Effects of Small Transfers and Traffic Patterns on Performance and Cache Efficacy of Ad Hoc Routing

Shao-Cheng Wang   Ahmed Helmy
Department of Electrical Engineering, University of Southern California
Los Angeles, CA 90034 U.S.A. Tel: +1 213 740 2685
email: {shaochew, helmy}@usc.edu

Abstract *Short-lived small transfers such as resource discovery and queries are likely to constitute a significant portion of the traffic in future ad hoc networks. In earlier work on ad hoc routing, randomly assigned long-lived connections have been studied. In this study we show that small transfers stress the route setup phase (vs. maintenance/repair phase) and exhibit significant different behavior than the commonly-studied long-lived transfers. Through extensive simulations, we attribute such differences to "cache" performance. A first-order estimation model is also developed to advocate this result. The outcome of this study strongly suggests the need to re-visit ad hoc routing protocols to address small transfers.*

Keywords
Mobile Ah Hoc Networks, Performance, Small Transfers, Cache Efficacy, Network Simulation

I. INTRODUCTION

Routing protocols in ad hoc networks can be generally categorized as proactive and reactive. Previous studies [1][2][3] have shown that on-demand (reactive) routing protocols perform a lot better in terms of high throughput and low overhead especially with node mobility. On-demand protocols (e.g. DSR[4], AODV[5]) employ efficient route caching mechanisms to avoid unnecessary route discovery floods and robust route maintenance mechanisms to deal with frequent route breaks.

Most performance studies [6][7] of on-demand ad hoc routing use *long-lived* randomly assigned connections that usually last throughout the duration of simulation. These connections emulate file transfer (ftp) or user-specific constant bit rate (cbr) applications. However, in today's internet, small transfers (internet mice) such as web browsing and domain name lookup (DNS), which are in average composed of 10-20 packets per connection, make up to 75% of total internet traffic[8]. A recent study [9] further observes that about 45% of internet streams last less than 2 seconds (internet dragonfly). In the universe of wireless networking, short-lived small transfers are likely to constitute a significant portion of the traffic in future ad hoc networks. Small transfers include applications such as resource discovery, text-messaging, object storage/retrieval, queries and short transactions. Therefore, studying ad hoc routing protocols' behavior with short-lived small transfers is essential and has not yet been well investigated before. Moreover, previous studies of long-lived traffic have shown that both the initial route discovery/setup phase and the route maintenance/repair phase of on-demand routing protocols play important roles on protocol performance[6]. As we shall show, those studies are not suitable for evaluating the performance of ad hoc routing with small transfers, where the route discovery/setup phase becomes the dominant factor affecting performance while route maintenance/repair is very rarely triggered.

This is the first work, we are aware of, that investigate routing protocols performance with small transfer traffic patterns. By small transfer, we mean either a single packet shot or a short stream of packets (at most 10 packets per connection) between source and destination. Our objectives are:

- Comparing two on-demand routing protocols, DSR and AODV, with small transfers by using metrics such as throughput, overhead and delay to check the performance impacts with varying the traffic load as well as time and spatial correlation among small transfer packet streams.
- Providing cache hit ratio and cache validity analysis to discuss the reason of performance differences.
- With a high-level simulator, we primarily investigate the impacts of scalability and mobility of reactive routing protocols with short-lived traffic flows.
- Proposing a first-order estimation model in order to further quantify the relationship between cache efficacy and protocol performance.

The rest of this paper is organized as follow. Section II briefly reviews previous ad hoc routing performance studies and core mechanisms of DSR and AODV. In Section III, we elaborate the study dimensions we are interested in and the performance metrics we use. In Section IV, we present our simulation results and discuss the effects of various kinds of small transfer traffic patterns on ad hoc routing performance. A high-level simulator for evaluating impacts of scalability and mobility are also presented in later part of this section. In Section V, an estimation model to study the relationships between cache and protocol performance is proposed. Finally, we provide our conclusions and future work in Section VI.

II. RELATED WORK

Numbers of ad hoc routing performance studies [1][2][3] clearly point out that compared with proactive routing protocols, reactive routing is more efficient and robust in high mobility scenarios. DSR [4] and AODV [5] are perhaps the most popular and well-investigated on-demand routing protocols in mobile ad hoc networks. In [7], the authors further compare the performance of DSR and AODV with different network load, mobility and network size. The authors of [6] use DSR as case study to investigate the effect of on-demand behavior on protocol performance and cache consistency. In all the above studies *long-lived* connections have been assumed.

In our study, we focus on the effects of various *short-lived* traffic patterns on the protocol performance and cache efficacy of DSR and AODV. We show the drastic difference in performance those protocols exhibit under small (vs. long-lived) transfers, especially for large-scale networks.

There are several common mechanisms shared by DSR and AODV – when the source node does not currently know a route to the destination, it initiates a route discovery process. Once the route is obtained, the source caches this information in order to save overhead and delay for further packet deliveries. However, the strategies of making use of caching are quite different for both protocols. DSR maintains multiple routes to any destination by aggressively caching all reply and overheard packets, where as AODV only keeps a single cache per destination and will expire it after certain preset timer. Moreover, both protocols have different ways to optimize the route request/reply process. DSR will first ask first-hop neighbors (non-propagating route requests) to see if they have such route information or not (we call this local cache). Then, after the route request is flooded out, if any intermediate node has route to the destination, it can quench the flooding by replying the request (we call it remote cache). We use this terminology throughout the document.

III. STUDY DIMENSIONS AND METRICS

Small transfers

With a large portion of today's internet traffic belonging to the class of small and short-lived flows, we believe that a similar phenomenon is likely to exist in future wireless mobile networks. Based on the characteristics of different applications that may be deployed in future wireless ad hoc/sensor networks, we generate various kinds of small transfer traffic patterns namely random shots, time-correlated and spatial correlated short packet streams. We are interested in the effects of these different dimensions on the performance and cache utilizations of ad hoc routing.

The first and simplest form of small transfer is independent single shots between random source and destination, spread randomly throughout the simulation. This is a complete contrary to long-lived transfers. In the source nodes' point of view, the destination of every packet is almost new to them. Therefore, source nodes must either flood out a route request or depend on the route information stored in the cache, at the risk that the cache entry can be arbitrarily old.

Besides totally random shots, we introduce small transfer traffic with time correlation and spatial correlation to capture other reality scenarios. One form of small transfer with time correlation is grouped packets. We group packets as 2, 4 or 10 packets per group and send them back-to-back with 0.1 sec separation. Traffic generated by applications such as distributed transactions and web-browsing typically fall to this category. On the other hand, by fixing 10 packets per group, we also investigate the impact of varying the separation interval between packets. By setting inter-packet arrival time from 0.1, 1.0 and 2.0 seconds, we vary the report/query frequency in a wireless sensor network environment.

Another interesting class of traffic pattern is packets with spatial correlation. Considering communication patterns such as only few commanders are allowed to send packets to a number of soldiers, or vice versa. We emulate such scenario by setting limits on the number of either sender or receiver or both (to 10). As we vary spatio-temporal correlation between packets for short flows, we analyze and compare the effectiveness of DSR's aggressive caching and AODV's per destination caching.

Performance and cache efficacy metrics

In our study, we use the throughput, overhead and delay metrics to evaluate the performance of ad hoc routing.

- *Packet delivery ratio (Throughput)*: packets successfully delivered to destinations over total number of packets sent.
- *Normalized overhead:* total routing overhead normalized with the overhead when flooding is used as a routing protocol.
- *Delay:* end-to-end packet delay, from source to destination.

We also provide cache efficacy analysis to discuss the reasoning of performance differences.

- *Cache hit ratio (CHR):* number of route discovery answered by the cache to the total number of route requests.
- *Cache validity ratio (CVR):* the ratio of by using the route provided by the cache, the packet delivery eventually succeeds to the total number of cache hits.

The first metric is mainly quantifying how widely the caches are spread out. The second one is to measure the cache consistency, if the validity is low, means the quality of caches is bad and route by these caches is highly likely to be lost. Combined effect of *CHR* and *CVR* is the *Cache efficacy (CE),* a measure of the total valid cache hits to the total number of route requests. We will extensively use these caching metrics to interpret the reasons of protocol behavior.

IV. SIMULATION AND RESULTS

We use ns-2 as our simulator, all protocol implementations and optimizations remain default as came with the simulator distribution package. We start our simulations in a scenario of 100 nodes randomly deployed in a 750m by 750m square field. We vary the network size to study scalability. Details given in Table I. The radio interface is standard 2Mbit/sec 802.11b MAC with a range of 125m. Packet size and interval is set as 64 bytes and 0.1 sec, respectively. Sources and destinations of each packet delivery are randomly chosen. Each node is moving according to Random Way Point model as pause time zero and a random chosen velocity between 0-10 m/s which is often considered a moderate mobility scenario. The simulation interval is 100 seconds and results are averaged over 5 runs.

No. of nodes	Area	Node degree	Ave. path length
50	500x500	3.557	6.328
100	750x750	4.6577	7.348
200	1000x1000	6.9469	10.362

We first compare the long-lived transfers with random short-lived small transfers. We then systematically evaluate the effect of network load and packet correlation. Lastly, we discuss the effects of scalability and mobility.

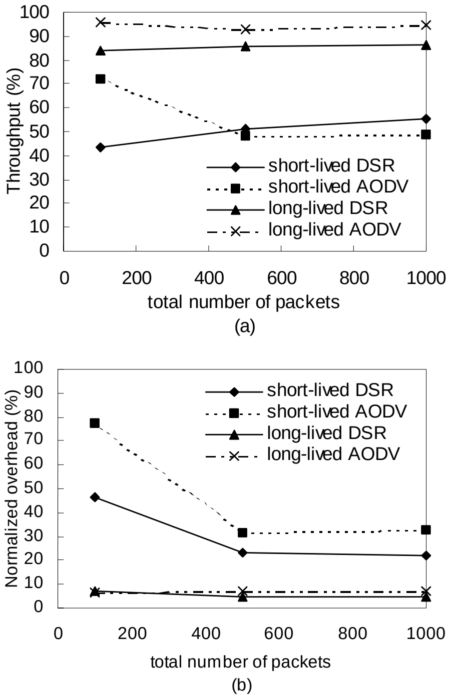

Fig. 1 Protocol performance of long-lived Traffic and short-lived traffic

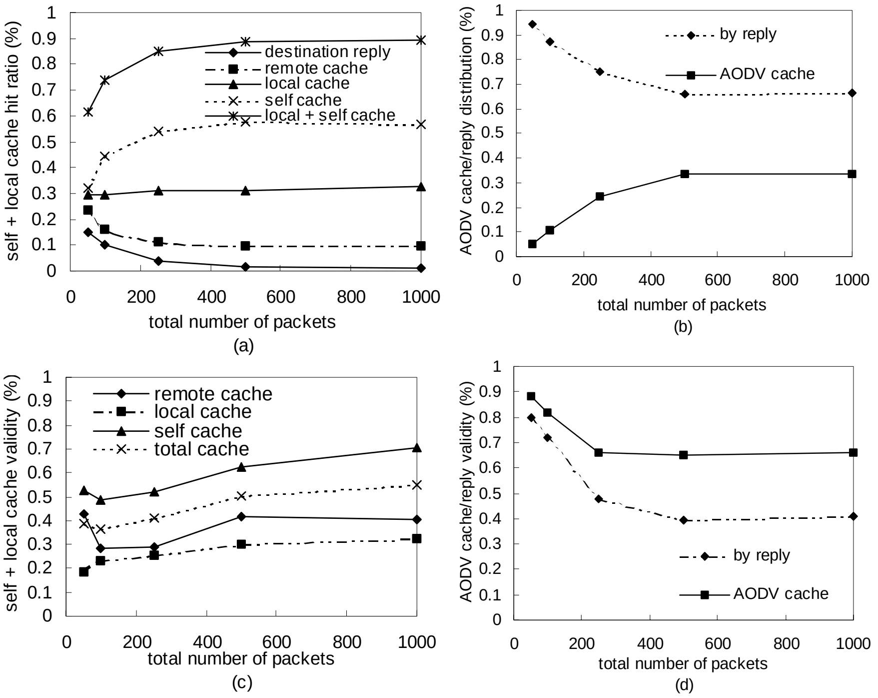

Fig. 2 Cache Analysis as traffic load increases
(a)(c) DSR (b)(d) AODV

A. Long-lived traffic vs. short-lived traffic

Before we proceed to investigate the performance impact of short-lived traffic patterns, we further motivate our work by illustrating the dramatic performance differences between long-lived and short-lived traffic patterns. With the same number of packets delivered in the network, we make each long-lived traffic connection consist of 100 consecutive packets which last about 25 seconds. For short-lived traffic, each packet is an independent single shot (1 packet) between random source and destination. As shown in Fig. I, short-lived traffic in both protocols has significant performance drop in throughput and generates about 5-8 times overhead compared with long-lived traffic.

In addition, we also observe that the breakdown of DSR's overhead changes dramatically. In long-lived traffic, about half (45%) of the routing overhead is attributed to the route maintenance mechanism, and the other half is for route requests. While in short-lived traffic, only 5-10% of overhead are for salvations and error reports, the mass majority is from route requests and subsequent replies. On the other hand, a similar observation from AODV's overhead shows that only 5% of long-lived packets have to flood out route requests, whereas others can be done by cached routing information. For short-lived traffic in AODV, more than 65% of packet deliveries have to bring up expensive route request mechanisms, consequently leading to drastic escalation of routing overhead.

B. Performance and cache analysis of short-lived traffic patterns

B-1 Experiment I - varying traffic load

Another significant finding of short-lived traffic from Fig. 1 is that when we vary the total number of packets injected into the network, these two protocols react totally differently. As the total number of packets increases, throughput of AODV drops while that of DSR slightly increases. There is a crossover point near 300 packets. At light traffic scenarios, AODV outperforms DSR drastically, but with heavy traffic, DSR performs only slightly better than AODV. Aside from throughput, in all simulation cases, AODV has about 2 times the routing overhead and 2-4 times the delay of DSR.[*]

The cache analysis in Fig. 2 may provide some clues as to why the protocols act this way. In cache distribution, DSR depends heavily on caching on getting route information, even in very light traffic scenarios. However, due to the lack of a cache expiration timer, routes stored in caches in such low traffic scenarios is often outdated so that trusting in such a cache would have an adverse effect on throughput. On the other hand, DSR's aggressive caching benefits from the increasing random traffic load as more up-to-date route information is stored in caches. As a result, the validity of caches increases and in turn translates to increased throughput.

The majority of AODV's route discovery was completed by flooding out the route request (RREQ) messages and obtaining route information by replies. This explains why AODV generates a lot more overhead and longer packet delivery delays than DSR. Besides, as traffic load is added in, the validity of AODV's route replies and caches both drop due to increasing contention and congestion and result in decreasing throughput.

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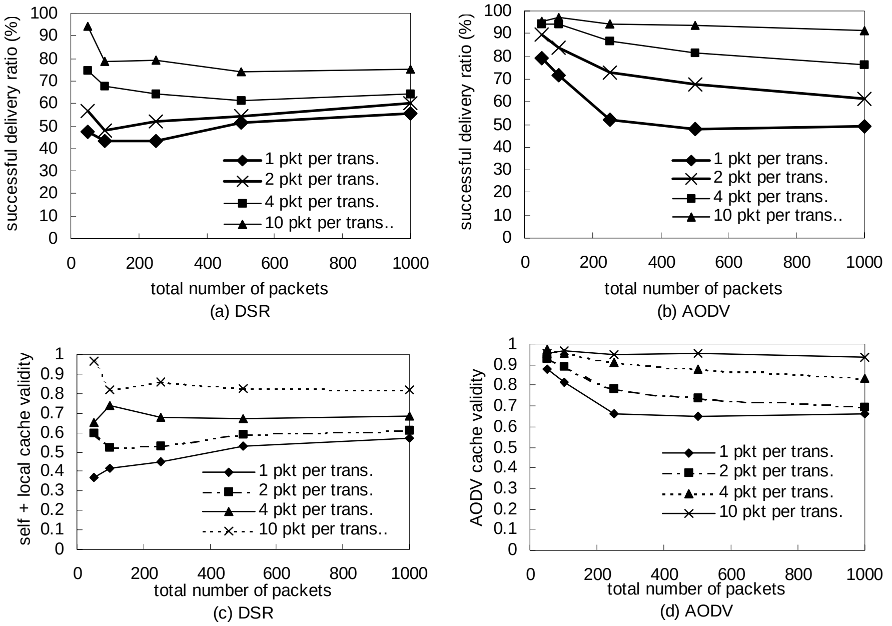
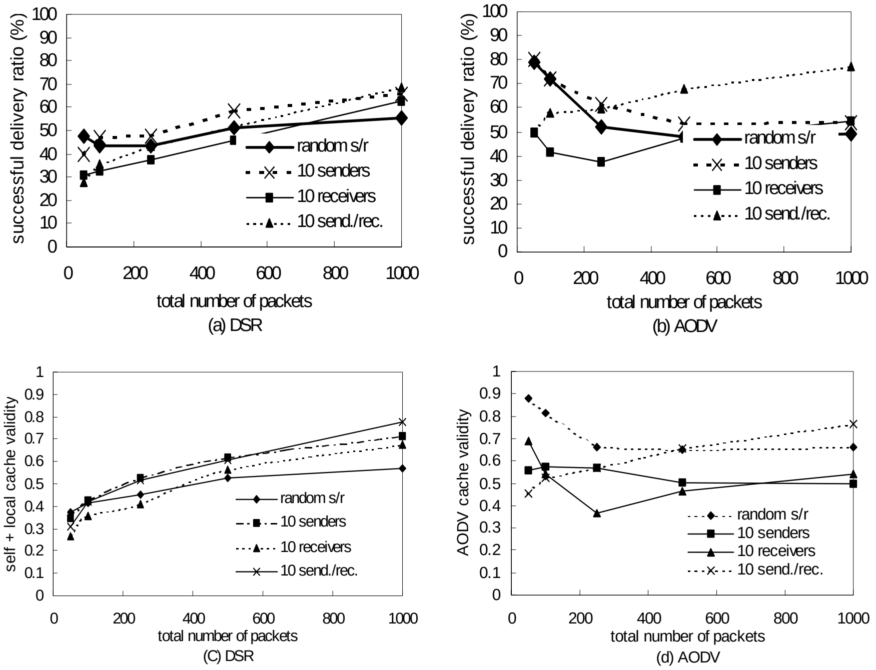
[*] Delay graphs omitted due to space limitations, please refer to the extended version in [16] for all graphs of simulation results.



(a) DSR (b) AODV

(c) DSR (d) AODV

Fig. 3 Performance and cache analysis for grouped packets



(a) DSR (b) AODV

(C) DSR (d) AODV

Fig. 4 Performance and cache analysis for packets with spatial correlation

B-2. Experiment II - packets with time correlation: grouped packets

In the second experiment, we group packets as 2, 4 or 10 packets per group and send them back-to-back with 0.1 sec separation. In Fig. 3a and 3b, we observe that AODV's throughput outperforms DSR's in all simulation cases, and even the routing overhead become comparable. Moreover, in 4 and 10 packets per group cases, both throughput and cache validity of DSR (Fig. 3e) no longer increases but keeps flat as more traffic load is added to the network. A possible explanation could be multiple routes to the same destination maintained in DSR's caches. For back-to-back packet streams, earlier packet delivery failures only trigger invalidation of such specific route entries involved with the broken link. There is still a good chance that other alternative routes can be found in the same cache and probabilistically the validity of such routes are the same as all other routes. On the other hand, there is only one cache entry per destination in AODV's cache mechanism. Once the preceding packets in the stream get a valid cached route, the chances that subsequent packets can be successfully delivered are almost guaranteed. Therefore, AODV seems to favor in such short grouped traffic patterns. This observation contradict earlier results in [3].

<u>B-3. Experiment III - packets with time correlation: varying packet inter-arrival time</u>

In this experiment, we fix the number of packets per group at 10, but vary the packet interval as random or 2 or 1 or 0.1 second. Again, we observe that performance of AODV is 20-100% better than DSR in all simulation scenarios. Similar caching analysis arguments in the last paragraph can be applied to this experiment. We still see no superiority of aggressive caching.

<u>B-4. Experiment IV- packets with spatial correlation</u>

In the last experiment, we discuss spatial correlation among packets. Considering communication patterns such as only few commanders are allowed to send/receive packets to a number of soldiers. Which protocol will be favored in such traffic patterns? We observe from Fig. 4a and 4b that in limited receiver patterns, AODV outperforms DSR in all cases. Also, it is first seen that the validity of AODV's cache goes up as the total number of packets increases in 10-receiver and 10-sender-receiver traffic scenarios (Fig. 4d). It is easy to interpret this observation since AODV maintains a per-destination cache, limited receiver communication patterns keep the cache very up-to-date.

C. Impacts of scalability and mobility

We implement a high-level simulator follows DSR design and primarily study the impacts of scalability. The results in Figure 5 show the cache efficacy vs. the max velocity (Vmax) for various network sizes. For very small scale networks (40-100 nodes) the efficacy is relatively high (~50-70%) especially for low mobility cases. This result is consistent with previous studies on on-demand ad hoc routing. As the number of nodes increases, however, the cache efficacy drops dramatically, even for very low mobility (1m/s), to ~10% for 1000 nodes and to ~5% for 2000 nodes!

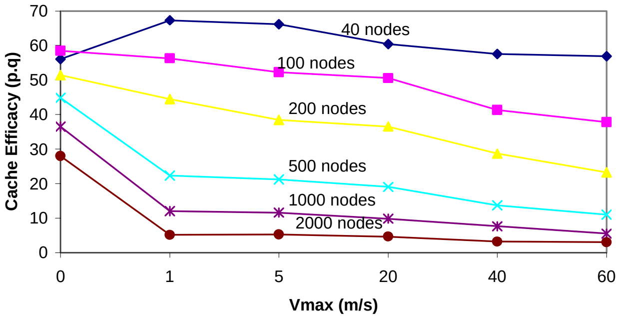


Fig. 5. The cache efficacy for various velocities and network sizes

We also observe the overhead for the DSR on-demand routing as compared to flooding. Form moderate to large-scale networks (above 1000 nodes) the performance of on-demand routing with caching approaches flooding, where the on-demand routing protocol resorts to flooding more than 90% of the time due to cache misses or invalid cache hits.

V. ESTIMATION MODEL

From the preceding experiments and discussions, we can see strong correlation between cache hit ratio/validity and protocol performance. We intensively use cache efficacy to explain why protocol performs in such a way. Therefore, we are interested in deriving an analytical estimation model to examine how strong the relationship is as well as verifying the validity of our arguments. In the following model, we use the case study of DSR.

Before developing the model, we first define the variables used.

p1 = self cache hit ratio
p2 = local (1-hop neighbors') cache hit ratio
N = total number of nodes
n = average number of neighbors (node degree)
L = average path length of the network
n_{rem} = average number of remote cache replies on a route request
L' = average path length of intermediate cache replies

Then, the overhead analysis model can be expressed as

$$\mathit{Overhead} = (1-p1-p2) * (N - n_{rem} + n*L + n_{rem}*L') \qquad (1)$$

By observing the breakdown of DSR's overhead, we know that the vast majority comes from the expensive flooding of route requests and subsequent replies. Thus, the first bracket of equation (1) is the portion that the source node fails to find the route either in its own cache or in 1-hop neighbors' and eventually triggers route request flooding. Then, the second bracket is to estimate how many transmissions will be involved in such a flooding and reply cycle. N stands for the total number of nodes in the network, which is a typical estimate of the number of transmissions a flooding course will provoke. However, we further fine tuning this number by subtracting n_{rem}, since the intermediate reply nodes will not continue to rely the broadcast. "n*L" is to show that the route request will be approximately delivered to the destination n times by its neighbors. Afterwards, the replies will take an average of L hops to propagate back to the source node. Other than the destination, there are n_{rem} intermediate nodes that may also have route information of the destination. The propagation of such replies is represented as L' hops. Note when an "intermediate" node intercepts a route request the average hops its reply travels, L', which is supposed to be smaller than the normal average path length of the network.

As we can see in Fig. 6, the estimation errors by equation (1) are within 5~10%. The correlation coefficient of estimated overhead and overhead generated in simulations is 0.996. The above facts indicate a strong correlation between the cache efficacy and the performance of DSR routing.

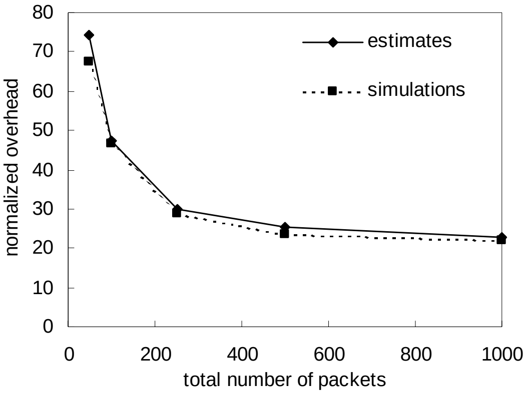


Fig.6. Overhead by estimation model vs. simulations

VI. CONCLUSIONS AND FUTURE WORK

Performance evaluations of ad-hoc routing protocols with small transfer traffic have not yet been well investigated in previous literature. In this study, we simulate DSR and AODV with either single packet traffic or short stream of traffic. We observe a considerable performance difference conducted with long-lived traffic in prior studies. We also compare these two protocols in various kinds of small transfer traffic patterns with certain temporal or spatial correlation. In random small transfer traffic patterns, DSR's aggressive caching mechanism helps with collecting more useful routing information and in turn increase the throughput as more traffic load is added. Whereas AODV's throughput decreases as traffic increases, but the absolute value is still comparable with DSR by sacrificing the overhead and delay in the expensive route discovery phase. On the other hand, when there are time correlation or spatial correlation between packets, AODV's per destination caching helps with keeping up-to-date caches and seems to fit in with such traffic patterns and outperforms DSR in throughput while providing about the same level of routing overhead.

Effects of scalability and mobility are preliminarily evaluated by a high-level simulator. We see a radical reduction on protocol performance when the network size grows to thousands of nodes, which raise our worries whether proactive routings are suitable for such scenarios. An estimation model of cache efficacy and protocol performance is proposed to realize how close the relation is between cache efficacy and protocol performance. The estimated overhead by such model is very close to that of simulations.

Investigating the effectiveness of the cache improvement strategies mentioned in previous work[12][13] with small transfers is part of our future work. Again, these studies were conducting by assuming long-lived traffic, whether these improvement strategies will work on short-lived traffic or not is an interesting topic. Moreover, as [14] has found that with short-transactional service-oriented manycast (1-to-many) communication, scoped-flood is the best behaved approach. Therefore, in the future, we also plan to include scoped-flood or intelligent flood schemes as comparisons with existing on-demand routing protocols.

Furthermore, we plan to extend our analysis to various node scales, node velocities or even other mobility models [8]. Also, we will include more ad-hoc routing protocols such as ZRP [9] and contact-based architecture [10] to see if these hybrid routing protocols can provide better performance in small transfer traffic patterns.

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