STIgmergy Routing (STIR) for Content-Centric Delay-Tolerant Networks

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***Abstract*—This paper introduces a STIgmergy based Routing protocol (STIR) for Content Centric Delay Tolerant Networks. STIR makes the most of spatio-temporal interactions between nodes to set up bio-inspired gradient fields between content producers and content users. STIR routing follows this gradient field to efficiently route information in Delay Tolerant Networks. The validation of this protocol has been coupled with the definition of a new mobility parametric model that makes possible to easily express the preferential locations and movements commonly observed in real human mobility traces. Performance evaluations by simulations demonstrate that STIR delivers better performances than traditional protocols even in case of highly dynamic networks.**

***Index Terms*—Content Centric Network, Delay Tolerant Network, routing protocol, diffusion algorithm, gradient field**

I. Introduction

Wireless network technologies evolved rapidly and dramatically in recent years. This evolution increased the qualitative and quantitative complexity of communication at the edge of a pervasive Internet that allows its users to access ubiquitously to an ever increasing space of ambient services. Advances in storage, processing, and communication performances of a sky rocketing population of mobile and wireless devices put a high pressure on access and core networks. Hence, the idea of using the processing, storage and communication capabilities of these mobile devices to extend and relieve the Internet from *Delay Tolerant Network (DTN)* inspired communication protocols and mechanisms applied amongst the galaxy of wireless devices. Indeed, when deployed at the periphery of the Internet, such an approach could reduce the Internet core traffic, while better exploiting the existing communication resources at the periphery.

Besides, the explosion of the amount of content accessible from the Internet today increased the complexity of information access by overloading the users and the network with the management of complex address spaces used for content access. Therefore, the user currently perceives and uses the Internet as a pervasive source of information and services "delivered by the network" and not by a specific source. This evolution of usage of the Internet entails potentially a sound paradigm shift from the legacy end-to-end communication paradigm to the *publish-subscribe* paradigm. The incoherence between the usage and the underlying communication architecture of the current Internet entails several availability, security and location-dependence issues ([6]). In order to solve these issues *Content Centric Network (CCN)* considers the content as a first class network citizens by replacing content address by content identifier. According to this approach the publish-subscribe paradigm allows content provider to publish their offers to the destination of contents users who express their interest on this content by subscribing to it. Therefore, one of the big challenges of CCNs is to define routing protocols that makes it possible to efficiently route and disseminate content between the providers and the users. This is the target of the contribution introduced in this paper: a contribution at the crossing of two evolutions of the Internet - DTN and CCN.

We define then *Content Centric Delay Tolerant Networks (CCDTNs)* as partially connected dynamic networks which provide content/service access through the content-centric publish-subscribe paradigm. In this paper, we address the issue of content routing problem in such dynamic networks.

The rest of this paper is structured as follows. At first, related works are discussed in Section II. We formulate the routing problem in CCDTNs in Section III followed by the details of STIR in Section IV. In Section V, we give some performance evaluation of STIR by simulations. Finally, Section VI will conclude the paper and discuss about future works.

II. State of the Art

The content-centric communication concentrates a lot of attention in the networking research community but to the best of our best knowledge, there are few works addressing it in the DTNs field. One of the most relevant works is SocialCast ([2]) where the authors solve the publish-subscribe routing problem in DTNs by using some social interaction metrics to select the best candidate to relay the message. Kalman filter is used to predict the future evolution of node's utility which is processed as a scalar value that takes into account the variation of node's connectivity and their social interests. The work is based on the assumption that nodes sharing the same interest are likely to be colocated. Although this contribution promotes the combination of social colocation metric and mobility pattern metric for processing node's utility, it appears that the routing's latency is lower when only the mobility based metric is used. Our approach is simpler and more universal because we leverage on spatio-temporal interaction between neighbor nodes whatever their social or interest relationship.

Another work in this field is SARAH ([4]). This work addresses the problem of supporting content-based communication in intermittently connected mobile adhoc networks (MANETs). Whereas DTN treats the worst case where nodes could be totally disconnected from the others ones, the authors consider the mobile network likes disconnected MANET islands. A content catalog is at first broadcast into the network. The interested nodes then reply to the content publisher via unicast communication. The publisher finally broadcast the content in the network to all the users. Regarding the routing, the authors use some kind of limited range flooding for the broadcasting and source routing for the unicasting. Although working with MANET, this type of routing can not be applied to DTNs where nodes can be totally disconnected in space and time. Moreover source routing and end-to-end communication mechanisms are not adapted to CCNs.

For DTNs, many routing protocols were proposed (see [10] for a review), manny of them deal only with the end-to-end communication. The most basic protocol is Epidemic routing which insures a global message diffusion with a low latency but at a high and prohibitive cost in term of buffering, bandwidth and power consumption. Constrained diffusion protocols try to find a good trade-off between a high probability to reach the receivers and resource use. In this protocol family, Spray and Wait ([9]) is a multiple-copies based protocol which limits the number of sent copy of each original message. At each contact, the message carrier node share a quantity of copies to the encountered node. The protocol was shown to provide better performances in term of delivery and delay while optimizing resources compared to Epidemic routing. PROPHET ([8]) is another interesting routing scheme in which an utility value denoting the probability of reaching the destination is attributed to each node. The node with higher utility will be a better candidate to forward message.

The content-centric paradigm is not a recent idea. Whereas many works addressed this issues by providing a specific application layer to support content-centric communication, the most relevant one was introduced by Van Jacobson et al in [6]. In this "clean slate" approach, the authors redesigned the Internet architecture by treating content as a network first class citizen and by decoupling location from identity.

Finally, the dynamic reinforcement of network path based on a gradient field established between information providers and users has been initially introduced in the wireless sensor network field in the well-known Direct Diffusion protocol ([5]). In this protocol, three phases are defined for data retrieval. A first sensing phase is used to disseminate the interest into the network. This dissemination sets up a gradient field to draw data towards receivers along the best path dynamically selected according to the performance of several potential paths.

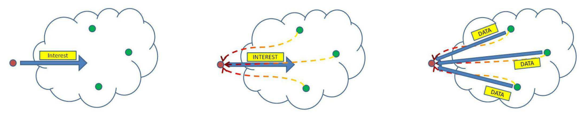
In this work, we inspire from these existing ideas to tackle the routing problem in CCDTN. We define an utility metric as the interest degree of a node with respect to a content. This metric will be dynamically computed at each node according the spatio-temporal characteristics of human mobility. The scalar field created by of node's utility value will establish evolutionary gradient which draw the content to the users.

III. Problem statement

In a CCDTN network, let N mobile nodes (i.e. communication devices carried by human) move according to a mobility model $\mathcal{M}$. In order to capture the spatio-temporal correlation of node's interactions and the locality of movement that have been observed in real mobile traces ([1], [3]), we have defined a new mobility model that will be described in section V. The network communication is via wireless links without any infrastructure. Nodes may suffer from intermittent connections due to the fragmentation of network and can only exchange information by opportunistic contacts. A contact occurs when a node moves into the radio range of another node. Let P nodes be the publishers of a content c and U nodes be the users of this content. We assume that the content publication is managed by an external mechanism apart from the routing protocol and that in consequence the users know already the descriptor of the content or service. To receive the content c, one or many user nodes begin to disseminate their interest message into the network (i.e. they register to the considered information or service). When a publisher receives a registration message corresponding to its published information/service, he returns the content or applies the service. In the next section we will show how in such networks, by exploiting a bio-inspired approach, we can define a routing scheme that delivers good performances (in term of latency, delivery ratio, etc) while optimizing the use of network resources.

IV. STIR algorithm

Our idea comes from the shortest path finding behavior applied by ants for food retrieval. When finding food ants drop pheromone along their path back to their nest. This adaptive path will be followed and be dynamically reinforced or modified by the other ants according to the evolution of the path conditions (e.g. obstacles, evolution of the state of the source of food). This mechanism exploits the stigmergy (i.e. spatio-temporal correlation of direct or indirect interaction of agents) involved between the considered mobile agents. In the case of ants the pheromone density plays as a spatio-temporal attractor for ants. As pheromone is volatile, ants always tend to choose the best path (i.e. the most used) and the less efficient paths gradually disappear. In the same manner, in our routing protocol, mobile nodes leverage on the spatio-temporal intensity of their interactions to create virtual paths (i.e. with no geographic significance) defined from gradient field between content publishers and content users. We leverage on the correlation in movement of nodes in space and time to maintain the best spatio-temporal path that offer the shortest delivery delay.



STIR consists of 3 mechanisms: Interest diffusion, Gradient management and Content diffusion. The figures illustrate these 3 mechanisms.

A. Interest diffusion

The goal of this mechanism is to efficiently disseminate the Interest message to content publisher. For this, we inspired from the the Binary Spray and Wait protocol ([9]). The algorithm works as follows.

```
Input: number of Interest copies ← L
while doesn't receive the data yet do
    foreach contact do
        if other node is a data carrier then
            Request and receive the data;
        else
            if number of Interest copies > 1 then
                Share a half of Interest copies to the
                encountered node;
```

Algorithm 1: Interest diffusion algorithm

B. Gradient management

This mechanism aims to define and maintain coherently on each node and for each content/service c, a scalar called utility for content c on node n that we note $U(c, n)$. This value reflects the proximity in time and space between the content user and the considered node (i.e. how often the node meets the user). The set of utilities for a given content c among the whole set of nodes defines a space of gradient pointing from the source to the destination of c. The mechanism ensures that:

- content user nodes keep their utility to the maximum value $U_{max}(c)$,
- content publisher nodes keep their utility to the minimum value $U_{min}(c)$,
- content carrier nodes have utility values ranged in $]U_{min}(c), U_{max}(c)[$ depending on the spatio-temporal correlation between them and the content user.

Two rules have been defined for the utility evolution according to the previous constraints:

- Reinforcement: at each contact between two nodes n_i and n_j, the utility evolution is defined by the formula
$$U_{\text{new}}(c, n_i) = \alpha \times U_{\text{contact}}(c, n_j) + (1 - \alpha) \times U_{\text{old}}(c, n_i), \quad (1)$$
where $\alpha \in [0, 1]$ is the reinforcement coefficient, $U_{\text{new}}(c, n_i)$ is the updated utility value of n_i, $U_{\text{old}}(c, n_i)$ is the old utility value of n_i and $U_{\text{contact}}(c, n_j)$ is the utility value of the encountered node n_j.
- Aging: the utility of a node decreases exponentially between encounters following the formula
$$U_{\text{new}}(c, n_i) = U_{old}(c, n_i) \times \beta^t, \quad (2)$$
where $\beta \in]0, 1]$ is the aging coefficient and t is the time elapsed from the last encounter.

Note that the content user and content publisher nodes don't change their utility during the algorithm. This results in the creation of gradient between the "picks" (content users) and the "wells" (content publishers). For utility value distribution, we use a constrainted flooding mechanism. Algorithm 2 summerizes how the mechanism works.

```
foreach contact do
    if the other node hasn't a gradient value then
        if k > 0 then
            The other node updates its gradient value
            following rule 1;
            k = k − 1;
    else
        Update gradient value following rules 1 et 2;
```

Algorithm 2: Gradient establishment algorithm

C. Content diffusion

The reinforcement rules coupled with the spatio-temporal correlation of node's movement leads to the convergence of the gradient field and creates shortest paths between content publishers and content users. Consequently, the content has to simply "flow" along these paths to reach the users. Therefore the content forwarding decision consist of selecting a node with a higher utility value. The dissemination is also provided by Binary Spray and Wait protocol. Algorithm 3 summerizes this mechanism.

```
Input: Number of content copies ← M
foreach contact do
    if the other node has a greater or equal gradient
    value then
        if Number of content copies left > 1 then
            Share a half of content copies to the other
            node;
        else
            Transfer the content;
```

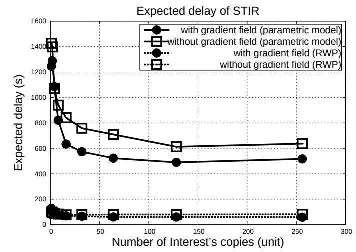
Algorithm 3: Content diffusion algorithm

V. Simulation results

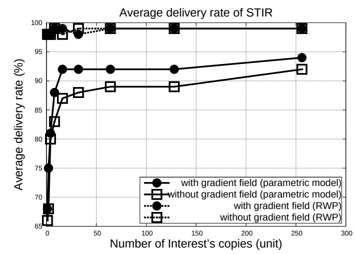
Since STIR bases on the spatio-temporal correlation in node's mobility patterns, it's vital that the mobility model we use can capture this characteristic. Therefore we developed a new parametric mobility model which abstracts the locality of interactions between nodes. By tuning the parameter, we can switch from a less correlated to a high correlated mobility pattern. Thus we can evaluate STIR in a large spectrum of mobility patterns. We implemented our routing protocol and mobility model in theOne - a JAVA discrete event simulator for DTNs ([7]). Three metrics are chosen to analyze the performance of STIR : expected delay, hop count and delivery rate. In each scenario, the measured metrics in our mobility model and the classical Random Waypoint (RWP) model are compared between the case of using the gradient field and the case without using it.

In Figures 1a 1b 1c, we can see that the the message forwarding decision based on the gradient field reduces significantly the delay and hop count while increasing the delivery rate. It's interesting to see that the improvement is more significative in our mobility model than in RWP. This proves our postulate that STIR performs better in high spatio-temporal correlated mobility patterns and that it could be used in human mobility contexts.

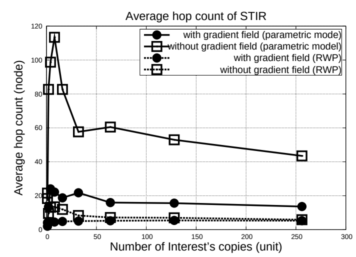
In Figure 1d, we measured the delay of STIR for a large range of the locality parameter of our mobility model. The curve shows a transition of phase when the mobility patterns become highly localized. The detailed understanding of this phenomenon and its impact on the routing in CCDTNs is one of our on-going works.



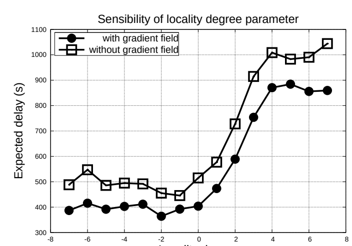
(a)



(b)



(c)



(d)

Fig. 1: Simulation results

VI. Conclusion & perspectives

In this paper, we have proposed STIR - a new routing protocol for Content Centric Delay Tolerant Networks. By exploiting the spatio-temporal correlation between mobile nodes, the protocol creates a gradient field allowing content reach the user by following its slopes. Performed simulations with STIR have shown that the message forwarding decision based on the gradient makes sense in human mobility patterns. These first promising results will serve as basic foundation for us to study the different characteristics of human mobility and their impact on routing strategies in CCDTNs.

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