Geo-LANMAR Routing: Asymptotic Analysis of a Scalable Routing Scheme with Group Motion Support

Floriano De Rango¹, Mario Gerla², Biao Zhou², Salvatore Marano¹
D.E.I.S. Department, University of Calabria, Italy, 87036
e-mail: ⎧ derango, marano⎪@deis.unical.it
Computer Science Department, UCLA, Los Angeles, CA 90095
e-mail: ⎧ zhb, gerla⎪@cs.ucla.edu

Abstract
This paper presents a novel routing protocol called Geo-LANMAR. This routing scheme is able to get full advantages of group motion of mobile nodes to reduce the routing overhead and offer high network scalability. This protocol inherits same advantages of LANMAR protocol regarding the group motion support and its idea is to use the long-distance geo-forwarding for the extra-scope routing such as the Terminodes Routing and the Optimised Link-State Routing (OLSR) for the intra-scope routing. Together the geo-routing forwarding scheme, a global update propagation scheme based on the Hazy Sighted Link State Routing (HSLS) between landmark nodes (cluster heads) is applied. An asymptotic analysis of Geo-LANMAR protocol is proposed and a rule that binds the intra-scope and extra-scope overhead cost is found. The novel routing scheme has been compared with the standard routing protocols such as AODV, GPSR and LANMAR.

1. Introduction

Network scalability is a critical issue in routing protocols for Ad Hoc networks. It is important to guarantee a good scalability properties to open systems or dynamic network when the number of nodes, the traffic load and mobility rate increases. Many scalable approaches have been proposed [1-10], which are based on either table-driven forwarding or geo-forwarding techniques. More specifically, in order to reduce the control overhead and to find a path from source toward destination, geo-routing inspired schemes such as GPSR [2] have been proposed. Geo-routing uses the positions of routers and a packet’s destination to make packet forwarding decisions [4]. By keeping state only about the local topology, geo-routing scales better in per-router state than shortest-path. Independently, good scalability results were also recently reported by the Landmark Routing Protocol (LANMAR) [10], using a totally different approach exploiting group mobility and hierarchical routing. A novel approach based on the long-distance geo-forwarding and the local link-state routing has been recently proposed and it is called Terminodes Routing [8].

This paper, according with recent advances in the Ad hoc networking routing and scalability issues, presents a novel routing scheme called Geo-LANMAR that is based on the basic idea of LANMAR and Terminodes Routing [8,9]. The proposed protocol makes use of the group motion support of the LANMAR routing through the clustering algorithm until k-hop to elect the cluster-head (landmark node), and it applies also the geo-routing scheme for long distances. A novel concept of Location Group Area (LGA) that represents the area associated to the group is introduced [15] and an optimised link-state routing called Hazy Sighted Link-State (HSLS) Routing [11] is applied to maintain the locations of LGAs. The routing adopted in the local scope has been the OLSR protocol [12].

The proposed protocol presents good scalability properties in respect of the number of nodes, groups, traffic load and mobility rate. An asymptotic analysis is realised according with the work in [16,17] and some rules that bind the project parameters with the number of groups and group size are obtained. Simulation campaigns are assessed and the Geo-LANMAR protocol has been compared with GPSR, AODV [18] and LANMAR.

The paper is organised as follows: section 2 presents the basic idea of Geo-LANMAR protocol; an asymptotic analysis of Geo-LANMAR is realised in section 3; section 4 offers the performance evaluation and simulation results; finally conclusions are summarised in section 5.

2. Geo-LANMAR

The GeO-LANMAR is composed by two routing protocols: link-state and geographic routing protocols. The link state routing protocol is managed inside the local scope of a fixed number of hops. The link-state protocol has been chosen in order to permit the calculation of the shortest path and to maintain a good information about the location information inside the local view. For any local scope there is a special node that transmits some information about the local scope to the entire network. This node is called Geo-Landmark and it transmits to the other scopes the information about its ID group, about the position info and the location information of the other Geo-Landmarks of the network. So as showed in fig.1, the Landmark node L(x,y) sends the information of all landmarks in the network L(x,y), LN-1 to its one-hop nodes. The position information is useful in sending the data packet outside the local scope, using the greedy forwarding technique.

In fig.1, if the source wants to communicate with a mobile node D, it first checks before inside its local scope to see if the destination D can be reached immediately through link-state routing. If there is no entry in terms of IP
address, it tries to send the packet toward the destination D through the geo-forwarding.

Through the knowledge of the group ID it is possible to get the location information of the destination landmark LD inside the local table. So without needing of the specific location of destination D, we can use the information of the destination landmark. Then, when the packet is near the scope of landmark LD, it can be directly sent through the table-driven forwarding.

To exploit this management, the nodes inside the local scope need to store a local routing table with a routing table typical of the link state routing, a landmark table with the location information and the group IDs of the landmarks in the networks. When a node needs to send a packet outside its local scope, it checks the landmark table and selects the nearest to the destination neighbour landmark. For example, in fig.1, node S selects C as the next node inside the local scope and the nearest neighbour landmark closest to the destination landmark LD. When the data packet arrives to E, the next hop Landmark, outside the scope, is selected as the next target node to reach because it is the closest to the destination landmark LD. This process is repeated until the last scope, in which is located the destination D, is reached.

Geo-LANMAR protocol presents the characteristics listed below:

1. Geo-LANMAR Route Forwarding: it is composed of a local table-driven forwarding scheme and a long-distance geodesic forwarding.
2. Geo-LANMAR routing tables: two main routing tables. The first one inside any local scope to map the topology of k-hop neighbours and the second one to give a coarse knowledge of all network state.
3. Geo-LANMAR Route Recovery Procedure: it is applied when a local maximum (hole) is reached. A GPSR-like technique is deployed. The choice of the neighbour node to use in the perimeter mode is based on a novel metric called Effective Travelled Distance explained below.
4. Geo-LANMAR update: routing table is differentiated in intra-scene and extra-scene update. The first update modality is associated with the applied link-state routing scheme. The second is associated with the area defined by the group motion (Group Area Location) and is limited in the space and in the time such as HSLS in order to offer scalability properties in terms of traffic, mobility and network size.
5. Effective Travelled Distance (ETD): this represents a new metric to select the best direction toward destination. Network partitions and holes can degrade the performance of geo-graphic routing. Through the real travelled distance it is possible to make the best choice of the neighbour node.
6. Hole Detection: it is possible to avoid the hole through a long-range knowledge of the network state. The proactive information exchange between LGAs permit the building of a virtual topology with geo-coordinates, where it is possible to know if there exist a path between two LGAs. This approach permits the choice of the best neighbour node in the right direction toward the destination to occur often.
7. Group Mobility Support: the clustering algorithm running in the local scope permits the election of a landmark node as the representative node of the group nodes. This cluster leader gives information about the Group Area Location to the entire network in order to permit the use of the geo-routing.
8. High Group Scalability: the link-state routing limited within the scope reduces the routing overhead. Optimized link-state routing with spatial and time diversity in the virtual topology of LGAs offers a higher scalability reducing the need to update local topology changes.

More details about the LGA and the basic idea of Geo-LANMAR we refer to [15]. In the following, other aspects of the novel routing scheme are addressed.

### 2.1 Effective Travelled Distance

In the update packet is inserted the position of the landmark as references for the LGA and a field distance called Effective Travelled Distance (ETL) that accounts for the real traveled distance between the landmark that sends the update packet and the landmark node that receives the packet. To send the update packet to the other landmark in the network the greedy forwarding is used and the perimeter mode can be triggered in the case of recovery from local maximums, holes or obstacles.

Imagine that the number of nodes used for the greedy or perimeter mode are $n$. In this case the ETL between two
The calculated optimal path. In this case, the landmark selects, it is possible to go toward a sub-optimal path because the geometric distance is so much higher than the geometric distance from the geometric distance.

$$\text{dist}(L_x, L_y) = \sum_{i=1}^{k} \sqrt{(x_{y,i} - x_{x,i})^2 + (y_{y,i} - y_{x,i})^2}$$ \hspace{1cm} (1)

This information is propagated in the link-state packet transmitted by the landmark node. To calculate the total real travelled distance between the landmark Lx and LD, respectively k hop far, as shown in fig.2, the ETD can be calculated as follows:

$$ETD = d_{x,d} = \sum_{i=1}^{k} \text{dist}(L_i, L_{i+1})$$ \hspace{1cm} (2)

### 2.2 Hole Detection

Comparing the ETD dx,d with the euclidean distance LxLD, there can be defined a new index α showed in eq.8 representing the deviation of the real physical distance from the geometric distance.

$$\alpha = \frac{L_xL_d}{ETD} \sqrt{(x_{x} - x_{y})^2 + (y_{x} - y_{y})^2} \sum_{i=1}^{k} \text{dist}(L_i, L_{i+1})$$ \hspace{1cm} (3)

the index α can change in the range [0,1]. If α→0 the travelled distance is so much higher than the geometric distance that a hole presence, network partition or very long path can be met. If α→1 the travelled distance is the shortest path. Typically if the α value of the path i is lower than 0.5, it is not suitable to send the data packet on this path because the deviation from the shortest path is high.

Through the info expressed in eq.9, it is possible to detect the hole at LGA level. In this case, it is possible to select another neighbour landmark in the network that can avoid the hole. An example is shown in fig.3.

![Virtual path between LGAs](image)

In fig.3, the node Lx receives the update packet from the destination landmark LD and it can detect a void or a sub-optimal path because the geographic distance $L_xL_d < \text{dist}(L_x, L_y)$. So, if the direction toward the Ly landmark is selected, it is possible to go toward a sub-optimal path. In this case, the Lx landmark selects the neighbour with the highest α value (shortest travelled distance STD) toward Ld. In fig.3 the path passing for Lz is selected.

### 2.3 Routing Updates

In order to offer a better scalability in terms of protocol overhead, a virtual topology between LGAs is defined. This topology is built to have a knowledge of the location of the LGAs and to use the geographic forwarding between LGAs. It is preferred to apply the link-state info propagation between LGAs because, this guarantees to have a refreshed information of the location info and a geo-forwarding can be more effectively applied. According with [8,10,11,13], because the position info can be timely refreshed for long distances and it can be refined approaching to the destination, to reduce the overhead of the link-state propagation to the entire network we use a link-state routing limited in the scope and in the time. The link-state propagation between LGAs can offer the advantages of the link-state routing to the macro-level (LGA level) in terms of the virtual path availability in a small amount of time in comparison with the reactive routing schemes. Through the link-state propagation, it is also easier to check the link-state in order to deploy load balancing or QoS reservation. Another important reason is avoiding the Location Server management. Because any node can know the zone location LGAx where the destination can be found, it is no longer necessary to get the position location of the destination through a query in a server disseminated in the wireless ad-hoc network. The proposed approach tries to localize the query request inside the local scope where runs the link-state routing runs (e.g. OLSR, fisheye etc) and it eliminates the update process of a Location Server in order to maintain accurate location info about each node in the network. A further advantage of the link-state propagation of LGAs location is to offer a knowledge of the group position avoiding to request the info of a specific destination where forwarding the data packet but needing only of the location of the group area where forwarding the packet.

There is also another problem associated with geo-forwarding that can be overcome by the link-state propagation of the LGAs position. Geo-routing, as in GPSR [2,3] and GEDIR [14], is blind for the long distances because of the local topology knowledge and the local topology view. This can determine, sometimes, in less dense networks, and often in sparse networks, the choice of the bad path towards the destination. A not suitable path is met if a recovery procedure by the local maximum is applied often. So, the link-state propagation of the position and the virtual link states can be useful in making better decisions about the direction in which to send the data packet. This mechanism tries to reduce the frequency of the local maximum recovery procedure and, in the case where the recovery procedure is applied, a more suitable neighbour node based on the minimum travelled distance is chosen for the perimeter forwarding.
Global Updates

The updating mechanism is inherited by the HSLS approach where the link-state protocol is made more scalable through spatial and time rate differentiation. Before explaining the link-state propagation, it may be useful to give some details about the virtual topology network between LGAs. It is said that there exists a virtual link between two LGAs if, considering respectively their average ranges $r_{i1}$ and $r_{i2}$ (they can be get referring to eq.6), the following condition is verified:

$$d = \sqrt{(x_{i1} - x_{i2})^2 + (y_{i1} - y_{i2})^2} < \min(r_{i1}, r_{i2})$$

(4)

As shown in fig.4 the virtual topology between LGAs is considered.

![Fig.4. Virtual topology between landmarks.](image)

![Fig.5. Link-state updates differentiated in the time and in the space.](image)

Each landmark node, representative of a group, transmits a link-state packet with its location. If the eq.10 is not respected the entry in the routing table is set to infinity. Considering the landmark’s topology, as shown in fig.5, the propagation rate is reduced for an increasing number of hops and the topological changes in the landmark’s network are aggregated and transmitted in some particular instant of time. Only the update of the first landmark’s network are aggregated and transmitted in fig.5, the propagation rate is reduced for an increasing number of hops and the topological changes in the landmark’s network are aggregated and transmitted. If the eq.10 is not respected and a virtual link breaks. The node wakes up every $2t_e$ seconds and transmits a LSU with TTL set to $s_j$ if there has been a link status change in the last $t_e$. In general, an LSU is transmitted with TTL set to $s_j$ if there has been a link status change in the last $2^{-i}t_j$ seconds. In addition, to guarantee a LSU transmission also in low mobility scenarios, a soft state protection is introduced in the algorithm and a LSU is sent also without a virtual link breakage every $t_b$ second where $t_b >> t_e$.

The above approach guarantees that nodes that are $s_j$ hops away from a reference node will learn about a link status change at most after $2^{-i}t_j$ seconds.

HSLS algorithm tries to minimize the total overhead produced by the LSU propagation. It is recalled that total overhead is represented by the overhead associated with the proactive update exchange and the overhead associated with the sub-optimal path. After a linear optimization problem presented in [16, 17], it is found that for fixing the time $t_e$ a better value of $s_j$ value (TTL) is $s_j = 2^i$.

Local Update

Inside each group a simple link-state routing algorithm can be applied (intra-scope routing). This is due to the reduced number of nodes belonging to the group in comparison with the total number of nodes in the network. In our analysis a full link-state routing and an optimised link-state routing (OLSR) have been applied. In the next section, an asymptotic analysis where the effect of intra-scope routing on the overall overhead cost of the GEO-LANMAR is accounted.

Asymptotic analysis of GEO-LANMAR

In this section, in accordance with analysis of authors in [16, 17], an asymptotic analysis of GEO-LANMAR protocol is carried out. In order to design a scalable protocol in respect of the most important network parameters, it is important to see if, when the number of nodes, the traffic load, the speed of mobile nodes and the number of groups increase, whether or not the performance of protocols can degrade. Here, before giving an idea of the protocol behaviour, the same assumptions proposed in [16, 17] are recalled.

Let $N$ be the number of nodes in the network, $G$ the number of groups in the network, $d$ the average in-degree,
\( \lambda_t \), the average link-breakage rate (number of link breakages per second), \( \dot{\lambda} \), the average traffic generation rate, and \( \dot{\lambda}_s \) the average session generation rate,

The assumptions in building the model are as follows:

1. When the network size increases, the average in-degree \( d \) remains constant.
2. Let \( A_g \) be the area covered by a group of \( K \) nodes, and \( \sigma_g = \frac{K}{A} \) be the group average density. The number of nodes inside the area \( A_g \) is \( \sigma_g \cdot A_g \).
3. The maximum and the average path length (number of groups) in the virtual network increase as \( \Theta(\sqrt{g}) \) in a subset of \( g \) groups or as \( \Theta(\sqrt{G}) \) in all network.
4. The traffic that a node generates in a second is independent of the network size \( N \). As the network size increases, the total amount of data transmitted/received by a single node will remain constant, but the number of destination increases.
5. For a given source node, all possible destinations (\( N-1 \) nodes) are equiprobable and the traffic from a node to a particular destination decreases as \( \Theta \left( \frac{1}{N} \right) \).
6. Link status changes are directly proportional to the intra-group mobility for local link-state routing and due to the group mobility.
7. Time scaling for the mobility model: let \( f_{t_0} \) be the probability distribution function of a node position at time \( t_0 \), given that the node was at the origin \((0,0)\) at time \( t_0 \). Then, the probability distribution function of a node at time \( t \) given that the node was at the position \((x_0,y_0)\) at time \( t_0 \) is given by

\[
N_{\text{LSU}} \approx \frac{c \cdot \text{size}_\text{LSU}}{t_e} \left( \sum_{i=1}^{\infty} \frac{R^2_i}{2^i} \right)
\]

(5)

\[
C_{\text{sub}} = \frac{\dot{\lambda}_s \cdot \text{size}_\text{LSU}}{N} \cdot \frac{4\cdot M \cdot R^2}{t_e} \left[ 2^{-1} \cdot \ln(n) + \sum_{i=1}^{\infty} 2^{-i} \cdot \ln(2) \right]
\]

(6)

\[
C_{\text{tot}} = C_{\text{pro}} + C_{\text{sub}}
\]

(7)

where \( \{s_i\} \) is the space where the LSU is propagated, \( R \) is the radius of the network, \( t_e \) is the basic observation time, \( \dot{\lambda}_s \), \( \sigma \) and \( N \) are defined above, and \( \beta \) is a constant associated with the number of nodes at a distance \( k \) or less from node \( S \). \( \text{LSU}_\text{size} \) is the average size of a LSU packet. \( M \) is a constant associated with mobility, \( L \) is the transmission range of a node, \( n \) is the minimum distance between \( S \) and its neighbours, \( x \in (1,3) \) is a constant, and \( n \) is the smallest integer, so that \( 2^n \geq R \).

A solution that minimizes the total overhead cost is given for \( s_i = \max \left[ \min \left[ |r_i-H \cdot 2^{i-1}| \right] \right] \) where

\[
H = \frac{\dot{\lambda}_s \cdot \text{size}_\text{LSU}}{4 \cdot N \cdot c \cdot \text{size}_\text{LSU}}
\]

Through the solution of a Linear Programming relaxed problem, it is observed that \( K \) can be fixed to 2. So, in a HSLS that uses the optimized LSU propagation, the value of \( s_i \) can be fixed to \( s_i = 2^{t_e} \).

Considering the worst situation in which each \( 2^{t_e-1} \cdot t_e \) is detected in a link-change, an LSU packet is transmitted until \( s_i = 2^{t_e} \). So, to account for proactive overhead, assuming that HSLS is run in the virtual network (landmarks network), the following considerations can be made:

1. Each landmark computes its maximum distance \( MD_e \) to any other landmark and if the value of its TTL is greater than the maximum distance, it will broadcast the LSU packet (TTL is set to infinity) and then reset its counter to zero.
2. If \( R_e < MD_e \leq 2R_e \), for each \( R_e \), the landmark broadcasts LSU and resets the counter to zero.
3. The bandwidth consumption for broadcast in LSU is

\[
\frac{\text{size}_\text{LSU} \cdot G}{R_e \cdot t_e}
\]

(8)

4. If TTL is set to \( R_e \), the LSU transmissions are

\[
\text{size}_\text{LSU} \cdot R_e \cdot t_e
\]

(9)

5. For TTL equal to \( R_e \), the generation rate of LSU doubles but the number of transmissions per LSU is reduced by a factor \( 2^{t_e-1} \).

The cost of the proactive transmissions for a single landmark can be summarized as follows:

To better understand the assumptions listed above, we refer to [16]. Only for assumptions 5 and 6 we recall that they can be justified by the behaviour of the existing network. As the network size increases, the traffic of users diversifies rather than increases. It is possible to think of the increasing in size and content in the Internet; it can produce more web pages to be visited (destination set diversifies) but the amount of bandwidth and time available for the user is fixed. In wireless networks, this can be different. Anyway, this assumption is used to simplify the analysis.

The total overhead cost associated to the FSLS family of protocols is expressed as follows:
\[ C_{\text{proc LSU}} \cdot \frac{G}{R_{\text{e}}} \cdot \frac{LSU_{\text{L}}}{{s_1}^{1.5}} \cdot \frac{LSU_{\text{S}}}{R_{\text{e}}} \cdot \frac{LSU_{\text{S}}}{2R_{\text{e}}} \cdot \frac{LSU_{\text{W}}}{2R_{\text{e}}} \]  
\[ \text{for} \quad R_{\text{e}} = \Theta(\sqrt{G}) \text{ and } \; s_k < G, \]  
only the first term in eq.15 gives a contribution so the proactive cost can be expressed as:

\[ C_{\text{HSLS landmark}} = G \cdot \frac{G^{0.5}}{t_e} = \Theta \left( \frac{G^{0.5}}{t_e} \right) \]  

if the number of groups (landmarks) in the network is \( G \), the total proactive cost is:

\[ C^\text{landmark}_{\text{sub-optimal}} = G \cdot \left( \frac{G^{0.5}}{t_e} \right)^2 = \Theta \left( \frac{G^{1.5}}{K^{0.5} t_e} \right) \]  

Another contribution of the landmarks to the overhead is the cost of sub-optimal routes, due to the bad next-hop decision cost.

A bad next-hop decision happens if the geometric distance for a transmitting node to the destination is not reduced. It is easy to understand that, in a dense network, there is an high probability that a node will choose as the next hop a node that increases the distance toward the destination. This is because geo-routing is able to find the shortest path. In a situation in which the network is sparse, this can even be more frequent and this can produce more local-maximum recovery procedures.

Considering that the probability of a node incurring a bad decision is \( p \), then \( 1-p \) is the probability of the node going in the right direction toward the destination. If we assume that two successive routing decisions are independent processes, it is possible to assume that the probability of addressing the packet in the right direction, minimizing by one hop the distance toward the destination, is \( \frac{1}{1-p} \). Moreover, the number of optimal transmissions is 1, so bandwidth consumption is given by:

\[ f_i \cdot \text{data}_{\text{acc}} \cdot \frac{P}{1-p}, \]  

where \( f_i \) is a constant that accounts for the number of nodes inside the local scope of the landmark, and that increases the shortest path. If we let \( L_i \) represent the distance in term of landmarks hops away from the destination, the average wasted bandwidth is expressed as follows:

\[ C_{\text{landmark bad next-hop}} = f_i \cdot \text{data}_{\text{acc}} \cdot \frac{P}{1-p} \cdot L = \Theta \left( f_i \cdot \lambda_i \cdot GL \right) \]  

considering that \( L = \Theta(\sqrt{G}) \), the cost of a bad next-hop can be summarized as:

\[ C_{\text{landmark bad next-hop}} = \Theta \left( f_i \cdot \lambda_i \cdot \frac{N}{K} \right)^{1.5} = \Theta \left( f_i \cdot \lambda_i \cdot \frac{N}{K} \right)^{1.5} \]  

To better specify the eq.19, it is important to observe that the probability \( p \) depends on the mobility rate and, consequently, on the link-change rate \( \lambda_i \) and on the time elapsed \( t_\text{clapsed} \) of the last LSU packet with the right information about the destination. Assuming an analogy with a cellular system, the probability \( p \) can assumed to be

\[ p = 1 - e^{-\frac{\lambda_i \cdot t_\text{clapsed}}{K}} \]  

and, consequently, the sub-optimal cost is as follows:

\[ C_{\text{landmark sub-optimal}} = f_i \cdot \left( e^{-\frac{\lambda_i \cdot t_\text{clapsed}}{K}} - 1 \right) \lambda_i \cdot \frac{N}{K} \]  

Because HSLS sends periodically a LSU packet, the node \( S \) will receive the updated info about the node \( D \) after almost \( 2 \cdot t_e \) seconds. On the average, it is possible to assume that node \( S \) will experience a delay of \( \frac{2}{\sqrt{K}} \cdot t_e \).

So, substituting this upper bound with the \( t_\text{clapsed} \) value, the eq.20 can be written again as follows:

\[ C_{\text{landmark sub-optimal}} = f_i \cdot \left( e^{-\frac{\lambda_i \cdot t_e}{K}} - 1 \right) \lambda_i \cdot \frac{N}{K} \]  

where \( f_i \) and \( c_i \) are constants. The total overhead associated with propagation in the virtual network of LGAs (landmarks) is expressed as:

\[ C^\text{landmark}_{\text{HSLS}} = f_1 \cdot \lambda_i \cdot \left( \frac{N}{K} \right)^{1.5} \cdot c_3 \cdot \left( e^{-\frac{\lambda_i \cdot t_e}{K}} - 1 \right) \lambda_i \cdot \left( \frac{N}{K} \right)^{1.5} \]  

If the exponential approximation \( (e^x - 1 \approx x) \) is used, the overhead can be expressed in the following way:

\[ C^\text{landmark}_{\text{HSLS}} = \frac{N^{1.5}}{K^{0.5}} + c_3 \cdot \lambda_i \cdot t_e \cdot \lambda_i \cdot \left( \frac{N}{K} \right)^{1.5} \]  

The value \( t_e \) that minimizes the overhead is:

\[ t_e = \Theta \left( \frac{1}{\lambda_i \cdot \lambda_i} \right) \]  

and \( C^\text{landmark}_{\text{HSLS}} = \Theta \left( \frac{N^{1.5}}{K^{0.5}} \right) \).

The approximation above is valid only if \( \frac{\lambda_i}{\lambda_i} \rightarrow 0 \) (for \( \lambda_i \rightarrow \infty \) and \( \lambda_i \rightarrow \infty \)). If \( \frac{\lambda_i}{\lambda_i} \rightarrow 0 \), \( t_e \) is \( \Theta \left( \frac{1}{\lambda_i} \right) \) and the total overhead is \( C^\text{landmark}_{\text{HSLS}} = \Theta \left( \lambda_i \cdot \frac{N^{1.5}}{K^{0.5}} \right) \).

Another contribution to the total overhead inside the network is given by intra-scope routing. In this case, we give an idea of the effect of link-state routing within the local scope, referring to the OLSR protocol.
If $D_N$ is the average number of MPR links per node, $R_N$ the average number of retransmissions in an MPR flooding, $h$ the rate of hello transmission per node, $\tau$ the rate of topology control generation, and $d$ the average degree (number of adjacent links) per node, then the intra-scope control traffic is expressed as follows:

$$C_{\text{GEO-LANMAR}} = (h d K + t R_k D_n K) \cdot G$$

(17)

In the worst situation $D_k = d$ and $R_k = K$, so the overhead is as a full link-state algorithm. However, through the same optimization, it is possible to obtain $D_k << M$ and $R_k << d$ offering a high reduction of intra-scope overhead. So, in this case, the total overhead of GEO-LANMAR associated with the more important project parameters is expressed below:

$$C_{\text{tot}} = \begin{cases} h d K + t R_k D_n K \cdot \lambda_i \cdot N^{1.5} & \text{if } \lambda_i = O(\lambda_i) \\ h d K + t R_k D_n K \cdot \lambda_i \cdot N^{1.5} & \text{if } \lambda_i = \Omega(\lambda_i) \end{cases}$$

(18)

The expression above consists of two contributions: the first is associated with intra-scope routing and the second one (extra-scope routing) is related to the routing between LGAs (landmarks). Intra-scope routing increases linearly with the increase of the number of nodes of the group; the routing associated with HSLS decreases as $K^{\sqrt{K}}$ for the increase in the group dimension.

The total overhead is:

$$C_{\text{tot}} \approx \begin{cases} \Theta\left(\lambda_i, \lambda_i \cdot N^{1.5}\right) = \Theta\left(\lambda_i \cdot G^{1.5}\right) & \text{if } \lambda_i = O(\lambda_i) \\ \Theta\left(\lambda_i \cdot N^{1.5}\right) & \text{if } \lambda_i = \Omega(\lambda_i) \end{cases}$$

(19)

If the contribution associated with the OLSR overhead (intra-scope routing), depending by the protocol parameters, is fixed as follows and $R_k = K$:

$$A = h d K + t R_k D_n K = O(K^2)$$

(20)

and the terms associated to the extra-scope routing (HSLS) is fixed as follows:

$$B_1 = \sqrt{\lambda_i \cdot \lambda_i \cdot N^{1.5}}$$

(21)

$$B_2 = \lambda_i \cdot N^{1.5}$$

(22)

The following functions can be analysed.

$$f_1(K) = AK + \frac{B_1}{K^{1.5}} \text{ if } \lambda_i = O(\lambda_i)$$

(23)

$$f_2(K) = AK + \frac{B_2}{K^{1.5}} \text{ if } \lambda_i = \Omega(\lambda_i)$$

Graphs that represent the effect of both local and global updating are presented in fig.6 and fig.7.

Because two opposite contributions are observed increasing the number of nodes belonging to groups and maintaining fixed the total number of nodes in the network, a trade-off between local cost and global cost associated to landmark nodes can be found. By derive calculation of the functions $f_i$ and $f_2$, the $K$ values that minimize the cost of Geo-LANMAR protocol can be obtained:

$$K = \left[\frac{B_i}{A}\right]^{2} \text{ with } i=1,2$$

(24)

The equation above permits to obtain the optimal $K$ value knowing the $B_i$ and $A$ values or viceversa it is possible to regulate the parameters of local routing ($A$) to
minimize the overall updating cost of the Geo-LANMAR protocol. Because the $B$ term depends from number of nodes and link breakage rate such as shown in eq.21, eq.22., it is possible only to change the parameters associated to the local link-state routing fixing the number of nodes belonging to a group. Thus if an optimised link state routing is applied in the local scope ($R_k<<K$) an optimal $K$ or $A$ values can be obtained, otherwise an increase in the number of group does not affect the overhead associated to the local scope (the increase of the cost associated to the local scope is balanced by the decrease of the cost associated to the reduced number of groups) but the overhead associated to the HSLS decreases as expressed in eq.19.

4 Performance Evaluation

The protocol has been implemented in a QUALNET simulator that represents an extension of the Glomosim simulator [19]. The considered channel capacity is 2 Mbits/sec. CBR sources are used to generate network data traffic. The source-destination connections are randomly spread over the entire network. During a simulation, a fixed number of connections are maintained all the time. When one session closes, another pair of communications will be randomly selected. Thus, the input traffic load is constantly maintained.

The adopted mobility model is the Reference Point Group Mobility (RPGM) [20,21]. Each node in a group has two components in its mobility vector: the individual component and the group component. In our simulation, the group component has been changed in the interval [0-25 m/s] while the intra-group movement has been fixed to 5 m/s.

GEO-LANMAR performances have been tested under many scenarios in which traffic load, mobility rate and network size have been considered. In order to test the scalability of the protocol in respect to the network size with group motion a scenario, where the number of groups is increased, is considered. Another considered scenario refers to a network with heavy traffic load and mobility in presence of holes. In this case, the number of connection pairs and the speed of groups are increased inside the network in order to see the scalability of GEO-LANMAR with respect to the traffic load and mobility rate. In this last scenario the ETD metric and the hole detection mechanism have been evaluated.

In summary the considered scenarios are summarized as follows:

1. Increasing Traffic Load: a grid of 1500 meters with 9 logical groups is considered. The number of connections is varied between 30 and 400 connections. Each connection sends 2 packets per second and lasts 30 seconds.
2. Mobility with Holes: in order to test the effectiveness of the novel mechanisms (Effective Travelled Distance and Hole detection) introduced in GEO-LANMAR, a particular scenario has been built. In particular, a grid with some obstacles has been considered as shown in fig.8.

The more commonly used metrics to evaluate routing protocols for wireless ad hoc networks have been considered:

- Packet Delivery Ratio: is the number of data packets delivered to the destination node over the number of data packets transmitted by the source node.
- Average end-to-end data packet delay: it includes the delay associated with MAC retransmissions, queueing delays, path detour delay when local maximum recovery procedure is applied for the geo-routing and buffering delays associated with the AODV protocol.
- Normalized Routing Overhead: is the total number of transmitted control packets for each delivered data packet; for packets sent over multiple hops, each packet transmission (on each hop) counts as one transmission.

Simulatio parameters are summarised in table I:

<table>
<thead>
<tr>
<th>TABLE I: SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Parameters</strong></td>
</tr>
<tr>
<td>Simulation area</td>
</tr>
<tr>
<td>Traffic sources</td>
</tr>
<tr>
<td>Number of connections</td>
</tr>
<tr>
<td>Sending rate</td>
</tr>
<tr>
<td>Size of data packets</td>
</tr>
<tr>
<td>Transmission range</td>
</tr>
<tr>
<td>Simulation Time</td>
</tr>
<tr>
<td><strong>Mobility Model</strong></td>
</tr>
<tr>
<td>Mobility Model</td>
</tr>
<tr>
<td>Pause time</td>
</tr>
<tr>
<td>Mobility group speed range</td>
</tr>
<tr>
<td>Mobility intra-group speed</td>
</tr>
<tr>
<td>Traffic pattern</td>
</tr>
<tr>
<td><strong>Simulator</strong></td>
</tr>
<tr>
<td>Simulator</td>
</tr>
<tr>
<td>Medium Access Protocol</td>
</tr>
<tr>
<td>Link Bandwidth</td>
</tr>
<tr>
<td>Confidence interval</td>
</tr>
</tbody>
</table>
4.1 Simulation Results

Performance evaluations of two scenarios, such as explained above, are presented in the following: AODV [22], LANMAR with intra-scope OLSR protocol, and GEO-LANMAR with two kinds of intra-scope routing (OLSR and FSR).

4.2 Increasing Traffic Load

In this scenario, GEO-LANMAR is tested in a situation of heavy traffic load. 300 connections are considered in fig.9 and fig.10. Group mobility is selected uniformly in the range [0-10 m/s] and the number of groups is increased from 4 to 36. For a heavy traffic load, LANMAR and GEO-LANMAR perform better than AODV as shown in fig.13. The reactive protocol (AODV) performs worst because of the increase in the control traffic in building the path toward the destination. The protocol produces a lot of route requests (RREQs) that consume bandwidth in spite of data traffic. The data packet delivery ratio is presented in fig.14. Under a heavy traffic load, LANMAR and GEO-LANMAR outperform AODV. Further, GEO-LANMAR outperforms LANMAR because it manages better the control traffic through update reduction in time (update differentiated in the $t_c$ value) and in space (LSU propagated until $s_i$).

![Fig.9. Normalized Control Overhead vs increasing number of groups. The number of connections is 300.](image)

![Fig.10 Data Packet Delivery Ration vs increasing number of groups. The number of connections is 300.](image)

The average end-to-end delay is shown in fig.15. 10 kbps corresponds to 5 connections while 800 kbps correspond to 500 pairs of connections. The data packet delay increases for high traffic load due to queuing delay. LANMAR and GEO-LANMAR behave similarly and they outperform AODV because the accuracy of the route to the landmark proves to be very cost effective, in spite of a possible minor detour toward the destination. GEO-LANMAR performs better than other protocols because the geo-routing scheme with the reference point represented by the LGAs permits reaching the destination at a low cost.

![Fig.11. Normalized Control Overhead vs increasing traffic load. The offered load is increased by increasing the number of connections.](image)

4.3 Mobility in presence of Holes

In this scenario, we have considered 20 groups with 25 nodes for each group. The group speed, in accordance with Random Way Point model, is uniformly chosen among the following values [0, 5, 10, 15, 20]m/s. The motion inside each group is characterized by a speed uniformly selected in the range [0-5m/s]. The considered grid is 2500x2500m and the transmission range for each node is 250 meters.

GEO-LANMAR protocols are expected to perform well also in more realistic scenarios in which the node movement is not totally free in space, but where there are obstacles or network partitions that can occur. In this case, GEO-LANMAR protocol can make use of the novel proposed metric that accounts for real travelled distance, and of the hole detection mechanism. The capability of seeing over the local scope through link-state propagation between LGAs permits the detection of a path not connected to the destination that avoids long detours. GPSR, on the other hand, makes only local decisions, applying perimeter forwarding often. This produces long detours for the data packet and a consequent increase of end-to-end data packet delay, as shown in fig.16. LANMAR protocol offers a lower delay than AODV and GPSR protocol. This is due, with reference to AODV, to its high control overhead, which produces a lot of collisions in the wireless channel, thus delaying the data packet. Instead, the greedy forwarding of GPSR, based on geometric distance, selects the wrong neighbour that, although geometrically nearest to the destination, is near a hole or obstacles, as shown in fig.3.

5 Conclusions

A novel routing protocol for scalable wireless ad hoc networks with group motion has been developed. The
proposed protocol, called GEO-LANMAR, assembles more characteristics belonging to many routing protocols. It uses the idea of LANMAR routing to support group mobility; it applies the routing scheme of Terminodes to apply link-state routing for short distances and long-distance geo-forwarding. The concept of Location Group Area (LGA) is introduced and a virtual topology of LGAs (landmarks) is built. The topology updates of LGAs are regulated by HLSS routing. An asymptotic analysis of GEO-LANMAR protocol is carried out and it shows the high scalability of the proposed routing scheme for increasing number of groups and nodes.

![Fig.12. Average end-to-end data packet delay vs increasing group speed. The intra-group mobility speed is 5 m/s.](image1)

![Fig.13. Data packet delivery ratio vs increasing group speed. The intra-group mobility speed is 5 m/s.](image2)

References


