Self-Organizing Wide-Area Routing

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Abstract

We consider the problem of routing in a Mobile Ad-Hoc wide area network called Terminodes Network. In our solution every node builds its personal view of the network, composed of local and remote views. Large scale routing in the terminode network is achieved by the combination of these two views. We describe two methods called Terminode Local Routing (TLR) and Anchored Geodesic Packet Forwarding (AGPF) that are used for routing in such a network, as well as path discovery and path maintenance mechanisms.
Keywords: mobile ad-hoc wide-area network, routing, terminodes

1 Introduction

We consider the problem of routing in a Mobile Ad-Hoc wide area network. An example of such network is being researched by the Terminode Project[1] in Mobile Ad-Hoc wide area networks, so called because the devices act as terminals and nodes at the same time.

In a terminode network, two important factors affect the design of a solution for packet routing. Firstly, scalability is required, both in terms of number of nodes and geographical coverage. This makes our work very different from MANET[7] proposals that focus on networks of up to several hundreds of nodes. Secondly, network nodes are user equipment, therefore might be sporadically available [2]. This second requirement imposes some incentive for users to collaborate and forward packets on behalf of others. A solution is discussed in [5]; it uses *beans* put by source nodes into packets and consumed by relaying nodes, much like virtual money.

Each terminode has a permanent End-system Unique Identifier (EUI), and a temporary, location-dependent address (LDA). The LDA is simply a triplet of geographic coordinates (longitude, latitude, altitude), obtained for example by means of the geographic positioning system (GPS). Discovery and maintenance of the LDA corresponding to an end-user is described for example in [9]. In this paper, we focus on the problem of unicast, packet forwarding, assuming that the source terminode knows or can obtain the LDA of the destination. A

[1] www.terminodes.org

packet sent by a terminode contains, among other fields, the destination LDA and EUI, and possibly some source routing information, as mentioned later.

Every terminode builds its personal view of the network, composed of local and remote views. Large scale routing in the terminode network is achieved by the combination of these two views.

The local view of a terminode consists of information about other terminodes in its vicinity. It is based on the *Terminode Local Routing (TLR)* method, which provides the following functions:

- Discover the identities (EUIs) of the terminodes that are reachable by TLR. Such terminodes are a few hops away, and are said to be *neighbours*, see Section 2 for details.
- Discover paths to neighbours. Source routing is used to reach neighbours, much like DSR[3].
- Discover location (LDA) of neighbours. This is used in support of the remote view. However, TLR does not use locations for itself, and like DSR, routes are based only on fixed identities (EUIs).

TLR is defined in Section 2.

In addition, a terminode builds its remote view by acquiring information about non-neighbour terminodes.

- The remote view is used by *Anchored Geodesic Packet Forwarding (AGPF)*, which is the method that allows to send data to non-neighbour terminodes. Unlike TLR, AGPF is heavily based on locations. AGPF is described in Section 3.
- The remote view is created by a combination of path discovery methods called *Friend Assisted Path Discovery (FAPD)* (Section 4.1) and *Directional Random Discovery (DRD)* (Section 4.2). FAPD is based on the concept of small world graphs[1].
- The remote view is constantly modified by *Path Maintenance* (Section 4.3), which allows to improve paths, and delete obsolete or mal-functioning paths.

Mobility management is performed by a combination of the following functions. Firstly, TLR allows a terminode to know who its neighbours are, and track them. Secondly, a location tracking algorithm is assumed to exist between communicating terminodes; this allows a terminode to predict the location (LDA) of corresponding terminodes. Thirdly, a distributed directory (VHR[9]) allows a terminode A to obtain a probable location of terminode B that A is not tracking by any of the previous two methods. Location tracking and the VHR methods are outside the scope of this paper.

2 Terminode Local Routing (TLR)

Terminode Local Routing (TLR) is a MANET-derived routing method that allows to reach destinations in the vicinity of a terminode. This method allows to reach terminodes that are several wireless hops away, but is limited in distance

and number of hops. We say that terminode B is a *neighbour* of terminode A if A has a means to reach B with the TLR method. The neighbourhood of A constitutes the *Local Area* of A. The local area of A includes the terminodes whose minimum distance in hops from A is at most equal to *local radius*. The local radius is a measure, in number of hops, of the local area. Every terminode defines its own local radius.

The only addressing information used by TLR is the EUI of the destination. This information is essential, and the *neighbour discovery* mechanism permits to discover it. More precisely, this mechanism allows a node to discover the information (EUI, LDA) of the terminodes that are in its local area, but further than its transmission range (i.e. not physically known). LDA of a neighbour is not used for TLR. However it is used in the Anchored Geodesic Packet Forwarding (AGPF) explained in the next section.

TLR allows a terminode to discover information (EUI and LDA) of one and two hops distant neighbours. This information can be discovered by the means of HELLO beacons that every terminode periodically broadcasts at the MAC layer. Terminode include in a HELLO beacon its own identity and identities of its one hop distant neighbours.

In order to discover other neighbours in its local area, we propose a mechanism that is inspired by the IERP part of ZRP[8]. Terminode A sends periodically a *neighbour request (NREQ)* packet. This packet is propagated within the local area of A and it accumulates the EUIs and LDAs of the neighbours of A. The terminodes at the boundary of the local area of A return back to A the accumulated *neighbours lists*.

A puts in the NREQ packet its local radius information and sends it to its two hops away neighbours. In addition, A puts in the NREQ packet the EUIs and LDAs of its one and two hops distant neighbours. A terminode B that receives the NREQ packet checks if it has already received the same NREQ packet. If so, the NREQ packet is discarded. Otherwise, B controls if:

$$local\_radius(A) - hop\_distance(A, B) \geq 2$$

If this condition is satisfied, B adds in the NREQ packet the information (EUI and LDA) of its one and two hops neighbours that are not presented in the accumulated neighbour list inside the NREQ packet. Then B forwards the NREQ packet to its two hops neighbours other than A. If $local\_radius(A) - hop\_distance(A, B) = 1$, B puts in the NREQ packet the EUIs and LDAs of its one hop away neighbours that are not already present in the accumulated neighbour list; B does not forward further the NREQ packet. In this way, the EUIs and LDAs of the neighbours of A are accumulated until the NREQ packet reaches the end of the local area of A. The accumulated list can also be used by the last terminodes to respond back to A.

Once a terminode has the EUIs of its neighbours, it needs to find out how to reach those nodes. For this a terminode performs *path discovery*. In our solution, terminode A does path discovery to B on demand when it has some traffic to send to B. Our solution is based on the reactive mechanism of DSR[3] and uses source routing to reach a neighbour.

Once A learns the path to B, it applies source routing to forward packets to B.

In the proposal we presented, neighbour discovery and path discovery are done independently with two separate mechanisms. It is also possible to use

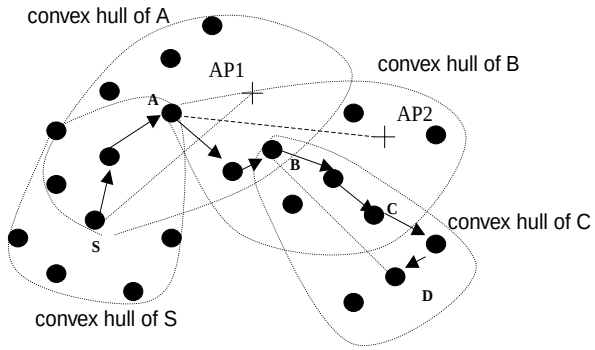

Figure 1: The figure presents how AGPF is done when S has some data to send to D. S has a path to D given by a list of anchored points: $\{AP1,\ AP2\}$. At first, S sends a packet to its good neighbour A, which is in the direction of $AP1$. Then, A send a packet to its good neighbour B that is in the direction of $AP2$. B sends to its good neighbour C that is in the direction of D. At last, C forwards a packet to D by means of TLR.

some proactive method that combines them. For example, a distance vector based approach can be used limiting the updates messages to local areas. A comparison of different methods is the subject of ongoing work.

3 Anchored Geodesic Packet Forwarding (AGPF)

In its simplest form, geodesic packet forwarding would consist in sending a packet in the direction of the destination, identified by its LDA. When an intermediate node receives such a packet, it checks whether the destination EUI is within reach of its TLR method, and if so, it uses this latter method. Else, the packet is sent to a neighbour in the direction of the destination LDA. The direction is computed as the shortest path (geodesic) on earth. In this simplest form, geodesic packet forwarding will not often work. If there is no connectivity along the shortest line, then the method would fail, typically because a relaying terminode would find no neighbour within the angle towards the destination. Our solution to this problem is to use *anchors*. An anchor is a point, described by geographical coordinates; it does not have to correspond to any terminode location. Anchors are computed by source nodes, using the methods described in Section 4. A source terminode adds to the packet a route vector made of a list of anchors, which is used as loose source routing information. Between anchors, geodesic packet forwarding is employed. When a relaying terminode receives a packet with a route vector (list of anchored points), it checks whether the convex hull of its set of neighbours includes the first anchor in the list. If so, it removes the first anchor and sends it towards the next anchor or the final destination, using geodesic packet forwarding. If the anchors are correctly set, we conjecture that there is a good chance that the packet will arrive at destination.

Figure 1 presents an example of AGPF. Terminode S wants to send to terminode D. D is not a neighbour of S, therefore S tries to use AGPF. Assume

that S has a path to D. This is a list of anchored points, in this case $\{AP1, AP2\}$. $AP1$ is not included in the convex hull of the set of the neighbours of S. Therefore, S discovers a *good* neighbour in the direction of $AP1$. Good means, in our model, that this is the most forward neighbour, inside a given angle, in the direction to the destination[2]. If there is no neighbours within a given angle, the angle is increased until it is possible to find one. In this example, a good neighbour of S is A. S applies the TLR method to route the packet to A; S adds a TLR header to the packet. In addition, S adds to the packet the list $\{AP1, AP2\}$ which is used as loose source routing information. Once A receives the packet it finds out that $AP1$ is included in the convex hull of its neighbours. A removes $AP1$ and sends towards $AP2$ that is the next anchor in the list. A determines that B is a good neighbour in direction of $AP2$ and therefore applies the TLR method to send the packet to B. When B receives the packet it discovers that $AP2$ is included in the convex hull of its neighbours. B now removes $AP2$ from the packet and tries to send towards the final destination D. B discovers that C is a good neighbour in direction of D and sends the packet to C. Upon reception of the packet, C discovers that D is its neighbour and forwards the packet to D by using the TLR method.

4 Path Discovery and Path Maintenance

Some path discovery mechanisms are present both at the local and at the remote view of the network. We have already presented path discovery mechanism for the first case in Section 2. Here we present other methods for gaining paths that are used in the case of a remote destination. We also present functions for path maintenance.

4.1 Friend Assisted Path Discovery (FAPD)

A terminode A keeps a list of terminodes that it calls *friends*. B is a friend of A if (1) A thinks that it has a good path to B and (2) A decides to keep B in its list of friends. A may have a good path to B because B is a neighbour of A, or because A managed to maintain one or several route vectors to B which work well. When A wants to discover a path to a destination C, then A may require assistance from a friend B. This is done by sending a route request packet to B, which contains an offer (counted in beans). If B accepts the offer, it has to find a path to C. When this path is found and authenticated by C, then B keeps the beans and returns to A the desired path. B may in turn use his own set of friends to identify a path to C.

FAPD is based on the concept of small world graphs[1]. Small world graphs are very large graphs that tend to be sparse, clustered and have a small diameter. This is justified by the fact that the scenario we have in mind is a wide, collaborative network, that presents several aspects in common with a social network (e.g. the type of relationships occurring between nodes). In the graph representation of the terminode network, the vertices of a graph are terminodes and the knowledge of the path from one terminode to another is represented by an edge. The resulting graph is highly clustered and dominated

[2]this is a derivation from the MFR method described in [10], which sends to the most forward neighbour within the transmission radius.

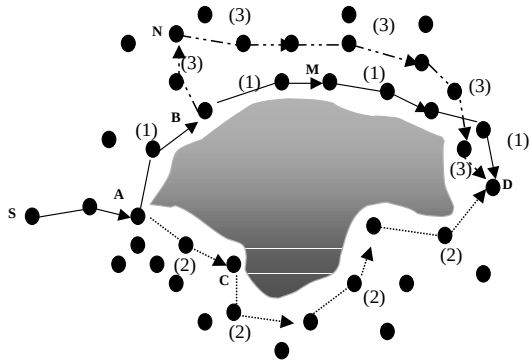

Figure 2: This figure presents how DRD is used by S to find paths to D. There is a connectivity hole in the direction from S to D. S sends the discovery packet to its good neighbour A that is in the direction of D. When A receives the discovery packet, it does not find any good neighbour in the direction of D. Thus it increases the angle and discovers its neighbours B and C, and it sends to them the discovery packet. In the same way, the discovery packet is forwarded until D is reached. In this example D receives three discovery packets and sends back to S a reply with the resulting accumulating path for each of them.

by edges between nearby nodes, but edges between remote nodes provide efficient long-distance connectivity. Packet forwarding in such a network is guided by existence of such short and long-distance paths between terminodes. We conjecture that the graph defined by friends and neighbours in a terminode network has the structural properties for consideration as a small world graph. This means, roughly speaking, that any two vertices are likely to be connected through a short sequence of intermediate vertices.

4.2 Directional Random Discovery (DRD)

Directional Random Discovery (DRD) is the last resort method. It consists in two mechanisms for forwarding a discovery packet towards the destination, and works as follows. When a terminode receives such a packet, it tries to send it to a good neighbour. As explained above, this is the most forward neighbour, inside a given angle, in the direction to the destination. When this first mechanism fails, i.e. there are no neighbours inside the given angle, the terminode applies the second mechanism. It determines the smallest angle towards the destination, which contains between 1 and 3 neighbours and sends to all neighbours within this angle. If there is an obstacle or a gap in the direction of the destination, then this angle may be large. Then the discovery packet is sent to these 1, 2 or 3 neighbours, who will forward it further, until the destination is reached. Every node accumulates its LDA into the packet, and consumes some beans. This method provides paths that tend to follow the boundary of holes in the terminode networks. The resulting paths are candidates to improvement as explained above.

Figure 2 is an example of the usage of DRD when there is some connectiv-

ity hole in the direction from source to destination (e.g. physical obstacle or terminodes desert). Source terminode S that does not have any path to destination D sends a discovery packet towards D. In this example, this means that S sends the discovery packet to its good neighbour A. Upon reception of the discovery packet, A finds out that it has no good neighbours in direction of D and, using the second mechanism, increases the angle until it discovers two neighbours (B and C), and then sends the discovery packet to B and C. Similarly, upon reception of the discovery packet, B decides to send the discovery packet to its neighbours M and N. The discovery packet is forwarded until D is reached. In this example D receives three discovery packets and sends back to S a reply with the resulting accumulated path for each of them. From them S derives some anchored paths to D.

4.3 Path Maintenance

Every terminode maintains a set of paths (described by route vectors) to all destinations that it is communicating with. The number of paths depends on the local resources available. Path maintenance consists of three main functions: path simplification; path monitoring and deletion; congestion control.

path simplification One method consists in approximating an existing path by a path with fewer anchors. Such an approximation yields a candidate path, which may be better or worse than the old one. We use a heuristic based on curve fitting.

path monitoring and deletion A terminode constantly monitors existing paths in order to collect necessary information that gives the value to the path. The value of the path is given in terms of congestion feedback information: beans [5], packet loss and delay. Other factors like robustness, stability and security are also relevant to the value of a path.

This allows a terminode to improve paths, and delete mal-functioning paths or obsolete paths (e.g the path that corresponds to two terminodes that do not communicate any more).

congestion control The value of the path given in terms of congestion feedback information is used for a terminode to decide how to split the traffic among several paths that exist to the destination. A terminode gives more load to paths that give least congestion feedback information. This method ensures that the utility of a terminode network approaches the optimum [4], [6].

5 Conclusions

In this paper we have considered the problem of routing in a mobile ad-hoc wide area network called terminodes network. In our solution every terminode builds its personal view of the network, composed of local and remote views. Large scale routing in the terminode network is achieved by the combination of these two views. We describe two methods called Terminode Local Routing (TLR) and Anchored Geodesic Packet Forwarding (AGPF) that are used for routing in such a network. TLR allows a terminode to reach destinations in its vicinity,

while AGPF is used to send data to remote destinations. We give a description of two path discovery mechanisms and some guidelines for path maintenance.

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