Delay/Disruption Tolerant Networks Based Message Forwarding Algorithm for Rural Internet Connectivity Applications

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***Abstract*—Rural networking connectivity is a very dynamic and attractive research field. Nowadays big IT companies like Google and Facebook are working to help connect all these rural disconnected people to Internet. Our research work is another effort in this direction. We are building a new solution based on previously tested ideas that can bring no real-time Internet connectivity to rural users using Delay/Disruption Tolerant Networking technologies. The advantage of our solution is that it is a low cost technology that uses locally available infrastructure to reach even the most remote towns. This paper introduces the problem, the current and previous efforts to solve it, and describes our solution, mathematically and algorithmically. Simulation results show that our algorithm delivers more messages than two of the most known DTN routing protocols for this rural connectivity scenario.**

***Index Terms*—Disruption-Tolerant; Delay-Tolerant; Delivery probability; Opportunistic forwarding; Rural telecommunications**

I. Introduction

The United Nations declared Internet as a human right in 2011 [1]; however, around 60% of the world population [2], especially in rural and underdeveloped regions does not have any Internet access. Access to Internet can improve life quality through access to more information, education and applications that will ease the life of citizens in remote areas [1]. Getting access to Internet to these communities is not an easy task. There are many technical and social challenges, such as a reliable supply of electricity, access to electronic devices, network coverage and training, that have to be overcome before a solution can be given.

Delay/Disruption Tolerant Networking (DTN) is a technology that was initially developed for spatial communications [3] [4] [5] but it has been used for earth-based communications like remote or isolated areas connectivity [6]. DTN enabled devices could help people in rural and remote regions to connect to Internet by relaying petitions and replies between nodes and mechanical transportation means, using local infrastructure like the public transportation. In this paper we are proposing a DTN-based solution for non-real-time Internet connectivity for rural communities around the world. Our solution needs little infrastructure and it can use the existing infrastructure in the towns like the town hall or the hospital or any building with constant or regular electricity supply. This solution implies asymmetric traffic, that is, small requests and bigger replies. Also, it assumes that users can wait for hours or days before getting an answer. We propose a mathematical model and a distributed forwarding algorithm for moving requests from users devices (user nodes) to Internet Connected Servers (ICs) and for getting their replies from these servers. Our architecture is built over the ideas of the DTN Architecture [4], the DTN Bundle [5] and Daknet [6]; however, these ideas are adapted for our specific scenario.

Our solution needs an Access Point (AP) to be installed at a place with constant or regular electricity supply (it could be the health-care building, the city town hall or the transportation enterprise building). The AP is responsible for receiving users requests and servers replies. The AP will automatically communicate with users devices when they are in range. Thus, users need to have a DTN platform on their devices (user nodes) that allows them to create requests to be sent to the towns AP and be able to wait for their replies. User nodes can send their requests directly to the towns AP or they can send them through other user nodes. Then, user nodes serve as relays to convey messages from other user nodes to the towns AP and viceversa. User nodes are DTN-enabled nodes, generating requests, waiting for replies and transporting other user nodes requests and replies. The other part of the solution involves sending messages from towns APs to Internet Connected Servers (IC). These ICs should be located in bigger towns where there should be a constant or regular Internet connectivity. ICs are responsible to retrieve users requested information from Internet Servers. ICs and APs are interconnected through mobile APs (MAP). MAPs are DTN-enabled nodes that will be installed on vehicles that periodically or eventually will visit those rural towns where APs are installed, and bigger towns with ICs installed. We propose, as in Daknet [6], to use the public transportation infrastructure, like buses, canoes or planes (for really isolated towns) that will visit the towns and cities, to carry our MAPs. MAPs will be installed on these vehicles and when they reach a town or a city, MAPs will communicate with the local APs or

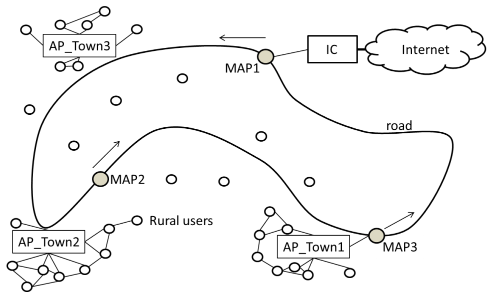

Fig. 1. Proposed solution scheme

ICs and they will exchange requests and replies. Some requests may not have their reply as fast as others, thus, the system needs global IDs that will enable any MAP to transport any request and any reply. These IDs are hierarchical Uniform Resource Identifiers (URI) taken from [4] with geographical information to locate where the reply has to be directed to. Figure 1 shows a general scheme of the proposed solution.

Our research work is focused on message transport, the layer 3 routing. Our algorithm works in two-phases, one from user nodes to towns APs and viceversa, and the other one from towns APs to ICs through MAPs and viceversa. In the first phase, user nodes will create communities and will learn which user nodes are more likely to reach the AP and deliver the messages. We will be working with the nodes delivery probabilities in this phase. Messages will have a time to live field that will prevent messages to keep going around in the network after a while. Messages can also be duplicated so they increase their delivery probability. In this phase, we expect the network to be very sparse and users to have more neighbors as they are closer to the AP. In the second phase, APs will wait until a MAP is in contact (within communication range) to deliver requests and receive replies. MAPs will only deliver the replies to the corresponding AP. MAPs can deliver requests to any IC, and pick replies from any other IC that covers the region they transit. There is also a third phase in our architecture, the one that communicates ICs with Internet Servers hosting the users requested information. This phase is based on traditional Internet protocols and we will rely on them.

Section 2 summarizes some of the current, previous and related works in this area. Section 3 presents our solution, the mathematical model that describes it and the algorithm for every DTN node in the network. Simulation parameters and results are shown in Section 4. Finally, conclusions and future work are given at the end of the paper.

II. Previous Works

In order to build a new protocol for DTNs in rural networking scenarios, it is necessary to review the basis for this technology and some current proposals for rural networking besides DTNs. The usual way to connect more people to Internet has been the networking infrastructure expansion promoted by national states, mainly, mobile cellular networks and satellital links. Both of these initiatives help connect more people, but they do so at a slow pace and at high costs, since getting infrastructure to remote and low-populated towns is not economic efficient and it usually has to be subsidized by the states or imposed to the carriers as a condition for them to be able to cover more economically attractive regions. Satellital links remain expensive, although they require little infrastructure (just an antenna and networking equipment), it is difficult for people in developing countries to afford the usual fees for this kind of service.

In this panorama and considering around a 60% of the world's population is in rural, developing countries and disconnected from Internet [2], many initiatives have emerged in the last years to connect them all. Two of the most known of these initiatives come from Facebook [13] and Google [12]. Facebook promotes its Internet.org initiative, an unlimited access to a restricted version of Internet. Facebook associates with local mobile carriers and national governments to offer its fee-free, unlimited access to a pool of services and websites such as facebook.com, weather, health, and employment information and news, among others. Internet.org uses mobile carriers infrastructure to transport data between users and the Internet.org services. Internet.org users, then, need to have a SIM card of the specific associated carrier for them to be able to access these services for free in regions where the mobile carrier has coverage. The other big initiative to connect all these rural population to Internet is being developed and deployed by Google. Google's Loon Project [12] is a mesh network of aerostatic balloons with earth based stations and satellital links. It allows users with special antennas to connect with the balloons circling the earth at different heights using atmospheric wind currents. The balloons will then transmit the users' requests using the mesh network between them to an earth-based base station where them would be transmitted to Internet via a satellital link. Once the answer is obtained, it would travel the same path in the other direction, using the balloon mesh network until it reaches the desired user. Google's Loon Project is a broadband, medium delay (around 2 secs) network. It is still in its testing state.

Another initiative that has been developed and deployed in the last decade is Delay/Disruption Tolerant Networking (DTN) for rural connectivity. Although DTN were developed for spatial communications, one of their current applications is rural networking. The DTN Architecture [4] describes a different kind of network, one with high delays, asymmetric traffic and no guarantees. Over this framework, it appears the Bundle Protocol [5], a new communications protocol that provides some services like reliable message delivery over the unreliable, unguaranteed DTN Architecture. The Bundle Protocol specifies a store-and-forward kind of communication between DTN nodes, passing the responsibility for delivery (custody) between them. When two nodes meet (a contact), they can exchange messages (bundles) and they will provide acknowledgements and reliability for communications between them, but they cannot guarantee if or when these bundles will be delivered to their final destination. In order

TABLE I
DTN ROUTING PROTOCOLS CLASSIFICATION

Category	Main Protocols
Replication	Epidemic [7], Spray and Wait [8]
Social	BubbleRap [9], SimBet [10]
Probabilistic	PROPHET [11]

to decide what to do with the bundles, several routing and forwarding protocols have been developed in the lasts years. The most used routing protocols for opportunistic networks like DTNs are replication ones. In this classification, Epidemic [7] and Spray and Wait [8] routing protocols are the most known. They create multiple copies of the message until it reaches its destination (Epidemic) or they create some copies and then try to deliver at least one of these copies to the destination (Spray and Wait). Other routing protocols classification used in DTNs are social based ones. They try to exploit social features of the network to make routing decisions. They can use nodes' contact history, centrality or popularity, and they can create clusters or choose next hops for communications based on these information. BubbleRap [9] and SimBet [10] are examples of social routing protocols for opportunistic networks. Finally, there are probabilistic routing protocols. They assign probabilities to nodes in their neighborhood and update them over time. The most known protocol in this classification is PROPHET [11]. PROPHET assigns a probability of delivery to every node it meets, and then it updates this probability, diminishing it, when some customizable time passes without a contact with that node. It also manages transitivity, this means that a node can deliver a message to another node via a relay node, the probability of delivery will be the probability to reach the relay node times the probability of the relay node to reach the destination. PROPHET is the most used protocol for DTN applications. Table 1 summarizes the most known DTN routing protocols by category.

For rural networking connectivity, there is already a successful DTN application being used, Daknet [6]. Daknet uses local transportation infrastructure to transport messages from users in remote towns, through local hubs and buses, until they reach a bigger town with Internet access. There, users requests can be delivered and their replies retrieved. Users can access a local hotspot in their disconnected towns, to make online (no real-time) purchases, and they receive their requested goods after a while via the same buses that transport the messages. Daknet uses PROPHET as its routing protocol and the e-commerce application just described is the main use for its network in India.

III. DTN-BASED RURAL INTERNET CONNECTIVITY

We are presenting a rural networking connectivity scenario, where communication requests will be originated from nodes in a usually disconnected rural area to other nodes or towards Internet servers. The originating rural nodes make a mobile, sparsely distributed network. They will communicate with each other and they will serve as relays to deliver messages to a static, always-on node in the nearest town, the Access Point (AP). The AP can store users' requests until a Mobile Access Point (MAP) can come to the town and retrieve them. The MAP will store the requests from the small, disconnected towns it visits and it will deliver them at the drop point, an Internet Connected Node (IC) in a bigger, connected town. The IC is the connection between the DTN for rural users and the usual Internet. The IC can deliver the rural users messages to the respective Internet Servers and retrieve the replies if they are expected. All users' replies will be stored in the IC until a MAP comes by and collects the replies for the users in any of the towns in its route. See Figure 1, for a general scheme of the proposed architecture. DTN nodes representing rural users are expected to get more sparsely distributed as they drew farther away from town's AP. They can use each other to convey requests to the AP and to deliver replies from Internet to the final user.

A. Mathematical Model

This paper introduces a new bidirectional, multiobjective, non-linear mathematical model for a DTN in a rural networking connectivity scenario. This model is extended from our previous model in [14]. The mathematical model maximizes the delivery probabilities over the paths that may exist through time and at the same time it tries to minimize the delivery time for each message. This model optimizes through time the routing of messages based on the availability of each node in a possible path at different moments. So, a path from a source node to a destination may not exist on a single moment but over various lapses. The model will try to deliver all messages to their destinations, restricted to the links and buffers capacities and nodes availabilities given by their movement. See Figure 2 for a graphical representation of the mathematical abstraction. The mathematical model is presented in equations (1) to (7).

The mathematical model assumes that there a set of rural nodes (N), with intermittent connections (E) between some of them and between a subset of them and the local AP. These connections are modeled through the time dependant availability probabilities ($a_{ij}(t)$). If the availability probability at any give time for a couple of nodes is bigger than zero, a path can be formed using them. The set P represents the possible paths that can exist in the network through time. Delivery probabilities ($d_{ij}(t)$) are calculated using availability probabilities of nodes to the destination. Nodes and links have capacities that should be respected. We assume that these capacities do not change over time, then, parameters c_{ij} and c_{ii} represent the link capacity from node i to node j and the node i capacity to store messages through time, respectively. Parameter $b_i(t)$ is a time based vector with demands and supplies for node i through time. All b vectors are grouped together in matrix B, representing the desired flow of information for the system. The model uses discrete times T. Each of them represent a moment lasting long enough for a node to reliably transfer a message to a neighbor. The lasting of each time interval is modeled through the parameter

TABLE II
MATHEMATICAL MODEL PARAMETERS AND VARIABLES

Var./Param.	Definition
N	Set of nodes, $i \in N$
E	Set of links, $(i, j) \in E$
P	Set of paths, $(i, j) \in P$, $a_{ij}(t) > 0$
T	Set of discrete time intervals
B	Matrix of information demands and supplies, $b_i(t) \in B$
$a_{ij}(t)$	Availability Probability of $(i, j) \in E$ at time t
$d_{ij}(t)$	Delivery Probability of node i through node j at time t
c_{ij}	Capacity of link $(i, j) \in E$
c_{ii}	Storage capacity of node i
t	discrete time interval, $t \in T$
δ_t	Time interval duration
$x_{ij}(t)$	Data flow through link $(i, j) \in E$ at time t

δ_t. Forwarding decisions are made based on the availability of the link, the size and the delivery time of the message. These decisions are represented by the positive integer variable $x_{ij}(t)$, which gives how much information should flow over a link at any given time. Table 2 summarizes all the model's parameters and variables.

Objective Functions

$$\max \prod_{(i,j)\in P} d_{ij}(t)x_{ij}(t) \tag{1}$$

$$\min \sum_{t\in T} \delta_t \tag{2}$$

Constraints

$$\sum_{j\in N} x_{ij}(t) - \sum_{j\in N} x_{ji}(t) + x_{ii}(t) - x_{ii}(t-1) = b_i(t) \quad \forall (i,j) \in E, i \neq j, t \geq 1 \tag{3}$$

$$\sum_{j\in N} x_{ij}(t) - \sum_{j\in N} x_{ji}(t) + x_{ii}(t) = b_i(t) \quad \forall (i,j) \in E, i \neq j, t = 0 \tag{4}$$

$$x_{ij}(t) + x_{ji}(t) \leq c_{ij}\delta_t \qquad \forall (i,j) \in E, i \neq j \tag{5}$$

$$x_{ii}(t) \leq c_{ii} \qquad \forall i \in N \tag{6}$$

$$x_{ij}(t) \in \mathbb{Z}_{\geq 0} \qquad \forall (i,j) \in E, p \in P, t \in T \tag{7}$$

Equations (1) and (2) represent the objective functions intended to maximize the delivery probability of messages over all paths through time and to minimize the time taken to deliver all messages. Equations (3) to (7) state the mathematical model constraints. Equations (3) and (4) are data flow constraints, requiring all messages to be delivered to their destinations. Equations (5) and (6) are capacity constraints, requiring all transmission to be in the limits of buffers and links capacities. Finally, equation (7) states that the decision variable is a positive integer variable defined over all available paths through time and representing the data flow over an edge for a time interval.

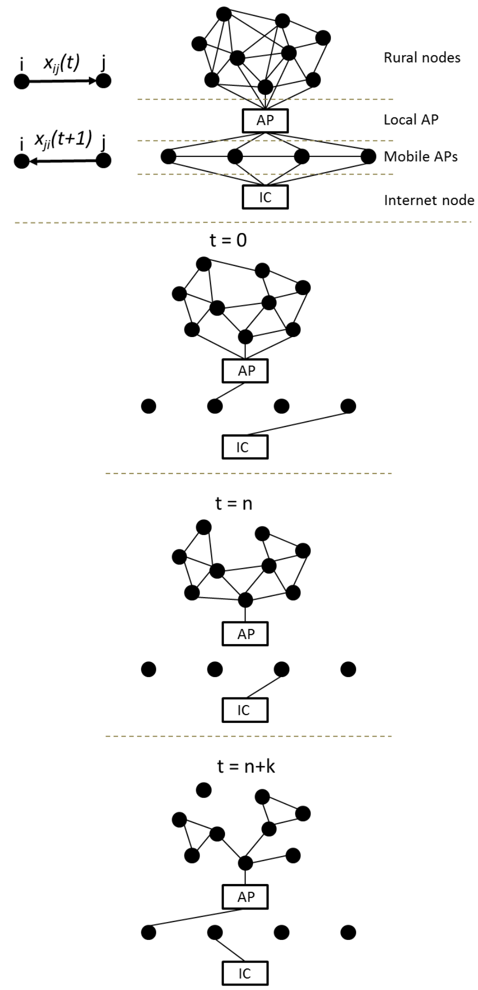

Fig. 2. Mathematical abstraction of the proposed solution.

B. Distributed Forwarding Algorithm

Every DTN node in the rural networking connectivity scenario, shown in figure 2, should use a distributed routing algorithm to deliver all its messages to their destination. Our algorithm takes into account that every node has limited and local information. A node only knows where it is based on a general location abstraction given by the URIs described in the DTN Architecture [4] and based on this general location it can direct its requests to the nearest AP, its gateway. Each node must create two tables that it should save to a non volatile memory. One table is for saving the name, address, availability probability, last contact time, average time between contacts and centrality of every node it meets (neighbors' table). The centrality is a measure of how many nodes a neighbor has met and it can be used to make forwarding decisions. Nodes with better centrality metrics will be preferred to send messages when no delivery probability is known. Delivery probabilities (d) are calculated from nodes that have a path to the destination. They can give a delivery probability based on previous contacts with the destination, and neighboring nodes of these nodes can have a delivery probability through

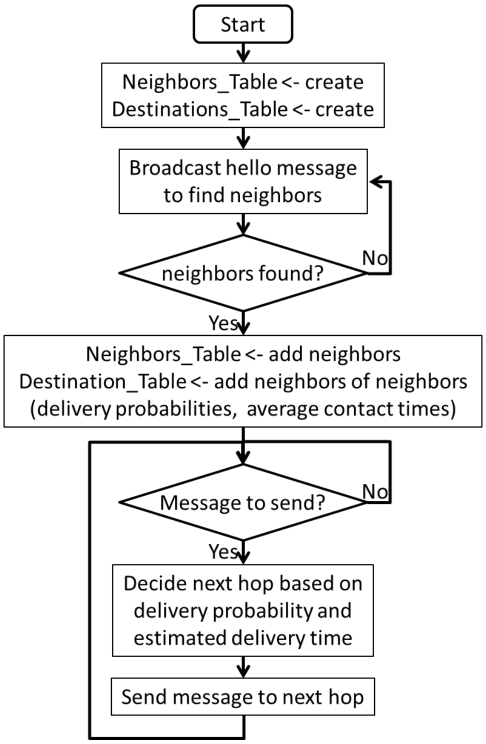

Fig. 3. Flow diagram for the proposed algorithm.

them. Delivery probabilities are kept a deliveries table. When a node wants to send a message to another node or to Internet (through the AP), it will create an entry in its deliveries table with the information about the neighbors with paths to the destination, the average time between contacts for each one of these neighbors, the delivery probability to the destination through the neighbors and the estimated time to deliver the message given by the neighbor. DTN nodes will store in memory these tables, so they can forward messages in an effective way, minimizing time and maximizing the delivery probability. Nodes should have enough capacity to store own's and neighbors' messages. Since the communication model is not a real time one, this should not be a problem. Nodes will communicate using wireless links (IEEE 802.11g/n/ac or a similar technology) that will give them at least 50 Mbps, so a contact of a few seconds should be enough for a couple of nodes to exchange the messages (requests and replies) that they have for each other. The AP should have a significantly bigger memory capacity, since it is the bottleneck for all messages leaving the rural network and going to Internet. It depends on the frequency of delivery and reception of messages. If MAPs pass frequently by the AP's position, the memory could be smaller than the ones for APs were MAPs pass once a day or even less frequently. Figure 3 depicts a flow diagram representing the routing and forwarding algorithm for each DTN node.

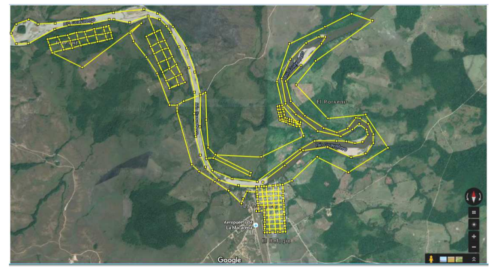

Fig. 4. Simulation scenario in OpenJump.

IV. Results

Our networking scenario was simulated in the ONE simulator framework [16], an Opportunistic Network Emulator where users can develop their own protocols and compare them against known and implemented protocols. For the proposed scenario we used a small and remote town in Colombia, named La Macarena, it is a small community of about 500 inhabitants, with difficult access conditions. There are currently three different ways to reach the town, a road to the nearest town (5 hours), two daily flights in small airplanes (for 5 to 10 people), and small canoes by the Guayabero river. This town also has a military base, where communication antennas work all day long. Rural users, then, have to go to the town in order to communicate to the capital or any other part of the country. We scaled the map around La Macarena using OpenJump to use the mobility models of The ONE simulator. Rural DTN users are scattered around the town and they move around from the town to small farms nearby. There are roads from the town to most farms and the river is also a very popular way of transportation. Messages have to get to the center of the town, at the military base, to be transmitted to Internet. For our simulations, DTN users can generate messages at any time and can receive replies from Internet (through the static node at the military base). There are DTN nodes moving in their farms, neighboring farms and the town, MAPs going from the farms to the town and viceversa over roads and the river, and the AP in the military base in the center of the town. This simulation scenario can be seen in Figure 4.

We created several scenarios changing the number of nodes (from 10 to 100 rural users), the size of messages (from 2kB to 2MB), and the time between messages (from 1 to 12 hours). These scenarios are described in table 3. Messages are generated from rural DTN user nodes and the AP. These messages can be sent from user node to user node, from user node to AP or from AP to user node. MAPs only serve as relays to carry the messages from one location to another. Every scenario was tested for 3 simulated days (72 hours) with 5 different random generator seeds. The simulation results were obtained by changing the nodes' buffers and changing the user nodes movement model from random to map-route (a model where nodes follow a predefined path at a constant speed defined randomly at the beginning of the simulation). However, buffer variations had no impact on results. We changed the nodes' buffers from 10MB to 640MB, but the

TABLE III
SIMULATION SCENARIOS

Scenario	Parameters
1	10 DTN nodes, 1 AP, 3 MAPs, 2MB, 1-2 hours
2	10 DTN nodes, 1 AP, 3 MAPs, 2kB, 1-2 hours
3	10 DTN nodes, 1 AP, 3 MAPs, 2MB, 1-12 hours
4	10 DTN nodes, 1 AP, 3 MAPs, 2kB, 1-12 hours
5	100 DTN nodes, 1 AP, 3 MAPs, 2MB, 1-12 hours
6	100 DTN nodes, 1 AP, 3 MAPs, 2kB, 1-12 hours

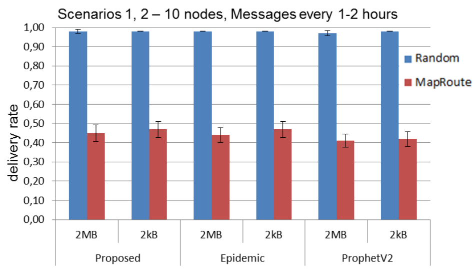

Fig. 5. Simulation results for scenarios 1 and 2.

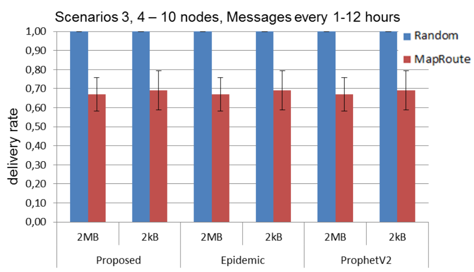

Fig. 6. Simulation results for scenarios 3 and 4.

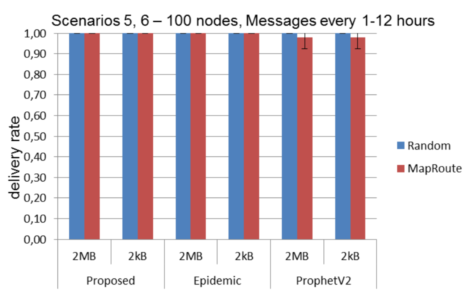

Fig. 7. Simulation results for scenarios 5 and 6.

delivery rate was always the same, it was not affected by the buffer size.

Results are shown in figures 5 to 7. They show the delivery rate of our proposed algorithm against PROPHET and Epidemic routing protocols. It can be seen that our proposed algorithm achieves the same delivery rate or even a better one in some cases than Epidemic routing and PROPHET for the proposed scenarios, and that all protocols deliver more messages with the random movement of the user nodes than they do with the map-route movement model of the nodes.

Figure 5 shows simulation results of delivery rates for Epidemic and PROPHET routing protocols against our proposed algorithm for scenarios 1 and 2 (see Table 3). These are scenarios with 10 nodes as rural users and where these nodes generate messages every 1 to 2 hours. Figure 6 shows simulation results for scenarios 3 and 4. These scenarios have 10 nodes as rural users, but they generate new messages every 1 to 12 hours. Figure 7 shows simulations results for scenarios 5 and 6. These scenarios are bigger ones, with 100 nodes as rural users and they are generating new messages every 1 to 12 hours.

V. CONCLUSIONS

Delay/Disruption Tolerant Networking is a technically feasible way to bring Internet connectivity to remote rural areas in the world. Simulations show promising results for several protocols and more tuning and field test are necessary to obtain a robust solution.

The protocol developed and presented in this paper combines the best characteristics of several DTN routing protocols and it performs as well as them. It is necessary to continue the developing and testing of this protocol to achieve even better performances. Our proposed solution delivers almost all messages when the mobility model given by the simulator allows rural nodes to interact more frequently. When the simulator is configured to use a mobility model that keep rural nodes apart from each other most of the time, the delivery rate of all protocols drops significantly. This effect is minimized when less messages are generated (one message per node every 1 to 12 hours).

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