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***Abstract*—Handheld devices owned by nomadic people can form intermittently connected mobile ad hoc networks spontaneously. Such networks appear as an attractive solution for service providers, such as local authorities, in order to extend a pre-existing infrastructure-based network composed of several infostations so as to provide nomadic people with application services in a large scale area (e.g., a city). In such hybrid networks, intermittent connections are prevalent, and end-to-end paths between clients and providers cannot be maintained all the time. Service provisioning thus remains a challenging problem today in these networks. In this paper, we propose a new time-aware opportunistic routing protocol called TAO. TAO is designed for service invocation in intermittently connected hybrid networks. This protocol makes it possible to select the best next message forwarder(s) among a set of neighbor nodes based on the dates of contacts of these nodes with infostations, and tends to implicitly estimate the distance separating these mobile nodes and the infostations. This paper gives a detailed description of this protocol supported with some simulation results.**

***Keywords*-Service invocation; Opportunistic Networking; Disconnected Mobile Ad hoc Networks.**

I. Introduction

With the increasing proliferation of handheld devices equipped with a wireless interface, such as smart-phones or internet tablets, new kinds of applications, services or networks relying on spontaneous communication, interaction and collaboration can be considered. Such devices, which can form mobile ad hoc networks spontaneously, can be exploited in order to extend networks composed of some sparsely distributed infostations across a large area, (e.g., a city), and so to create hybrid networks in which infostations can act as service providers and mobile devices as service clients. This kind of networks, illustrated in Figure 1, is said hybrid because they are formed of a fixed part (the set of infostations connected together via a wired infrastructure) and a mobile part (the ad hoc network of mobiles nodes). Hybrid networks could appear as an opportunity for service providers, such as local authorities, to provide nomadic people with new ubiquitous services, without resorting to any expensive infrastructure, such as those provided by Global System for Mobile Communications (GSM) operator companies.

The fixed part of these hybrid networks can obviously present various topologies. For instance, the services can be provided by dedicated servers that can be accessed by the mobile devices through the infostations, which act as gateways. We focus in this paper on message routing in the mobile part of the hybrid network. Consequently, we will assume, without loss of generality, that a service is provided by an infostation, directly or via another infostation.

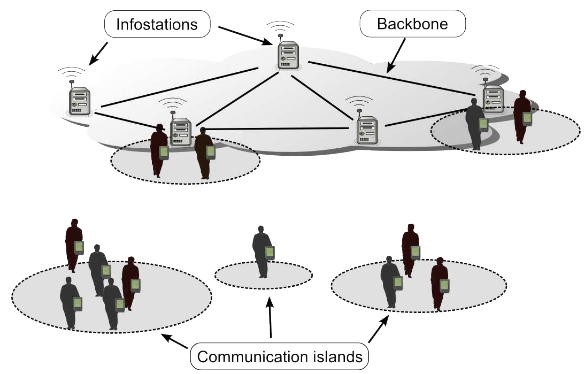

Figure 1. Example of an intermittently connected hybrid network.

Both the free movements of people and the short communication range of Wi-Fi wireless interfaces accompanied with the radio interferences induce some frequent and unpredictable disruptions in the communication links. These disruptions entail the creation of disconnected communication-islands formed near or far from the infostations embedded in the physical environment (see Figure 1). Moreover, the volatility of the devices, which are frequently switched off due to their limited power budget, increases the number of changes in the network topology. In these networks, which we will qualify as intermittently connected hybrid networks (ICHN), it is difficult, and most often even impossible, to maintain an end-to-end path between two devices thanks to traditional routing protocols designed for wired networks or thanks to dynamic routing protocols such as Ad hoc On Demand Distance Vector (AODV) or Optimized Link State Routing Protocol (OLSR).

To cope with these issues, routing protocols devised for networks that suffer from frequent and unpredictable disruptions, such as delay tolerant and opportunistic networks, implement the “store, carry and forward” general principle. When two devices cannot communicate directly because they are not in the transmission range of each other, these protocols make it possible to exploit other mobile nodes as intermediate relays that can carry a copy of a message when they move and forward it afterwards to other nodes so that it eventually reaches its destination. The provision of application services with this kind of opportunistic and asynchronous communications has been addressed so far only by a few number of research works [1], [2], [3], [4]. Mahéo and Said [1], and Conti and Kumar [3] focus on service provisioning in opportunistic networks composed solely of mobile nodes. In [1], the authors propose content-based service discovery and invocation solutions in order to exploit the redundancy of the services offered by the mobile devices that can move freely (i.e., no assumptions are made regarding the mobility of the devices). Conti and Kumar [3] target networks relying on social interactions between mobile nodes that act as both clients and providers of services. Due to the volatility and the limited resources of the mobile devices, the number of relevant services that can be offered by these devices are limited in comparison to those that could be offered in hybrid networks. Unlike [1] and [3], in Le Sommer et al. [2] the services are provided by fixed infostations in limited geographical areas. In [2], mobile devices and infostations are aware of their own location. Mobile devices can invoke remote infostations thanks to an opportunistic and location-aware forwarding protocol. In contrast with the environments we consider, in [2], the infostations were not connected together. We believe that the design of routing protocols suited for service discovery and service invocation in ICHN should take the specificity of ICHN into account, namely the interconnection of the infostations, in particular when defining heuristics or functions that allow to select among a set of neighbor nodes the node(s) that are considered as the best relay(s) to reach one of the infostations.

In this paper, we propose TAO, a new opportunistic and time-aware routing protocol devoted to service invocation in ICHN. TAO adopts a temporal heuristic to perform efficient message forwarding decisions. The basis of our approach is to take into account the disconnection dates between the fixed infostations and the mobile nodes. Assuming a homogeneous speed of the mobile nodes, a node implicitly estimates the distance from its neighbors to the target infostation and is able to select the best carriers among them. Our proposal applies to situations in which routing decisions cannot be taken according to geolocation information.

The rest of the paper is structured as follows. Section II describes protocol TAO, and Section III the evaluation of this protocol. Related works are discussed in Section IV. Section V presents our conclusions and gives some perspectives.

II. The TAO Protocol

TAO aims at supporting the invocation of software services in ICHN such as those formed by fixed infostations and portable devices used by nomadic people. The description of the discovery phase that should occurs before the invocation is not in the scope of this paper. The remainder of this section details how service invocation requests and responses are forwarded by TAO in an ICHN.

A. Assumptions

TAO relies on four main assumptions:

1) Mobile hosts are able to perceive their one-hop neighborhood.
2) Each mobile host is able to temporarily store the messages it receives, and can associate to each of them some pieces of information.
3) All the infostations are continuously running and are connected to each other using a backbone. An infostation is never out of order and can provide services itself, or can act as a proxy to another infostation.
4) The time synchronization between mobile devices does not need to be very accurate, given the low movement speed of the mobile devices, which are carried by pedestrians. We can legitimately consider that TAO can tolerate a clock-shift on the order of half a minute.

B. Overview of TAO

TAO implements the ”store, carry and forward” principle, a multiple-copy message forwarding algorithm, source routing mechanisms and a time-stamping-based heuristic that aims at selecting the best next message forwarder(s) among a set of neighbor nodes. This heuristic relies on lists of last dates of contact of a node with its neighbors. Mobile nodes are expected to use these lists when they are solicited by a neighbor node that wants to forward a message to an infostation or to a given mobile node, and to return to this node their last date of contact with an infostation. These pieces of information are then processed by the mobile node that must forward the message in order to select the best next forwarder(s) to deliver the message to an infostation. Such an algorithm tends to reduce progressively the area where the messages are disseminated until reaching their destination (i.e., a fixed infostation). Indeed, from a logical point of view, a node will disconnect from an infostation when it starts moving away from it, and the distance separating them is increasing progressively.

In order to improve the service delivery and to avoid the bad carrier dilemma (i.e., delivering the message to a mobile node abruptly moving in the wrong way), TAO implements a multiple-copy message forwarding algorithm. The source node is first expected to forward a copy of this message to its best neighbors. Later these carriers, and the source node, will forward a copy of this message only when they encounter a *better carrier* than themselves, while a limited number of copies will be forwarded toward *bad carriers*. A neighbor will be considered as a *good* carrier by a node if the last date of contact of this neighbor with an infostation is more recent than its own date of contact, or if this neighbor is a new neighbor and its last date of contact with an infostation is more recent than those of the other neighbors. This classification aims at estimating the ability of these intermediate nodes to deliver the message to an infostation. Furthermore, sometimes it might be critical to forward copies exclusively to good carriers, especially if the source node is located remotely from an infostation. In this case, the major number of neighbors might be classified as bad carriers, while the contact with a good carrier is uncertain. Thus in TAO, each mobile node has a stock of a few number of copies dedicated to bad neighbors. This number of copies is limited in order to avoid network overload and resource consumption on mobile devices. Finally, TAO makes it possible to control the propagation of messages in the network using two parameters: a lifetime and a number of hops. When the lifetime is expired or when the number of hops is zero, the message is removed from the local cache and will not be forwarded anymore.

Unlike Prophet [5], PropicMan [6] or HiBOp [7], TAO needs neither to record any large set of history values nor to use complex algorithms to select the next message carriers. In TAO, each node maintains 3 kinds of lists: a neighbor list, a list of last local contacts with infostations and a list of the last remote contacts with the infostations. These 3 lists will be referred to as NL, LLCI and LRCI respectively in the remainder of this section. NL contains the one-hop neighbors of the node and the date of reception of their last beacon. This set is obtained thanks to a background beaconing performed periodically by each node. Furthermore, mobile nodes or infostations are considered disconnected from the neighborhood of a mobile node if no beacons have been received from them during a time gap superior to an already define disconnection time threshold.

The LLCI list contains a limited number of entries (on the order of the number of two-hop neighbors). Each entry includes the IDs of the infostations the node has encountered and the time of the last beacon it received from these infostations. The LRCI list is similar to the LLCI list, but it is related to the neighbor nodes found in the NL list. Each entry of the LRCI represents the ID of the most recent infostation each neighbor had contact with and the value of the last contact date.When a new neighbor joins the one-hop neighborhood of the node it will directly send the ID and the most recent time of contact with an infostation to be registered in the LRCI.

TAO is a reactive and an event-driven protocol. Five events are considered in TAO:

1) The emission of an invocation request by a local client application.
2) The reception of an invocation request sent by a neighbor node.
3) The reception of a service response sent by a neighbor node.
4) The arrival of a new neighbor node.
5) The disappearance of a neighbor node.

C. Forwarding of service invocation requests

When a node receives an invocation request from a local application for a service provided by a remote infostation (event 1), or when it receives such a request from one of its neighbors (event 2), the node will process this request according to the forwarding Algorithm 1. On each message reception, a mobile node will forward a copy of this message to E_{emit} direct neighbors at the most. In this algorithm, the good carriers will always obtain a copy of the message. The

Algorithm 1 Emission or forwarding of an invocation request.

emission or forwarding of a Service Invocation Message :
 if *it exists an infostation in the one-hop neighborhood* ***then***
   forward request to the infostation
   remove the Service Invocation Message from the cache
 else
   check *LRCI list for good carriers*
   for *number of emissions is less than* E_{emit}
      if *good carriers are found* ***then***
         forward a copy of the Service Invocation Message
         Update the best contact time with an infostation relative to this invocation message
      else
         if *local stock related to this Service Invocation Message > 0*
            forward a copy of the Service Invocation Message
            decrement the stock
         endif
      endif
   endfor
 endif

infostation contact time of the best carrier of each invocation request will be recorded in the lists of the local node in order to be compared later with those of the new nodes that appear in the neighborhood of the current carrier. A copy of each invocation request will only be forwarded toward a new neighbor if its infostation contact time is more recent than the locally recorded value. As a result, this process prevents from forwarding multiple copies to the same node. On the other hand, bad carriers will receive a copy from the stock of copies dedicated to them only when the number of good carriers is less than E_{emit} in the neighborhood of the carrier node. The stock will be decremented, and when this stock is empty no more copies of the message will be forwarded to the bad carriers.

In order to select the best next carriers among its neighbors, the local host checks the content of the LRCI list and chooses the nodes with the most recent infostation contact time. Service invocation messages will be stored, carried and forwarded by intermediate carriers in the same manner.

When a node discovers that it exists in its one-hop neighborhood an infostation, it forwards to this infostation all the service invocation requests it has in its cache and that are still valid, and removes them from its cache of messages. This infostation is expected to either deliver the service itself or forward the request to the appropriate infostations.

Any invocation request copy will stay alive until its lifetime expires or its number of hops is zero. Moreover, each message will store in its header the route it followed to reach the infostation.

D. Forwarding of service responses

The next event is the reception of the reply from the infostation toward the client node. The infostation will send the reply message with a reverse routing, in other words, send the message back on the route it has just traversed. Reverse source routing can be reliable if the mobility of the nodes in the network is relatively slow. In fact, TAO is designed to function in ICHN, where mobile nodes are volatile and end-to-end paths between nodes cannot be maintained all the time.

As a result, a forwarding mechanism must be applied when the reverse source routing fails at some point (i.e., a disconnection in the route is encountered).

Algorithm 2 Management of the forwarding mechanism of the service response.

emission of a Service Response Message
if *the original-service-requester is connected* ***then***
forward the Service Response Message to the original-service-requester
remove the Service Response Message from cache
else
if *next id recorded in header is connected (reverse source routing)* ***then***
forward the Service Response Message
else
scan NL list for a node of id recorded in the header
if *id found in the neighborhood* ***then***
forward a copy of Service Response Message
remove the id of the node from the header of the message registered in the cache
endif
endif
endif

When such a disconnection occurs, the node carrying the message will perform a multiple-copy message forwarding algorithm dedicated to the service responses (Algorithm 2). A copy of the service response will be forwarded to the best neighbors (setting higher priority to the nodes closer to the destination). Thus, all of the new carriers will try to resume the source routing process. If they cannot resume this process, they forward a copy of the message when they encounter a better carrier than themselves.

E. Management of neighborhood changes

Algorithm 3 Management of the service messages after the contact with a new neighbor.

forwarding service messages toward the newly arriving neighbor:
if *event is arrival* ***then***
if *the new neighbor is a good carrier or size of stock > 0* ***then***
foreach *valid request in the local cache* ***do***
forward the request to the new neighbor
endforeach
if *the size of the sock > 0* ***then***
decrement the stock
endif
endif
foreach *valid response in the local cache* ***do***
run algorithm 2
endforeach
endif

The last two above-mentioned events are triggered when changes occur in the one-hop neighborhood of a node. When a new neighbor joins the one-hop neighborhood of another node, the LLCI and LRCI lists are updated using the pieces of information obtained from the beaconing process. Then, the current carrier is expected to check if it exists in its local cache some messages (requests or responses) that should be delivered. If so, it conditionally forwards copies of these messages to its new neighbor using Algorithm 3. If the new neighbor has a date of contact with an infostation that is more recent than those of the other neighbors of the current carrier, this one will forward to this new neighbor all the service invocation requests it has and that are still valid. The service responses stored locally will be forwarded by the current carrier to this new neighbor only if this one is the destination or has been used as intermediate node to forward the request (i.e., if this one appears in the reverse source path header of the response).

Algorithm 4 Management of the disappearance of a neighbor to the mobile node.

disappearance of a neighbor:
if *event is disappearance* ***then***
if *the node is an infostation* ***then***
update the LLCI list with the time and the id values of the infostation included in set NL
endif
if *the node is a mobile node* ***then***
update the LRCI by eliminating the id and time values of the respective disconnecting neighbor
endif
endif

As Algorithm 4 shows, when a node is notified of the disappearance of an infostation from its one-hop neighborhood (i.e., from the neighbor set NL), it updates its LLCI list with the ID and the date of the last beacon of the infostation, that has been removed from the neighbor set. Otherwise, if the disconnected neighbor is a mobile node, all the related information will be removed from the NL and LRCI lists.

III. SIMULATION

In this section, we present the simulation results we obtained for TAO regarding the service delivery performances in comparison with a simple routing protocol RANDOM. The RANDOM routing protocol has the same characteristics as TAO, but instead of relying on the time heuristic implemented in TAO, RANDOM relies on a random mechanism in choosing the next carriers of the service invocation messages. The main objective of these simulations is not to compare the global performance of TAO with other protocols such as [7], [8] and [9], but instead to assess the effectiveness of the time heuristic in delivering messages between a mobile node and a fixed infostation. The simulations have been performed on the OMNeT++ network simulator. In these simulations, we focus on a simple, but realistic, hybrid network composed of only one infostation providing a service and a set of mobile devices carried by pedestrians. A part of these pedestrians act as clients, forming a set of nodes that request services from the infostation.

A. Setup

The simulation environment we consider is a square open area of 1 km^2. The infostation is located in the middle of this area. All mobile nodes move according to a random waypoint mobility model with a speed of 0.5 m/s. The communication range of the mobile devices and of the infostation is approximately 30 m. After discovering the service they are looking for, the mobile clients invoke this service every 3 minutes. In our experiments, we have not assigned any lifetime or maximum number of hops to any message for both protocols.

We ran the simulations for each routing protocol, varying the number of nodes forming the network. For each setup, we made 10 simulation runs with a different random seed. A *warm up* period of 10 minutes is used in the beginning of the simulations before clients start to generate invocation request messages, to allow LLCI, LRCI and NL lists to be initialized. The simulation is run for another 1 hour before stopping all the invocation requests from all the clients. Finally, the simulation is left for 10 minutes to allow all the messages to be delivered.

We present below the obtained results. The objectives of these experiments was to measure the ability to satisfy the client service delivery with a small number of message copies, where we have fixed the number of copies (size of the stock) to 3 copies for both protocols and the maximum number of emissions E_{emit} to 3.

B. Results

Each of the following graphs contain curves for both TAO and the RANDOM routing protocols, while changing both the number of clients and the number of mobile nodes forming the network. The two metrics we are studying are the satisfaction ratio and the delay. The satisfaction ratio is the percentage of successful service invocation (i.e., the number of invocations for which a client node receives their response from an infostation), while the delay is the total time needed by a successful invocation message to travel from the client node toward an infostation and on the way back toward the same client node.

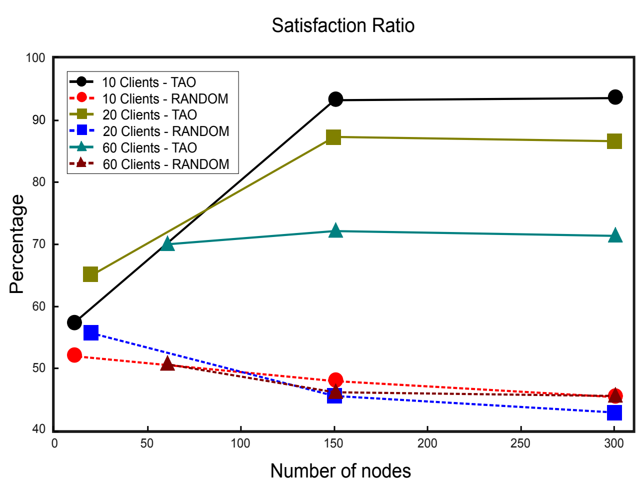

Figure 2. Satisfaction ratios of TAO and RANDOM Routing Protocols

First, we analyze the satisfaction ratio of each of the protocols in order to study the impact of increasing the number of nodes forming the network on the performance of each protocol. Three scenarios for each protocol are presented in Figure 2, where each scenario is characterized by the number of clients found in the network. As we notice, when having few nodes in the network, the satisfaction ratio of both protocols is almost the same. This observation is coherent with what is expected, because, due to the limited number of neighbors, TAO and RANDOM will select most of the time the same carriers. The performance of TAO increases with the number of nodes forming the network due to the selection of good carriers among a large set of neighbors. On the contrary, the performance of RANDOM decreases due to the bad selection of next carriers.

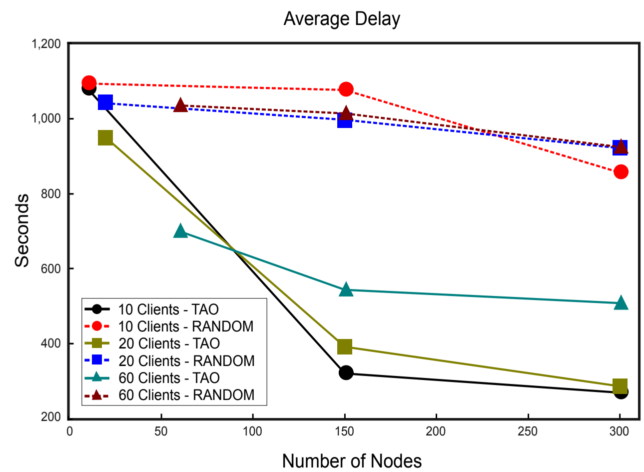

Figure 3. Delay of TAO and RANDOM Routing Protocols

Based on (Figure 3), we notice that when the network is formed of a few number of nodes, the delay values are relatively high. This is totally normal, since few nodes with limited transmission range and random waypoint mobility have to cover a large area. When the number of mobile nodes increases in the network, the average delay of RANDOM remains relatively high due to the random choices of carriers that contribute in transmitting the invocation messages toward the infostations. On the contrary, the average delay of TAO decreases due to the presence of more carriers that can fill the gap between the client and the infostation and the ability of TAO in choosing good carriers to perform this operation. As a result, the mechanism used by TAO to choose among the carriers of service invocation messages results in shorter delays and higher delivery ratio than what RANDOM can offer.

Finally, the application we utilized in these primary simulations was simply a mobile node invoking an infostation and waiting for the response back. This was done to study the effect of the time heuristic implemented in TAO. Since the number of hops and the lifetime message parameters are directly related to the application and the expected delays in the targeted network, we did not specify any limits over these two parameters. So, the number of messages that are disseminated in the network increases continuously. That's why we do not give in this paper details about the network load and the efficiency of TAO regarding this point precisely. Nevertheless, the measurements we conducted show that the number of messages disseminated by TAO and RANDOM is approximately the same.

IV. Related Work

TAO combines the originality of being designed to support service invocation and to specifically target hybrid intermittently connected MANETs. Indeed, most of the research work concerning intermittently connected MANETs consider networks solely formed of mobile devices and multi-purpose communication. However TAO uses the "store, carry and forward" principle and several techniques that are shared with many protocols in delay-tolerant and opportunistic networking. In the remainder of this section, we present some representative routing protocols.

The Message Ferrying paradigm is a mobility-assisted approach [8]. It introduces non-randomness to the node mobility and exploits it to provide physical connectivity among nodes. Two variations are introduced both with movement constraints. The first is targeting the message ferries, which are special nodes introduced as data carriers toward specific positions to collect data. The second forces the clients to move toward the ferries in order to send and receive messages. Although this approach ensures reliability, it introduces a lot of constraints on the mobility of clients, which is considered disturbing and impractical in real life.

The constraint of intervening with clients' mobility was addressed by other protocols that aimed to benefit from the natural uncontrolled movements of nodes. The most general attempt is the flooding-based routing protocols such as Epidemic Routing [9]. In such types of protocols, messages are flooded in the network and stored by all available neighbor nodes. No precautions are considered to limit the number of messages exchanged and forwarded. Therefore, network congestion is very likely to happen, especially in high density regions.

Some approaches resort to probabilistic solutions [5], [6] and prediction techniques [10] to choose the best relay nodes for each specific message. For routing, these protocols rely on the context and history information in order to compute delivery probabilities and predictabilities. A history-based approach such as the one described in [7] relies on an algorithm to predict the future movements and patterns of the node and route packets according to these predictions. Such algorithms can achieve high efficiency and delivery ratio, but the major drawback is assuming that a node is able to register a large amount of contact history in its buffers, taking into consideration that the majority of the devices forming such networks are small portable devices with limited capabilities and capacities. Moreover, computing histories and predicting movement patterns is a tricky problem, especially in environments composed of numerous mobile devices that move following irregular patterns, such as those held by pedestrians in a city. On the contrary, TAO simply utilizes recent history to predict near future. TAO tends to estimate the distance separating the nodes and the infostations in the network, relying on the disconnection times recorded locally by the mobile nodes. By this approach we aim to reduce the complexity and the resources needed to take correct routing decisions.

V. Conclusion

Intermittently connected hybrid networks is a quiet original perspective that can be exploited to provide nomadic people with a wide access to pervasive services, eliminating the need for any expensive infrastructures, such as those provided by GSM operators.

In this paper, we have proposed a new simple time-aware opportunistic routing protocol, called TAO, devoted to service invocation in ICHN. TAO implements a multiple-copy message forwarding algorithm, source routing mechanisms, and a time-stamping-based heuristic that aims at selecting the best next message forwarder(s) among a set of neighbor nodes.

TAO is a recent work, and its evaluation through real conditions is still in progress. TAO will shortly be included in a service-oriented middleware platform. Furthermore, in the future, we would like to improve the service delivery process by implementing a handover mechanism in the infostations, thus allowing to provide nomadic people with a continuous access to a given service. Then, a service will be delivered all the time to the client by the best infostation, which will be, the most of the time, the nearest infostation.

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