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Hybrid Routing: A pragmatic approach to mitigating position uncertainty in geo-routing

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Abstract

In recent years, research in wireless Ad Hoc routing seems to be moving towards the approach of position based forwarding. Amongst proposed algorithms, Greedy Perimeter Stateless Routing has gained recognition for guaranteed delivery with modest network overheads. Although this addresses the scaling limitations with topological routing, it has limited tolerance for position inaccuracy or stale state reported by a location service. Several researchers have demonstrated that the inaccuracy of the positional system could have a catastrophic effect on position based routing protocols. In this paper, we evaluate how the negative effects of position inaccuracy can be countered by extending position based forwarding with a combination of restrictive topological state, adaptive route advertisement and hybrid forwarding. Our results show that a hybrid of the position and topology approaches used in Landmark Guided Forwarding yields a high goodput and timely packet delivery, even with 200 meters of position error.

1 Introduction

With the proliferation of cheap, short-range wireless communication devices, researches engineering solutions for local area communication networks are turning more towards Ad Hoc systems. Wireless Ad Hoc networks provide an infrastructure-less solution for multi-node communication, that can be deployed anywhere and adapt to the environment in order to provide communication. Ad Hoc networks depend upon cooperation amongst the nodes in order to build routes and forward data from sources to receivers. To add further complexity, nodes may roam freely within the environment, potentially causing neighbouring peer relationships to change at a fast rate.

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Basic routing approaches can be categorised into two classes; topological and positional approaches.

Topological approaches resemble Internet wire-line routing. Maps are constructed by distributing information about the cost of links that connect nodes in a graph with no regard for actual physical location. Forwarding is based on computing paths over the map from the source to the destination, either as part of the distribution mechanism (as in distance-vector approaches) or at each node on the total graph (as in link-state schemes). Scaling is achieved by information hiding mechanisms such as hierarchy. In the case of Ad Hoc topological routing it has been further classified [10] into two fundamental approaches; pro-active and reactive protocols.

Pro-active routing protocols are challenged because the routing traffic overhead increases with the number of nodes or as topology changes become more frequent. Consequently, as the group size increases, either the channel capacity must decrease proportionally or the reaction rate to routing updates must slow down.

Reactive routing protocols adapt well to topological changes by requesting routes on demand at the expense of increased setup latency prior to forwarding data. Simulation results show that the reactive approach copes well with dynamic route changes but suffers from scalability challenges as the traffic load increases over a wider network diameter.

An alternative to topological routing approaches is to use *position based forwarding*. Essentially, position based forwarding requires every node to have some awareness of it's own geographic position, whether through a Global Positioning System (GPS) or other means. Typically such geographic solutions reduce the amount of state propagated since every node advertises its own position only to its one hop neighbours. A packet is subsequently forwarded using a *greedy* forwarding algorithm. Every node forwards the packet to one of its adjacent nodes that is the closest to the destination until it reaches the destination node. Geodesic proximity to the destination does not, however guarantee that there will always be an available path, and a packet may in fact be passed to a node that does not have an adjacent neighbour for forwarding further.

Greedy Perimeter Stateless Routing (GPSR) [1] is one of the most advanced geographical routing solutions. It addresses the challenge of locating a suitable route using a technique known as *Face Routing* [2] on a planar graph when a greedy algorithm would be unable to forward the packet to the destination. We describe the algorithms and limitations of Face Routing in the next section. GPSR presents a very efficient solution for building an efficient geographically-based routing system. However we will demonstrate that there are two specific areas in which GPSR is not optimal and in fact can perform poorly under certain circumstances. The first area is uncertainty in the geographical location accuracy due to inherent limitations with the position tracking technology in use. The second area is the problem of dealing with inconsistency of location service, where consequently a less up-to-date destination location is used by a sender to construct the packet header for position based forwarding.

To address these challenges we have designed a novel solution named *Landmark Guided Forwarding* (LGF) which builds upon the existing research in the area of geographical routing protocols, in particular GPSR, but provides greater robustness and scalability in the infrastructure-less Ad Hoc node environment. In this paper we will demonstrate that LGF can improve upon GPSR performance by 71 % in the face of position inaccuracy of up to 200 meters, as illustrated in figure 11.

The paper is structured as follows. The next section describes GPSR in some details, and analyses the protocol's behaviour under inaccurate node location information. The following section presents our proposed protocol, LGF. We then describe our simulation experiments where we compare the performance of GPSR and LGF under a variety of plausible scenarios, detailing our assumptions, models, and simulation scenarios. The subsequent section is the analysis of the simulation results and a discussion of their causes and consequences. We then summarise the results, and discuss future work that we plan to carry out. Related work is discussed as it arises in the flow of the paper.

2 Position based forwarding limitations

The problems of position inaccuracy for GPSR have been discussed in earlier research work [6, 11, 12]. Under certain conditions, it can be shown that there are limitations in the robustness of the system when subjected to position inaccuracy and less frequent updates of location information. Location inaccuracy occurs as a result of the lack of precision of services such as the GPS or base station triangulation in systems such as GSM, IEEE 802.11 or Bluetooth. In this section we first outline some of the related work, then outline GPSR and then explore the elements of position based forwarding that are not resilient to position inaccuracy.

2.1 Related work

A number of papers have shown the relationship between position inconsistency and significant negative impact on position based forwarding protocols. In [6], it was shown that the effects of location inconsistency on greedy forwarding and perimeter mode routing caused wrong greedy decisions to be made that led to suboptimal routing and looping. In particular it was shown that a significant proportion of the construction of the planar graph was invalid when the standard deviation of position accuracy was set to 25 meters. These findings confirm that the impact of location inconsistencies could compromise the correctness of position based routing protocols.

In another paper, researchers proposed a fix to the disconnection problem caused by the false removal of an edge found in RNG planarization [11]. Although these results show a significant improvement in packet delivery, they only resolve one of the position inconsistency problems.

An alternate approach [12] to the location inconsistency problem has been to use mobility prediction to mitigate the effects of location inconsistency. However, this work considers only the effects of position inconsistency caused by the beacon frequency of neighbours and node mobility. It recommends the use of spatial and temporal correlation between nodes, together with information about geographic restrictions to reduce the effects of location inconsistency. It propose a Neighbour Location Predication, (NLP) and Destination Location Prediction, (DLP) schemes. These schemes however assume that the node knows its transmission range and would not attempt to forward a packet outside this range to an estimated node position. This paper did not include a model of the inconsistencies caused by position accuracy or a delayed location report.

2.2 Overview of GPSR routing

Greedy Perimeter Stateless Routing (GPSR) [1] is a wireless routing protocol where each node makes a local decision based on the locally available routes via immediately connected neighbours in order to forward packets towards a destination. *Greedy* routing is the process of choosing the next hop route based on the geographic proximity to the destination. A greedy routing decision is made based on the connectivity of neighbouring nodes and the most direct geographic forwarding path available. Upon reaching an area where greedy forwarding is not available, the algorithm switches to *Perimeter* routing, also referred to as face routing, which allows the packet to be forwarded around the perimeter of a region; an example of such a region would be a void. This provides a recovery mechanism to avoid dead-end routing situations and locates an alternative path based upon the same geographic routing principles.

Since only local routing state is required at each node, GPSR is able to scale to larger numbers of nodes. As the effect of GPSR state changes are limited to local area, it enables GPSR to adapt quickly. These changes could be caused by changes in the network topology. The robustness of GPSR derives from to its ability to dynamically switch between alternative routing algorithms in order to select a different route and thereby avoid dead-end forwarding situations.

The efficiency of the GPSR routing protocol does however depend upon the accurate reporting of geographic coordinates by individual nodes. Location accuracy is a common problem for all geographic Ad Hoc routing protocols since all the mechanisms that might typically be used for identifying the geographical coordinates of a node have an associated degree of error. Even GPS devices, the most accurate and most widely available technology, cannot guarantee perfect results, and suffer from additional errors when the absolute line of sight is obstructed by buildings or other causes of interference.

An important component of an Ad Hoc network that uses location based routing is an element called the *Location Service*. In order to make a routing decision, the source node must initially identify the current location of the destination node. This is accomplished using a location service which stores mapping from ID to location for all nodes within the system. When a node moves, it must update its mapping within the location service. There is no clearly defined mechanism for providing such a service, and in all cases the performance of such a service is typically assumed to be an orthogonal issue with respect to the Ad Hoc routing protocol definition. In the case of GPSR, it is assumed that such a service exists, and that all nodes have access to the relevant information at all times. In this paper we do not address any performance issues relating to the availability of the location service, nor the overhead associated with inserting or reading records from the database.

In the following subsections we consider the impact of node position reporting accuracy on both the *greedy* forwarding and the *perimeter* routing algorithms. We also consider the impact of the location update frequency by nodes in the system on the robustness of the routing algorithm and, in particular, the impact of outdated location information in the Location Service causing inaccurate routing decisions to be made by the source or intermediate forwarding node.

2.3 The impact of position inaccuracy on greedy packet forwarding

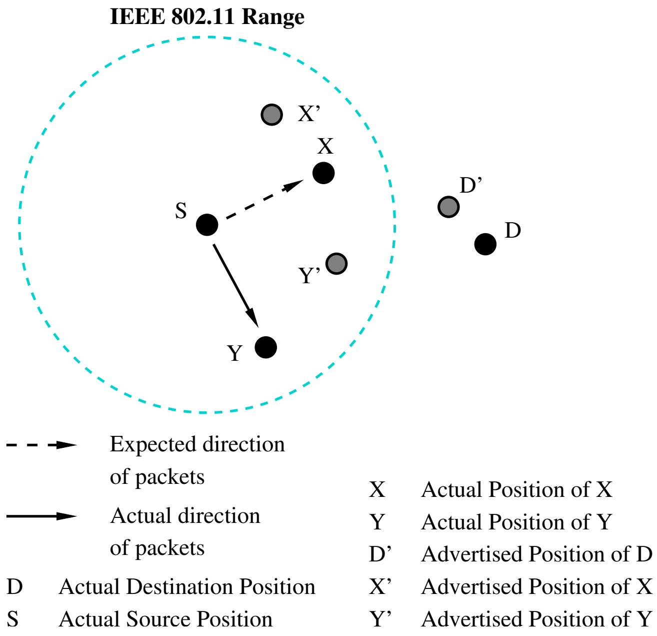


Figure 1: False Greedy Packet Forwarding

Figure 1 illustrates a scenario in which an incorrect greedy forwarding decision is caused by device position inaccuracy, incorrectly directing the packet towards a sub-optimal neighbouring route. Figure 1 shows two nodes, X and Y which are adjacent to the packet source node S. The packet is to be forwarded to the destination node D which is outside the range of S and therefore must be relayed via the Ad Hoc routing system. As a result of limited precision in the position tracking system, node Y inaccurately advertises its position as location Y' and node X inaccurately advertises its position as location X' to the *surrounding neighbours*. Based on the announced location and connectivity of X and Y, S incorrectly assumes that the optimal forwarding route for the packet is via node Y when in fact, as illustrated in figure 1, the optimal path is via node X.

This is a simple example of the impact of position inaccuracy on greedy forwarding, however it is apparent that when applied throughout a larger system, this inaccuracy may be compounded by incorrect decisions at many locations along a multi-hop path on account of position inaccuracy, thereby lowering the general ability of the system to forward data. We present results to illustrate the impact of position errors on GPSR in section 5. An alternative example of the situation where this issue would cause a problem is where the incorrect routing decision caused the packet to be directed incorrect around a void or into a dead end.

2.4 The impact of position inaccuracy on perimeter routing

Perimeter routing is a position based forwarding approach that guarantees delivery of a packet if a path between a source and destination exists. It is used to eliminate the incorrect decision that would otherwise be made through a greedy packet forwarding

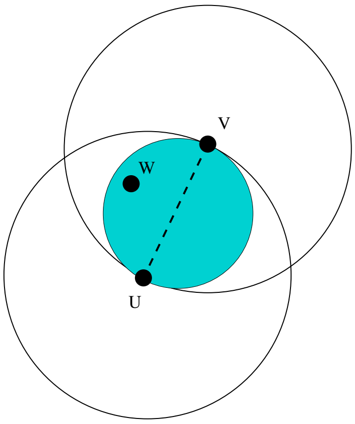


Figure 2: Removal of Cross Edge while Planarizing Gabriel Graph

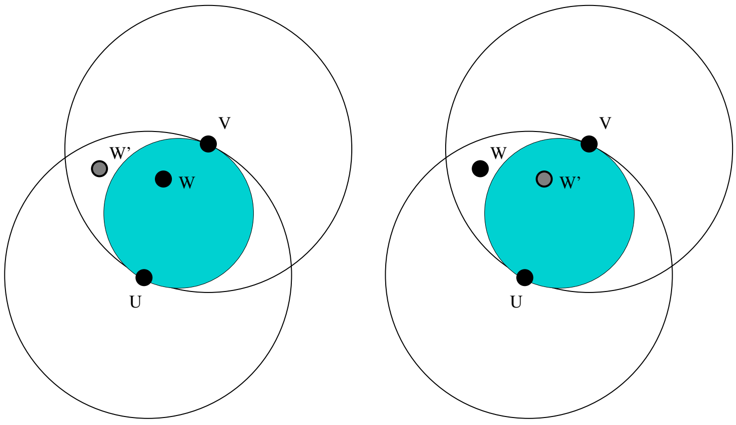
algorithm causing packets to be forwarded to a dead-end. In perimeter routing each node to builds a planar graph of all surrounding nodes, where a planar graph is inferred by a table of neighbouring nodes with all *intersecting* intermediate nodes removed. In figure 2, a node W is considered to intersect the path between 2 other nodes, U and V, if W lies within the shaded circle with $|UV|$ as the diameter of the circle. In this manner, each node constructs a planar graph incorporating a subset of all neighbouring nodes. The purpose of constructing such a graph is to be able to apply a perimeter routing algorithm that will allow forwarding along the graph and has the property that if a route between the source and destination exist, even if it is not a direct route, the algorithm will discover the path [9] [2] . Two algorithms that can construct a planar graph are the Relative Neighbour Graph (RNG) planarization algorithm and the Gabriel Graph (GG) planarization algorithm. RNG uses the intersection between the two radii of the distance between 2 nodes (in this case U and V). The GG algorithm uses a smaller region encompassing a circle between the 2 nodes U and V as illustrated in figure 2. In this section, we illustrate the vulnerability of the GG planarization algorithm to position inaccuracy causing the algorithm to mis-construct the planar graph and potentially cause incorrect *perimeter* routing decisions as a result of device position inaccuracies. We consider the case of GG planarization algorithm decisions based on inaccurate node location information. The first case illustrates incorrect exclusion of a witness, and the second case illustrates incorrect inclusion of a witness. In both cases we denote W' as the inaccurate position advertised by W.

2.4.1 Incorrect witness exclusion

In Figure 3(a), based on the GG planarization Algorithm, edge UV would not be removed since W' lies outside the inclusion circle between node U and V, however this decision is in fact incorrect since the real location of W lies within the inclusion zone.

2.4.2 Incorrect witness inclusion

In Figure 3(b), while W physically resides outside the inclusion zone, W' appears to reside within the zone. The GG algorithm therefore incorrectly includes W and wrongly removes edge UV.



(a) (b)

Figure 3: False Planar Graph Construction

2.5 The impact of location service update frequency on GPSR

In order for nodes in the network to forward packets to their destinations, position based forwarding protocols require the source node to encode the destination position into the packet header. Intermediate nodes then extract the destination position from packet header to decide on the next hop. To discover the location of the destination node prior to forwarding, the source must first lookup the location using the location service. One such mechanism might be the Grid Location Service (GLS) [8], which uses a consistent hash function to distribute node positions across a set of other nodes within a region. In this paper we do not consider the mechanism used to retrieve the information, but rather we consider the impact of slow insertion of location information by the individual nodes into the location service database thereby causing a source node to retrieve incorrect or stale location state relating to the destination.

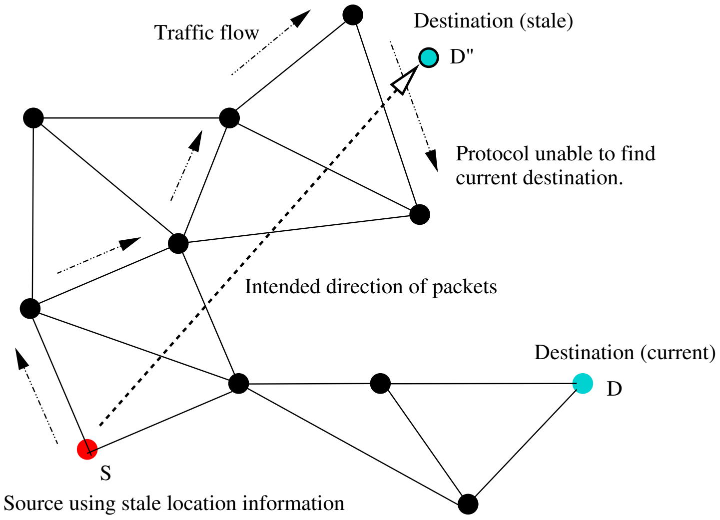


Figure 4: Position Forwarding with Stale Destination Position State

In Figure 4, D” represents the stale and therefore inaccurate state of destination D that was deposited in the location service. As the source node encodes the packet header with an incorrect location for D, it confuses the position based forwarding algorithm, driving the packet towards an incorrect position. Earlier research has demonstrated that this false state could cause the packet to loop searching for D at D” without ever actually reaching D [11] [12].

3 Landmark guided forwarding

Landmark Guided Forwarding (LGF) is a protocol that is designed to overcome some of the limitations of existing Ad Hoc routing approaches. In particular it is designed to be resilient to position inaccuracies whether arising from location device error or from the update frequency of the *Location Service.*

LGF is a hybrid protocol, that subsumes some of the design decisions made in position based forwarding protocols. It limits the propagation of advertisements and uses position information to steer a packet when a node does not have an established path to reach the destination. This approach allows the protocol to contain its overheads and scale to a larger network. This also enables the reactive element of the protocol to generate more frequent advertisements while adapting to fast changing connectivities. In order to resolve the issues encountered as a result of the inaccuracy of the position system and the stale state of a node's location within the *Location Service*, LGF uses *Restrictive Hybrid Route Advertisement* along with stateful *LGF Exploration* combined with its *Next Hop Selection* algorithm. In this section we describe the features of LGF in detail and discuss it's resilience to position inaccuracy.

3.1 LGF protocol description

We now present an overview of the features of LGF. LGF is based upon existing Position based Forwarding techniques, however many new features are introduced to make the protocol more resilient to failure, and to minimise routing overhead both in terms of state and forwarding decision complexity.

3.1.1 Restrictive hybrid route advertisement

Unlike generic position based forwarding where each node only exchanges information on its location with immediate neighbours, LGF exchanges both topological and location information within a short radius which includes a few hops. *Restrictive Hybrid Route Advertisement* states that each node's neighbours include all nodes within a topological area defined by the perimeter P. For each neighbour node j, node i maintains its position, x_j, y_j, z_j, and the distance between node i and node j, d_{ij}. Each node i maintains this information and additional information as a routing entry RE_{ij}, in the routing table RT_i. For each neighbour j, a node i may hold multiple routing entries, RE_{ij}, a sequence number s_{ij} is associated with each entry to ensure timeliness. A routing entry RE_{ij} is given below:

$$RE_{ij} = \{j,\ NextHop_{ij},\ HopCount_{ij},\{x_j, y_j, z_j\},\{\dot{x}_j,\ \dot{y}_j,\ \dot{z}_j\ \},\ Seq.Num._{ij}\}$$

Where j is the destination and is a globally unique node identifier of all nodes within P, and the *NextHop* is the identifier of an adjacent node to which a packet should be forwarded in order to reach *destination* which is *HopCount* hops away. The position and velocity of the destination j, are $\{x_j, y_j, z_j\}$,$\{\dot{x_j}, \dot{y_j}, \dot{z_j}\}$ respectively. These attributes are used by the forwarding algorithm to resolve a locally optimal path when the destination address dst_p of a packet p is not in RT_i, $\forall j, dst_p \neq j$.

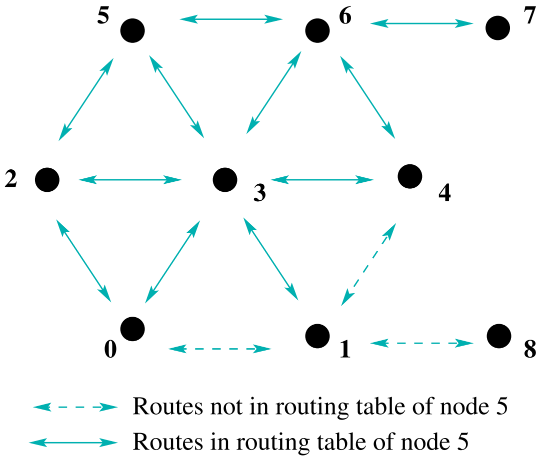


Figure 5: Restrictive Hybrid Advertisement

Figure 5 shows a scenario with 2 hops of restrictive hybrid advertisement. Since node 8 is the only neighbour that is more than 2 hops away from node 5, so when $i = 5$, $\forall j, j \neq 8$.

3.1.2 Next hop selection

With respect to the forwarding algorithm, LGF takes advantage of the geographical position of those nodes that are within each node's topological scope as its basis. Each node i maintains the distance d_{ij} and position x_j, y_j, z_j for every other node j that is within its topological scope. The next hop is selected using the shortest path algorithm to each packet's destination d, if it is found in the set J with $j \in J$. Otherwise, the next hop is determined by Landmark Guided Forwarding.

The term *Landmark* was first used to refer to a geographic point in hierarchical routing over very large networks[14] and has more recently been used to describe a physical point of reference for an Internet coordinate system [13]. In this paper, we consider a *Landmark* as a temporary reference node amongst the set J, that acts as a virtual destination to assist in the routing of a packet towards its final destination. A packet is therefore forwarded via *Landmark* nodes which are selected out of the subset of locally advertised nodes. The exploration algorithm is progressive, such that as soon as the packet reaches the selected next hop, a new *Landmark* is uncovered amongst the new set of local nodes and the packet will progress in the same manner until it arrives at a node with a topological path to the destination. In the case where no valid *Landmark* node is available with a suitable forwarding capability, the path exploration algorithm rolls back to the previous hop and seeks an alternate path.

Figure 6 shows a subgraph that demonstrates our forwarding algorithm where the topological scope is limited to 2 hops. If we consider the packet arrives at node 0, with

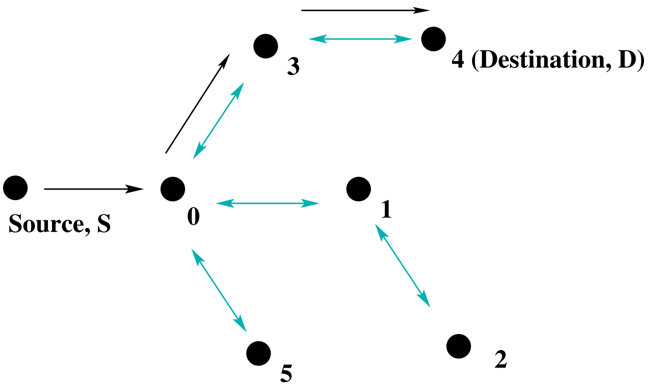


Figure 6: Next Hop Selection - shortest path

next hop forwarding option of either node 1,3 or 5. If the destination for the packet is node 4. The next hop is found to be node 3 by applying the shortest path algorithm to the destination.

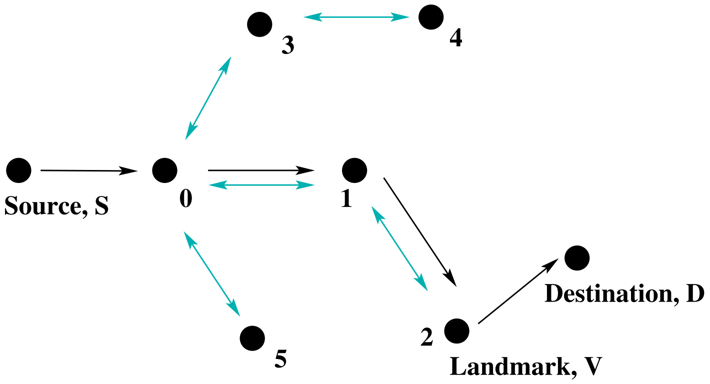


Figure 7: Next Hop Selection - geographic

In the case where a packet's destination is not within the coverage of the topological scope, the next hop is chosen by the shortest path algorithm to a landmark node V, where node V is geographically closer to the destination D and topologically further away from i. In the example in figure 7, the next hop is node 1, with node 2 become a temporarily landmark node V, if node 2 is found to be closer to the destination than node 4.

3.1.3 LGF exploration

Simply forwarding a packet towards its destination position without maintaining any forwarding path history does not provide any facility for preventing the packet being trapped by a localised loop or dropped due to a routing dead-end, thereby preventing any subsequent backtracking. The approach adopted in LGF is to include a source path in the packet header and to also maintain soft forwarding state amongst all nodes traversed by a packet. By maintaining a source path in the packet header it provides a trail of forwarding nodes such that in the event a dead-end is encountered, the packet can be back-tracked until it reaches a node with an alternative path to the destination.

The purpose of maintaining soft-state within the network is to isolate and explore the network systematically. A node temporarily marks a link with the tuple {*Packet_Sequence_Number, Next_Hop, Soft_State_Expiry*}, once it has forwarded a packet along that link. This not only ensures the protocol is loop-free, but also guarantees packet delivery where a path is available between a source and destination.

3.1.4 Mobility sensitive neighbourhood update

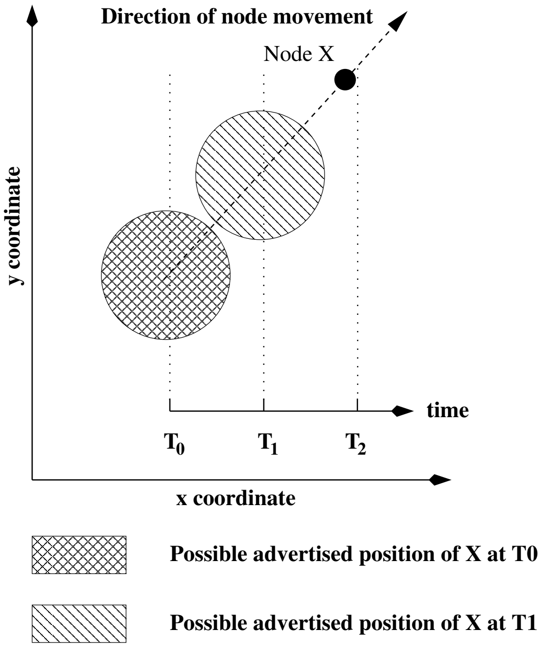


Figure 8: The effects of time lapse with position uncertainty

Figure 8 illustrates the effects of time lapse with respect to locating mobile nodes within the local neighbourhood. The circle area represents the region where X would advertise it's position, with the radius equal to the accuracy of the positioning system. As the figure makes apparent, the advertised position of X is more likely to be closer to the actual locale of X if the lapse from last position update is shorter. Therefore it is clear that increasing the neighbourhood update frequency in conditions of faster mobility could help to mitigate the problem of refreshing stale state in the neighbourhood. This does however introduce greater routing overhead into the network. Based on these observations we define a *Mobility Sensitive Neighbourhood Update* algorithm that regulates the neighbourhood update frequency to compensate for the effects of position uncertainty as a result of node mobility. The following pseudo-code shows how this is achieved through the introduction of a variable component, the *Adaptive_Update_Interval*, to influence the scheduling of the next neighbourhood update timer. In addition, we introduce bounds on both the lower limit of the interval in order to restrain network overheads as well as the upper limit of the interval to always ensure freshness of neighbourhood state tables.

```
procedure $Configure\_Next\_Update$ begin

$Adaptive\_Update\_Interval = \frac{Constant}{Distance\_to\_furthest\_adjacent\_node}$
```

```
$if(Adaptive\_Update\_Interval > upper\_limit)$
  $Adaptive\_Update\_Interval = upper\_limit$
    else if($Adaptive\_Update\_Interval < lower\_limit$)
      $Adaptive\_Update\_Interval = lower\_limit$
$Next\_Update = now + Adaptive\_Update\_Interval$
invokes $schedule(Next\_Update)$

end procedure
```

3.2 Resilience of LGF to inaccurate location information

With restrictive hybrid state in every node, LGF uses hierarchical routing to preserve an equilibrium between selecting an optimal routing decision and minimising routing overheads. In the following section we describe scenarios that illustrate how local routing and path exploration operate in the presence of inaccurate location information and stale node location state held at the location service. We consider 2 scenarios where LGF performs differently depending upon the proximity of the destination to the source node. The first scenario is where the destination is located within the source local forwarding set, and the second scenario is where the destination is further away.

3.2.1 Scenario 1 - Local destination

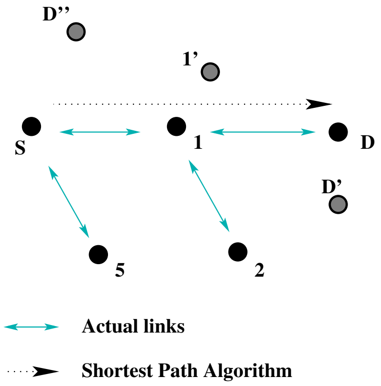


Figure 9: When destination is within local area

Figure 9 is a scenario in which the destination lies within the local scope of 2 hops hybrid advertisement from the source S. Let R be the set of nodes in this diagram. $r \in R$, $R = \{S, 1, 2, 3, 4, 5, D\}$. $\forall r$, r' represents the inaccurate location of r. In addition, D'' represents the stale position information of D in the location service depository. Since D is within the range of the hybrid advertisement of S, the source S would be able to apply the shortest algorithm to deliver the packet from $S \rightarrow 1 \rightarrow D$ regardless of the inconsistencies of surrounding neighbours r' and D''.

This illustrates that neither inaccuracy of position system nor stale state reported by the location service have an impact on the protocol within the local area.

3.2.2 Scenario 2 - Destination outside local scope

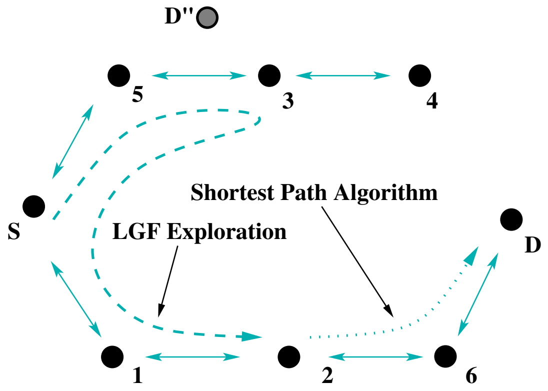


Figure 10: When destination is beyond local area

Figure 10 is a scenario in which the destination is beyond the local scope of 2 hops hybrid advertisement from the source S. Let R be the set of nodes in the diagram. $r \in R$, $R = \{S, 1, 2, 3, 4, 5, D\}$. $\forall r$, r' represents the inaccurate location of r. In addition, D'' represents the stale position information of D in the location service repository. To simplify figure 10, we did not show the exact location of r' but we could assume r' is not too far away from r in this example.

As the Source S does not have a shortest path to the destination, it applies LGF exploration to locate a path to the destination D. However, since S takes D'' as the destination position, the exploration leads the packet to traverse $S \rightarrow 5 \rightarrow 3$, bearing in the direction of D''. At node 3, the exploration algorithm detects a dead-end, and backtracks to continue path exploration from an alternative route. Upon arriving at node 2, the algorithm finds the packet's destination in its routing table, and directs the packet to the destination through the shortest path. This show LGF exploration is able to find the destination regardless of the influence from inconsistency from surrounding neighbours r' and D''.

4 Assumptions, models and simulations

In this section, we outline the models, parameters and assumptions of our evaluation. The focus of our evaluation is to model the performance of existing position based forwarding techniques and to establish the resilience of LGF to position error. We discuss the mechanisms and parameters we have used to measure the performance, beginning with a discussion of the positioning system accuracy model, followed by discussion of the update frequency for the location service model, and concluding with a detailed account of how the simulations were conducted.

4.1 Accuracy of positioning system

With regards to modelling the position tracking system, we considered various techniques and their reported accuracy. Some researchers have proposed using the Global Positioning System (GPS) to retrieve geographical information for position based forwarding protocols[8]. In general the GPS system relies on outdoor access and consequently is not practical indoors, or in cities with many tall buildings. In addition, GPS devices are still quite expensive for ordinary consumers, although it does have a distinct benefit of providing world wide coverage, with accuracy ranging from 10 to 100 meters. Interestingly, recent results from Intel's PlaceLab project [7], as shown in Table 1, demonstrate that positional accuracy of 13.4 m to 31.3 m can be achieved with 100% coverage in urban, residential and suburban by using a combination of IEEE 802.11 and GSM position tracking systems.

Table 1: Accuracy and coverage of GSM and IEEE 802.11 position tracking system.

	IEEE 802.11		GSM+ IEEE 802.11	
	Accuracy	**Coverage**	Accuracy	**Coverage**
Urban	107.2 m	**100** %	21.8 m	**100** %
Residential	161.4 m	**100** %	13.4 m	**100** %
Suburban	216.2 m	**99.7** %	31.3 m	**100** %

In other work [3], researchers have found the accuracy of location could be improved to 5 meters by synchronising the measurement of signal strength from three IEEE 802.11 base stations.

In our simulation, a Gaussian Distribution function was used, with mean value of 0. To model the accuracy of a wide range of location services, we vary the standard deviation. We use standard deviations of 0, 10, 20, 40, 80, 160 and 200 meters to model accuracy of 0, ±5, ±10, ±20, ±40, ±80 and ±100 meters respectively.

4.2 Update frequency for location service

Grid Location Service (GLS) has been proposed as a distributed location service that stores updates, and returns responses to queries from a set of nodes in a spatial hierarchical order [8]. Using a consistent hash function, each node periodically updates its position in a set of nodes in the network. Likewise, a destination location is retrieved by applying the same hash function. Although GLS is a robust system for providing a location repository service for a wireless Ad Hoc network, there is always a time lapse between the last update and the later retrievals of a destination's position. In our simulation, we use update frequencies of 0, 5, 15, and 20 seconds to model the inconsistency caused by the update frequency time lapse.

4.3 Simulation scenario

The simulations have been carried out using the NS2 simulator [4], with each simulation lasting for 900 seconds. Each node uses the IEEE 802.11 MAC and physical models with the radius of the radio range being 250 meters. The simulation uses the random way-point model to model node mobility. In all simulation scenarios, each node selects a random destination and moves at a speed uniformly distributed between 0 and the maximum speed. Upon reaching the destination, the node selects the next random destination and moves on. The traffic model uses constant bit rate UDP traffic flows, with 512 byte payloads. The start time for the different flows is uniformly distributed between 0 and

180 seconds with each of the 30 traffic sources at the rate of 2 packets per second. To model the position uncertainty, as discussed above, we apply a Gaussian distribution , with a mean of 0 and standard deviations of 0, 10, 20, 30, 40, 50, 100, 150 and 200 meters. When modelling the stale state within the location service, we simulate a range of update frequencies of 0, 5, 10, 15 and 20 seconds for LGF, while retaining an idealised location server model for GPSR. In essence, our objective is to assess the performance and adaptability of the routing protocols when the following constraints are introduced into the simulations.

4.3.1 The effects of position accuracy with varying velocity

To evaluate the effects of position accuracy on constantly changing connectivity, we use 5 different sets of mobility patterns generated with maximum velocity of 0, 1, 2.5, 5, 7.5, 10, 12.5 and 15 m/s at 0 pause time, with 100 nodes in a geographic area of 1500 × 500 m^2. To isolate the influence of position accuracy from the effects of location update frequency, we use an ideal location update setting for both protocols.

4.3.2 The effects of location update frequency with varying position accuracy

In addition, we evaluate the effects of variable update frequency with position accuracy variation on LGF. In the case of GPSR, we have not found a way to reconfigure GPSR location service from its ideal location service model. Nevertheless, this set of simulations focuses solely on demonstrating the resilience of LGF with GPSR configured with an ideal location service. We use 5 different sets of mobility patterns generated with maximum velocity of 15 m/s at 0 pause time, with 50 nodes in a geographic area of 1500 × 300 m^2.

We compare LGF and GPSR with the above effects. Each Ad Hoc routing protocol has some settings specific to it which we present in more detail in the tables below.

Table 2: GPSR specific parameters

Parameter	Value
Beaconing interval	3 s
Random variation of beaconing interval	0.5 %
Beacon expiration interval	13.5 s
Promiscuous mode	enable
Removal of neighbour from neighbour list when link broken	enable
Perimeter mode	enable

5 Results and analysis

In this section, we present our findings of two sets of simulations into subsections; namely, performance with varying maximum velocity and position accuracy, performance with varying position accuracy and location update frequency and cumulative distribution of path length with varying positional accuracy and location update frequency.

Table 3: LGF specific parameters

Parameter	Value
Tuning factor	1.5
Max expiry	15 s
Min expiry	1.2 s
Topological scope	3

5.1 Performance with varying maximum velocity and position accuracy

Figure 11 shows the delivery ratio of LGF and GPSR with various settings of maximum velocity and position accuracy. From our observation, there is a declining delivery ratio trend for GPSR as the standard deviation of accuracy increases. In the worst case in which maximum velocity is reset to 0 m/s, our results show a substantial drop of delivery ratio from 95.66 % to 10.59 %, as the standard deviation of positional accuracy increases from 0 to 200 meters. In contrast, LGF maintains a relatively stable delivery ratio in the 80 % region, with a marginal decline of 6 %, as the standard deviation of position accuracy increases from 0 to 200 meters. In general, both protocols present a gradual decline of delivery ratio when node maximum velocity increases from 1 m/s to 15 m/s. However, in the simulation scenario with the standard deviation of position accuracy reset to 0, using the GPSR routing protocol, the delivery ratio falls significantly, from 95.66 % to 63.64 %, when the maximum velocity setting increases from 0 m/s to 15 m/s.

From these findings, it is apparent that the hybrid stateful approach implemented by LGF is more resilient to position inaccuracy as compared to the near stateless position based forwarding technique. However, in scenarios with 0 standard deviation of position accuracy, GPSR yields a better packet delivery ratio than LGF when maximum velocity is below or equal to 7.5 m/s. This performance difference could be accounted for by the advantage of the link failure handling feature implemented in GPSR. Upon link failure, LGF drops the packet immediately, while GPSR marks the failed link and re-queues the packet to use an alternate link. This seems to allow GPSR to perform generally much better in terms of delivery ratio, without the influence of position accuracy.

Looking at Figure 12, we see that the routing overhead of LGF increases approximately from 109000 to 128000 packets while the position accuracy setting increases from 0 to 200 meters. This is an effect of the *mobility sensitive neighbourhood update* being applied in the LGF scheme. The protocol generates adaptive updates to compensate for a neighbourhood's position inconsistency, caused by positional inaccuracy. In contrast, the figure illustrates that the overhead of GPSR declines from approximately 142000 to 100000 packets, when the position inaccuracy increases from 0 to 200 meters. This however does not match the characteristic of periodic advertisement used in GPSR. The exact cause of this overhead change is unclear, however, as it is reducing broadcast exchange of states between neighbours in the network, the protocol is more vulnerable to false construction of the planar graph, which could compromise the correctness of the forwarding technique. Our results consistently show position accuracy has negative effects on average packet delay. In figure 13, we see a trend of increases in GPSR average packet delay with increases in standard deviation of position accuracy. However, in the series of simulations while we remove the influence of position accuracy by resetting its standard deviation to 0, our readings show that the average packet delay for GPSR remains steady, in the region between 0.08 and 0.90 seconds, even when we increase the maximum velocity from 0 m/s to 15 m/s. On the other hand, the figure illustrates that LGF maintains stable average packet delay between 0.28 to 1.09 seconds across all combinations of maximum speed and standard deviation of position accuracy.

Considering this set of results collectively, it shows there is a correlation between the reduction of routing overhead found in GPSR with its performance in terms of delivery ratio, as well as its undesirable average packet delay. The results also show that LGF is resilient to the effects of position inaccuracy, even when all nodes in the network constantly moving at 0 pause time with maximum velocity set to 15 m/s. We also note that in all static scenarios, when maximum velocity are reset to 0, GPSR gains a slight advantage in performance while LGF remains insensitive to node mobility.

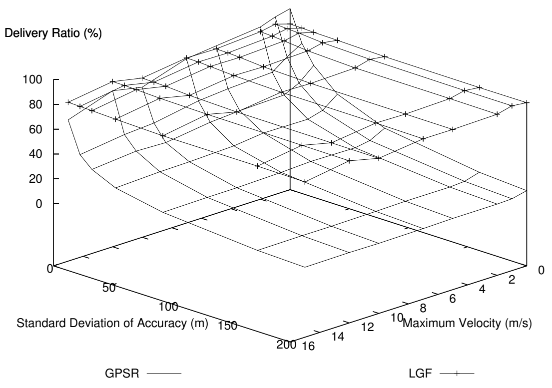


Figure 11: Delivery ratio with varying maximum velocity and position accuracy

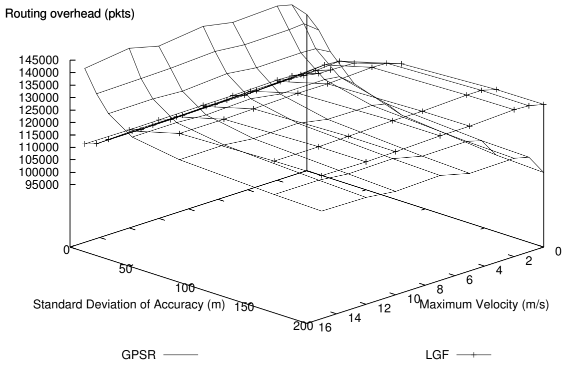


Figure 12: Routing Overhead with varying maximum velocity and position accuracy

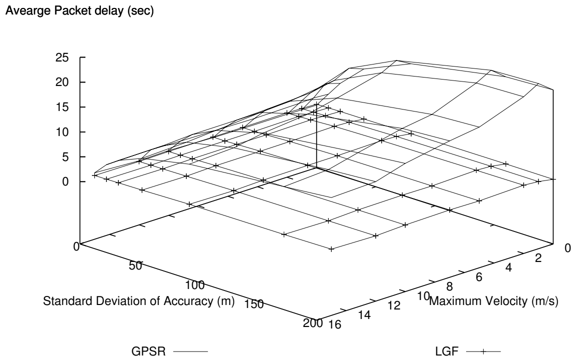


Figure 13: Packet Delay with varying maximum velocity and position accuracy

5.2 Performance with varying position accuracy and location update frequency

Figure 14 shows the delivery ratio of LGF with a combination of various position accuracy and location update frequency settings, alongside the GPSR delivery ratio obtained from different settings of position accuracy. The graph shows LGF is able to sustain a steady delivery ratio of about 83 % region with a standard deviation of position accuracy running from 0 to 200 meters, and a location update frequency setting of 0, 5, 10, 15 and 20 seconds. This shows that LGF is not significantly degraded even by substantial position inaccuracy or by high levels of location update staleness. Conversely, consistent with the previous the set of results, there are signs of deterioration with increasing standard deviation of position accuracy induced in GPSR. The graph shows that the delivery ratio decreases from 77.61 % to 10.95 %, as the standard deviation of position accuracy increases from 0 to 200 meters.

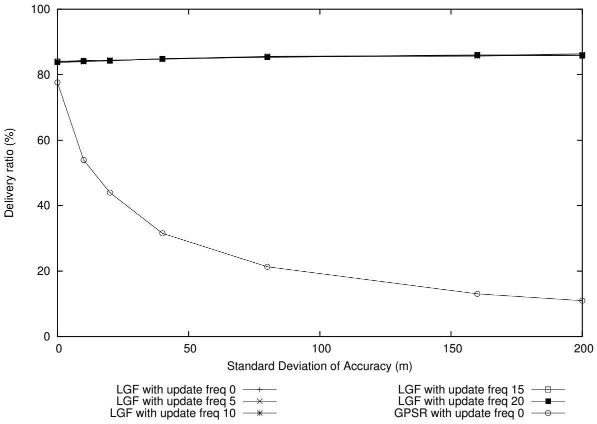


Figure 14: Delivery ratio with varying update frequency

Figure 15 shows the routing overhead of LGF with a range of position accuracy and location update frequencies. We notice that the line for LGF stays approximately constant when we run the simulation with different location update frequencies. This is because the location update frequency has no effects on the *mobility sensitive neighbourhood update*. However, the *mobility sensitive neighbourhood update* compensates for the position accuracy by increasing its update frequency. As discussed, there are indications of a reduction of the routing overhead in the GPSR case, as the standard deviation of position accuracy increases.

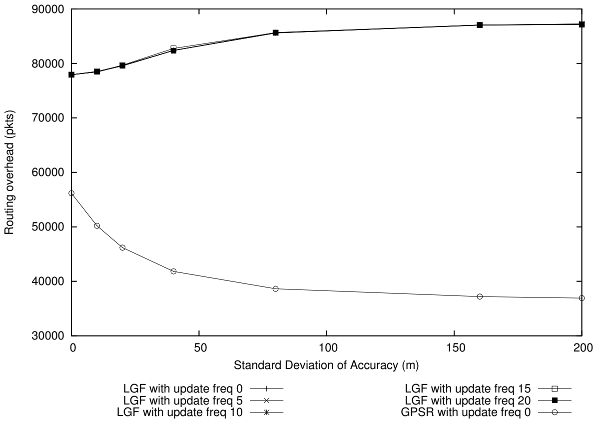


Figure 15: Routing overhead with varying position accuracy and update frequency

Figure 16 shows the average packet delay with a range of position accuracy and location update frequency settings. Despite the constraints of position accuracy and location update frequency, all results of average packet delay for LGF are below 0.08 seconds. In contrast, there is a tendency for an increase in average packet delay of GPSR, as the standard deviation increases from 0 to 200 meters. Based on the readings from this set of results, LGF robustly maintains its performance despite significant constraints imposed by a combination of position accuracy and location update frequency.

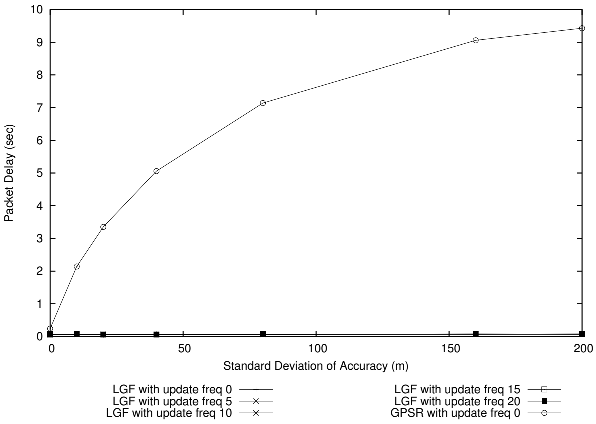


Figure 16: Packet delay with varying position accuracy and update frequency

5.3 Cumulative Distribution of Path length

Table 4 shows the cumulative distribution of path length for successfully delivered packets, for GPSR and LGF, versus the ideal shortest path retrieved from the simulator. The

Table 4: Cumulative distribution of path length for successfully delivered packet.

Protocol	Location Update Frequency	Std. Dev. of position accuracy	Cumulative Distribution of Path Length (%)					
			0	1	2	3	4	≥ 5
LGF	0	0	82.94	**98.43**	99.76	**99.80**	99.82	**100**
LGF	0	200	81.70	**97.94**	99.56	**99.85**	99.94	**100**
LGF	20	200	81.15	**97.64**	99.51	**99.84**	99.93	**100**
GPSR	0	0	98.09	**99.46**	99.61	**99.67**	99.72	**100**
GPSR	0	10	82.56	**94.30**	95.83	**96.67**	97.72	**100**
GPSR	0	20	65.65	**85.71**	90.08	**92.60**	94.01	**100**
GPSR	0	40	45.72	**68.70**	78.20	**84.06**	87.25	**100**
GPSR	0	80	31.26	**51.57**	63.57	**72.42**	78.20	**100**
GPSR	0	160	25.81	**43.02**	55.81	**65.38**	72.69	**100**
GPSR	0	200	26.58	**43.70**	55.77	**64.72**	72.59	**100**

ideal shortest path is the shortest possible path only constrained by the physical radio range. The table shows the cumulative path length discovered by GPSR, with a range of settings of the standard deviation for position accuracy, along with cumulative path length produced by LGF, gathered from the following three settings as in table 5.

Table 5: Evaluation Parameters for LGF Path Length Distribution

Std. Dev. of Accuracy	Location update Freq.
0 m	0 s
200 m	0 s
200 m	20 s

For GPSR, the results display a trend towards a less optimal path length distribution as the standard deviation of accuracy increases. In the worst scenario in which the standard deviation of position accuracy is configured to 200 meters, only 26.58 % of packets are successfully delivered through an optimal path. In contrast, with the standard deviation of position accuracy reset to 0, GPSR delivers 98.09 % of packets successfully through the optimal path. This phenomenon however does not occur in the simulations in LGF. Our results shows LGF is relatively consistent in distribution of path length even with extreme step change of settings. Our results show only approximately 82 % of the LGF packets are routed through an optimal path, however approximately 98 % of the packets reach the destination with one additional hop. The results support the argument that LGF produces a better distribution of path lengths, when under the influence of position uncertainty.

6 Conclusions and future work

A variety of Ad Hoc wireless networking solutions have been proposed to overcome the challenge of infrastructure-less systems. The most recent developments have moved towards position based forwarding solutions which leverage geographical information in order to build routing tables and forward data amongst nodes. The most well know positional based forwarding protocol is GPSR which adopts a hybrid approach utilising greedy packet forwarding and perimeter routing to ensure a highly successful completion rate for system-wide packet forwarding.

Current solutions, however are not resilient to location errors in the system. Location errors occur as a result of device location detection inaccuracies such as GPS tracking which can range from 10 to 100 m accuracy depending upon the environment. Other approaches include GSM and/or IEEE 802.11 base station triangulation to detect location of nodes, all of which introduce a significant element of inaccuracy. In addition to location coordinate errors, we find that systems typically experience error also as a result of stale state within the Location Server which stores mappings of node ID to current location, and is actively updated by the nodes themselves. For nodes which are mobile and potentially moving at a fast rate, we find that a slow update frequency of the location server by a node can significantly impact the performance of the overall system in routing packets to a destination.

We have designed and simulated Landmark Guided Forwarding, a hybrid routing protocol that leverages position based forwarding techniques and introduces some new elements in order to build a more robust routing algorithm in the face of position inaccuracy. *Restrictive Hybrid Route Advertisement* is used to increase the local knowledge area of each node, limiting the scope to a small number of hops. *Landmark* forwarding is used to guide packets on a higher level to simplify routing decisions at each node. *Path Exploration* is used to allow recovery of packets from dead-end routes via maintaining soft forwarding state in the nodes as well routing history in the packet header. The final feature of LGF that separates it from existing positional approaches is the *Mobility Sensitive Neighbourhood Update* algorithm that allows a node to increase the rate at which it informs it's neighbours of it's current position when it is moving at a faster rate or experiencing an increases in position error, thereby increasing the local resilience to movement of nodes. LGF holds the property that it guarantees packet delivery if there is a path between two nodes, and the state along the path is valid.

Through extensive simulation of LGF and GPSR, we have demonstrated that LGF is much more resilient to inconsistency of Location Service. The resilience can be accounted for primarily due to the *path exploration* features of the algorithm which provide the ability to search around the local area for a node and therefore increase the success rate of the overall system. We have demonstrated that in the basic case where location accuracy is perfect, LGF performs relatively similarly to GPSR, only introducing minor overhead, but as error precision is decreased we show that LGF can outperform GPSR in terms of delivery ratio and average packet delay.

Our results show LGF is able to tolerate low position accuracy with a standard deviation of up to 200 meters, even with a maximum node velocity of 15 m/s, and no pause time. In addition, our simulation results demonstrate LGF is resilient to a combination of 200 meters standard deviation of position inaccuracy and an update frequency of 20 seconds, again with node mobility and no pause time and maximum velocity set to 15 m/s. With respect to the distribution of path length, the results show LGF is able to sustain a stable distribution even under significant position inaccuracy conditions and with slow update frequency of node locations. In conclusion, therefore the hybrid approach used by LGF is able to sustain a high delivery ratio and low average packet delay even with substantial degrees of position uncertainty.

With regard to future developments, we intend to extend LGF for use in cases where only partial sets of nodes have access to geographic location information. Most importantly, we would like to implement LGF in a test-bed and test it's performance under real environmental conditions. This will allow us to investigate the impact on LGF of a variety of other factors, including: mobility models drawn from real world data; further measured values for position uncertainty taken from testbeds and the complexity in terms of memory and computation of LGF for real world deployment. The NS2 code discussed in this paper will be made available to other researchers in the near future from the authors website [5] for general use by the wider research community.

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