is updated by maintaining a tree structure rooted at the HQ. Here, we assume that the wireless links are bi-directional.

2.1 ROUTING TREE

To provide automated capability for data flow control with minimal interruption when communication nodes are on-the-move, it is desirable to seamlessly integrate the multiple-tier heterogeneous systems into one well organized network architecture. These communication systems vary widely in their bandwidth, device capability, channel availability and bit error rate. To adapt to network dynamics, the routing metric used must adapt to the varying network environments. The best way to evaluate routes in such a dynamic network is the end-to-end delay, from the HQ to the node in question. We observe that the end-to-end delay of each candidate route consists of:

1. the node processing delay which is determined by the number of hops traveled and the processing capability of the intermediate nodes.
2. the node queuing delay, which depends on the traffic load along the route and the hops traveled.
3. the radio propagation delay, which depends on the length of the route.

Thus, the end-to-end delay represents the aggregated weights of the traffic load, the processing capability of the heterogeneous intermediate nodes along the route and the length of the route taken by the packet.

We denote the route with minimum end-to-end delay as the optimal path for each node. As shown in Figure 2, a tree-like topology can be generated by connecting each node to the top tier via its optimal path. Such topology seamlessly integrates heterogeneous nodes in the multi-tier communication systems into a well-defined network structure, which provides both the flexibility of ad hoc routing and the scalability of hierarchical tree topology.

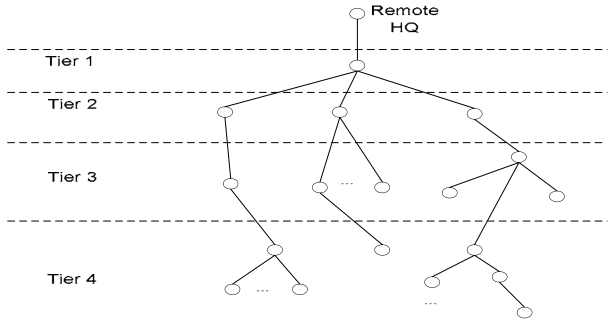

Figure 2: Routing tree for multi-tier wireless systems

2.2 TOPOLOGY DISCOVERY

Given the exact optimal path for each node in real-time, optimal load balancing for each node can be achieved at per packet level by sending each packet along the current optimal path. Unfortunately, due to the stochastic traffic patterns, the noise interference of the wireless media and the node mobility, the optimal path as well as the wireless connectivity of every node is changing from time to time. It is impossible for each node to know its optimal path in real-time. Thus, we adopt periodical topology discovery to update discretely the tree topology shown in Figure 2, which provides both the network connectivity and the traffic load information.

The topology discovery beacon is sent from the HQ to the entire network. The format of the periodic beacon is given as: (Uplink node, Sequence number). The “Uplink node” field indicates where the beacon comes from, i.e., the parent of the receiving node in the tree topology. The “Sequence number” is used to distinguish different rounds of the topology discovery process.

In a potentially unsynchronized mobile environment, we can not measure the exact route delay based on the receipt of the beacon. Fortunately, since the beacon is generated centrally from the HQ, for each lower tier node the desired optimal path is obviously the route where the beacon arrives first. By receiving a beacon with a larger sequence number, the node will record the sequence number and the corresponding uplink node where the beacon comes. The late coming beacons with the same or smaller sequence number will be discarded. A node will only forward beacons with sequence number values larger than the value that the node maintains. Before forwarding the beacon, each node will replace the “Uplink node” field with its own address.

Since each node will forward at most one beacon packet for each round of the topology discovery process, the overhead of the topology discovery process is a linear function of the beacon update rate. To obtain an up-to-date topology which optimizes the traffic balancing, it is desirable to reduce the interval between consecutive beacon packets. However, frequent beacons will increase the overhead of the protocol by increasing the bandwidth and battery power consumption. Some intelligence may be applied to dynamically adjust the beacon interval according to the network status, e.g., node mobility and traffic pattern information provided in the uplink flows.

2.3 ROUTING ALGORITHM

After the topology discovery, each node maintains the uplink node in its optimal path. Based on the tree topology, uplink routing in AMR is simply forwarding all the packets to the parent node in the tree. The great advantage is that there is no route request latency and any additional routing overhead. In addition, since the network topology is updated periodically, it adapts swiftly to traffic dynamics, route breaks and topology changes.

Unfortunately, due to the unidirectional downlink beacon propagation, the HQ located at the root of the tree topology does not have any route information to reach a specific mobile node. Therefore, additional effort is needed for the downlink routing. For the purpose of traffic balancing, the optimal path should also be used for downlink traffic. In AMR, we use the reverse path of its latest uplink packet as downlink route for any mobile node. Thus, the downlink route for any mobile node is automatically updated by its uplink traffic.

In AMR, each node maintains a per-node downlink routing table in the following format:

(Mobile Node, Next Hop, Time stamp)

The “Next Hop” field indicates the next hop of the downlink route, i.e., the node where the latest uplink packet of the “Mobile Node” comes. To guarantee the freshness and loop-free property of the downlink route, the departure time of the uplink packet from its source is included in the header of the uplink packet and recorded by the forwarding nodes in the “Time stamp” field of their downlink routing table. The forwarding nodes will only update its downlink routing table if a received uplink packet has a larger “Time stamp” than their current value in the table. Thus, the freshness of the downlink route is automatically updated by the latest uplink packet and immune to the detoured out-of-date packets.

When an intermediate node receives a downlink packet, it checks its routing table and forwards the packet to the corresponding next hop. If no route entry is found, the packet can either be discarded or be broadcasted in a top-down manner to the entire sub-tree rooted at the intermediate node in question.

2.4 PRIORITY BEACONING

Since time critical information constitutes an essential component of tactical operations, we need to incorporate in AMR the quality of service capability. We present AMR with Priority Beaconing (AMR_PB) as an extension to the AMR protocol.

In the basic AMR scheme, a unique tree topology is built for routing all the traffic in the network. By default, the beacon used has the same priority as the best effort traffic. As a result, it only provides load balancing to the aggregated traffic in the network. However, the high priority traffic is not necessarily balanced given the aggregated traffic in the network is balanced. Based on the different user priorities, we can divide the traffic in the network into Access Categories (AC) [2]. In an ideal case, distinct tree topology should be maintained for each AC for the purpose of traffic balancing. To achieve this, different classes of control beacons will participate in the topology discovery process. For each class of beacon received, the same process is triggered at each mobile node as described in Section 2.2. As a result, the network maintains multiple overlaid tree topologies for different traffic classes and packets of different ACs are routed distinctly within their own trees.

The number of beacon classes supported by the AMR_PB should be no more than the number of ACs supported at the MAC layer. For example, there will be no benefit at all to perform priority beaconing if most of the nodes in the network only have a best-effort MAC layer. Certain knowledge about the underlying MAC layer is beneficial for the AMR_PB to avoid unnecessary overheads of propagating more classes of beacons than needed.

3. PERFORMANCE EVALUATION

To evaluation the performance of the protocol, we have implemented the protocols in the OPNET Modeler. The network configuration used in all the simulations is introduced in subsection 3.1. In subsection 3.2 we investigate the performance of AMR and AMR_PB in service differentiation.

3.1 NETWORK CONFIGURATION

As shown in Figure 3, we have randomly deployed 30 nodes in a field of 400 meter wide by 800 meter long. The random way point mobility model [6] is used for each mobile node. Node speeds are determined by an independent uniform distribution between zero and some maximum value, where the maximum speed is 5m/s. The pause time is 30 seconds. Two inter-tier access points (IAPs) are located at coordinates (0, 200) and (800, 200) respectively, connecting the mobile nodes to the HQ via a satellite.

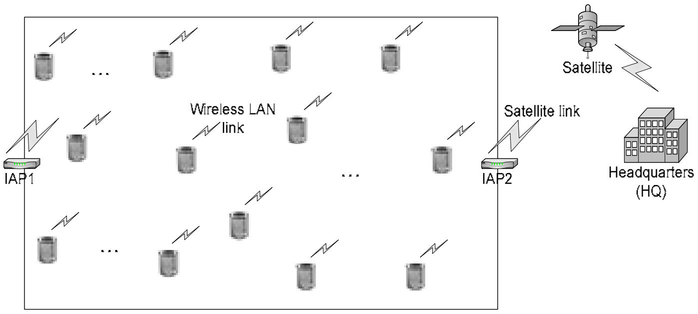

Figure 3: A three-tier network scenario

Bi-directional constant bit rate (CBR) flows are used to evaluate both the uplink and downlink efficiency of the proposed protocol. Each flow has 80 Kbps (half of which is downlink and half uplink) with fixed packet size of 512 Bytes. There are 8 best effort CBR flows and 8 real-time CBR flows established between the HQ and the randomly chosen mobile nodes. The flows start randomly between 5 and 10 seconds.

As described in the prior section, service differentiation can be achieved only if there is a prioritized MAC protocol. The MAC protocol we used in all simulations is a simplified version of EDCF [2] MAC protocol which is presented in the Appendix. The MAC protocol parameters are defined in Table A in the Appendix. The mobile nodes and the IAPs have a nominal data rate of 2 Mbps and range of 200 meters.

As shown in Figure 4 below, the distribution and movement of each mobile node with real-time traffic is I.I.D in the region X while that of best effort nodes are within region Y. All the other nodes are moving randomly within the entire field. We vary the distribution balance of the different ACs for the follows two cases:

- Distribution A: X covers a sub-field whose x-coordinate within [0, 600], and Y covers a sub-field whose x-coordinate within [200, 800]
- Distribution B: X covers a sub-field whose x-coordinate within [0, 400], and Y covers a sub-field whose x-coordinate within [400, 800].

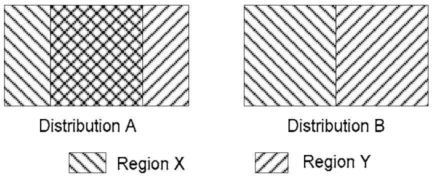

Figure 4: Traffic distribution patterns

Both AMR and AMR_PB are simulated with the overall beacon interval of 1 second. For AMR_PB, two classes of beacons are used by the HQ for best-effort (BE) and real-time (RT) ACs, respectively. The beacons of each traffic class are evenly interleaved and, thus, have the same beacon interval of 2 seconds. We define and measure the following key performance metrics for service differentiation:

1) *Average end-to-end delay*: the average end-to-end delay of data packets that belong to the same AC;
2) *Aggregated throughput*: the total throughput of data packets that belong to the same AC.

All simulations run for 900 simulated seconds. Each point in the following figures represents the average value from 6 runs under the same settings with different random seeds.

3.2 PERFORMANCE

From Figures 5 to 8, we observe that for both AMR and AMR_PB routing protocols, the performance of real-time traffic (indicated by the shadowed bars) is always better than the best effort traffic (white bars). This is due to the fact that we use a QoS enabled MAC layer in both cases. However, notice that AMR_PB provides better service differentiation, (i.e., larger performance gain for RT traffic over BE traffic) than AMR in both traffic distributions, with the same overall beacon overhead. The improvement on service differentiation by AMR_PB is due to the fact that AMR_PB interacts with the MAC and builds different routing trees for each AC. Such performance improvement in AMR_PB demonstrates the effectiveness of traffic load balancing achieved by the proposed protocol.

As shown in Figure 5 and Figure 6, the delay of the RT flows is reduced by 50% under AMR_PB in both traffic patterns, compared to AMR. As shown in Figure 7 and Figure 8, the aggregated throughput of RT flows in AMR_PB is also higher than that in AMR.

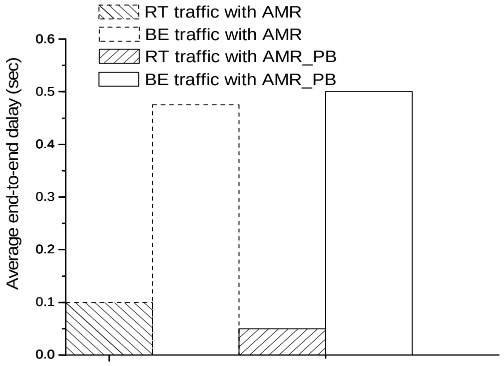

Figure 5: Average end-to-end delays with traffic pattern A

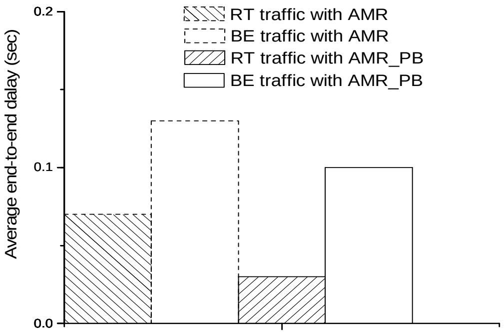

Figure 6: Average end-to-end delays with traffic pattern B

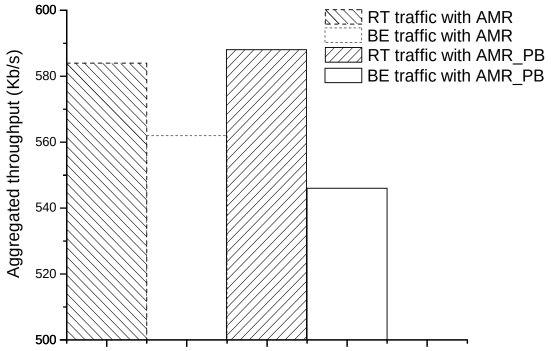

Figure 7: Aggregated throughput with traffic pattern A

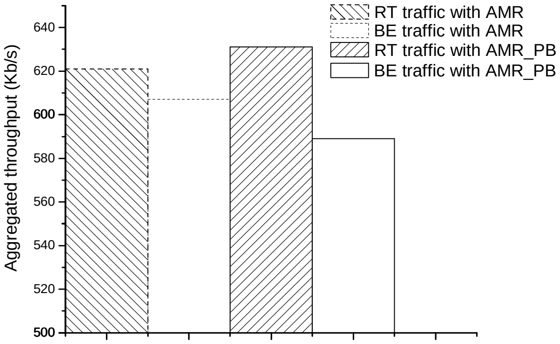

Figure 8: Aggregated throughput with traffic pattern B

4. CONCLUSION

In this paper, we introduced a lightweight proactive routing protocol, AMR, for vertical communication in heterogeneous multi-tier tactical networks. By maintaining a tree topology for the multi-tier network, the proposed AMR protocol provides effective load balancing and routing with minimum control overhead and computation complexity. By building distinct routing trees for different traffic classes, and using a MAC protocol that provides service differentiation, AMR can provide service differentiation at the network layer. Simulation results show that AMR provides reliable data delivery; reacts dynamically to network changes and provides network layer service differentiation with low overhead.

APPENDIX: SIMPLIFIED EDCF (S-EDCF)

Due to the fact that the wireless channel is a shared resource requiring MAC layer arbitration, QoS enhancement at the MAC layer is inevitable to achieve neighbor-wide prioritized channel access. To provide distributed neighbor-wide prioritized medium access, the IEEE 802.11 task group E has proposed an Enhanced DCF (EDCF) in their recent draft [2]. In EDCF, each node has up to 8 Access Categories (AC) to support 8 user priorities (UP). One or more user priorities can be assigned to each AC, where the priority of each AC refers to the lowest user priority assigned to that AC. EDCF proposes the use of traffic classification and prioritized CSMA/CA using distinct inter frame spacing intervals (AIFS) and contention windows (CW) for different ACs. Collisions between contending ACs within a node are resolved within the node such that the higher priority ACs receives the transmission opportunity and the lower priority colliding AC(s) behave as if there were an external collision on the channel. The basic channel access scheme of EDCF is illustrated by Figure A.

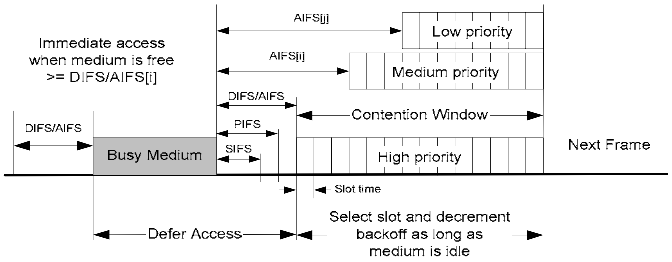

Figure A: IEEE 802.11e EDCF

As we observe, there are multiple DCF processes in each node which introduces heavy operational overhead. To reduce the implementation complexity of each node while still providing distributed neighbor-wide priority channel access, we introduce a simplified derivative function based on EDCF, named S-EDCF. The difference between S-EDCF and EDCF is that S-EDCF uses a per-node medium access strategy instead of per-AC based approach in EDCF.

For each node using S-EDCF, only the highest priority AC (currently with packets to send) will compete for the channel. The node will automatically choose a different parameter set based on the priority of the packet currently under service. Since the node can decide which packet to send right before transmission, this approach allows strict priority scheduling within a node. Similar to EDCF, data streams with higher AIFS, CWmin and CWmax values, i.e., longer defer and back-off times, have lower priority access to the wireless media. Table A shows an example of the employed parameters for two traffic classes, real time and best effort.

Access Categories (ACs)	**Inter Frame Spacing (IFS)**	**Contention Window (CW)**
(1) Real-time	DIFS	CWmin, CWmax
(2) Best effort	DIFS+TimeSlot	2CWmin, CWmax

Table A: Parameter sets for S-EDCF

TimeSlot is the duration of a time slot, DIFS is the distributed inter-frame spacing interval, CWmin is the minimum contention window size for DCF, and CWmax is the maximum contention window size for DCF. The values of these parameters are determined by the IEEE 802.11 standard [1].

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