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Heinz Nixdorf Institute, University of Paderborn, Germany
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Participants: Research Academic Computer Technology Institute (CTI), Patras, Greece
University of Paderborn (UPB), Germany
Technical University Wroclaw (TUWroclaw), Poland
Author of deliverable: Sotiris Nikoletseas (nikole@cti.gr)
1 Introduction

We focused on two types of networks: mobile ad-hoc networks and single-hop radio networks. We here try to summarize some efficient protocols for important problems in suitable network models.

2 Single-hop radio networks

We consider basic problems (such as initialization, size approximation, broadcasting and sorting) in single hop radio networks (i.e. networks of stations communicating by exchanging radio messages, where each station is in the range of all other stations). Depending on the problem, we consider slightly different model approximating such network. We want to make it as general as possible, while considering the details significant for specific problems and proposed algorithms (such as abilities and initial knowledge of the stations, restrictions on the number of stations, or even the presence of adversary trying to scramble certain communication steps). The main complexity measures of our algorithms are time and energy dissipated for sending and receiving messages.

2.1 Initialization for Ad Hoc Radio Networks

We consider an ad hoc network in which some active stations wish to send messages through a shared radio channel. We assume that it is unpredictable which stations are active – this happens for instance when the network is highly dynamic. Each station is capable to sense the carrier – i.e. a station can identify the channel status as either busy (some station is sending signals) or idle (no station is sending a signal). Carrier sensing is a standard feature of modern wireless devices, for example those using IEEE 802.11. We take into account problems due to propagation delay of electromagnetic signals.

The problem is to design a protocol so that each of active stations gets its time slot for transmission, while the total time used should be kept as small as possible. The scenario that we proceed is that active stations receive the subsequent numbers 1, . . . , m (initialization procedure), and afterward transmit data: station i during the ith time slot. For the initialization procedure neither infrastructure nor central control unit is established – the active stations have to self-organize themselves.

In [1] we develop n-station initialization algorithm with carrier sensing and runtime very close to the theoretical lower bound. We use combinatorial classes for a rigid mathematical analysis of algorithm performance. In [2] we design a new initialization algorithm for an unknown number of active stations. If their number is n, then the expected runtime achieved is (1 + C) · n, where C is a parameter depending on propagation delay in a quite complicated way described in [2]. Our scheme outperforms existing algorithms, concerning the runtime constant in front of n.

These and further yet unpublished results have been included in a PhD dissertation of Marcin Zawada submitted at Wroclaw University of Technology.

2.2 Size approximation

We design a time and energy efficient algorithm approximating size of a single-hop radio networks. The most important feature of the algorithm is that it is immune against an adversary that may scramble a certain number of communication steps. The previous algorithms presented in the literature provide false estimations, if an adversary is able to cause communication collisions. We presented an algorithm [4] that allows size approximation problem of a single-hop radio network consisting in N stations to be solved in time $O(\log^3 N)$ and energy cost $O(\log^2(\log N) \cdot \sqrt{\log N})$ where a correct output is given with probability at least $1 - 2^{-z}$ where $z = \Omega(\sqrt{\log N})$ in the presence of an adversary with energy cost $\log(N)$. The same (correct) answer will be known to at least $N - \frac{N}{\log^2 N}$ stations. (The other stations have a less accurate estimate.)
While the above results are of asymptotic nature, we examine behavior of the algorithm for small \( N \). In particular, in order to reduce estimate’s bias, we use median instead of mean while calculating the estimate value [3].

2.3 Broadcasting on a Highway

In [7] we propose a dynamic, ad-hoc communication network consisting of mobile units that, in particular, can warn about traffic jams on motorways. Our goal is to provide a practical, low cost solution. Therefore we consider very simple wireless communication hardware, without collision detection and with very small bandwidth. We provide a complete system architecture. For this purpose we design and analyze solutions for size approximation, leader election and broadcasting. Our solutions are fine-tuned for fast operation in a practical setting. We provide both a theoretical and experimental evaluation of our solutions. Our contribution is much different from the previous work, where either pure theoretical models with a pure theoretical analysis are provided or algorithms working in practical models are evaluated only through simulations.

In [7] we present sharper results for the multi-round size approximation algorithm than in [6]. We precisely bound deviations from the expectation value of estimated number of stations. Our proof is based on martingale techniques and Azuma’s Inequality. Moreover, we present a rigid proof of properties of the broadcasting algorithm. For link unreliability parameter \( p_r \) we prove that \( P_{i,t,x} \) – probability that a message sent in the sector \( i \) reaches sector \( i + t \) in less than \( x \) rounds of the algorithm is independent from the number of stations in sectors and satisfies the following inequality:

\[
P_{i,t,x} \geq c^t \sum_{t=0}^{x} \binom{i+t-1}{i-1} p_r^t (1 - p_r)^{t} \quad \text{for constant } c \approx 0.98.
\]

2.4 Sorting

We consider problems of sorting and merging the sequences of keys distributed among \( n \) distinct stations of the network. We assume that the stations are synchronized, each station knows its position in the sequence \( 1 \ldots n \), and a single message may contain a single key or single index in the sequence of keys.

In [8] we consider the case when each station is able to store a single key (and a constant number of auxiliary variables). We show that merging of two sequences of length \( m \) can be done with energy cost \( O(\lg^* n) \). No merging algorithm with asymptotically lower energy cost has been known so far. We also argue that sorting based on a very simple merging algorithm is attractive in practical applications, due to low constant factors. In [9] we consider the case when each station stores \( k \) keys of the sequence and \( O(k) \) auxiliary variables. We propose an algorithm merging two sequences of length \( k \cdot m \) stored in two sequences of \( m \) stations with energy cost \( 8 \cdot k + 4[\lg_2(m + 1)] \) in time \( 6m \cdot k + 4m - 4 \). We may apply this algorithm in merge-sort yielding a sorting algorithm that is suitable for practical applications and, for \( k = \Omega(\log n) \), its asymptotic energetic cost is \( O(k \log n) \). We may also mix it with other merging procedures (e.g. based on Batcher algorithms) that could be more efficient in initial phases.

3 Mobile Ad-hoc Networks

3.1 Interactions in Mobile Communications

Wireless Networks are composed of a large number of hosts that move in the network area and communicate in a wireless manner. In the particular case where no fixed infrastructure is available (either because it is expensive/impossible to build one, or because such an infrastructure has been damaged) the mobile hosts must form a temporary network where the hosts may act as intermediate relays for forwarding information. Such networks are called ad-hoc mobile networks. In other wireless
networks a fixed topology underlying network exists, such as in the case of cellular networks. To better highlight the impact of mobility and interaction between hosts we focus on the ad-hoc mobile case.

One of the most essential characteristics of such wireless networks is their highly dynamic nature: mainly due to movement (but also due to failures, power saving modes etc) communication links may appear and disappear as hosts move in and out of the transmission range of other hosts. Thus, the underlying communication graph of the network is highly dynamic, changing according to the way hosts interact with each other as they move in the network area.

Another crucial feature of mobile wireless networks is the importance, necessity and impact of interaction between mobile hosts. Indeed, communication in such networks is impossible without having hosts to act as relays for information propagation (since the transmission range of hosts does not usually cover the network area and several “hops” are needed to forward a message to a target user). This interaction of hosts is closely related to their mobility, since hosts exchange information when, due to their movement, they come within transmission range of each other.

We note that this necessity of interaction applies to even the most basic versions of the communication problem, such as in pairwise communication i.e. when the sender host (MHS) wishes to send information to a single receiver host (MHR).

Other phenomena when interaction plays a key role include a) virus spread (i.e. a host may become infected when it contacts an infected one, or a virus “moving” in the network may be destroyed when reaching a host with special anti-virus software), b) intrusion propagation (the process of spreading of an attack to the security of hosts) and c) mobile agents.

**An Infection Model for Communication.** Consider $k$ particles, 1 red and $k - 1$ white, chasing each other on the nodes of a graph $G$. If the red one catches one of the white, it “infects” it with its color. The newly red particles are now available to infect more white ones. When is it the case that all white will become red? It turns out that this simple question is an instance of information propagation between random walks and has important applications to mobile computing where a set of mobile hosts acts as an intermediary for the spread of information.

In [10] we model this problem by $k$ concurrent random walks, one corresponding to the red particle and $k - 1$ to the white ones. The infection time $T_k$ of infecting all the white particles with red color is then a random variable that depends on $k$, the initial position of the particles, the number of nodes and edges of the graph, as well as on the structure of the graph.

We develop a set of probabilistic tools that we use to obtain upper bounds on the (worst case w.r.t. initial positions of particles) expected value of $T_k$ for general graphs and important special cases. We get that an upper bound on the expected value of $T_k$ is the worst case (over all initial positions) expected meeting time $m^*$ of two random walks multiplied by $\Theta(\log k)$. We demonstrate that this is, indeed, a tight bound; i.e. there is a graph $G$ (a special case of the “lollipop” graph), a range of values $k < n$ (such that $\sqrt{n} - k = \Theta(\sqrt{n})$) and an initial position of particles achieving this bound.

When $G$ is a clique or has nice expansion properties, we prove much smaller bounds for $T_k$. We have evaluated and validated all our results by large scale experiments which we also present and discuss here. In particular, the experiments demonstrate that our analytical results for these expander graphs are tight.

**Antagonism between mobile entities.** We study here dynamic antagonism in a fixed network, represented as a graph $G$ of $n$ vertices. In particular, we consider the case of $k \leq n$ particles walking randomly independently around the network. Each particle belongs to exactly one of two antagonistic species, none of which can give birth to children. When two particles meet, they are engaged in a (sometimes mortal) local fight. The outcome of the fight depends on the species to which the particles belong. Our problem is to predict (i.e. to compute) the eventual chances of species survival. We
prove here that this can indeed be done in expected polynomial time on the size of the network, provided that the network is undirected. We focus on the situation when individual members of each species “move” on a finite network (e.g. among neighbour nodes of a graph). In this case, the basic “random mating” assumption of classical evolutionary game theory collapses. Only those individuals that happen to meet currently are involved in local fights. Given this new situation (which abstracts reality in networks) can we predict efficiently the “eventual” population mixture, e.g. the chance of survival of one (the weakest) of the species? Moreover, is our prediction method better than a simulation of the evolution of the population mixture?

We embark here in the study of this question. We first define the simplest, yet nontrivial, model of two-species antagonism: Our population members (called particles also) are either very malicious “hawks” or peaceful “doves”. Hawks kill doves when they meet. Also, when two hawks meet they kill each other. Each particle performs an independent random walk in the graph. Doves do not harm each other when they meet. We then concentrate on the simplest possible question: Can we calculate efficiently the chance of eventual survival of the weakest species? We assume that the graph (of motions) and the initial particles positions are given. As a worst case scenario, we examine the weakest possible case of the weak species (just one dove). Note that the chance of eventual survival of a single dove is a lower bound for the case of many doves, since doves do not reproduce.

Then, by using standard techniques for Markov Chains we show how to compute the probability that the dove survives in \( O(n^3k) \) steps, where \( n \) is the number of vertices of the motion graph and \( k \) is the number of individuals initially on it.

We first prove the following result: When \( G \) is directed, then the probability of eventual survival of the dove can be exponentially small. We believe that in this case the problem is hard, thus, we do not expect to be able to efficiently predict the final outcome. It turns out however that, when \( G \) is undirected, then:

- We can decide in polynomial time (in the number \( n \) of the graph’s vertices) when the probability of eventual survival of the dove is non-zero.
- We prove that the probability of the doves survival (when non-zero) is lower bounded by the inverse of a polynomial in \( n \).
- We can approximate the exact value of the probability of dove survival to any degree 5 of accuracy in expected polynomial time (on \( n \) and the accuracy of the approximation). This result is a consequence of our main result in this paper, namely that the probability of doves survival (when non-zero) is bounded below by the inverse of a polynomial on \( n \).

### 3.2 Self-organization / Coordination

**Rapid Self-organization in Direct Communication Systems.** We have considered a communication model in which each peer of the network may try to contact directly any other peer, but the communication fails with a constant probability and a constant fraction of the stations might be down. This model is motivated by practical issues occurring in self-organizing phase of ad hoc networks such as P2P networks. While the standard initialization procedures require assigning consecutive numbers to all active nodes, we consider a phase of “pre-initialization” which yields much less structure in the network, but the cost of the procedure (time, the number of messages) is much lower, so that it can be regarded as an intermediate phase in organizing an ad hoc structure.

A prototype for such an approach is a scheme in which we build a structure in which most nodes are arranged in a ring (or in a few rings) in which a node knows only its successor and predecessor. Both energy cost and time cost of this solution is low: energy cost is \( O(1) \) and the time is of order \( \log n \) or below. This prototype works well even with faulty communication.
Motion Coordination of Mobile Robots. In [11] we study systems of multiple mobile robots each of which observes the positions of the other robots and moves to a new position so that eventually the robots form a circle. In the model we use, the robots are anonymous and oblivious, in the sense that they cannot be distinguished by their appearance and do not have a common x-y coordinate system, while they are unable to remember past actions.

We propose a new distributed algorithm for circle formation on the plane. We prove that our algorithm is correct and provide an upper bound for its performance. In addition, we conduct an extensive and detailed comparative simulation experimental study with the DK algorithm described in the recent literature. The results show that our algorithm is very simple and takes considerably less time to execute than algorithm DK.

3.3 Routing / Broadcasting

Ad-hoc Algorithms for Highway Broadcasting. We focus in [5, 6] on a practical (implementable) solution for broadcasting messages over networks composed of mobile units on a motorway. Our prototype is aimed to be a component of an ad hoc warning system about traffic jams on a highway. We consider the issues that are specific to particular parameter size and fine tune the algorithms to find a prototype solution for dealing with networks of a specific size.

Presented ad hoc algorithms concern broadcasting in a highway traffic: radio channel collisions can be detected (thanks to separate transmitter and receiver on a car); highway is divided into sections – within a given section only one frequency is used and neighboring sections use different frequencies. Within each section size approximation algorithm and leader election procedure are considered. Considering the length of the section and the maximal density in a jam, we get a bound on the number of transmitters. In such a scenario we design a method to estimate the number mobile units. The method is based on transmitting at a randomly chosen moment, counting the number of collisions and clear messages, and final estimation of the number of units with an appropriate (unbiased) estimator. It turns out that with an appropriate setting of constants this approach practically outperforms theoretically more efficient algorithms designed for single hop networks. The point is that the classical size approximation algorithms yield much less accurate results – and this is crucial in our scenario.

We consider a leader election that implements the following idea: in the first round, every mobile unit within a section sends the small message (could be a single bit) with a probability \( p \) (based on the car’s quantity estimate). If there is a SINGLE case, the unit which succeeded, becomes a leader. In a case of NULL, the first round is repeated. If a COLLISION took place, only those, who were sending in the previous round, enter the next phase. In this case, the second round participants change probabilities. The main issue here is to assign appropriate strategy of adopting probabilities. The first prototype assumed that in the second round sending probability is \( 1/2 \) for every participating unit, whereas for the second prototype each unit draws its own new probability from the Bernoulli distribution \( B(\lfloor \hat{n} \rfloor, \frac{1}{n}) \).

Different cases, assuming different car’s quantity distributions are considered. Furthermore, expected time for successful transmission as well as confidence intervals and quantiles are obtained. Prototype broadcasting algorithm is fast and reliable. Within few seconds a message travels for many kilometers. The total overhead of the system is about 20%.

Routing in Ad-hoc Mobile Networks. In [12] we demonstrate the significant impact of (a) the mobility rate and (b) the user density on the performance of routing protocols in ad-hoc mobile networks. In particular, we study the effect of these parameters on two different approaches for designing routing protocols: (a) the route creation and maintenance approach and (b) the “support” approach, that forces few hosts to move acting as “helpers” for message delivery. We study one
representative protocol for each approach, i.e. AODV for the first approach and RUNNERS for the second.

We have implemented the two protocols and performed a large scale and detailed simulation study of their performance. For the first time, we study AODV (and RUNNERS) in the 3D case. The main findings are: the AODV protocol behaves well in networks of high user density and low mobility rate, while its performance drops for sparse networks of highly mobile users. On the other hand, the RUNNERS protocol seems to tolerate well (and in fact benefit from) high mobility rates and low densities. Thus, we are able to partially answer an important conjecture in the literature. In [13] we investigate the impact of different mobility rates on the performance of routing protocols in ad-hoc mobile networks. Based on our investigation, we design a new protocol that results from the synthesis of the well known protocols: ZRP and RUNNERS. We have implemented the new protocol as well as the original two protocols and conducted an extensive, comparative simulation study of their performance. The new protocol behaves well both in networks of diverse mobility motion rates, and in some cases even outperforms the original ones by achieving lower message delivery delays.

Another approach to this subject is included in [14]. The basic idea is to synthesize the two different approaches in a way such that the new routing protocols will benefit from the very high delivery rates of the support approach, while delivering the messages with short delays as done by the protocols that follow the path construction approach. In this work, we propose the use of a metric, named stability, which is used for characterizing the relative mobility of the nodes. The metric is using the notion of associativity, which is the time (in beacons) that nodes are associated (i.e. they retain a connection). According to its stability, every node is classified to a mobility class. Based on these mobility classes, we design a novel protocol framework that operates on top of the network layer and for any pair of origin and destination, determines the routing technique (among those available to the nodes) that best corresponds to their mobility properties.

In contrast to [13] we take special care to limit any changes made to the software agents that implement the routing protocols, rather than synthesizing (by re-designing and reimplementing) the original protocols. This design decision allows us to integrate with relatively minimal effort, the large volume of routing protocols available in the literature of mobile ad hoc networks (e.g. we used the protocols available in ns-2 without making any significant changes). Our detailed performance evaluation (via software simulations) indicates the advantages of employing this mobility sensitive approach over using a single routing strategy.

References


