Communication Algorithms for Ad Hoc Mobile Networks Using Random Walks (2003; Chatzigiannakis, Nikoletseas, Spirakis)

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1 PROBLEM DEFINITION

A mobile ad hoc network is a temporary dynamic interconnection network of wireless mobile nodes without any established infrastructure or centralized administration. A *basic communication problem*, in ad hoc mobile networks, is to send information from a *sender* node, A, to another designated *receiver* node, B. If mobile nodes A and B come within wireless range of each other, then they are able to communicate. However, if they do not, they can communicate if other network nodes of the network are willing to forward their packets. One way to solve this problem is the protocol of notifying every node that the sender A meets and provide it with *all the information* hoping that some of them will eventually meet the receiver B.

> Is there a more efficient technique (other than notifying every node that the sender meets, in the hope that some of them will then eventually meet the receiver) that will effectively solve the communication establishment problem without flooding the network and exhausting the battery and computational power of the nodes?

The problem of communication among mobile nodes is one of the most fundamental problems in ad hoc mobile networks and is at the core of many algorithms, such as for counting the number of nodes, electing a leader, data processing etc. For an exposition of several important problems in ad hoc mobile networks see [13]. The work of Chatzigiannakis, Nikoletseas and Spirakis [5] focuses on wireless mobile networks that are subject to highly dynamic structural changes created by mobility, channel fluctuations and device failures. These changes affect topological connectivity, occur with high frequency and may not be predictable in advance. Therefore, the environment where the nodes move (in three-dimensional space with possible obstacles) as well as the motion that the nodes perform are *input* to any distributed algorithm.

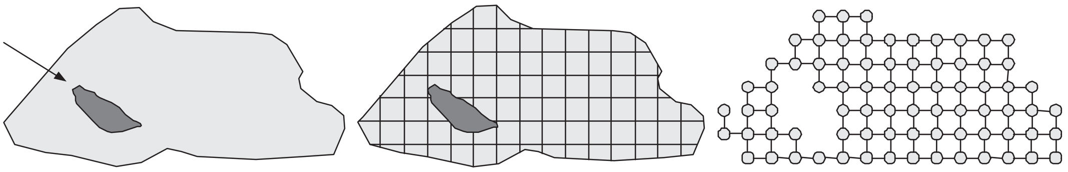
The motion space The space of possible motions of the mobile nodes is combinatorially abstracted by a *motion-graph*, i.e. the detailed geometric characteristics of the motion are neglected. Each mobile node is assumed to have a transmission range represented by a sphere tr centered by itself. Any other node inside tr can receive any message broadcast by this node. This sphere is approximated by a cube tc with volume $\mathcal{V}(tc)$, where $\mathcal{V}(tc) < \mathcal{V}(tr)$. The size of tc can be chosen in such a way that its volume $\mathcal{V}(tc)$ is the maximum that preserves $\mathcal{V}(tc) < \mathcal{V}(tr)$, and if a mobile node inside tc broadcasts a message, this message is received by any other node in tc. Given that the mobile nodes are moving in the space $\mathcal{S}$, $\mathcal{S}$ is divided into consecutive cubes of volume $\mathcal{V}(tc)$.

Definition 1. *The motion graph $G(V, E)$, ($|V| = n$, $|E| = m$), which corresponds to a quantization of $\mathcal{S}$ is constructed in the following way: a vertex $u \in G$ represents a cube of volume $\mathcal{V}(tc)$ and an edge $(u, v) \in G$ exists if the corresponding cubes are adjacent.*

The number of vertices n, actually approximates the ratio between the volume $\mathcal{V}(\mathcal{S})$ of space $\mathcal{S}$, and the space occupied by the transmission range of a mobile node $\mathcal{V}(tr)$. In the extreme case where $\mathcal{V}(\mathcal{S}) \approx \mathcal{V}(tr)$, the transmission range of the nodes approximates the space where they are moving and $n = 1$. Given the transmission range tr, n depends linearly on the volume of space $\mathcal{S}$ regardless of the choice of tc, and $n = O\big(\frac{V(\mathcal{S})}{V(tr)}\big)$. The ratio $\frac{V(\mathcal{S})}{V(tr)}$ is the *relative motion space size* and is denoted by ρ. Since the edges of G represent neighboring polyhedra each vertex is connected with a constant number of neighbors, which yields that $m = \Theta(n)$. In this example where tc is a cube, G has maximum degree of six and $m \leq 6n$. Thus *motion graph* G is (usually) a *bounded degree graph* as it is derived from a regular graph of small degree by deleting parts of it corresponding to motion or communication obstacles. Let Δ be the maximum vertex degree of G.

The motion of the nodes-adversaries In the general case, the motions of the nodes are decided by an *oblivious adversary*: The adversary determines motion patterns in any possible way but independently of the distributed algorithm. In other words, the case where some of the nodes are deliberately trying to *maliciously affect* the protocol, e.g. avoid certain nodes, are excluded. This is a pragmatic assumption usually followed by applications. Such kind of motion adversaries are called *restricted motion adversaries*.

For purposes of studying efficiency of distributed algorithms for ad hoc networks *on the average*, the motions of the nodes are modelled by *concurrent and independent random walks*. The assumption that the mobile nodes move randomly, either according to uniformly distributed changes in their directions and velocities or according to the random waypoint mobility model by picking random destinations, has been used extensively by other research.



(a) original network area $\mathcal{S}$ (b) divided in cubes (c) motion graph G

Figure 1: The original network area $\mathcal{S}$, how it is divided in consecutive cubes of volume $\mathcal{V}(tc)$ and the resulting motion graph G

2 KEY RESULTS

The key idea is to take advantage of the mobile nodes natural movement by exchanging information whenever mobile nodes meet incidentally. It is evident, however, that if the nodes are spread in remote areas and they do not move beyond these areas, there is no way for information to reach them, unless the protocol takes special care of such situations. The work of Chatzigiannakis, Nikoletseas and Spirakis [5] proposes the idea of forcing only a small subset of the deployed nodes to move as per the needs of the protocol; they call this subset of nodes the *support* of the network.

Assuming the availability of such nodes, they are used to provide a simple, correct and efficient strategy for communication between any pair of nodes of the network that avoids message flooding.

Let k nodes be a predefined set of nodes that become the nodes of the support. These nodes move randomly and fast enough so that they visit in sufficiently short time the entire motion graph. When some node of the support is within transmission range of a sender, it notifies the sender that it may send its message(s). The messages are then stored "somewhere within the support structure". When a receiver comes within transmission range of a node of the support, the receiver is notified that a message is "waiting" for him and the message is then forwarded to the receiver.

Protocol 1. The "Snake" Support Motion Coordination Protocol. *Let* $S_0, S_1, \ldots, S_{k-1}$ *be the members of the support and let* S_0 *denote the leader node (possibly elected). The protocol forces* S_0 *to perform a random walk on the motion graph and each of the other nodes* S_i *execute the simple protocol "move where* S_{i-1} *was before". When* S_0 *is about to move, it sends a message to* S_1 *that states the new direction of movement.* S_1 *will change its direction as per instructions of* S_0 *and will propagate the message to* S_2*. In analogy,* S_i *will follow the orders of* S_{i-1} *after transmitting the new directions to* S_{i+1}*. Movement orders received by* S_i *are positioned in a queue* Q_i *for sequential processing. The very first move of* S_i*,* $\forall i \in \{1, 2, \ldots, k-1\}$ *is delayed by a* δ *period of time.*

The purpose of the random walk of the head S_0 is to ensure a *cover*, within some finite time, of the whole graph G without knowledge and memory, other than local, of topology details. This memoryless motion also ensures fairness, low-overhead and inherent robustness to structural changes.

Consider the case where any sender or receiver is allowed a general, unknown motion strategy, but its strategy is provided by a restricted motion adversary. This means that each node not in the support either (a) executes a deterministic motion which either stops at a vertex or cycles forever after some initial part or (b) it executes a stochastic strategy which however is *independent* of the motion of the support. The authors in [5] prove the following correctness and efficiency results. The reader can refer to the excellent book by Aldous and Fill [1] for a nice introduction on Makrov Chains and Random Walks.

Theorem 1. *The support and the "snake" motion coordination protocol guarantee reliable communication between any sender-receiver* (A, B) *pair in finite time, whose expected value is bounded only by a function of the relative motion space size* ρ *and does not depend on the number of nodes, and is also independent of how* MH_S*,* MH_R *move, provided that the mobile nodes not in the support do not deliberately try to avoid the support.*

Theorem 2. *The expected communication time of the support and the "snake" motion coordination protocol is bounded above by* $\Theta(\sqrt{mc})$ *when the (optimal) support size* $k = \sqrt{2mc}$ *and* c *is* $\frac{e}{e-1}u$*,* u *being the "separation threshold time" of the random walk on* G*.*

Theorem 3. *By having the support's head move on a regular spanning subgraph of* G*, there is an absolute constant* $\gamma > 0$ *such that the expected meeting time of* A *(or* B*) and the support is bounded above by* $\gamma \frac{n^2}{k}$*. Thus the protocol guarantees a total expected communication time of* $\Theta(\rho)$*, independent of the total number of mobile nodes, and their movement.*

The analysis assumes that the head S_0 moves according to a continuous time random walk of total rate 1 (rate of exit out of a node of G). If S_0 moves ψ *times faster* than the rest of the nodes, all the estimated times, except the inter-support time, will be divided by ψ. Thus the expected total communication time can be made to be as small as $\Theta\left(\gamma \frac{\rho}{\sqrt{\psi}}\right)$ where γ is an absolute constant. In cases where S_0 can take advantage of the network topology, all the estimated times, except the inter-support time are improved:

Theorem 4. *When the support's head moves on a regular spanning subgraph of* G *the expected meeting time of* A *(or* B*) and the support cannot be less than* $\frac{(n-1)^2}{2m}$*. Since* $m = \Theta(n)$*, the lower* *bound for the expected communication time is $\Theta\big(n\big)$. In this sense, the 'snake" protocol's expected communication time is optimal, for a support size which is $\Theta(n)$.*

The "on-the-average" analysis of the time-efficiency of the protocol assumes that the motion of the mobile nodes not in the support *is a random walk on the motion graph G.* The random walk of each mobile node is performed independently of the other nodes.

Theorem 5. *The expected communication time of the support and the "snake" motion coordination protocol is bounded above by the formula*

$$E(T) \;\leq\; \frac{2}{\lambda_2(G)}\,\Theta\!\left(\frac{n}{k}\right) \;+\; \Theta(k)$$

The upper bound is minimized when $k = \sqrt{\frac{2n}{\lambda_2(G)}}$, where λ_2 is the second eigenvalue of the motion graph's adjacency matrix.

The way the support nodes move and communicate is robust, in the sense that it can tolerate failures of the support nodes. The types of failures of nodes considered are permanent, i.e. stop failures. Once such a fault happens, the support node of the fault does not participate in the ad hoc mobile network anymore. A communication protocol is *β-faults tolerant*, if it still allows the members of the network to communicate correctly, under the presence of at most β permanent faults of the nodes in the support ($\beta \geq 1$). [5] shows that:

Theorem 6. *The support and the "snake" motion coordination protocol is 1-fault tolerant.*

3 APPLICATIONS

Ad hoc mobile networks are rapidly deployable and self-configuring networks that have important applications in many critical areas such as disaster relief, ambient intelligence, wide area sensing and surveillance. The ability to network *anywhere*, *anytime* enables teleconferencing, home networking, sensor networks, personal area networks, and embedded computing applications [13].

Related Work The most common way to establish communication is to form paths of intermediate nodes that lie within one another's transmission range and can directly communicate with each other. The mobile nodes act as hosts and routers at the same time in order to propagate packets along these paths. This approach of maintaining a global structure with respect to the temporary network is a difficult problem. Since nodes are moving, the underlying communication graph is changing, and the nodes have to adapt quickly to such changes and reestablish their routes. Busch and Tirthapura [2] provide the first analysis of the performance of some characteristic protocols [8, 13] and show that in some cases they require $\Omega\big(u^2\big)$ time, where u is the number of nodes, to stabilize, i.e. be able to provide communication.

The work of Chatzigiannakis, Nikoletseas and Spirakis [5] focuses on networks where topological connectivity is subject to frequent, unpredictable change and studies the problem of efficient data delivery in sparse networks where network partitions can last for a signicant period of time. In such cases, it is possible to have a small team of fast moving and versatile vehicles, to implement the support. These vehicles can be cars, motorcycles, helicopters or a collection of independently controlled mobile modules, i.e. robots. This specific approach is inspired by the work of Walter, Welch and Amato [14] that study the problem of motion co-ordination in distributed systems consisting of such robots, which can connect, disconnect and move around.

The use of mobility to improve performance in ad hoc mobile networks has been considered in different contexts in [6, 9, 11, 15]. The primary objective has been to provide intermittent connectivity in a disconnected ad hoc network. Each solution achieves certain properties of end-to-end connectivity, such as delay and message loss among the nodes of the network. Some of them require long-range wireless transmission, other require that all nodes move pro-actively under the control of the protocol and collaborate so that they meet more often. The *key idea* of forcing only a subset of the nodes to facilitate communication is used in a similar way in [10, 15]. However, [15] focuses in cases where only one node is available. Recently, the application of mobility to the domain of wireless sensor networks has been addressed in [3, 10, 12].

4 OPEN PROBLEMS

A number of problems related to the work of Chatzigiannakis, Nikoletseas and Spirakis [5] remain open. It is clear that the size of the support, k, the shape and the way the support moves affects the performance of end-to-end connectivity. An open issue is to investigate alternative structures for the support, different motion coordination strategies and comparatively study the corresponding effects on communication times. To this end, the support idea is extended to hierarchical and highly changing motion graphs in [4]. The idea of cooperative routing based on the existence of support nodes may also improve security and trust.

An important issue for the case where the network is sparsely populated or where the rate of motion is too high is to study the performance of path construction and maintenance protocols. Some work has be done in this direction in [2] that can be also used to investigate the end-to-end communication in wireless sensor networks. It is still unknown if there exist impossibility results for distributed algorithms that attempt to maintain structural information of the implied fragile network of virtual links.

Another open research area is to analyze the properties of end-to-end communication given certain support motion strategies. There are cases where the mobile nodes interactions may behave in a similar way to the Physics paradigm of *interacting particles* and their modeling. Studies of interaction times and propagation times in various graphs are reported in [7] and are still important to further research in this direction.

5 EXPERIMENTAL RESULTS

In [5] an experimental evaluation is conducted via simulation in order to model the different possible situations regarding the geographical area covered by an ad-hoc mobile network. A number of experiments were carried out for grid-graphs (2D, 3D), random graphs ($G_{n,p}$ model), bipartite multi-stage graphs and two-level motion graphs. All results verify the theoretical analysis and provide useful insight on how to further exploit the support idea. In [4] the model of hierarchical and highly changing ad-hoc networks is investigated. The experiments indicate that, the pattern of the "snake" algorithm's performance remains the same even in such type of networks.

6 URL TO CODE

http://ru1.cti.gr

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