Implicit merging of overlapping spontaneous networks

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***Abstract*— Due to mobility, spontaneous networks composed of nodes following similar group mobility patterns are likely to overlap. Previous solutions invariantly considered overlapping as a permanent state where the networks combine to form a new network. In this paper, we propose a more realistic model where merging is either permanent or transient. Our contributions are twofold. First, we introduce a methodology to identify transient merging and detect implicit permanent merging. Second, we propose an efficient routing protocol between merging networks while in the transient state. Our approach is completely distributed and incurs low routing control overhead. We also investigate a solution to prevent respective intra-network communications from interfering.**

I. Introduction

Large-scale spontaneous networks are large ad hoc networks formed by members willing to participate in some collaborate activity (*e.g.*, emergency disaster relief, battlefield troops, conference attendees) or with similar interest in spatial movement (*e.g.*, public transport users). Due to mobility, these networks are subject to topology changes that can lead to frequent splits and merges. Such networks may operate in a stand alone fashion but with the ability to dynamically adapt to merging and splitting.

In such a scenario, address allocation schemes and routing protocols must adapt to the changing nature of the network characteristics. Although both split and merge are challenging issues, the procedure of merging networks leverages particular difficult problems. Many scalability problems related to network merging result from the assumption that overlapping networks must combine to form a new single network requiring a partial or total reconfiguration. Nevertheless, merging may be in some circumstances a transient state that may later lead to a permanent merging.

Former proposals such as Buddy [1] and Prophet [2] provide solutions to obtain a coherent addressing space with no duplicate addresses in case of merging. Either flooding is used to resolve conflicts and synchronize merged partitions or one network discards its addresses and restarts an address allocation scheme from the nodes in the other network. If used for transient merging, these solutions do not scale well because every possible merging would require a complete synchronization of the networks.

Another problem concerns specific routing algorithms. Similarly to address synchronization, if proactive routing protocols were used, (*e.g.*, DSDV [3], OLSR [4] or TBRPF [5]), synchronizing the different routing tables between the two merging networks would generate high communication overhead. Existing proposals based on synchronization techniques do not consider this particular problem and may lead to suboptimal results.

In this paper, we focus on an adaptive inter-network routing scheme that is aware of the network context. On the one side, if merging is permanent, both networks are considered to have merged and existing solutions can take over. On the other side, an efficient routing scheme that incurs low overhead must be used if merging is transient. We propose a scalable routing scheme dedicated to inter-network routing when transient merging is involved. We also propose a distributed scheme to determine whether merging is transient or permanent. We extend our work with some insights into important issues of radio networks like capacity limitation. In order to limit undesired inter-network traffic while merging is transient, we propose a filtering technique that enables local traffic to remain within the boundaries of its original network.

The paper is organized as follows. Section II introduces our network model called cell model. Section III details our approach leading to the final goal of determining whether merging is transient or permanent. In Section IV, we present our scalable routing solution dedicated to inter-network routing while transient merging occurs. Section V presents how traffic is filtered. Section VI discusses the benefits of our approach and concludes the paper with future research investigation.

II. The Network Cell Model

We propose in this paper a completely different approach that combines network identifiers (`NID`s) and specific tasks carried out by nodes located at the network border. We assume nodes know their coordinates through some positioning system (*e.g.*, GPS).

We define the concept of a *cell*, C, which is the spatial region spanned by a set of nodes, N_C, inherently showing a similar group mobility pattern. The set of nodes near the cell border, M_C, forms a *cell membrane* while nodes inside the cell, I_C, are *interior nodes*. For the sake of simplicity, we illustrate our algorithms with only two network cells that span circular coverage areas. When cells C_1 and C_2 merge, the overlapping region $\mathcal{S}_{C_1,C_2} = C_1 \cap C_2$ is called a *scar-zone* and is delimited by a *scar-zone membrane* (cf. Fig. 1). All defined symbols are summarized in Table I.

The cell membrane is responsible for detecting merging. The scar-zone and its membrane are responsible for inter-cell communications and for traffic filtering to keep local traffic within the bounds of a cell.

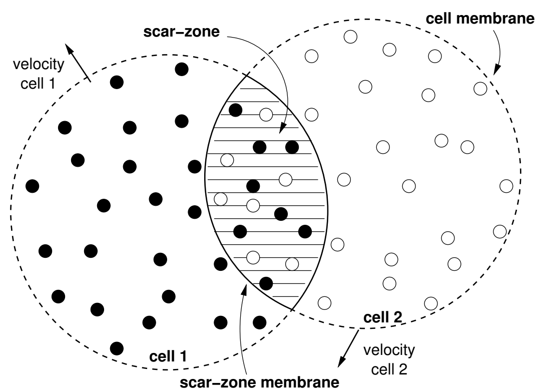


Fig. 1. Network cell model.

III. Cell merging

As a consequence of mobility, spontaneous networks are likely to spatially overlap and enable inter-network communications. Nevertheless, there are two requirements before inter-cell communications can take effect. First, merging must only be detected when the overlapping cells detect the presence of each other. Second, the overlapping region – the region through which all communications will pass – must be clearly delimited. In order to scale, routing protocols must adapt automatically to the network conditions. Thus, the routing scheme involved while cells are merging depends on the type of merging procedure. In order to address this point, we propose then a mechanism that enables merging to be classified as transient or permanent.

A. Merge detection

Merge is usually detected by nodes belonging to different networks through the exchange of a network identifiers (`NID`). One simple technique is to assign random numbers to different networks. Clearly, `NIDs` must be unique for a network to detect merging is about to occur. We use a similar approach to detect merging but we extend the semantic of the `NID` as explained in the following.

In the following, we use the model presented in Section II. In spontaneous networks, nodes periodically exchange one-hop `hello` messages to maintain an up-to-date neighbor list. We piggyback `NIDs` in `hello` messages and, as soon as a node $m \in M_{C_1}$ receives a distinct `NID` from a node belonging to the membrane of another cell, M_{C_2}, the merging procedure is triggered. We use a common property of nodes belonging to the same cell for the definition of an `NID`. In general, `NIDs` are either broadcasted or allocated during the address allocation process. Nevertheless, this does not scale well. In our case – where geographic routing is used and no specific address allocation is applied – we propose a more scalable and more reliable scheme based on local information.

In Wang [6], the RPGM (*Reference Point Group Mobility* model defined by Hong et al. [7] is extended to RVGM (*Reference Velocity Group Mobility*). In RVGM, nodes are classified in groups with similar velocity vectors using a sequential clustering algorithm from the field of pattern recognition. The mobility pattern of a group can be computed from the nodes' velocity vectors. The RVGM model also defines a way of computing a group velocity vector on the x and y axis, defined as

$$\mathbf{v} = [v_x \ v_y]^T. \tag{1}$$

We propose to use such a vector as the `NID` of a cell. An interesting property of using such a `NID` is its high probability of uniqueness in case of merging. In fact, this `NID` – besides extending the `NID` semantic from a random number to an indication of velocity – has the property that for two cells C_1 and C_2 with respective velocity vector $\mathbf{v}_{C_1}$ and $\mathbf{v}_{C_2}$, merging may occur if and only if $\mathbf{v}_{C_1} \neq \mathbf{v}_{C_1}$, if we assume of course that the networks are originally disjoint.

In [6], the mean group velocity computation requires all nodes to communicate their velocity vectors to a centralized server. We propose a local estimation of the mean cell velocity based only on the neighbors' velocity vectors. We assume that a cell's velocity is linear and time-invariant. We also assume that it is a random variable following a normal distribution, $\mathbf{v}_C \sim \mathcal{N}(\mu, \sigma^2)$ where μ and σ^2 are *a priori* unknown. Node $n \in N_C$ estimates these parameters by using a training set based on q observations of the neighbors' velocities, $V(\mathbf{v}_n) = \{v_1^n, \ldots, v_q^n\}$. The obtained parameters result in n's local estimation of its cell's velocity and is used as the cell identifier, $\mathtt{NID}_C^n$. This cell identifier aimed at detection merging will also be used for the scar-zone delimitation.

B. Cell Edge detection

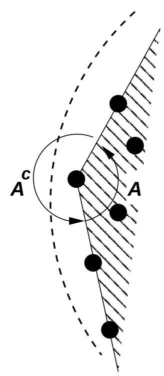
The effectiveness of our approach depends on the accuracy of the algorithm that computes the membrane. In [8], the authors show that two-hop broadcasts enable nodes to detect the presence of edges using either image processing or classifier-based approaches. In our proposal, we rely on an unsupervised clustering algorithm [9] performed periodically by each node in order to distinguish membrane nodes from interior nodes. We use a *k*-means clustering algorithm where the number of clusters k is unknown. Depending on its position in the cell, a node may see one or two clusters – respectively only interior nodes or both interior and membrane nodes. Two components are responsible for distinguishing interior nodes from membrane nodes: node's edge count, n_{edge}, and two-hop neighborhood coverage area A, $A \in [0, 2\pi[$. These components are exchanged periodically between neighbor nodes. For a given node n, A (which is different from the radio coverage area R), represents the radian covered by its one and two-hop neighbors. The edge count is lower for membrane

TABLE I

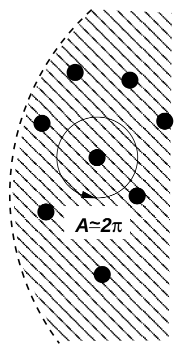
NETWORK CELL MODEL SYMBOLS.

Symbol	Definition
C	Spatial extend of a Cell
$\mathcal{S}_{C_1,C_2}$	Spatial overlapping region of two cells, C_1 and C_2
N_C	Set of nodes composing a cell
M_C	Set of nodes composing the membrane, (*i.e.*, edge nodes)
I_C	Set of inside nodes

nodes than for interior nodes, and the coverage area is likely to converge toward 2π in average for interior nodes. Figure 2 illustrates A for both an edge node (cf. Fig 2(a)) and an interior node (cf. Fig 2(b)). We then compute a Minimum Squared Error linear discriminant function and, if a given threshold is reached, clusters are separated into two classes. Nodes that are in the lower class deem themselves as membrane nodes. The discriminant function is further used as a trial classification for nodes changing from the cell membrane to the cell interior and vice-versa.



(a) Edge node.



(b) Interior node.

Fig. 2. Edge detection.

C. Scar-zone delimitation

When two cells, C_1 and C_2 merge, the scar-zone limits have to be precisely determined. We use an approach similar to the edge detection to compute the scar-zone but using a supervised classification algorithm [9]. `NID`s exchanged during the merging procedure are used as a prior knowledge of class-conditional probability density functions $p(x|\omega_i)$, where $i = \{C_1, C_2\}$, $\omega_1 = \mathtt{NID}_{C_1}$, and $\omega_2 = \mathtt{NID}_{C_2}$. Features observed by nodes belonging to the scar-zone membrane are different from the observations of other nodes. Nodes detecting an area A with the same `NID` class and a complementary area A^c with an increased node density and two `NID` classes deem themselves as scar-zone membrane nodes. Figure 3 illustrates this case where node n declares itself as a scar-zone membrane node. Node n covers an area A with nodes having a similar `NID`, $\mathtt{NID}_{C_1}$ and a complementary area where two classes of `NID` coexist *i.e.*, $\mathtt{NID}_{C_2}$ (similar to its class) and the other cell's `NID` class, $\mathtt{NID}_{C_1}$. The increase in nodes' density is only used as a reinforcement feature for the classification.

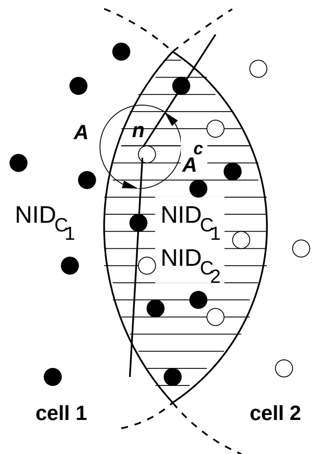


Fig. 3. Scar-zone membrane detection.

D. Transient vs. Permanent merging

If merging is transient, our classification algorithm detects a set of nodes belonging to the scar-zone membrane. Let $\mathbf{v}^r_{C_1,C_2}(t)$ be the relative velocity between merging cells C_1 and C_2 in function of time t,

$$\mathbf{v}^r_{C_1,C_2}(t) = \mu_{C_1}(t) - \mu_{C_2}(t). \tag{2}$$

If $\mathbf{v}^r(t)$ asymptotically decreases toward zero, this implies that cells are converging toward a similar group velocity which leads to a permanent state. We consider then that after some time cells have definitely merged.

In this case, the classification algorithm executed by nodes to delimit the scar-zone no longer identifies two distinct `NID` classes, but only one. Since the scar-zone membrane nodes no longer deem themselves as such, the scar-zone membrane automatically disappears and the two cells implicitly combine to form a new single cell.

IV. ROUTING

We have proposed in the previous sections a scheme to characterize merging under different assumptions. We now present intra-cell routing and describe our inter-cell routing scheme dedicated to situations where cells are transiently merging.

A. Intra-cell Routing

For intra-cell routing, we use geographic forwarding with nodes registering to a DHT node-lookup service that is local to a cell. While in the transient state, it is desirable that a communication between two nodes of a same cell remains within the boundaries of that cell. We propose to use the scar-zone membrane as a filter that lets only inter-cell traffic to pass. We detail filtering in the next section.

B. Inter-cell Routing

For inter-cell routing, we also use geographic forwarding but we propose node-lookups to follow an on-demand approach similar in their philosophy to on-demand routing schemes like AODV [10] and DSR [11]). Since each cell's registering database is purely local, for a given node x to be found, node-lookups must be performed in each overlapping cell either successively or in parallel. On-demand routing approaches are particularly suited to network situations with high mobility. The case we study in this paper where merging can be transient meets these requirements.

A node n located in $C_1 \setminus \mathcal{S}_{C_1,C_2}$ may perform node-lookups in two ways. In the first, it sends a `node-lookup` message in both cells for a global lookup. In the second way, a local lookup has failed and the node tries to lookup in the other cell. In both cases, a `node-lookup` message must be headed for the other cell. Scar-zone nodes can be used as *relays* for inter-cell communications. Each cell has a distributed set of *relay RDV-points* (*r-RDV*) – reachable through a specific address – dedicated to indicate the closest node in the scar-zone membrane, s, that enables to reach the other cell. Relay RDV-points of a cell C_1 store coordinates of C_2's scar-zone membrane nodes. These latter send their position updates to the relay RDV-points at a periodicity based on the observed relative velocity between cells. In order to reduce update overhead, nodes probabilistically choose to send updates based on a uniform probability p. We define a threshold p_0 such that if $p > p_0$ an update is sent, otherwise nothing is done. Hence, updates follow a bimodal behavior where the frequency of draws $f_{draw}(t)$ is proportional to the current relative velocity,

$$f_{draw}(t) \propto \mathbf{v}^r_{C_1,C_2}(t) \qquad (3)$$

Relay RDV-points can reconstruct a fair representation of the scar-zone membrane with the received updates. When node n has to perform a node-lookup in cell C_2, the relay RDV-point determines node s that minimizes both the path length and at the same time the inter-communication interferences. Let $\mathbf{p}_n = (x_n, y_n)$ be the position of node n and $S(C_2) = \{s_1, s_2, \dots, s_z\}$ be the set of z coordinates representing C_2's scar-zone membrane nodes' position. The nearest node s is obtained through

$$s = \mathrm{argmin}_{s_k}\, d_{\mathbf{p}_n}(s_k), \qquad (4)$$

where function $d_{\mathbf{p}_n}(s_k)$ gives the Euclidean distance for $k = 1, \dots, z$:

$$d_{\mathbf{p}_n}(s_k) = \sqrt{(x_n - x_{s_k})^2 + (y_n - y_{s_k})^2}\ . \qquad (5)$$

Figure 4 shows a node $n \in C_1$ which performs a node-lookup in cell C_2. In a first step, node n requests its *relay RDV-points* for the closest node that can relay its `node-lookup` message. The relay RDV-points responds by indicating to send the `node-lookup` to node s. This latter then relays n's `node-lookup` to cell C_2.

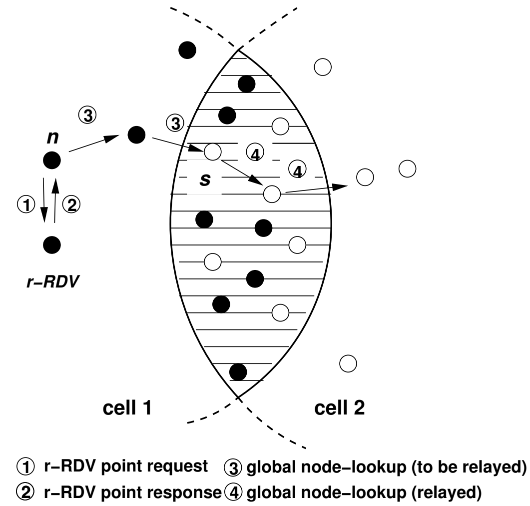


Fig. 4. Inter-cell routing.

If node n is located in $\mathcal{S}_{C_1,C_2}$, node-lookups can automatically be performed in both cells and do not require to request a relay RDV-point node since relay nodes are in the neighborhood.

V. Traffic Filtering

One of the ideas behind this work is related to the scaling properties of spontaneous network in terms of capacity. Large scale networks face the capacity limit inherent to multi-hop radio networks. In [12], the authors show that for nodes uniformly distributed on a plane with randomly chosen source-destination pairs, the achievable capacity of each node is bounded by the number of nodes and the physical path lengths. The less local the traffic pattern, the faster per node capacity decreases with network size. With similar hypothesis, Gupta and Kumar [13] demonstrated that the per-node capacity scales as $\Theta(1/\sqrt{(n \log(n))})$ with n, the number of nodes composing the network. These results show the need to restrict traffic as much as possible to a local scope.

Intra-cell routing uses geographical routing protocol. In Figure 1 where two cells overlap, we do not want traffic following a local communication pattern to be forwarded to the other cells, this in order to scale. We propose to use scar-zone border nodes as filtering nodes that lets only inter-cell traffic to pass.

Any emitted packet (control or data) is embedded with the source node's `NID` and flagged with one header bit indicating whether it should follow local or global scope. Prior to forwarding a packet, scar-zone membrane nodes compare the packet's `NID` field and forward it if and only if the forwarding direction of the packet is within the radian A or A^c containing a similar class of the packet's `NID`. Otherwise, the packet is discarded.

To reinforce local scope packet discarding at scar-zone membrane nodes, we use another tagging technique. A packet entering a scar-zone is flagged in the dedicated packet header field. This packet is not able to cross the other scar-zone border unless intended for a global scope. Hence, if it has not reached its final destination in the scar-zone, the packet is discarded. If a packet is emitted from the scar-zone, it is flagged straight away. This method enables the reinforcement of the discarding process executed by scar-zone membrane nodes. Only packets with the global scope field set to true are not filtered.

VI. Final Remarks

Our inter-cell routing protocol avoids bottleneck links by geographically spanning the attribution of relay nodes to nodes willing to communicate with a node in a different cell. Former hierarchical routing protocols were based on the election of a cell *cluster-head* (or *landmark* node). Such a node is responsible for exchanging routing tables and filtering traffic with its peers. Our approach adapts well to self-configuring spontaneous networks since it requires neither cluster-heads nor landmark nodes.

In this paper, we propose a novel approach for implicit merging of spontaneous networks following a group mobility model. Contrary to previous proposals, we consider the case of transient merging. One of our main goals is to address the effects of network merging on routing using completely decentralized mechanisms. Our solution also addresses the capacity bounds of mobile radio networks by restricting communication to a local scope. Critical situations can particularly benefit from our approach since it aims at achieving low complexity, low communication cost, and low latency. It is also applicable to GPS-free positioning system and can be generalized to other network paradigms such as rooftop, sensor, and wireless mesh networks.

This paper also introduces the fundamental role of border nodes in a wireless spontaneous network. We will extend this role by assigning border nodes the task of applying the concept of group policies.

Future work would also extend our approach to GPS-free networks. Two major issues we did not address in this paper are the address conflict problem and the network split prediction and detection problem. By extending our scheme to predict the time when two merging cells physically uncover, our algorithms can be easily adapted to detect group partitioning.

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