COST ADAPTIVE MECHANISM TO PROVIDE NETWORK DIVERSITY FOR MANET REACTIVE ROUTING PROTOCOLS

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ABSTRACT

We develop a Cost Adaptive Mechanism (CAM) that can be used with any MANET reactive routing protocol employing a route discovery *mechanism. Through CAM, various link cost metrics are gathered, including transmission power required on a link, remaining battery life, and traffic load of each node. A* route selection time window *is introduced to allow the destination node and the source node to select among viable routes according to current network needs, thereby providing a level of* network diversity. *We evaluate the performance of CAM and present our preliminary results.*

I. INTRODUCTION

A mobile ad hoc network (MANET) is an autonomous collection of mobile nodes forming a dynamic wireless network. The administration of such a network is decentralized: each node acts both as host and router and forwards packets for nodes that are not within transmission range of each other. A MANET provides a practical way to rapidly build a decentralized communication network in areas where there is no existing infrastructure or where temporary connectivity is needed, e.g. emergency situations, disaster relief scenarios, and military applications.

The changing topology of MANETs and use of the wireless medium justify the need for different routing protocols than those developed for wired networks or multi-cell environments. Various routing protocols have been proposed in the Internet Engineering Task Force (IETF) MANET working group [1] to address the problem of decentralized routing.

In this paper, we consider MANET routing protocols that employ a *route discovery* mechanism, e.g., Dynamic Source Routing (DSR) [2], Ad hoc On Demand Distance Vector (AODV) Routing [3], and Zone Routing Protocol (ZRP) [4]. We modify the *route discovery* phase to gather various link cost metrics and introduce a *route selection time window* whereby the destination node and the source node can choose a path among viable routes according to the current network needs, e.g., choose a route which minimizes network congestion. This provides a level of *network diversity* since routes are chosen among a number of alternatives and according to the dynamic nature of the network. We refer to these enhancements as a Cost Adaptive Mechanism (CAM).

Mobile nodes operating on a battery supply have strong power constraints and network life depends on the management of this resource. The desire to use less power in routing has benefits beyond conserving power for battery life. For example, in military networks or “hostile” emergency networks (hostage situation), the nodes may desire to radiate with the least amount of power in order to minimize the probability of detection/interception. Therefore, a MANET routing protocol should be *power efficient*. However, none of the proposed protocols consider the power consumption and battery life of each node in the choice of the “best” route from a source to a destination. The shortest path does not necessarily correspond to the most power efficient route, as shown in [5], where a minimum power routing (MPR) algorithm was developed. MPR selects the path between a given source and destination that will require the least amount of total power expended, while still maintaining an acceptable signal-to-noise ratio (SNR) at each receiver. However, a power efficient path may not route all of the intended packets and respect the network time constraints simultaneously. Therefore, the routing protocol should also consider the *traffic load* of each node in order to minimize the end-to-end delay.

In this paper, we introduce the concepts of CAM and propose to extend the ideas developed in [5] to MANET reactive routing protocols that use a *route discovery* mechanism. Specifically, we propose to modify the *route discovery* and *route maintenance* mechanisms to take into account transmission power required on a link, remaining battery life of a node, and traffic load of each node.

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II. MANET REACTIVE ROUTE PHASES

A. Route Discovery Mechanism

In a MANET reactive routing protocol, e.g., DSR, if node S wants to communicate with node D, it needs to find a route on demand by using a *route discovery* mechanism. Node S broadcasts a route request packet (RRQ) in the network. The first node receiving the RRQ that has a valid route in its Route Cache for node D initiates a route reply (RRP) back to node S containing the list of nodes along the path from node S to node D. It may occur that destination node D itself receives an RRQ packet, e.g. no node along the way before node D has an accurate route from node S to node D in its Route Cache. In this case, node D sends an RRP packet containing the path just created dynamically from source S to destination D, i.e., the path traversed by the first RRQ packet received by node D. This path is the minimum delay route from node S to node D. Node D discards all RRQ packets arriving after the first RRQ packet.

B. Route Maintenance Mechanism

The *route maintenance* mechanism ensures that the paths stored in the Route Cache are valid. If the *data link layer* of a node detects a transmission error, the node creates a route error packet (RER) and transmits it to the original sender of the data packet. For the error detection, several acknowledgement mechanisms may be used. This RER packet indicates which link is "broken", i.e., the node that detected the error and the node it was trying to reach. When a node receives an RER packet, it removes the link in error from its Route Cache and for each route containing this link, truncates the route from the hop before the broken link.

III. COST ADAPTIVE MECHANISM

A. Standard Model

We implement a reactive routing MANET protocol in order to have a benchmark for CAM. This model uses the *route discovery* and *route maintenance* phases. The main ideas of these mechanisms are extracted from the DSR specification [2].

For the *route discovery* phase**,** we assign a maximum length of a route: MaxLength, i.e., an RRQ packet is not forwarded if the current number of hops is equal to MaxLength. An RRQ packet (Fig.1 without gray fields) is assigned a time to live (TTL) by the initiator of the request and has a sequence number, which prevents a node from forwarding an RRQ packet it has already seen. If a node is already in the path collected in the RRQ packet, it discards the packet. If after a *Waiting Reply* period no RRP packet has been received, the RRQ is renewed. After five retransmissions of the RRQ packet, the target is declared unreachable for a certain *back-off period*. After this period, the node may retry to obtain a route to this destination node.

When an RRP packet is created by a relay node or directly by the target of the RRQ packet, it is sent by reversing the path followed by the RRQ: this allows only bi-directional links to be used. Every node along the route updates its Route Cache: it updates its Cache from itself to the target of the RRQ and also from itself to any intermediate nodes in the route toward the target node.

We implement the *route maintenance* mechanism with the following three characteristics: i) We use the pure ALOHA medium access layer and add a no-delay acknowledgement (ACK) mechanism on each link in order to detect a link in error. ii) We use a promiscuous mode in which every node that hears an RER packet (Figure 2) cleans its Route Cache from the broken link. iii) When the original sender of a data packet receives an RER packet, it cleans its Route Cache and creates a new RRQ packet whose target is the previous unreachable destination of the data packet.

The *route maintenance* mechanism is the same as described in section II.B for the use of an RER packet. The difference is that in our model a route error is detected at the MAC layer level (when no ACK is received).

B. Model with CAM

We enhance our Standard Model with the concepts of CAM and adapt the *route discovery* and *route maintenance* mechanisms.

For the *route discovery* phase, we modify the format of an RRQ (Figure 1 with gray fields) packet and use it to collect several metrics along the path as described in Section III-C. This allows the destination node D to select a route based on the collected metrics. CAM capitalizes on the fact that destination node D may receive several RRQ packets. When node D receives the first request from node S, it starts a timer for the *route selection time window*. When this period is finished, node D selects a route among all viable routes according to the computation of a decision function. The parameters of the function may be any of the metrics, i.e., current network needs, or a weighted expression of the metrics, thereby providing a level of *network diversity.* The decision function is described in Section III-D. Once the "best" route is selected, node D sends an RRP to the initiator of the RRQ packet by reversing the route.

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Likewise, node S uses a *route selection time window* to select a route among the several RRP packets that it may receive. This time window must be longer than the one at the destination node in order to receive an RRP packet from the target. Moreover, if node S receives an RRP packet directly from node D, it chooses the route provided by this RRP packet, since it must be the most accurate one.

Source	Destination	Relay	Type	Location
Seqnumber	Sizeroute	segleft	TTL	Powertx
Node_I	Power_i	Load_i	Battery_i	Activity_i

Figure 1: RRQ packet format (i from 0 to MaxLength)

Source	Destination	relay	Type	Brokenlink
Segleft	Sizeroute	Node_0	Node_1	Node_2
Node_3	Node_4	Node_5	Node_6	Node_7

Figure 2: RER packet format

C. Cost Metrics for Network Diversity

In CAM, we compute various link cost metrics and store the values in the header of an RRQ packet (Figure 1). Let (i,j) denote a link between node i and node j, where $i, j \in \{1,\ldots,N\}$ with N as the number of nodes in the network. Without loss of generality, consider an RRQ transmission on link (i,j). Before node i forwards the RRQ to node j, it stores the value of the transmission power P_{Tij} it will use to transmit the packet in the header of the RRQ in the field « Powertx ». Also, it stores its location provided by a positioning system (e.g., GPS) in the field «Location ». Note that the « Powertx » and « Location » fields are overwritten by the next node forwarding the RRQ packet. When node j receives the RRQ packet, it computes its remaining battery power B_j and its load L_j (buffer queue size).

Initially, a battery life $B_j(0)$ is allocated to every node j. The battery life is a decreasing function of time and of the number of processed packets. For example, when a packet is received, power is expended to receive and process the packet. The battery life at time t can be expressed as

$$B_j(t)=B_j(0)-\sum_{t=0}^{t=G_j(t)}\left[C_P(t)+C_T(t)\right]-\sum_{t=0}^{t=X_j(t)}\left[C_R(t)+C_P(t)\right]-\sum_{t=0}^{t=R_j(t)}\left[C_R(t)+C_P(t)+C_T(t)\right] \quad (1)$$

where:

$G_j(t)=$ Number of packets generated by node j up to time t.

$X_j(t)=$ Number of packets received by node j up to time t.

$R_j(t)=$ Number of packets relayed by node j up to time t.

$C_P(t)=$ Processing power cost of packet t.

$C_T(t)=$ Transmitting power cost of packet t.

$C_R(t)=$ Receiving power cost of packet t.

Node j also computes the transmission power required by node i to *reliably* communicate with it based on current channel conditions at node j. Let P_{Rij} denote the received power, which is given by $P_{Rij}=KF_{ij}P_{Tij}r_{ij}^{-h}$, where F_{ij} is a non-negative random attenuation for the effects of shadowing and fading on link (i,j), r_{ij} is the distance between node i and node j, h is the path loss exponent and K *is* a constant for channel characteristics, e.g., bandwidth and antenna gains.

Let N_0 /2 denote the power spectral density of the thermal noise, P_{Iij} the power of the interference at node j due to all nodes excluding node i, R the data rate in bits per second, and W the system bandwidth in Hertz. The estimated bit-energy-to-noise density ratio $\bar{x}_{ij}$ is given by

$$\bar{x}_{ij}=\frac{P_{Rij}/R}{N_0+P_{Iij}/W}=\bar{S}_{ij}P_{Tij}r_{ij}^{-h} \quad (2a)$$

$$\text{where } \bar{S}_{ij}=\frac{KF_{ij}}{R(N_0+P_{Iij}/W)} \quad (2b)$$

$\overline{S_{ij}}$ can be interpreted as a dynamic link scale factor that reflects the current channel characteristics and interference on link (i,j), $\overline{S_{ij}}$ is determined from $\bar{x}_{ij}$, P_{Tij}, and r_{ij}. Then the estimated transmission power necessary to reliably communicate on link (i,j) is given by

$$\bar{P}_{Tij}=\frac{x}{\bar{S}_{ij}r_{ij}^{-h}} \quad (3)$$

where x is the required bit-energy-to-noise density ratio to achieve an acceptable SNR. Estimated power $\bar{P}_{Tij}$ is stored in the field « Power_i » of the RRQ packet and will be used in the decision function at the destination node.

We modify the format of an RRP packet in order to spread the estimated transmission powers along the path. Note that the RRP packet format is similar to the format of an RRQ format (Figure 1): all the gray fields are removed except « Power_i » fields. When a node receives an RRP packet, it updates its Route Cache as in the Standard Model. The difference is that a route is not only a list of nodes but also a list of transmission powers to be used on the links forming the path. Thus we modify the Route Cache as shown in Figure 3.

Dest	**Route**
j	$\{i;P(i\to i_1)\},\{i_1,P(i_1\to i_2)\}\ldots,\{i_n,P(i_n\to j)\}$

Figure 3: Route Cache of node i.

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Moreover, each node maintains (and updates) a Transmission Power Table, with entries for immediate neighbors, containing the estimated optimal transmission powers that the node obtains via RRP packets. Note that this table is the result of all the RRP packets received, and each power level is more accurate than in the Route Cache, since the information is fresher. Thus, when a node forwards a data packet, it uses the transmission power indicated in the Transmission Power Table (Figure 4).

Link i to:	**Power level**
j	$P(i \rightarrow j)$

Figure 4: Transmission Power Table of node i

In CAM, we also consider the *activity* around a node as an indication of the ability of a node to successfully receive a packet. To this end, we define the activity of a node j as

$$A_j(t) = \int_{u=0}^{t} n_j(u) \cdot u^2 du\,, \tag{4}$$

where t is the current time, $n_j(t)$ is the number of packets heard by node j upto time t. It should be noted that this definition of nodal activity gives more significance to recent transmissions because of the increasing function $u \rightarrow u^2$. The activity $A_j(t)$ is also stored in the header of the RRQ packet.

D. Decision Algorithm

A decision algorithm is used at the target of an RRQ packet and at the target of an RRP packet in order to select the "best" route among all routes discovered in the *route selection time window*. Let Ω_{SD} denote the set of routes discovered in this time period between source S and destination D. Since various metrics are collected through the propagation of an RRQ as described in Section III-B, the cost of a path in terms of a particular metric (without loss of generality, denoted *M*) is given by the sum of the link costs along the path. Specifically, the cost of path $K \in \Omega_{SD}$ with respect to metric *M* is given by

$$K_M = \sum_{i \in K} M_i\,. \tag{5}$$

Using this notation, a weighted cost function for path *K* of metrics load *L*, activity *A*, and power *P* as defined in Section III-C, is defined as:

$$\Phi_K = a\ K_L + b\ K_A + (1 - a - b)K_P\,, \tag{6}$$

where α and β are weighing factors determined through simulation.

Let $P_{THRESHOLD}$ be the maximum power transmission of the radio device.

The following is the pseudo code for the decision algorithm:

For $K \in \Omega_{SD}$

If Maximum Power needed on a link < $P_{THRESHOLD}$

If for all links $(i, j) \in K$, $P_{ij} < B_i$

Compute the route cost Φ_K

Choose the route K such that Φ_K is minimum.

IV. PERFORMANCE OF COST ADAPTIVE MECHANISM

CAM can be used with any MANET reactive routing protocol that employs a *route discovery* mechanism. As a design choice, we implement CAM on our Standard Model, and use the simulation tool OPNET for our simulation study. In this work, we focus on route selection based on network power constraints and compare the performance of the Standard Model and CAM.

A. Scenarios

We assume a MANET using the ALOHA random access protocol. We consider a 16-node mobile network with packet generation ρ = 10 packets/second/node and a total of 16,000 packets being created. We employ a waypoint mobility scheme, which allows nodes to move in a square of 500m×500m with a constant speed varying from 0 to 10 m/s. The maximum size of a route is set to 7 hops. A list of the simulation parameters is given in Figure 5.

Parameters	Value
Frequency	2.4 GHz
Bandwidth	83 MHz
Modulation	Direct Sequence BPSK
Transmission Range	250 m
Path Loss Exp.	3

Figure 5: Network simulation parameters.

For CAM, we choose a *route selection time window* of 1 ms at the destination and 2ms at the source of the RRQ packet. As we focus on route selection based on power in the decision algorithm, α and β, in (6), are equal to zero and the battery life metric is not implemented in this first version.

Performance measures of *efficiency, average power per route*, and *number of route requests* are computed to analyze the performance of the routing protocols. Efficiency is defined as the number of received data packets divided by the number of transmitted data packets. The average power per route is the average power cost of the route discovered by the RRQ packets and corresponds to the average power necessary to reliably communicate along these routes. Finally, the number of route requests is an indication of the stability of the route used by a protocol and is proportional to the routing overhead.

B. Results

For the cases studied, CAM selects a route according to the minimum power cost constraint, which frequently results in routes with more hops *and* shorter hops than those chosen by the Standard Model. Since each hop is generally shorter, this results in more reliable links and therefore, fewer route errors. This translates directly into more efficient use of network resources since fewer new route requests need to be sent. As shown in Figure 6, there are 40% fewer route requests sent by CAM than by the Standard Model. Moreover, since a route is more often available in CAM than in the Standard Model, data packets may reach their final destination with less delay.

Mobility (m/s)	0	1	2	5	10
CAM	80	818	1039	1852	2125
Standard	120	1254	1566	2258	2704

Figure 6: Number of route requests

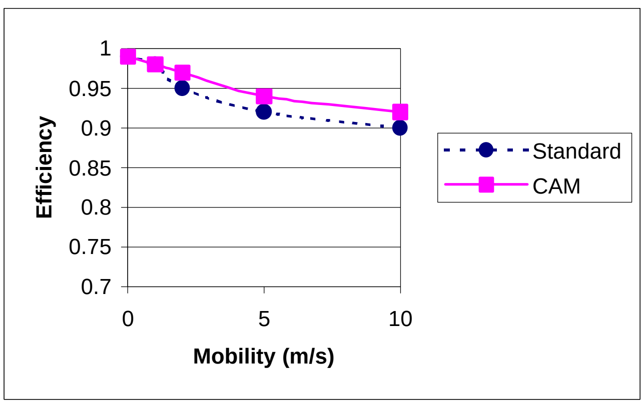

Figure 7: Efficiency vs. Mobility

CAM has more overhead in the *route discovery mechanism* than the Standard Model, since the RRQ and RRP packets have more fields and time selection windows are used for waiting for RRP or RRQ packets instead of sending data. But CAM still achieves less *overall* overhead. This is simply because in CAM an RRQ packet is sent less often than in the Standard Model (Figure 6). This also results in slightly better efficiency for CAM than for the Standard Model as shown in Figure 7.

Finally, CAM is designed to minimize power consumption by selecting routes that are the most power efficient. As expected, we observe in Figure 8 that the chosen routes consume less power than in the Standard Model, i.e., CAM routes are 15% to 20% less power costly than routes in the Standard Model. In both protocols, as mobility increases, the power consumption per route increases.

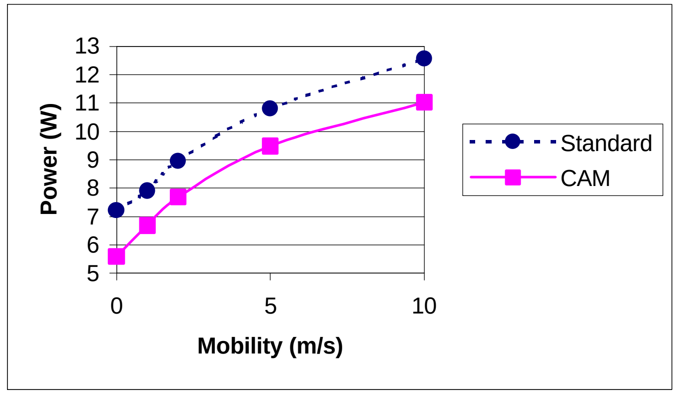

Figure 8: Power per route vs. Mobility

V. CONCLUSION

We developed a Cost Adaptive Mechanism that can be used with any MANET reactive routing protocol that uses a *route discovery mechanism*. CAM provides a level of network diversity and adapts to changing network conditions. We implemented CAM on our Standard Model of the route discovery phase and conducted an investigation of energy-efficient wireless routing in MANETs. We presented our results and conclude that using the concepts of CAM provides better utilization of network resources and more power conscious routes.

References

[1] IETF MANET Working Group Charter, http://www.ietf.org/html.charters/manet

[2] Josh Broch, David B. Johnson and, David A. Maltz, "The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks", IETF MANET Working Group, Internet-Draft, October 99.

[3] Charles E. Perkins, Elizabeth M. Royer and, Samir R. Das, "Ad Hoc On-Demand Distance Vector (AODV) Routing", IETF MANET Working Group, Internet-Draft, March 00.

[4] Zygmunt J. Haas and Marc R. Pearlman," The Zone Routing Protocol (ZRP)", IETF MANET Working Group, Internet-Draft, June 99.

[5] Madhavi W. Subbarao, "Dynamic Power-Conscious Routing for MANETs: An Initial Approach", IEEE VTC, Amsterdam, The Netherlands, September 1999.