WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2011; **11**:392–409
Published online 1 July 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/wcm.986

SPECIAL ISSUE PAPER

M-DART: multi-path dynamic address routing†

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ABSTRACT

The paper proposes a Distributed Hash Table (DHT)-based multi-path routing protocol for scalable *ad hoc* networks. Specifically, we propose a multipath-based improvement to a recently proposed DHT-based shortest-path routing protocol, namely the Dynamic Address RouTing (DART). The resulting protocol, referred to as multi-path DART (M-DART), guarantees multi-path forwarding without introducing any additional communication or coordination overhead with respect to DART. The performances of M-DART have been evaluated by means of numerical simulations across a wide range of environments and workloads. The results show that M-DART performs the best or at least comparable with respect to widely adopted routing protocols in all the considered scenarios. Moreover, unlike these protocols, it is able to assure satisfactory performances for large networks by reducing the packet loss by up to 75%. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS
ad hoc networks; multi-hop wireless networks; multi-path routing; distributed hash table (DHT); dynamic addressing

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1. INTRODUCTION

In the last 10 years, *ad hoc* technologies have tremendously grown. Most of the research has mainly regarded relatively small networks and has been focused on performances and power consumption related issues. More recently, due to the importance of *ad hoc* paradigm in applications involving a large population of mobile stations interconnected by a multi-hop wireless network [1], great attention has been devoted to self-organizing routing protocols with satisfactory scalability requirements.

However, most of the proposed protocols, regardless of the belonging class (reactive, proactive, and hybrid), do not scale efficiently when the number of nodes grows [2,3] mainly since they have been proposed for wired networks and modified to cope with *ad hoc* scenarios [4]. More specifically, they are based on the assumption that node identity equals routing address, that is they exploit static addressing which of course is not yet valid in *ad hoc* scenarios.

Recently, some routing protocols have exploited the idea of decoupling identification from location by resorting to Distributed Hash Table (DHT) services, which are used to distribute the node's location information throughout the network. Several proposals based on this approach have been recently presented, and they can be classified according to the lookup model in two main groups.

The former group requires the knowledge of the geographical node's position which can be provided by a central infrastructure such as the GPS (a survey can be found in Reference [5]), and clearly this solution is not suitable in the case of self-organizing networks.

In the latter one, the information stored in the DHT is the node address, which reflects the node topological position inside the network. In few words, the proposals belonging to this group introduce a logical and mathematical structure on the address space based on connectivity between nodes. After that the node identifiers has been retrieved by the lookup procedure in the DHT, the routing is performed

†This work is partially supported by the Italian National Project 'Global & Reliable End to End e-Commerce & On Line Service Platform' (GRECO).

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using the topological information associated with the node address, resembling the routing procedure performed for wired networks [6–12].

All the above-cited schemes are hierarchically organized and exploit a tree structure for both the node identifier management and routing. Although this structure offers a simple and manageable procedure, it lacks for robustness against mobility and/or link failure and exhibits unsatisfactory route selection flexibility [5]. In order to improve the performances, more complex structures can be used, like ring ones [13–15]. However, in such a case the increased complexity in the identifier allocation mechanism could discourage their use in presence of channel hostility and very large networks.

In this paper, we give a contribution toward such an approach by focusing our attention on the problem of implementing a DHT-based routing protocol whose performances are competitive with those of other widely adopted protocols [16–18].

The proposed protocol, namely the multi-path dynamic address rouTing (M-DART), is based on a prominent DHT-based shortest-path routing protocol known as DART [10,11]. M-DART extends the DART protocol to discover multiple routes between the source and the destination. In such a way, M-DART is able to improve the tolerance of a tree-based address space against mobility as well as channel impairments. Moreover, the multi-path feature also improves the performances in case of static topologies thanks to the route diversity.

M-DART has two novel aspects compared to other multi-path routing protocols [19–23]. First, the redundant routes discovered by M-DART are guaranteed to be *communication-free* and *coordination-free*, i.e., their discovering and announcing though the network does not require any additional communication or coordination overhead. Second, M-DART discovers all the available redundant paths between source and destination, not just a limited number.

Previously, the multi-path improvement to DART protocol has been considered in Reference [24], and some preliminary results have been presented. However, in the performance comparison the DHT system is replaced by a global lookup table available to all nodes, neglecting the impact of the address discovery, which is a key process of the whole routing protocol, on the performances. Moreover, the performance analysis considers a limited set of environmental conditions and it adopts as radio propagation model the *Two-Ray Ground* one, which is based on unrealistic assumptions [25]. In References [26,27], the authors propose a metric, the terminal-pair routing reliability, to evaluate the tolerance of multi-path route discovery processes against route failures for mobile *ad hoc* networks, and the metric validation involves, among other protocols, the M-DART one. Therefore, in this paper the performances of M-DART are discussed only in terms of such a metric. Finally, in References [28,29] the feasibility of multi-path dynamic addressing is evaluated with reference to mobile peer-to-peer (P2P) systems, and some results are provided with reference to the P2P functionalities, neglecting the routing ones.

The reminder of the paper is organized as follows. Section 2 briefly reviews the DART protocol. In Section 3 we provide the design and implementation details of M-DART. We also discuss in the same section the communication-free and coordination-free properties of M-DART routing and we provide a useful upper bound on the size of the routing tables. Section 4 presents the performance evaluation and finally in the last section conclusions and open problems are drawn.

2. DYNAMIC ADDRESS ROUTING

DART [10,11] is a proactive distance vector routing protocol based on the *dynamic addressing* paradigm. According to such an approach network addresses are assigned to nodes on the base of the node position inside the network topology. By means of dynamic addressing, DART is able to implement hierarchical routing in a feasible way, reducing so considerably the routing state information maintained by each node.

Since the whole routing process is based on the transient network addresses, they have to be efficiently distributed across the network. The mapping between node identities and network addresses is provided by a DHT.

In the following sections, we give an overview of some key features of the DART protocol required for the understanding of the M-DART design presented in Section 3.

2.1. Address space

The network addresses are strings of l bits, thus the address-space structure can be represented as a *complete binary tree* of $l + 1$ levels, that is a binary tree in which every vertex has zero or two children and all leaves are at the same level (Figure 1a). In the tree structure, each leaf is associated with a network address, and an inner vertex of level k, namely a *level-k subtree*, represents a set of leaves (that is a set of network addresses) sharing an address prefix of $l - k$ bits.

For example, with reference to Figure 1a, the vertex with the label 01X is a level-1 subtree and represents the leaves 010 and 011. Let us define *level-k sibling* of a leaf as the level-k subtree which shares the same parent with the level-k subtree the leaf belongs to. Therefore, each address has l siblings at all and each other address belongs to one and only one of these siblings. Referring to the previous example, the vertex with the label 1XX is the level-2 sibling of the address 000, and the address 100 belongs only to this sibling.

In Figure 1b, the address space is alternatively represented as an *overlay network* built upon the underlying physical topology. Its tree-based structure offers simple and manageable procedures for address allocation, avoiding to rely on inefficient mechanisms like flooding.

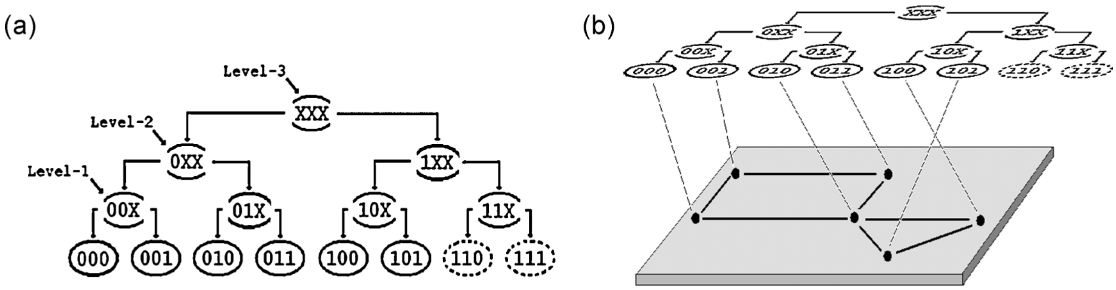

Figure 1. Relationship between the address space overlay and the physical topology.

2.2. Route discovery and packet forwarding

Each node maintains a routing table composed by l sections, one for each sibling, and the kth section stores the path toward a node belonging to the level-k sibling. Each section stores five fields: the sibling to which the entry refers to, the next hop, the cost needed to reach a node belonging to that sibling using the next hop as forwarder, the network id used for address validation, and the route log used by the loop avoidance mechanism.

Figure 2 shows the routing table of node 000 for the network depicted in Figure 1. The table has three sections: the first stores the best route, according to a certain metric, toward the node 001, the second toward a node belonging to the sibling 01X, and the last toward nodes belonging to the sibling 1XX.

The routing state information maintained by each node is kept consistent through the network by means of periodic routing updates exchanged by neighbor nodes. Each routing update stores l entries, and each entry is composed by four fields: the sibling id, the cost, the network id, and the route log.

The packet forwarding process exploits a hop-by-hop routing based on the network addresses and it is summarized by Algorithm 1. To route a packet, a node compares its network address with the destination one, one bit at a time starting with the most significant (left-side) bit, say the lth. If the ith bit is different, the node forwards the packet towards one the route stored in the ith section.

With reference to the previous example, if the node 000 has to send a packet to the node with the address 101, then it will forward the packet to the next hop stored in the third section (i.e., the node 010).

Algorithm 1 DART forwarding rule. A node i applies the rule whenever it receives a packet directed to node j. k denotes the most significant bit that differs between i and j addresses.

```
k = levelSibling(i.add, j.add)
if routingTable[k].nextHop is valid then
    nextHop = routingTable[k].nextHop
end if
```

The hierarchical feature of DART is based on the concept of sibling and it allows nodes to reduce both the routing state information and the routing update size, with respect to a traditional approach, from $\Theta(n)$ to $\Theta(\log(n))$, where n is the overall number of nodes in the network. Moreover, it assures that routes toward far nodes remain valid despite local topology changes occurring in the vicinity of these nodes.

3. MULTI-PATH DYNAMIC ADDRESS ROUTING

The M-DART extends the DART protocol to proactively discover all the available routes between a source and a destination.

In this section, we first present an example of how the M-DART's multi-path approach improves the tolerance of the address space overlay against mobility as well as channel impairments. Then we give an overview of how M-DART is capable to implement a multi-path routing strategy without introducing any communication or coordination overhead. Finally, we provide a detailed description of the multi-path data forwarding strategy and a polynomial bound on the routing table size.

Sibling ID	Next Hop	Route Cost	Network ID	Route Log
001	001	C(000,001)	$\min_{N \text{ in } 000} ID(N)$	001
01X	010	C(000,010)	$\min_{N \text{ in } 01X} ID(N)$	010
1XX	010	$C(000,010) + \min_{N \text{ in } 1XX} C(010,N)$	$\min_{N \text{ in } 1XX} ID(N)$	100

Figure 2. DART routing table for node 000.

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DOI: 10.1002/wcm

Sibling ID	Next Hop	Route Cost	Network ID	Route Log
001	001	C(000,001)	$\min_{N \in 000} ID(N)$	001
01X	010	C(000,010)	$\min_{N \in 01X} ID(N)$	010
	001	$C(000,001) + \min_{N \in 01X} C(001,N)$	$\min_{N \in 01X} ID(N)$	010
1XX	010	$C(000,010) + \min_{N \in 1XX} C(010,N)$	$\min_{N \in 1XX} ID(N)$	100
	001	$C(000,001) + \min_{N \in 1XX} C(001,N)$	$\min_{N \in 1XX} ID(N)$	100

Figure 3. M-DART routing table for node 000.

3.1. False route breakage avoidance

As illustrated in Section 2, a DART routing table is composed by l sections, one for each sibling, and each section stores one route towards the set of nodes belonging to the sibling to which the section refers to. In such a way, the routing state information is considerably reduced.

This attractive property is obtained at the price of low fault-tolerance as well as traffic congestion vulnerability since there exists only one path between any pair of nodes [5]. Moreover, the address overlay embeds only a partial knowledge about the physical network topology, since only a subset of the available communication links is used for the routing [27].

Therefore, a major issue is raised for DART protocol: a data flow may also experience a *false route breakage* if a reliable path in the network exists. Such issue is particularly harmful since the breakage affects a whole set of nodes due to its hierarchical nature.

Let us take an example by considering the simple network depicted in Figure 1 and by assuming that node 000, whose routing table is illustrated in Figure 2, has to communicate with node 100. According to the considered example, the node 000 routes the packets basing on the entry stored in the third section, i.e., toward node 010.

If we suppose that the link between nodes 000 and 010 fails due to mobility and/or wireless propagation instability, a *false route breakage* happens. Unlike flat routing, such a breakage affects all the nodes belonging to the third sibling and, therefore, all the communications toward such nodes have to be interrupted until the completion of the next route discovery process, which involves the exchange of several routing update packets.

Otherwise, M-DART solves the *false route breakage* issue by exploiting multi-path routing. With reference to the same previous example, in case of link failure the node 000 can use all the available neighbors (Figure 3), avoiding, therefore, to stop the communications until at least one path is still available. In other words, M-DART exploits the route diversity avoiding, therefore, to waste the resources already spent for route discovery and packet forwarding.

3.2. Protocol overview

M-DART shares several characteristics with DART. It is based on the distance vector concept and it uses the hop-by-hop routing approach. Moreover, M-DART also resorts to the dynamic addressing paradigm by using transient network addresses.

The main difference between DART and M-DART lies in the number of routes stored in the routing table: the former stores no more than l entries, one for each sibling, while the latter stores all the available routes toward each sibling.

The core of M-DART protocol lies in ensuring that such an increase in the routing state information stored by each node does not introduce any further communication or coordination overhead by relying on the routing information already available in the DART protocol.

In particular, it does not employ any special control packet or extra field in the routing update entry (Figure 4) and, moreover, the number of entries in the routing update packet is the same as DART: l. No special coordination action is needed by nodes and the node memory requirements (subsection 3.4) constitute the only additional overhead in M-DART relative to DART.

These valuable characteristics are obtained by means of *blind route notification*, that is by notifying neighbors only about the presence of routes towards a sibling without detailing the paths that the packets will be forwarded through. Although such a strategy allows us to avoid introducing any communication or coordination overhead, a major issue arises when a *blind route notification* is used in multi-path hierarchical routing. In fact, in such a case the cost associated with a path is not enough to single out the best route among multiple ones.

Sibling ID	Route Cost	Network ID	Route Log

Figure 4. DART and M-DART routing update entry.

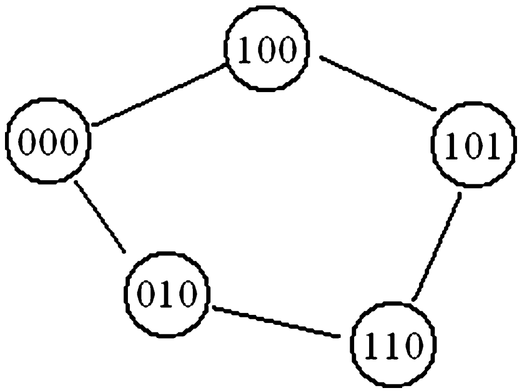

Figure 5. Path cost information is insufficient to guarantee best route selection in multi-path routing.

Table I. Routing table for node 100.

101	101	1	ID(101)	001
11X	101	2	$\min_{N \in 11X}$ ID(N)	010
0XX	000	2	$\min_{N \in 0XX}$ ID(N)	100

Table II. Routing update sent by node 100.

101	1	ID(101)	001
11X	2	$\min_{N \in 11X}$ ID(N)	010
0XX	2	$\min_{N \in 0XX}$ ID(N)	100

Table III. Routing table for node 010.

011	—	-	-	—
00X	000	1	$\min_{N \in 01X}$ ID(N)	010
1XX	110	1	$\min_{N \in 1XX}$ ID(N)	100

Figure 5 illustrates this problem using a simple network where the hops represent the cost associated with a path. Suppose that node 000 is the source and node 101 is the destination. There are two paths toward 101: a good path *via* node 100 and a bad one *via* node 010. Table I and Table III summarize the routing tables of node 100 and 010 respectively, while Table II and Table IV show the respective routing updates.

By listening the neighbors' route updates, the node 000 is unable to discover which one is the best suitable to communicate with the destination. In fact, both nodes 100 and 010 announce a route with cost 1 respectively toward the sibling 101 and 1XX and the destination address belongs to both the siblings.

In fact, the cost c_k announced by the node i in the k-entry of a routing update refers to the minimum cost to reach one

Table IV. Routing table for node 010.

011	-	-	—
00X	1	$\min_{N \in 01X}$ ID(N)	010
1XX	1	$\min_{N \in 1XX}$ ID(N)	100

of the nodes belonging to the sibling related with that entry:

$$c_k = \min_{j \in kth\ sibling} C(i, j) \tag{1}$$

where $C(i, j)$ is the minimum cost associated with the path (i, j). In other words, *the more the destination node is far from the announcing node in the address space, the larger is the set of nodes to which the route update entry refers to*.

This simple and straightforward observation is the basis for our mechanism to select the best path among multiple ones. In the following subsection, we detail the M-DART forwarding rule that allows us to implement the above idea.

3.3. Multi-path data forwarding strategy

For data-packet forwarding at a node having multiple routes to a destination, different strategies could be adopted [30,31]. Here, we adopt a simple approach of using the best available path until it fails and then switching to the next best available route, although M-DART can be easily extended to more effective schemes [32,33]. This choice allows us for a fairness comparison between M-DART and shortest-path routing protocols (Section 4).

The M-DART forwarding procedure is summarized by Algorithm 2. According to such a procedure, the route is singled out by taking into account the hierarchical feature of dynamic addressing, that is by choosing, as next hop, the neighbor which shares the longest address prefix with the destination. If there are multiple neighbors sharing the longest address prefix, the node will select the one with the lowest route cost.

As example, let us consider again the network illustrated by Figure 5. We assume that the node 000 has to forward a packet towards the node 101. Since the destination belongs to the level-3 sibling, namely the 1XX, the node looks for routes in the third section of its routing table.

Algorithm 2 M-DART forwarding rule. A node i applies the rule whenever it receives a packet directed to node j. l is the network address length and k denotes the most significant bit that differs between i and j addresses.

```
k = levelSibling(i.add, j.add)
nextHop = NULL
level = l
cost = maxCost
for each mth section, with m ≥ k do
  for each entry in mth section do
    if levelSibling(j.add, entry.nextHop) < level OR
    (levelSibling(j.add, entry.nextHop) == level AND
    entry.routeCost < cost) then
      nextHop = entry.nextHop
      level = (j.add, entry.nextHop)
      cost = entry.routeCost
    end if
  end for
end for
```

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DOI: 10.1002/wcm

Moreover, we assume that this section stores two entries: the former through the next hop 010 and the latter through 100. Thus the node selects, as next hop, the node 100, regardless of the costs associated with the routes. We recall that this rule is due to the hierarchical architecture of dynamic addressing routing tables: the closer a neighbor is to the destination in terms of address prefix, the more accurate the routing information owned by the neighbor is.

Differently, if we assume that the two entries stored by the node be through the next hop 010 and 011, respectively, and thus both share the same address prefix, the node will select the one with the lowest route cost.

3.4. Polynomial bound on the routing table size

In this subsection, the memory requirements of the M-DART protocol are estimated by means of a polynomial upper bound E on the number of entries stored in the routing table. In particular, we have that:

$$E = \sum_{i=1}^{\min\{l,n-1\}} \min\{\nu, 2^i - 1\} \quad (2)$$

where $l \geq \lceil \log_2 n \rceil$ is the network address length and $\nu < n$ is the number of neighbors of the node.

Proof. It is sufficient to prove by means of mathematical induction that the bound is true for a fully connected topology of n nodes, since in such a case both the number of neighbors and the number of available paths are the highest ones ($\nu = n - 1$).

Let us define :

$$E(\nu) = \sum_{i=1}^{\min\{l,\nu\}} \min\{\nu, 2^i - 1\} \quad (3)$$

The bound is clearly valid for $\nu = 1$, since in such a case there is only a path in the network and $E(1) = 1$.

Supposing that the bound is valid for $\nu = \bar{n}$, that is:

$$e(\bar{n}) \leq E(\bar{n}) \quad (4)$$

where $e(\bar{n})$ is the number of entries for a node with $\nu = \bar{n}$, we want to demonstrate that the bound is still valid for $\nu = \bar{n} + 1$.

We assume that the additional node belongs to the level-k sibling. Moreover, we assume that $\dot{n}$ nodes belong to the first $k - 1$ siblings and $\ddot{n}$ nodes belong to the level-k sibling.

By noting that a node belonging to the level-i sibling cannot be used as next hop toward the first $i - 1$ siblings due to the hierarchical approach, we have that:

$$e(\bar{n} + 1) - e(\bar{n}) \leq 1 + \dot{n} + \min\{\bar{n} - \dot{n} - \ddot{n}, l - k\} \quad (5)$$

In fact, the first term of the second member of the inequality accounts for the entry (if any) toward the level-k sibling with the additional node as next hop. The second one accounts for the possible entries toward the level-k sibling with the nodes belonging to the lower siblings as next hops; clearly the number of these entries is no greater than $\dot{n}$. Finally the last term accounts for the entries toward the higher siblings with the additional node as next hop. Since the highest siblings are $l - k$ and since $\bar{n} - \dot{n} - \ddot{n}$ nodes belong to these siblings, the entries are no greater than $\min\{\bar{n} - \dot{n} - \ddot{n}, l - k\}$.

Then, we have that:

$$\begin{aligned} e(\bar{n} + 1) = &\\ & e(\bar{n}) + 1 + \dot{n} + \min\{l - k, \bar{n} - \dot{n} - \ddot{n}\} \leq \\ & E(\bar{n}) + \min\{l - k + 1 + \dot{n}, \bar{n} - \ddot{n} + 1\} \leq \\ & E(\bar{n}) + \min\{l - k + 1 + 2^k - 1, \bar{n} + 1\} \leq \\ & E(\bar{n}) + \min\{2^l - 1, \bar{n} + 1\} \leq \\ & \sum_{i=1}^{\min\{l,\bar{n}+1\}} \min\{\nu, 2^i - 1\} = E(\bar{n} + 1) \end{aligned} \quad (6)$$

■

4. PERFORMANCE ANALYSIS

In this section, we present a numerical performance analysis of the proposed protocol by resorting to *ns-2* (version 2.29) network simulator [34].

At this end, for the sake of performance comparison we consider three widely adopted routing protocols besides the DART one. More in detail, we consider two reactive protocols, namely *Ad Hoc* On Demand Distance Vector (AODV) [16] and Dynamic Source Routing (DSR) [17], and two proactive ones, namely DART and Destination-Sequenced Distance Vector (DSDV) [18].

We underline that for a fair comparison in our simulations the differences between DART and M-DART reside in the multi-path diversity, since both use the same link-quality-aware routing metric, namely the expected transmission count (ETX) [35], and the same DHT functionalities. To assure a fairness comparison with the other shortest-path routing protocols, M-DART adopts the simple strategy of using the best available path until it fails and then switching to the next best available route.

We ran several sets of experiments to explore the impact of different workloads and environmental parameters on the protocol performances (Table V), and the adopted metrics are the following:

- routing entries: the number of entries stored in the routing table;
- delivery ratio: the ratio between the number of data packets successfully received and those generated;

Table V. Experiments.

Section	Protocols	Scope
Section 4.3	DART, M-DART	evaluating the memory overhead as the node density increases
		evaluating the memory overhead as the node number increases
Section 4.4	AODV, DART, DSDV, DSR, M-DART	evaluating the performances as the node number increases for UDP flows
	AODV, DART, DSDV, DSR, M-DART	evaluating the performances as the node number increases for TCP flows
Section 4.5	AODV, DART, DSDV, DSR, M-DART	evaluating the performances as the data load increases
Section 4.6	AODV, DART, DSDV, DSR, M-DART	evaluating the performances as the fraction of mobile nodes increases
Section 4.7	AODV, DART, DSDV, DSR, M-DART	evaluating the performances as the shadow deviation increases
Section 4.8	DART, M-DART	evaluating the performances as the node distribution becomes more skewed
Section 4.9	DART, M-DART	evaluating the performances as the network address length decreases

– delivery count: the number of data packets successfully received;
– hop count: the number of hops for a data packet to reach its destination (this metric accounts only for the data packets successfully received);
– end-to-end delay: the time spent by a packet to reach its destination (this metric accounts only for the data packets successfully received);
– routing overhead: the ratio between the number of generated data packets and the total number of generated routing packets.

Each experiment ran ten times, and for each metric we estimated both its average value and the standard deviation.

4.1. Channel model

Usually, routing performance analysis for ad-hoc networks adopts, as radio propagation model, the *Two-Ray Ground* one [11,12,15,36], based on the following assumptions:

(i) the radio's transmission area is circular and all the radios have equal range;
(ii) communications are bidirectional (if a node receives a packet from a neighbor, then that neighbor will receive its packets too);
(iii) the channel model is time-invariant (if a node can send a packet to a neighbor once, it will be possible until the topology does not change).

To remove these often non-realistic assumptions [25], we consider a propagation model, the *Shadowing* one, which accounts for the long-term fading effects by means of a zero-mean Gaussian variable $N(0, \sigma)$. Therefore, the received mean power $P_{dB}(d)$ at distance d is:

$$P_{dB}(d) = P_{dB}(d_0) - 10\beta \log(d/d_0) + N(0, \sigma) \qquad (7)$$

where $P_{dB}(d_0)$ is the received mean power at the first meter, β is the path-loss exponent, and σ is the shadow deviation, both empirically determined for a certain environment.

Moreover, unlike most routing performance analysis [37,38], we take into account the effects of both the additive thermal noise and the interferences, by assessing the signal-to-interference-plus-noise (SINR) ratio at the receiver side:

$$\text{SINR} = 10log \frac{P}{\sigma_n^2 + \sum_i P_i} \qquad (8)$$

where P is the received useful mean power, σ_n^2 is the additive noise mean power, and finally, P_i is the ith received interference mean power. The SINR ratio is thus used to state if the received packet has been correctly received according to Xiuchao and Ananda [39].

We set the path-loss exponent to 3.8, the shadow deviation to 2.0, and the mean noise power to -82 dBm to simulate an IEEE 802.11b Orinoco network interface [40] with long preamble, CCK11 modulation, and two-handshake mechanism, resulting in a transmission range of roughly 35 m which limits hardly the allowed node speed value.

4.2. Experimental setup

Static network topologies have been generated by placing the nodes uniformly in the squared scenario area, while mobile ones resort to *Random Way-point* [2] as mobility model.

The mobility parameters have been set to simulate pedestrian mobility, since the transmission range requires lower speed values in order to allow the routing protocols to build reliable paths. However, neither DART nor M-DART are suitable for networks with higher levels of mobility due to their proactive characteristic. More specifically, the speed and the pause values are uniformly taken in [0.5 m/s; 1.5 m/s] and in [1 s; 100 s] ranges, respectively, according to Yoon *et al.*,[41] to avoid the speed decay problem.

The node density has been set to 4096 nodes/Km^2. This value corresponds to a mean node connectivity degree of 12, which is a reasonable value to avoid the presence of network partitions [42], and the size of the scenario area was chosen according to this connectivity degree.

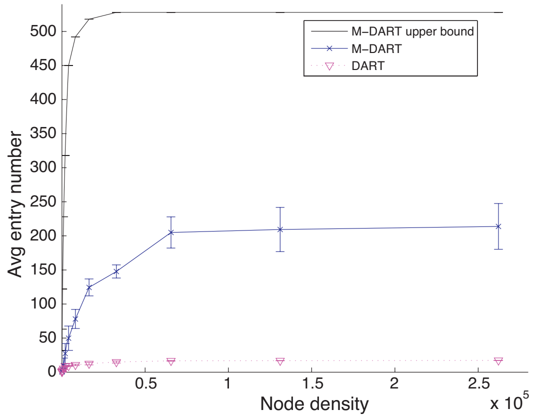

Figure 6. Routing table entries as a function of the node density.

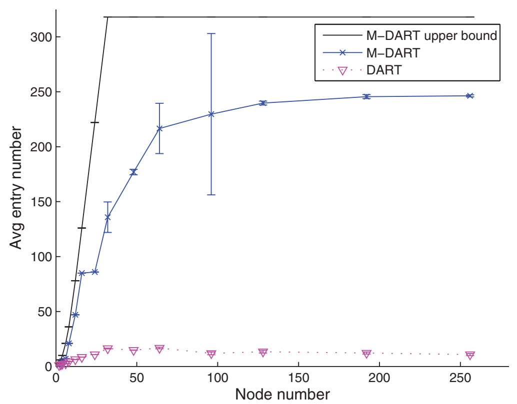

Figure 7. Routing table entries as a function of the node number.

The duration of each run is 2060 s, longer then de facto standard value (900 s) to increase the accuracy of the measurements. All the measurements are taken during the interval [1000 s; 2000 s], since the initial 1000 s are used to ensure that the routing protocols reach a steady state.

The well-known *random traffic model* [2] is adopted as data pattern: every node singles out randomly a destination according to a uniform distribution among the remaining nodes. Thus, in a network with n nodes there are n flows, each of one starts at 1000 s and ends at 2000 s.

In case of TCP transport protocol, the workload is modeled as a FTP transfer of a file with unlimited size, while for UDP scenarios the workload is modeled as a constant bit rate (CBR) with 1000 byte as packet size and to effectively assess the scalability property of the analyzed protocols, we set the data throughput λ generated by each source to:

$$\lambda = \frac{W}{n\sqrt{n}} \tag{9}$$

where W is the link data throughput for a 802.11b channel with CCK11 modulation (about 5.4 Mb/s) and n is the number of nodes in the network.

Such a choice is justified by the Gupta-Kumar bound [43] for static scenarios, scaled by a factor of n to take into account the throughput reduction effects due to the routing service. In fact, such a scaling factor accounts for the routing overhead generated by the periodic signaling of proactive protocols. It is worthwhile to underline that the adopted data load is much heavier than those usually adopted in routing performance analysis [2,15,12,44].

4.3. Memory requirements

The first set of experiments aims at evaluating the memory overhead of M-DART with respect to DART in terms of routing entries by estimating both the average value and the standard deviation. Such a metric represents the overall cost due to the multi-path approach (Section 3).

Two are the considered scenarios: in the former the node density increases whereas the node number is set to 64 (Figure 6), and in the latter the node number increases while the node density is set to 4096 nodes/Km^2 (Figure 7). In both the scenarios the nodes are static and uniformly distributed.

Clearly, in both the scenarios M-DART exhibits an overhead higher than DART in terms of memory space and the number of entries in the M-DART routing tables exceeds the number of nodes in the network. This result is reasonable, since the same neighbor can be recognized as next hop for multiple siblings as illustrated in subsection 3.3.

In the first scenario (Figure 6), the number of entries of both DART and M-DART grows for lowest values of the density and exhibits a saturation effect for the highest ones. We observe the same behavior by considering the polynomial upper bound proposed in subsection 3.4. This result is reasonable, since the number of entries depends on the network address length l (fixed in this scenario), the node number n (fixed as well), and the average number of neighbors ν (varying with the node density). Therefore, the number of routing entries grows with the node density until a threshold value is reached.

We note that the number of entries stored in the routing tables by M-DART is strictly lower than the number estimated by the upper bound. The reason is that the upper bound assumes a fully connected topology and a particular node distribution inside the address space.

Also in the second scenario the presence of a saturation effect is evident (Figure 7). More in detail, in such a scenario the routing entries grow with the node number (Equation 2). However, since both the network address length and the average number of neighbors are fixed, the upper bound becomes steady when $n \geq l$. As regard to the differences in terms of both routing entries and threshold value for the M-DART protocol between the simulated values and the upper bound ones, the motivations presented for the previous scenario are still true.

We note that the memory requirements of M-DART are very affordable and comparable with those of flat proactive routing protocols. In particular, as regards to the first scenario, by representing each field of a routing entry with

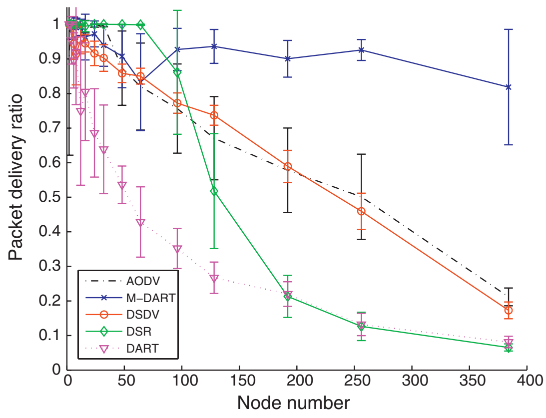

Figure 8. Delivery ratio as a function of the node number for UDP flows.

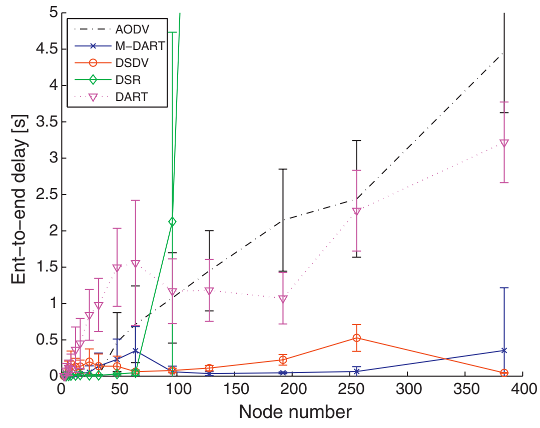

Figure 10. End-to-end delay as a function of the node number for UDP flows.

32 bit a node needs on an average less than 4 Kb of memory space while in the second scenario M-DART requires on an average less than 5 Kb of memory space.

4.4. Scalability in terms of node number

The second set of experiments aims at comparing the protocol performances for a static scenario as the number of nodes increases. We consider two scenarios described in subsection 4.2: in the first one the data load is modeled as CBR traffic over UDP protocol (Figure 8–11) while in the second one it is modeled as FTP traffic over TCP protocol (Figure 12–15).

In the first scenario, as regards the packet delivery ratio (Figure 8), M-DART performances remain largely unaffected as the number of nodes increases. This is a valuable result, since it clearly shows that M-DART is capable to deliver a data traffic in accord with the Gupta-Kumar bound (subsection 4.2) in network with several hundreds of nodes. On the other hand, DSDV and AODV performances decrease roughly linearly with the number of nodes, while

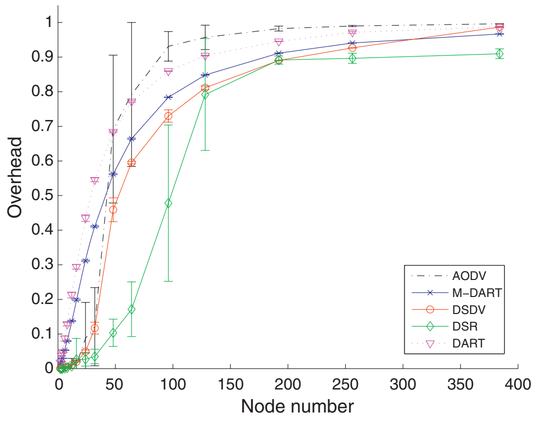

Figure 11. Routing overhead as a function of the node number for UDP flows.

DSR outperforms all the remaining protocols only for small networks whereas, as the number of nodes increases, its performances decrease very fast. Such a behavior lies in the source routing nature of DSR. In fact, as the network

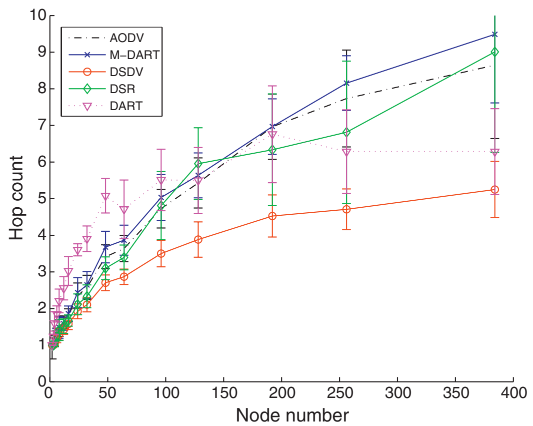

Figure 9. Hop count as a function of the node number for UDP flows.

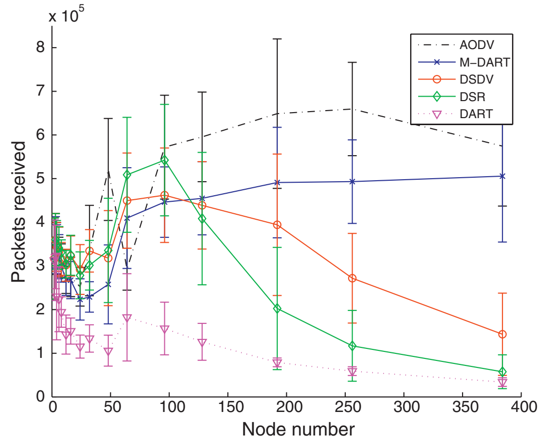

Figure 12. Delivery ratio as a function of the node number for TCP flows.

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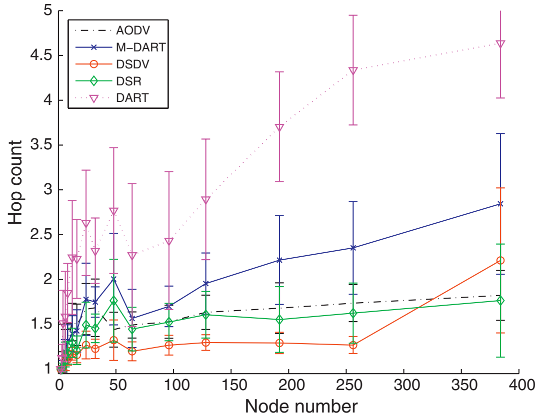

Figure 13. Hop count as a function of the node number for TCP flows.

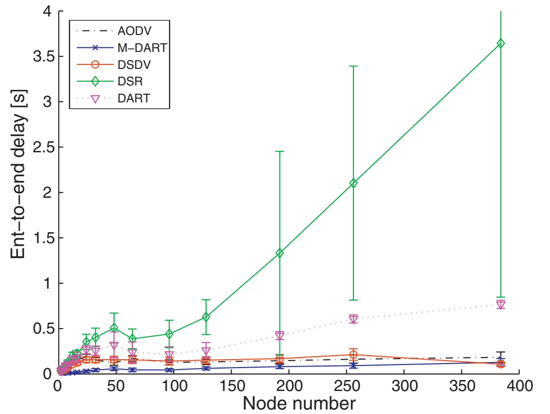

Figure 14. End-to-end delay as a function of the node number for TCP flows.

size grows the complete ordered list of nodes representing the packet path and stored in the packet header can likely become out-of-date. Finally, DART performances are always the worst and, with reference to largest networks,

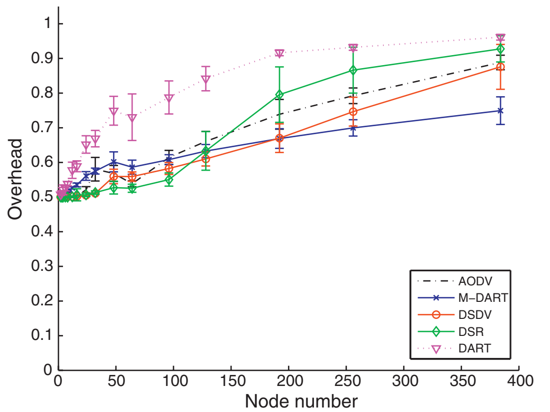

Figure 15. Routing overhead as a function of the node number for TCP flows.

nearly an order of magnitude separates them from those of M-DART. As regards to standard deviation values, we note that the maximum value (0.28) is exhibited by AODV for two nodes, while M-DART maximum value is equal to 0.17 for 384 nodes and DART one is equal to 0.21 for 12 nodes.

Figure 9 shows the hop count for the delivery ratios presented in Figure 8. We note that both DART and M-DART protocols adopt as route metric the ETX, which does not minimize the hop number. In other words, they have been designed to prefer reliable paths, rather than the hop number. Moreover, their hierarchical nature is a potential source of path length inefficiency. However, their performances are comparable with those of AODV and DSR, which experience a path stretch, defined as the ratio between the discovered path length and the shortest path length, of roughly 2.

In fact, by bounding the average shortest path length $\overline{h}$ measured in hop number as [27]:

$$\overline{h} = \left\lceil \frac{2\sqrt{\frac{n}{\delta}}}{3\sqrt{\pi r}} \right\rceil \tag{10}$$

where n is the number of nodes, δ is the node density, r is the transmission range, and $\lceil\rceil$ rounds to the higher integer, we have that $\overline{h} = 5$ for a network with 384 nodes, while the AODV and DSR average hop count values are respectively equal to 8.6 and 9.

With regard to DSDV, it is able to discover routes very close to the shortest ones, since its average hop count value is 5.2. Moreover, if we account for both the delivery ratio and the hop count performances, DSDV performs better than AODV since, by delivering the same number of packets on shorter routes, it uses more efficiently the network resources.

With regard to the end-to-end delay results shown in Figure 10, DSR exhibits the same behavior shown in Figure 8: it outperforms all the other protocols for small networks but it performs worse when the number of nodes exceed 64. We have not reported the DSR values for the larger networks for picture clearness, however its end-to-end delay is about 16 s for 96 nodes and 116 s for 384 nodes.

Both AODV and DART performances increase roughly linearly with the number of nodes while M-DART and DSR ones are substantially steady. Therefore, only DSDV and M-DART are suitable for time-constrained applications, like multimedia ones, in large networks although in such topologies DSDV is unable to assure a steady connectivity (Figure 8). Moreover, these results show that M-DART does not suffer from its hierarchical approach, thanks to the multi-path routing. In fact, it is able to deliver packets faster than DART although both of them exploits the same path quality metric.

Finally, the results reported in Figure 11 show that DSR outperforms all the considered protocols in terms of routing overhead due to its aggressive route caching policy. Again, DSDV and AODV perform similarly in small networks but, when the number of nodes grows, AODV performs worst

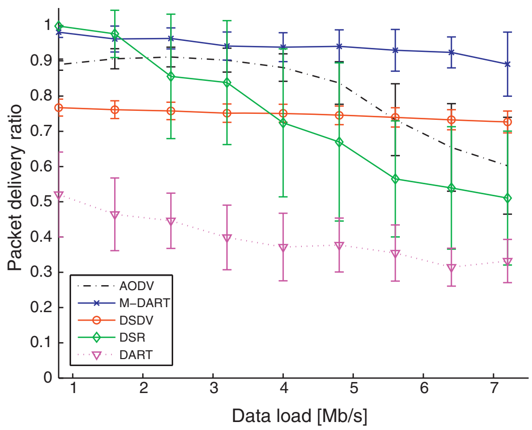

Figure 16. Delivery ratio as a function of the data load.

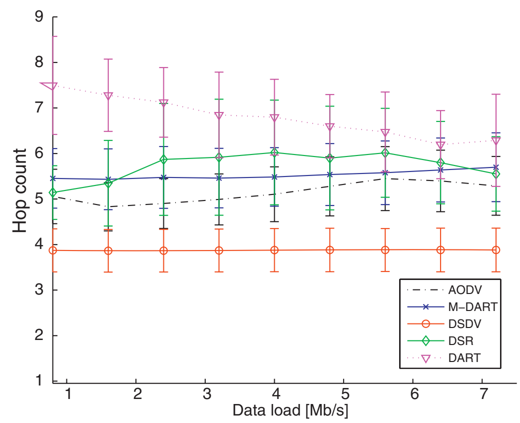

Figure 17. Hop count as a function of the data load.

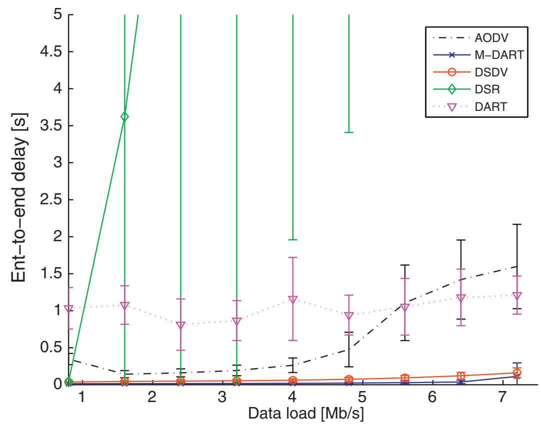

Figure 18. End-to-end delay as a function of the data load.

due to its reactive nature. In small networks, M-DART exhibits the highest overhead, since its routing update packets have fixed size, regardless of the node number. However, when the number of nodes grows, its behavior becomes comparable with those of the other proactive protocol, i.e., the DSDV.

Numerical results not here reported show that, if we account for the ratio between the total number of bytes sent at the routing layer over the total number of data bytes received, M-DART outperforms all the considered protocols thanks to its multi-path approach. In fact, in largest networks, M-DART ratio is about 15, AODV and DSR ones are about 60 and DSDV and DART ones are about 100.

In the second scenario the data load is modeled as TCP flows and the first metric is the delivery count (Figure 12). In such a case, AODV performs best but M-DART performs comparable to AODV, especially for the largest networks. On the other hand, DSDV and DSR performances decrease when the node number exceeds 100 while DART performs worst.

As regard to the hop count metric (Figure 13), DART and M-DART perform worse than the remaining protocols. However such a result is expected since their path metric does not minimize the number of hops. In particular, M-DART is able to find routes that assure the lowest end-to-end delays (Figure 14), while DSR performs again worst in terms of packet delay.

Finally, as regard to the routing overhead (Figure 15), DSR exhibits the same behavior of the first scenario while M-DART performs best in large networks.

4.5. Scalability in terms of data load

The third set of experiments (Figure 16–19) aims at comparing the routing scalability in terms of data load, namely as the value of the link data throughput W in Equation 9 grows in a static network with 128 nodes and CBR traffic.

The results in terms of packet delivery ratio (Figure 16) show that DSDV and M-DART are able to scale well in terms of data load, whereas both DSR and AODV performances are seriously affected by the data load and DART ones are slightly affected. The result is quite interesting. In fact, DART is a proactive protocol and thus, its route discovery overhead is steady irrespective of the data load. AODV and DSR are reactive ones, and thus, their route discovery overhead depends from the number of flows, which in our model (subsection 4.2) is fixed for a fixed number

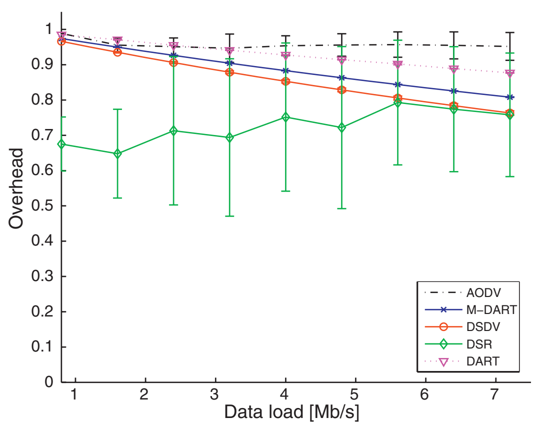

Figure 19. Routing overhead as a function of the data load.

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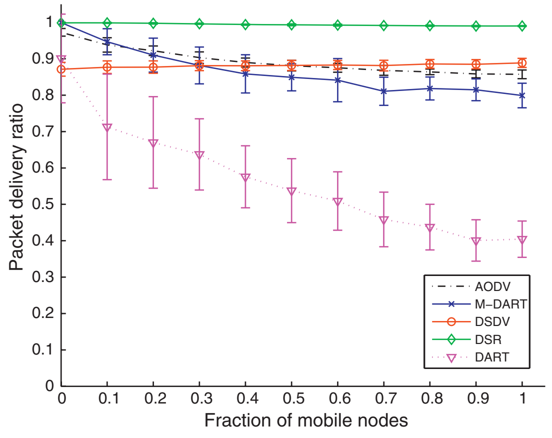

Figure 20. Delivery ratio as a function of the fraction of mobile nodes.

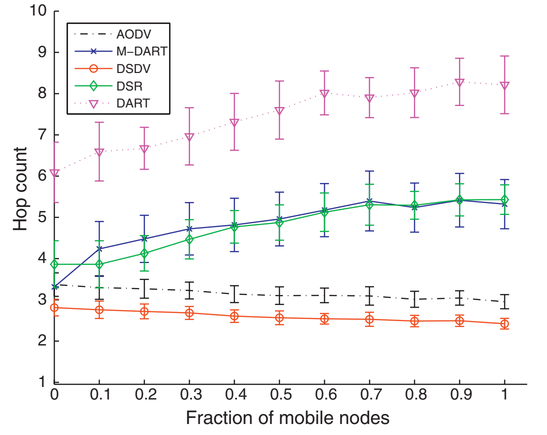

Figure 21. Hop count as a function of the fraction of mobile nodes.

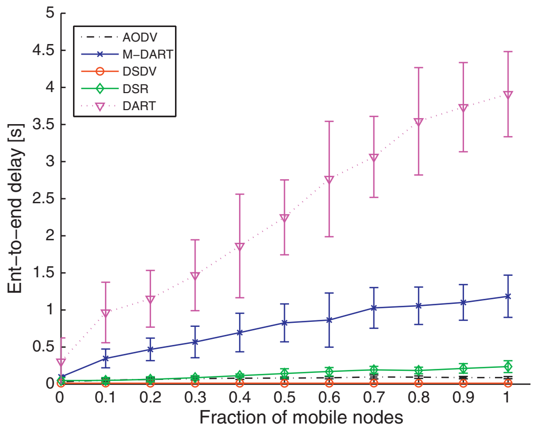

Figure 22. End-to-end delay as a function of the fraction of mobile nodes.

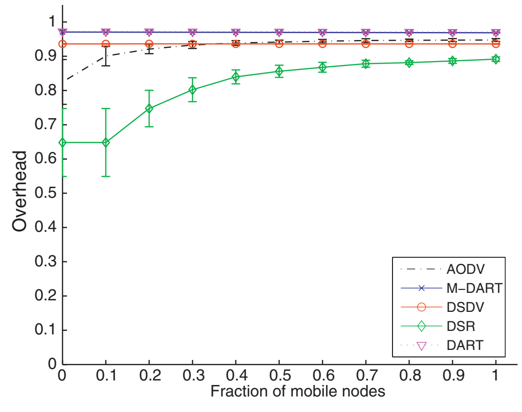

Figure 23. Routing overhead as a function of the fraction of mobile nodes.

of nodes. Therefore, both DART and the reactive protocols suffer from an unbalanced data load through the networks, while DSDV and M-DART better distribute the data load among all the available links.

We note that among all the protocols, M-DART outperforms for nearly each data load. Moreover numerical results, not reported here, show that M-DART outperforms all the considered protocols in terms of delivery ratios for roughly every data load when the number of nodes exceeds 64, whereas in small networks DSR reaches the best performances, confirming, therefore, the previous results (Figure 8).

Regarding the hop count and the delay results (Figure 17–18), the behaviors are the same of the previous figure: DSDV and M-DART performances are substantially unaffected by the data load, while the ones of the other protocols change with the data load. More in detail, DSDV routes have length closer to shortest ones ($\overline{h} = 3$ according to Equation 10) and DSR protocol suffers from very excessive delays, confirming, therefore, the considerations made for the same metrics in the previous subsection (Figure 9–10). As regards to DART protocol, we note that it suffers from higher delays with respect to M-DART. This behavior is reasonable, since DART introduces both a path stretch and an unbalanced load effects caused by false route breakages (see subsection 3.1).

Finally, Figure 19 illustrates the performances in terms of routing overhead, and the results confirm the same behavior exhibited by the delivery ratios. The proactive routing traffic does not depend on the data load, since the routing overhead decreases linearly with the data load, whereas AODV reactive routing traffic increase is unaffected by the data load and DSR one depends on the hop count metric due to its source nature.

4.6. Scalability in terms of node mobility

The fourth set of experiments (Figure 20–23) aims at assessing the performances for mobile scenario with 64 nodes and CBR traffic as the fraction of mobile node increases, according to the mobility model illustrated in subsection 4.2. The link data throughput W is set to 0.54 Mb/s to avoid the congestion effects.

Both DART and M-DART delivery ratios are affected by the node mobility (Figure 20), since their routing process exploits the topological meaning of the network addresses. However, the augmented structure builds upon the address space by means of the multi-path approach allows M-DART performances to be slightly affected by moderate mobility and comparable with those of AODV. The DART performances significantly decrease as the fraction of mobile node increases, while both the DSDV and the DSR delivery ratios are nearly independent of the node mobility. However, this behavior is exhibited only in small networks, and both DSR and DSV protocols perform poorly for largest networks according to the results not reported here for sake of brevity.

As regard the hop count metric performances (Figure 21), DSDV and AODV take advantage by the route diversity introduced by node mobility and their performances slightly increase as the mobility grows. Differently, the other protocols performances are significantly affected by this parameter.

Moreover, the end-to-end delays increase with the node mobility for both DART and M-DART (Figure 22). Therefore, they are not suitable for time-constrained applications in mobile networks even if M-DART is able to assure satisfactory connectivity.

Finally, the results regarding the routing overhead (Figure 23) show as expected that the proactive protocols exhibit constant mobility-independent overhead.

4.7. Scalability in terms of channel hostility

This set of experiments aims at evaluating the performances when the hostility of the channel, namely the shadow deviation, increases for a static scenario with 64 nodes, $W = 0.54\ Mb/s$ and CBR traffic (Figure 24–27).

The shadow deviation affects in different ways the delivery ratios of all the protocols. DSR performance exhibits a non-linear behavior: the delivery ratio is nearly one in case of line-of-sight communications ($sigma \leq 4$) but, as the shadow deviation increases, DSR becomes unable to deliver packets. DART, AODV, and M-DART delivery ratios have an approximately linear relationship with the shadow deviation, but M-DART performances remain still satisfactory also for $\sigma = 6$, outperforming the other protocols for a large set of propagation conditions. DSDV performance initially

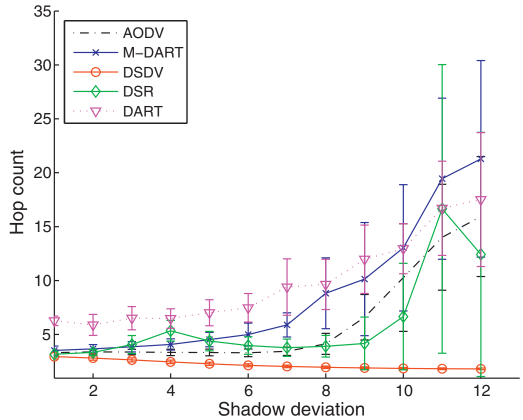

Figure 25. Hop count as a function of the shadow deviation.

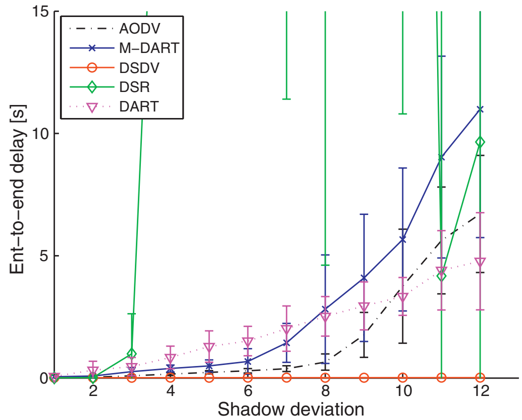

Figure 26. End-to-end delay as a function of the shadow deviation.

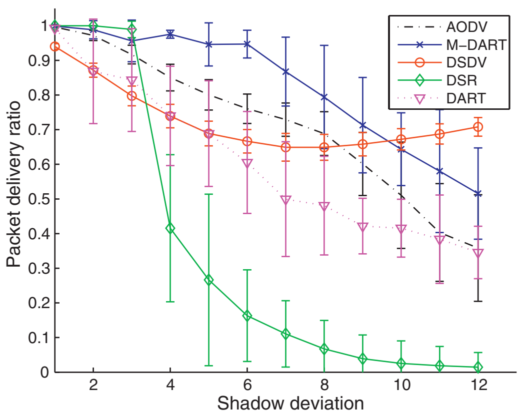

Figure 24. Delivery ratio as a function of the shadow deviation.

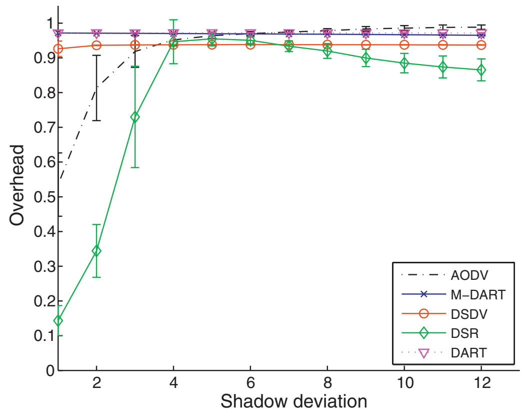

Figure 27. Routing overhead as a function of the shadow deviation.

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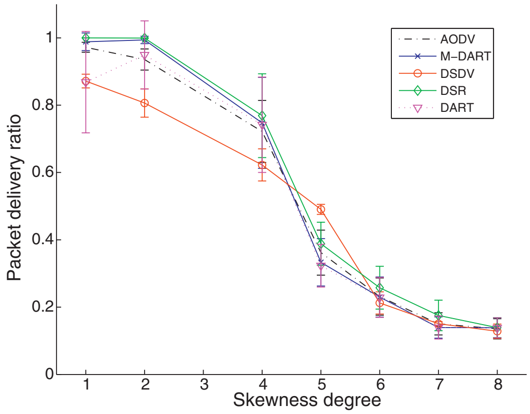

Figure 28. Delivery ratio as a function of the skewness degree.

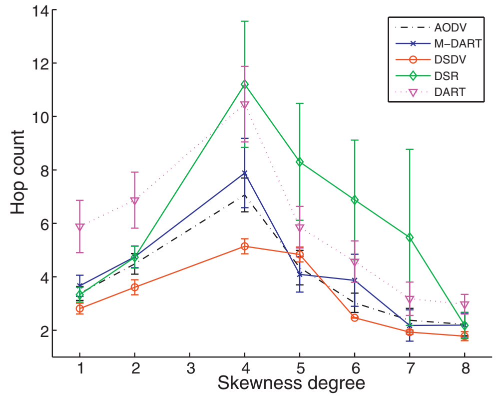

Figure 29. Hop count as a function of the skewness degree.

decreases as the shadow deviation grows, but it outperforms the other protocols in absence of line-of-sight communications, namely for the highest values of σ.

The previous considerations are confirmed by both the hop count metric (Figure 25) and the delay ones (Figure 26). More in detail, DSDV is the unique protocol whose performances are unaffected by the channel hostility. On the other hand, AODV, DART, and M-DART performances increase roughly linearly with the shadow deviation.

Finally, the considerations regarding the overhead metric as the hostility increases (Figure 27) are the same of those made for node mobility (Figure 23): the proactive overhead, unlike the reactive one, is independent of shadow fading.

4.8. Scalability against skewed node distribution

In this set of experiments we evaluate the performances for a static scenario with 64 nodes, $W = 0.54\,\text{Mb/s}$ and CBR traffic as the node distribution becomes more skewed. More in detail, the nodes have been located in a rectangular area with sides l_1 and l_2, and the parameter $s_k = 2\frac{l_1}{l_2}$ represents the degree of *skewness* of the node distribution. In such a way, we can assess both the DART and the M-DART performances in presence of unbalanced (skewed) address allocation.

Figure 28 presents the results related with the delivery ratio metric and the considered protocols perform almost the same for each value of the skewness degree. In particular, their delivery ratios decrease as the skewness increases and this result is reasonable, since a skewed node distribution involves an unbalanced data load through the network. However, since the performance of both DART and M-DART are comparable with those of the other protocols, they do not suffer particularly from skewed node distribution.

The resilience of dynamic addressing against skewed node distribution is confirmed by the other metrics (Figure 29–31). In fact, dynamic addressing performs comparable with the other protocols for each metric. More in detail, DSDV performs best for almost each value of skewness, while M-DART often outperforms DART, thanks to its multi-path feature.

4.9. Scalability against network address length

In the last set of experiments we aim at evaluating the scalability of the dynamic addressing protocols against the network address length. In such a way, we want to assess the resilience of the address space against an increasing number of nodes. Clearly, since we cannot simulate enough nodes to saturate a 32 bit address space, we evaluate the performances with a fixed (64) number of nodes for static scenario with $W = 0.54\,\text{Mb/s}$ and CBR traffic for a decreasing address space length. In this set we do not report the overhead metric, since it does not depend on the network address length.

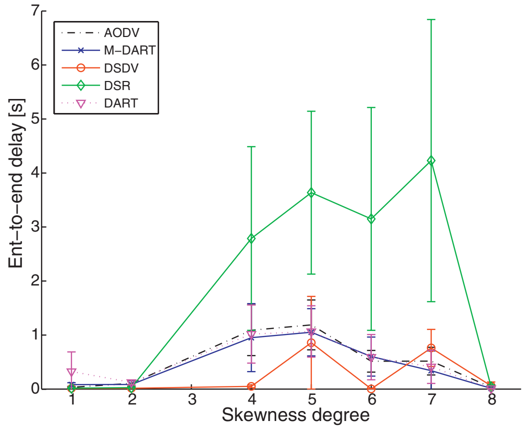

Figure 30. End-to-end delay as a function of the skewness degree.

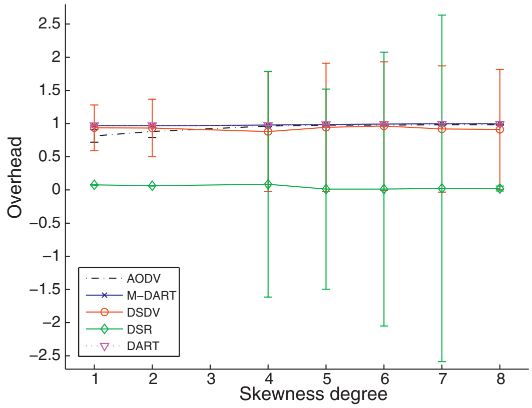

Figure 31. Routing overhead as a function of the skewness degree.

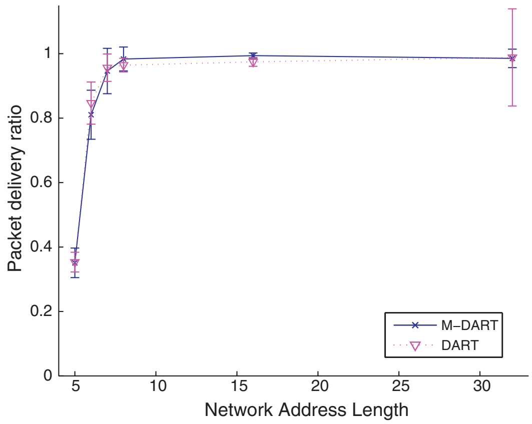

Figure 32. Delivery ratio as a function of the network address length.

Clearly, the network address length affects the dynamic addressing delivery ratios (Figure 32), since an inadequate address space gives rise to address duplication and incorrect route discovery. However, for uniform node distribution

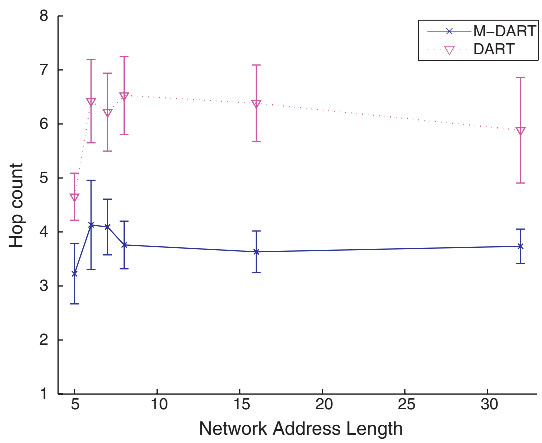

Figure 33. Hop count as a function of the network address length.

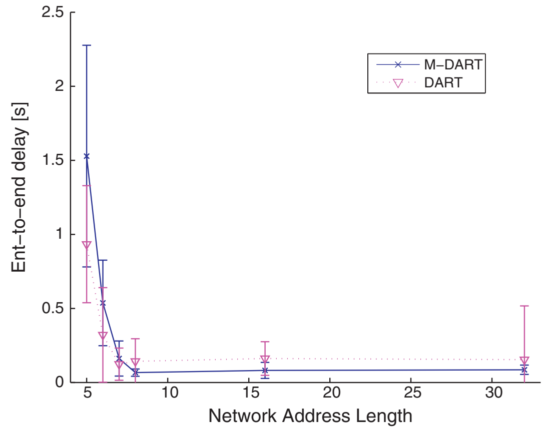

Figure 34. End-to-end delay as a function of the network address length.

the address space is well balanced for both DART and M-DART protocols. In fact, the protocols are able to deliver the packets for $l \geq 8$ in a network, just 2 bits more than the minimum network address length ($6 = 2^{64}$).

The results in terms of hop count (Figure 29) and end-to-end delay (Figure 30) confirm the previous consideration: the hop count and the delay metrics are unaffected by the network address length for $l \geq 8$, while for lower values of l the delays become very large due to address duplication.

5. CONCLUSIONS AND FUTURE WORK

The paper proposes the M-DART protocol, a multipath-based improvement of a recently proposed DHT-based shortest-path routing protocol, namely the DART. M-DART is able to exploit all the available paths without introducing any communication or coordination overhead with respect to the original protocol.

Simulation results and performance comparisons with existing protocols substantiate the effectiveness of M-DART for scalable networks with different workloads and environmental conditions in presence of moderate mobility. In particular, M-DART is able to perform best or comparable with the best protocol for each considered scenario.

Several additional issues related to the design and evaluation of the M-DART protocol requires further investigation. First, the protocol can be improved by resorting to more effective multi-path schemes. Second, we need to validate the obtained results with experimental results, at least for the scenarios that do not involve large networks, and to carefully study the interaction between timeout settings and M-DART performances. Third, evaluating the performances of M-DART for P2P applications is another issue for future work. Finally, it will be useful to see if the opportunistic approach applied to the dynamic addressing can

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DOI: 10.1002/wcm

assure satisfactory performances in scenarios characterized by high mobility.

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