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Scalability and routing performance of future autonomous networks

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Abstract: The increasing availability of wireless gadgets motivated the development of autonomous networks and protocols. In addition to typical rural and disaster scenarios, dense urban areas must also be considered for mobile ad hoc networks. Handling a large number of decentralised wireless nodes raises several scalability issues. Even though routing solutions resort to clustering and hierarchies in order to limit the dissemination of routing information, nodes' interactions and mobility are typically disregarded. In this work, the scalability of three routing protocols is analysed, defining different network size scenarios, while assessing their routing performance with mobility. This assessment includes simulation-based results as well as a theoretical analysis of the impact of different hierarchical transitions. This evaluation's contribution reveals that the scalability of hierarchical organisations is closer to what is theoretically expected, contrary to non-hierarchical solutions. Moreover, the obtained results confirm the potential of future autonomous and ubiquitous networks.

Keywords: scalability; routing; autonomous networks; multi-hop wireless networks; ad-hoc networks.

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1 Introduction

An increasing dissemination of wireless capable devices has promoted a generalised connectivity of users to a myriad of services. In a near future, users are expected to own several hundreds of gadgets requiring wireless connections (Cimmino and Donadio, 2009), demanding a considerable amount of physical resources from the existing infrastructures, which may not be available.

In order to cope with the limitations of existing infrastructures, or even with non-existing infrastructures in certain scenarios (e.g., rural areas), the concept of ad hoc networks has been proposed, allowing the creation of wireless multi-hop networks, where each wireless node behaves as router. Even though these networks may be very promising in the future, especially for local sharing of data, they must be able to autonomously handle user mobility and to scale efficiently.

Regarding the existing work on mobile ad hoc networks (MANETs) for future wireless communication, a number of routing schemes already exists using different approaches such as proactive or reactive route establishment and even hybrid approaches.

Proactive routing protocols for MANETs were inspired by the typical protocols used in wired networks, based on the periodic exchange of update messages in order to maintain the routing tables.

Some well-known proactive routing protocols are the ‘highly dynamic destination sequenced distance-vector (DSDV) routing protocol’ (Perkins and Bhagwat, 1994), the ‘clusterhead gateway switch routing (CGSR) protocol’ (Chiang et al., 1997), the ‘dynamic address routing for scalable ad hoc and mesh networks’ (DART) (Eriksson et al., 2007) and the ‘optimised link-state routing (OLSR) protocol’ (Clausen and Jacquet, 2003).

As an alternative to the expensive periodic update of proactive routing schemes, reactive protocols were introduced, performing route discoveries on-demand and avoiding the waste of resources experienced with proactive solutions. This approach seems more suitable for MANETs, where topology changes occur constantly. However, on-demand solutions suffer from an initial delay on retrieving a routing path which may not be acceptable. Moreover, the flooding for route retrieval may be too expensive for the entire network.

In this category, the ‘dynamic source routing (DSR) protocol’ (Johnson et al., 2007), the ‘ad hoc on-demand distance vector (AODV) routing protocol’ (Perkins et al., 2003) or, one of the most recent, the ‘dynamic MANET on-demand (DYMO) routing protocol’ (Chakeres and Perkins, 2009), represent some of the existing reactive protocols.

In the existing literature, the usage of clusters or routing hierarchies is found in order to efficiently keep a MANET scalable. For instance, and regarding the OLSR (Clausen and Jacquet, 2003) protocol, this issue has been addressed by proposing special topology control (TC) messages and a hierarchical architecture (Canourgues et al., 2008; Villasenor-Gonzalez et al., 2005). Another example is found in the ‘cluster-based optimised link-state routing (COLSR) extensions to reduce control overhead in MANETs’ (Ros and Ruiz, 2007), where clusters are abstracted as nodes using the OLSR scheme, defining cluster TC and HELLO messages (C-TC and C-HELLO), as well as cluster multipoint relays (C-MPRs).

Additionally, other approaches such as the ‘fisheye’ and ‘hazy sighted link state’ routing protocols (Pei et al., 2000; Koltsidas et al., 2005) aim at maintaining scalable routing mechanisms by having imprecise or slightly out-of-date routing information regarding distant nodes.

While these mechanisms are capable of reducing the total amount of routing information in their own way, the only routing scheme that employs them all is deferred routing (Palma and Curado, 2012). However, the impact of such approach must be assessed, in order to determine whether it is beneficial or not to the overall routing scalability.

The performance of existing routing approaches has already been extensively studied, mostly through simulation evaluations, but some also through theoretical models. However, a work entitled ‘deferred aggregated routing for scalable ad hoc networks’ proposal (DASH) (Palma and Curado, 2010), which proposes a new proactive routing approach taking into account existing communities among nodes in a network, still lacks a proper evaluation. In this paper, the scalable properties of the DASH protocol will be analysed, as well as the impact of node mobility between different levels of its hierarchy, using not only simulation results but also a theoretical analysis. The obtained results will be compared against the well known OLSR protocol and its clustered version COLSR.

In Section 2, the DASH protocol is described, presenting the overall idea behind the concept and how the network is organised. The description of a routing evaluation for this protocol is provided in Section 3, defining relevant scenarios to thoroughly assess the protocol, followed by a theoretical and simulation analysis in Sections 4 and 5, respectively. Finally, in Section 6, the concluding thoughts on this work are presented.

2 Dash overview

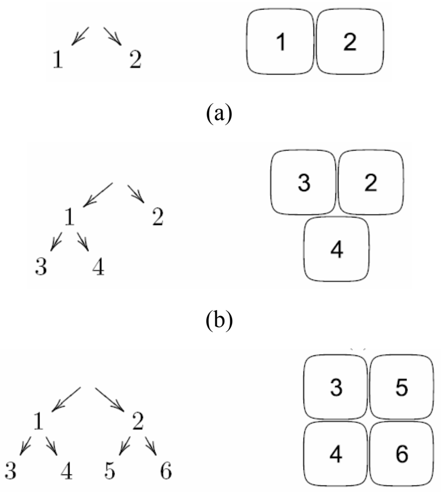
The DASH protocol employs the deferred routing approach which can shortly be explained as a routing procedure where nodes postpone routing decisions by forwarding traffic to appropriate gateway (Gw) nodes, among different clusters. The target of this protocol is to handle large-scale networks where communities can be detected in order to create suitable clusters. Moreover, since this protocol uses both clusters and a well-defined hierarchy for scalable routing, several virtual views of the existing communities in the network are maintained, allowing a more efficient resilience to mobility, while reducing routing overhead.

The approach taken by DASH assumes that each node will solely keep detailed information about its own community, and will maintain aggregated information about the network according to a pre-defined community hierarchy, allowing smaller and more stable routing tables. Since the most detailed view of a community corresponds to a cluster, routing decisions are cluster-based, being postponed to further communities in the hierarchy if necessary, without previously knowledge of the entire path taken. Even though this scheme may simplify the routing process, whenever a node changes its community, the hierarchy needs to be locally updated, side-by-side with the routing table.

By adapting OLSR for intra-cluster routing, the DASH protocol defines a network hierarchy where different network views exist, reducing the amount of exchanged routing information typically required by proactive routing protocols. A binary tree hierarchy is defined with the assignment of cluster IDs (CIDs) to each cluster and by creating ‘virtual clusters’ which represent different granularity levels of the existing clusters. While inside the clusters nodes will only exchange routing information about their own cluster, between different clusters no additional messages are required, being the gateway nodes responsible for overhearing existing routing information. For example, if a gateway node receives a routing message from a different cluster, it will retain information about that cluster and the clusters to which is connected, discarding the rest of the message.

In Figure 1, a simple network hierarchy is depicted for two, three and four clusters. In a two cluster network no virtual clusters exist as shown in Figure 1(a), however as soon as a new cluster is added to the network, in Figure 1(b) the cluster with the CID 1 represents a virtual cluster, such that only CIDs 3, 4 and 2 correspond to real clusters. In this scenario, any node in cluster 2 will keep its previous perspective where only CID 1 exists, being oblivious to the new ramification and, as sibling clusters, 3 and 4 will see each other. This aggregation of the network views allows less disruption when nodes change between clusters. In a similar way, if a fourth cluster is introduced, as presented in Figure 1(c), clusters with CIDs 3 and 4 will perceive the network as having only the cluster with CID 2 apart from their own clusters.

Figure 1 Network hierarchy for two clusters, (a) 2 clusters (b) 3 clusters (c) 4 clusters

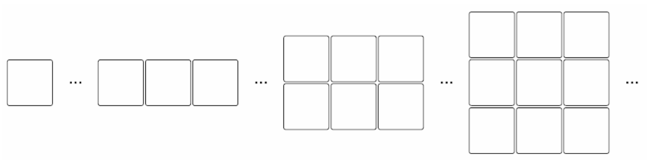


(a)

(b)

(c)

Figure 2 Increasing number of clusters



Similarly to everyday routines, such as driving, the DASH scheme chooses paths towards gateways as a driver chooses highways from one landmark to another until the final destination is reached. In fact, instead of thoroughly analysing all the existing paths in a very accurate map, a typical and easy solution is to simply drive towards well known and marked areas, such as capitals, important cities, regions or even countries. These landmarks act as gateways for the driver, and throughout the journey, more and more detailed information will be available on the road signs when the driver gets closer to a desired destination.

Taking into account this driving approach, adapting it to computer networks is straightforward and allows a significant improvement in routing performance when compared with typical routing approaches for wireless ad hoc networks. Moreover, this scheme limits the impact of node mobility, as it relies on condensed views of the network, such that a node moving from one cluster to another (a cluster can be seen as a city or region in a map), will not impact someone travelling from a more distant cluster (which can correspond to a country), allowing the coexistence of several devices.

3 Routing evaluation

Flat un-clustered protocols such as OLSR, do not usually scale and even protocols with flat but clustered views of the network, such as COLSR, may suffer from costly overheads when handling routes between clusters, usually relying on clusterheads. On the other hand, routing protocols that manage a network using a hierarchy for clustered nodes, require a lower communication overhead in order to maintain their routes.

While hierarchical organisations may reduce the overall routing overhead, keeping a hierarchy updated may introduce additional costs, resulting from required mechanisms such as dynamic addressing (Eriksson et al., 2007). The hierarchy presented by DASH aims at avoiding similar overheads, resorting to a virtual aggregation of the existing clusters, however, it still lacks a proper evaluation in literature. For this purpose, different scenarios will be defined so that several hierarchies and hierarchical transitions are assessed in DASH. These scenarios will be used for both a theoretical and simulation-based evaluation.

3.1 Objectives

As previously mentioned, wireless ad hoc networks have become interesting for future networks due to their unique characteristics, such as being infrastructure-less, mobile and self-X. As a result, large-scale scenarios using these networks have been proposed, from rescue operations to social events.

Considering the particular specificities of the routing approach used by DASH, it is important to engage a thorough evaluation of its hierarchy and how it performs when different transitions between distinct clusters exist. Therefore, the following aspects must be taken into consideration:

- traffic delivery
- routing overhead.

Taking into account the performance of a protocol, the traffic delivery indicates a protocols' ability to handle the entire network, mobility phenomenons and increased routing information when more nodes are introduced. Moreover, for scalability purposes, it is important to measure the overhead introduced a protocol and how it varies in different conditions and scenarios.

3.2 Methodology and scenarios specification

Bearing in mind that the DASH Routing protocol is cluster-based and that it uses the OLSR protocol for intra-cluster routing, the differences between these two protocols will only be noticeable in a network with at least two clusters. Thus, three different scenarios with 2, 3 and 4 clusters were defined. These scenarios will allow the evaluation of the impact of node mobility between clusters on the routing performance. In particular, since the DASH protocol has a well defined hierarchy, a node moving to different clusters will trigger a hierarchical transition and, therefore, an assessment of the impact rendered by different level transitions will also be possible.

In each of the defined scenarios a single node moves between two different clusters, where each cluster has a total of 49 nodes distributed using a Poisson point process, described later, along a square area of 500 × 500 m^2. It starts by being stationary for 250 seconds and after that it will move in the direction of a destination cluster at a speed of 12 km/h, similarly to travelling by bicycle or walking (3GPP, 2008), travelling a total distance of 600 metres. Since the purpose of this work is to evaluate the performance of the DASH protocol, the moving node will also be the destination for a constant bit rate flow of 32 kbit/s (8 packets per second) and all the remaining nodes are static. This type of traffic flows is representative of typical interactive gaming, simple file transfers or information exchange (ITU-T, 2003), which are all well suited applications for MANETs.

Figure 3 Same level transition example, (a) cluster view (b) hierarchical view

(a) (b)

Figure 4 2 clusters transition examples, (a) same level (b) one level

(a) (b)

By specifying a moving node which is part of a traffic flow while keeping all the other nodes static, a more accurate understanding of the impact of different level transitions will be obtained. This will reveal how efficiently a routing protocol is when updating its existing routes, allowing not only the analysis of its scalability, but also overall routing performance regarding delivered traffic. Moreover, it is important not to introduce any other additional node mobility as it would likely reduce the connectivity between nodes, thus influencing the intended scalability analysis.

In addition to the three well-defined scenarios, where the majority of the nodes is static, a more dynamic set of scenarios will also be considered. By using the random waypoint mobility model, with a pause time of 60 seconds, all nodes are mobile, without any distance or clusters restrictions, such that they are able to move freely across the entire network. Regarding the network topology, a set of results from 1 cluster of nodes, with 49 nodes [which is the best number of nodes handled by OLSR (Palma and Curado, 2009)], up to 10 clusters is provided. The dimension of each cluster is of 500 × 500, ensuring an initial constant density of the network. Figure 2 depicts the configuration of the network used in this scenario, where 16 traffic flows with same characteristics as previously defined are used, randomly choosing the final destination node.

1 *Two-cluster network*: The most straightforward hierarchy in DASH is found in a network with two clusters. In this hierarchy, the only possible transitions will occur in the same hierarchical level (0 level transition), when nodes move from the cluster with CID 1 to CID 2 and vice-versa. Figure 3 shows the configuration of such network, where the fully circled CID and the end of the arrow respectively correspond to the origin and destination clusters. Since there are two possible transitions, this scenario was evaluated twice, one where the node moves from clusters 1 to 2 and the other from clusters 2 to 1.

   In this scenario, all the clusters are affected by any occurring transition since they are sibling clusters. However, in a scenario with more clusters this will not always occur, as shown for the three-cluster network.

2 *Three-cluster network*: As the number of clusters increases in a network, so does the number of possible transitions in the DASH hierarchy. In a network with three clusters, in addition to same level transitions between clusters 3 and 4, there is also a one level transition between CIDs 3 or 4 and 2. Figures 4(a) and 4(b) depict some of these transitions, when a node moves from clusters 3 to 4 and from clusters 3 to 2. Moreover, in order to better illustrate the protocol's behaviour, in these figures the clusters which are affected by each transition, in addition to the source and destination, are depicted in a shaded box. This highlights the existing aggregated views used by DASH, such that for same level transitions nothing is changed for nodes in cluster 2.

   Since there are three clusters in this scenario, six different transitions may occur – from clusters 3 to 4 and 2, from clusters 4 to 3 and 2 and finally from clusters 2 to 3 and 4. Similarly to the previous scenario, all these transitions were individually simulated, leading to four one level transitions and 2 same level transitions.

3 *Four-cluster network*: In a network with a total of 4 clusters, two level transitions may occur when a node changes its cluster association to a cluster in a different branch of the network. Even though same level transitions still exist [Figure 5(a)], one level transitions will never occur, since a node moving to a non-sibling cluster will have to go one level higher into the hierarchy and then lower to a leaf cluster. In Figure 5(b) a two level transition is presented, where a node from cluster 3 moves to cluster 6, affecting not only the source and destination clusters, but also their sibling brothers. This transition represents the worst case scenario, since same level transitions only affect 2 clusters. This reduced impact is related with the adoption of the deferred routing concept, where in a network with 4 clusters each node perceives only 2 clusters. In fact, for a network with C clusters, at any given point a node recognises at most $\lceil \log_2 C \rceil$ clusters (due to the aggregation of real clusters into virtual clusters), which also corresponds to the number of levels in the hierarchy. Thus, for a l-level transition in a network with C clusters, knowing that $l \leq \log_2 C$, the maximum number of real clusters affected by a transition is $2 + l$.

   Once again, since several transitions among the four different clusters exist (12 possibilities), this scenario was evaluated individually for each transition, leading to a total of 4 same level transitions and 8 two level transitions.

4 *Growing size network*: Due to the dynamic characteristics of this scenario, several different level transitions occur in each simulated run. For this reason instead of tracking each type of transition, the overall impact of these hierarchical transitions will be analysed. In the largest version of this scenario, with 10 clusters, there are in theory 90 possible hierarchical transitions ($P(10, 2)$) which result at most in a 5-level transition.

   By analysing the global performance of the protocol with all the inherent transitions for different size networks, a more detailed understanding of the protocol's scalability will be achieved.

Figure 5 4 clusters transition examples, (a) same level (b) two level

(a) (b)

4 Theoretical analysis

Even though the DASH routing protocol uses OLSR for intra-cluster routing, its scalability properties are entirely distinct. One key aspect in the performance of the OLSR protocol is its usage of multipoint relay (MPR) nodes, responsible for issuing and forwarding TC messages. These messages convey a large overhead if they are entirely flooded. For a single cluster network, the same performance will be registered by the OLSR and DASH protocols, however as the number of clusters increases, the number of forwards per TC message is kept stable for the DASH protocol and increases with OLSR.

In order to demonstrate the performance gains obtained with DASH, a wireless network shall be represented by using a Poisson point process over the plan betoken by S and with intensity γ. Moreover, assuming that the number of nodes N, follows a Poisson Law of intensity $\gamma \times S$, the total number of nodes per unit of area M, is represented by γ ($M = \gamma$). This network layout ensures that each node has on average M neighbour nodes and thus the radius of the network will be $\sqrt{N/M}$, since in a K-hop neighbourhood the number of nodes in a disk radius K is on average K^2M.

In link-state routing protocols, the forwarding of routing messages is responsible for most of the control traffic overhead.

Bearing this in mind, it is important to analyse the impact of the number of TC messages forwarded by the OLSR-based protocols, which depends on the number of MPR nodes in a K-hop neighbourhood. As demonstrated by Adjih et al. (2004) and Jacquet et al. (2002), the average number of MPRs selected by a node (M_{MPR}) is defined by equation (1) and further that for an increasingly large number of neighbour nodes ($M \rightarrow \infty$), M_{MPR} is represented by equation (2).

$$M_{MPR} \leq \sqrt[3]{9\pi^3 M} \tag{1}$$

$$M_{MPR} \sim \beta \sqrt[3]{M} \wedge \beta \approx 5 \tag{2}$$

Taking into account the average number of MPRs selected by a node, it follows that the probability of a node to be an MPR is M_{MPR}/M (Canourgues et al., 2008). Since the number of TC retransmissions corresponds to the number of MPRs times the number of nodes in a K-hop network, the average number of retransmissions is defined in equation (3). Furthermore, the number of nodes that may retransmit a TC message, at precisely K hops of a TC transmitting node, is on average defined by equation (4).

$$\frac{M_{MPR}}{M} \times K^2 M = M_{MPR} K^2 \tag{3}$$

$$\frac{M_{MPR}}{M} \times \left(K^2 - (K-1)^2\right) M = M_{MPR} \left(K^2 - (K-1)^2\right) \tag{4}$$

The previous equations assume an un-clustered network where OLSR is used for routing purposes. However, despite using OLSR for intra-cluster routing, in a clustered network with C clusters the radius of the network will be $\sqrt{N/(M \times C)}$. In fact, the entire network can be considered as C distinct Poisson point processes, as DASH forwards no messages across different clusters. Other cluster-based protocols using OLSR, such as COLSR, have a similar perception of the network, but still, in the distributed version of this protocol, TC messages may be forwarded among different clusters such that, for the cluster-based radius the average number of nodes transmitting a TC message is defined by equation (5).

$$(C-1)\times M_{MPR}\left(K^2-(K-1)^2\right) \qquad (5)$$

Despite the theoretical performance expected by each protocol, the MPR selection process is NP-complete (Jacquet et al., 2002) and therefore the actual number of MPR nodes may vary. By analysing the presented protocols through simulation, a better understanding of the actual behaviour of these protocols can be obtained.

5 Routing performance and results

In order to achieve a complete analysis of the routing protocol performance it is helpful not only to perform a theoretical analysis of its behaviour but also to complement the analysis with extensive simulation results. This will provide a better understanding of the protocol by comparing the expected results in theory with the simulation results which take into account aspects such as wireless interferences and node mobility.

The performance evaluation of the DASH protocol and its hierarchy in the presented scenarios, has been carried out using the OPNET simulator, with a total of 30 runs per scenario, always using different seed values, for a total simulated time of 15 minutes (900 seconds). The considered wireless nodes follow the IEEE 802.11g standard, having a maximum range of 100 metres (transmit power of $3.7e^{-4}W$). However, due to the accurate radio model implemented by default in the OPNET simulator, asymmetric links or even unidirectional links may occur, as well as channel errors and multi-path interferences respectively. All other simulation parameters not mentioned here use their values set by default in the OPNET Modeler Wireless Suite Simulator, version 16.0.A PL1.

The simulations of each scenario were performed using not only the DASH protocol but also the COLSR and the OLSR protocols. A distributed version of the COLSR protocol was used as it avoids bottlenecks from using clusterheads. Moreover, the obtained simulation results have a 95% confidence interval calculated from the central limit theorem.

5.1 Controlled transitions results

The results presented first consider individually the existing transitions in the scenarios with 2, 3 and 4 clusters. These simulation-based results are compared with theoretical results in order to understand how efficient the algorithms from each protocol are in a more realistic environment.

1 *Average number of forwards per TC*: As previously stated, a protocol using OLSR should minimise the average number of forwards per TC message, avoiding an expensive flooding of routing data. As it is shown in Figure 6, in a small network with two clusters, the pure OLSR performs worse, having not only higher theoretical but also simulated values for the number of TC forwards, while the COLSR and DASH protocols perform equally well. In particular, the OLSR protocol forwards more TC messages than what was theoretically predicted since the election of MPR nodes a challenging task which is influenced by the number of nodes involved in the election. On the other hand, the clustered-based protocols are more efficient than what is theoretically expected due to the efficient reduction of the nodes considered in the MPR election process.

Figure 6 Average number of forwards per TC with 2 clusters

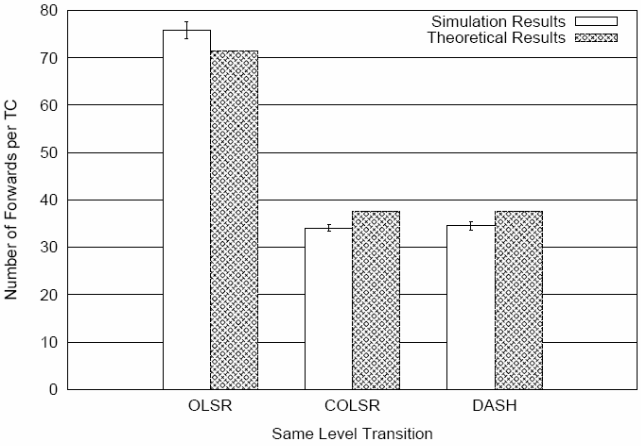


Figure 7 Average number of forwards per TC with 3 clusters

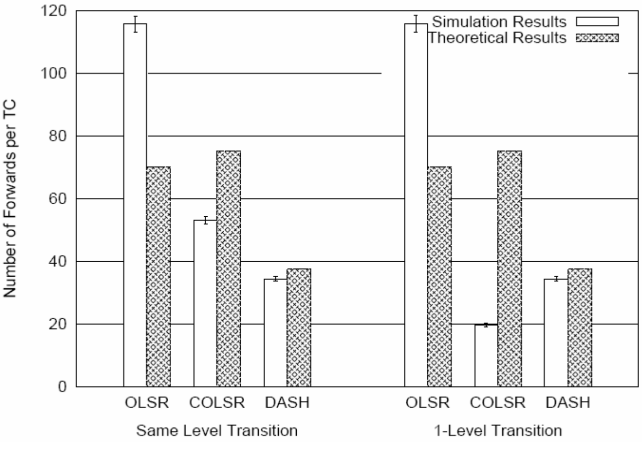
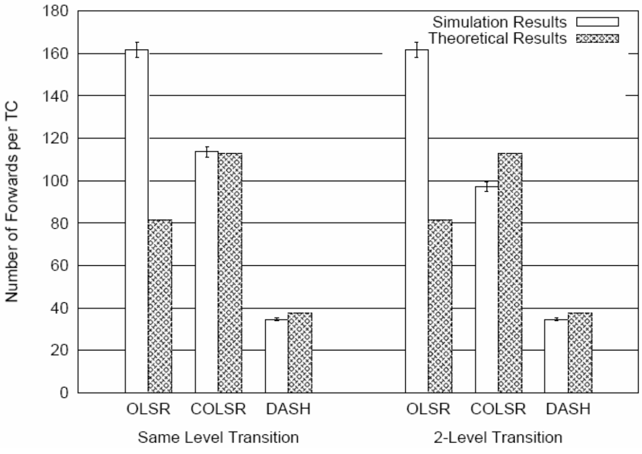


Table 1 Additional results

		Two clusters	*Three clusters*		*Four clusters*	
		Same level transition	*Same level transition*	*One level transition*	*Same level transition*	*Two levels transition*
Losses	OLSR	87.90%	92.46%	93.18%	92.42%	94.67%
	COLSR	84.46%	90.76%	90.25%	90.26%	92.36%
	DASH	19.35%	41.21%	33.32%	22.57%	23.27%
Delay (ms)	OLSR	10.01	10.22	13.54	12.65	13.33
	COLSR	9.35	9.70	12.17	10.81	12.17
	DASH	29.56	36.20	35.24	30.23	33.20
Sent TCs	OLSR	18.73	28.10	28.09	38.26	38.25
	COLSR	17.93	40.42	53.06	37.51	35.88
	DASH	17.93	26.91	26.90	37.26	35.88
Routing overhead (kbit/s)	OLSR	220.63	509.14	509.46	1,020.11	1,019.37
	COLSR	170.98	511.14	517.20	883.00	837.28
	DASH	176.70	339.78	340.06	530.47	530.78

In the two cluster network only same level transitions were possible, however for a three cluster scenario one level transitions will also occur. Even though in theory no change should be registered between these two transitions, Figure 7 reveals that in the simulated results the COLSR protocol abnormally decreases the number of forwards. This is related with the number of TCs sent by the COLSR protocol, which, for cluster organisation purposes, may create additional TC messages, lowering the average number of forwards as explained later in this analysis.

Figure 8 Average number of forwards per TC with 4 clusters



Apart from the COLSR's unexpected behaviour, the OLSR protocol, as predicted, increases its number of forwards while the DASH protocol has a constant number for both transitions. This steady value registered by the DASH protocol both theoretically and through simulation reveals its scalable properties, whereas the OLSR protocol shows why it does not scale, registering more forwards than what would be expected.

In a four cluster network, with the exception of the DASH protocol, both the OLSR and COLSR protocols register a significant climb in the number of forwarded messages. In fact, the difference between the simulated results and theoretical analysis is increased, being the only anomaly registered by the COLSR for two level transitions, as shown in Figure 8. The significant variances of the COLSR protocol when compared with the theoretical results is a consequence of the use of cluster-MPRs which themselves add an additional complexity to the network management. This process, similarly to the election of normal MPR nodes, is influenced by the number of entities involved in the process, being vulnerable to changes in the network.

2. *Routing traffic performance*: In Table 1, the percentage of registered losses for each scenario is presented, revealing that the DASH protocol outperforms both OSLR and COLSR. Despite considering mobility on one single node, these results show that the OLSR and COLSR protocols have routing problems even in a simple scenario. Thus, adding more traffic flows and mobile nodes would only mask these problems, not being suitable for the evaluation intended in this work.

   Another aspect that concerns traffic performance is the end-to-end delay. Regarding this, the COLSR protocol has the best results, while the DASH protocol registers the highest delay among the three protocols. Despite this fact, the obtained delay is acceptably low, being adequate for almost any type of application. Moreover, DASH delivers a higher amount of data when compared with its competitors, suggesting that the higher delay may also result from more challenging and distant routes, which are likely to occur in future wireless networks.

3 *Scalability performance*: The average number of forwards per TC message is the most important aspect when considering the scaling properties of an OLSR-based protocol. However, the total number of sent TCs may also be important as it reflects the total number of MPRs in the network. Since the network has the same number of nodes, a similar number of sent TC messages, and consequently MPRs, is registered for all the protocols in a two and four cluster scenario, while for a three cluster scenario the COLSR has higher number of TCs, as seen Table 1. This abnormal behaviour results from the poor cluster management from COLSR which issues unnecessary TC messages due to its instability. As a result, a lower average number of TC forwards (previously analysed) will be detected since many of these TCs are discarded.

In addition to the TC messages the OLSR protocol also uses HELLO messages, which usually have a smaller overhead as they are not forwarded to other nodes. The total overhead generated by the protocols' routing messages is presented in Table 1, which reveals that the DASH protocol is more scalable than both the clustered and un-clustered versions of the OLSR protocol.

5.2 Growing size network results

After having analysed the overhead and behaviour of the protocols in a fairly stable environment, where only one node moves between different clusters, the following results demonstrate the actual performance of each protocol in an entirely dynamic scenario, using different network sizes. Ten scenarios with a different number of clusters each have been analysed, presenting the differences in scalability for each one.

The presented results, for each scenario, are an average of the simulation values obtained in the OPNET simulator, using the same configuration as the previous scenarios.

For a more detailed analysis of the routing protocols' scalability and their traffic delivery performance, not only will the number of forwarded TC messages be analysed, but also each one of the metrics previously considered in the most stable scenarios.

1 *Percentage of losses*: The percentage of registered losses is presented in Figure 9, where the obtained percentage of losses is clearly influenced by the number of clusters in the network. In fact, with the increasing number of competing links and higher traffic load, the transmission error ratio can reach more than 60% (Sarikaya et al., 2012).

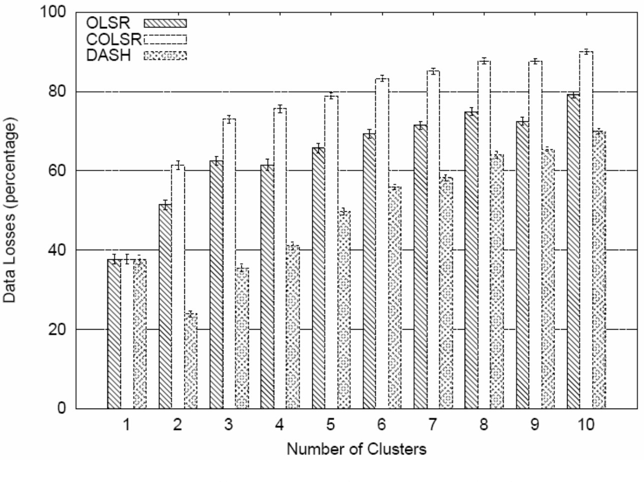
In a single cluster network, the three protocols have a similar performance as all of them simply use the OLSR protocol for maintaining routing paths. The increasing number of clusters has a high impact due to inter-cluster routing, such that the COLSR protocol registers more than 80% of losses in networks with more than 4 clusters.

Regarding the overall percentage of losses, the DASH protocol has the best performance since it to constantly delivers more data packets than its competitors. However, the DASH protocol still has a significant amount of losses in larger networks. While this is not desirable, it results from the intrinsic nature of MANETs. It is important to take into account that the proposed scenario is extremely demanding, where a path from source to destination may often not exist. Despite this fact, the proposed routing approach managed to perform two times better than the COLSR protocol in some network configurations.

2 *End-to-end delay*: In realistic multi-hop wireless networks, the constraint of an existing path between any two nodes cannot be guaranteed. As a result delay tolerant networks have been proposed, focusing in the delivery of data packets, regardless of the time interval it might take between source and destination. While the OLSR and COLSR protocols simply discard packets when a route is not found, the DASH gateways are able to re-route packets if alternative paths exist. As a result of an improved traffic delivery, the DASH protocol has a higher end-to-end delay, as seen in Figure 10.

Even though the DASH scheme is outperformed by the other two protocols, its increased traffic delivery must not be disregarded as it helps to understand the origin of this delay. In fact, after a closer analysis of the obtained results, the high standard deviation reveals that the registered delay is only introduced by some flows which are likely be failed by the other protocols. This is the only reason for such a standard deviation as the three protocols were equally simulated 30 times and only DASH was this dynamic.

Figure 9 Average percentage of losses



3 *Path length*: A different evaluation metric that confirms the DASH ability to deliver packets in more challenging destinations is the average path length. The number of hops from source to destination is presented in Figure 11, where the OLSR protocol stands out for being able to achieve the shortest routes. Regarding the cluster-based routing protocols, the DASH protocol is

able to keep up or even surpass the COLSR protocol's performance, while always delivering more data packets.

Once again, the increasing network size affects proportionally the metric results. The average path length increases with the number of nodes, similarly to the behaviour found for the delay metric, showing how these two metrics are linked since in larger paths longer distances are travelled by the packets being forwarded.

Figure 10 Average end-to-end delay

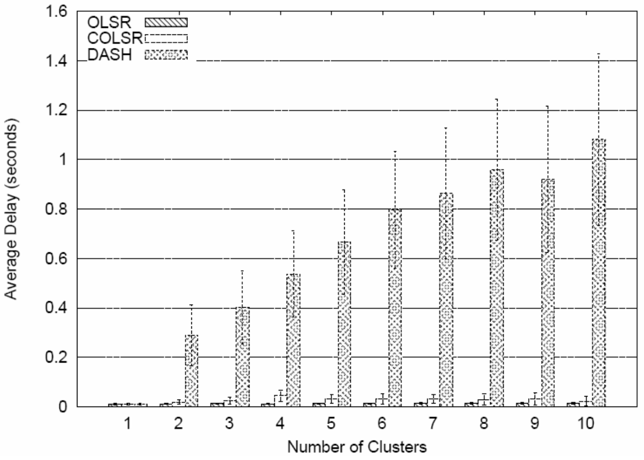
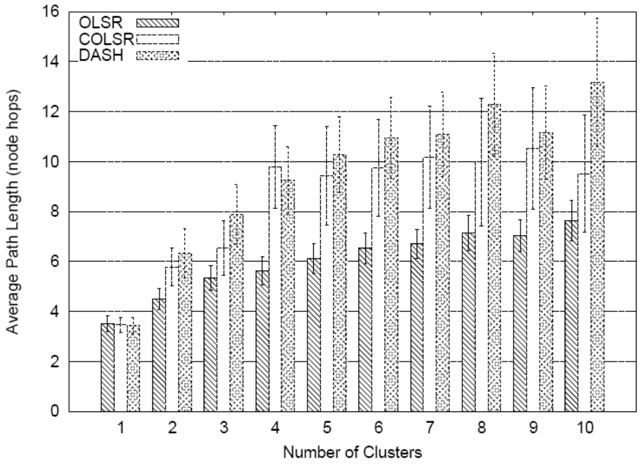


Figure 11 Average number of hops



4 *Number of forwards per TC message*: The number of forwarded TC messages is also a token of a protocol's ability to scale. The forwarding of TC messages deals a large amount of overhead in the network and should be kept to a minimum. Due to containment of routing information within clusters, the DASH and COLSR protocols require a rather small number of forwards in order to disseminate their routing information. In particular, the COLSR protocol requires the smallest amount of forwards. However, an excessively low number of updates may indicate that existing routes are not entirely valid, resulting in a higher number of losses.

Figure 12 shows the number of forwards per TC messages and reveals that the OLSR protocol requires its TC messages to be forwarded to most of the nodes in the network. This results from instability of the protocol in larger networks, making the MPR selection task much more challenging than in a more stable network with clusters, even though the same algorithm is used.

5 *Control traffic overhead*: Figure 13 shows the total overhead of routing control traffic issued by each protocol, where the amount of existing routing information increases for any protocol, as the number of nodes also increases. However, the DASH protocol increases its overhead slower than its competitors since it requires less routing messages and its capable to more efficiently deal with mobility. Moreover, the performance of the proposed protocol can event be further improved by using information from the clustering algorithm, since it already maintains a table with the mappings of each node to its CID.

Figure 12 Number of forwards per TC message

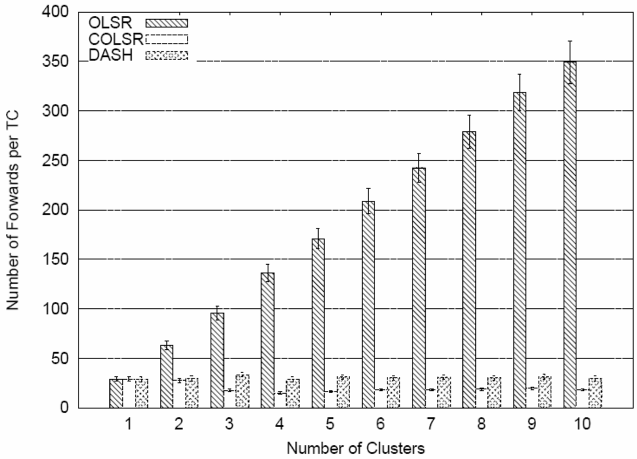
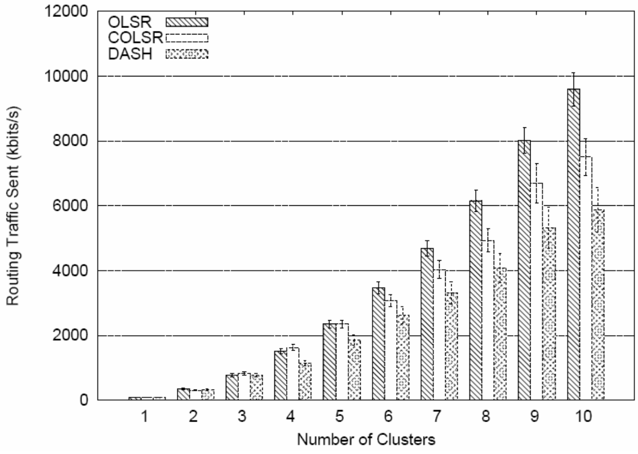


Figure 13 Generated routing traffic overhead



Even though the COLSR protocol has slightly lower ratio of forwarded TCs, when compared with DASH, it generates a higher routing traffic overhead since it sends more routing data per message. This will have a strong impact in the network lifetime as it requires more routing information to be propagated, re-enforcing that the DASH protocol is more scalable than its competitors.

6 Conclusions

In a world where ubiquitous and autonomous networks are expected to prevail, the DASH routing approach has been proposed for handling large-scale wireless multi-hop networks. This protocol is mainly characterised for having a well defined hierarchy in conjunction with an aggregation of network clusters into virtual clusters. While such routing conception may reduce the typical routing overhead found in a network, the impact of node mobility among different hierarchical levels could influence the overall performance of the routing protocol. In this paper, a thorough evaluation of the DASH protocol was performed, comparing its results against the OLSR and COLSR protocols, by defining three different scenarios of increasing scale, with a total of twenty possible hierarchical transitions among distinct contexts.

A theoretical analysis of the average number of forwards per TC message was considered in order to assess the scaling capabilities of each protocol, being these results compared with simulation results. The obtained values reveal that, as the number of nodes in the network increases, the worse the performance of OLSR protocol gets, registering more forwards than what would otherwise be expected.

An additional scenario with an increasing number of clusters (49 nodes each), up to ten clusters, was also defined. The evaluation of this scenario included all the possible hierarchical transitions since every node was mobile and further demonstrated the scalability of the DASH protocol in large-scale autonomous wireless networks.

Not only did the DASH protocol reveal itself as being more scalable with a lower routing overhead, it also achieved a considerably better performance regarding data traffic delivery. The obtained results suggest that deferred routing approach can be a viable solution for routing in future large-scale wireless networks in upcoming portable devices, keeping its performance stable as the number of nodes in the network increases, thus resulting in energy efficient routing scheme.

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