Self-Organization in Mobile Ad Hoc Networks: The Approach of Terminodes

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ABSTRACT

The Terminodes project is designing a wide-area mobile ad hoc network which is meant to be used in a public environment; in our approach, the network is run by users themselves. We give a global description of the building blocks used by the basic operation of the network; they all rely on various concepts of self-organization. Routing uses a combination of geography-based information and local MANET-like protocols. Terminode positioning is obtained by either GPS or a relative positioning method. Mobility management uses self-organized virtual regions. Terminodes employ a form of virtual money called nuglets as an incentive to collaborate. Lastly, we discuss directions for providing some level of security.

INTRODUCTION

The Terminodes project is a long-term research project (2000–2010) aimed at studying and prototyping large-scale self-organized mobile ad hoc networks. In this framework the nodes are called *terminodes* (terminal+node). The project distinguishes itself from other research projects in this area in several ways. First, it encompasses all layers and explores interlayer interactions, from the fundamentals of the physical layer up to software architecture and applications. Second, it is free from short-term compatibility constraints such as interoperation with IPv4 networks (which will be studied in the project, however). Last but not least, it tries to capture the business and societal potential generated by the paradigm shift previously described.

Self-organization is the keyword of the project [1]. Self-organized networks distinguish themselves from traditional mobile ad hoc networks, based on the traditional Internet two-level hierar-

chy routing architecture [2], by emphasizing their self-organization peculiarities [3]:
* Self-organized networks are non-authority-based networks; they can act in an independent way from any provider or common denominator, such as the Internet, even if they still require regulation (self-organization).
* Self-organized networks are potentially very large and irregularly distributed. In principle, one single network can cover the entire world. Density is supposed to be very high in small areas (e.g., towns), and low in large areas.
* Self-organized networks are highly cooperative. The tasks at any layer are distributed over the nodes, and any operation is the result of the cooperation of a group of them.

Terminodes correspond to totally self-organized mobile ad hoc networks. In this kind of network, there is no operator at all: users purchase their device from a vendor, turn it on, and are automatically connected (as if they had purchased walkie-talkies). Therefore, all management functions (configuration, setup of security mechanisms, resource allocation, etc.) have to work without any human intervention or server.

Can all the mechanisms of mobile ad hoc networks be self-organized? To the best of our knowledge, this question has never been tackled in a systematic way. Each of the following five sections illustrates the solution we envision for a specific mechanism: routing, mobility management, Global Positioning System (GPS)-free positioning, incentive to cooperation, and security. More details can be found in [4].

PACKET FORWARDING

Each terminode has a permanent end-system unique identifier (EUI), and a temporary, location-dependent address (LDA). The LDA is
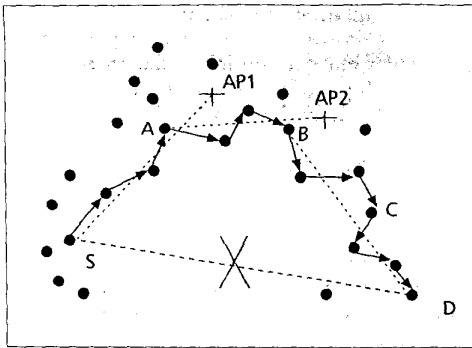
■ Figure 1. *How AGPF works when a terminode with EUI_S has some data to send to a terminode with EUI_D, and there is no connectivity along the shortest line from S to D. S has a path to D given by a list of geographical locations called anchored points {AP1, AP2}. First, geodesic packet forwarding in the direction of AP1 is used. After some hops the packet arrives at terminode A which finds that it is close to AP1. At A the packet is forwarded by using geodesic packet forwarding in the direction of AP2. Second, when the packet comes to B (i.e., close to AP2), it starts sending the packet towards D. Last, when the packet comes to C it finds that D is TLR-reachable and forwards the packet to D by means of TLR.*

simply a triplet of geographic coordinates (longitude, latitude, altitude) obtained, for example, by means of the GPS or the GPS-free positioning method discussed later.

In a terminode network, two important factors affect the design of a solution for packet routing. First, scalability is required, in terms of both number of nodes and geographical coverage. Second, network nodes are user equipment, and therefore maybe available only sporadically. This second requirement imposes some incentive for users to cooperate and forward packets on behalf of others. A solution is discussed later.

As a consequence of the above requirements, our solution is designed such that a terminode relies only on itself and a small number of other terminodes for packet forwarding. In addition, we cope with uncertainty in the network by considering multipath routing as a rule, not as an exception. We use a combination of two routing methods: terminode local routing (TLR) and terminode remote routing (TRR). TRR uses geographic information: it is the key element for achieving scalability and reduced dependence on intermediate systems. However, when a packet gets close to the destination, positional errors and inconsistent location information can result in routing errors and loops if locations are used for making packet forwarding decisions. Therefore, when close to the destination, the packet forwarding method becomes TLR, which does not use location information. Once a packet has been forwarded with TLR, the "don't use TRR" bit is set within the packet header, thus preventing downstream terminodes from using TRR for this packet. This avoids loops due to the combination of the two routing methods.

TERMINODE LOCAL ROUTING

TLR allows terminodes to be reached that are several wireless hops away, but is limited in distance and number of hops. TLR is inspired by the Intrazone Routing Protocol (IARP) in ZRP [5].

We say that terminode D is *TLR-reachable* for terminode S if S has a means to reach D with the TLR protocol. The TLR-reachable area of S includes the terminodes whose minimum distance in hops from S is at most equal to a *local radius*. The local radius is a measure, in number of hops, of the TLR-reachable area.

Every terminode proactively maintains the information (EUI, LDA) of the terminodes in its TLR-reachable area. TLR uses a distance vector routing protocol to send data to TLR-reachable destinations, and thus the only addressing information used for packet forwarding is the EUI of the destination.

TERMINODE REMOTE ROUTING

TRR allows data to be sent to *non-TLR-reachable* destinations. TRR consists of the following elements.

Anchored Geodesic Packet Forwarding (AGPF) [6] — This is a method to send data to remote destinations. Unlike TLR, AGPF is based solely on locations.

When S has some data for D and D is non-TLR-reachable, S first discovers LDA_D using a mobility management method described later.

Then S sends packets by geodesic packet forwarding: the packet is sent to some neighbor X within a transmission range where the distance to D is reduced the most. In its turn, X performs the same steps: it checks whether D is TLR-reachable. If not, X sends the packet by geodesic packet forwarding; otherwise, X uses TLR.

In this simplest form, geodesic packet forwarding often will not work. If there is no connectivity along the shortest line, the method fails.

Our solution to this problem is to use *anchors* (Fig. 1). An anchor is a point described by geographical coordinates; it does not, in general, correspond to any terminode location. Anchors are computed by source nodes using path discovery methods. One such method is presented later in the article. 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 it is close to the first anchor in the list. If so, it removes the first anchor and sends it toward the next anchor or the final destination using geodesic packet forwarding. If the anchors are correctly set, the packet will arrive at the destination.

Friend Assisted Path Discovery (FAPD) — This is a path discovery method based on the concept of small world graphs [7]. It can be summarized as follows: A terminode A keeps a list of terminodes that it calls *friends*. B is a friend of A if:
• A thinks it has a good path to B.
• A decides to keep B in its list of friends.

Figure 2. *An example of the simulation area that consists of three towns. Terminodes stay within a scope of the same town for a certain number of movements, and then choose at random another town area to which they move.*

A may have a good path to B because A can reach B by applying TLR, or because A managed to maintain one or several route vectors to B that work well. When A wants to discover a path to destination C, A may require assistance from a friend B. B may try to find a path to C (perhaps with the help of its own friends). If B finds the desired path it returns it to A. A pays for the service provided by B in *nuglets*.

We view a terminode network as a graph, with edges representing the friends relation. We conjecture that this graph has the properties of a small world graph. Small world graphs are very large graphs that tend to be sparse and clustered and have a small diameter [7]. In a small world graph, roughly speaking, any two vertices are likely to be connected through a short sequence of intermediate vertices. This means that any two terminodes are likely to be connected with a small number of intermediate friends.
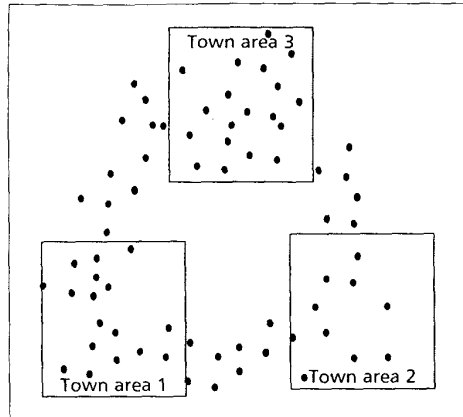
Terminode remote routing is constantly modified by **path maintenance**.

A terminode normally attempts to maintain several paths (described by route vectors) to any single destination of interest to it, and uses several of them in parallel. A terminode constantly monitors the cost of each path; the cost is given in terms of nuglets, packet loss, and delay. Other factors like robustness, stability, and security are also relevant to the cost of a path. This allows a terminode to improve paths, and delete obsolete or malfunctioning paths. In addition, information about the value of the paths is used for a terminode to decide how to split the traffic among the multiple paths that exist to the destination. A terminode sends more data along the paths that give the least congestion feedback information.

PERFORMANCE OF TERMINODE ROUTING

We carried out simulations of the TLR and TRR protocols. We briefly explain here the mobility model used in our simulations and some simulation results. For further details on the simulations, the interested reader is referred to [6].

The simulation area is composed of a number of regions called *towns*. Inside town areas, terminodes move according to the *random waypoint* mobility model. After a certain number of movements within the scope of the same town, a terminode moves to another town area. Terminodes that move between town areas simulate highways between towns. We believe that this mobility model is closer to a real-life situation for a wide-area mobile ad hoc network than the random waypoint, since it better represents the fact that most people move for a certain period within one area, and then move away to another distant area.

An example of the model of a simulated area that consists of three towns is presented in Fig. 2. If source and destination are in two different towns, say, town areas 1 and 2, the source may send data to the destination using two paths. One is the direct geodesic path that connects towns 1 and 2. Another path is via town 3, and consists of an anchor point in the area of town 3.

In [6] are presented detailed simulation results with 600 terminodes moving according to the mobility model described above. These results show that terminode routing is able to deliver over 80 percent of user data in a large and highly mobile simulation environment, where traditional MANET routing protocols, because they are not designed for such an environment, achieve less than 10 percent delivery.

MOBILITY MANAGEMENT: THE VIRTUAL HOME REGION

Mobility management is performed by three components. First, TLR is able to track a destination terminode in the vicinity of a relaying terminode. Second, LDA management is performed by the method described below; it is required for TRR. Third, hosts that are engaged in a conversation keep track of each other using a tracking protocol, not described in this article.

The main objective of LDA management is to distribute the location information inside the network in a dynamic, scalable, secure, and fair way (i.e., without privileging any node or region). At the same time, we are not concerned with maintaining the exact location information. All we require is that the LDA of the destination, learned at the source, is accurate enough that the packet eventually arrives at some terminode which finds the destination inside its TLR-reachable area.

Any mobility management system where the management is assigned in a fixed or static way to one or a group of nodes is in conflict with the security and the peer-to-peer characteristics of a terminode network, because the node(s) that plays the manager role could profit from its position of superiority. Moreover, these systems are not applicable on a large scale because they require a large amount of communication among nodes.

Therefore, we introduce a new architecture where the information is dynamically distributed inside the network, and the communication involved is only due to the upgrade or retrieval

of location information. The main functions of this architecture are:
- Maintaining location information
- Distributing location information inside the network

These functions are performed in a reliable and robust way.

In this architecture, each node advertises its current position (LDA) to a geographical region called the *virtual home region* (VHR). The VHR has a fixed center C_{VHR} and a variable radius that adapts to the density of the area containing the VHR, in order to maintain an approximately constant number of nodes inside the VHR.

The fixed center is computed using some pre-defined publicly known hash function H. H is a static mapping between the space of EUIs $\{EUI_i\}$ and the geographical space of a termi-node network such that $H(EUI_A) = C_{VHR}$ for each $A \in \{EUI_i\}$.

Terminode A does location update by sending position advertisements toward its VHR. All terminodes in A's VHR store the mapping between A's EUI and LDA. They act as a management system for A for the time they belong to A's VHR; once they leave it, they lose this role.

The radius of the VHR is increased or decreased if the number of nodes in the VHR is inadequate. This can happen because either there are too many nodes in the VHR, and the management and retrieval of the location information requires too many communications, or there are not enough nodes, and the system is not robust.

When terminode B wants to retrieve the location of A (it must know A's EUI), it sends a query toward A's VHR (which can be computed by B since the hash function is publicly known). Once this request is received, the location information of A is sent back by the nodes of the VHR of A. This information is used to start communication with A. During the communication, A and B rely on a direct system of mobility tracking. Figure 3 illustrates the distribution and retrieval of the location information in a terminode network.

There are several possible location update schemes that can be applied in a terminode net-work.

The following schemes are proposed for per-sonal communications networks (PCNs) [8] and can be used in a terminode network. In the *timer-based* location update scheme, each termi-node periodically sends a location update to its VHR. In the *distance-based* update scheme, each terminode tracks the distance it has moved since its last update and sends its location update whenever the distance exceeds a certain thresh-old. In the *predictive distance-based* scheme, the terminode reports to its VHR both its location and velocity. Based on this information and a mobility pattern, the location of the terminode can be predicted. The terminode checks its loca-tion periodically and sends a location update to its VHR whenever the distance between the pre-dicted location and its exact location exceeds the given threshold. When terminode B needs the location of terminode A, it does the prediction of A's LDA from the information in A's VHR. In our current design we use the *distance-based* location update scheme.
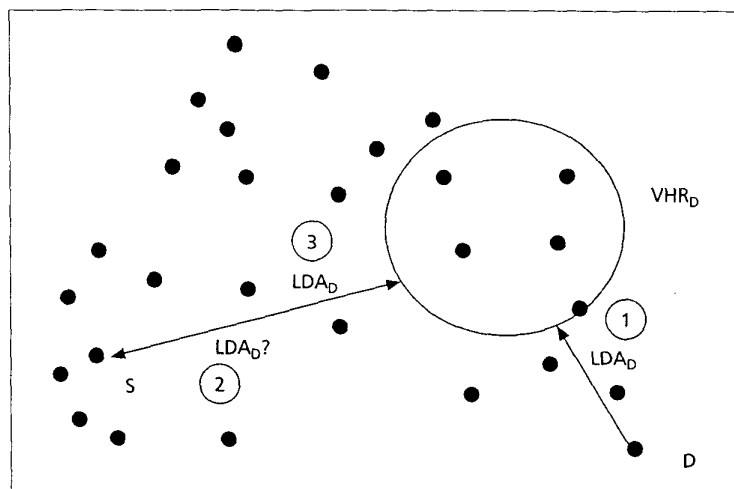
Figure 3. *An example of the distribution and retrieval of location informa-tion. (1) Terminode D periodically sends its position (LDA_D) to its VHR. When terminode S wants to communicate with D, it first computes the center of the VHR of D as H(EUI_D) and then sends a request toward the region around this point. When this request is received by the terminodes in the VHR of D, (3) LDA_D is sent back to S.*

In order to have robust and self-operating management, terminodes must cooperate to store location information and serve as tempo-rary distributed memory for other terminodes. This may be stimulated by paying nuglets to the terminodes in the VHR. The advantage of this approach is that it has a reasonable amount of communications to distribute and retrieve loca-tion information, and no central or statically defined servers are necessary.

In the proposed solution for mobility man-agement, terminode B that needs a location of close terminode A may contact a potentially dis-tant VHR of A. One possible solution to this problem is to organize the VHR-based mobility management in a hierarchical way in order to scale better in a large network. In this solution, every terminode would have several geographi-cally distributed VHRs that contain its location. For retrieving location information of another terminode, a terminode would contact the corre-sponding VHR closest to it. Reference [9] pre-sents how to geographically distribute location servers in a large network.

GPS-FREE POSITIONING

Terminode positioning is used by every terminode to obtain its position. The position of a terminode can be obtained by means of the GPS positioning method. However, there are situations where GPS is not available. This happens, notably when the GPS signal is too weak (e.g., indoor), when it is jammed, or when a GPS receiver must be avoid-ed for cost or integration reasons.

In this section we briefly describe the Self Positioning Algorithm (SPA) for positioning of terminodes in a terminode network that is GPS-free. SPA provides position information to ter-minodes in the scenarios where an infrastructure does not exist and GPS cannot be used. A com-plete description of SPA is given in [10].
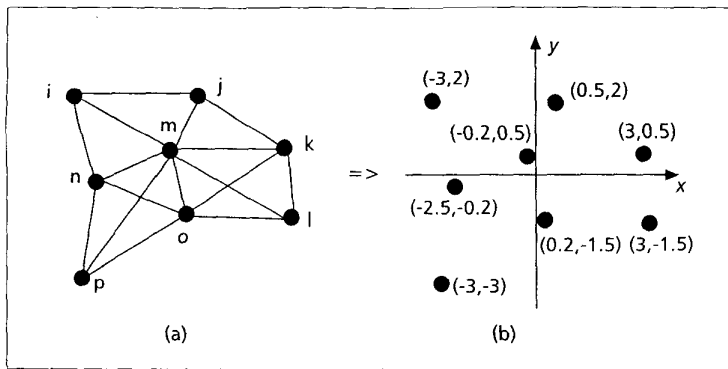
Figure 4. *SPA uses the distances between the terminodes and builds the NCS. Lines in Fig. 4a represent the distances terminodes can obtain by applying the TOA method. This is done by measuring signal propagation time between the two neighboring terminodes. Figure 4b shows the NCS. The value next to each terminode represents its position within the NCS.*

SPA uses distance measurements between terminodes to build the *network coordinate system* (NCS) (Fig. 4). The time of arrival (TOA) [11] method is used to obtain the distance between two terminodes. Despite the distance measurement errors and the motion of terminodes, SPA provides sufficient location information and accuracy to sustain basic network functions. For the sake of simplicity we present SPA in two dimensions, but it can easily be extended to provide position information in three dimensions.

SPA is performed at each terminode and consists of the following steps:

- A terminode measures distances to its neighbors and sends this information to all its neighbors.
- A terminode builds its *local coordinate system* (LCS) and computes the positions of its neighbors in LCS.
- A terminode computes the density factor of its *n*-hop neighborhood (i.e., the number of terminodes in the *n*-hop neighborhood).
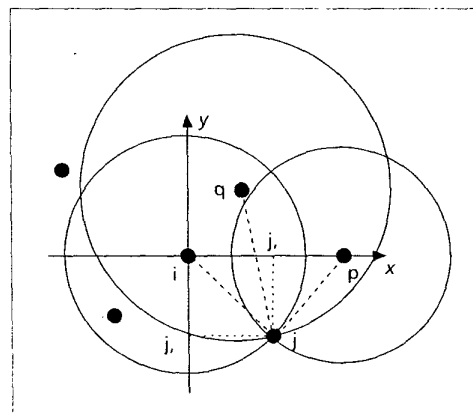

Figure 5. *Terminode i defines its local coordinate system (LCS$_i$) by choosing two neighbors (e.g., p and q). The position of its neighbor j in LCS$_i$ can be obtained by triangulation. j is positioned at the intersection of the three circles with centers in i, p, and q, and with radii equal to distances from these terminodes to j, respectively.*

- A terminode with the highest density factor forms a *location reference group* (i.e., the terminodes in its *m*-hop neighborhood) and computes the center and direction of the NCS.
- All terminodes compute their position in the NCS.

Below, we define the operation of SPA in more detail.

LOCAL COORDINATE SYSTEM

Every terminode *i* defines its LCS (LCS_i) by choosing two neighbor terminodes *p* and *q* such that the distance d_{pq} between *p* and *q* is known and larger than zero, and the terminodes *i*, *p*, and *q* do not lay on the same line. Terminode *i* becomes the center of LCS_i with the coordinates (0,0). The direction of LCS_i is defined such that terminode *p* lays on the positive x axis of the coordinate system and terminode *q* has a positive y component.

Every terminode *i* computes positions of its neighbors in its LCS_i. If terminode *j* is the neighbor of *i*, *p*, and *q* (i.e., the distances d_{ij}, d_{qj}, d_{pj} are known to *i*), its position is then computed by triangulation (an intersection of three circles) [11]. This is illustrated in Fig. 5. If *k* is not a neighbor of *p* and *q*, *i* obtains *k*'s position in LCS_i by choosing two neighbors of *k* whose positions in LCS_i are already obtained.

The choice of *p* and *q* can be optimized with respect to the desired coverage and accuracy of the algorithm.

NETWORK COORDINATE SYSTEM

After building their LCSs, terminodes compute their density factors. The terminode with the highest density factor will "slave" the other terminodes and its *m*-hop neighborhood becomes a *location reference group* (LRG) of the network. The center and direction of the NCS are then computed as the geometric center of the terminodes in LRG and the average of the directions of their coordinate systems, respectively. This information is then propagated to the terminodes in the network, and they compute their position in NCS.

PERFORMANCE OF THE SELF POSITIONING ALGORITHM AND LIMITATIONS

We have evaluated SPA, and detailed performance results can be found in [10]. A network of terminodes is represented by a graph G_N, where vertices correspond to terminodes and an edge exists between a pair of terminodes if they are in each other's power range. We construct another graph G_{GPS}, where vertices correspond to terminodes and an edge exists between a pair of terminodes if they can propagate the information about the NCS to each other. We observe the edge connectivity of these graphs, being the minimum number of edges whose removal from a graph make a graph disconnected. The edge connectivity of G_N is here referred to as the connectivity of the terminode network, and the edge connectivity of G_{GPS} is referred to as the connectivity of SPA.

Clearly, the connectivity of SPA will always be smaller or equal to that of the terminode net-

work. In the ideal case, the information about the NCS would be propagated between each *pair* of nodes in each other's power range, and thus the node connectivity and SPA connectivity would be equal. The connectivity of SPA therefore shows the sensitivity of SPA to the given connectivity of the network.

Figure 6 illustrates the network connectivity and the connectivity of SPA for a randomly generated network of terminodes. In this example, for the chosen power range network connectivity is clearly higher than SPA connectivity. The example also indicates and our results in [10] further show that not very high network connectivity ensures that the SPA connectivity remains larger than zero.

The accuracy of the positions obtained by SPA strongly depends on the distance measurements and on the speed of movement of terminodes. Higher speeds of terminodes introduce additional errors, and the positions of terminodes need to be frequently recomputed. Inaccurate positions of terminodes have negative impact on the performance of the packet forwarding algorithm in a terminode network.
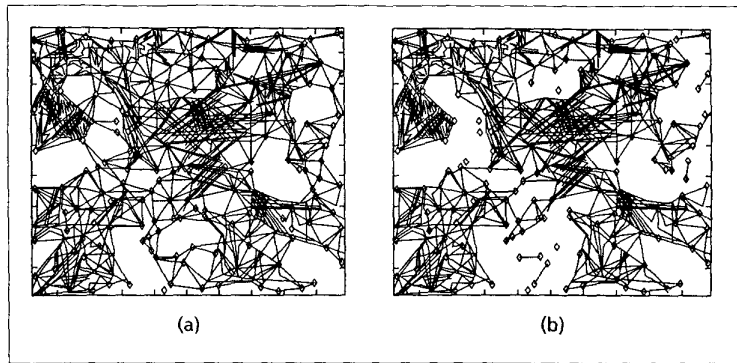
INCENTIVE FOR COOPERATION

In a terminode network, *all* networking services are provided by the terminodes themselves. However, service provision is not in the interest of terminodes (or, more precisely, their users), because it consumes energy (reduces battery lifetime) without any direct advantages. Therefore, terminodes (their users) may tend to be selfish: they use services provided by others, but do not want to provide services to the community.[1] Clearly, selfish terminodes may hinder the functioning of the network completely. Therefore, a stimulation mechanism is required that encourages users to provide services to each other.

So far, wireless mobile ad hoc networks have been envisioned mainly for military applications and crisis situations (e.g., in rescue operations). In both cases, the users of the network are assumed to belong to the same administration authority (e.g., to the same platoon or rescue team), and thus naturally motivated to cooperate. In terminode networks this assumption does not hold, because each user can be considered to be a distinct administration authority with selfish objectives.

Our approach to solve this problem and stimulate terminodes to coopere is based on the introduction of a virtual currency, which we call nuglets, and mechanisms for charging/rewarding service usage/provision. We assume that the terminode hardware comes with an initial stock of nuglets, which have no

■ **Figure 6.** *An example of (a) network connectivity and (b) SPA connectivity for a network of 400 terminodes with a power range of 110 m and a node density of 400 terminodes/km².*

monetary value and can only be used within terminode networks. The natural idea is that terminodes must pay for a service to those terminodes that provided the service. This makes nuglets indispensable for using the network; thus, each (rational) user is interested in increasing her stock of nuglets. The exclusive way to achieve this is to provide services to the community. In the sequel we illustrate this idea on a specific example: charging/rewarding the packet forwarding service.

Packet forwarding can be paid by either the originator or the destination of the packet. We call the approach in which the originator pays the *packet purse model*. In this model, the service charge is distributed among the forwarding terminodes in the following way. When sending the packet, the originator loads it with a number of nuglets sufficient to reach the destination. Each forwarding terminode acquires some nuglets from the packet and thus increases the stock of its nuglets. The exact number of nuglets taken from the packet may depend on many things, including the cost of forwarding (in terms of battery power), the current battery status of the forwarding terminode, and its current number of nuglets. If a packet does not have enough nuglets to be forwarded, it is discarded. Figure 7 illustrates the packet purse model.

The main advantage of this model, besides stimulating cooperation among the terminodes, is that it may also deter users from sending useless data and overloading the network. The main disadvantage is that it might be difficult to estimate the number of nuglets required to reach a given destination.

This latter problem is overcome in the *packet trade model* where the destination pays for the packet forwarding. In this model the packet does not carry nuglets, but is traded for nuglets by forwarding terminodes. Each forwarding terminode "buys" it from the previous one for some nuglets,[2] and "sells" it to the next one (or to the destination) for more nuglets than it paid. In this way, each forwarding node increas-

[1] *We assume that users have full control over their terminodes: they can tamper with hardware and software, and modify behavior. We understand that regular users usually do not have the required level of knowledge and skills to do this. Criminal organizations, however, can have enough interest and resources to reverse engineer a terminode and sell tampered terminodes with modified behavior on a large scale.*

[2] *Except for the first forwarding terminode that receives the packet for free from the originator.*
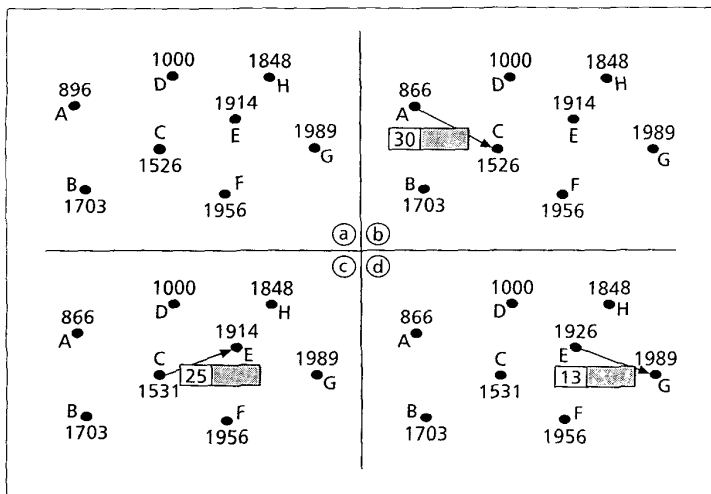
Figure 7. *In the packet purse model, the packet is loaded with nuglets by the originator. Forwarding terminodes take some nuglets out of the packet as a reward for the packet forwarding service they provide. In the figure, the numbers beside the terminodes represent their current stock of nuglets (a). When sending a packet to G, A loads 30 nuglets in it (b). Forwarding terminodes C and E then take 5 (c) and 12 (d) nuglets out of the packet, respectively.*

es its number of nuglets, and the total cost of forwarding a packet is covered by the destination of the packet.

Besides relieving the originator of estimating the number of nuglets that would be required to deliver a packet, another advantage of this model is that it is better suited for multicast communications. A disadvantage is that this approach does not deter users from flooding the network.

Clearly, the models described above must be secured and protected against various attacks. The basic problems to be solved are related to nuglet forgery, protection of the integrity of the packet purse (in the packet purse model), and the fair exchange of packets for nuglets (in the packet trade model). Protection may be based on the application of a tamper-resistant hardware module in each terminode, which can be used for the management of nuglets and cryptographic coding of messages [12]. The challenge is to find a trade-off between the robustness of the solution and its efficiency: forwarding a single packet should not require complex cryptographic protocols and heavy computational effort, because the cost of these may well exceed the value of the service.

In order to see the effects of the introduction of the charging models on the performance of the network, we conducted appropriate simulations. We compared the throughput of the geodesic packet forwarding algorithm described in an earlier section to the throughput the network achieves when this algorithm is extended with the packet purse model. We simulated two versions of the packet purse model: one in which each forwarding terminode acquires a constant number of nuglets, fixed by the originator, from the packet purse (PPM with fixed per-hop charges), and another in which the number of nuglets charged by the forwarding terminodes is determined hop by hop using auctioning princi-

ples (PPM with auctions). Figure 8 shows the results we obtained for various initial battery levels. As expected, the throughput decreases when the PPMs are used, since in this case packets can be dropped by forwarding terminodes due to the low value of the packet purse or the fixed per-hop charge. However, except for very low battery levels, the difference among the performance of the three algorithms is not significant (less than 5 percent). For further details on the simulations, the interested reader is referred to [13].

SECURITY

Security in networks (including wireless mobile ad hoc networks) is concerned with confidentiality and integrity of information, as well as legitimate use and availability of services. Although the security concerns remain the same, there are certain limitations in wireless mobile networks that are not typically found in fixed networks, and make security problems more complex:

- Mobile ad hoc networks do not have centralized monitoring and/or management points.
- Because of node mobility, the topology of the network changes dynamically; the nodes are often sporadically connected.
- The nodes communicate via wireless links, which can be eavesdropped easily.
- The nodes are often battery-powered; therefore, communication and computing costs should be reduced.
- Because of their physical characteristics, the nodes have limited computing power (certainly less than nonmobile devices).
- The nodes can be physically captured and compromised, unlike in fixed networks, where critical devices (e.g., routers) can be locked in "safe rooms."

A fundamental tool to achieve network security objectives is cryptography. Cryptography is indispensable to confidentiality and integrity protection of information, and also used in mechanisms that ensure legitimate use of services (e.g., authentication protocols). The challenge of using cryptography in a terminode network is management of cryptographic keys.

Since terminodes are mobile, their interactions are spontaneous and unpredictable, which makes public key cryptography more appropriate in this setting than conventional cryptography. The most widely accepted solution for the public key management problem is based on public key certificates issued by (offline) certification authorities and distributed via (online) certificate directories. Unfortunately, the application of certification authorities and certificate directories contradicts the self-organized[3] and self-operated features of a terminode network.

[3] *Note that in military networks self-organization is not required at this level. Indeed, these networks can rely on a hierarchically organized system of certification authorities, which are represented by headquarters at different levels. Self-organization of the network is required only on the battlefield, which does not effect the key management problem in such a radical way as it does in a terminode network.*

One possible approach to solving the key management problem may be based on the replacement of certification authorities with communities of users (a PGP-like solution [14]) and the distribution of the certificate directory function among the terminodes (a VHR-like solution). Another approach may be to adopt a system that implicitly guarantees the authenticity of public keys, such as identity-based systems [15] and those using implicitly certified keys [16]; however, this kind of solution still requires a trusted authority, at least at system initialization. We are investigating a way to provide public key cryptography in a totally self-organized manner.

CONCLUSION

We present a global description of some aspects of the Terminodes project. More specifically, it can be described at three levels of abstraction.

At the most concrete level, terminodes are a technical challenge in the general domain of mobile ad hoc networks. We present a global design of a terminode network. Self-organized routing, location management, GPS-less positioning, and nuglets are our main ingredients. The combination of a public environment with the absence of an operator poses a number of challenges; we have shown how our global design addresses them by focusing on self-organization. A remarkable feature of terminodes is the presence of nuglets: they are used as the basis for inciting users to cooperate, and as a congestion control mechanism for discovery and routing mechanisms. We have focused in this article on the most basic elements of a terminode infrastructure, mainly those related to the network layer, roughly speaking. There are many other important topics in the terminode project that we do not address in this article. One is the organization of software and components. Self-organization can be viewed as a form of competition, and a terminode component may become obsolete simply because more efficient ones exist which are more able to get the most utility out of the network. Thus, all of our components are modules that can be upgraded or completely modified as they become obsolete. Second, terminode applications are a way to continue the path opened up by Internet peer-to-peer computing applications such as Gnutella: network crawling, search for information resources, and highway traffic jam alerts are just a few examples. A key feature of all our design is self-organization. While this tends to make the design considerably more complex, we believe that the benefits in terms of robustness and ease of use have the potential to change the way in which we think of networks and information systems.

At the intermediate level, terminodes are an intellectual stimulus; in other words, they are a way to fuel creativity in order to identify new research challenges. An example of a question already generated is "How do we define a formal model for fair exchange?"

At the highest level of abstraction, terminodes are a societal/political vision, in which the ultimate aim of self-organized communication is considered. Indeed, we believe that long-term
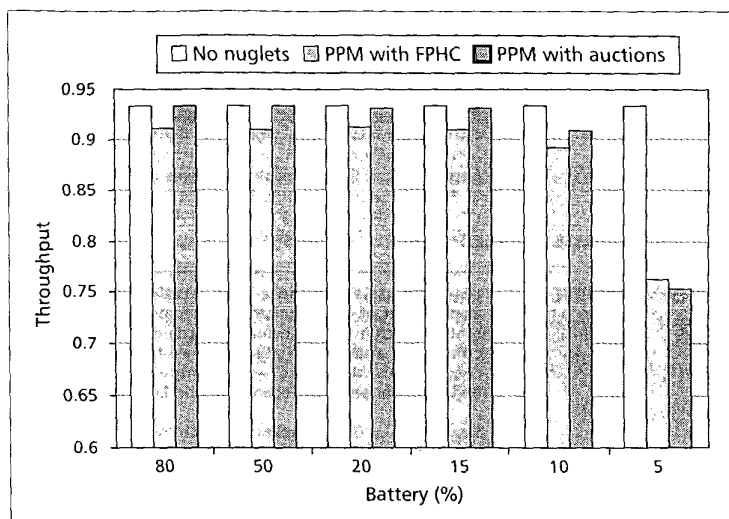

Figure 8. *The throughput of the network when the pure geodesic packet forwarding algorithm is used as well as when this algorithm is extended with the packet purse models (PPM with fixed per-hop charges and PPM with auctions). The results show that, except for very low battery levels, the throughput does not decrease significantly with the introduction of the PPMs.*

research should contain a dimension that goes beyond purely technical questions.

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At the highest level of abstraction, terminodes are a societal/political vision, in which the ultimate aim of self-organized communication is considered.

BIOGRAPHIES

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JEAN-PIERRE HUBAUX (jean-pierre.hubaux@epfl.ch) joined EPFL as an associate professor in 1990; he was promoted to full professor in 1996. He is co-founder and co-director of ICA. His current research is focused on mobile networking with a special interest in self-organized mobile ad hoc networks and therefore in "terminodes." At the beginning of his activity at EPFL, he defined the first curriculum in communication systems. In October 1999 he became thè first chair of the newly created Communication Systems Department. Before joining EPFL, he spent 10 years in France with Alcatel, where he was involved in R&D activities, mostly in the area of switching systems architecture and software.
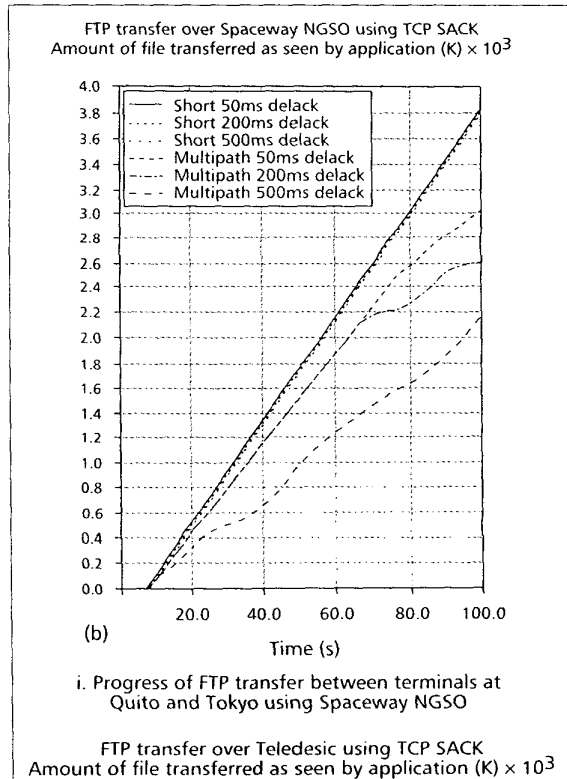
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ERRATA

In the article by Lloyd Wood *et al.* entitled "Effects on TCP of Routing Strategies in Satellite Constellations," which appeared in the March 2001 issue of *IEEE Communications Magazine* (pg. 172), portions of Figs. 3 and 5 were reproduced incorrectly. Those portions are reproduced here as they should have appeared.

(b) Time (h)

i. One-way propagation delay showing smooth satellite motion and abrupt handoffs
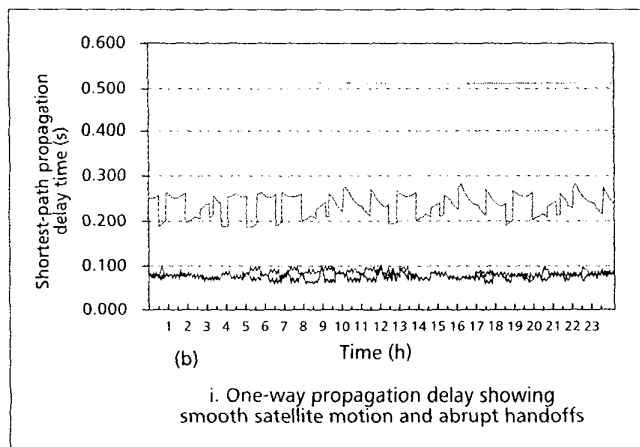
■ **Figure 3.** *One-way total propagation delays of path across the constellation over 24 hours: a) routing packets between ground terminals from Quito to London; b) routing packets between ground terminals from Quito to Tokyo.*

FTP transfer over Spaceway NGSO using TCP SACK
Amount of file transferred as seen by application (K) × 10³

- Short 50ms delack
- Short 200ms delack
- Short 500ms delack
- Multipath 50ms delack
- Multipath 200ms delack
- Multipath 500ms delack

(b) Time (s)

i. Progress of FTP transfer between terminals at Quito and Tokyo using Spaceway NGSO

FTP transfer over Teledesic using TCP SACK
Amount of file transferred as seen by application (K) × 10³

■ **Figure 5.** *Delayed acks degrading the rate of file transfer over multiple paths: a) transfers using New Reno TCP; b) transfers using SACK TCP.*