Scalability and Routing Performance of Future Autonomous Networks

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***Abstract*—Nowadays, the existing myriad of wireless capable devices has led to the development of numerous multi-hop routing protocols. From proactive to reactive and even hybrid routing approaches, these protocols have motivated the definition of autonomous and ubiquitous ad-hoc networks. Such networks have been idealized not only for disaster and rural scenarios, but also for an increasingly demanding social context in urban areas. However, being able to handle these networks in a large scale, still remains a challenge. Even though several routing solutions resort to clustering and hierarchies in order to limit routing information, the existing nodes' interactions are typically disregarded and mobility amongst different clusters still raises routing issues. In this work the scalability of three routing protocols will be analysed, by defining different size scenarios, while also assessing their routing performance with a mobile node moving between different clusters. Theoretical and simulation based results are presented, using twenty different possible transitions through the existing clusters. This evaluation provides an important contribution, revealing that hierarchical routing organizations' scalability is closer to what is theoretically expected, contrary to other routing solutions. Moreover, regarding the best routing performance which takes into account communities, these results motivate the further utilization of such schemes for future large scale ubiquitous networks.**

I. Introduction

An increasing dissemination of wireless capable devices has promoted a generalized connectivity of users to a myriad of services. In a near future, users are expected to own several hundreds of gadgets requiring wireless connections [1], 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.

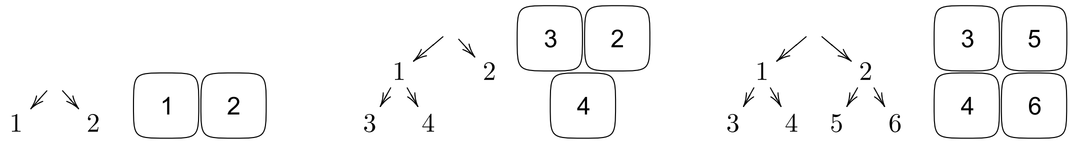
In the existing literature, the usage of clusters or routing hierarchies is found in order to efficiently keep a MANET scalable. For instance, and regarding the OLSR [2] protocol, this issue has been addressed by proposing special Topology Control (TC) messages and a hierarchical architecture [3][4]. Another example is found in the "Cluster-based OLSR extensions to reduce control overhead in mobile ad hoc networks" (COLSR) [5], where clusters are abstracted as nodes using the OLSR scheme, defining Cluster Topology Control and HELLO messages (C-TC and C-HELLO), as well as Cluster Multipoint Relays (C-MPRs).

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) [6], which proposes a new 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 II the DASH protocol is described, presenting the overall idea behind the concept and how the network is organized. The description of a routing evaluation for this protocol is provided in Section III, defining relevant scenarios to thoroughly assess the protocol, followed by a theoretical and simulation analysis in section IV. Finally, in Section V, the concluding thoughts on this work are presented.

II. 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



(a) 2 Clusters (b) 3 Clusters (c) 4 Clusters

Fig. 1. Network Hierarchy for Two Clusters

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. A binary tree hierarchy is defined with the assignment of Cluster IDs (CID) 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 1a a simple network hierarchy is depicted for two, three and four clusters. In a two cluster network no virtual clusters exist, however as soon as a new cluster is added to the network, in Figure 1b 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 1c, clusters with CIDs 3 and 4 will perceive the network as having only the cluster with CID 2 apart from their own 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.

III. 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 cluster-heads. 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 [7]. 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.

A. Objectives

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 it is important to consider the following aspects:

- 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.

B. Methodology and Scenarios Specification

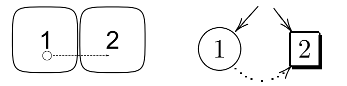
Bearing in mind that the DASH Routing protocol is cluster-based and that it uses the OLSR protocol for intra-cluster routing, the differences between these two protocols will only be noticeable in a network with at least two clusters. Thus, three different scenarios with 2, 3 and 4 clusters were defined. 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 500x500m^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 $12km/h$, similarly to travelling by bicycle or walking [8], travelling a total distance of 600 meters. 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 [9], which are all well suited applications for mobile ad-hoc networks.

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.

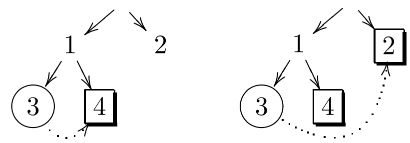
1) Two-Cluster Network: The most straightforward hierarchy in DASH is found in a network with two clusters. In this hierarchy the only possible transitions will occur in the same hierarchical level (0 Level Transition), when nodes move from the cluster with CID 1 to CID 2 and vice-versa. Figure 2 shows 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 cluster 1 to 2 and the other from cluster 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



(a) Cluster View (b) Hierarchical View

Fig. 2. Same Level Transition Example



(a) Same Level (b) One Level

Fig. 3. 2 Clusters Transition Examples

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 3a and 3b depict some of these transitions, when a node moves from cluster 3 to 4 and from cluster 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 cluster 3 to 4 and 2, from cluster 4 to 3 and 2 and finally from cluster 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 4a), 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 4b 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 recognizes at most $\lceil \log_2 C \rceil$, 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 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

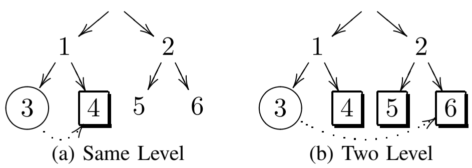


Fig. 4. 4 Clusters Transition Examples

Level transitions and 8 Two Level transitions.

IV. 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.

A. 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 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 Multipoint Relay (MPR) nodes in a K-hop neighbourhood. As demonstrated by Adjih et al. in [10] and Jacquet et al. in [11], 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 ($M \to \infty$), M_{MPR} is represented by Equation 2.

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

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

Taking into account the average number of MPRs select by a node, it follows that the probability of a node to be an MPR is M_{MPR}/M [3]. 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.

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

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

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.

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

Despite the theoretical performance expected by each protocol, the MPR selection process is NP-Complete [11] 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.

B. Simulation Results

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 meters (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.

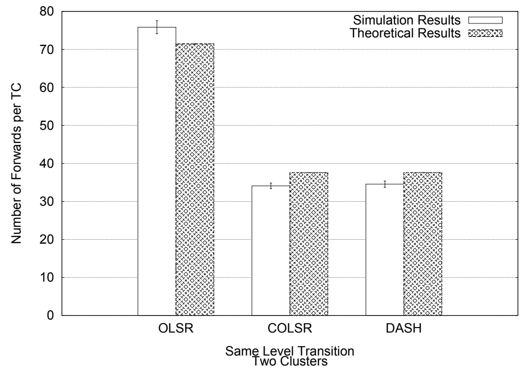


Fig. 5. Average Number of Forwards per TC with 2 Clusters

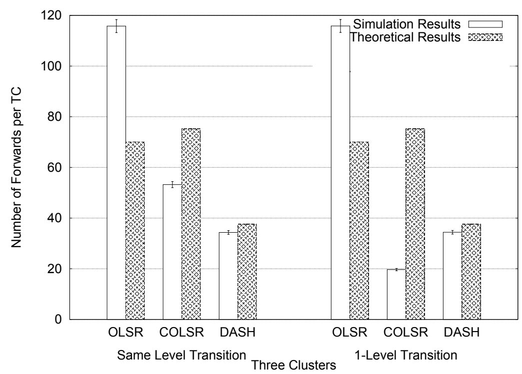


Fig. 6. Average Number of Forwards per TC with 3 Clusters

1) Average Number of Forwards per TC: As previously stated, a protocol using OLSR should minimize the average number of forwards per TC message, avoiding an expensive flooding of routing data. As it is shown in Figure 5, 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 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 6 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 organization purposes, may create additional TC messages, lowering the average number of forwards as explained later in this analysis.

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, apart from the DASH protocol,

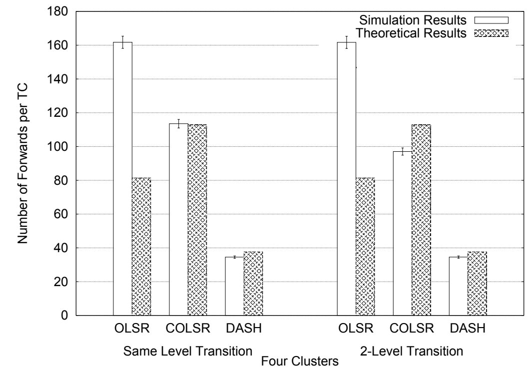


Fig. 7. Average Number of Forwards per TC with 4 Clusters

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, the only exception being COLSR for Two Level transitions, as shown in Figure 7.

2) Routing Traffic Performance: In Table I 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 I. 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 I, which reveals that the DASH protocol is more scalable

TABLE I
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	1020.11	1019.37
	COLSR	170.98	511.14	517.20	883.00	837.28
	DASH	176.70	339.78	340.06	530.47	530.78

than both the clustered and un-clustered versions of the OLSR protocol.

V. CONCLUSION

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 characterized 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.

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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