Easily-Managed Location in SONs by exploiting Space-Filling Curves

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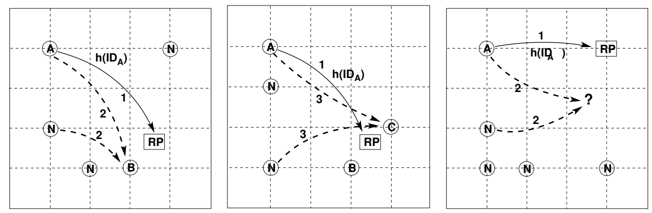
I. Motivation

The design of self-organized network architecture requires an efficient tradeoff of robustness and complexity. The resilience of existent proposals and consequently the performance of the routing protocols are strongly related to the complexity of deployed addressing structure. Tree-like structures [1], [2], for example, lead to simple manageable spaces. Nevertheless, they have low route selection flexibility and poor resilience to mobility. Their low complexity is obtained at the cost of some loss of robustness. More complex structures like multidimensional Cartesian spaces are robust to mobility but introduce complexity to the management of the addressing and location space.

Due to the complexity involved with a dynamic multidimensional partitioning and management, existing scalable location service approaches [3], [4] are inherently dependent on the spatial distribution of nodes in the topology. They associate nodes to geographic positions in the space which requires the presence of at least one node near the mapped geographic position to play the role of its location server (see Fig. 1). This cannot be guaranteed in a SON because of its variable nature, in time and in space. Topology changes imply that the network needs to be periodically checked in order to accordingly update the associated location servers. The selection of this servers is strongly correlated to their physical coordinates, which introduces some loss of freedom in the indirect location service and extra overhead. This may be prohibitive in many dynamic networks. To overcome the abovementioned issues, our novel architecture *Twins* performs position-based routing in a multidimensional space, and assures an easily-managed one-dimensional location service.

II. Twins design

Twins implements a DHT-based location service completely independent of the physical location of the nodes. The topological-independence of the location service is based on the mapping between nodes' identifiers into *rendezvous points* (RP), and on the association of these rendezvous points with *rendezvous nodes* (RN). Each node has an identifier, which is hashed into a RP (*i.e.* a geographic position) of an addressing space. Partitions of this addressing space are assigned to nodes in the network. A node whose partition contains a RP is the RN responsible for storing the current location information

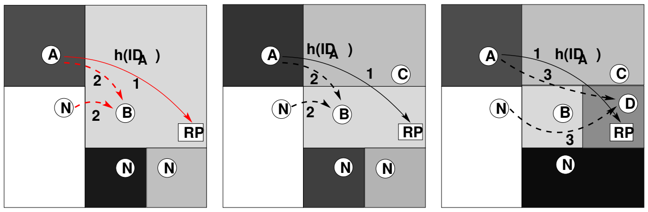


(a) (b) (c)

Fig. 1. **Lookup phase in a topological-dependent location service:** (a) $h(ID_A)$ results in a geographic position $RP(A)$ (arrow 1), where the closest node is B. Lookup messages are then forwarded to node B (arrow 2). (b) With topology change, the closest node is now node C (arrow 3). The periodical scan of the network will then update A with its new RN information. (c) Nodes are geographically far from RP(A). It is then difficult to determine and manage which node must play the role of RN(A).

of the node associated with that RP. The basic operation in our location service is Lookup(RP), which returns the node controlling the partition of the space containing that point (see Fig. 2). Thus, by mathematically representing the geographic distribution of nodes in a logical addressing space, we dynamically assign: (1) slices of this addressing space to RN; (2) nodes to points/addresses in those slices. Twins assures that there exists at least one node per slice of space containing the RP and the accurate forwarding of messages toward the corresponding RN. In the case of topology changes, the space partitioning is automatically updated by the Twins management plane operations.

Twins completely decouples the geographic plane, used for routing, from the localization plane, used by the location service, without, however, to establish an overlay network. By using Hilbert space-filling curves, Twins provides a bijective mapping between points of an n-dimensional space and points of a line. With space-filling curves, a multidimensional hierarchical structure can be designed, where geographic coordinates of points in the structure identify nodes location in the topology. As stated before, the main advantage of using geographic coordinates is that routing possibilities are fully exploited. At the same time, the need for efficient location models is even more important in environments where topologies become larger and more complex in their addressing structures. Increasing the number of the addressing space's dimensions results in more neighbor-space-partition state per



(a) (b) (c)

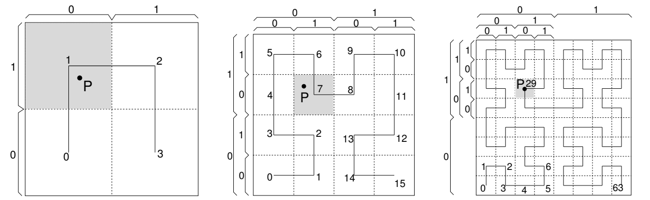
Fig. 2. **Lookup phase in a topology-independent location service:** (d) $h(ID_A)$ results in a RP managed by the node B (arrow 1). Lookup messages to RP(A) are then forwarded to node B (arrow 2), the node that manages the slice of space where RP(A) is contained. (e) With a topology change, node B is still the node managing RP(A), though C is the closest node to this point. Messages are correctly forwarded to B without generating any overhead/update in A. (f) If the topology changes and node B is no more RN(A), messages are correctly forwarded to the new node D (arrow 3).

node ($O(d)$ for a d-dimensional space) and, consequently, more maintenance traffic for correctly repartitioning the space when changes in the topology happen. In a one-dimensional space, these tasks are simplified by reducing the complexity of the space partitioning maintenance to two neighbor-space-partition state per node. In this way, mapping multi-dimensional addresses into a single dimension can enable easily-managed and simple location models to be exploited. Hilbert space-filling curves offer a way of effectuating such a mapping by passing through every point in a space once and only once. Geographic routing can be then performed through multi-dimensions while the location model is implemented in a single dimension – a curve. At the best of our knowledge, the use of Hilbert space-filling curves for the implementation of easily-managed location service for SON is an original approach.

Space-filling curves partition the network space in a recursive way. The process terminates after k steps to produce a curve of order k. The resulting curve passes through 2^{kn} sub-hypercubes of a n-dimensional space.[1] We can then introduce a multi-dimensional and hierarchical addressing model based on the logical partitioning of the network, where node locations can be represented at different accuracy levels. In this context, each node is assigned a concatenated coordinate corresponding to its position in the squares' hierarchy of the two-dimensional sliced space – the *n-point* address – and to the number equivalent to its ordinal position on the highest order space-filling curve – the *derived-key* address (cf. Fig. 3).

For the location model, nodes are assigned a segment of the highest order space-filling curve. Each node assigned to a segment of the space-filling curve (called control region of a node) becomes the rendezvous node of RPs contained in its control region. The advantage of this approach is that each node manages a segment of line, instead of managing a sub-space of a plane. This enables the deployment of a simple one-dimensional location model that is completely independent of the physical node location.

[1]Without loss of generality, we represents the network space as a two-dimensional plane.

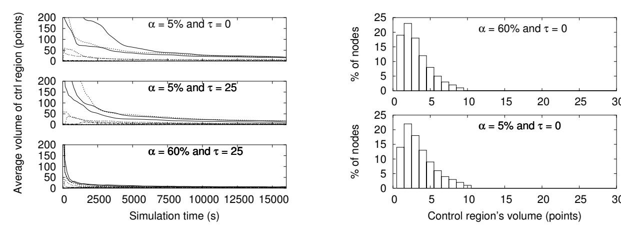


(a) 1st-order (b) 2nd-order (c) 3rd-order

Fig. 3. The line connecting the centers of the sub-squares in each sub-figure is a filling curve and defines an ordered sequence of sub-squares in 2 dimensions. The point P in the 3rd-order curve, has *derived-key* = 29 and *n-point* = 01 10 01 (resulted of $< 010, 101 >$ concatenation).

III. Evaluations and work in progress

The *volume* of the control region assigned to a node represents a good measure of the overall control overhead that the node incurs. Performed simulations show that Twins achieves fair distribution of the control overhead among all present nodes via a management protocol that strives to allocate (almost) equal partitions of the addressing space to each node (Fig. 4). In all scenarios shown in Fig. 4(a), as the network size grows with time, the volumes converge to equal and thus fair values. The same behavior of convergence was observed for all nodes, which are implicitly represented in the histogram shown in Fig. 4(b). The histogram show a large concentration of nodes with the same control region's volume, which validates the Twins fairness property. We are currently performing more detailed Twins' analysis. Nevertheless, we have already done a more rigorous analysis about the Twins fairness property, which can be found in [5].



(a) (b)

Fig. 4. Evaluation of the Twins fairness using the OPNET Modeler v10.5 simulator, for 1000 nodes, variable probabilities of node mobility (noted α), and variable rejoin time intervals (noted τ).

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