Scalable Hybrid Ad Hoc Routing Approach

Jose Costa-Requena, Tuna Vardar, Mohammad Ayyash and Raimo Kantola
{Jose, Tuna, Mayyash,Raimo}@netlab.tkk.fi
Networking Laboratory, Helsinki University of Technology, Otakaari 5, Espoo, FINLAND

Summary
Ad hoc networking is a technology still under development and there are several proposals for defining the most suitable routing protocol. No single routing protocol proposed so far performs optimally under the kind of dynamic conditions possible in Ad hoc networks. We analyze the performance of existing Ad hoc routing protocols using simulations and a test bed. Based on the results, the goal of this work is to design a hybrid routing approach for Ad hoc networks that we name Scalable Hybrid Ad hoc Routing Approach.

Key words:
Ad hoc networking, Hybrid Routing, Performance evaluation

Introduction

Ad hoc networks are envisioned as a key technology for ubiquitous networking. It is a suitable technology for embedded network devices in multiple environments such as vehicles, mobile telephones and personal appliances. As an infrastructure-less technology, it will allow users to create their Personal Area Networks (PAN). The benefit of Ad hoc networks is that users can create the network automatically when needed and tear it down if it is not required anymore. The network can be created at any point in time for any communication purpose such as leisure, military or disaster situations. Ad hoc networks have an undefined lifetime since they can be up and running momentarily or permanently as long as there is a group of users that are willing to be part of the network.

In Ad hoc networks the link state information changes whenever users move. Ad hoc networks are self-established without previous knowledge of the environment. Ad hoc nodes require a set of mechanisms to allow the devices to be autonomously integrated and configured as part of the Ad hoc network.

Network scalability is the ability to expand or reduce the number of nodes and size of the network while maintaining similar performance for each user. Ad hoc nodes have to perform the routing functionality and maintain the network topology information, while keeping track of the connection with other nodes. They must also be able to react fast to network changes and dynamically adapt to the new topology. Therefore, the overall Ad hoc network performance is affected by the size of the network, the number of nodes, their mobility and resources.

In recent years it has been proven that there is no single protocol that accommodates different conditions in Ad hoc networks. Moreover, not all the nodes have the same requirements in terms of mobility and resources. Therefore, it is difficult to design a single protocol that simultaneously meets all the network variations and the different node requirements.

The objective of this work is to design and implement a new hybrid routing approach named Scalable Hybrid Ad hoc Routing Protocol (SHARP). SHARP main purpose is to enable Ad hoc network scalability. This approach has to be able to meet the demands of the Ad hoc network when it reduces or increases the size and the number of nodes. Moreover, it has to be suitable for nodes with different mobility and resource constrains. Test bed results and simulations of existing routing protocols are used as the basis for SHARP design.

The rest of the paper is structured as follows. Section 2 describes the basic Ad hoc routing protocols. Section 3 presents the performance results based on simulations. This chapter models the performance evaluation of existing Ad hoc routing protocols. The results demonstrate that there is no single protocol suitable for all the Ad hoc networks. Section 4 provides the performance results based on a small scale test bed to verify the performance modeling in Section 2. This section highlights the scalability limitations of some of the existing routing protocols. Section 5 presents the basic requirements in Ad hoc networks, and based on the performance evaluation we design a novel hybrid routing approach for Ad hoc networks named Scalable Hybrid Ad hoc Routing Protocol (SHARP).

2. Ad hoc routing protocols

Ad hoc routing protocols can be classified into three categories reactive, proactive and hybrid.

2.1 Reactive routing protocols

Reactive Ad hoc routing protocols determine a path on-demand only, meaning that they search for a single path when a message needs to be delivered. In this section we briefly describe the Ad hoc On Demand Distance Vector (AODV) [1], the Dynamic Source Routing (DSR) [2] and the Temporally Ordered Routing Algorithm (TORA) [3] as the most widely used reactive Ad hoc routing protocols.

In AODV the source node initiates a Route Request (RREQ) message that is flooded through the network to the destination. The intermediate nodes in the route record the RREQ message. A Route Reply (RREP) unicast message is sent back to the source node as the acknowledgement following the reverse routes established by the received RREQ message. The intermediate nodes in the route also record the RREP message in their routing table for future use. Each node keeps the most recently used route information in its cache. Therefore, AODV is a simple protocol and does not require excessive resources on the nodes. However, the routing information available in the nodes is limited, and the route discovery process may take too much time. The initial RREQ is sent with TTL=1 and if no RREP is received within certain time, the TTL is incremented and a new RREQ is sent. Thus, if the destination node is not close enough, the network is flooded several times during the RREQ process before a route is found or an error is notified.

DSR is similar to AODV where RREQ and RREP messages are also used for discovering the route to the destination. The main difference is that in this case, these messages also include the entire path information (i.e. addresses of the intermediate nodes). The drawback is that the route information generates an overhead that can be excessive when the number of hops or node mobility increase.

TORA is a reactive routing protocol with some proactive enhancements where a link between nodes is established creating a Directed Acyclic Graph (DAG) of the route from the source to the destination. The routing messages are distributed to a set of nodes following the graph around the changed topology. TORA provides multiple routes to a destination quickly with minimum overhead. In TORA the optimal routes are of secondary importance versus the delay and overhead of discovering new routes.

2.2 Proactive routing protocols

The proactive protocols are the traditional routing protocols used in fixed IP networks. These protocols maintain a table with the routing information, and perform periodic updates to keep it consistent. In this section we will introduce the Destination Sequenced Distance Vector Routing (DSDV) [4] and the Optimised Link State Routing (OLSR) [5] as the most representative proactive Ad hoc routing protocols.

DSDV looks for the optimal path using the Bellman-Ford algorithm. It uses a full dump or incremental packets to reduce the traffic generated by the routing updates in the network topology. However, it creates an excessive overhead because it constantly tries to find the optimal path.

OLSR defines Multipoint Relay (MPR) nodes for exchanging the routing information periodically. The nodes select the local MPR node that will announce the routing information to other MPR nodes in the network. The MPR nodes calculate the routing information for reaching other nodes in the network

2.3 Hybrid routing protocols

This section introduces a hybrid model that combines reactive and proactive routing protocols but also a location assisted routing protocol.

The Zone Routing Protocol (ZRP) [6] is a hybrid routing protocol that divides the network into zones. The Intra-Zone Routing Protocol (IZRP) implements the routing within the zone, while the Inter-zone Routing Protocol (IERP) implements the routing between zones. ZRP provides a hierarchical architecture where each node has to maintain additional topological information requiring extra memory.

The Location Aided Routing (LAR) [7] is a location assisted routing protocol that uses location information for the routing functionality. LAR works similarly to DSR but it uses location information to limit the area where the route request is flooded. The source node knows the neighbours location and based on that selects the closest nodes to the destination as the next hop in the route request

3. Ad hoc routing protocol evaluation

After describing different routing protocols and based on the basic characteristics of reactive and proactive routing protocols we can formulate a set of propositions. The propositions will consider the impact of system variables such as the used routing protocol type, the node mobility and the number of nodes (i.e. node density) on performance measures such as routing overhead, percentage of packet loss, end to end packet delay and percentage of optimal routes. At this stage we are not able to indicate whether there is a linear or polynomial relationship between the system variables and the performance measures.

The routing protocols under consideration in this evaluation are the most representative of reactive and proactive categories. AODV and OLSR are the only two experimental protocols standardized in the IETF as reactive and proactive routing protocols.

In our propositions we assume that the following conditions do not change: bit rate, number of connections and size of the Ad hoc network. Let us now formulate the set of propositions using the terminology introduced in Table 1.

Table 1: Performance metrics and system variables

System Variables				Performance metrics			
Proactive routing protocol	Reactive routing protocol	Num of nodes	Node mobility	Routing overhead	% of packet loss	End to end packet delay	% of optimal routes
P	R	N	M	W	L	D	Π

Proposition 1. The routing overhead increases with the node mobility in both proactive and reactive routing protocols. $W_P'(M) \geq 0$, $W_R'(M) \geq 0$

The routing overhead increases with the node mobility due to the extra route discovery transactions generated in reactive protocols and the route updates required in proactive routing protocols.

Proposition 2. The end to end packet delay increases with the node mobility in both proactive and reactive routing protocols. $D_P'(M) \geq 0$, $D_R'(M) \geq 0$

In proactive routing protocols, the end to end packet delay increases when there is network congestion because of the increment in the number of transactions required to exchange topology information with all the nodes. The end to end packet delay increases with the node mobility in reactive routing protocols because of the increment of route discovery transactions.

Proposition 3. The percentage of packet loss increases with the node mobility in both proactive and reactive protocols.
$L_P'(M) \geq 0$, $L_R'(M) \geq 0$

When mobility increases, links are more frequently broken and percentage of packet loss increases.

Proposition 4. The percentage of optimal routes decreases in both proactive and reactive routing protocols when the node mobility increases. $\Pi_P'(M) \leq 0$, $\Pi_R'(M) \leq 0$

Proposition 5. The percentage of optimal routes obtained with proactive routing protocol is higher than in reactive protocols. $\Pi_P(M) > \Pi_R(M)$

The routing protocols obtain the network topology based on periodic routing updates (i.e. proactive) or on demand route discovery (i.e. reactive). The proactive routing protocols apply an additional algorithm over the discovered routes to select the most optimal route (e.g. lower number of hops). As a consequence proactive routing protocols obtain a higher percentage of optimal routes compared to the routes obtained with reactive routing protocols. When mobility increases, the routes obtained become stale due to frequent links broken.

Proposition 6. The routing overhead increases with the number of nodes in both proactive and reactive routing protocols. $W_P'(N) \geq 0$, $W_R'(N) \geq 0$

Proposition 7. For the same number of nodes and mobility conditions the routing overhead is higher in proactive than in reactive protocols. $W_P(M,N) \geq W_R(M,N)$

The routing overhead increases with the number of nodes due to additional topology information required in proactive protocols, and the additional route requests forwarded by each of the intermediate nodes in reactive protocols.

Proposition 8. The end to end packet delay increases with the number of nodes in both proactive and reactive routing protocols. $D_P'(N) \geq 0$, $D_R'(N) \geq 0$

Proposition 9. The percentage of packet loss increases with the number of nodes in both proactive and reactive routing protocols. $L_P'(N) \geq 0$, $L_R'(N) \geq 0$

When the number of nodes increases, the network gets congested because of the additional signalling, causing an increment of the packet delay and the percentage of packet loss. According to Proposition 1, the routing overhead increases with the mobility, therefore the throughput will decrease reducing the available bandwidth and increasing the percentage of packet loss.

Proposition 10. The percentage of optimal routes obtained with proactive and reactive routing protocols decreases with the number of nodes. $\Pi_P'(N) \leq 0$, $\Pi_R'(N) \leq 0$

When calculating the optimal routes, increasing the number of nodes will decrease the efficiency of the protocols because of the additional topology information collected from all the nodes that has to be processed.

3.1 Proactive versus Reactive Simulation Comparison

In this section, the simulation results justify the advantages and drawbacks of the reactive and proactive Ad hoc routing protocols. The routing protocols comparative has been done using ns-2 simulator [8] version 2.27. We also verify some of the propositions introduced in previous section.

The results are obtained from the average of three simulations rounds considering the following parameters:
- Simulation area: 1500m x 300m
- Simulation time: 900 seconds
- Constant Bit Rate (CBR) traffic: 20 IP unidirectional connections
- Connection rate: 8 packets/second
- Packet size: 65 bytes.
- Number of nodes: 50 nodes using random waypoint mobility pattern.
- Pause time between node movements: 0, 30, 60, 120, 300, 600 and 900 seconds.

The literature shows that the different mobility patterns affect Ad hoc networks performance results [9]. Ad hoc networks will be deployed under different mobility patterns and the routing protocols have to perform in different environments. Therefore, in the simulations, the nodes follow a different mobility pattern after each waiting time as characterized in the random waypoint model.

The simulations are made considering that the network is handling the traffic generated by 20 active connections transmitting 8packets/second. The simulations reflect the performance of Ad hoc networks with real time applications under different mobility conditions and using different routing protocols. The simulations last for 900 seconds, thus a pause time of 900 seconds is equivalent to static nodes that do not move during the simulation.

The simulation results can be associated with an equation that can be linear $f(x) = cx + b$, polynomial $f(x) = b + c_1x + c_2x^2 + ... + c_nx^n$, logarithmic $f(x) = c\ln x + b$ or exponential $f(x) = ce^{bx}$. The constants c and b of these equations are adjusted using the r-squared value $r^2 = 1 - \frac{\sum (Y_i - \hat{Y}_i)^2}{\sum Y_i^2 - \frac{(\sum Y_i)^2}{n}}$, where Y_i represents the value obtained in the simulation and $\hat{Y}_i$ represents the estimated value from the associated equation. The r-squared value represents the approximation error, thus it tends to 1 when the values from the simulation and the associated equation match.

Figure 1 shows the routing overhead generated by reactive and proactive routing protocols during the simulation time versus node mobility. Proactive protocols have a higher routing overhead than reactive protocols, which can be caused by the additional topology information they exchange. In particular, AODV generates less routing overhead compared to OLSR in similar conditions.

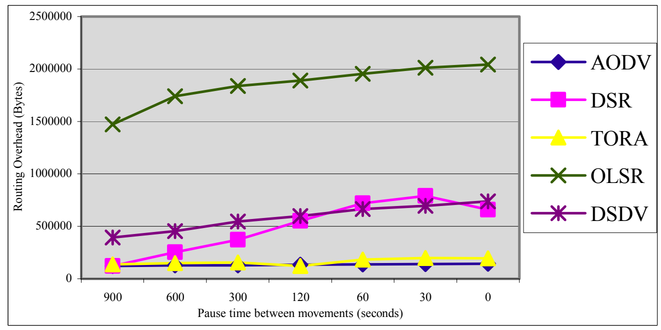

Figure 1. Routing overhead versus node mobility.

From the different equations that can be associated with the results of the AODV routing overhead, the one with the lowest approximation error $r^2 = 0.976$ is Eq 1.

Eq 1. $\Omega_R(M) = 120.9e^{0.025M}\ (Kbytes)$

The first derivative is $\Omega_R'(M) = \frac{d(\Omega_R)}{dM} = 3.02e^{0.025M} = \begin{matrix} 3.02|_{M\to 0} \\ +\infty|_{M\to\infty} \end{matrix} \geq 0$, proving **Proposition 1**.

The associated equation to the OLSR routing overhead simulations results with the lowest approximation error $r^2 = 0.835$ is Eq 2.

Eq 2. $\Omega_P(M) = 2000e^{0.047M}\ (Kbytes)$

The first derivative is $\Omega_P'(M) = \frac{d(\Omega_P)}{dM} = 94e^{0.047M} = \begin{matrix} 94|_{M\to 0} \\ +\infty|_{M\to\infty} \end{matrix} \geq 0$, proving **Proposition 1.**

Figure 2 shows the end to end packet delay generated by reactive and proactive routing protocols during the simulation time versus node mobility. In high mobility conditions, proactive routing protocols such as OLSR present higher delay than reactive routing protocols as stated in proposition 2. In case of low mobility, performance of reactive and proactive routing protocols is similar.

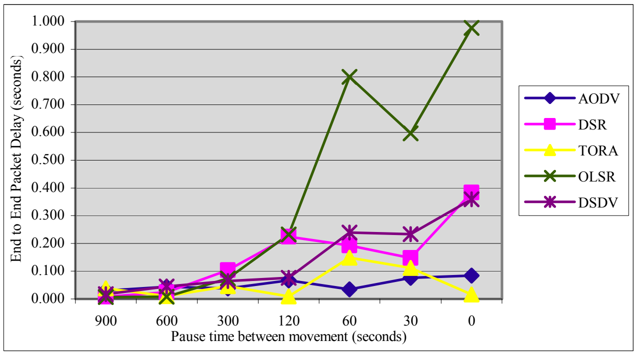

Figure 2. End to End packet delay versus node mobility.

The node mobility affects the end to end packet delay because of different reasons such as network congestion and connectivity. The network congestion increases with mobility due to the link breaks that generate new topology updates in proactive protocols, and additional route requests initiated in reactive protocols. The connectivity is immediately re-established after the link break in the reactive protocols but it is performed after the periodic route update in proactive protocols. The associated equation to the AODV end to end packet delay simulation results with the lowest approximation error $r^2 = 0.625$ is Eq 3.

Eq 3. $D_R(M) = 0.008M + 0.021(s)$

The first derivative is $D_R'(M) = \frac{d(D_R)}{dM} = 0.008 \ge 0$, proving **Proposition 2**.

The associated equation to the OLSR end to end packet delay simulation results with the lowest approximation error $r^2 = 0.851$ is Eq 4.

Eq 4. $D_P(M) = 0.172M - 0.302(s)$

The first derivative is $D_P'(M) = \frac{d(D_P)}{dM} = 0.172 \ge 0$, proving **Proposition 2.**

Figure 3 shows the percentage of packet loss generated by reactive and proactive routing protocols during the simulation time versus node mobility.

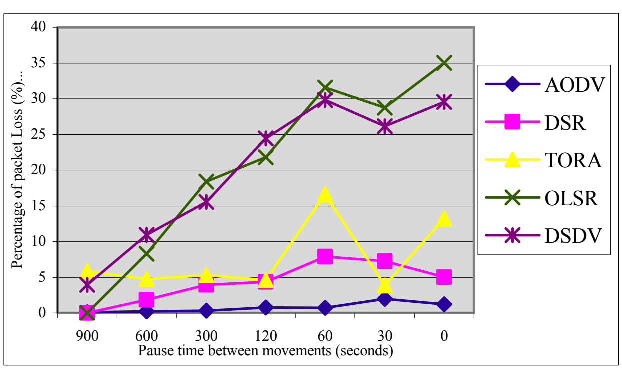

Figure 3. Percentage of packet loss versus node mobility.

We measured the packet loss as the percentage of packets that did not reach the destination from the total number of packets sent. Percentage of packet loss is higher in proactive routing protocols than in reactive routing protocols and increases with mobility as stated in **Proposition 3**.

The associated equation to the AODV percentage of packet loss simulation results with the lowest approximation error $r^2 = 0.881$ is Eq 5.

Eq 5. $L_R(M) = 0.083e^{0.455M}$ (%)

The first derivative is $L_R'(M) = \frac{d(L_R)}{dM} = 0.038e^{0.455M} = \begin{matrix} 0.038|_{M\to 0} \\ +\infty|_{M\to\infty} \end{matrix} \ge 0$, proving **Proposition 3**.

The associated equation to the OLSR percentage of packet loss simulation results with the lowest approximation error $r^2 = 0.64$ is Eq 6.

Eq 6. $L_P(M) = 0.225e^{0.89M}$ (%)

The first derivative is $L_P'(M) = \frac{d(L_P)}{dM} = 0.2e^{0.89M} = \begin{matrix} 0.2|_{M\to 0} \\ +\infty|_{M\to\infty} \end{matrix} \ge 0$, proving **Proposition 3.**

Figure 4 shows the percentage of optimal routes obtained by reactive and proactive routing protocols during the simulation time versus node mobility. Proactive routing protocols perform better than reactive routing protocols when obtaining the optimal routes. Proactive routing protocols maintain up to date the routing information and apply the appropriate routing algorithms (e.g. Shortest Path). The percentage of optimal routes decreases in both reactive and proactive protocols with node mobility as stated in **Proposition 4**.

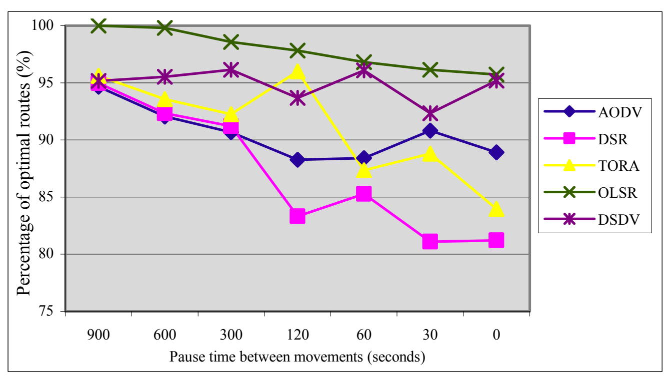

Figure 4. Percentage of optimal routes versus node mobility.

The associated equation to the AODV percentage of optimal routes simulation results with the lowest approximation error $r^2 = 0.729$ is Eq 7.

Eq 7. $\Pi_R(M) = 94.028 - 2.864\ln(M)(\%)$

The first derivative is $\Pi_R'(M) = \frac{d(\Pi_R)}{dM} = -\frac{2.864}{M} = \begin{matrix} -\infty|_{M\to 0} \\ -0|_{M\to\infty} \end{matrix} \leq 0$,

proving **Proposition 4**.

The associated equation to the OLSR percentage of optimal routes simulation results with the lowest approximation error $r^2 = 0.902$ is Eq 8.

Eq 8. $\Pi_P(M) = 100 - 2.381\ln(M)(\%)$

The first derivative is $\Pi_P'(M) = \frac{d(\Pi_P)}{dM} = -\frac{2.381}{M} = \begin{matrix} -\infty|_{M\to 0} \\ -0|_{M\to\infty} \end{matrix} \leq 0$,

proving **Proposition 4.**

The associated equations show that 100% of the routes obtained with the proactive protocol can be optimal in case of zero node mobility compared to the case of reactive protocol where with similar conditions only 94% of the routes obtained are optimal, which proves **Proposition 5**.

We have verified some of the propositions based on the results from the simulations but the scalability effect on the routing protocols remains to be verified. The simulator has some limitations in terms of number of nodes (i.e. max number of nodes is 100).

Therefore, in order to see the effect when increasing the number of nodes in the performance results, new simulations have been performed with 25, 50 and 100 nodes keeping the same value for the rest of the parameters.

Figure 5 shows that the routing overhead increases with the number of nodes in both proactive and reactive routing protocols as stated in **Proposition 6**.

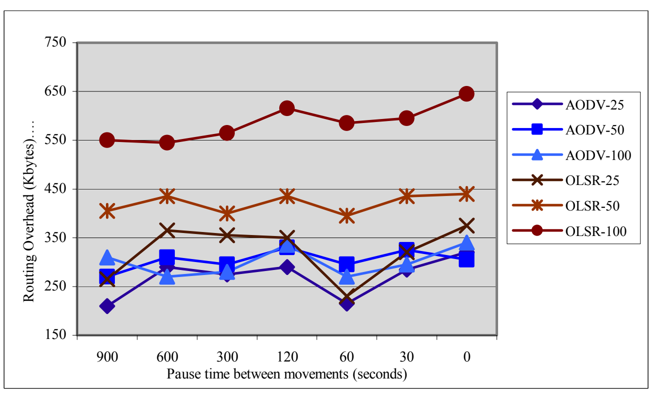

Figure 5 Routing overhead for reactive and proactive routing with 25, 50, 100 nodes

The associated equations to the AODV routing overhead simulation results for the different number of nodes, with the lowest approximation error $r^2 = 0.74$ are Eq 9, Eq 10 and Eq 11.

Eq 9. $\Omega_R(M, N = 25) = 231.5e^{0.035M}$

Eq 10. $\Omega_R(M, N = 50) = 284.3e^{0.016M}$

Eq 11. $\Omega_R(M, N = 100) = 281.5e^{0.015M}$

In reactive routing protocols there is a certain increase of the routing overhead with the number of nodes as stated in **Proposition 6.** The simulation results could be associated with linear equations but it has a higher approximation error than the exponential equation. The major increase of the routing overhead takes place when incrementing from 25 (i.e. 231.5Kbytes) to 50 (i.e. 284.3Kbytes) nodes, while the values for 50 and 100 nodes are almost the same. The routing overhead value obtained for 50 nodes in previous simulations is different (i.e. Eq 1. $\Omega_R(M) = 120.9e^{0.025M}(Kbytes)$), which is due to the inaccuracy of the simulations. Including the different number of nodes as a new variable, introduces a new approximation error $r^2 = 0.74$. The generic equation associated to the AODV routing overhead is done taking the equations Eq 9, Eq 10 and Eq 11 resulting in Eq 12.

Eq 12. $\Omega_R(M, N) = (180 + 20N)e^{0.02M}(Kbytes)$

The associated equations to the OLSR routing overhead simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.62$ are Eq 13, Eq 14 and Eq 15.

Eq 13. $\Omega_P(M, N = 25) = 303.11e^{0.012M}$

Eq 14. $\Omega_P(M, N = 50) = 406.38e^{0.009M}$

Eq 15. $\Omega_P(M, N = 100) = 530.01e^{0.025M}$

In proactive routing protocols there is a significant increment of the routing overhead with the number of nodes as stated in **Proposition 6**. From the associated equations, the routing overhead value roughly increases 100Kb when doubling the number of nodes, and the exponential factor is double when the number of nodes increases from 25 to 100.

When comparing Eq 14 with Eq 2. $\Omega_P(M) = 2000e^{0.047M}(Kbytes)$ the results are considerably different due to the inaccuracy of the simulations and the fact that the latest simulations have a higher approximation error $r^2 = 0.62$ associated.

The generic equation associated to the OLSR routing overhead is done taking the equations Eq 13, Eq 14 and Eq 15 resulting in Eq 16.

Eq 16. $\Omega_P(M.N) = (185 + 114N)e^{(0.002+0.006N)M}(Kbytes)$

Therefore, routing overhead increases with the number of nodes as stated in **Proposition 6** and the proactive routing protocols present higher overhead than reactive protocols as stated in **Proposition 7**. Increasing the number of number of nodes affects more to proactive protocols routing overhead while node mobility affects more to reactive protocols routing overhead. For this reason, proactive routing protocols are not scalable in Ad hoc networks.

Figure 6 shows that end to end packet delay is similar in reactive and proactive routing protocols when the increase in the number of nodes is low (i.e. ±0.02sec end to end packet delay variation when 25≤N≤50). However, the end to end delay is higher in proactive routing protocols when increasing the number of nodes (i.e. N=100).

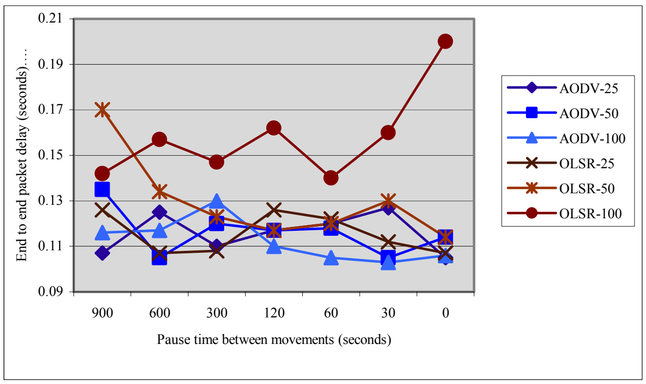

Figure 6. End to end packet delay for reactive and proactive routing with 25, 50 and 100 nodes.

The associated equations to the AODV end to end packet delay simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.41$ are Eq 17, Eq 18 and Eq 19.

Eq 17. $D_R(M, N = 25) = 0.0003M + 0.115(s)$

Eq 18. $D_R(M, N = 50) = 0.0023M + 0.125(s)$

Eq 19. $D_R(M, N = 100) = 0.003M + 0.124(s)$

The end to end packet delay is almost constant for reactive routing despite increasing of the number of nodes when mobility is zero. The delay is independent of the number of nodes (i.e. between 115-125ms for M=0) zero. However, the end to end packet delay increases with the number of nodes with as stated in **Proposition 8**.

The simulations associated with Eq 3. $D_R(M) = 0.008M + 0.021(s)$ are optimistic, giving a end to end packet delay value of 21ms when M=0. The latest simulations provide more realistic values despite of the higher approximation error. Therefore, we will use these results to estimate the end to end packet delay for reactive protocols including mobility and number of nodes. The generic equation associated to the AODV end to end packet delay is done taking the equations Eq 17, Eq 18and Eq 19 resulting in Eq 20.

Eq 20. $D_R(M, N) = (0.003N)M + 0.110 + 0.01N(s)$

The associated equations to the OLSR end to end packet delay simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.43$ are Eq 21, Eq 22 and Eq 23.

Eq 21. $D_P(M, N = 25) = 0.0012M + 0.120(s)$

Eq 22. $D_P(M, N = 50) = 0.0013M + 0.126(s)$

Eq 23. $D_P(M, N = 100) = 0.0062M + 0.133(s)$

From the equations Eq 17, Eq 18, Eq 19, Eq 21, Eq 22 and Eq 23 we observe that proactive and reactive protocols have similar end to end packet delay when the number of nodes is low (i.e. between 120-126ms delay for mobility zero and a mobility incremental factor of 0.003-0.0023 when the number of nodes is between 25 and 50). However, when the number of nodes is high N=100, the end to end packet delay in proactive routing protocols show more dependency with the mobility (i.e. mobility incremental factor of 0.0062) than reactive routing protocols.

When comparing Eq 22 with Eq 4. $D_P(M) = 0.172M - 0.302(s)$), there is considerable difference due to the applied approximation.

Therefore, generic equation associated to the OLSR end to end packet delay is done taking equations Eq 21, Eq 22 and Eq 23 resulting in Eq 24. The approximation error $r^2 = 0.43$ is high but it provides more realistic values.

Eq 24. $D_P(M, N) = (0.0025N)M + 0.113 + 0.07N(s)$

Therefore, from end to end packet delay point of view reactive and proactive protocols are not highly affected by the number of nodes. Proactive protocols present scalability issues when the number of nodes is high due to network congestion because of the additional routing overhead as stated in **Proposition 7**.

Figure 7 shows that the percentage of packet loss increases with mobility and number of nodes in both reactive and proactive routing protocols.

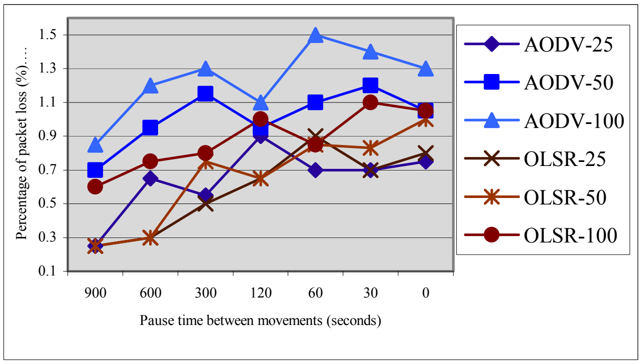

Figure 7. Percentage of packet loss for reactive and proactive routing with 25, 50 and 100 nodes.

The associated equations to the AODV percentage of packet loss simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.61$ are Eq 25, Eq 26 and Eq 27.

Eq 25. $L_R(M, N = 25) = 0.36e^{0.132M}$ (%)

Eq 26. $L_R(M, N = 50) = 0.79e^{0.058M}$ (%)

Eq 27. $L_R(M, N = 100) = 0.95e^{0.062M}$ (%)

The equations Eq 25, Eq 26 and Eq 27 show that the percentage of packet loss is low in reactive protocols but it increases with the number of nodes as stated in **Proposition 9**.

The generic equation associated to the AODV percentage of packet loss considering mobility and the number of nodes is done taking the equations Eq 25, Eq 26, Eq 27 and the estimation error $r^2 = 0.61$, resulting in Eq 28.

Eq 28. $L_R(M, N) = (0.1 + 0.3N)e^{0.06M}$ (%)

The associated equations to the OLSR percentage of packet loss simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.64$ are Eq 29, Eq 30 and Eq 31.

Eq 29. $L_P(M, N = 25) = 0.23e^{0.21M}$

Eq 30. $L_P(M, N = 50) = 0.24e^{0.22M}$

Eq 31. $L_P(M, N = 100) = 0.6e^{0.1M}$

When comparing Eq 30 with Eq 6. $L_P(M) = 0.225e^{0.89M}$ (%) the major difference is in the exponential factor. This is due to the higher approximation error. Nevertheless, assuming the inaccuracy of the simulations and the associated approximation error $r^2 = 0.64$, the generic equation associated to the OLSR percentage of packet loss considering mobility and the number of nodes is done taking the equations Eq 29, Eq 30 and Eq 31, resulting in Eq 32.

Eq 32. $L_P(M, N) = (0.2N)e^{0.2M}$ (%)

Figure 7 and the associated equations show that the percentage of packet loss in static conditions (i.e. M=0) and for a small number of nodes (i.e. N=25) is similar for reactive and proactive routing protocols. The impact of the mobility in proactive routing protocols is higher than in reactive routing protocols. However, when the number of nodes increases (i.e. 50≤N≤100), the percentage of packet loss is higher for reactive routing protocols than proactive routing protocols. This means that from percentage of packet loss point of view reactive protocols are less scalable than proactive routing protocols but mobility has lower impact in the reactive routing protocols than in proactive routing protocols.

Figure 8 shows that the percentage of optimal routes obtained with reactive and proactive routing protocols decreases with the number of nodes as stated in **Proposition 10**.

The proactive routing protocols exchange topology information periodically and can implement different algorithms to optimise the routes. The reactive protocols implement the route optimisation during the route request based on number of hops and sequence numbers to avoid loops.

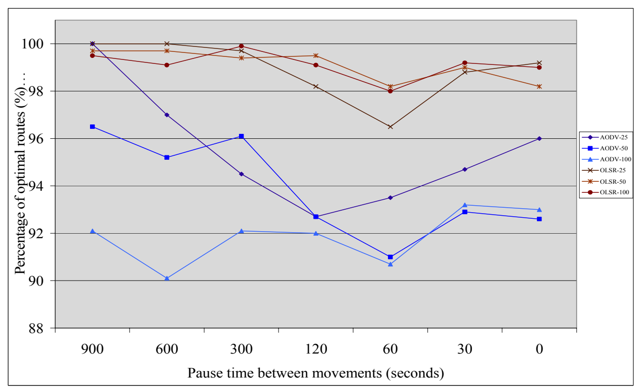

Figure 8. Percentage of optimal routes obtained with proactive and reactive routing with 25, 50 and 100 nodes.

The associated equations to the AODV percentage of optimal routes simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.67$ are Eq 33, Eq 34 and Eq 35.

Eq 33. $\Pi_R(M, N = 25) = 98.7 - 2.66\ln(M)(\%)$

Eq 34. $\Pi_R(M, N = 50) = 96.8 - 2.48\ln(M)(\%)$

Eq 35. $\Pi_R(M, N = 100) = 91.1 - 1.8\ln(M)(\%)$

When comparing Eq 34 with Eq 7. $\Pi_R(M) = 94.028 - 2.864\ln(M)(\%)$ both are similar due to the fact that in both cases the approximation error is almost the same $r^2 = 0.729$ and $r^2 = 0.67$. The generic equation associated to the AODV percentage of optimal routes considering mobility and the number of nodes is done taking equations Eq 33, Eq 34 and Eq 35, resulting in Eq 36.

Eq 36. $\Pi_R(M,N) = (103 - 3.9N) - (3.2 - 0.4N)\ln(M)(\%)$

The associated equations to the OLSR percentage of optimal routes simulation results for the different number of nodes with the lowest approximation error $r^2 = 0.61$ are Eq 37, Eq 38 and Eq 39.

Eq 37. $\Pi_P(M, N = 25) = 100 - 1.04\ln(M)(\%)$

Eq 38. $\Pi_P(M, N = 50) = 100 - 0.74\ln(M)(\%)$

Eq 39. $\Pi_P(M, N = 100) = 99.6 - 0.36\ln(M)(\%)$

There is a difference between Eq 38 and Eq 8. $\Pi_P(M) = 100 - 2.381\ln(M)(\%)$ mainly in the logarithmic factor due to the difference in the approximation error (i.e. $r^2 = 0.902$ versus $r^2 = 0.61$).

The generic equation associated to the OLSR percentage of optimal routes considering mobility and the number of nodes is done taking the equations Eq 37, Eq 38 and Eq 39, resulting in Eq 40.

Eq 40. $\Pi_P(M,N) = 100 - (1.4 - 0.3N)\ln(M)(\%)$

In reactive protocols the percentage of optimal routes decreases with the number of nodes while in proactive protocols the impact of the number of nodes is low. Therefore, when obtaining optimal routes, the reactive routing protocols are not scalable.

Table 1 compares reactive and proactive protocols in terms of complexity. The *storage complexity* indicates the size of the routing table required by each protocol. The *communication complexity* indicates the processing resources required to find routes or perform a route update operation. N denotes the number of nodes in the Ad hoc network, and complexity is represented with the big-O notation.

Table 1. Comparative of reactive and proactive routing

	Reactive Routing		**Proactive Routing**		
	AODV	**DSR**	**OLSR**	**TORA**	**DSDV**
Storage Complexity	O(e)[1]	O(e)	O(N)[2]	O(N)	O(N)
Communication Complexity	O(2N)[3]	O(2N)	O(N)[4]	O(N)	O(N)

1 Requires maintaining in the cache only the most recently used routes.
2 Requires maintaining tables with entries for all the nodes in the network.
3 Requires additional route discovery and maintenance that increases with high mobility.
4 Routing information is maintained periodically up to date in all the nodes.

3.2 Ad hoc Routing Protocols Simulation Conclusions

The reactive routing protocols under analysis have clear drawbacks such as the excessive flooding traffic in the route discovery and the route acquisition delay. When the network is congested, the routing information is lost and a consecutive set of control packets are issued to re-establish the links, increasing the routing latency (i.e. time the routing protocol requires for obtaining the route to the destination node) and percentage of packet loss. If the hello messages are not received, then error requests are issued and new route requests are sent to re-establish the link. Thus, the reactive protocols do not scale when the load and node density increase. Moreover, the reactive routing protocols do not have knowledge about the QoS in the path before the route is established and the routes are not optimised (some extensions are proposed for QoS support in AODV).

The reactive routing protocols suffer from high routing latency and percentage of packet loss, which increase with mobility and large networks. The percentage of optimal routes calculated with reactive protocols is lower than in proactive protocols and it decreases in large networks. An advantage of reactive protocols like AODV is that they maintain only the active routes in the routing table, which minimizes the memory required in the node. Moreover, the protocol itself is simple so the computational requirements are minimum, extending the lifetime of the node in the Ad hoc network. If we consider that routing overhead is equivalent to additional packet processing, then reactive protocols will have lower power consumption than proactive protocols. In simulations with a small number of nodes and stability, AODV has lower percentage of packet loss than OLSR. Therefore in networks with light traffic and low mobility reactive protocols are scalable because of the low bandwidth and storage requirements.

The proactive routing protocols under analysis maintain the topology information up to date with periodic update messages. The proactive routing protocols minimize the route discovery delay, which minimizes the percentage of packet loss since the routes are known in advance and no additional routing overhead and processing is required. However, under high mobility more and more of the routes established based on the previous periodic update become stale leading to an increased percentage of packet loss.

The proactive routing protocols have low routing latency since all the routes are available immediately even in large networks. The proactive routing protocols calculate the most optimal routes since they apply hop count based routing algorithms. The proactive routing protocols have higher percentage of packet loss than reactive protocols in networks with reduced number of nodes and high mobility as depicted in Figure 3. However, in large networks, proactive protocols present lower percentage of packet loss than reactive protocols as depicted in Figure 7.

A drawback of proactive routing protocols is that they require a constant bandwidth and cause a processing overhead to maintain the routing information up to date. This overhead increases with the number of nodes and mobility since the updates have to be more frequent to maintain accurate routing information. The proactive routing protocols have lower routing latency but they do not react quickly enough to topology changes. The proactive routing protocols have been enhanced towards hybrid and hierarchical solutions to deal with this scalability problem in Ad hoc networks. OLSR reduces the control and processing overhead by selecting some nodes (i.e. MultiPoint Relay nodes) within the network to maintain the routing information. The link information updates are propagated between MPR nodes only, reliving the rest of the nodes from participating in the topology maintenance.

Other optimisations consist of exchanging only the differential updates, implementing hybrid solutions such as ZRP that combines reactive and proactive routing protocols or routing protocols that use the nodes location data such as LAR.

In order to analyse the performance of the hybrid protocols versus reactive and proactive, additional simulations were performed. Figure 9 and Figure 10 show the simulation results performed in the ns-2 simulator consist of 50 nodes with 15 connections of 5packets/sec constant bit rate (CBR) and 64 bytes of packet size, transmitter range is 250m and 2Mbit bandwidth.

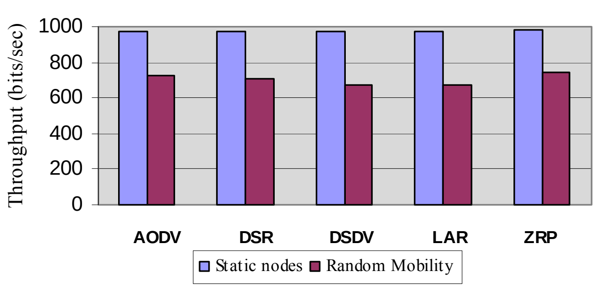

Figure 9. Throughput versus mobility for reactive, proactive and hybrid routing.

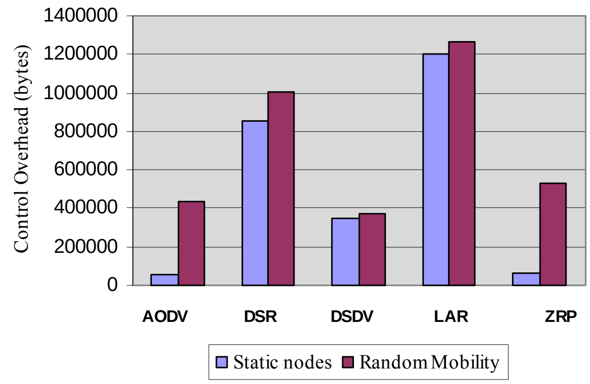

Figure 10. Routing overhead versus mobility for reactive, proactive and hybrid routing.

Figure 9 and Figure 10 show the routing overhead and throughput for AODV, DSR, DSDV, LAR and ZRP, comparing two scenarios; zero node mobility and random pause time (i.e. static nodes and random mobility). Mobility affects similarly on the throughput of the different routing protocols for both static and random node mobility while the overhead is affected differently. The simulations have been executed for ZRP with the radius of 1 hop and they show the same throughput results as for AODV. If we extend the ZRP radius to several hops, where proactive routing is used, then it should have a similar behaviour to DSDV where the overhead is not affected by mobility. Routing overhead with static nodes is the same for AODV and ZRP but it is 15% higher with random mobility. LAR introduces the highest routing overhead than any other protocol for the same mobility conditions.

In addition to hybrid routing protocols such as ZRP and LAR, other alternatives have been proposed to improve the reaction time to link breaks of proactive routing protocols.

One of them is a cross-layer architecture to receive information directly from the link layer when route breaks happen in order to react quickly to topology changes. Despite of this when the network size increases, the bandwidth and processing overhead can still reach limits that cannot be afforded by Ad hoc nodes. Another alternative consists of moving from flat to a more scalable hierarchical routing as proposed in the Fuzzy Sighted Link State (FSLS) routing [10]. FSLS defines a multilevel routing update hierarchy where each level has a different routing packet size and frequency of the routing updates. FSLS minimizes the flooding traffic but increase the complexity when defining levels with different updates frequency.

In this thesis we will analyse a third alternative, which consists of a new hybrid routing approach based on AODV. AODV is extended with scalability optimizations in order to reduce the routing latency, the percentage of packet loss and increase the routing efficiency when the mobility, the number of nodes or the network size increases.

4. Ad hoc Routing Protocols Test Bed

The goal of this section is to verify that simulations results are aligned with the values obtained from real Ad hoc networks. The simulations results highlight the overall performance results but they do not reflect the requirements from applications in real Ad hoc networks, or they may differ from results in real devices with limited resources. The simulations provide Ad hoc networks performance results considering a wide range in the variation of parameters such as node density and node mobility. The small-scale real Ad hoc networks introduce new parameters such as number of hops and route discovery latency that affect the performance. Therefore, in order to verify the accuracy of the simulations and measure the effect of those new parameters, we run a set of tests with real Ad hoc nodes, different routing protocols and a real time VoIP application. The tests were carried out using different devices and in various locations to avoid any bias by environmental factors.
This section analyses the Ad hoc test bed results for an application with real time requirements like Voice over IP (VoIP). The selected traffic with a Constant Bit Rate (CBR) of 15packets/second over UDP used in the simulations is similar to real time VoIP sessions transmitting 20ms voice packets encapsulated with GSM codec and using Real Time Protocol (RTP) protocol over UDP.

Figure 11 depicts the layout of the three tests cases performed using PDAs (i.e. HP 3850 iPAQs, running Familiar Linux distribution, 206 MHz Intel StrongARM processor and 64 MB memory) with wireless card 802.11b at 11Mbps, channel 10 (2.457MHz) and the following system parameters.
- Jitter buffer length: 60ms.
- Recording buffer length: 1 buffer x 1024 bytes.
- Playback buffer length: 4 buffers x 512 bytes.
- RTP payload: 3 GSM packets (GSM library v06.10).
- Traffic measurement tools: Ethereal and Tcpdump
- Signalling protocol: SIP
- Transport protocol: JRTP library v2.9
- Ad hoc routing protocols: OLSR v0.45 and AODV v0.91

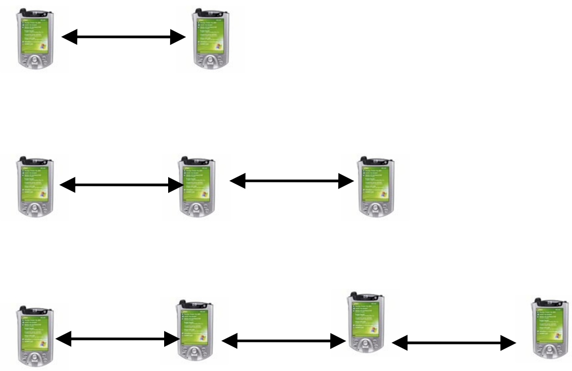

Figure 11. Test bed layout.

Table 2. Summary of performance metrics for AODV and OLSR in 1, 2 and 3 hops

Performance metrics	AODV/ 1hop	AODV 2hops	AODV 3hops	OLSR 1hop	OLSR 2hops	OLSR 3hops
End to end packet delay						
Average (ms) Std deviation (ms) 90% percentile	163.5 21.91 188.419	177.4 25.29 202.487	195.7 20.85 228.611	158.4 27.25 187.411	171.4 43.66 227.539	187.1 37.638 244.214
Jitter delay						
Average (ms) Std deviation (ms) 90% percentile	0.061 0.031 0.099	0.062 0.034 0.100	0.061 0.032 0.092	0.060 0.026 0.092	0.060 0.033 0.097	0.061 0.043 0.106
Packet loss						
Number of packets lost % of packet loss (packets lost/RTP packets)	1 0.04% (1/2353)	4 0.06% (4/6858)	15 0.4% (15/3665)	3 0.09% (3/3215)	4 0.08% (4/4688)	16 0.2% (16/7969)
Routing overhead						
% routing overhead (Routing packets/RTP packets)	7.22 % 170/2353	7.38% 506/6858	18.17 % 666/3665	3.39 % 109/3215	3.86% (181/4688)	3.584% 286/7969
Routing latency (seconds)	0.5	1	1.5	1	8	15

From this summary and considering the limitations of the results obtained from a small-scale real Ad hoc network we conclude that the jitter delay remains almost constant regardless of the number of hops and the routing protocol. The percentage of packet loss is low in both AODV and OLSR. The percentage of packet loss increases with the number of hops for both protocols but it is higher in AODV that in OLSR. The jitter delay in the receiving node will increase with the packet loss if it cannot be resolved with interleaving or additional buffering in reception. The end to end packet delay tends to increase equally in both AODV and OLSR and it increases almost linearly with the number of hops. The routing latency in AODV is lower than OLSR and in both cases it increases linearly with the number of nodes. The routing overhead is higher in AODV than in OLSR. This is contradicting with the results from the simulations and Proposition 7. This is because of a small-scale Ad hoc network where OLSR maintains a small amount of routing information compared to AODV that has to flood the entire network for the routing discovery process. The routing overhead remains almost constant in OLSR regardless of the number of hops while in AODV it remains constant with small number of hops (1-2 hops) but it increases exponentially when the number of hops grows (i.e. 3 hops). This behaviour was not observed in the simulations and supports the statement that AODV performs efficiently in small networks but in large networks with long end to end path, its routing overhead increases significantly.

The end to end packet delay obtained from the simulations is modelled with Eq 20 and Eq 24. Replacing the values for the number of nodes and node mobility used in the test bed (i.e. N=4 and M=0) the results are the following.

$$D_R(M=0, N=4) = 0.110 + 0.01*4 = 150(ms)$$
$$D_P(M=0, N=4) = 0.113 + 0.07*4 = 393(ms)$$

The end to end packet delay results from the simulation and the test bed for the reactive routing protocol are quite similar (i.e. around 200ms). This verifies the Eq 20 obtained from the simulations. The end to end packet delay should be similar in both reactive and proactive routing protocols when node mobility is zero. The results from the simulations for proactive routing protocol are two times higher than the results obtained in the test bed. The higher end to end packet delay in proactive routing than in reactive routing obtained in the simulations results is due to the effect of link breaks where the routing latency increases the overall delay. The simulations provide an average end to end packet delay values that include the effect of the routing latency in proactive protocols required when the links break in high mobility conditions.

Therefore, we conclude that the equations obtained from the simulations to model the end to end packet delay are accurate enough, assuming that in low mobility conditions the results are pessimistic for proactive routing protocols.
The percentage of packet loss obtained from the simulations is modelled with Eq 28 and Eq 32. Replacing the values for the number of nodes and node mobility used in the test bed (i.e. N=2, N=4 and M=0) the results are the following.

$$L_R(M=0, N=2) = 0.1 + 0.3*2 = 0.7(\%)$$
$$L_R(M=0, N=4) = 0.1 + 0.3*4 = 1.3(\%)$$
$$L_P(M=0, N=2) = 0.2*2 = 0.4(\%)$$
$$L_P(M=0, N=4) = 0.2*4 = 0.8(\%)$$

These results are over pessimistic and they reflect different behaviour than we observe in the test bed, where proactive routing protocols present higher percentage of packet loss than reactive routing protocols for a reduced number of nodes. On the other hand, the percentage of packet loss in reactive routing protocols is higher than in proactive routing protocols when the number of nodes increases. The order of magnitude in the simulations is 10 times higher than the results obtained from the test bed for a reduced number of nodes and 3 times higher when the number of nodes increases. The reason is that the equations obtained from the simulations results are obtained from a medium network, thus when applying the equations to small network the approximation error is higher. Moreover, the simulations consider multiple connections at the same time while in the test bed there is a single connection. In the simulations, several connections with different routes and number of hops are established. The fact is that packet loss is measured in the test bed considering the increase in the number of hops, which cannot be estimated in the simulations since the nodes move randomly (i.e. waypoint mobility model). The test bed provides a more controlled environment where we can measure the number of active connections, the routes and the number of hops on each route.
Therefore, we conclude that the equations obtained from the simulations to model the percentage of packet loss are not accurate when considering small network with a reduced number of hops but they are more accurate when considering medium network with higher number of nodes.
The routing overhead results from the simulations are modelled using Eq 12 and Eq 16, where after replacing the values for the number of nodes and node mobility of the test bed (i.e. M=0 and N=4) we obtain the following values.

$$\Omega_R(M=0, N=2) = 180 + 20*2 = 220(Kb)$$
$$\Omega_R(M=0, N=4) = 180 + 20*4 = 260(Kb)$$
$$\Omega_P(M=0.N=2) = 185 + 114*2 = 413(Kb)$$
$$\Omega_P(M=0.N=4) = (185 + 114*4 = 641(Kb)$$

The simulations were executed during 900seconds having 20 active connections with a packet rate of 8packets/sec packet rate and 65bytes of packet size. This means that the total data transmitted during each simulation was 9360Kb as calculated in Eq 41.

Eq 41. $DataTransmitted = 20_{conn} * 8_{packet/\sec} * 65_{bytes/packet} * 900_{\sec} = 9360Kb$

The total data received is the data transmitted minus the packet loss for each case, which is the following.

$$L_R(M=0, N=2) = 0.1 + 0.3*2 = 0.7(\%) \Rightarrow Data\ Received = 9360(1-0.07) = 9294.48(Kb)$$
$$L_R(M=0, N=4) = 0.1 + 0.3*4 = 1.3(\%) \Rightarrow Data\ Received = 9360(1-0.13) = 9238.32(Kb)$$
$$L_P(M=0, N=2) = 0.2*2 = 0.4(\%) \Rightarrow Data\ Received = 9360(1-0.04) = 9322.56(Kb)$$
$$L_P(M=0, N=4) = 0.2*4 = 0.8(\%) \Rightarrow Data\ Received = 9360(1-0.08) = 9285.12(Kb)$$

Therefore, the percentage of routing overhead for each case will be:

$$\Omega_R(M=0, N=2) = \frac{220}{9294.48} = 2.37\%$$
$$\Omega_R(M=0, N=4) = \frac{260}{9238.32} = 2.81\%$$
$$\Omega_P(M=0, N=2) = \frac{413}{9322.56} = 4.43\%$$
$$\Omega_P(M=0, N=4) = \frac{641}{9285.12} = 6.9\%$$

Figure 12 shows that routing overhead in AODV is higher than in OLSR based on the results obtained from the test bed. OLSR almost doubles the routing overhead when increasing the number of nodes.

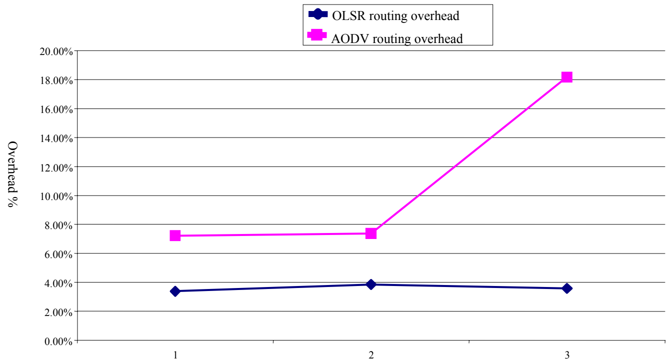

Figure 12. AODV and OLSR protocol overhead in 1, 2 and 3 hops connection.

The equations obtained from the simulations show that both protocols are affected by the number of nodes. OLSR presents higher overhead than AODV for the same number of nodes. AODV maintains an almost constant routing overhead with a minor percentage increase with the number of nodes. The test bed shows the opposite results, OLSR has lower routing overhead than AODV and its value is almost constant regardless the number of nodes. AODV presents a routing overhead three times higher than OLSR when the number of nodes increases. Therefore, the estimated equations for modeling the routing overhead based on the simulation results are not accurate.

However, we have to highlight that when increasing the number of nodes in the test bed, we are also increasing the number of hops. This leads to the fact that in the test bed AODV generates higher routing overhead because there is a dependency with the number of hops, which cannot be reflected in the simulations. The simulations provide an overall value that represents the average results including different factors such as number of hops, multiple connections running in parallel with different paths and link breaches that may generate additional overhead. OLSR routing overhead results from the simulations are pessimistic compared to the results from the test bed. OLSR in small scale networks does not generate a considerable amount of routing overhead since the link information to be distributed within few nodes is low.

Therefore, based on these results we conclude that the number of hops is a relevant metric to consider when designing an efficient routing protocol. It has to be taken into account in the equations that model the routing overhead in order to accurately reflect the actual behaviour of the different protocols.

Figure 13 shows the test bed results of the routing latency (i.e. F), a new metric that we did not measure in the simulations.

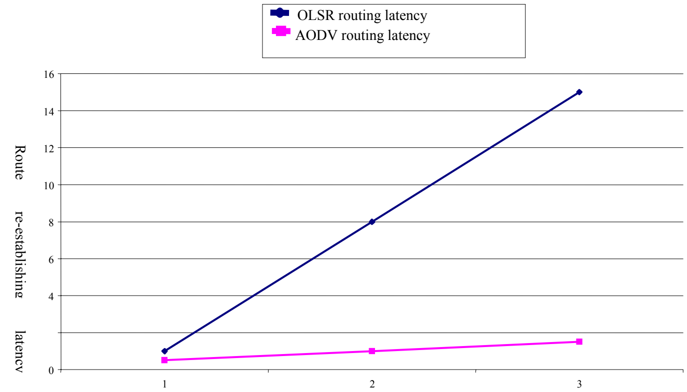

Figure 13. AODV and OLSR routing re-establishment latency in 1, 2 and 3 hops connection.

This metric varies with mobility but mainly with the number of hops in the route to be re-established. The routing latency affects the network QoS performance mainly when considering real time applications that suffer from jitter and end to end packet delay.

Figure 13 shows that the routing latency in AODV and OLSR increases with the number of hops (i.e. g). However, AODV reacts faster in order to obtain a new route and follows a linear increment with a smaller factor than OLSR. The AODV and OLSR routing latency can be modelled with Eq 42 and Eq 43.

Eq 42. $\Phi_{AODV} = 0.5\gamma$

Eq 43. $\Phi_{OLSR} = 7(\gamma - 6)$

OLSR requires a link layer alert mechanism to detect broken routes and the node has to communicate the topology update to their neighbours so they can re-calculate the new route. This link layer mechanism is not implemented in the test bed.

In general, the results obtained from the real time VoIP application and the simulations are comparable but there are some exceptions that we will review in this section
The simulation results are quite accurate in the end to end packet delay for AODV but over pessimistic in the case of OLSR. The values for OLSR in real Ad hoc networks are lower than the ones obtained in the simulations. This is due to the fact that simulations may include multiple connections with several hops while in the test bed we run a single connection with few hops. The difference can also be due to the fact that the estimated equation from the simulations may include the mobility effect where links

can be broken, and for that reason OLSR presents a higher end to end delay to re-establish the route. However, in the test bed, with zero mobility, both AODV and OLSR introduce similar end to end delay.

The simulation results are not quite accurate when measuring the percentage of packet loss but they are in line with the results from the test bed when increasing the number of nodes since both indicate that the percentage of packet loss is lower in OLSR than in AODV. The simulations provide overall results from several connections with certain duration where the endpoints are selected randomly, while in the test bed a single bidirectional connection is maintained between the same nodes during the testing session. This difference causes the variation of the results.

In terms of routing overhead OLSR shows higher values than AODV in the simulation results, while in the test bed it is just the opposite. The difference in the results is due to the fact that simulations obtain the overall value without considering number of hops. In the test bed results AODV presents higher increase of the routing overhead with the number of hops while OLSR is not affected. Thus the equations from the simulations can be used to estimate the overall routing overhead in different protocols. However, they do not reflect the impact of certain metrics like the number of hops and they are not suitable for the protocol design.
The test bed provides measures about routing latency which cannot be obtained from the simulations. The test bed shows that routing latency is crucial for the real time communications performance in Ad hoc networks with multihop routes.
In general the simulations provide about network performance with the different routing protocols but we need the results from the test bed to correct and in some cases complement the simulation results.

Based on the results from the test bed, we conclude that proactive routing protocols in stable networks obtain a higher percentage of optimal routes, which minimises the end to end packet delay for real time applications. Obtaining the optimal routes is critical because of the impact of the number of hops in the end to end packet delay and jitter. Proactive routing protocols show lower packet loss than reactive routing protocols in large networks. Reactive protocols present a lower percentage of packet loss in small networks (i.e. reduced number of hops) with low mobility as well as prompt reaction under link breaks. These are all requirements necessary for real time applications. Moreover, to accommodate real time applications in Ad hoc networks a cross-layer architecture is required to establish a communication channel between end points. This will allow receiving routing information during an ongoing real time session to dynamically accommodate the RTP payload to the link conditions.

5 Scalable Hybrid Ad hoc Routing Protocol

Routing protocols in Ad hoc networks need to rapidly adapt to network changes. They have to minimise the consumption of network processing, transmission and storage resources during the adaptation process to maximise the availability of the nodes. Ad hoc routing protocols have to cope with the topology dynamics, variable bandwidth, mobility and unreliable wireless connections. Simulation and test bed results demonstrate that protocols targeted for small and medium Ad hoc networks do not perform well in large networks.

Figure 14 shows that different routing protocols are required depending on the size of the Ad hoc network. The test bed results show that in small networks, the packet loss and routing latency for reactive protocols is low while in large networks it is significantly high. Moreover, the end-to-end path in small networks includes few hops while in large networks the number of hops is bigger with the consequent end to end packet delay

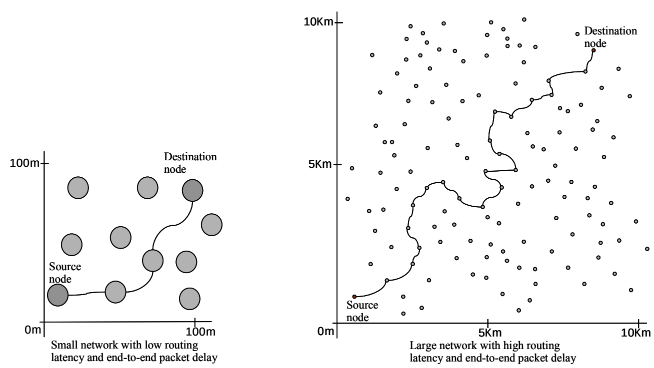

Figure 14. Small versus large networks routing requirements.

The simulations results show that proactive routing protocols obtain the most optimal routes regardless of the number of nodes and mobility. Proactive routing protocols maintain the network topology information up to date, reducing the routing latency. The routes are optimised using algorithms based on different metrics such as number of hops and link cost. Different routes can be used depending on the application requirements (i.e. multipath routing optimization [11]]). An equivalent procedure in reactive routing protocols would take several iterations until the optimal route would be found, with the consequent routing latency. The proactive routing protocols are suitable for small networks with a limited number of nodes because the routing overhead, the routing

table storage and the computational overhead are low. However, when the number of nodes increases, they are inefficient.
Therefore, in Ad hoc networks a simple and low resource consuming protocol should be used for routing within a cluster while few selected nodes act as gateways providing network scalability [12].

5.1 Fully Distributed Virtual Backbone Routing Protocol

The existing Ad hoc routing protocols are reliable in small and stable networks, where each node can efficiently perform the routing functions based on the state information obtained from the entire network. However, in large networks the entire state information of the network is not available for the nodes, and the routing is based only on partial topology knowledge.

5.1.1 Nodes Classification

We explore one solution for the Ad hoc routing scalability based on a hybrid routing mechanism where the physical network is transformed into a virtual network [13]. In this virtual network we differentiate two types of nodes. The ordinary nodes that perform the minimum routing functionality such as packet forwarding and on demand route discovery, and the smart nodes that additionally acquire and maintain topology information to be distributed through the network via other smart nodes. The diameter of the network is reduced by having this set of nodes that abstract the network state and reduce its variability. The smart nodes will facilitate the routing for the ordinary nodes in the network by reducing the number of hops, end to end packet delay [1] and increasing the connectivity between distant nodes in large networks.
Based on the topology information, the smart nodes calculate the shortest path and optimal routes necessary to have a stable network. A stable network means that the topology changes have to be slow enough to allow the updates to reach all the nodes in the network. The Ad hoc nodes may have high mobility and the topology information is not steady during the necessary period of time required for the algorithm to calculate the optimal path based on known conditions. This sets a requirement for Ad hoc networks that is difficult to accomplish due to lack of nodes that maintain the network state when using reactive protocols. The heterogeneous conditions in Ad hoc networks make the routing unreliable and difficult to optimize based on metrics like shortest path, minimum delay or energy cost.
The routing in Ad hoc networks will not converge into the shortest path unless there are smart nodes maintaining the topology information and calculating the optimal routes. Therefore, Ad hoc networks require a proactive routing protocol to maintain the network topology information despite in some cases it will be stale due to high node mobility. The smart nodes implement a higher hierarchical routing level than the ordinary nodes as represented in Figure 15. The ordinary nodes do not participate in the shortest path calculation and use reactive routing represented in Figure 15. The smart nodes also use the reactive routing and participate in the lower hierarchical routing layer together with the ordinary nodes.

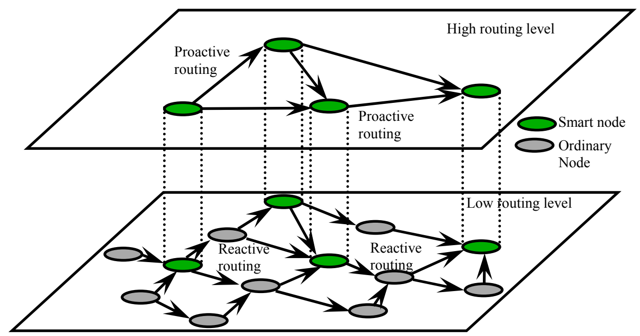

Figure 15. Node classification based on contribution to network topology calculation.

The main criterion for the proposed node classification is based on the connectivity and the capability for maintaining and distributing topology information in a reliable manner. In principle, any node can maintain the topology information if it has enough resources (i.e. memory, battery and processing power, etc). The nodes can share the topology information within the network if they have a reliable connectivity (i.e. low mobility) that allows continuous topology updates. The smart nodes will create the virtual backbone to maintain and distribute the network topology information at the expense of consuming their own resources. The virtual backbone will provide a mechanism to allow quick network knowledge to converge with minimal control messaging and complexity.

5.2 ScalableHybrid Ad hoc Routing Protocol

We identified the need of having smart nodes performing extra routing functionality in the Ad hoc networks. However, the preferred routing protocol to be implemented is the most critical part to guarantee scalability in Ad hoc networks, and it remains to be selected.

[1] Each node has a fixed delay from the MAC layer to access the shared channel, the transmission delay from the message processing and the radio delay when the node switches from reception to transmission mode since the same node has to handle routing and data packets regardless they belong to the node or not.

Based on the simulation results and test bed analysis, the combination of a reactive protocol that responds quickly to link breaks and a proactive protocol that provides optimal routes and reduces the routing latency seems to be the optimal solution. Therefore, we propose a novel hybrid approach named Scalable Hybrid Ad hoc Routing Protocol (SHARP) to overcome the drawbacks of existing routing protocols to scale up to large Ad hoc networks. We refer to a hybrid approach when the nodes are grouped into clusters and the cluster heads provides scalability by taking care of the heavy routing functionality between clusters. The drawbacks in cluster-based routing protocols are the additional complexity required on the nodes to implement the clustering algorithm. These protocols have additional overhead required for selecting the cluster head and the fact of having a single node acting as a bridge between clusters may become a bottleneck. SHARP is based on the fully distributed virtual backbone concept where the ordinary nodes run reactive routing protocols while the smart nodes abstract the network and run an hybrid routing protocol (i.e. reactive together with proactive routing).

Each node interested and capable of becoming cluster head (i.e. smart node) will create its own cluster and will set up the fully distributed virtual backbone. SHARP does not define any cluster selection logic that forces the nodes to become cluster heads depending on their location (i.e. in the centre of the cluster) or other metrics. SHARP algorithm allows the nodes to become cluster heads just based on their resources availability. A node can measure the environment (i.e. local traffic, channel utilisation) and based on its resources available decides to become a cluster head or not. Therefore, there is no logic for selecting the cluster heads, and any node can become a cluster heads at any point in time. The nodes have the possibility to become cluster heads (i.e. smart) randomly and they can fall back and act as cluster nodes (i.e. ordinary) after exhausting some of their resources. Thus, smart nodes have enough resources and willingness to maintain route and service information. Ordinary nodes are devices with limited resources, running an Ad Hoc MANET [14] protocol with low complexity and computational requirements (i.e. a reactive protocol such as AODV).

Only the nodes that become cluster heads (i.e. smart nodes) will engage in additional control transactions for exchanging cluster information. The cluster heads will form the virtual backbone within the same cluster and expand to different clusters if the network size increases. The virtual backbone is composed by the smart nodes to exchange link state information between them for sharing network topology information (i.e. a proactive protocol such as OLSR, DSDV or a reactive protocol such AODV with new extension messages).

The cluster is setup by the TTL, and all the nodes that are close to the cluster head (i.e. nodes within TTL=1 or 2) will be just ordinary nodes. SHARP does not impose any additional requirements to the rest of the ordinary nodes and they perform reactive routing and packet forwarding functionality as usual. In the same area we can have several smart nodes each of them with its own cluster, thus the clusters can overlap and the ordinary nodes can be part of multiple clusters. This leads into a fully distributed cluster creation that will benefit the ordinary nodes. A cluster head will receive a route request from a cluster node, and if the cluster head has the route information available, it will return the route response to the cluster node. If the route information is not available in the cluster head, it will initiate a request to other cluster heads in the virtual backbone, thus reaching all clusters.

Figure 16 shows the concept of fully distributed virtual backbone, where the concept of cluster disappears, and instead several cluster heads that are randomly distributed within each cluster form a virtual backbone.

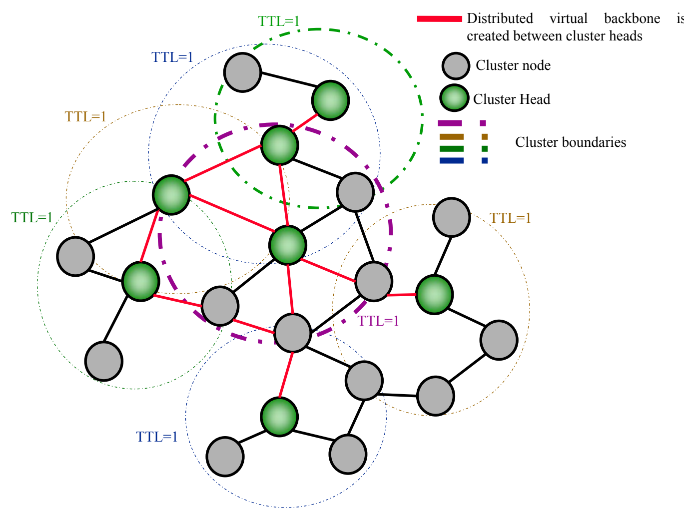

Figure 16. Distributed backbone created with multiple cluster heads.

SHARP is an alternative approach to existing hybrid routing protocols such as the Clusterhead-Gateway Switching Routing (CGSR), the Hierarchical State Routing (HSR) or the Zone Routing Protocol (ZRP).
CGSR is a proactive routing protocol that uses the Least Cluster head Change (LCC) algorithm to partition the network into clusters. In addition to the proactive routing overhead, LCC introduces some additional overhead and complexity in the creation and maintenance of the clusters. HSR is another proactive routing protocol that defines different layers where the cluster heads maintain two

hierarchies each of them with two instances of the proactive routing protocol. With the first instance of the proactive protocol the cluster head maintains the topology of the cluster nodes in the neighbourhood. The cluster head uses the second instance to maintain topology information with other cluster heads from the neighbour clusters. HSR presents additional overhead of maintaining two instances of the proactive routing protocol.

ZRP is quite similar to our SHARP proposal but still there are few differences. ZRP specifies the logic for selecting which nodes act as cluster heads and which ones act as border nodes (i.e. gateways between clusters). SHARP is based on the concept of the fully distributed virtual backbone where the logic for the nodes to become cluster heads is based on their resources, and the nodes themselves decide whether they are capable of becoming cluster heads. SHARP does not specify border nodes and instead all smart nodes act as border nodes. ZRP specifies the Intra-Zone Routing Protocol (IZRP) and the Inter-zone Routing Protocol (IERP). IZRP implements a proactive routing protocol used by all the nodes within the zone. IARP implements a reactive protocol used by the cluster head and the border nodes for routing purposes between clusters. SHARP use a reactive routing protocol within the cluster nodes and proactive routing protocol between cluster heads.

The big question at this point is why another hybrid routing protocol. Based on the simulations we deduced that reactive routing protocols behave more efficiently within small networks. Therefore, reactive routing protocol would be enough for most of the cases, however when the network size increases reactive protocols are not scalable. Thus, we need to form some grouping or clusters but that means additional complexity requiring additional efforts from all the nodes. This decreases the efficiency of the reactive routing protocols and exhausts the node resources. Thus, the best approach is to keep most of the nodes running an efficient reactive protocol within a small area, and let smart nodes perform the clustering to support the network scalability. The selection of the cluster heads does not affect the rest of the nodes, so the additional clustering complexity should be minimised and hidden to the ordinary nodes.

Based on the results from the simulations and the test bed SHARP has been proposed to fix some of the drawbacks of reactive, proactive and some hybrid routing protocols.

Acknowledgments

This work has been carried out as part of MobileMAN EU project.

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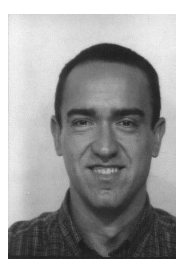

Jose Costa-Requena received the M.Sc. degrees in Telecommunications Engineering from Polytechnic University of Valencia in 1999 and the Lic Sc. in Technology degree in 2004 from Helsinki University of Technology, respectively. During 1999-2003, he worked as Sr. Technology Manager at Nokia Mobile Phones and stayed in the Networking Laboratory to research on VoIP, number portability, service discovery, IP routing, mobile communication systems, and wireless access network.