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Energy Efficient Node Caching and Load Balancing Enhancement of Reactive Ad Hoc Routing Protocols[1]

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Abstract: Enhancing route request broadcasting protocols constitutes a substantial part of recent research in mobile ad-hoc network (MANET) routing. We suggest a novel approach to modify route request broadcast based on *node caching*. The intuition behind node caching is that the nodes involved in recent *data packet* forwarding have more reliable information about its neighbors and have better locations (e.g., on the intersection of several data routes) than other nodes. We cache nodes which are recently involved in data packet forwarding, and use only them to forward route requests. Stopping forwarding route requests from the other nodes considerably reduces routing overhead at the expense of possible destination missing. The suggested node caching techniques can be also viewed as a dynamic implementation of a connected dominating set (CDS). We overcome the known drawback of CDS – overuse of dominating (cached) nodes – by a new load-balancing scheme.

Our contributions include: (i) a new energy-efficient node caching enhancement of route request broadcast for reactive ad hoc routing protocols; (ii) an extensive simulation study in NS2 of the novel node caching enhancement of AODV (AODV-NC) showing drastic reduction in overhead, significant improvement of the packet delivery ratio and the end-to-end delay and overhead; (iii) an analysis of the forwarding load distribution and energy consumption, and (iv) an extensive simulation study in NS2 of the novel AODV-NC based routing protocol with adaptive workload balancing (AODV-NC-WLB) showing considerable improvement in throughput, overhead, delivery ratio and delay over the standard AODV for stressed MANETs.

Key Words: routing protocols, mobile ad hoc networks, Ad-hoc On-demand Distance Vector, routing load balancing, performance evaluation, node caching, energy efficiency.
Category: C.2.2

1 Introduction

A Mobile Ad-Hoc Network (MANET) is a special type of wireless network in which a collection of mobile network interfaces may form a temporary network without the aid of any established infrastructure or centralized administration. Ad hoc wireless networks have applications in emergency search-and-rescue operations, decision making in the battlefield, data acquisition operations in hostile terrain, etc. These networks are featured by dynamic topology (infrastructureless), multi-hop communication, limited resources (bandwidth, CPU, battery,

[1] Preliminary results have been published in Jung et al. (2005a) and Jung et al. (2005b). This work was supported in part by the NSF Grant CCF-0429735 and CRDF Award MOM2-3049-CS-03.

etc.) and limited security. These characteristics put special challenges in routing protocol design - see Sinha et al. (1999).

Several routing protocols for MANET's have been suggested in late 90's: DSR, AODV, DSDV, TORA, OLSR, TBRPF and others (see Perkins (2001) for comprehensive review of these protocols). The classical MANET settings assume that neither node locations nor relative locations of other nodes are available. In this paper, we consider only protocols which do not rely on location knowledge – even if each node is supplied with GPS, the node mobility implies significant communication overhead caused by location updates.

The primary objectives of MANET routing protocols are to maximize network throughput (total data reaching its destination), to minimize energy consumption, and to minimize delay. The network throughput is sometimes defined as the amount of data reaching its destination per second, while the most significant contribution to energy consumption is measured by routing overhead, which is the number and/or size of routing control packets. The general consensus based on simulations (e.g., in the network simulator NS2 (see Fall and Varadhan (1997))) is that reactive protocols, i.e., those finding routes on fly by request with no work in advance, perform better than proactive routing protocols, which try to maintain the routs for *all* source-destination pairs (see Broch et al. (1998)). Although, AODV's performance deteriorates because of flooding it is better than proactive protocol's performance. In this paper we only consider reactive routing protocols.

In hop-by-hop routing (e.g. used in Ad-hoc On-demand Distance Vector routing (AODV) (see Perkins (2001))), every intermediate node decides where the routed packet should be forwarded next. AODV uses periodic neighbor detection packets in its routing mechanism. At each node, AODV maintains a routing table. The routing table entry for a destination contains three essential fields: a next hop node, a sequence number and a hop count. All packets destined to the destination are sent to the next hop node. The sequence number acts as a form of time-stamping, and is a measure of the freshness of a route. The hop count represents the current distance to the destination node. For path discovery, route requests are generated at each hop. These route requests packets are a subset (which may or may not be proper) of the control packets. Simple flooding broadcast for route requests generates a considerable redundant packet overhead which is a major cause of inefficiency of MANET reactive routing protocols. Jung et al. (2005a) suggested constrained route request broadcast which is based on *node caching*. The nodes which are recently involved in data packet forwarding are cached and are used to forward route requests. Lee and Riley (2005) presented a workload-based adaptive load balancing technique that is based on the idea that by dropping route request packets (RREQ) according to the load status of each node, nodes can be excluded from route paths. On the contrary, Dynamic

Source Routing (DSR) uses the source routing in which each packet contains the route to the destination in its own header and each node maintains multiple routes in its cache. In case of less stressed situation (i.e. smaller number of nodes and lower load and/or mobility), DSR outperforms AODV in delay and throughput but when mobility and traffic increase, AODV outperforms DSR (see Perkins et al. (2001)). However, DSR consistently experiences less routing overhead than AODV. A hybrid protocol enhancing AODV with the advantageous route caching feature of DSR is proposed in Gwalani et al. (2003).

This paper is focused on enhancing route request broadcasting protocols constituting a substantial part of the MANET reactive routing. Several broadcasting techniques are compared in Tseng et al. (2002) and Willams and Camp (2002) concluding that neighbor-knowledge based broadcasting is better than probabilistic and area based methods in reducing packet redundancy. Another interesting approach constrains the number of detours or deviations from the known routes resulting in 50% overhead and delay reduction but insignificant decrease in *delivery ratio* (the number of packets delivered over the total number of packets sent) for DSR - see Castenada et al. (2002). The AODV protocol has been enhanced in Mosko et al. (2003) by pruning non-dominant nodes, i.e. effectively constraining route requests to a certain connected dominated set.

In this paper, we suggest a novel approach to constrain route request broadcast which is based on *node caching*. Our intuition is that the nodes involved in recent *data packet* forwarding have more reliable information about its neighbors and have better locations (e.g., on the intersection of several data routes) than other MANET nodes. We cache nodes which are recently involved in data packet forwarding, and use only them to forward route requests. As well as the previous approaches, node caching also employs the fact that the broadcast for route request is not really a broadcast - it does not need to reach all nodes but only a single required destination. Therefore, we do not forward route requests from the nodes which are not cached at the expense of possible destination missing.

Our node caching techniques can be also viewed as a dynamic implementation of a connected dominating set (CDS) based routing. Indeed, the cached nodes are supposed to cover the recent sources and destinations and are mostly connected by recent intersected paths. The known drawback of CDS is overuse of dominating nodes. We suggest to measure the protocol fairness using as parameter the distribution among MANET nodes of the *forwarding load*, defined as the total size of packets re-transmitted by a node. Note that both data and route-raquest packets contribute to the forwarding load; however data and route-request packets originating at a node do not count in its forwarding load. We confirm that node caching may cause unfair forwarding load distribution and propose a load-balancing scheme for fixing this drawback.

In this paper, we apply new energy efficiency metrics to MANET routing protocols. The goal of energy-aware routing protocols is to maximize the *network lifetime*, which is the time between beginning of operation and the moment when the first node exhausts its batteries. Also, we present a new energy efficient routing protocol that applies adaptive load balancing technique to our previously proposed node caching enhancement of the MANET reactive routing protocol.

Our contributions include:

1. A new node caching enhancement of route request broadcast for MANET reactive ad hoc routing protocols;
2. An implementation of AODV-NC, the node caching enhancement for AODV;
3. An extensive simulation study of AODV-NC in NS2 showing that in case of highly stressed MANET the routing overhead is reduced by 90% in average, the delivery ratio is increased by 20% in average, and the end-to-end delay is decreased by 63% in average;
4. An evaluation of routing protocol fairness measured as the distribution of forwarding load among nodes;
5. An implementation and simulation study in NS2 of forwarding load balanced AODV-NC showing considerable improvement in overhead, delivery ratio and delay over the standard AODV;
6. A new energy efficient AODV-based Node Caching routing protocol with Adaptive Workload Balancing (AODV-NC-WLB);
7. Novel applications of energy efficiency metrics to MANET routing protocols;
8. An implementation and simulation study in NS2 of energy efficient AODV-NC-WLB showing considerable improvement in throughput, overhead, delivery ratio and delay over the standard AODV for high work load scenarios.

The preliminary results of contributions (1-5) have been published in Jung et al. (2005a) and the preliminary results of contributions (6-8) in Jung et al. (2005b).

The rest of the paper is organized as follows. In the next section, we describe the node caching and the AODV-NC protocol. Section 3 describes the simulation study of the forwarding load distribution and suggests load-balancing modifications of AODV-NC and the adaptive workload balancing technique applied to reactive MANET reactive routing protocols. Also, we present AODV-NC-WLB, the new node cached MANET reactive routing protocol with adaptive workload balancing. Section 5 exhibits the new approaches to evaluate energy efficiency in MANET routing protocol and details of application of energy efficiency metrics to the protocols. Section 6 explains how we generate our scenarios. In Section 7 we give the results of our simulations in NS2 comparing original AODV,

AODV-NC, non-adaptive load balanced AODV-NC, and adaptive load balanced AODV-NC-WLB protocols.

2 Node Caching Enhancement of Route Request Protocol

In this section, we describe node caching enhancement of route request broadcasting in reactive ad hoc routing, give implementation details of node caching AODV (AODV-NC) and present simulation results illustrating the hit ratio and the size of the node cache.

Our goal is to cache a connected dominating set of nodes that have updated information about their neighbors while wasting no resources for finding and maintaining the cache. These requirements are very well satisfied by the nodes which have recently forwarded data packets. Indeed, a union of recent source-destination paths is expected to be well connected and dominate almost all nodes since the nodes on these paths are somehow in the center of the network. Of course, such set does not require any maintenance.

The modified route request uses a fixed threshold parameter H. The first route request is sent with the small threshold H. When a node N receives the route request, it compares the current time T with the time $T(N)$ when the last data packet through N has been forwarded. If $T - H > T(N)$, then N does not belong to the current node cache and, therefore, N will not propagate the route request. Otherwise, if $T - H \leq T(N)$, then N is in the node cache and the route request is propagated as usual. Of course, the node cache cannot guarantee existence of paths between all source-destination pairs, therefore, if the route request with the small threshold H fails to find a route to destination, then a standard route request (which is not constrained by the cache) is generated at the source.

In the default settings of AODV, if the route to the destination is broken, obsolete or unestablished, the route request originated from the source is propagated through the entire MANET. If the route reply is not received by source in a certain period of time, then the route request is periodically repeated several times. If all these Route Requests happened to be unsuccessful, several more requests with increasing time gaps are sent.

In our implementation, we tried to avoid drastic changes to the very well established AODV protocol. We restrict modifications solely to the Route Request protocol and its initiation.

2.1 Route Request in AODV-NC(H)

(1) If a requested route is not available, then send an H-restricted route request with the threshold H, i.e., for each route request, recipient N will do

- if the destination is the known neighbor of N, then N forwards the route request to the destination
- if no more than H seconds are gone from the last time a data packet has been forwarded by N, then N rebroadcasts the route request to all its neighbors

(2) The source repeats H-restricted route request 2 times if route reply is not received during time 0.3 sec after route request

(3) If no route reply received, the source sends unconstrained (standard AODV) route request with the standard repetition pattern.

We did not attempt to find the best initial threshold H theoretically. Our simulations show that on average the best choices of H are between 0.1 sec and 1 sec. If we would know in advance MANET parameters, then we can tune threshold more carefully – higher traffic intensity and mobility level correspond to the smaller threshold. As H is decreased from 1800 sec (corresponding to the original AODV) to 0.1 sec, the delay is reduced 3 times, the overhead is reduced about 10 times, while the delivery ratio does not change.

The value of H directly affects the hit ratio of the node cache, i.e., the fraction of cache-constrained route request attempts that succeeded to find the destination over all cache-constrained requests. Fig. 2 (Section 7) illustrates our simulations with different values of H - larger H corresponds to larger hit ratio. The value of H is also proportional to the average cache size, i.e. the number of nodes forwarding a route request (see Fig. 3) (Section 7). Note that the standard route request will be forwarded by all nodes except source and destination.

3 Routing Protocol Fairness and Forwarding Load Balancing

In this section, we discuss fairness of routing protocols, show how fairness and network lifetime can be measured, compare AODV and AODV-NC protocols and suggest a load-balancing scheme increasing lifetime and improving fairness of AODV-NC.

As we have mentioned in Section 1, the node cache can be viewed as CDS. While being very efficient, CDS-based protocols can overexploit the nodes which belong to CDS. This results in reducing network lifetime, defined earlier as the time between beginning of operation and the moment when the first node exhausts its batteries (assuming, e.g., equal battery supply for all nodes). We can also look at this phenomenon from *fairness* prospective as follows[2]. Each node by joining an ad hoc network is required to support multi-hop communication,

[2] The first attempt to measure fairness of CDS-based routing uses a different approach - see Mosko et al. (2003).

i.e., forward data and control packets upon request. If certain nodes are unlucky enough to forward too many of such packets, then they can claim unfairness of the network protocol and drop membership. Note that it does not matter how many packets are *generated* by a node – if a node generates too many packets, then it is fair that such node spends the energy amount for sending them. Only forwarding load is fair to account for.

For measuring unfairness, we use the *fairness ratio*, defined as the ratio of the maximum forwarding load among individual nodes over the average forwarding load. We exclude the number of sent packets since it does not depend on the routing protocol rather it depends on the scenario. Note that the absolute value of the maximum forwarding load is also important – if the network lifetime is considerably larger for one protocol than for another, then fairness ratio loses its relevance.

Fig. 4 (Section 7) illustrates the distribution of forwarding loads among 50 nodes for several protocols – the range between 0 and 4000 Kbytes is partitioned into 250/125 Kbytes subintervals and the number of nodes with forwarding load in each subinterval is reported. We can see that AODV is fair – its fairness ratio is below 1.7 – while AODV(1) and AODV(0.1) are unfair because of a jump in the distribution at 4000 Kbytes. Also the lifetime of the AODV(1) and AODV(0.1) protocols is 1.6 times shorter than AODV's.

In order to prevent unfairness of node caching we should relieve nodes which stay in the cache for too long time. Several geometric models have been proposed (see Ganjali and Keshavarzian (2004),Pham and Perreau (2003)) to impose load balancing. Our simple scheme balances the control and data packet forwarding load without using geometric knowledge of the network. We suggest a load-balancing scheme AODV-NC($H : n - t$) with the following two additional parameters – the threshold number of packets n forwarded during time t. If number of data packets forwarded by a node N during time period t is greater than n, then we relieve the node N from forwarding cache-constrained route requests for the same time period t. During the break t, the node N still forwards data packets as well as standard unconstrained route requests. But the forwarding load for N decreases since new routes with high probability will avoid N. In Fig. 4 (Section 7), one can see that AODV-NC($1 : 300 - 120$) is almost as fair as AODV and has longer lifetime. Relieving prevents unfairness but slightly worsens performance (see Fig. 6). The delivery ratio increases by 2% while delay increases by 5%.

4 Node Cached Routing Protocol With Adaptive Work Load Balancing

The forwarding-load balancing algorithm described in the previous section is not self-adaptive because the proper parameter values are found through several experiments. It means that the value of parameters should be changed for every different situations.

Below we discuss the adaptive workload balancing technique for MANET reactive routing protocol by Lee and Riley (2005). Finally, we present a new node caching AODV with adaptive workload balancing which combine the protocols from Jung et al. (2005a) and Lee and Riley (2005).

Lee and Riley (2005) presented workload-based adaptive load balancing technique that is based on the idea that by dropping route request packets (RREQ) according to the load status of each nodes, nodes can be excluded from route paths. This algorithm uses the length of the message queue in nodes and the outstanding workload which is defined as the combination of the queue length and residence time of packets in the queue. At the beginning of simulation, the minimum and maximum lengths of message queue and workload threshold are initialized. When a node receives RREQ packets, it checks the length of queue and calculates the average of two thresholds values and outstanding workload. If queue length is greater than the average threshold value and outstanding workload is greater than workload threshold, it drops RREQ packets. Otherwise, the node forwards the RREQ packet to neighbors. Meanwhile, each node calculates a new threshold value of message queue length in case of outstanding workload being greater than workload threshold. Thus workload threshold values are changed automatically.

In this work we propose AODV-NC-WLB , a combination of the adaptive workload balancing technique presented in Lee and Riley (2005) with the node cached routing protocol in Jung et al. (2005a). The node caching technique is orthogonal to the adaptive workload balancing technique that allows to combine them without major modifications. Our simulations with AODV-NC(0.1)-WLB, a version of AODV-NC-WLB, show the following:

- Workload-based adaptive load balancing (WLB) (see Lee and Riley (2005)) does not completely eliminate the original unfair load distribution in AODV-NC bounds maximum workload (see Fig. 1).

- With regard to routing efficiency, for various speeds AODV-NC shows better performance than AODV-NC- with non-adaptive load balancing as well as AODV-NC-WLB. In scenarios with a large number of pairs of nodes communicating, AODV-NC-WLB shows slight improvement in delivery ratio, *relative overhead* (the ratio of the number of control packets over the number of delivered data packets), and end-to-end delay than the rest of the protocols (see Fig. 6 and Fig. 7).

- AODV-NC-WLB improves fairness and load distribution (see Fig. 8 and Fig. 9)

5 Energy Efficiency Metrics for Routing Protocols

In this section, first we discuss the energy efficiency metrics introduced in Michail and Ephremides (2003). Then we present the details of applying energy efficiency metrics to evaluate energy efficiency in MANET routing protocols. We also discuss how to measure the energy consumption in NS2.

Michail and Ephremides (2003) introduced several performance metrics for energy efficiency - among them the average number of accepted calls per unit of simulation time. We proposed earlier the network lifetime metric.

We evaluate energy efficiency using following performance metrics:

- the total energy consumption for three different workload regimes,
- throughput with limited energy amount in nodes,
- the energy usage per packet, which is the ratio of the total energy consumption over the number of delivered data packets,
- the energy usage per hop, which is the ratio of the total energy consumed over the number of hops,
- network lifetime, which the time from beginning of simulation until first node in MANET runs out of energy.

We used energy model in NS2 to measure energy consumption of AODV, AODV-NC and AODV-NC-WLB. Even though the accuracy of energy model in NS2 has been questioned in Margi and Obraczka (2004), we used this tool because we just focus on comparing efficiency of routing protocols in the same condition.

Energy model in NS2 has three states where energy is consumed: transmitting, receiving and idle state. Every node in NS2 starts with initial value which is the level of energy defined by user at the beginning of the simulation. It also has transmitting power(TXpower), receiving power(RXpower) and idle power parameters required by the node's physical layer. These values also can be defined by user. Initial energy level is decremented for transmission and reception of packets by TXpower and RXpower. When energy level in a node becomes zero, the node does not accept or send any packets.

Following NS-2, we call *connection* a pair of nodes communicating. We implemented the experiments under three different scenarios: with 20, 40, or 60 connections. A speed of 20 m/s was used in all test cases, and the rate of packet sending used was 4 packets/sec.

In an experiment that assumes unlimited amount of energy, each of the nodes start with energy 1000J, which is enough to maintain the whole 1800 sec of simulation. We set the TX power to 0.6W, RX power to 0.3W. In this scenario, we did not consider idle states because we are just interested in energy consumed by transmitting and receiving packets.

We also tested the situation when the energy level is not enough to allow all nodes to stay alive until the end of the simulation. In this situation , we set initial energy to 300J and set the power of idle state to 0.1W.

6 Simulations

The test cases were generated using built-in random generator in Network Simulator 2 (version NS2.26) (see Fall and Varadhan (1997)). Our protocol evaluations are based on the simulation of 50 wireless nodes forming an ad hoc network, moving about over a rectangle. The basic rectangle is 1000m×300m, but we also repeated simulations for 1500m×300m and 1000m×1000m rectangles. The maximum simulation time was 1800 sec but we have recalculated the basic parameters each 250 sec. The physical radio characteristics approximate the Lucent WaveLan direct sequence spread spectrum radio. In our experiment, we have set the communication range of mobile node to 250m. At media access control (MAC) layer the 802.11 MAC protocol has been used.

Parameters of our simulation model have been chosen close to one described in Broch et al. (1998). Nodes in simulation move according to a "random waypoint" model (see Johnson and Maltz (1996)). We generated all the movement scenarios using, *setdest* program in NS2. We have chosen traffic sources to be constant bit rate (CBR) sources. The sending rate varies from 1 to 4 packets per second, the node speed varies from 1 to 20 m/s, the number of connections varies from 10 to 50. Data packet size is 512 bytes and control packet size is 48 bytes. All traffic scenarios are generated using *cbrgen.tcl* in NS2.

6.1 Performance Metrics

We compare ad hoc routing protocols reporting the following main parameters:

- the relative routing overhead, which is defined earlier as the ratio of the number of control packets over the number of delivered data packets,
- the delivery ratio, which is defined earlier as the number of packets delivered over the total number of packets sent, and
- end-to-end delay, which is average of delays between each pair of a data communication session.

6.2 Simulation Results

All results are the average of five different scenarios that have different seed numbers – 1500, 2000, 2500, 3000, and 3500. Jung et al. (2005a) found in their experiments with different threshold values of H = 0.01, 0.05, 1, 0.1, 1,5, and 10 for AODV-NC(H) that 0.1 demonstrates the best performance. Therefore, we used threshold value of H = 0.1 for AODV-NC(H) protocol for this experiment. For AODV-NC($H : n - t$), we used threshold value of H = 1 and the number of forwarded packet threshold n = 300 during time t = 120 sec. since, these parameters minimize delay. In AODV-WLB, we initialized five parameters with the exactly same values as in Lee and Riley (2005).

6.3 Routing Efficiency Metrics

We compare ad hoc routing protocols reporting the following:

- the relative routing overhead
- the delivery ratio, which is the number of packets delivered over the total number of packets sent, and
- the end-to-end delay, which is average of delays between each pair of a data communication session,
- the average number of hops and optimal hops,
- the normalized number of hops, which is the ratio of the average hops over the optimal hops, and
- the plot describing dependency between the number of delivered packets and the average number of hops.

Fig. 6 and Fig. 7 compare delivery ratio, routing overhead and end-to-end delay of 4 protocols: AODV, AODV-NC(1), AODV-NC(0.1), AODV-NC(1:300-120). Fig. 6 explores behavior of the protocols when the speed is growing from 1 to 20 m/c. All three proposed node caching protocols increase delivery ratio by 10-20% and reduce overhead by factor 10. The delay reduction for unfair protocols AODV-NC(0.1) and AODV-NC(1) is 3-4 times while the fair protocol AODV-NC(1:300-120) has a delay reduction of only 10-20%.

When there is no path to the destination through cached nodes then delay and overhead are obviously larger than that of original AODV. But due to the high hit ratio AODV-NC frequently uses cached nodes which significantly reduces overhead and delay. Also, due to lower overhead the message queue is not swamped with RREQs, and AODV-NC is less likely to drop messages, resulting in an increase in the packet delivery ratio.

Fig. 7 explores behavior of the protocols when the number of connections is growing from 10 to 50. Unfair AODV-NC protocols (respectively, the fair AODV-NC(1:300-120) protocol) increase the delivery ratio by 20% (respectively, 15%) and reduce the overhead by factor 7 (respectively, 3). The delay reduction for the unfair protocols AODV-NC(0.1) and AODV-NC(1) is 40% while the fair protocol AODV-NC(1:300-120) has only a 25% delay reduction.

We also simulate all four protocols in different rectangular regions – 1000×1000 and 1500×300. In all our simulations all NC protocols improved AODV in all three main parameters except for square region, where AODV is better than the fair AODV-NC(1:300-120). Average improvements are practically the same as for a 1000×300 rectangle.

We have also compared all four protocols for the case of high mobility and low traffic with the intention to make node caching useless. Even in this case the routing overhead has been reduced and the delivery ratio has been increased, while the only drawback compared to AODV is higher delay.

Separately we compared our protocols with AODV-PA (see Gwalani et al. (2003)) on comparable test cases. While both AODV-PA and AODV-NC(1:300-12) have the same delay as AODV, AODV-NC(1:300-12) has delivery ratio better than AODV-PA by 7%, and has considerably larger reduction in routing overhead with respect to AODV (80% vs 19% reduction).

Energy consumption of a node is proportional to the number of the sent and forwarded (data and control) packets. From Fig. 4, it follows that the maximum and average number of forwarded data packets per node for AODV-NC is considerably less than that for the original AODV. Also, from Fig. 6 and Fig. 7 it follows that the average number of control packets is 3-5 times less than that for the original AODV. Thus, our simulation data confirm that AODV-NC is significantly more energy efficient than the original AODV.

7 Results

In this section, we discuss energy efficiency and routing efficiency of MANET routing protocols using the performance metrics discussed in earlier sections.

7.1 Node Caching

Fig. 2 illustrates our simulations with different values of H - larger H corresponds to larger hit ratio. The value of H is also proportional to the cache size, (defined earlier as the average number of nodes forwarding a route request - see Fig. 3).

7.2 Forwarding-Load Balancing

Fig. 4 illustrates the distribution of forwarding loads among 50 nodes for several protocols. The range between 0 and 4000 Kbytes is partitioned into 250/125 Kbytes subintervals and the number of nodes with forwarding load in each subinterval is reported. We can see that AODV is fair – its fairness ratio is below 1.7 – while AODV(1) and AODV(0.1) are unfair because of a jump in the distribution at 4000 Kbytes. Also the lifetime of the AODV(1) and AODV(0.1) protocols is 1.6 times shorter than AODV's.

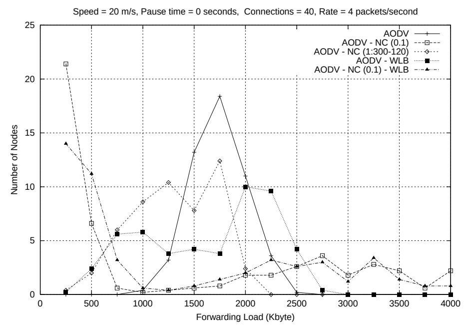

Figure 1: Distribution of the forwarding load among nodes for 40 connections.

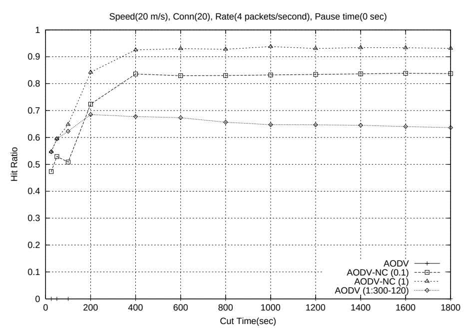

Figure 2: Average success rate of cache-constrained route requests.

7.3 Energy Efficiency

Fig. 8 shows the energy usage of five routing protocols. AODV-NC$(1:300-120)$ uses the least energy for a scenario with 20 connections while AODV-NC(0.1)-WLB has the lowest cumulative energy usage for a scenario with 40 connections. This performance can be explained by looking at the relative overhead shown

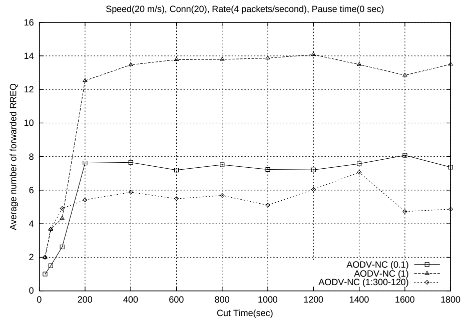

Figure 3: Average number of forwarding nodes per cache-constrained route request.

in Fig. 7. AODV-NC$(1 : 300 - 120)$ and AODV-NC(0.1)-WLB show relatively lower routing overhead for connections 20 and 40 respectively. Since, these two protocols reduce the number of routing-request packets, resulting in energy savings. AODV-NC(0.1)-WLB works better for high workload and requires fewer control packets, and therefore it is energy efficient in such scenarios.

However, the differences between AODV and the enhanced AODV protocols proposed by us in regard to energy consumption are very small. In other words, energy consumption by itself is not suitable metric to compare energy efficiency. So, we measure the throughput of protocols in networks with limited energy nodes. For the same energy consumption there is a significant difference in the throughput of different protocols. In addition, we measure network lifetime using throughput and simulation time.

In Fig. 9, AODV-NC(0.1)-WLB records the highest throughput in every scenario. AODV-NC(0.1)-WLB delivers almost 30% more packets than AODV. AODV shows the lowest throughput when the number of connections is high. Also, in this figure, we can see that the AODV-NC(0.1) is the first protocol in which a node looses all its power followed by AODV - the lifetime of AODV-NC(0.1) is the shortest among five protocols. Because of overused nodes in AODV-NC, the result is short network lifetime. On the other hand, AODV-NC$(1 : 300 - 120)$ keeps the simulation running approximately 1180 sec without having any node run out of its power supply. It means that load balancing techniques in AODV-WLB, AODV-NC(1:300-120) and AODV-NC(0.1)-WLB extend the network lifetime as well as network throughput.

From Figures 8 and 9, we observe that the total energy consumption of all the protocols is almost the same. However, the throughput of AODV-NC and AODV-NC-WLB is higher than AODV's. The throughput, measured that is the

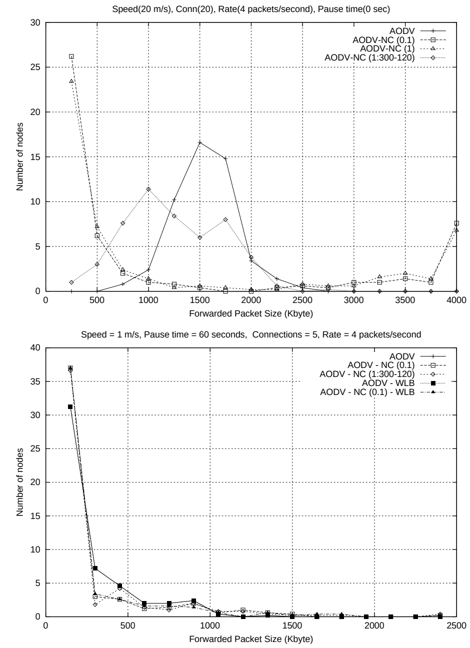

Figure 4: Distribution of the forwarding load among nodes for high (top) and low (bottom) traffic and mobility.

number of delivered packets per cut off time, is a good metric of the efficiency of a protocol.

Fig. 5 shows the energy consumption per delivered data packet and the energy consumption per hop in the scenario of 40 connections (this is a relatively high workload scenario in our simulation). AODV-NC protocols use less energy to deliver a data packet compared to AODV. Especially, AODV-NC(1:130-200) obtains almost 35% energy savings. Also, for the energy consumption per hop, AODV-NC(0.1)-WLB shows the least energy consumption. From the two plots, we can derive that load balancing technique is effective for saving energy in AODV and AODV-NC.

7.4 Routing Efficiency

We also compare the routing efficiency metrics to the average number of hops. Note that the optimal number of hops for different protocols is different since different protocols deliver different packets, e.g., AODV delivers 20% less packets than AODV-NC(0.1).

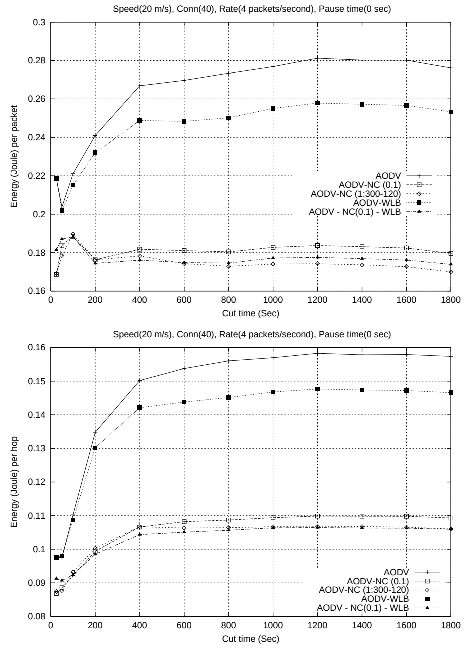

Figure 5: Energy consumption per delivered packet and hop in connection 40.

The first plot shows the ratio of average hops to optimal hops. AODV and AODV-WLB show higher ratio than other protocols while AODV-NC(0.1) shows the lowest ratio. It means that AODV-NC protocols find a shorter path than AODV. The last plot shows the distribution of delivered data packets per hops. In this plot, AODV-NC tends to send packets with smaller number of hops than AODV. AODV uses larger number of hops compared to other protocols. Between 6 and 9 hops, one can see the solid line(AODV) which is above the dotted lines(AODV-NC protocols).

Fig. 6 and Fig. 7 compare delivery ratio, routing overhead and end-to-end delay of 5 protocols: AODV, AODV-NC(0.1), AODV-NC(1:300-120), AODV-WLB and AODV-NC(0.1)-WLB. Fig. 6 explores behavior of the protocols when the speed is growing from 1 to 20 m/c. At speed 1 m/s, AODV-WLB increases delivery ratio by 12% but results in increase in the relative overhead and delay. However, AODV-NC(0.1)-WLB increases delivery ratio with decrease of relative overhead and delay. At other speeds such as 5 m/s, 10 m/s and 20 m/s, AODV-NC(0.1) shows better performance than AODV-NC(0.1)-WLB. It means that in high mobility scenarios, routing with AODV-NC combined with workload-based

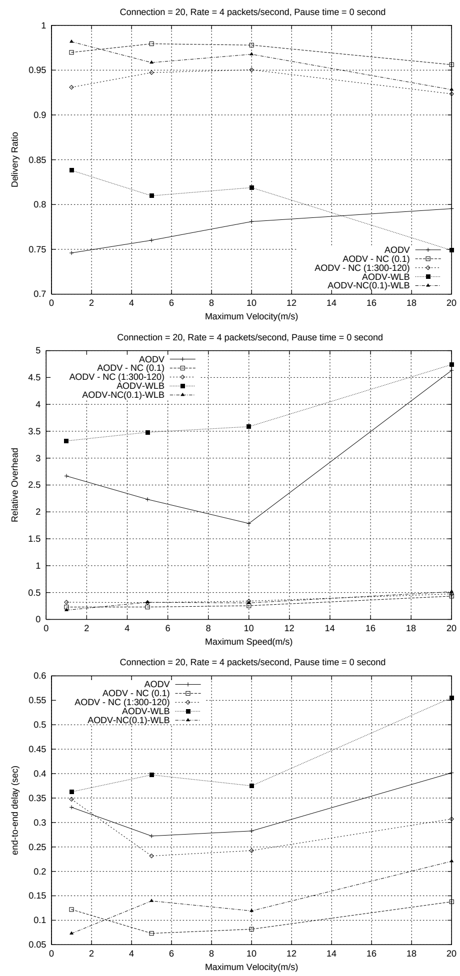

Figure 6: Delivery ratio, routing overhead and end-to-end delay for different velocities.

load balancing failed to find a path at the first attempt. It causes a node to send route request packets again. As a result, routing overhead as well delay increases.

Fig. 7 explores behavior of the protocols when the number of connections grows from 10 to 60. We fix the maximum speed to 20 m/s. In the case of 30 connections, AODV-NC(0.1)-WLB improves delivery ratio and decreases relative overhead. Also, AODV-WLB shows better performance than AODV itself at high workload. Lee and Riley (2005) showed that WLB is efficient at the high

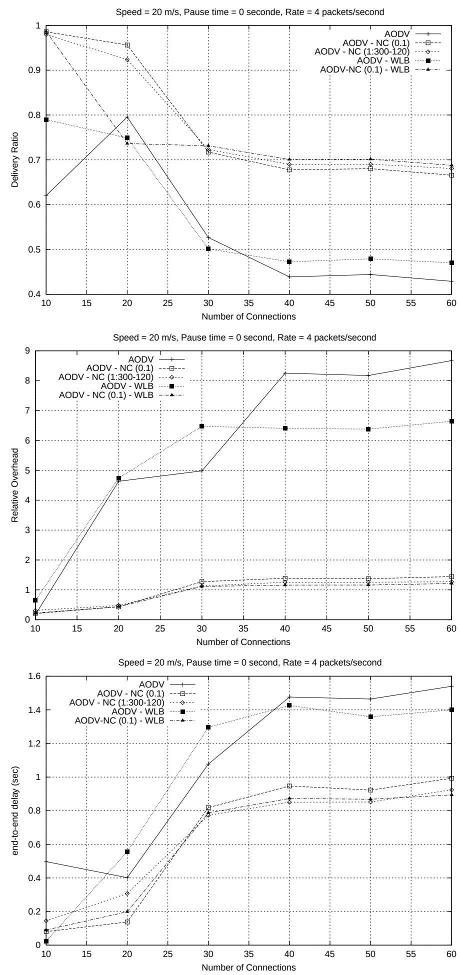

Figure 7: Delivery ratio, routing overhead and end-to-end delay for different number of connections.

workload condition. In the case of 40 and 50 connections, AODV-WLB improves delivery ratio, relative overhead and end-to-end delay by up to 6%, 23% and 7.5% respectively. With AODV-NC, WLB improves delivery ratio, relative overhead and end-to-end delay by up to 32%, 85% and 41% respectively. These results are better than those of AODV-NC. This implies that workload-based load balancing technique shows better performance when working with AODV-NC instead of working with AODV alone, especially in a high workload environment.

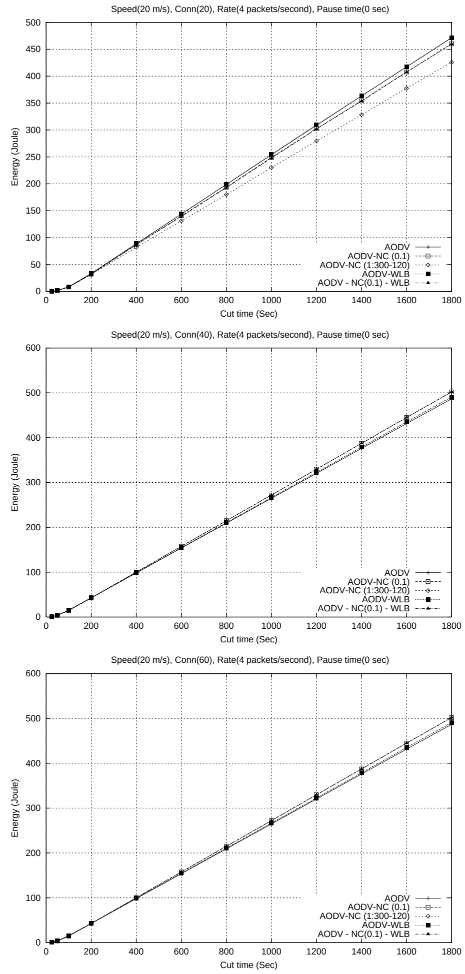

Figure 8: Energy Consumption versus time for connection 20, 40 and 60.

8 Conclusions

In this paper we introduce a novel node caching approach for constraining the route request protocol in ad hoc routing. We have implemented node caching routing protocol AODV-NC which improves the original AODV in all three metrics – extensive simulations in NS2 show average decrease of 90% in communication overhead as well as average decrease of 63% in the delay, and average increase of 20% in the delivery ratio.

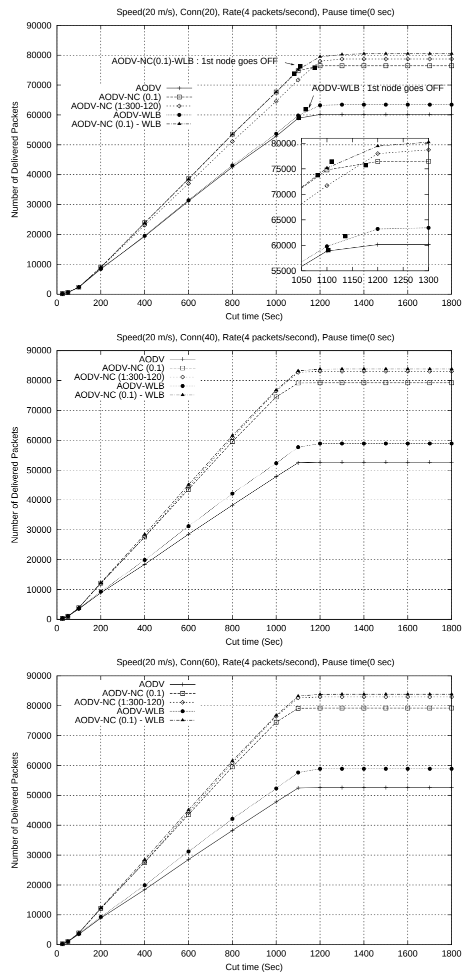

Figure 9: Throughput and Network Lifetime: Cumulative number of the delivered packets with energy 300J for connections 20, 40 and 60.

We have also proposed a new measure of fairness of ad hoc routing protocols based on the forwarding load distribution. The AODV-NC protocols are shown to be unfair and make certain overused nodes exhaust their batteries prematurely. We suggest a load-balancing scheme that improves fairness and lifetime of AODV-NC sustaining considerable improvement in overhead, delivery ratio and delay over the standard AODV. Both non-adaptive and adaptive load balancing techniques combined with AODV-NC showed better performance

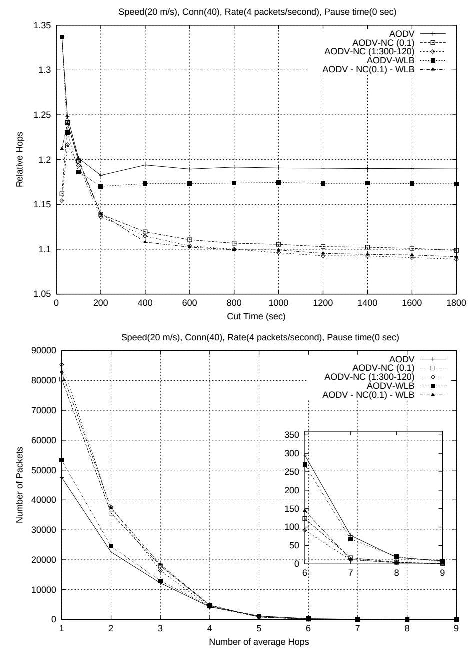

Figure 10: Optimal number of hops, normalized hops and distribution of average number of hops with 40 connections.

in energy efficiency as well as routing efficiency.

From the energy efficiency point of view, AODV-NC(0.1)-WLB showed the best network throughput and AODV-NC(1:300-120) showed the longest network lifetime by our new metrics. AODV-NC(0.1)-WLB increased throughput almost 30% more than AODV. Also, AODV-NC(1:300-120) and AODV-NC(0.1)-WLB used the least amount of energy per data packet to deliver to the destination and also to jump to the next hop. Regarding routing efficiency, AODV-NC(0.1) showed the best performance in relatively low workload scenarios. However, in high workload scenarios, AODV-NC(0.1)-WLB and AODV-NC(1:300-120) showed higher performance improvement than AODV-NC(0.1). In 40 connections, AODV-NC(0.1:300-120) found short paths which are close to the optimum, with respect to number of hops. Also, AODV-NC(0.1)-WLB improved the performance in high workload environments.

In conclusion, on average, our fair forwarding-load balanced AODV-NC protocol. compared to conventional AODV, improves routing overhead by 89%, delay by 20%, and delivery ratio by 17%. These improvements are in general larger than those of the best-to-date protocol AODV-DS, recently proposed in Mosko et al. (2003), which also considerably improves routing overhead (by 70%), but only slightly improves delivery ratio (by 5%). We believe that combining AODV-NC-WLB and AODV-DS can be beneficial for both.

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